Development and experiences of a fully wireless satellite bus for the InnoCube CubeSat mission

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ABSTRACT

The Innovative CubeSat for Education (InnoCube) mission aims to demonstrate new and innovative technologies. One of the innovative technologies is SKITH (SkipTheHarness), a wireless satellite bus system. The goal of the mission is to demonstrate the "wireless satellite", where the conventional data harness is replaced by a robust, high-speed, real-time, short-range radio communications bus using the SKITH technology. Integrated into the main-satellite bus, this will make InnoCube the first satellite relying only on a fully wireless data system architecture.

There are several advantages using this approach: Cable harness mass is reduced and the common problem of broken wires or connectors is mitigated. Flexibility in the design of the satellite does not affect the data harness configuration. It also increases the flexibility and testability of the data bus on the integrated satellite. Short-range radio communications might also be suitable for inter-satellite communication in close satellite formations or docking situations.

Using a wireless data bus also brings several advantages in the every-day development process of the satellite systems and might differ from traditional experiences. Flat-Sat models can easily be extended by additional modules which share the same wireless interface. Connected systems do not need to be physically in the same location and might even be worked on in different offices, whilst accessing the same shared satellite hardware in the lab. Especially analyzing bus traffic between the different nodes and even injecting simulated network data for hardware in the loop tests seems to be a very efficient feature.

Developing a fully wireless satellite and applying new technologies also brings new challenges to the design and development process, since it might differ from the traditional forms. This paper will discuss the several real-world experiences and use-cases from a developer point of view while working on the InnoCube mission. We will give an introduction into the SKITH wireless technology and how it affected our development process by giving examples of its particular application eg. in the AIVT-phases of the ADCS-subsystem.

As a collaborative project between the University of Wuerzburg and TU Berlin, InnoCube also aims to provide educational purpose for students as well as the development and teaching of important engineering, technical and scientific skills. This article gives an overview of the overall InnoCube mission and

will then focus on the SKITH wireless technology and its real-world application throughout the mission phases.

1 INTRODUCTION AND BACKGROUND

Removing the cabling within the satellite reduces the weight and complexity of the spacecraft. This allows for smaller and more flexible systems. A modular satellite can be built by bolting the components together without having to worry about cabling for data exchange. In current satellites, the wiring harness often takes up over 10% of the total weight [1]. As an example, the Mars Express probe launched in 2003: Of the total dry mass (without propellant) of 640 kg, the cable harness alone accounted for 64 kg [1]. If only 10% of this mass could be saved, this would already be a saving of 76,000 € to 204,800 € (launch costs approx. 10,000 € to over 20,000 € per kilogram for LEO or SSO [2]). In SKITH we want to show that the concept of using wireless communication can be used upon spacecraft in general.
Typically, many sensors and actuators are directly connected to the on-board computer, so that it requires a correspondingly large number of input-output interfaces (IO interfaces). However, since the components used are mission-dependent, the on-board computer must be adapted accordingly to the interfaces of the respective components for each new mission.
At the University of Wuerzburg, several research projects have been developing programmable wireless modules for radio transmission that provide the typical interfaces for IO connections [3, 4, 5]. The following interfaces are often used in hardware design and are covering a wide range of possible storage-devices, sensors or actuators which might be connected to:

- Analog input via analog-to-digital converter (A/D)
- Inter-Integrated Circuit (I2C, serial data bus)
- Serial Peripheral Interface (SPI, serial data bus)
- Universal Asynchronous Receiver Transmitter (UART, serial interface)
- Controller Area Network (CAN, serial bus system)

These front-end modules perform all the necessary protocol conversions accordingly and thus provide a uniform, wireless interface for all IO devices. In this way, the on-board computer becomes completely independent of the interfaces of the sensors and actuators used. Replacing one device with another within the satellite after integration has begun or has been completed is normally unthinkable. Due to the uniform radio standard, the system offers the necessary flexibility to make this possible without any problems.
A nice side effect of this effort is the ease of monitoring, even after final integration, without having to provide interfaces for external devices or additional software. Sensor data can be easily recorded and analyzed via a receiver outside the satellite, and sensor data can also be fed into the avionics network from outside via a transmitter. Thus, even hardware or software in-the-loop tests are possible on the fully integrated satellite, which would only be feasible with great effort on conventional satellites.
These modules have preiviously been based on a STM32F4 using the DecaWave DW1000 wireless transceiver [6]. These modules have been used in many of the university projects such as Space Maneuvering Simulators or drones with added extension boards (see figure 1). The InnoCube CubeSat will use different wireless hardware which will be described in this paper.

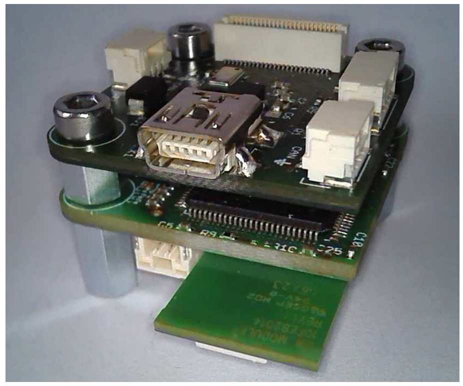


Fig. 1: The predecessor of SKITH on InnoCube

The following table gives a comparative overview of the advantages of the wireless system compared to the state-of-the-art cable harnesses:

Conventional	Wireless
• On-board computer must be adapted to the required interfaces for each mission • Complex and error-prone integration of the cable harness • Interfaces and cable harnesses must be provided for tests on the integrated satellite • Approx. 10 % of the total weight of a satellite is accounted for by the cable harness • Cables and connectors always carry a high risk of interference in the event of vibrations (rocket launch)	• On-board computer requires standardized radio interface • Modules of the satellite can be easily plugged together • Easy testing and monitoring from outside the satellite (multi monitor capabilities) • Miniature radio modules weigh only a few grams for each connected module • Transmission path unaffected by mechanical stress • Redundant hardware does not affect each other: No power, no wireless signal

2 MISSION OVERVIEW

InnoCube is a 3U-CubeSat mission currently under development as a joint effort at the University of Wuerzburg and TU Berlin. Two main innovative technologies will be tested: Wall#E and SKITH. The wireless technology SKITH will be discussed thoroughly later in this paper. It is worth mentioning, that InnoCube will use exclusively wireless connections for communication between the main subsystems.

Wall#E is a technology which allows the supporting structure of the spacecraft to be used as energy storage. This structural battery uses fibre composites as well as solid-state battery materials [7]. For InnoCube, a prototype of this battery will be tested for its space suitability. Since Wall#E will be a first technology demonstration, the prototype will be integrated as a payload and not as the main power storage system of InnoCube [8].
Additionally, the payload EPISODE has the goal of testing hardware for the concept of a software-based solution for global navigation satellite systems (GNSS) for precise on-orbit positioning of CubeSats. Therefore InnoCube will also be fitted with a laser-ranging reflector for the validation of the payload data.
InnoCube will be developed by students and research assistants and will go through all phases (A to F) of a product life cycle. The project team will thus gain experience from the preparation phase, conception and definition phase through the design and development phase to the operation and disposal phase. Phase E is divided into an Launch and Early Orbit Phase (LEOP) of the satellite, which includes a complete functional check of all subsystems followed by a calibration and commissioning of the EPISODE and laser ranging payloads. This is expected to be completed within three months. This will be followed by nominal operational operation of the payloads and generation of data for science objectives. The total mission duration is set at 1 year in orbit. In addition to the scientific goals, one of the primary objectives of the project is to educate students. This includes not only component development, technical and electrotechnical training, but also satellite operation. In summary, within 4 years the design, the manufacturing, the launch and the operation of a small satellite will be performed with the following boundary conditions:

- Fabrication, validation and verification of a CubeSat flight model within a maximum of 3 years
- Successful launch with up to three months of LEOP and payload calibration
- Mission life expectancy 12 months (in-orbit)
- Both the satellite and science payloads are expected to operate reliably for 9-12 months operationally until mission end (active) and until end of life (passive laser ranging)
- Verify science experiments and collect data
- Meet science and engineering objectives
- Hardware and software testing

Figure 2 depicts the main systems of the InnoCube satellite. Communication will be achieved by the use of an omnidirectional UHF-antenna and two redundant up- and downlink modules including the transceiver for the operation in the 435 to 438 MHz frequency-band. Depending on availability, a Globestar Modem can be used as secondary means of communication.
InnoCube relies on a single NanoPower BPX Battery pack using lithium-ion batteries in a 2S-4p configuration [9]. EnduroSat solar-panels are being used on all four main CubeSat sides [10]. Charging as well as power conditioning and distribution will be handled by two power modules developed at DLR Bremen. A backplane will be used for the distribution of the power-lines to the satellite systems. Since we use wireless connections on all of our modules, the backplane will not carry any data signals.
On-board-data-handling will be accomplished by four cold-redundant on-board-computer modules. The on-board-software will be based on RODOS, a real-time operating system developed for the use on

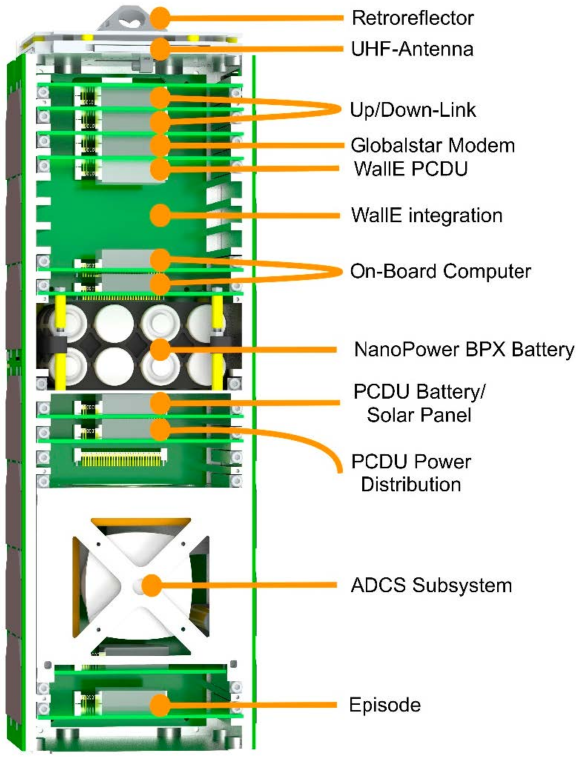


Fig. 2: InnoCube Systems overview

satellites [11]. The software-framework CORFU is being used to create the on-board-software based on easy to use configuration files, which allow auto-generation of general software capabilities such as telemetry and telecommand capabilities [12, 13].

The attitude determination and control system (ADCS) is integrated into the main satellite structure using a dedicated sub-structure. This allows for easy testing and integration. Six wireless sun-sensors are being placed on all sides of the cubesat, which along with a magnetometer and a rate-gyro allow for absolute attitude determination using an extended kalman-filter algorithm. Three magnettorquers and reaction-wheels are being used for controlling the attitude of the satellite. The ADCS is mainly being used for controlling the alignment of the laser ranging reflector during laser ranging experiments and the antenna pointing of the EPISODE antenna.

3 SKITH WIRELESS BUS

There have already been some missions which tested single components that communicate with the main satellite bus using a wireless connection [14]. The Defli-C3 mission for example tested an autonomous wireless sun sensor, but only one of two units remained functional and the main satellite bus used conventional data harness [15]. In InnoCube, the main satellite data-bus will rely solely on wireless data connections. Figure 3 depicts the wireless node network of InnoCube. The communication between these modules relies solely on the wireless system, there are no traditional data connections available. The technology used in SKITH will be used in the following sections.

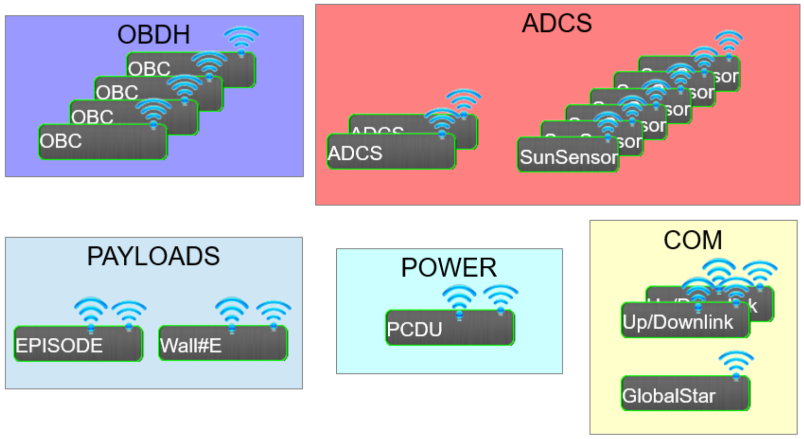


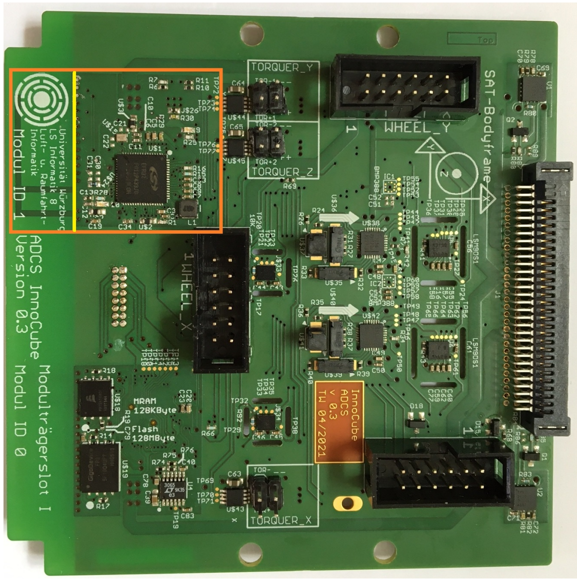
Fig. 3: InnoCube wireless nodes

3.1 Hardware

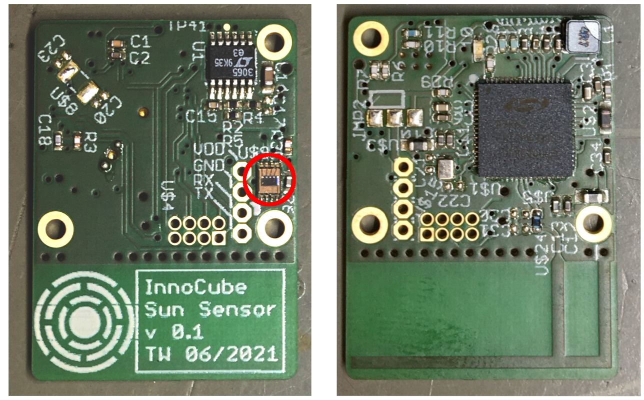
The Silicon Labs "Gecko" EFR32FG12 40 MHz micro controller used for the InnoCube hardware has an integrated 2.4 GHz radio interface. This makes it possible to send and receive any data without a fixed protocol in the 2.4 Ghz band with up to 19 dBm transmission power, 2 Mbit/s data rate and various modulations [16]. The controller takes care of preamble, sync word (frame start detection), frame length and a CRC-16 check. The rest, especially the avoidance of collisions, has to be handled by the user himself. On this interface we build our SKITH protocol. We use a GFSK modulation with +/- 1 MHz frequency deviation at 1MBit/s data rate. The bandwidth of 2 MHz is twice as large as necessary for the data rate, because we have enough spectrum available. This gives us more stability for data transmission. We define 20 channels with 2MHz spacing in the range of 2400-2440 MHz and the usage of 9dBm transmission power. The satellite will only use one fixed channel. A change via command or software update is not provided for security reasons. The other channels can be used for development. We have no other 2.4 GHz radio systems on board and can choose the channel for SKITH arbitrarily.
The minimal footprint using the pcb-antenna currently is approx. 21mm x 31mm and can be seen as used by the sun-sensor and ADCS mainboard design in figure 4. Only very few external components are required for the operation of the internal radio interface. The antenna is integrated into the PCB and occupies approx. one-third of the total footprint. The used micro controller provides a wide range of IO sufficient for most on-board data handling operations and can therefore be used on all satellites subsystems, all sharing the same minimal SKITH PCB layout.

3.1.1 Power Consumption

SKITH on InnoCube uses the radio-interface of the EFR32FG12 micro-controller, which is designed to be used in low-power application. The power-draw is summarized in table 1. It should be noted, that the power measurements were taken during maximum transmission power of 80mW. The actual power used on the satellite will be much lower, thus the power consumption will be lowered additionally. It can be seen, that for lower data-rates (such as 56kpbs in InnoCube), a very low power draw can be achieved, which is comparable to the consumption by other micro controllers such as the STM32F4, also used in CubeSat missions [17].



(a) ADCS Board (SKITH marked orange)



(b) Sun Sensor PCB (optical sensor marked red)

Fig. 4: SKITH and micro controller interface layout

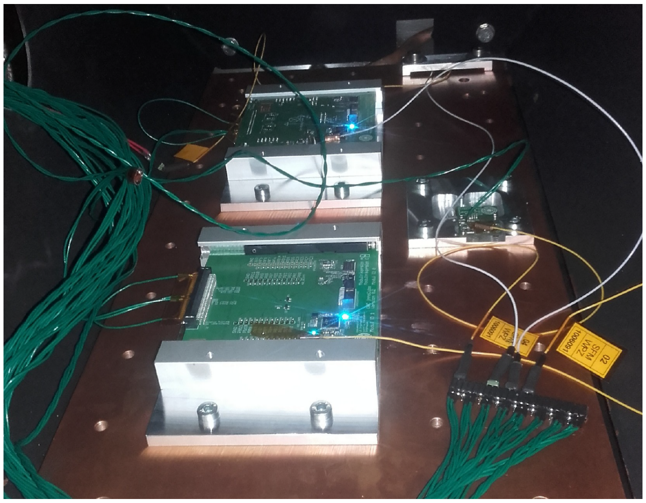
Mode	Power (@3.3V)
Idle	79 mW
Continuous Random Sending	323 mW
SKITH (13 Nodes, 54 kbps)	98 mW

Table 1: Power consumption in different modes using 80mW transmission power

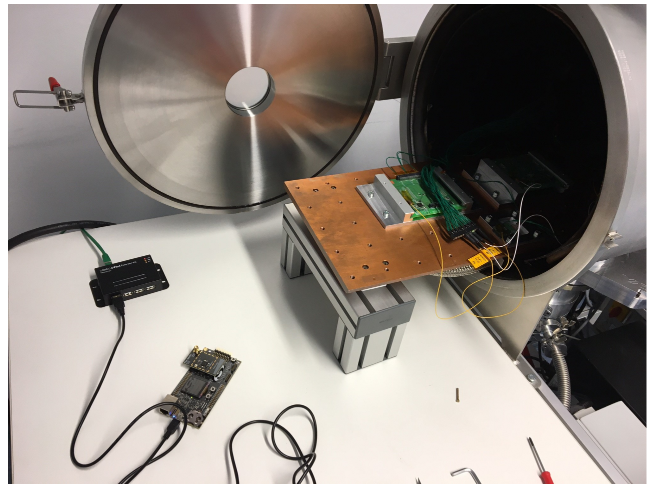
3.1.2 Environmental tests

An important step in developing new hardware for spaceflight application using commercial off the shelf (COTS) components is the qualification process. Therefore, environmental tests have been conducted. For the SKITH hardware, thermal vacuum (TV) and total dose radiation (TID) tests are from particular interest. Mechanical testing will be conducted at a later stage of the project but since there are no external interfaces such as antenna-connectors or other mechanical parts involved, we do not expect any degrading effects.

TV-Tests took place at the vacuum chamber at the University of Wuerzburg. Three PCBs have been subject to the testing procedure: The ADCS board, the OBC and one sun-sensor. All PCBs share the same SKITH hardware, but differ in peripherals. Test-data has already been collected using the SKITH wireless interface, with an external SKITH transceiver placed outside of the chamber (see figure 5). Signal-strength showed to be sufficient up to a few meters away from the chamber by using maximum transmission power. Frame-loss could therefore be measured directly from the received test data. During testing, no wireless dropouts or change in frame-loss occurred. Currently, we measure a frame loss of less than 0.02%. We expect this loss to be caused by interference with other terrestrial signals at the same frequency, but this effect has to be evaluated further. Test-parameters can be found in table 2. It should be noted, that the receiving SKITH node outside of the chamber was kept at room temperature, resulting



(a) OBC, ADCS and sun sensor TV-Test



(b) TV-Chamber

Fig. 5: TV test setup - Data collection done using wireless connection only

in a temperature difference of approx. 50 °Celsius. Still, transmission and receiving operated normally.

Parameter	Specification
Temperature Range	-30 - +70 °C
Dwell Time	2 hours at peaks
Slope	< 5K/min
Cycles	8
Pressure	10^{-5} bar

Table 2: Thermal vacuum test parameters

Total Dose Radiation suitability has been tested twice at the Helmholtz-Zentrum Berlin using a Cobalt-60 source. In the first test, the micro controller have been tested for general suitability Cobalt-60 source with a mission dose of 0.64 krad/h and a total ionisation dose of 10.8 krad over 20 hours. Test parameters of the second test can be found in figure 3, which also include the expected mission dose of 10.8 krad in LEO. The wireless connection remained stable during the whole test duration and showed no effect of degradation. Even a high dose test with a TID of 37.5 krad did not alter this behaviour.

Test	TID	Rate	Time
Mission Dose	10.8 krad	0.64 krad/h	17 h
High Dose	37.5 krad	7.22 krad/h	5.2 h

Table 3: Second radiation test parameters for dedicated flight hardware

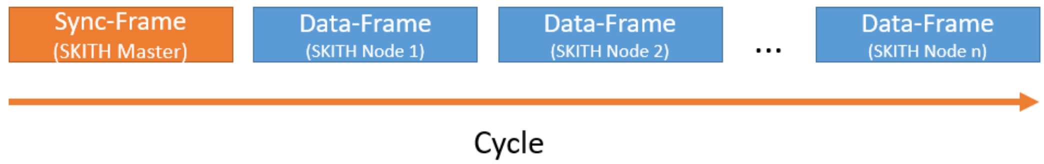


Fig. 6: SKITH protocol message cycle

3.2 Software and Protocol

The radio protocol must coordinate the communication of the modules with each other, so that it is prevented that several modules transmit at the same time and thus the transmission is disturbed. A central, defined coordinator is used, who regularly assigns time windows to each module during which they are allowed to transmit. This ensures a low complexity of the system and a fixed known system state. To prevent this central coordinator from becoming a single point of failure, redundant modules are available. A mechanism independent of the radio system ensures that exactly one of the two coordinators is always switched on. The active coordinator is always monitored for the function of the complete radio link.

The radio hardware integrated in the EFR32FG12 "Gecko" micro controller takes care of the channel encoding, framing and securing the transmitted data with a checksum. The addressing of the data is already taken over by the RODOS middleware in the system, the SKITH radio system always sends all data as broadcast to all modules. The protocol then only has to take care of collision avoidance. For this purpose, the coordinator sends out so-called sync frames at periodic intervals. These contain a list that defines a time slot for each module contained in the satellite in which it may transmit. These time slots are always relative to the time of reception of the sync frame, which allows a high accuracy of the slots without time consuming synchronization. A Sync-frame with all corresponding data frames of the modules is called a SKITH cycle (figure 6). For InnoCube, the slot length has been set to 6ms with a resulting cycle length of 78ms. Each slot can contain up to 520 Bytes of payload data, resulting in a bandwidth of approx. 54 kbps per node.

3.2.1 Time Sync

The coordinator distributes its current UTC time with each sync frame. Because the sync frame is received by modules always at exactly the same time using interrupts, an exact time synchronization can be achieved by very simple means. In addition, a "One Pulse Per Second" flag is set in the sync frame approximately every second. This can be used to trigger processes that have to run regularly at exactly the same time on several modules. (e.g. sun sensor measurements). Since one second is not necessarily an integer multiple of the cycle time and the cycle time can also change, this flag cannot be used for operations that must run exactly every second.

3.3 Redundancy Concept

For the reliable function of the entire system, it is important that only one of the coordinators is switched on at a given time. If both would be switched on, both would send out uncoordinated sync frames and then it is unclear which one the other modules would follow. Likewise, any possible failure of the active coordinator must be detected in order to switch to the other one. This includes both the correct functioning

of the software and the transmitting and receiving units of the radio hardware. As the two redundant modules of the PCDU are at the same time the radio coordinators, this switching is realized with special power switches. Both modules are supplied with power via keep-off switches. These switches remain in the off as long as periodic pulses are applied to the control input at intervals of max. one second. If these pulses do not occur, the switches switch on. One coordinator controls the switch of the other and vice versa. As long as the active coordinator determines that it is working, it continuously sends Keep-Off pulses to the switch of the other coordinator. This ensures that only one of the modules is switched on at the same time. These pulses are only generated when all essential threads regularly send "I am alive" messages and regularly receive radio messages from the other modules. Thus the function of both the sending and receiving directions of the coordinator is ensured, because other modules can only answer if they have received a sync frame from the coordinator before (see next section). For this, at least one other module must always be switched on. The design provides that this is always the case for at least one of the COMS modules. If something does not work, the keep-off pulses remain off and the other coordinator module starts. This now generates keep-off pulses itself and switches off the first one. When switching on the power supply, e.g. after separation, both coordinator modules start simultaneously. The first keep-off pulse is delayed randomly by a few milliseconds. So one of the two modules is determined randomly and none is preferred.
We expect the following failure scenarios:

- SKITH transmitter/receiver fails
- Spontaneous error e.g. due to radiation induced bit flip
- Software error

Keep-Off pulses are only generated when frames are received from other modules. This in turn means that the radio communication works, because other modules would not transmit if they do not receive a sync frame from the coordinator. Any failure of the radio communication caused by one of the above errors (or others) is thus secured. To protect the case that the coordinator keeps the radio communication active due to an error but cannot be commanded anymore, the keep-off pulses are also interrupted, if no commands have been processed for a defined period of time. A problem exists if the coordinator restarts regularly due to an error after the first keep-off pulse has been generated. Then there is not enough time for the redundant module to switch on. To prevent this, the reason for the restart is checked before sending the first Keep-Off. If this is something other than "Power-On", i.e. the module was switched off for a other reason than switching on the power switch, it does nothing and waits until the redundant module starts and switches itself off by keep-off.

4 EXPERIENCES

4.1 Development

The EFR32FG12 allows the use of up to 20 different channels for communication. Interference whilst working in the vicinity of other SKITH boards (eg. in the next office) can therefore be avoided just by using different channels. Using the maximum power of 19 dBm, communication with the SKITH nodes has been possible inside our office building ranging through several offices. This came in handy eg. for sun-sensor testing, where we had to place a sun-sensor at the window of one of the south-facing offices

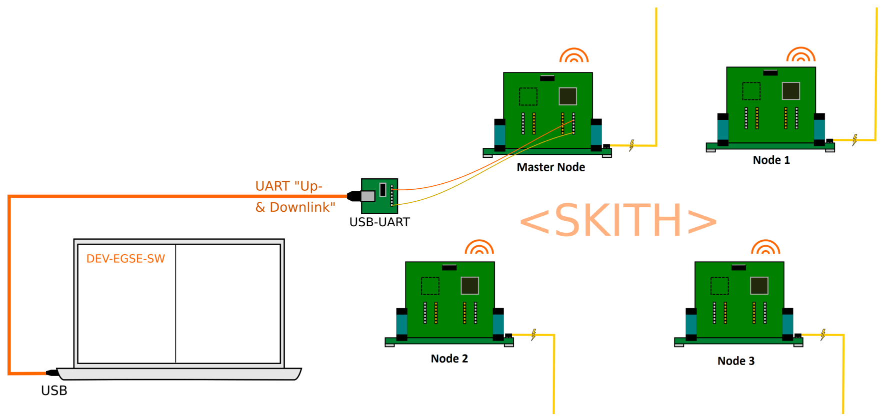


Fig. 7: EGSE and development

by using a 9V battery as power source. Reception and data-usage was possible in the own office at the other side of the building.
Using the wireless interface, introducing "fake-nodes" has been particularly easy, since it does not require one to have access to the whole satellite structure or subsystems which might require special connectors or environments. Fake-data can just be introduced into the RODOS middleware topics using a SKITH node connected to a computer (see figure 7).

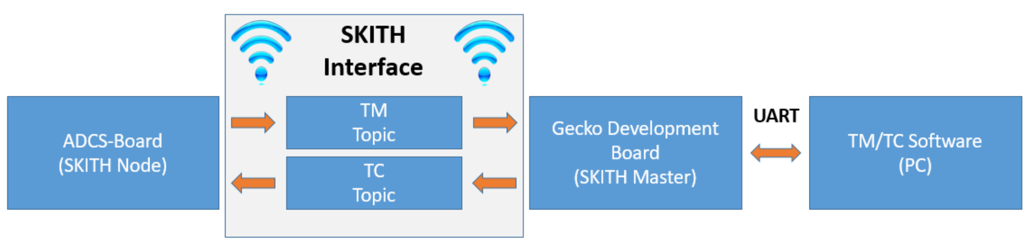
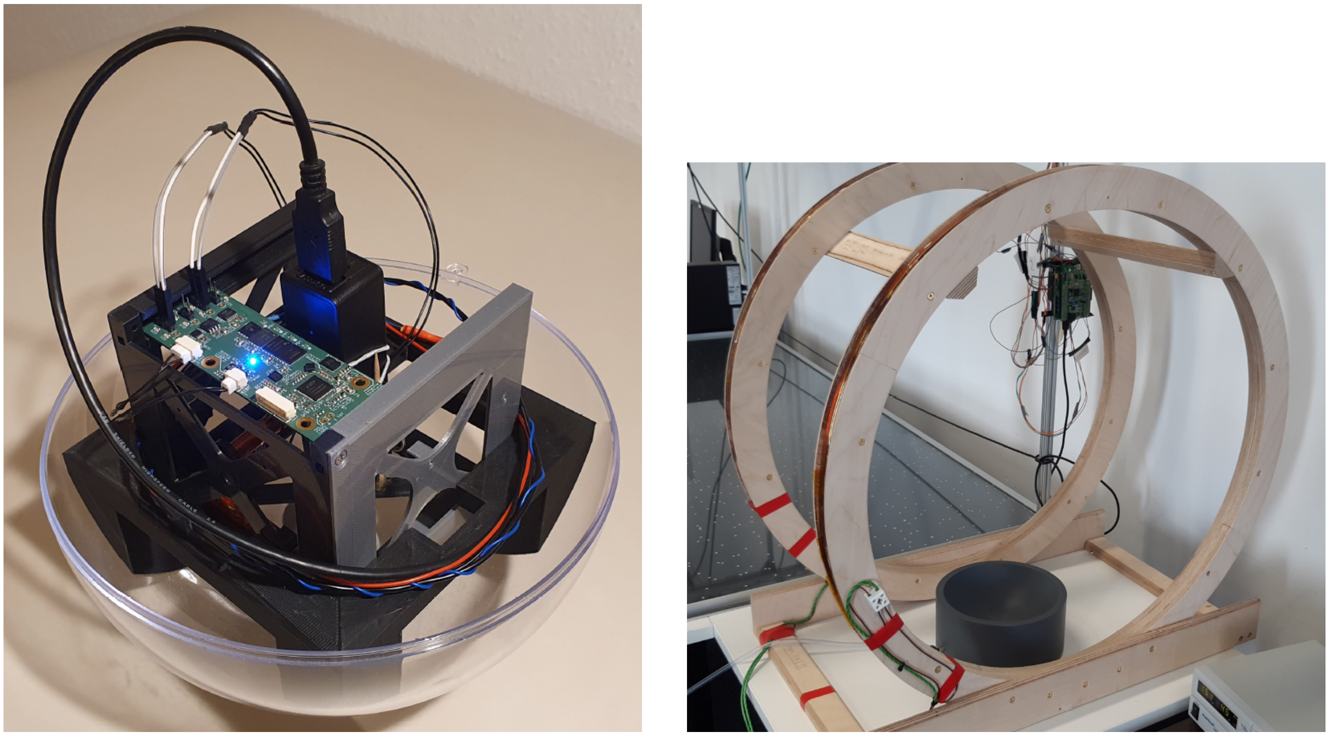


Fig. 8: Interface bewtween the adcs board and the TM/TC development software

4.2 AIVT

There are many examples, where the use of a wireless connection during the assembly integration and testing comes in handy. During our development, wireless connectivity has been especially helpful during test of the attitude determination and control system (ADCS). The ADCS typically consists of a distributed network of sensors and actuators. For InnoCube, we use 6 wireless sun sensors. During Hardware in the loop (HIL) tests, it is easy to mimic simulated sensor information, since we can replace the actual sensors with simulated nodes from the development computer.
For air-bearing tests, power-supply can be accomplished by the easy use of batteries. Data connections in conventional satellites is typically only available through eg. a debug UART interface or the actual communication system of the satellite. Since using cables in the air-bearing setup are not possible, the wireless connectivity of the SKITH modules allows for very easy testing.
The general usage principle is depicted in figure 8. Messages between the ADCS Board (containing one SKITH-Node) and the development computer can be exchanged by a SKITH-UART interface. This



(a) ADCS test-box using external power supply (b) Air-bearing table and helmholtz coils test setup

Fig. 9: ADCS AIV-testsetup using wireless connections

interface is directly provided by the EFR32FG12 Gecko development board, which also serves as the SKITH master node. A software on the development computer allows to publish telecommands and read telemetry of the measured data, by using the same middleware interface as on the SKITH nodes (RODOS Topics).

4.3 Security

The Delfi-C3 mission showed, that even low-power wireless connections might be monitored from earth using high-gain antennas on ground. The opposite might be accomplished by using high-gain transmission antennas in order to inject commands or interfere with the on board communication bus [14]. A research group at our chair already studies the use of ultrawideband wireless communication technology in order to increase resilience against signal interference and jamming [4, 5]. Prototypes using this technology have proven to be reliable in our student-projects. The use of state-of the art message encryption technologies such as public-private key or other cryptography techniques might be considered in order to avoid unwanted message encoding or injection.

4.4 EMI (Electromagnetic Interference)

Using wireless communication in a satellite, where EMI susceptible devices or payloads might be on board, EMI becomes a very important issue. On InnoCube, we do not have such devices on board. However, we conducted some tests which analyzed the interaction of our SKITH wireless nodes with a S-band transmitter, typically used in spacecraft applications. The frequency band of the S-band communications

lies in a similar range than our used 2.4 GHz wireless communication. Using appropriate channels in order to increase the band separation, no interference occurred during our measurements. The general idea of wireless connection in SKITH and the protocol allow the freedom of using different hardware modules, which of course could use different frequency bands if the mission requires because of interference with other modules.
However, this topic has to be evaluated further in order to understand the possible implications and usage-restrictions in some missions.

4.5 Frequency allocation

The usage of wireless modules in space might require frequency allocation in accordance with international agreements. For the frequency allocation procedure, we are now in contact with the German Aerospace Agency (DLR) Frequency Management, which will forward our request to the Federal Network Agency. It has to be clarified whether a general allocation e.g. for Short Range Devices (SRD) is suitable. Due to the very low transmission power of only 9mW, which takes place inside a metal housing, the InnoCube satellite, it should also be clarified whether there is a lower limit below which an allocation is not required. Once all structural components are in our department, we will measure the shielding effect and feed it into the calculations for e.g. the power flux density (PFD) of the SKITH transmitter on board.

5 ACKNOWLEDGEMENTS

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