IHP

“Investigation of Radiation Tolerances and Designs of Ultra-Wide Band Wireless Solutions”

ESA Contract No. 4000133591/20/NL/AS

Deliverable ESR
- Executive Summary Report -

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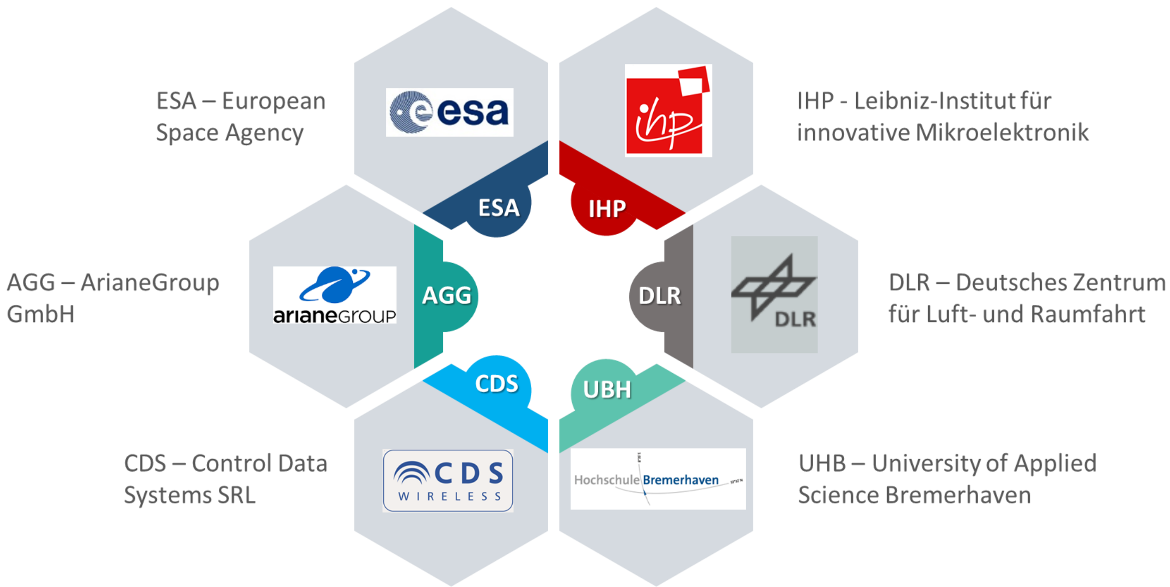
1 Project Overview

The Ultrawideband (UWB) radio technique has proved successfully as a promising candidate for wireless communication in Space applications. Based on an impulse transmission scheme it shows superior performance in harsh radio environments compared to traditional and commonly used radio techniques. In addition, the UWB radio technique is well suited for radio-based ranging and localization applications with very good precision when applying Time-of-Arrival and Two-Way-Ranging schemes.

Today, existing demands for UWB solutions come from launcher systems towards reliable wireless sensor networks applications, from intra-satellite wireless communications as well as inter-satellite communications and distance measurements (nano-satellite swarms), and from Human Space Flight applications. Unfortunately, there are no radiation-tolerant space-grade UWB radio modules available yet, which would meet the current needs. As understood from the Statement-of-Work, existing off-the-shelf-components (COTS) can fulfil the expectations only partly and lack approval concerning the necessary radiation tolerance. Furthermore, the variety on available UWB-COTS is very limited.

Since there is no radiation-tolerant UWB radio solution emerging on market, the project consortium aims to create an own solution, based on an existing UWB-RFIC design of IHP (originally not intended for Space applications). This initial design demands for several development steps in order to fulfill all functional and environmental requirements. In opposite to digital design methodology, radiation-hardening design methods for RF and analogue circuits are not well established. Circuit simulation methods need to be improved in order to identify the most sensitive circuit nodes. Measures to desensitize these circuit nodes shall not sacrifice the RF circuit performance. Therefore, the related risk should be mitigated by developing hardware fulfilling the functional requirements first, and then applying measures for ensuring radiation tolerance afterwards.

1.1 Participating companies and research institutions



1.2 Project Goal

The project aims the development of a radiation tolerant UWB-RFIC to be integrated in a Reliable Wireless Network Node (RWN) for different Space applications. Several intermediate steps (shown in fig. 1, related to hardware revisions) are essential to achieve the expected goal. Corresponding to the UWB hardware revisions, Wireless Node hardware and related software will be developed and adapted accordingly. Hardware and software will be designed in such a way that most of the parts can be reused for different UWB hardware implementations.

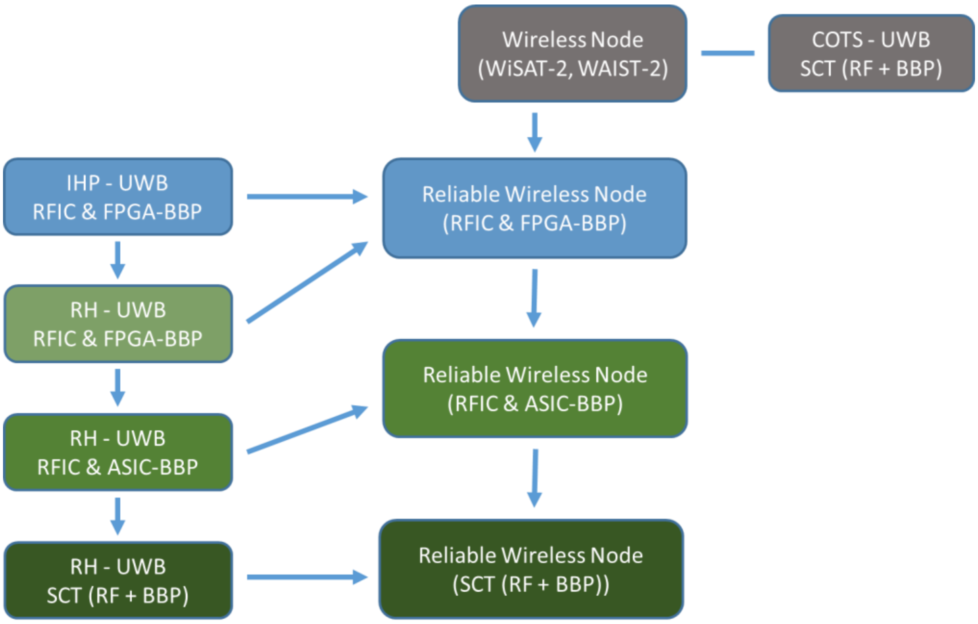


Figure 1: Overview on intended UWB development, blue boxes indicate the activities of this project, green boxes indicate future plans; (RFIC = Radio Frequency Integrated Circuit, ASIC = Application Specific Integrated Circuit, BBP = Baseband Processor, SCT = Single-Chip-Transceiver)

1.3 Development Logic

The project team deploys an existing, self-developed UWB-RFIC with necessary PHY features, all conform to the IEEE 802.15.4-2015 standard. This allows further adaptions in view of the functional requirements as well as the transfer of the design towards a radiation-tolerant UWB wireless solution. Deploying IHP processes SGB25RH and SG13RH ensures enforcement of radiation-hard design rules as well as application of special device models reflecting radiation and aging effects.

Furthermore, “radiation hardening by design” measures are applied. In digital circuit design, dedicated rad-hard cell libraries are used, which provide dice-flipflops, partially and full triple-mode redundancy solutions and so on. Radiation-hardening design in the RF- and analogue circuit domain needs other approaches. Here, biasing circuitry requires special attention in order to avoid parameter drifts and single event failures. Unavoidable transitional signal spikes induced by single events need to be tackled by error correction methods. By applying appropriate circuit simulation methods, the trade-offs between radiation hardness and RF circuit performance have to be examined in order to determine the necessary performance margin in real Space applications.

In parallel, Wireless Nodes (access points and sensor nodes) are developed providing the single entities of a Reliable Wireless Sensor Network. These nodes shall be equipped either with COTS-UWB hardware or with IHP-UWB hardware in order to enable wireless communication. Specific requirements (derived from different Space applications) will make the sensor network deterministic in terms of the timing of sensor data acquisition and wireless data transmission. This development starts with available COTS-UWB hardware and shall migrate later towards IHP-UWB hardware. In order to minimize development efforts, hardware replacement will happen on a low level, maintaining the whole software stack above.

Functional tests of the stand-alone IHP-UWB radio as well as the Wireless Node (equipped with different UWB radios) will monitor the development progress. In addition, a first assessment of the radiation tolerance of the existing UWB-RFIC will lead to detailed recommendations for future RFIC design development steps, finally resulting in a Space-grade UWB wireless communication solution.

2 Requirement Identification

The high-level Functional Requirements for the UWB IC are established in view of Launcher, Orbital and Human Spaceflight applications. Launcher requirements have been identified by ArianeGroup based on Ariane 6 requirements and ESA funded FLPP project "Reliable Sensor Network (RSN)". For Orbital Systems and Human Space Flight the requirements have been provided by DLR. In parallel, Wireless Node Requirement Specification are established for the network components (sensor nodes and access points) using either IHP-UWB or COTS-UWB radio hardware.

3 UWB Chipset of IHP

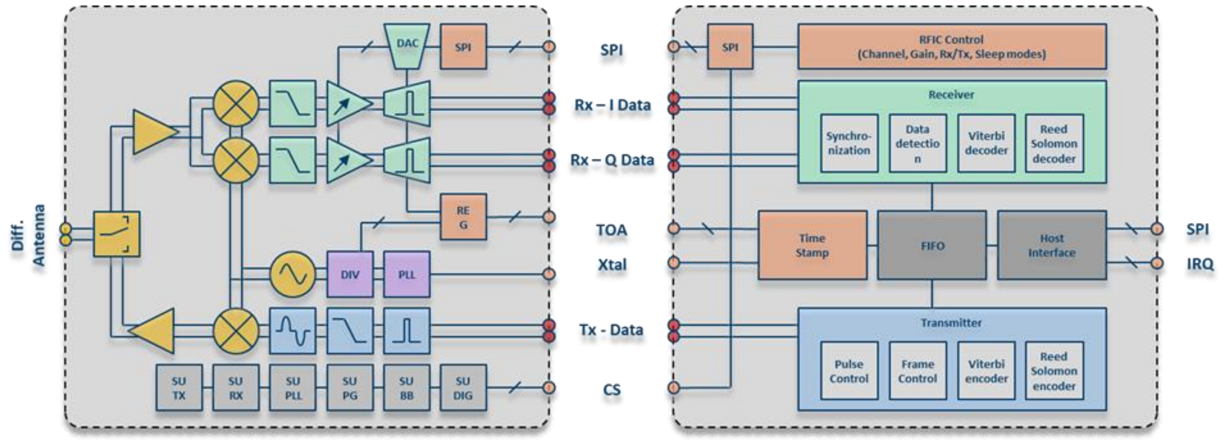


Figure 2: Block diagram of the intended two-chip-solution (left: RF-frontend, implemented in a dedicated RFIC; right: baseband processor, implemented in a FPGA platform)

The UWB radio implementation of IHP consists of an IHP UWB-RFIC, a monolithically integrated chip fabricated in the IHP SGB25RH process, as well as an UWB-BBP implemented on FPGA. This chipset is based on a pre-existing experimental solution, which was further modified in order to allow a radiation-hardness assessment of the UWB-RFIC, including the entire RF- and Analogue Frontend. The baseband processor represents an intermediate development stage (apart from the intended final implementation within an ASIC). Fig. 2 shows the block diagram of the intermediate two-chip-solution.

4 Wireless Node

4.1 Wireless Sensor Network Design

The Wireless Sensor Network (WSN) consists of multiple Wireless Nodes, which are either configured as Access Point (AP) or Sensor Node (SN). The Sensor Nodes acquire measurement data from sensors and transfer it wirelessly to the Access Point, which is concentrating the sensor data from the SNs. It may also act as a gateway to a wired avionic network and e.g. to the onboard computer. Since the communication to the higher avionic level is not in focus of this project, it is substituted with a PC/notebook implementation.

The WSN is especially designed to be a reliable deterministic network working in real-time. Great attention has been paid to the time-stamping accuracy (better than 10 µs). A time synchronization protocol is implemented between the Access Point providing the master clock and the Sensor Nodes running on their slave clocks.

The hardware architecture of the Wireless Node is based on attaching UWB radio modules (daughterboard) to a Zynq-7000 SoC which includes a Processing System with 2 ARM cores besides the Programmable Logic. Both flavours of UWB modules come with the same interface connector, allowing easy exchange. The Programmable Logic within the PDGA is used for the implementation of the Base-Band Processor (BBP) of the IHP-UWB radio and additional logic needed for interfacing the sensors. One ARM core in the Processing System is used for the Application Processor, while the second ARM core is currently not used.

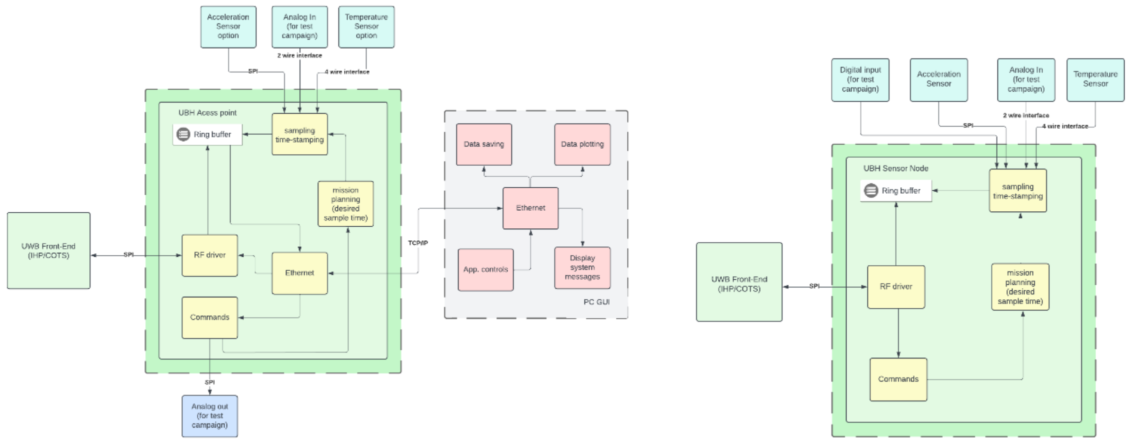


Figure 3: Access point’s functional diagram (left), sensor node functional diagram (right)

The functional diagram of the AP (left) and SN (right) are shown in the figure 3. They are composed of four main components which are the UWB radio, the application processor, IO peripherals and the PC GUI (only AP). The PC GUI is used only for testing purposes and shall be replaced by a higher avionic device level.

The application processor of the AP has the following functions:

- Sampling and time-stamping sensors’ measurements which is required for some test campaigns.
- Reading the time-stamped measurements stored in the Ring buffer by the RF driver.
- Receiving commands from the PC GUI.
- Sending the time-stamped measurements to the PC GUI.
- Sending messages to the connected SNs. The messages can be operation commands, new operating sample rate or an update for the network clock.
- Generating digital signals which is required for measuring the time stamping accuracy.

The Application processor of the SN has the following functions:

- Sampling and time-stamping sensors’ measurements.
- Storing the time-stamped measurements in a ring buffer, keeping them available for the RF driver.
- Processing AP’s messages which can be a new operation command, new operating sample rate or an update of the clock ‘s clock.

4.2 Network Performance Analysis

An examination of ultra-wideband (UWB) systems designed for spacecraft and launcher environments was conducted. It primarily focuses on ensuring robust data communication and precise ranging capabilities. The analysis encompasses both simulated environments and an actual deployment on the International Space Station (ISS).

The simulation aspect of the study evaluates the UWB system using a deterministic medium access protocol in a controlled launcher-like setting. It specifically assesses the system's performance under predefined conditions aimed at simulating space deployment. This is complemented by an analysis of a real-world deployment on the ISS, where the system's data rate, packet loss, and latency were measured to gauge its operational efficiency in space.

Key findings highlight the system’s ability to maintain 100% packet delivery ratios (PDR) in simulations, demonstrating its potential for reliable communication in space. Additionally, the system exhibited high PDRs (>99%) during the ISS deployment, confirming its effectiveness in challenging RF environment.

While the simulations showed high reliability and performance, they did not account for non-deterministic physical layer effects, indicating an area for future enhancement in simulation accuracy. Overall, the analysis underscores the UWB system’s robust performance in challenging space conditions.

4.3 Deterministic network scheduling

The AP provides a super frame structure with a length of 250 ms, composed of 25 time slots (10 ms each). The first time slot is reserved for a beacon; odd time slots are reserved for downlink (AP to SN) and even time slots are reserved for up-link (SN to AP). Thus, within the super frame there are 12 opportunities for the AP to send data to SN and vice versa. The beacon frame is the delimiter of a super frame. In order to facilitate the up- and downlink, a time division multiplexing is deployed. The beacon, broadcasted every 250 ms, contains in its payload the network time, which allows all the nodes to synchronize with a master clock.

The MAC frame structure is compliant with the IEEE 802.15.4-2011 standard (see next point). Address fields are foreseen in the frame, but currently not used (only a peer-to-peer connections will be established). After reception of a data frame an acknowledgement is sent in the next time slot, whereas the beacon frames won’t become acknowledged.

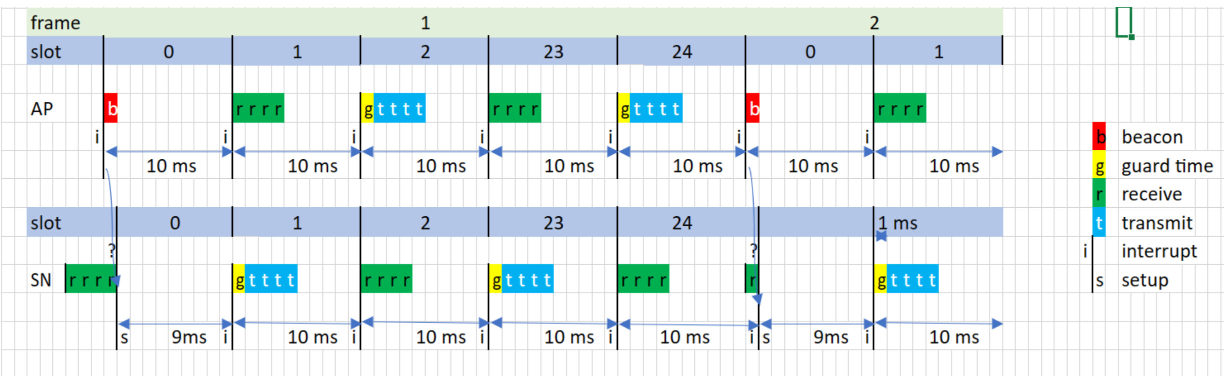


Figure 4: Scheduling in the deterministic network

5 Functional Tests

A number of functional tests, either dedicated to the UWB-RFIC only or the entire wireless node, were conducted resulting in the following main findings:

Wireless Data Transfer
The receiver sensitivity was measured using RF attenuators between transmitter and receiver. The results were reasonable for varying signal strengths. The demonstration of wireless communication using omni-directional antennas was done in laboratory over short distances (1 – 2 m). Further optimization and enhancements of RFIC as well as the baseband algorithms to increase processing gain are needed in order to achieve the intended communication distance.

Different PHY data rates (850 kbps, 6.81Mbps, 27.24 Mbps)
The UWB radio has shown wireless communication at three different data rates (0.85 Mbit/s, 6.81 Mbit/s, and 24.27 Mbit/s), as defined by the IEEE standard. The evaluation was conducted in the time domain by investigating impulse sequences including the preamble, SFD, PHR, and payload.

Transmit Output Power Adjustment
Measured results show that the RF output power can be set in steps of 1 dB and 10 dB for the UWB frequency channels 6, 8, and 9.

Inter-Operability COTS and IHP radio
Measurements of the RF spectrum confirm that the COTS hardware can operate in channel 5 and 9.

Sensors Data Acquisition
The ability of the Sensor Node to collect temperature and acceleration measurement data was successfully demonstrated.

SN Sampling Rate
The Sensor Node was able to gather 10 K samples per second. Unfortunately, the wireless link was not able to transfer the data in time due to the limited data throughput.

Time-Stamping Accuracy
An accuracy of better than 10 us was demonstrated.

Data Latency
The requirement concerning the latency was met. Note that higher avionic levels were not involved in this setup, but need to be considered in future activities.

Transmit Output Power Spectral Density
The frequency spectra of the UWB transmitter while generating an impulse train in UWB channels 9, 6 and 8 show no violations of the spectrum mask specified in the IEEE 802.15.4-2015 standard.

6 Radiation Test

Radiation tests were conducted at the cyclotron resource Centre at UC Louvain in Belgium. The primary focus is on Single Event Effects (SEE) testing, adhering to the guidelines specified in the ESCC-22900 and ESCC-25100 standards. The test setup includes both a Device-Under-Test and a Reference Device including an FPGA board managing data exchanges (all placed in a vacuum chamber). This setup is designed to monitor the response of the DUT to radiation through changes in analog and digital signals, as well as RF signal integrity. The methodology aims to detect critical failures, analyze RF performance, and ensure the DUT's ability to recover from radiation-induced interruptions. One specific test was conducted to measure the Bit Error Rate (BER) in order to assess the data integrity under radiation.

Throughout the multiple test runs, no destructive events or SELs were observed, indicating robust physical construction and design. While the UWB-RFIC demonstrated a strong resistance to radiation in terms of structural integrity, the testing highlighted areas for improvement in electronic robustness and thermal management within the test setup. Furthermore, a clear trend over three tested DUTs shows a visible degradation in RF performance with increasing radiation dose rates (LET).

7 Recommendations for Radiation-Tolerant RFIC-Design

In general, the UWB-RFIC is fully functional and it fulfils the functional requirements. Nonetheless, in terms of RF performance, the receiver sensitivity requirement is not met. This observation was already predicted from RF circuit simulations. The most obvious solution would be to mitigate the RFIC design into the SG13RH process, which offers significantly better RF device parameters, while promising also drastic reduction of DC power dissipation and reduced chip area.

The overall result of the radiation test concerning the radiation tolerance of the UWB-RFIC of IHP is consistent and leads to clear recommendations for future developments. Special attention should be paid to bandgap voltage references, control logic circuitry, and clock distribution concepts.

8 Recommendations for Wireless Node Design

A deterministic Wireless Sensor Network (WSN) that operates in real-time environments needs to be meticulously engineered in order to guarantee predictability and reliability in data transmission and processing. This determinism is accomplished through a combination of factors including its network topology, development precision, sampling predictability, and the Medium Access Control (MAC) protocol.

The star network topology, enabling direct communication between nodes and the central hub, plays a pivotal role in minimizing latency and data collisions. Hardware and software components have to be co-designed for efficient data processing and minimizing interferences. In real-time applications, sensors are required to gather data at precise time-intervals, ensuring that the system can anticipate and manage the workload effectively. Furthermore, the MAC protocol is specially designed for deterministic access to the communication medium, thereby preventing data collisions and ensuring timely data transfer.

For the higher avionic level, the selection of an Ethernet is recommended, which enables real-time communication in Space launchers. A potential good candidate for the task is the Time-Sensitive Networking (TSN).

The maximum sample rate is currently limited, but could be increased by reducing the sample size and enlarging the data throughput. Further improvements are possible by optimizing the data frame structure and communication protocols. In addition, data latency could be minimized by reducing the duration of the radio super frame, either by decreasing the number of timeslots within the super frame, reducing the duration of individual time slots.

The time-stamping accuracy could be further improved by introducing a calibration process (i.e. PTP synchronization). Furthermore, hardware involving more accurate crystal references might be used. In addition, the potential impact of the SPI implementation needs to be reduced. Here, interrupt handling should be in focus. Finally, an SPI clock of at least 20 MHz is advised. Sensors itself may also affect the time-stamping-accuracy, if data acquisition and data transmission might be delayed randomly due to data processing activities within the sensor.

In terms of safety and reliability, it is advised to employ redundant SNs using alternative wireless communication channels (for instance different frequency channels).

9 Conclusions and Recommendations for Continuation

Reflecting the achieved results within this activity it is strongly recommended to continue as originally planned. A wireless node was developed, which can either operate with COTS UWB hardware (Decawave DW3000 modules) or with IHP UWB- hardware (RFIC + BBP) as radio module. The design of the wireless node was established in such a way that the radio hardware could be exchanged on a low hardware level while larger (higher) system portions including software can be further used without any changes.

The UWB radio development at IHP was expedited by this activity. In particular, the radiation tolerance of the UWB RF frontend (RFIC) was investigated and conclusions for further developments were drawn. It is recommended to mitigate the whole RFIC circuit design from current SGB25RH process into the more advanced SG13RH process. This promises a distinct step in improvements of the RF performance, reduction of DC power dissipation, smaller Si chip area, enhanced radiation tolerance, and final co-integration with the baseband processor into a single chip.