ESTEC/ITT AO/1-7206/12/NL/AK

Ultra-Wideband as a Multi-Purpose Robust and Reliable Wireless Technology for Testing, Spacecraft and Launcher Communications

« UWB4SAT »

Final Presentation Days

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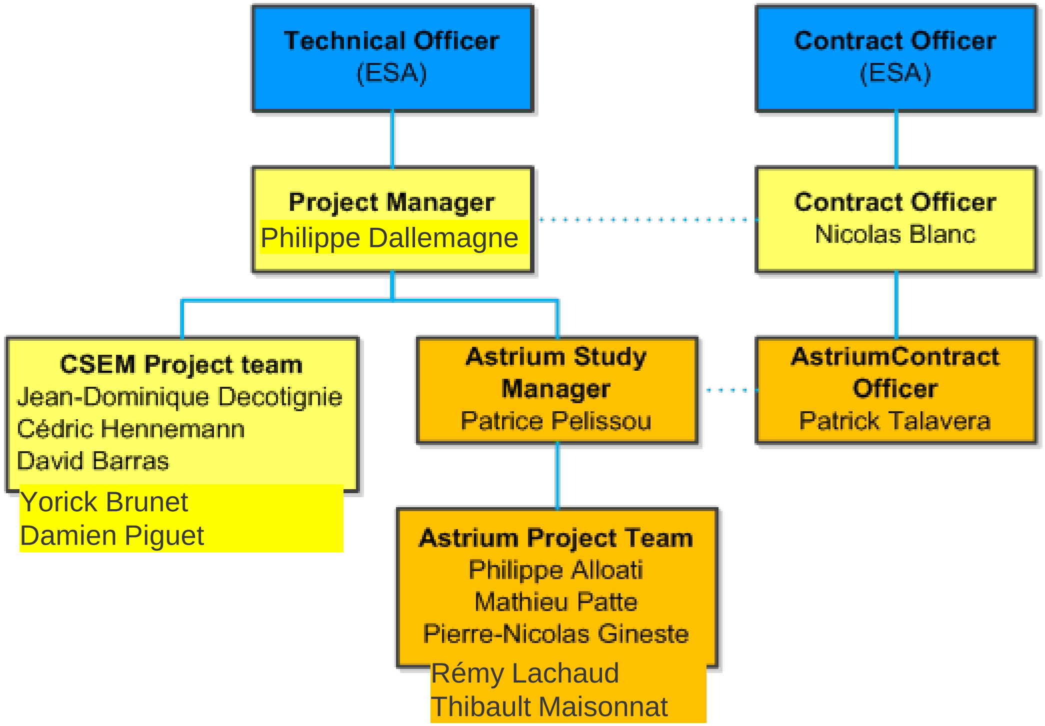
Noordwijk 10.12.2014ESA

UWB4SAT: Team



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Agenda – robust UWB wireless

- Objectives
- Methodology
- Context, potential applications of UWB
- Use cases
- Platform
    - Communication architecture, protocol, real-time/determinism
    - Hardware, why Decawave?
- Setup & tests
- Results, good news, bad news
- Conclusion: New requirements on the components

Project objectives: SoW

Number	Requirement	Verification Method
R-001	The UWB-based Communication System shall play the role of data communication interface between the on-board computer and/or RTU and/or EGSE and the satellite sub-systems.	R
R-002	The UWB-based Communication System shall play the role of data communication interface between the on-board computer and/or RTU and/or EGSE and dedicated standalone on-board sensors.	R
R-003	The UWB-based Communication System shall allow bi-directional data traffic.	R
R-004	The UWB-based Communication System shall access the RF medium in a very deterministic way.	R/T
R-005	The UWB-based Communication System shall present a near-fixed latency (better than 100ms TBC) with a low jitter (better than 50us TBC).	R/T
R-006	The UWB-based Communication System shall permit a precise measurement of latency and jitter values.	R/T
R-007	The UWB-based Communication System shall support the star topology.	R/T
R-008	The UWB-based Communication System shall support wireless data routing to increase the network’s reliability in case of failure.	R/T
R-009	It shall be possible to use two different networks in parallel (e.g. one network for command and control and a network for sensor data acquisition).	R/T
R-010	It shall be possible to use two identical networks in a cold redundancy configuration.	R/T
R-011	It shall be possible to use cross-strapping techniques.	R/T
R-012	The UWB-based Communication System’s interface to the OBC, RTU, EGSE or Sub-systems shall be one or several of the following: Ethernet [RD22], Spacewire [RD18], SPI, milbus 1553b [RD17], or RS422 [RD20].	R
R-013	There shall be an interface to connect the UWB-based Communication System to a host microcontroller from or instead of the main interfaces mentioned in requirement R-012 when the system is used by a “standalone” sensing unit (e.g. sensor).	R
R-014	The bandwidth/timeslot allocation/reservation shall be statically configurable (e.g. preliminarily loaded in non-volatile memory) as well as dynamically configurable (e.g. following requests for reservations).	R/T
R-015	The minimum payload data throughput supported by the UWB-based Communication System shall be 1Mbps.	R
R-016	The over-the-air data rate shall be 27Mbps.	R
R-017	The UWB-based Communication System shall consist of a single board.	I
R-018	The UWB-based Communication System shall use energy-saving techniques to reduce overall power consumption (e.g. sleep modes).	R/T
R-019	The UWB-based Communication System shall not consume more than 1 watt peak of power during nominal operations (TBC).	R/T
R-020	The UWB-based Communication System shall provide means to verify the correct status/behaviour of all the implemented functionalities.	R/T
R-021	The UWB-based Communication System shall ensure the link budget between all the nodes of the network.	R/T

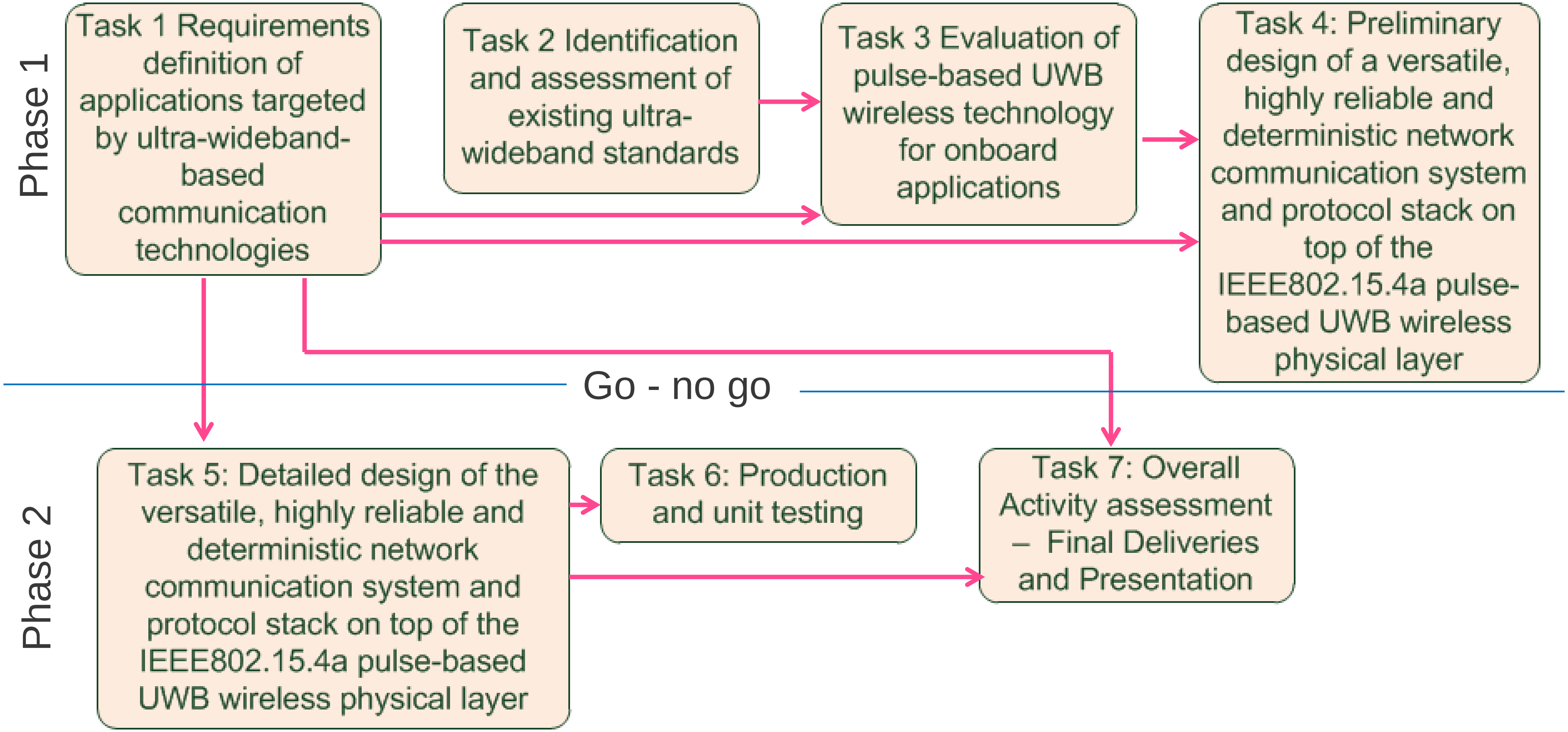
Number	Requirement	Verification Method
R-022	The UWB-based Communication System shall have a single power source feed.	R
R-023	The UWB-based Communication System may support a battery-powered source feed in the case of sensors.	R
R-024	The master power interface shall be compatible with typical on-board equipment power supplies [3V - 12V].	R/T

Number	Requirement	Verification Method
R-025	The UWB-based Communication System shall not interfere with other standard spacecraft equipment and systems in accordance with the guidelines found in [AD3].	T/A
R-026	The UWB-based Communication System shall sustain external interferences from other standard spacecraft equipment and systems in accordance with the guidelines found in [AD3].	T/A

Project objectives

- Assess the applicability of Ultra Wide Band to wireless space craft communications
  - Explore IR-UWB (802.15.4a) capability to sustain communications
    - In or between spacecraft cavities
    - Without interfering (too much) with existing wireless systems
  - Achieve the required level of determinism for control/command or high frequency sampling
    - Synchronisation, jitter
    - Latency
  - Prototype the design
  - Measure the performance
  - Define the roadmap towards a “UWB for Satellites”

UWB4SAT: Methodology



Phase 1

Task 1 Requirements definition of applications targeted by ultra-wideband-based communication technologies

Task 2 Identification and assessment of existing ultra-wideband standards

Task 3 Evaluation of pulse-based UWB wireless technology for onboard applications

Task 4: Preliminary design of a versatile, highly reliable and deterministic network communication system and protocol stack on top of the IEEE802.15.4a pulse-based UWB wireless physical layer

Go - no go

Phase 2

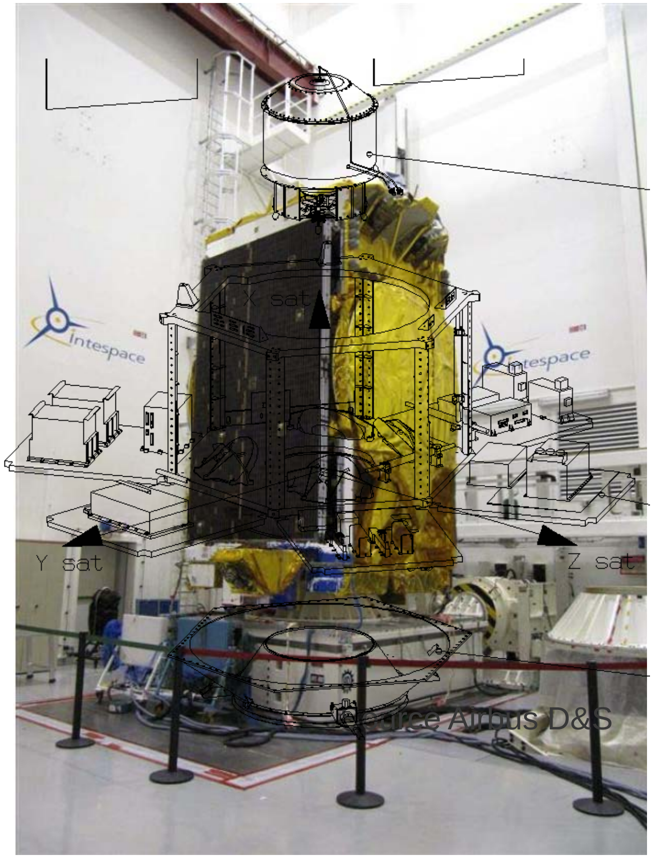
Task 5: Detailed design of the versatile, highly reliable and deterministic network communication system and protocol stack on top of the IEEE802.15.4a pulse-based UWB wireless physical layer

Task 6: Production and unit testing

Task 7: Overall Activity assessment – Final Deliveries and Presentation

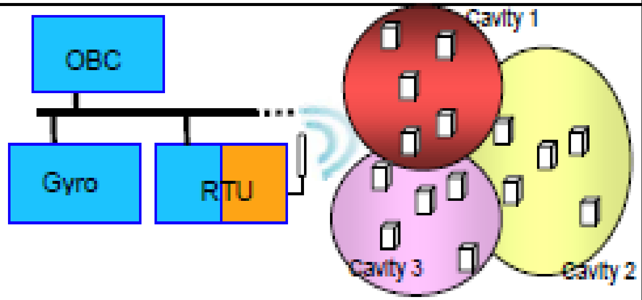
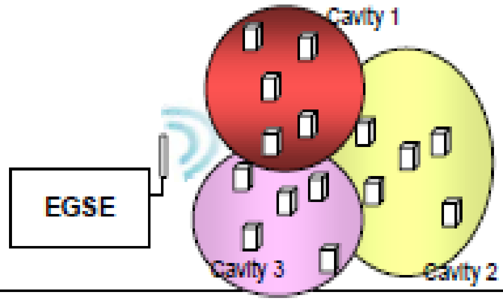
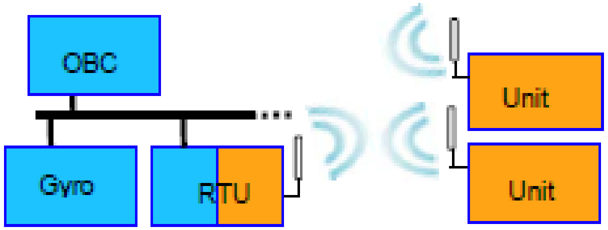
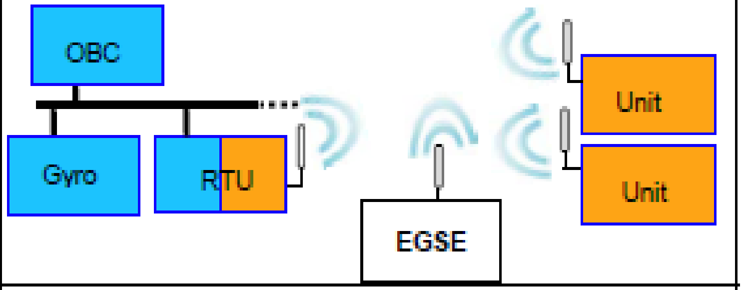
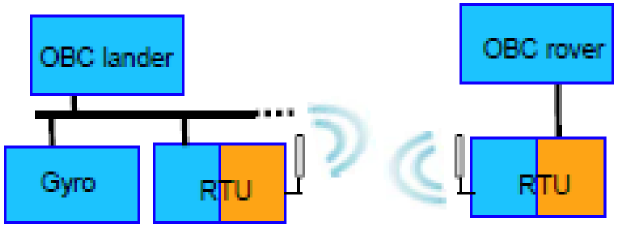
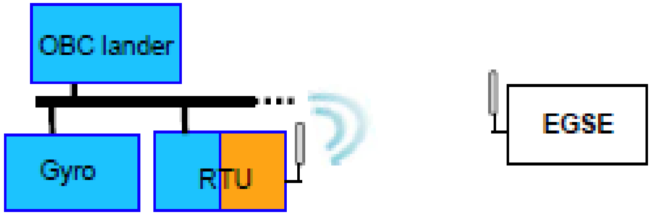
Potential benefits: why wireless in spacecrafts?

- Communication in spacecrafts rely on wired networks
  - MIL StD 1553, CAN, SpaceWire/Fibre
- Wireless would be an option, but…
  - Should be predictable
  - Complex metallic environment
    - Cavities and holes
  - Pretty high throughput required
  - Low latency
  - Low power consumption



Source Airbus D&S

Use cases: on-board and ground applications

	Onboard application	Ground application
High data-rate sensor networks UC1		
Highly reliable command and control data bus UC2		
Wireless bridge i.e Spacewire to UWB bridge UC3		

Source Airbus D&S

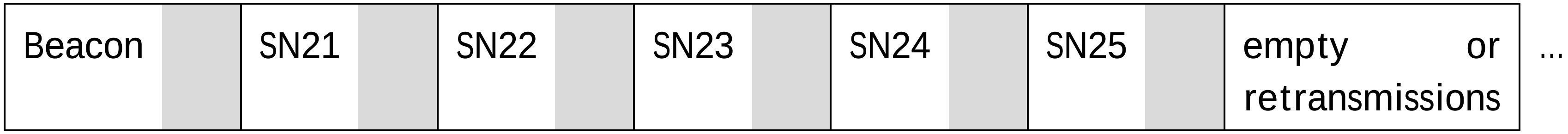
Summary of communication specification

- Initial requirements

	UC1	UC2	UC3
Nb of nodes	20, 400, 40	40	2
Sampling rate [Hz]	20K, 20K, 20K	32	NA
Latency	0.1ms, 1800s, NS	NS (>0.7ms)	12 µs
Raw throughput	6.4M, 8.54M, 12.8M	20.48K	>10 Mbit/s full duplex
Specialty		Multiple sampling rates simultaneously	
Time synchronization	1 µs	1 µs	NA

Protocol design decisions

- Star network topology
- If necessary, multiple stars will be used
- TDMA MAC with beacon and fixed size slots
  - Traffic schedule is maintained centrally and not communicated to the sensors. Requests are notified by the coordinator in the beacon.

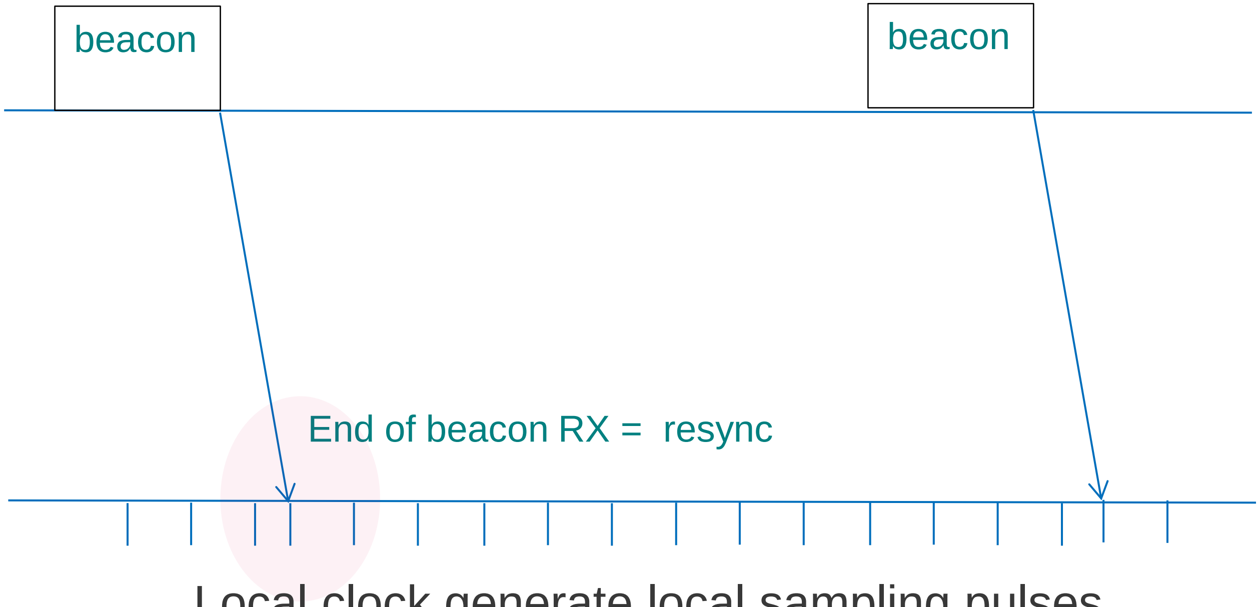


Beacon		SN21		SN22		SN23		SN24		SN25		empty or retransmissions	…

  - Beacon-based distributed synchronized clock
  - Sampling signals can be generated locally on each sensor node

⇨ Time-constrained master-slave communication model

Protocol design decisions



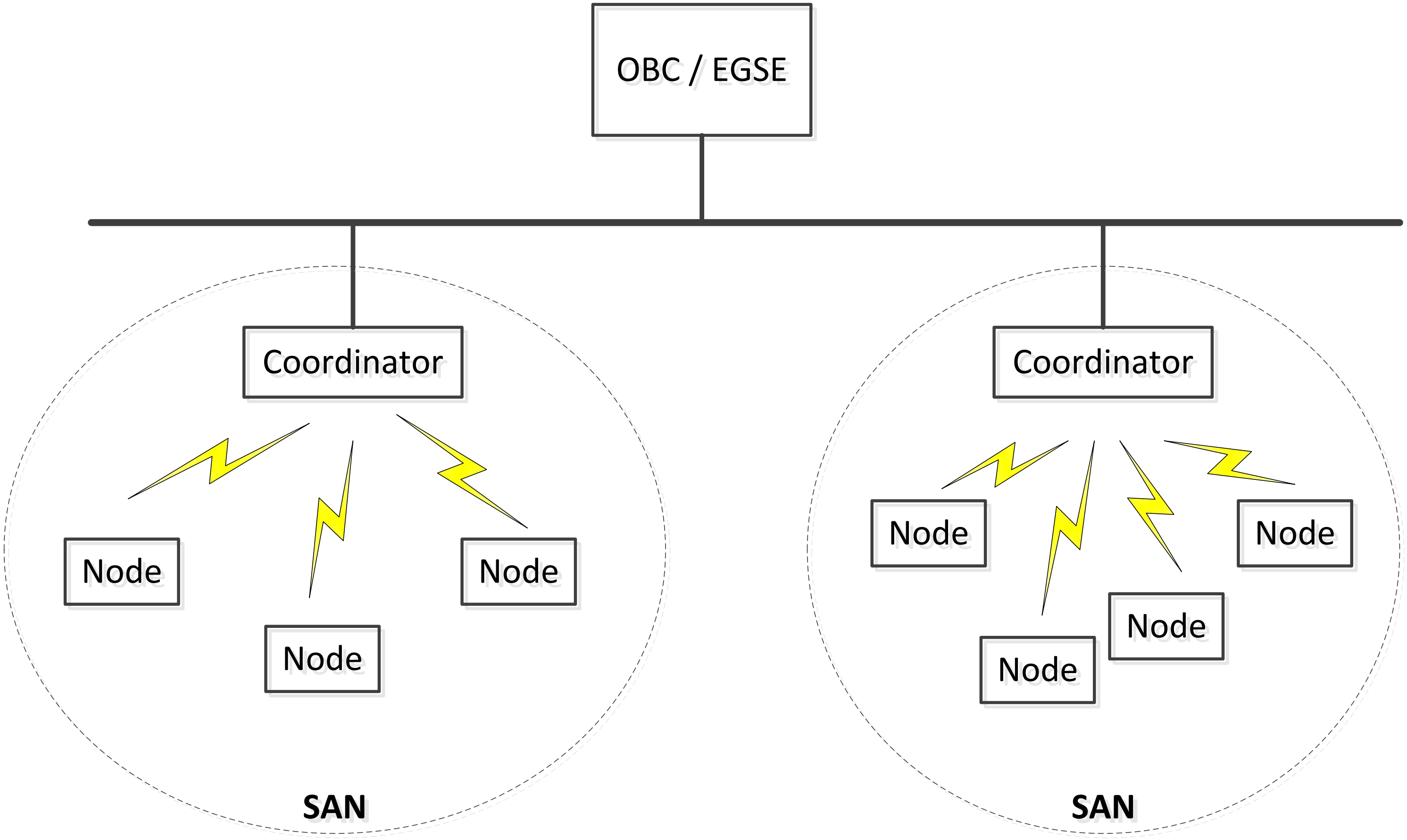
Local clock generate local sampling pulses

- Clock drift < 100 ppm => pulses sync drift < 1 us (over 1 ms beacon interval)

Protocol design decisions

- Data samples may be packed in a single packet provided latency (deadline) constraints are met
- Data compression may be used to support the requirements
- All 3 use cases are implemented using the same basic TDMA solution.
- With respect to synchronisation
  - Beacon-based synchronisation of local clocks
  - IEEE 802.15.4e can do the job (e.g. LLDN)
- With respect to the redundancy
  - For lack of precise reliability information, no decision may be taken.
  - Design does not preclude redundancy to be introduced at a later stage

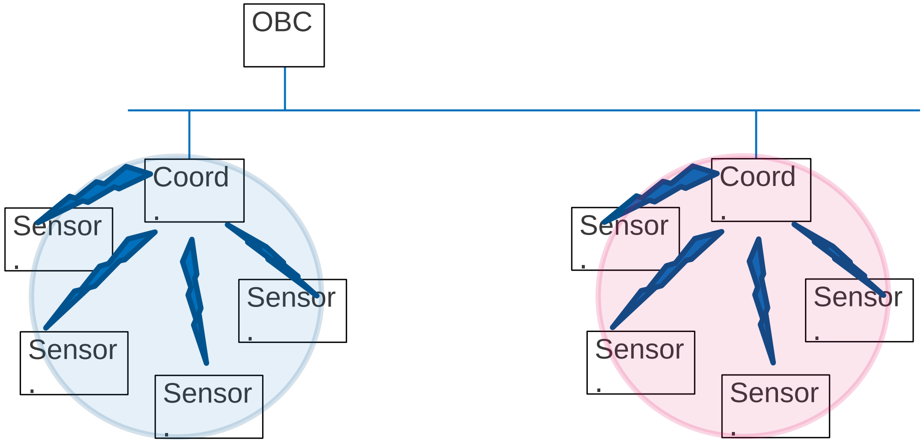
Network architecture



SAN = Spacecraft Area Network

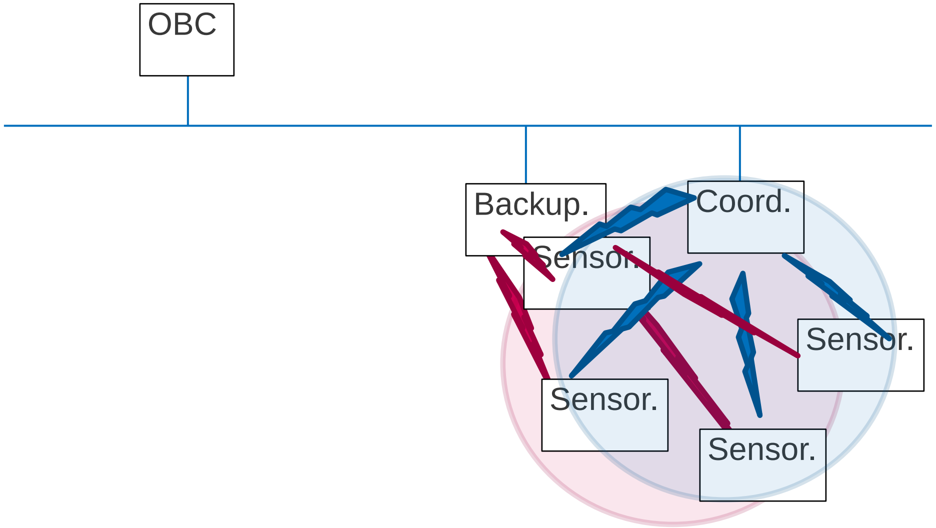
Network architecture (multiple networks)

- Global network architecture (UC1, UC2): star topology
  - Sensors around Coordinator
  - Interconnection to the on-board backbone, to OBC
  - N.B.: coexistence of several networks is possible
    - different channels,
    - Network ID



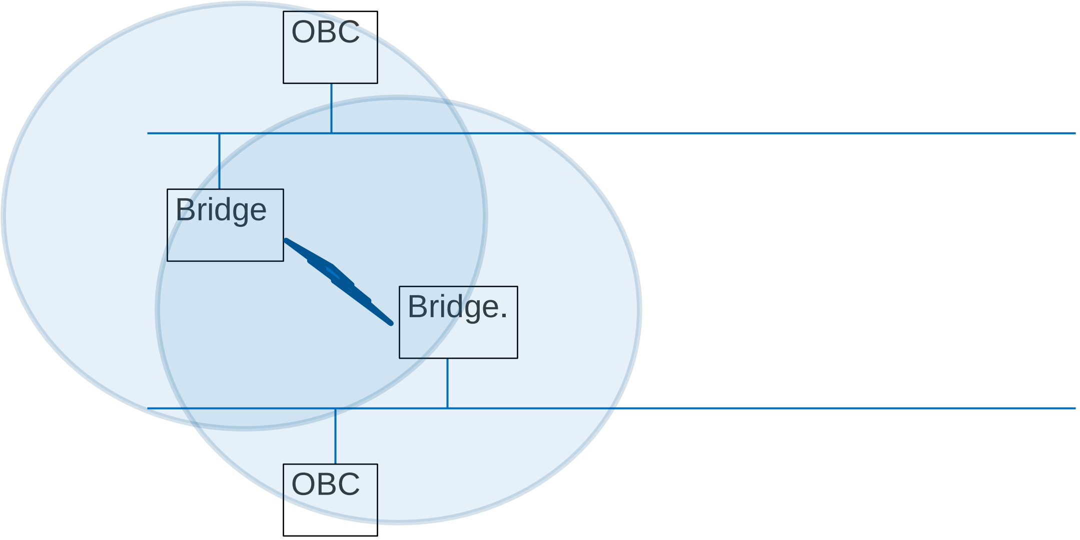
Network architecture (redundancy)

- Global network architecture (UC1, UC2): redundancy
  - E.g.: two coordinators for one set of sensors



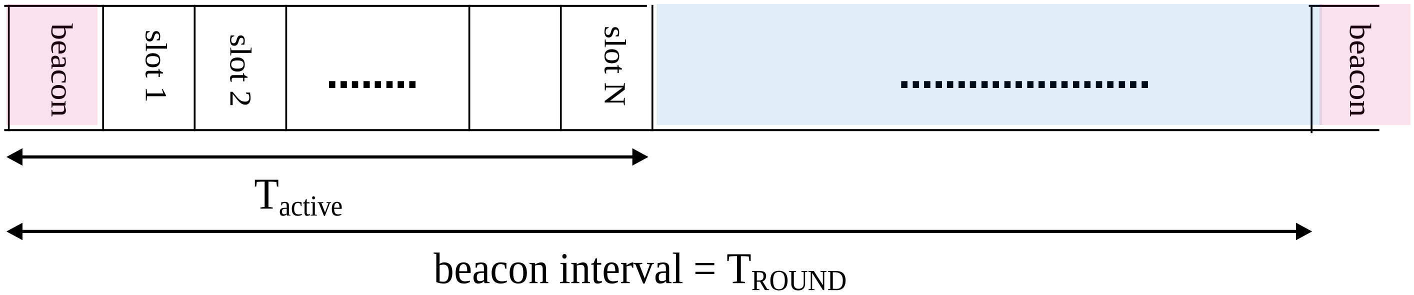
Network architecture (point to point)

- Global network architecture (UC3): point to point
  - Two nodes, that can act as backbone nodes (e.g. 1553)

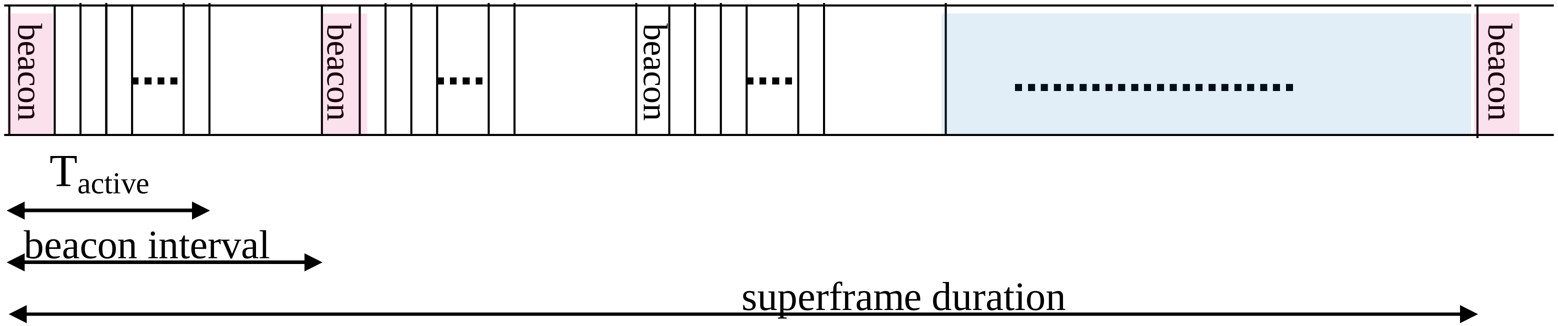


Protocol: retransmission schemes

- Wireless transmission is prone to errors
- Having an efficient retransmission scheme is important
  - Retransmission immediately after TDMA slots in the remaining bandwidth



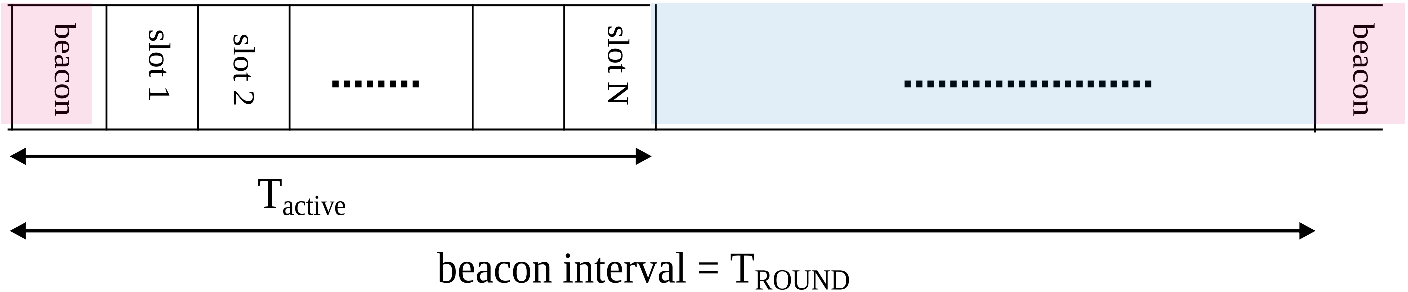
  - Retransmission after K beacons intervals (better usage, higher latency)



Protocol: retransmission schemes

1. Assign slots for retries in a static manner (fixed)
    - 1 slot for transmission and KR slots for retry (in KR beacon interval)
2. Assign slots for retries in a dynamic manner
    - In each beacon interval, there are NSR slots for retries
    - The slots are assigned dynamically to recover from failures in previous beacon interval

- We chose



    - Second option for slot assignments: the beacon contains the indication of failed transmissions that happened in the previous beacon interval.

Estimated performance

- Most of the requirements can be met by a system based on IR-UWB, except for latency.
- **Latency**: minimum latency (in a request response interaction) ~ 1 ms. (10, 50 and 100 µs not possible).
  - but synchronisation accuracy for the sampling can be about 1 µs (even 500 ns), as required.
- **Support for 400 sensors**: OK (addresses on 16 bits.)
- **Delay for retrieving the 400 sensor data**: need to have at least 2 networks
- **Overall throughput of 10 Mbit/s and more**: NC, need to have at least 2 networks

Evaluation of existing solutions and protocol design

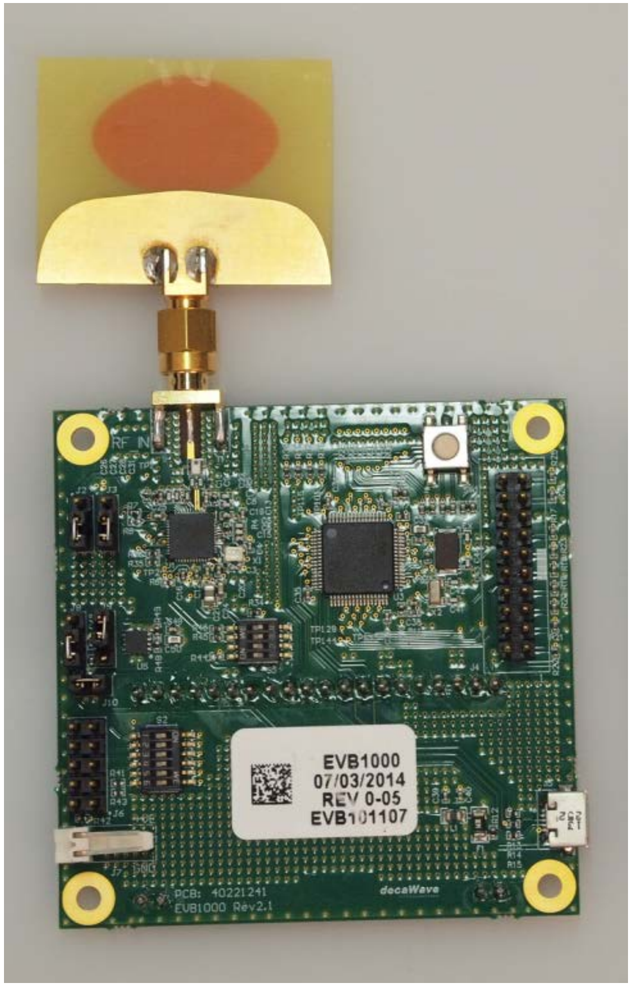
- Requirements for wireless com in spacecrafts are challenging
- Existing wireless technologies are not able to meet these requirements
- Promising approach: IEEE 802.15.4a IR-UWB together with a modified 802.15.4e slotted protocol
  - IEEE 802.15.4e provides the necessary support for clock synchronization, but is overly complex for the task
  - But retry policy has a strong impact on residual PER
    - A dynamic policy is necessary for low residual PER
    - Smallest impact on maximum latency is required
  - Immediate acks are useless in a centralized system

⇨ Dedicated TDMA slotted protocol with the preferred retransmission scheme

What about Decawave?

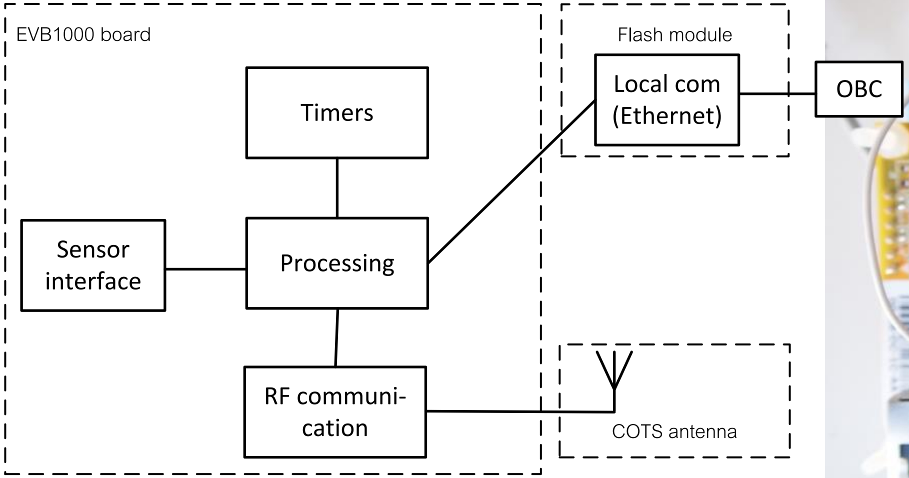
- Decawave DW1000 chip is available
  - Designed for ranging application
  - But provide data communication with data rates up to 6.8 Mbit/s (no 27 Mbit/s!)
- Evaluation kits are available
- Documented and sample source available
- Rather good support

- Actual performance? Timings?
- Parameters, flexibility?
- Stability?
- Track record?



Test environment & equipment: platforms under test

- Coordinator / Bridge



EVB1000 board

Timers

Sensor interface

Processing

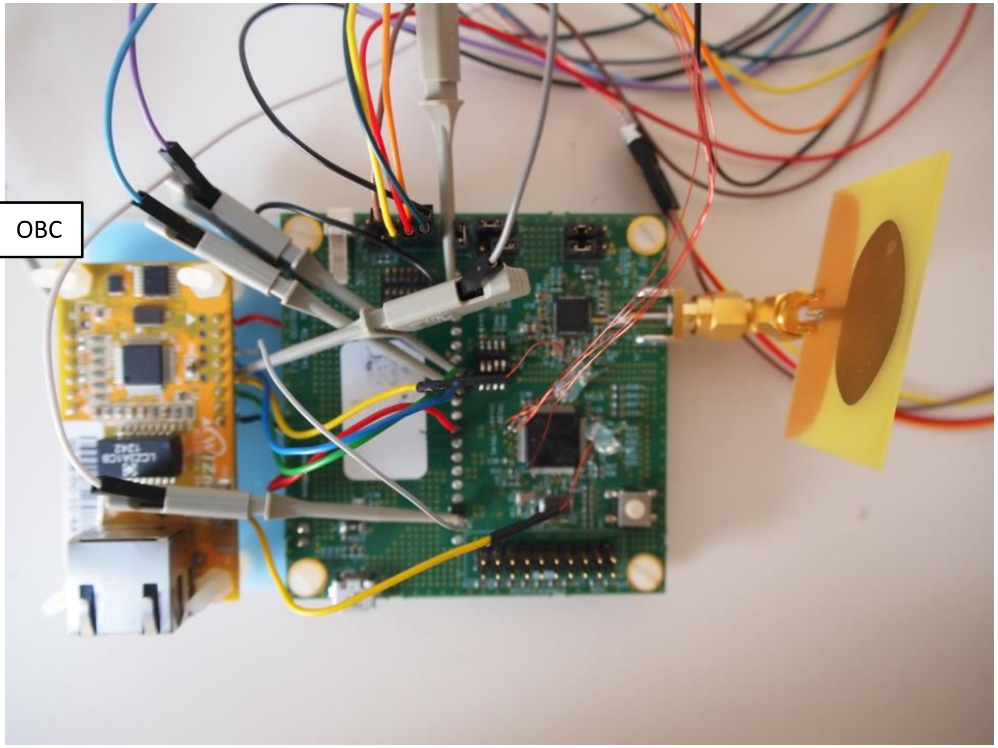
RF communi- cation

Flash module

Local com (Ethernet)

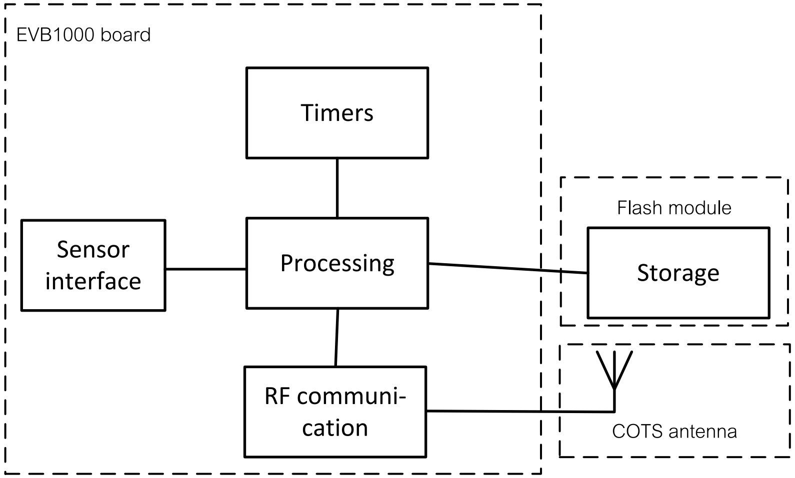
OBC

COTS antenna



Test environment & equipment: platforms under test

- Sensor node


EVB1000 board

Timers

Sensor interface

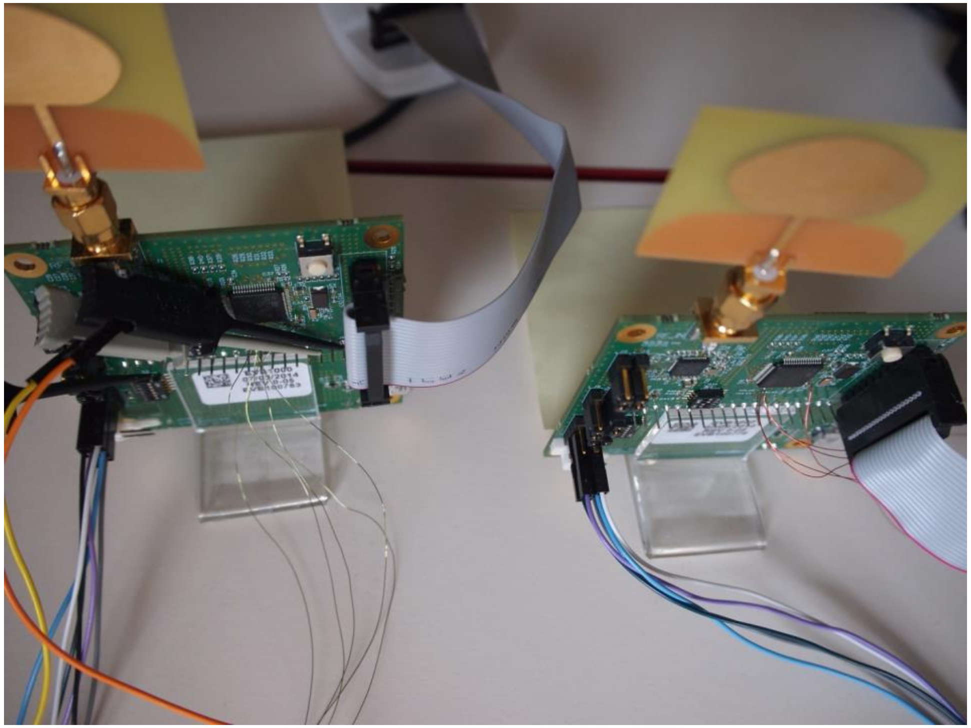
Processing

RF communi-cation

Flash module

Storage

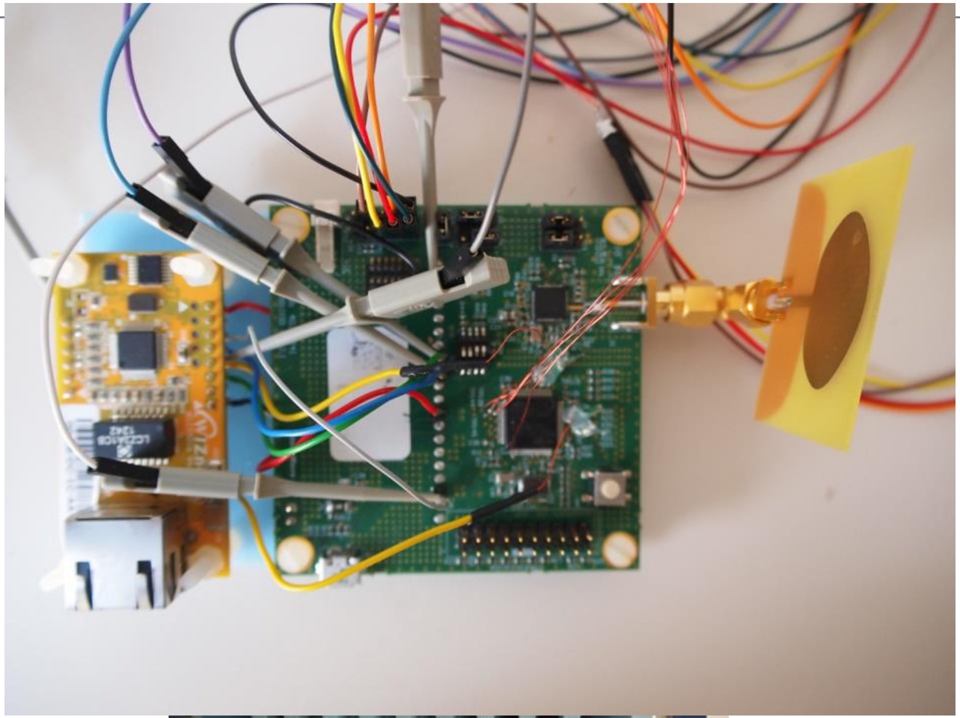
COTS antenna

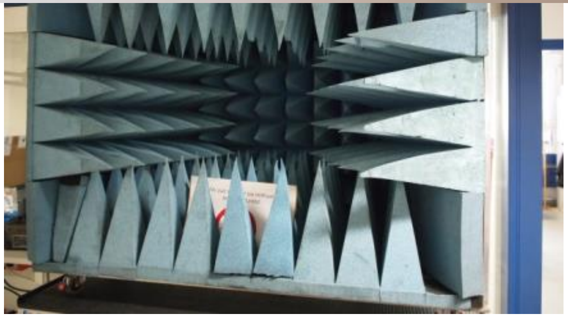


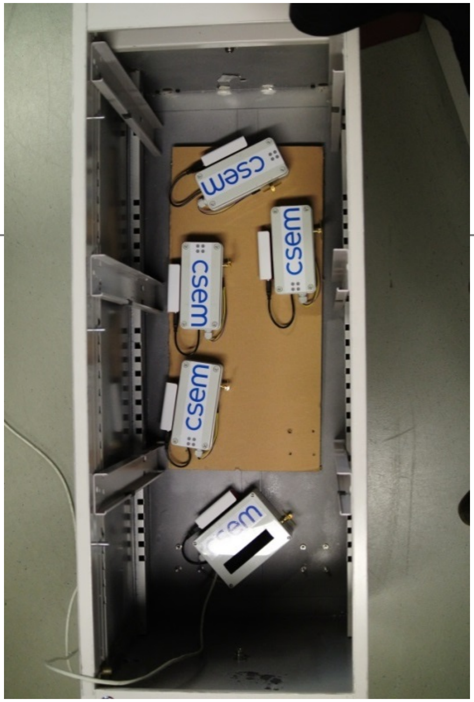
Tests

- Verification Plan
  - Validation of the computation hypothesis and simulation models
  - UWB performances in free space
  - UWB performances in spacecraft cavities
  - UWB coexistence with NB interference

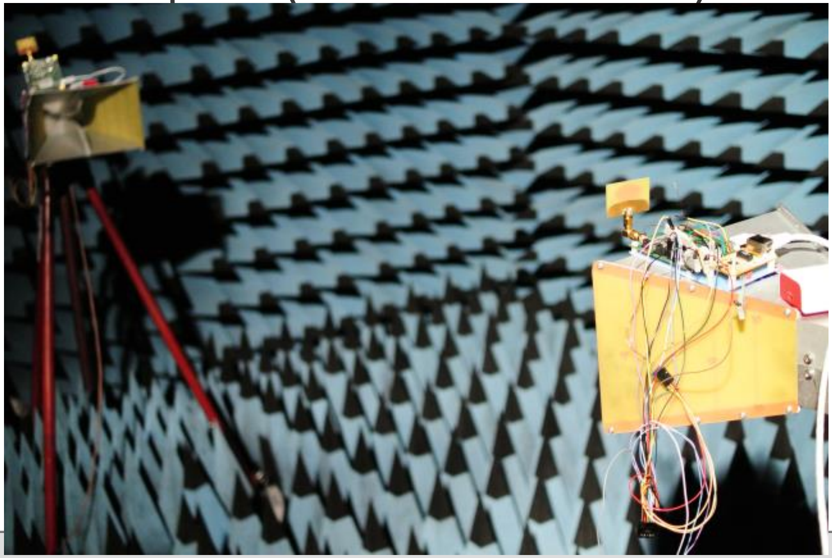
Laboratory test environment





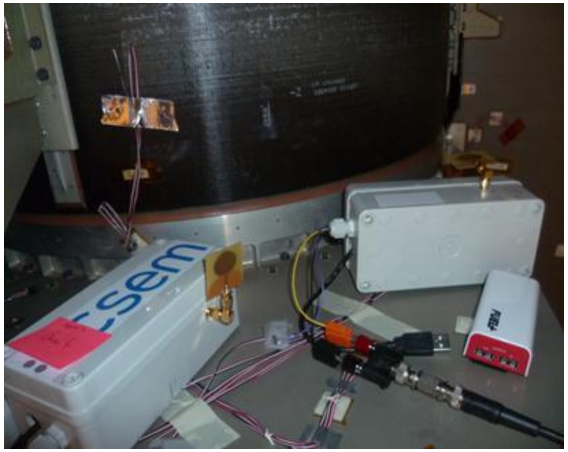


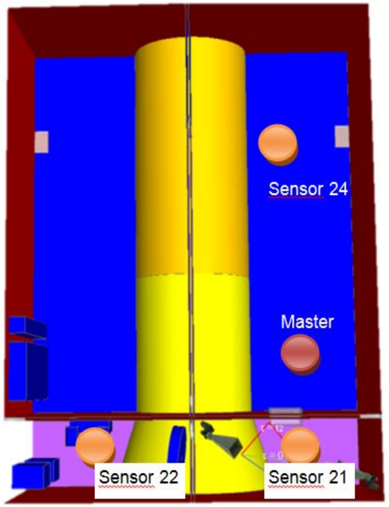
Free space (anechoic chamber)

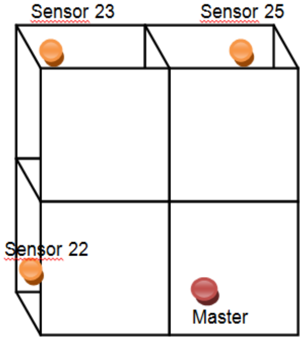


Spacecraft environment

- Intra-cavity
- Inter-cavity
- External-internal

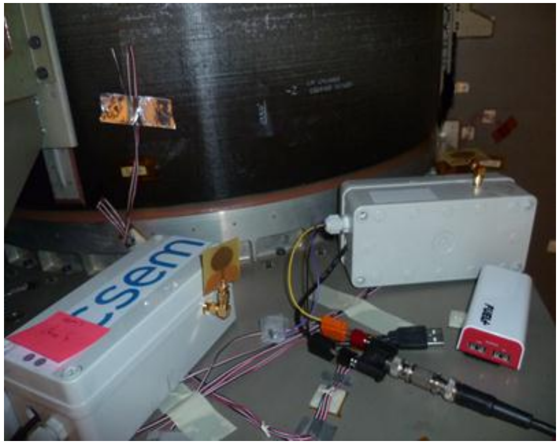






Characterisation, spacecraft tests, coexistence

- Tests performed in Airbus D&S Toulouse
  - Physical layer characterization
    - RF measurement of the DecaWave UWB signal
    - PER=f(Eb/N0) curve characterization
  - Link budget in wired configuration
  - Performance measurements in spacecraft cavities
    - PER=f(Eb/N0)
    - Link budget threshold
    - Synchronisation
    - Latency
  - Coexistence with NB interference

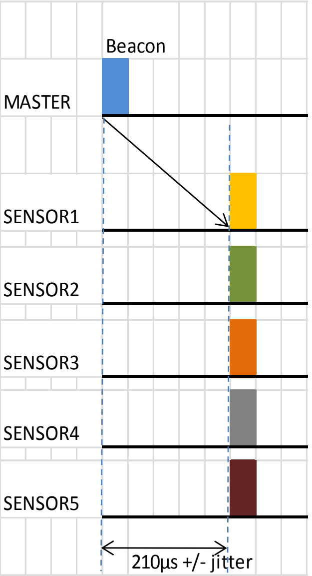


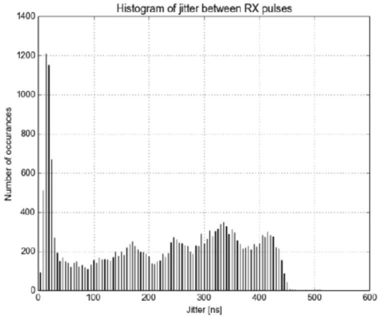
Results (Spacecraft, 1)

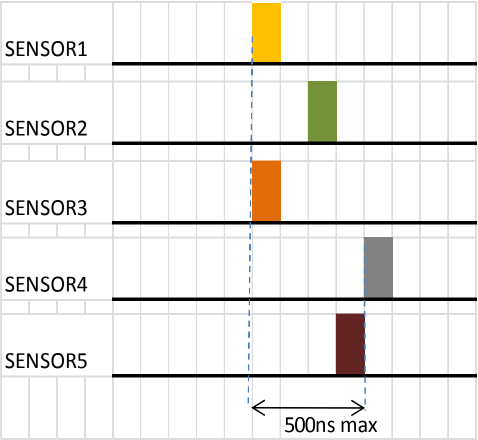
- The Decawave RF spectrum is **compliant** with the IEEE 802.15.4a standard (+/-1.3dB)
- **Recommended** preamble length to use a minimum preamble length of 128 symbols for 6.8Mbps
- PER=f(Eb/N0) curve very **close to the theoretical** BER curve for PER>1E-3
- Link budget measurement has shown that the **QoS is degraded** when the UWB signal level increases at the receiver input. This could be explained by the fact that the input stage (low noise amplifier) is saturated when the UWB signal is too high
- Measurements inside the spacecraft show **robustness to multipath**: only +11dB degradation at 6.8Mbps in the worst case configuration
- Link budget measurements demonstrate **comfortable margins** (>+18dB at 6.8Mbps) in term of signal power in the worst case configuration i.e. emitter & receiver located in opposite cavities
- Open and closed wall configurations demonstrate also **positive margin** (>+9dB at 6.8Mbps) in term of signal power in flight configuration (all external apertures closed and walls covered by MLI), the link budget between an UWB emitter located outside the spacecraft cavity and the receivers inside the spacecraft will not be ensured due to the attenuation provided by the structure and MLI

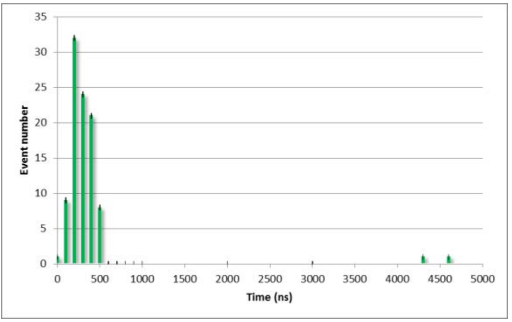
Results (Spacecraft , 2)

- The interference test with a **narrowband signal** has shown the coexistence feasibility with the UWB signal when a maximum NB E-field level inside the spacecraft is lower than 4V/m. This is compatible of a UWB system implementation inside the spacecraft.
- Synchronisation measurements have demonstrated, in most of the data, a maximum time deviation between sensors of **500ns** which is lower than the system requirement of 1µs. Nevertheless, deviation of 4µs is also measured explained by two interrupts raising at the same time. H/W or S/W modifications will solve this issue





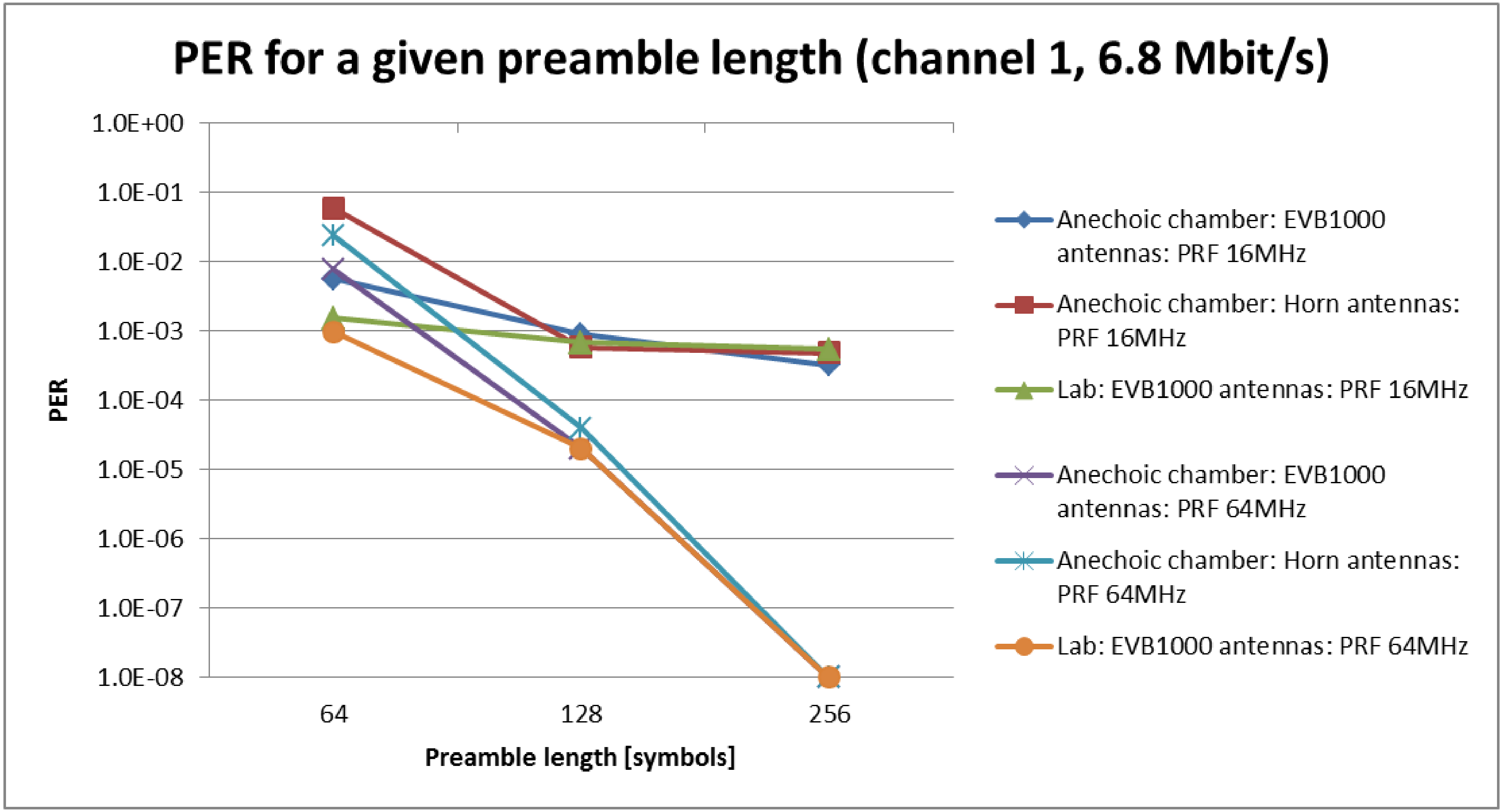




Results (in-lab)

- PRF=64 MHz MHz, preamble=128 symbols, data rate=6.8 Mbit/s
- Synchronisation jitter of the receptions: measure the end of RX on the different sensor nodes: 500 ns max.
- Transmission time of a 30 bytes packet: 200 us
- Latency: delay measured on the master between start of beacon TX and end of response RX: 350 us + n*1000 us (n is slot number)
- Minimum slot size: 250 us => max. beacon frequency of 2 kHz with a response, 4 kHz without response.
- PER (30 bytes): with 64 symbols preamble = 10^{-2}; with 128 symbols = 10^{-5}.
- Maximum throughput is about half to two-thirds of the nominal raw data rate

Results (in-lab)



Communication system analysis

- Three different use cases and their requirements in terms of communications
- Measurements
  - Minimum latency: about 300 us for the first node
  - Error rate: PER 10^{-4} worst case
  - Bandwidth: 3 to 4 Mbit/s in the best conditions
  - Functionality: compliant
- Error correction effect: residual PER < 10^{-6}
- Energy consumption: max. < 700 mW

UWB4SAT Project output

- The development of the UCS is terminated
  - Communication protocol simulated and tested on UCS
    - Functionally implemented and debugged in simulator (many nodes, variable parameters)
  - Command software
  - Test scripts allows full parameterisation of tests
- Three Coordinators and eleven nodes
  - 2 x (1 coordinator and 5 networked nodes)
  - 1 coordinator and 2 individual sensor nodes

- UCS tested according to test plan
  - UC1 and UC2 tested
  - UC3 (two Bridges) tested (throughput evaluation)

UWB4SAT Project output

- Four UCS set-ups tested
  - 2 for PER/BER and throughput tests
  - 2 for networking, synchronisation and delay tests
- UWB4SAT tested in spacecraft and in-lab
- Deliverables, measurements and test reports delivered

Deviations

- from the SoW
  - Reliability analysis dropped (no information about the Decawave chip)
  - Mechanical characteristics of an installed node and its mechanical interfaces (attachments, fixtures, etc.) is out of scope.
- from the application requirements
  - The bridge application dropped (limited data rate of the Decawave DW1000 chip) but DW1000 analysed wrt. performance and bottlenecks

Specification and requirements for a new UWB chip

- Required:
  1. Fix the problem with the increased error rate when link budget increases
  2. Raise the data rate to 27 Mbit/s at least;
  3. Make a rad-hard version
- Desired
  1. Reduce or hide inter packet gaps, preambles and data transfer delays over SPI
  2. Several Interrupt Request lines for handling different events
  3. Allow for simpler programming (API);
  4. Keep the good things of DW1000: compliance to IEEE 802.15.4a, appropriate behaviour for TDMA protocol
  5. Keep the good documentation and responsive e-mail support
  6. Offer even more optimisations options (SPI, double-buffering)
  7. Keep the good EVK1000 evaluation kit

Thank you for your attention!

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