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A Flexible LEO Satellite Modem with Ka-Band RF Frontend for a Data Relay Satellite System

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SUMMARY

From a geostationary Earth orbit (GEO) satellite's perspective a low Earth orbit (LEO) satellite is visible on more than half of its orbit. Albeit the free-space loss of an inter-satellite link is much higher than the one of a direct ground link, considerable data rates and download volumes can be achieved. In this paper we describe the system architecture of an integrated approach for a data relay satellite system and the development of LEO satellite and ground station modems. The approach allows serving several small and inexpensive LEO satellites at the same time both with low rate telemetry/telecommand links and with high rate download of sensor data. Copyright © 2018 John Wiley & Sons, Ltd.

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KEY WORDS: satellite, modem, Ka-band, data relay, modulation, forward error correction (FEC), inter-satellite link (ISL), LEO, GEO, digital signal processor (DSP)

1. INTRODUCTION

There is a plethora of applications for low Earth orbit (LEO) satellites. A non-exhaustive list of examples includes remote sensing with passive and/or active sensor systems, communication payloads for ground-to-ground or air-to-ground data exchange, various scientific missions like space observatories, but also academic micro/nano/pico satellite projects for the in-orbit verification of technologies. Over the past decades the market for LEO satellites has grown significantly and analysts expect a mean four-digit number of small satellite launches from 2016 to 2025 with half of that being Earth observation satellites [1].

In comparison to geostationary Earth orbit (GEO) satellites both free-space loss and latency of direct links between a LEO satellite and a ground station are considerably smaller, but a single

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ground station can maintain the contact to a passing LEO satellite for relatively short durations only. In fact, depending on the actual orbit parameters (altitude and inclination) and the ground station's latitude the long-term average visibility as seen from a fixed ground station is only 1% to 6% of the overall in-orbit time [2].

Advances in on-board sensor technologies lead to higher resolutions and significantly increased data volumes to be cached and downloaded in (unchanged) short time slots. Furthermore, from the satellite and payload operators' point of view bidirectional links with longer availability for telemetry, tracking and command (TT&C) are desirable. Last but not least, upcoming satellite-augmented logistics and collision avoidance services like automatic identification system (AIS) for ships or automatic dependent surveillance – broadcast (ADS-B) for aircraft require quasi-real-time information forwarding and cannot rely on store-and-forward architectures.

State-of-the-art world-wide networks of ground stations are costly, such as ESA's tracking station network Estrack, providing relative access times of about 30% to 45% despite a considerable effort in terms of resources and coordination. Alternatively, constellations of LEO satellites providing near global coverage with inter-satellite links (ISLs) can be used in order to increase the contact times to ground stations.

GEO satellites acting as data relays are another elegant possibility to overcome these challenges, since the majority of LEO satellites will be visible to the GEO satellite for at least 50% of their orbital period. The advantages for TT&C are obvious, and data downloads benefit from more steady data rates resulting in relaxed transmit power and transmit antenna requirements on-board the satellite and among the receiving antenna on ground. Using the ESA Advanced Relay and TEchnology MISsion (Artemis) GEO satellite as an example for such a relay system, contact times to LEO satellites with an orbit altitude between $500\,\mathrm{km}$ and $900\,\mathrm{km}$ of about 60% to 75% of their orbit period times are feasible, which applies to around 80% of all LEO satellites currently in operation [2]. In general, a GEO data relay increases the access time to a satellite on a polar orbit by a factor of around 10 to 15 in comparison to a single ground station.

The concept of GEO data relay satellites is well known and the NASA has operated the Tracking and Data Relay Satellite System (TDRSS) since 1983 with currently nine satellites in orbit [3]. TDRS M, the third satellite of the third generation, was launched in August 2017. The Japan Aerospace Exploration Agency (JAXA) commissioned the experimental Data Relay Test Satellite (DRTS) in 2002 [4]. Optical and Ka-band ISLs were verified, including an experiment with a Ka-band ISL between DRTS and Envisat [5]. Both TDRSS and DRTS have steerable Ka-band receive antennas limiting the maximum number of simultaneous ISLs to the number of on-board antennas (plus optical transceivers). TDRSS satellites can receive data by means of electronically steerable antenna beams in the S-band from five senders simultaneously (ground-based beam-forming), while transmitting data to one [6]. The European Data Relay Satellite System (EDRS) hosts a Ka-band payload with steerable reflector antenna and a laser communication terminal (LCT) for ultra high speed data download [7]. Prerequisite are LCTs onboard the served LEO satellites with notable requirements in terms of mass, power consumption, and platform stability, too.

Main challenges of GEO data relays are the higher free space loss and the substantial Doppler-shift caused by the relative movement of the LEO satellite. Besides, varying link budgets are caused

- by distance variations between LEO and GEO satellites,

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- by gain variations due to possible misalignment of receive (RX) and transmit (TX) antennas and their beam-patterns, and
- by atmospheric channel impairments between the GEO satellite and a ground station.

With our research work we bridge this gap by developing a Ka-band satellite modem engineering model (EM) with physical layer (PL) and a suitable data link layer (DLL) protocol. The approach is based on highly channel-efficient adaptive/variable coding and modulation with low-density-parity-check (LDPC) codes for forward error correction saving bandwidth and transmit power. An advanced DLL protocol realizes flexible multi-frequency time-division multiple access (TDMA) and multiplexing schemes and supports both simultaneous bidirectional low rate TT&C links and unidirectional high rate download of sensor data with defined quality of service (QoS) levels. Doppler compensation for RX and TX is implemented in the LEO satellite modems and adaptable SYNC-Frame injection allows fast (re-)synchronization with little overhead.

In terms of data rates our approach named "GeReLEO" does not compete with optical transmitters [8]. In fact, the key objective is to provide connectivity via a data relay to LEO satellites (or other mobile platforms) with considerable constraints in size, mass, and electrical power.

Our paper is organized as follows. After the general concept of the overall data relay system, we describe the protocol layers and protocol management entities. Major shares of the development works were dedicated to modem hardware development with the analogue signal conversion and the digital signal processing, which are explained in the subsequent sections. Then, we describe the demonstration of the complete transmission chain and in the conclusion we summarize the paper.

2. SYSTEM CONCEPT

2.1. Overview

An important objective of the modem design was high flexibility in terms of data rates in order to support a large signal-to-noise ratio (SNR) range. Thus, the modem will be able to support high rate systems with big antennas as well as low rate systems with smaller antennas.

Figure 1 depicts the overall system architecture focusing on the GeReLEO system components with five LEO satellites as an example.

The main building blocks of the GeReLEO concept are:

- one or more LEO satellites, each equipped with a GeReLEO modem with a Ka-band frontend;
- a GeReLEO gateway including also GeReLEO modems with Ka-band frontends;
- a data relay payload on-board a transparent GEO satellite comprising:
  - a low gain (small size) Ka-band RX/TX conical horn antenna providing low rate bidirectional access to the LEO satellites. Because of its global coverage there are no beam handovers for the LEO satellite;
  - a novel multi-beam Ka-band RX antenna, providing high rate unidirectional access for LEO satellites;
- the GeReLEO network control center (NCC) for radio resource management, which uses the low rate telecommand link to transmit GeReLEO control messages to the LEO satellites.

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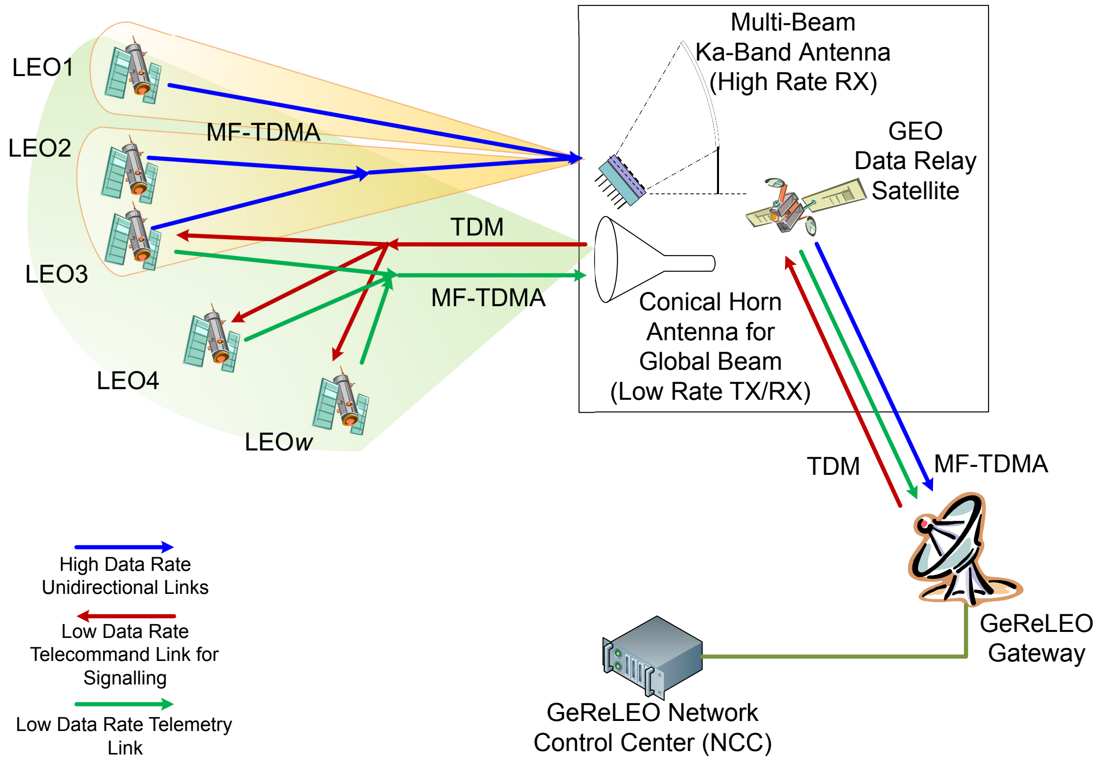

Figure 1. GeReLEO data relay satellite system architecture.

We assume that all LEO satellites, the NCC, and the GeReLEO gateway are equipped with Global Navigation Satellite System (GNSS) receivers, so that precise positioning and a time reference are available. In order to support parallel communication to several LEO satellites even in one beam, a multi-frequency time division multiple access (MF-TDMA) scheme is used on the high rate links and on the low rate telemetry links, whereas a time-division multiplexing (TDM) scheme is used on the low rate telecommand link.

The SNR changes significantly over time for each LEO satellite due to the time varying free space path loss (FSPL), beam pattern, antenna mispointing, and due to possible atmospheric attenuation (e.g., rain) on the feeder link. On one hand the high gain multi-beam RX antenna on the GEO satellite mitigates a significant amount of the FSPL for the high rate link. On the other hand adaptive coding and modulation (ACM) and variable coding and modulation (VCM) mitigate the remaining effects.

For the ISL of the LEO satellite we select 23 GHz as TX and 26 GHz as RX frequency bands, because these are often used in data relay systems.

2.2. *Protocol Stack*

At the bottom of the GeReLEO protocol stack the PL generates the waveforms towards the air interface. The data link layer (DLL) above controls the access to the frequency and time resources and provides encapsulation and fragmentation functionality. On top of the DLL there is an adaptation layer that provides services to different kinds of higher layer protocols like TCP/UDP, SpaceWire, or Consultative Committee for Space Data Systems (CCSDS) standards. On the LEO

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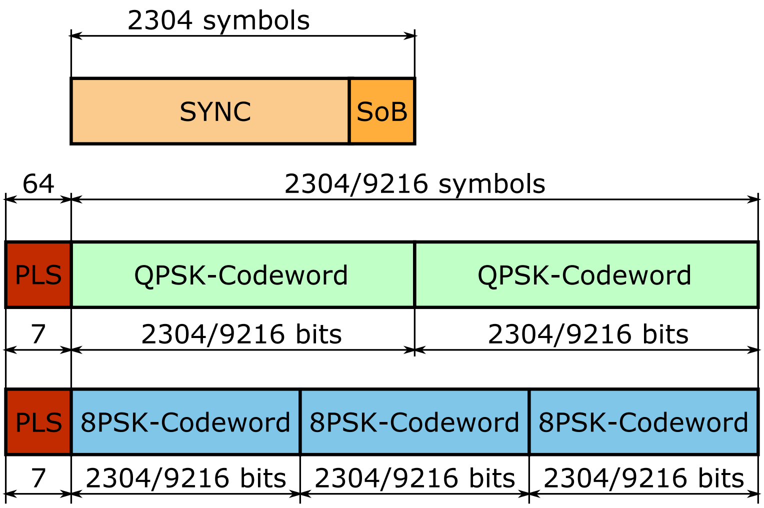

Figure 2. Physical layer (PL) waveforms.

side this layer is specific to the concrete satellite since it needs to provide the interfaces for the satellite equipment.

The data handling layers are accompanied by a resource management layer consisting of resource management modules in the gateway/NCC and the LEOs.

2.3. Transmission Scheme

Our GeReLEO transmission scheme is the key to energy efficient and concurrent transmission of data between multiple LEO satellites and the GeReLEO gateway modem(s). It enables the adaptation to the instantaneous channel conditions and provides flexible multiple access.

The transmission scheme allows an implementation in a field programmable gate array (FPGA) with limited complexity and supports the single channel per carrier mode up to MF-TDMA. The specification covers a big range of symbol rates (starting from $1\,\mathrm{kBd}$ to several hundred MBd) and allows adaptation to the different needs and link budget limitations. Our actual implementation described in section 3.2 supports two symbol rates of $364\,\mathrm{kBd}$ and $5.8\,\mathrm{MBd}$.

In total 12 different modulation and codings (ModCods) are available with LDPC forward error correction (FEC) and quadrature phase-shift keying (QPSK) or 8-phase-shift keying (8-PSK) modulation. We additionally support two codeword lengths of $2304\,\mathrm{bit}$ and $9216\,\mathrm{bit}$ for the low rate and high rate links, respectively [9].

Figure 2 depicts the PL waveform variants [9]. The signal consists of physical layer data frames (PLD-Frames). A sequence of PLD-Frames starts with a synchronization frame (SYNC-Frame) and may contain other SYNC-Frames at configurable, regular intervals for fast carrier recovery. Each PLD-Frame starts with a header for physical layer signaling (PLS) and contains either two QPSK-modulated or three 8-PSK-modulated codewords. The sizes are chosen so that the PLD-Frame size as well as the number of codeword bits is independent of the modulation scheme. The frame and codeword lengths for the high rate link are four times the length of those for the low rate link. The PLS transmits seven signaling bits, of which four are used to signal the ModCod scheme. The

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SYNC-Frame consists of a string of alternating binary phase-shift keying (BPSK) symbols and a sequence for frame synchronization.

2.4. Doppler-shift Compensation

The motion of the LEO satellite with regard to the GEO and the ground station introduces a frequency shift caused by the Doppler effect. Since the GEO transponder needs to see the signal always in the allocated frequency range, the Doppler for the return links is compensated in the LEO transmitter, while the Doppler for the forward link is compensated in the LEO receiver. The Doppler-shift can vary in the range of $\pm 800\,\mathrm{kHz}$. Proper satellite orbit propagation algorithms allow forecasting the position and velocity of the satellites, enabling the calculation of the Doppler-shift in advance. As a consequence, the LEO satellite is able to adjust the TX or RX frequency with respect to the expected Doppler-shift, such that the GEO and the ground station will see the correct frequency. The Doppler correction on the TX side is performed in the digital domain, before the analogue intermediate frequency is generated with the digital-to-analogue converter (DAC).

2.5. Multiple Access and Multiplexing Scheme

On the forward link the system employs a multiplexing scheme based on the return link encapsulation (RLE) protocol which allows putting packets for different destination satellites inside a single stream [10]. This works even with ACM. In consequence, a common ModCod for all destination satellites has to be selected which is the most robust one supported by the actual link budgets of these satellites.

Channel access to both return links (low data rate telemetry link and unidirectional high data rate link) is based on a MF-TDMA. Figure 3 illustrates the concept.

The radio resource allocation algorithm running at the NCC assigns frequency and time resources to the LEO satellites. The latter are called slots and the NCC ensures that these allocations do not conflict. Slots have typically a duration of a couple of seconds and their length is limited by the visibility times of the LEO satellites. Additionally, the NCC may specify short interruptions in the slots which are necessary to switch between beams of the multi-beam antenna (beam handover). These interruptions are normally in the order of a few milliseconds.

2.6. Data Link Layer (DLL)

The DLL controls access to the frequency and time resources. It contains also an encapsulation layer based on the RLE protocol [11] standardized by ETSI and in the DVB-RCS2 specification [12]. RLE is a protocol that is designed to be tailored to the actual communication system. The tailoring used for GeReLEO is different for the return and the forward link and both are different from the one used in DVB-RCS2. The protocol decouples the frame sizes of the physical layer from those of the higher layers by fragmenting higher layer data as required. It also provides multiplexing of data streams to different LEO satellites on the uplink and of different higher layer streams for a given satellite and the transport of meta-information like protocol numbers and labels. On the transmission side the DLL contains a QoS-aware adaptive scheduler that handles ACM, too.

Our generalised DLL software architecture supports arbitrary physical layers and applications both in space and on ground.

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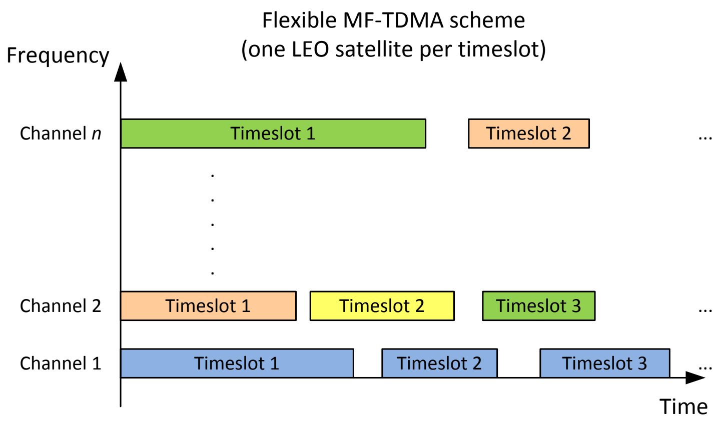

Figure 3. GeReLEO multi-frequency time division multiple access (MF-TDMA) for the return link.

2.7. *Control Plane and Signaling*

The control and management planes consist of several resource management, dispatch and management modules in the modems and the NCC. All planning of resources is done at the NCC on request from satellite and payload operators and transmitted via the normal transmission scheme to the satellites using a dedicated signaling protocol developed by us. This protocol is extensible and currently consists of around 30 messages which handle allocation of RLE protocol instances, exchange of channel state information, management of resources and overall management functions. The modems employ GNSS receivers to synchronize the resource usage.

3. HARDWARE COMPONENTS

Main building blocks of the modem hardware are the analogue radio frequency (RF) frontend (power amplification, frequency conversion between Ka-band and intermediate frequency (IF)) and the Zynq system-on-a-chip (SoC) containing two ARM© Cortex™-A9 MPCore™ application processors and a Xilinx Virtex™-7 FPGA for high performance applications. The latter is responsible for the digital signal processing, the former is used for digital control including the DLL protocol and resource management implementation ("upper layers"). The digital control software runs as application within the QNX® Neutrino® real time operating system [13] on top of the SoC's ARM© cores.

The control software forwards/receives data to/from the FPGA, which performs FEC encoding/decoding and modulation/demodulation. On the TX path signal processing includes digital signal forming, filtering and a digital-to-analogue converter (DAC) at 70 MHz (IF). In the opposite direction on the RX path an analogue-to-digital converter (ADC) samples the IF signal (70 MHz) with subsequent de-modulation (including filtering), signal acquisition, and error correction units. Modem commands can be issued via the Ethernet interface (optional: serial interface).

The EM hardware has additional built-in memory for data storage (modem firmware, configuration files etc.) as well as a 28 V DC power supply. All printed circuit boards and hardware components were integrated in an aluminum housing supporting passive thermal control. Figure 4

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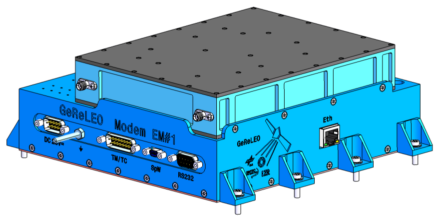

Figure 4. Computer aided design (CAD) view of the integrated modem.

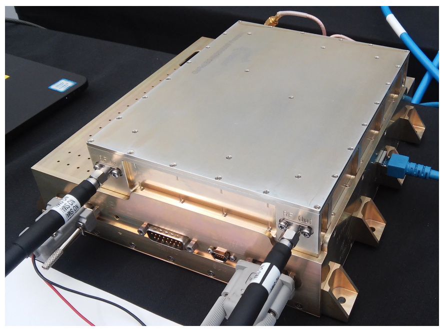

Figure 5. Modem EM consisting of the RF frontend on top and digital hardware (bottom).

Table I. Modem parameters.

Power Consumption	
Digital board	6 W (@5 V)
DC-DC converter	6 W (@28 V)
Total (incl. RF-frontend)	21 W (@28 V input)
Electrical Interfaces	
Power	9 pin D-Sub DE-9 28 V DC
Data	Ethernet
Data optional	SpaceWire, RS-232
Data optional	CAN (controller area network)
Data Rates	
Low data rate	up to 1 Mbit/s depending on code rate
High data rate	up to 16 Mbit/s depending on code rate
LDPC code rate	$0.25 - 0.78$ selectable
Modulation schemes	QPSK and 8-PSK selectable
Physical Properties	
Mass	2400 g incl. RF-frontend
Dimensions	$203\,\mathrm{mm} \times 200\,\mathrm{mm} \times 77\,\mathrm{mm}$

depicts the CAD view of the integrated modem. The top layer accommodates the RF frontend and signal amplification; the bottom layer contains the digital hardware. The manufactured, assembled, integrated and verified satellite modem EM is depicted in Fig. 5. Table I summarizes the main modem parameters.

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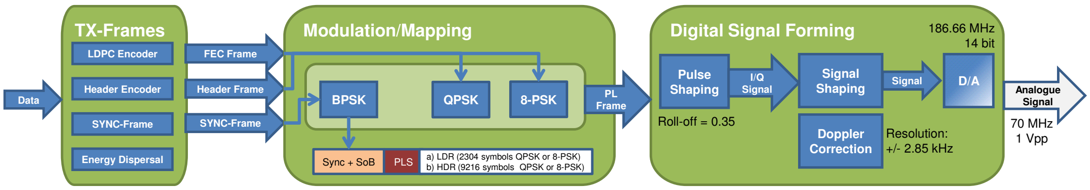

Figure 6. TX path (digital transmitter) with encoding, modulation/mapping, and signal generation/shaping.

3.1. Digital Signal Processing

TX and RX functions of the digital signal processing run concurrently in the FPGA hardware. Both signal directions will be described in the subsequent sections.

3.2. Transmitter

As depicted in Fig. 6 the digital transmitter is divided into three major blocks:

- generation of the data and header frames (encoding);
- modulation and mapping;
- signal generation and shaping.

The first stage fragments the user data stream into single frames such that the resulting frame length after the chosen FEC remains constant. FEC is based on LDPC codes with the code rate being a parameter set by the transmitting scheme and depending on the actual quality of the transmission link. Header frames are generated accordingly (using a different error correction code) and SYNC-Frames with variable repetition rates are inserted. Energy dispersal is run over the frames for a uniform energy distribution.

In the modulation/mapping block, the data frames/headers are mapped to BPSK, QPSK, or 8-PSK modulation schemes (defined by the transmission control software and depending on the link quality) and the frame components are combined to PL frames, that are forwarded to the digital signal forming.

Finally, the signal is generated on a digital level with a pulse shaping roll-off factor 0.35. At this stage, the intermediate frequency is defined and can be shifted according to a presumed Doppler-shift (Doppler correction). Actually, the transmission frequency can be adapted in $2.85\,\mathrm{kHz}$ steps. A DAC processes the digital signal at $186.66\,\mathrm{MHz}$ to obtain the analogue IF signal at $70\,\mathrm{MHz}$, as depicted in Fig. 7 for a low data rate link with $364\,\mathrm{kBd}$.

3.3. Receiver

The RX signal processing path in Fig. 8 consists of three consecutive steps:

- demodulation and downsampling,
- signal correction, interpolation and decoding (recovery of symbols), and
- demapping and decoding (FEC).

In parallel, the received signal is processed concurrently for

- signal acquisition (estimation of frequency, phase and timing),

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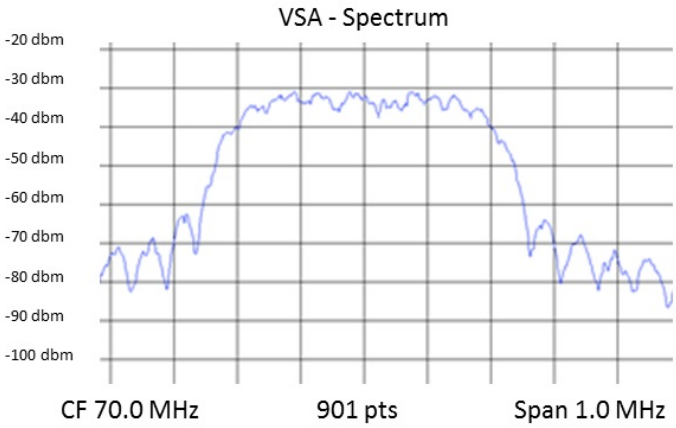

Figure 7. Analogue TX signal spectrum.

- tracking (frequency, phase and timing), and
- header evaluation (i.e. signal/noise estimation, start of burst (SoB) detection).

First, the digitized (undersampled) signal is demodulated into the I and Q parts and filtered/downsampled accordingly. If data (i.e. energy) are recognized in this stream, an initial estimation of frequency, phase, and timing (i.e. signal acquisition) starts. A tracking algorithm running simultaneously to the next stage corrects these early estimates.

The subsequent step corrects the oversampled I/Q data in frequency and phase and downsamples them to symbols in an interpolation step. Figure 9 shows exemplary results of the overall process: green - oversampled decoded I/Q signal; blue - corrected I/Q; yellow - after shaping filter; red - after interpolation/downsampling (i.e. samples). Apart from the QPSK constellation of the user data Fig. 9 depicts BPSK header symbols, too.

The obtained symbols are then divided into header and data symbols and demapped. The header symbols are evaluated to find the SoB to identify the used ModCod and to estimate the transmission channel quality by means of a signal/noise estimation performed on the header symbols.

Depending on the symbol rate (actually high data rate with $5.8\,\mathrm{MBd}$ and low data rate with $364\,\mathrm{kBd}$ were implemented), the receiver may run several concurrent LDPC decoder tasks in order to achieve the required channel decoding throughput.

3.4. RF Frontend for Ka-band

In order to be compatible with auxiliary equipment (e.g., channel simulator) the carrier frequency of the interface between the digital modem and the RF frontend module was chosen to be the standard intermediate frequency of $70\,\mathrm{MHz}$. We identified in Ka-band $25.995\,\mathrm{GHz}$ for the TX path carrier frequency and $23.040\,\mathrm{GHz}$ for the RX path carrier frequency, respectively, as potential frequency bands for future missions. For both of them we assumed the standard satellite transponder bandwidth (BW) of $36\,\mathrm{MHz}$. Key aspects of the RF frontend design were low power consumption and small size/mass in order to be compatible with small LEO satellites. A triple conversion architecture was chosen both for the TX and RX paths, as depicted in Figures 10 and 11, respectively.

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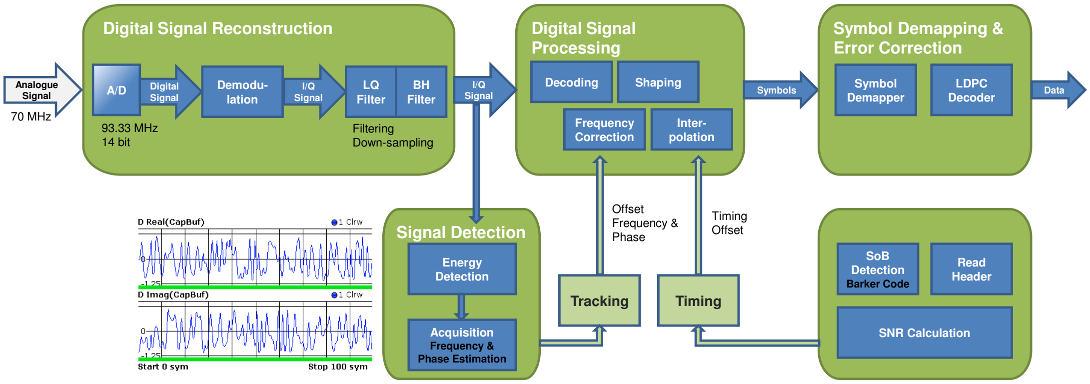

Figure 8. RX path with signal acquisition, signal correction, demodulation, and decoding.

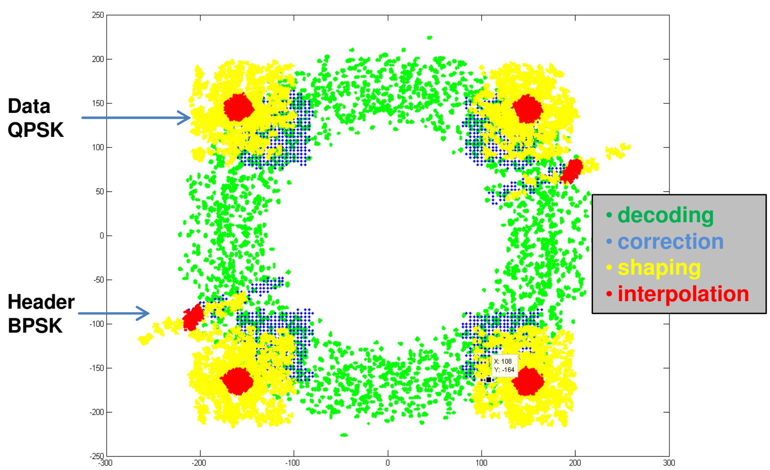

Figure 9. Constellation diagram after different signal processing steps.

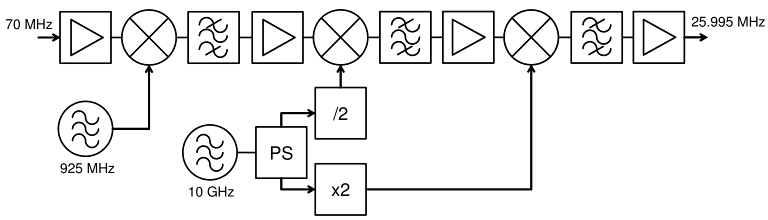

Figure 10. Blockdiagram of the up-converter.

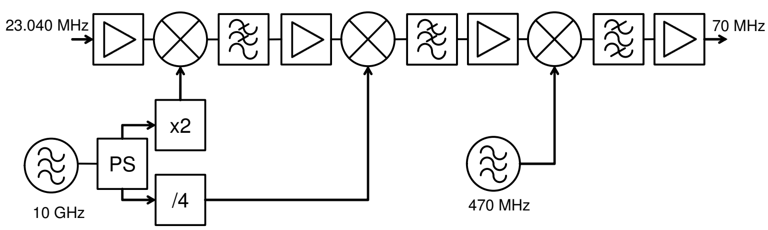

Figure 11. Blockdiagram of the down-converter.

The generation of the local oscillators (LOs) was mainly based on a 10 GHz low phase noise dielectric resonator oscillator (DRO) in order to keep the number of phase-locked loop synthesizers

Table II. Technical specification of the RF frontend.

TX input frequency	70 MHz, BW 36 MHz
TX input power	-40 dBm to -20 dBm
Gain	max. 30 dB
Output power	max. 5 dBm
Output frequency	25.995 GHz
RX input frequency	23.040 GHz, BW 30 MHz
RX input power @ 70 MHz	-40 dBm to -20 dBm
Gain	max. 30 dB
Output power	max. 5 dBm
Output frequency	70 MHz
Power consumption	9 W
Mass	980 g
Dimensions	178 mm $\times$ 138 mm $\times$ 33 mm

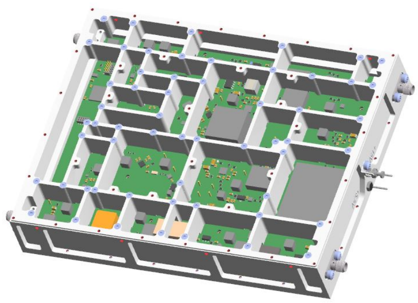

Figure 12. 3D design of the RF frontend.

small. To achieve frequency stability in the parts per billion (ppb) range, the DRO is phase-locked to an internal 100 MHz oven controlled crystal oscillator (OCXO). If available, the internal OCXO can be replaced by an external reference frequency saving some power.

The up-converter multiplies the 10 GHz DRO signal on one path by 2 and divides it by 2 (division by 4 for the down-converter) on the other path in order to generate two out of three LO frequencies needed in both branches each. The remaining third LO frequency is generated via a separate phase-locked voltage-controlled oscillators for RX and TX separately.

Frequency agility of the frontend was not needed for the current project demonstrator, but can be easily implemented by adding an external command interface like SpaceWire or RS-422 e.g., via the internally used microcontroller.

We chose a radiation-hardened (rad-hard) low power Atmel™ AVR™ 8-bit ATmegaS128 microcontroller [14], since the readily available software development tools are identical both for the commercial and for rad-hard versions. Using the internal microcontroller an additional gain adjustment stage or even an automatic gain control could be implemented, too.

The frontend is foreseen as the frequency conversion stage for the RX and the TX branch of the modem. Table II lists the technical specification. Depending on the satellite infrastructure, an external low noise amplifier (LNA) may be added to the RX path. The TX signal can be followed by an external power amplifier to increase transmit power.

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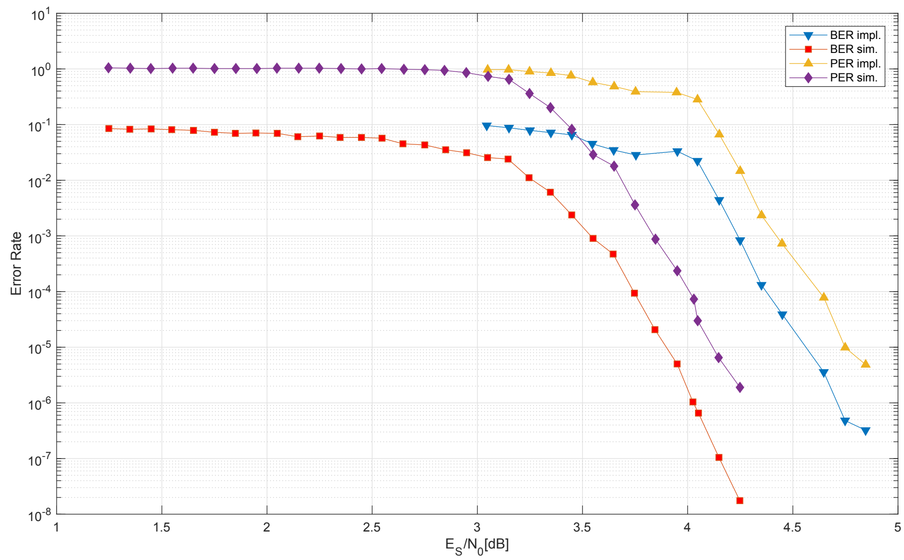

Figure 13. Comparison of bit error rate (BER) and packet error rate (PER) between simulation and real hardware implementation for QPSK with code rate 2/3.

4. RESULTS AND DEMONSTRATION

4.1. Measurement Results

We simulated the performance of the modem with MATLAB®and conducted hardware tests with two identical modems connected via an intermediate frequency interface with an additional noise source in between to emulate distortions on the link. Furthermore, in the demonstration setup (see section 4.2) real video data were transmitted from one modem to the other, but without further evaluation of the modem performance.

Figure 13 depicts exemplarily the performance of the implementation (BER/PER impl.) versus the performance of an idealised simulation (BER/PER sim.). The results are provided for QPSK modulation with a code rate of 2/3 (i.e. the low data rate link with ModCod scheme 6).

The resulting implementation loss is in the order of 0.8 dB. This performance degradation can be explained by effects of the numerical resolution in the hardware implementation (internal representation of figures with a limited number of bits). Further optimisation may be possible to close the gap to the theoretical limit at the expense of increased hardware effort.

4.2. System Demonstration

Main objective of the demonstration was a bidirectional Ka-band data transmission between the LEO satellite modem and the gateway modem. The demonstration setup architecture is shown in Fig. 14.

In this setup, the LEO satellite is on the left hand side with a laptop representing the LEO satellite sensor as data source. On the right side is the gateway with a laptop representing the LEO satellite operator. Even though, we assume that the LEO satellites and the ground station

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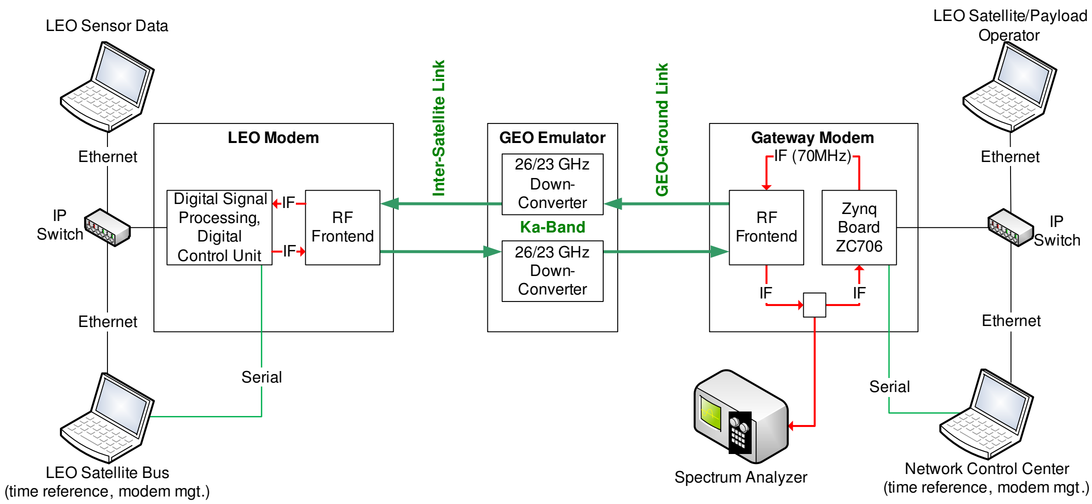

Figure 14. The architecture block diagram of the demonstration.

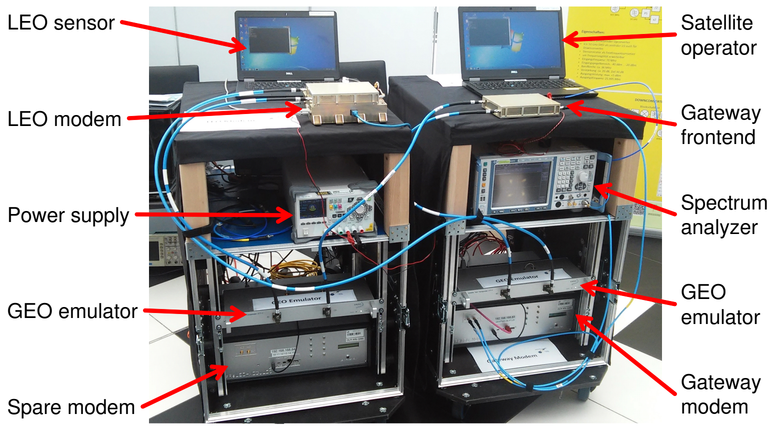

Figure 15. Demonstration setup.

have GNSS receivers providing precise time synchronization, the demonstration setup was designed by intention for indoor usage and makes use of the network time protocol (NTP) service as time reference instead.

The management laptops at the bottom of Fig. 14 on both sides are responsible for running the NTP servers and for console access to manage the modems. The spectrum analyzer is also part of the setup to show the constellation diagram of the modulated symbols. The GEO satellite is a transparent satellite, and its data relaying functionality is emulated by the Ka-band frequency translation shown in the middle of Fig. 14.

The demonstration was shown in Bonn, Germany, during the 5th National Conference on Satellite Communications that took place in March 2017. The realized setup is shown in Fig. 15. All components can be seen in the photo apart from the two management laptops which were located behind the racks.

5. CONCLUSION

The present paper explained the concept and the architecture of the GeReLEO data relay satellite system. It introduced a power efficient transmission scheme, a flexible multiple access and multiplexing scheme and described the protocol stack and data link layer, which implements a QoS aware scheduler. Furthermore, we explained the hardware components of the LEO modem and the Ka-band RF frontend. We showed how the designed algorithms, protocols, waveforms, and baseband signal processing are implemented in an engineering model of the LEO modem together with the RF frontend.

Last, but not least we described the demonstration setup and performed the demonstration on the 5th National Conference on Satellite Communications in 2017. We established a bidirectional link for data transmission in Ka-band between a LEO modem and a gateway modem.

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Financial disclosure

None reported.

Conflict of interest

The authors declare no potential conflict of interests.

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