GeReLEO-MODULOS - A Versatile LEO-Modem for Data Relay Satellite Systems

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Abstract

Earth observation satellites – typically low Earth orbit (LEO) satellites – require both data links for telemetry, tracking and command, and for download of mission data. Maintaining a contact to a passing LEO satellite for more than half of its orbit is possible with geostationary Earth orbit (GEO) satellites using suitable antennas onboard. Main objective of the GeReLEO-MODULOS project is to develop an engineering model of a modem for LEO satellites, which supports both bidirectional telemetry/telecommand (TM/TC) and unidirectional high-rate download of data via a GEO relay satellite. Key features of the modem are (i) support of several LEO satellites at the same time, and (ii) both high/low rata data transmission to/from big and small (inexpensive) LEO satellites. The software/firmware for the physical layer and for the higher layer protocols including interface(s) to the satellite bus allows flexible adaptation to missions' needs. Apart from size and power consumption, bandwidth efficiency is an important requirement. Because of the time-variant free space loss on the inter-satellite link, varying antenna gain caused by relative movement between LEO and GEO, and due to changing atmospheric conditions on the feeder link the modem supports different modulation and coding (ModCod) schemes. Switching between ModCod schemes is either triggered via the return channel, or is determined by a pre-computed deterministic pattern. The modem hardware consists mainly of Ka-band up/down-converters and a Zynq-7000 XC7Z045 all programmable (AP) system on a chip (SoC). This SoC integrates a processing system (PS) containing two ARM© Cortex™-A9 MPCore™ application processors, and a programmable logic (PL) for high performance applications. The former is used for the higher layer protocol implementation; the latter takes care of the digital signal processing and the physical layer. In this paper we will introduce the GeReLEO-MODULOS hardware and software concept. The chosen SoC approach allows both efficient modem software development and high-rate data transmission.

Key words: low earth orbit satellite; geostationary earth orbit; data relay; modem; adaptive modulation and coding.

1. INTRODUCTION

Especially low Earth orbit (LEO) satellites offer multiple capabilities for global Earth observation. Their low altitude satellite orbits and advances in remote sensing instruments enable global gathering of measurement data with high resolution. The number of such satellites and the amount of data to be transmitted is steadily growing. Moreover, an increasing number of small science and technology driven LEO satellites are launched transmitting data of various on board sensors or acting as small data communication satellites. The versatile tasks of these LEO satellites are for example weather monitoring, observation of climate changes, geo-sciences such as measuring of land-use, gravity field measurements, or monitoring of and responding to disasters. Furthermore, aircraft and ships can forward information about their position and course to LEO satellites with little free space path loss.

In case of automatic dependence surveillance-broadcast (ADS-B) for air traffic management via satellite, messages are only useful for a very short period of time. Therefore, reliable and long connectivity data links to ground stations are of paramount importance for these LEO satellites.

The traditional data transfer method of LEO satellites is to establish direct ground links. This method works without any additional communication infrastructure in space, but has the drawback of limited access times. A LEO satellite pass over a ground station lasts typically in the order of 5-15 minutes, depending on the inclination angle and altitude of the LEO satellite orbit, and on the latitude of the gateway. This limits connectivity and the amount of data that can be transmitted. A global ground station network is required for longer connectivity times. But ground station networks are sparse and do not cover the oceans. Therefore, gaps of hours between two download opportunities may occur. Moreover, the ground stations have to be equipped with tracking antennas allowing to trace only single LEO satellites during an overpass.

An appealing method is therefore to relay the data via a geostationary Earth orbit (GEO) satellite to one single ground station. This allows long connectivity times and simultaneous serving of several LEO satellites, which is a matter of number and size of the tracking beams of the GEO satellite's inter-satellite link (ISL) antenna. In average a single GEO satellite is visible to LEO satellites approximately 65% of the time. This results in an improvement factor of around 30 compared to the direct LEO-gound connection [1].

The GEO data relay concept is well known, and the National Aeronautics and Space Administration (NASA) operates the Tracking and Data Relay Satellite System (TDRSS) with currently six active and three backup satellites in orbit [2]. The first satellite TDRS A was launched in 1983, TDRS K is a third generation satellite and was launched in January 2013. It supports five LEO satellites at a time with its S-band transponder (ground-based beam-forming), whereas the Ku and Ka-band payloads are single-access systems. The Japan Aerospace Exploration Agency (JAXA) launched the experimental Data Relay Test Satellite (DRTS) in 2002 [3]. Optical and Ka-band ISLs were verified, including an experiment with a Ka-band ISL between DRTS and Envisat [4], which is operated by the European Space Agency (ESA). Both TDRSS and DRTS have steerable Ka-band receive antennas, so that the maximum number of simultaneous high-rate ISLs is equal to the number of antennas (and/or optical receivers). The European Data Relay System (EDRS) will have similar functionality, including a Ka-band payload and a laser communication terminal (LCT) for ultra high speed data download with up to $1.8\,\mathrm{Gbit/s}$ [5]. These systems provide very high data rates, but serve only single or few LEO satellites simultaneously.

So far the above mentioned systems have not addressed the provision of low and high data rate services of up to $30\,\mathrm{Mbit/s}$ to $100\,\mathrm{Mbit/s}$ with low-complexity for a considerable number of LEO satellites at the same time (e.g., 15 satellites). Especially for such scenarios novel key technologies are proposed in this paper. Core elements of the concept are a multi-beam array-fed reflector antenna for the GEO satellite, and LEO satellite modems realizing flexible multiple access and multiplexing scheme, which enable the access to several LEO satellites on one or more carriers, and adaptive coding and modulation based on low-density parity-check (LDPC) codes to save transmit power and to maximize the throughput for a given symbol rate. Our proposed approach supports both simultaneous low-rate telemetry/telecommand (TM/TC) links and high-rate download of sensor data. Main advantage is that many (even small) LEO satellites share a data relay system and do not require exclusive communication links.

In this paper, we focus on the LEO satellite modem realized in the GeReLEO-MODULOS project, in which the key objectives are as follows:

- energy-efficient high-rate sensor data relaying with $30\,\mathrm{Mbit/s}$ to $100\,\mathrm{Mbit/s}$ in order to reduce LEO TX power consumption; use of adaptive coding and modulation;
- flexible simultaneous TM/TC support of up to 10-15 LEO satellites on one or more carriers with a time division multiple access scheme and with data rates of $1\,\mathrm{kbit/s}$ up to $2\,\mathrm{Mbit/s}$;
- Ka-band LEO modem with target weight < 5 kg.

The system concept addresses explicitly low complexity data relaying for small LEO satellites. The focus is not on extreme peak data rates, but on serving several satellites at the same time with energy-efficient data transmission services.

This paper is organized as follows. After the general system concept we describe the transmission scheme, the multiple access and multiplexing scheme, and the link adaptation schemes. In the subsequent sections we explain the LEO modem hardware and the implemented digital signal processing.

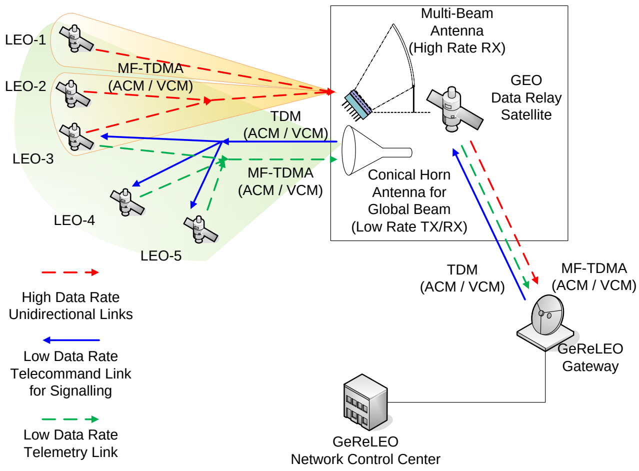

Figure 1. GeReLEO system architecture.

2. SYSTEM CONCEPT

Figure 1 depicts the overall logical system architecture focusing on the GeReLEO system components, showing 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 Ka-band modem;
- a GeReLEO gateway including also GeReLEO modems;
- a data relay payload onboard a transparent GEO satellite comprising
  - a low-gain (small size) Ka-band RX/TX conical horn antenna providing low-rate TM/TC access to the LEO satellites with a low complexity on board the LEO and the GEO satellites using a global beam, and
  - a novel multi-beam Ka-band RX antenna, providing high-rate unidirectional access for LEO satellites with a higher complexity on board the GEO satellite but still with a lower complexity on the LEO satellite; (planned in-orbit verification of the key technology as payload of the Heinrich-Hertz Satellite (H2Sat) in the GeReLEO-SMART project)
- the GeReLEO network control center (NCC) for radio resource management using the low-rate telecommand link to transmit GeReLEO control messages to the LEO satellites.

We assume that all LEO satellites 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 concurrent communications to several LEO satellites even in one antenna 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 signal-to-noise ratio (SNR) changes significantly over time for each LEO satellite due to the time varying free space path loss, antenna gain pattern, and due to possible atmospheric attenuation (e.g., rain) on the feeder link. Thus, it is important to mitigate these effects. The high gain multi-beam RX antenna on the GEO satellite mitigates a significant amount of the free space path loss on the ISL to enable high-rate data reception with low TX power on board the LEO satellite. The GeReLEO system uses in addition adaptive coding and modulation (ACM) or variable coding and modulation (VCM) on all of the links, in order to mitigate varying free space path loss and varying antenna gain on the ISL, and to mitigate potential rain attenuation on the feeder link (see Sect. 5).

After this high level overview of the GeReLEO system concept, we provide more details on the transmission scheme, which is designed in a way to have regularly repeating, systematic structures allowing uncomplex operation for the LEO satellite modems.

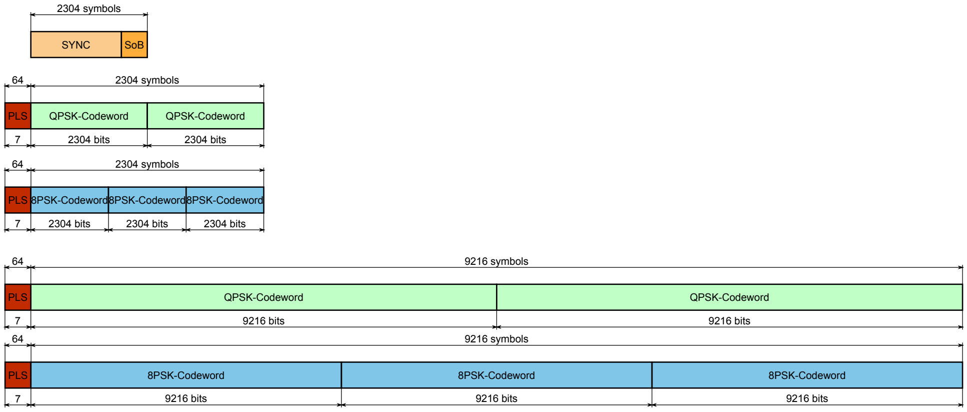

Figure 2. Physical layer frames.

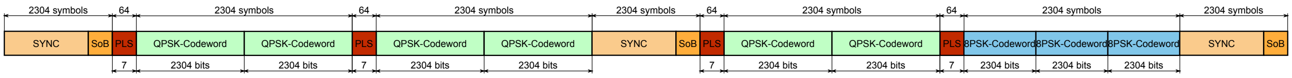

Figure 3. Transmission example.

3. TRANSMISSION SCHEME

This section describes the transmission scheme on a high-level. The transmission scheme employs two sorts of frames: synchronization frames and physical layer data frames (PLD-frames) (see Figure 2):

Synchronization frames: These frames are used to acquire and keep frequency, phase and timing synchronization. They consist of 2183 symbols of alternating binary-phase-shift keying (BPSK) symbols and 121 symbols of a sequence with very good autocorrelation for frame synchronization. The total length of the synchronization frame is 2304 symbols. A synchronization frame is sent as the first frame after transmission has been started or resumed and may be sent at periodic intervals between the other frames.

Physical layer data frames (PLD-frame): These frames consist of a physical layer header (physical layer signalling (PLS)) of 64 symbols and a payload of either 2304 symbols for the low data rate link or 9216 symbols for the high data rate link. The PLS contains 7 bits used for signaling. The first 4 bits out of the 7 bits encode one of the 16 possible modulation and coding (ModCod) combinations for all codewords (L2-frames) of the PLD-frame. The remaining bits are reserved. The payload consists of either two quadrature phase-shift keying (QPSK) or three 8-phase-shift keying (8-PSK) modulated codewords (L2-frames), each of which contains 2304 bits of coded information. The resulting total length of the physical layer data frame is 2368 symbols for the low data rate link and 9280 symbols for the high data rate link.

When the physical layer runs out of data during transmission it inserts dummy frames, which are physical layer data frames reusing the ModCod of the previous frame (or the lowest ModCod in case there was no previous frame) and containing just zeros (before channel encoding).

The transmission consists of timeslots corresponding to a certain period of satellite visibility and communication needs. Timeslots may be temporaryly suspended (e.g., to switch multi-beam antennas on the GEO-satellite), splitting the timeslot into transmission runs. Each transmission run starts with a synchronization frame followed by PLD-frames. At regular intervals synchronization frames may be interspersed into the stream of PLD-frames. The interval at which these synchronization frames appear is called the synchronization frame distance (SFD). An SFD equal to 1 means that there is a synchronization frame after each PLD-frame, while an SFD of 10 means one synchronization frame after 10 PLD-frames. An SFD of zero is handled specially and means that no synchronization frames are inserted between PLD-frames: the only synchronization frames are those at the beginning of a transmission run.

Figure 3 provides an example of a transmission where the SFD has a value of 2. In this case after every two physical layer frames a synchronization frames is inserted.

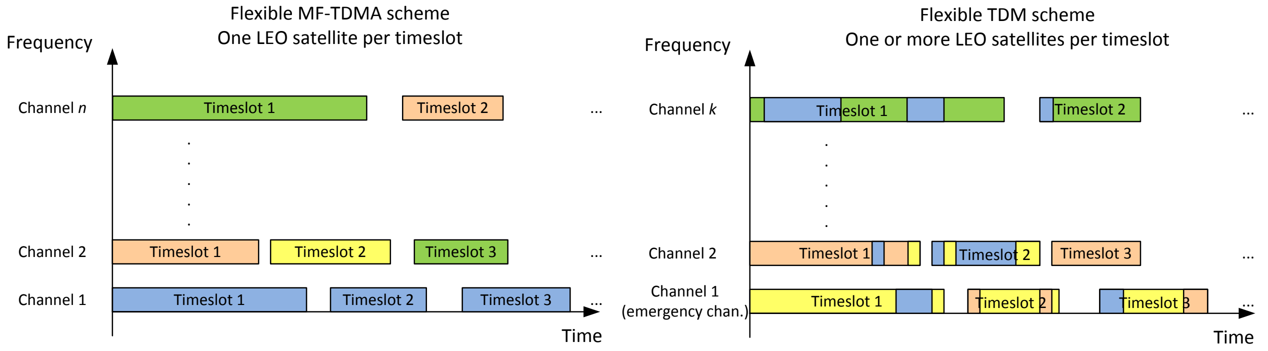

Figure 4. GeReLEO MF-TDMA multiple access and TDM multiplexing schemes.

On the transmitter side transmission can be suspended for short periods of time to support beam switching at the GEO satellite in case of the high data rate link. Beam switching results in a short signal interruption. Since the NCC knows exactly the position of the LEO satellite, it can command at the same time both the GEO satellite to switch the beam and also the LEO satellite to pause transmission for a short duration. When the transmitter resumes it will start with a synchronization frame.

In the following section, we provide a high level overview of the novel multiple access and multiplexing schemes, which enable the system to serve several LEO satellites simultaneously in a flexible way, taking into account requirements both from the physical layer (satellite visibility) and higher layers (service level agreements).

4. MULTIPLE ACCESS AND MULTIPLEXING SCHEMES

This subsection discusses the multiple access and multiplexing schemes on the available links of the GeReLEO system.

As depicted in Figure 1, a MF-TDMA scheme is used for the low-rate telemetry link and on the high-rate link, whereas a TDM scheme is used on the low-rate telecommand link. The structure of the multiple access and multiplexing schemes are shown in Figure 4.

According to the current planning, both the MF-TDMA and the TDM scheme will allow using variable length time slots. The length of the time slots is restricted by the visibility times of the LEO satellites, and are determined by the radio resource allocation algorithm running at the NCC. The NCC is using also service level agreements (SLAs) as input to perform the resource allocation. The guard time interval between consecutive time slots is variable, too, and is determined by the NCC. All of these pieces of information are transmitted by the NCC to the GeReLEO modems using GeReLEO control signals.

There is an important difference between the MF-TDMA and the TDM scheme caused by the nature of the links. While the TDM links are broadcast ones (forward direction), on the return links MF-TDMA schemes are applied. As a consequence, only one LEO satellite is assigned to each time slot in the MF-TDMA scheme, however the TDM scheme can handle more than one LEO satellite per time slot. In this case, the gateway—transmitting using the TDM scheme—enables and disables the queues belonging to the specific LEO satellites in the gateway modem, while the physical layer in the gateway modem is continuously transmitting.

The channels and the access to the channels are coordinated by the NCC. As a consequence, the frequency plan shall also be determined by the NCC in advance—with manual interaction if necessary. This is also transmitted to the GeReLEO modems as the content of control signalling.

We must note here, that a specific channel on the forward link shall be selected for emergency transmissions. This emergency channel shall have predefined properties (carrier frequency, bandwidth, roll-off factor, SFD, etc.), which shall be known by all GeReLEO modems operating in the GeReLEO system. The emergency channel shall be used at least in the following use cases: GeReLEO modem onboard the LEO satellite is powered up, so no configuration is available, or the GeReLEO modem onboard the LEO satellite for some reason has a wrong configuration, and thus has to wait to receive new configuration data from the NCC. The NCC sends the resource allocation table (RAT) control signal to allocate resources to the modems. The emergency channel however is not used exclusively just for transmitting control

Table 1. *ModCod parameters for the low-rate and high-rate links.*

Index	**Modulation**	**Coding rate**	**Information bits (low-rate, high-rate)**	**Spectral efficiency** $[\mathrm{bit/Hz}]$	**Threshold** $\boldsymbol{E_S/N_0}$[1] $[\mathrm{dB}]$ **(low-rate, high-rate)**
0	QPSK	0.25	576, 2304	0.5	$-1.11, -1.86$
1	QPSK	0.33	768, 3072	0.66	$0.1, -0.55$
2	8-PSK	0.25	576, 2304	0.75	$0.65, -0.1$
3	QPSK	0.42	960, 3840	0.833	1.21, 0.61
4	QPSK	0.5	1152, 4608	1.0	2.25, 1.65
5	8-PSK	0.42	960, 3840	1.25	2.97, 2.37
6	QPSK	0.67	1536, 6144	1.33	4.25, 3.5
7	8-PSK	0.56	1280, 5120	1.667	4.72, 4.02
8	8-PSK	0.61	1408, 5632	1.833	5.28, 4.63
9	8-PSK	0.67	1536, 6144	2.0	6.01, 5.26
10	8-PSK	0.72	1664, 6656	2.167	6.66, 6.01
11	8-PSK	0.78	1792, 7168	2.33	7.23, 6.78

[1] at codeword error rate (CER)= 10^{-6}

signals, but in case no control signal is available it shall be used also to transmit normal data. However, the control signal shall have higher priority than normal data.

In the following section, we provide a high level overview of the link adaptation schemes supported by the GeReLEO system and the LEO modems enabling power and spectral efficient transmission.

5. LINK ADAPTATION SCHEMES

It is of utmost importance to mitigate time varying channel conditions due to changing slant range between the LEO and the GEO satellite, due to the changing gain of the GEO antenna observed by the LEO satellite, and finally due to the rain fading on the feeder link. Without any kind of link adaptation techniques, the spectral efficiency of the link is very low. ACM and VCM are two link adaptation techniques that are applied in the GeReLEO system to increase spectral efficiency and to save power (see below). Both use the same ModCod scheme. The available ModCods are listed in Table 1. These 12 ModCods are shown for the low- and for the high-rate links. The thresholds are provided using floating point calculations at decoding (without implementation losses).

The GeReLEO system supports two kinds of channel adaptation techniques by default: VCM and ACM. If the SNR is significantly higher on the feeder link than on the ISL, then the total SNR is mainly influenced by the time-varying free space path loss and the time-varying gain on the ISL. The signal variation can be determined in advance. There is no need for a feedback channel from the receiver to the transmitter in this case, thus this is actually an open-loop control scheme allowing a less complex link adaptation scheme on the LEO satellite. ACM, however, is especially useful if the feeder link has a comparable or smaller SNR than the ISL, so the total SNR is significantly influenced by non-deterministic atmospheric effects. VCM is quite advantageous in case a small LEO satellites supporting only the unidirectional high rate link (e.g., due to mass or power constraints etc.) through the GEO data relay satellite, thus there is no possibility sending concurrent feedback.

The NCC is in charge of transmitting the ACM/VCM related control information to the GeReLEO gateway modem and the GeReLEO modems located on the LEO satellites.

In the following section, we provide a high level overview of the LEO modem hardware and the employed digital signal processing techniques.

6. HARDWARE AND DIGITAL SIGNAL PROCESSING

The ZC706 evaluation board from Xilinx was used for the development. Custom made FPGA mezzanine Cards (FMCs) were used to connect a high speed analog-to-digital converter (ADC) and digital-to-analog converter (DAC) to the evaluation board. The following subsection gives an overview of the implementation.

6.1. Application of the FPGA with ARM Core

Real time system on ARM: A realtime operating system (QNX 6.5.0 SP1) was selected to run on the processing system (PS) of the Zynq. It runs the software of the modem and provides libraries for communication interfaces. For board specific drivers and libraries a board support package (BSP) is used.

Digital signal processing on field programmable gate array (FPGA): The programmable logic (PL) of the Zynq is used for the physical layer containing the signal processing. The PL firmware was developed using a high-level programming language (Handel-C).

Internal interface: A high speed interface is needed for the internal communication between the software (PS) and the firmware (PL). The ARM Advanced Microcontroller Bus Architecture (AMBA) interconnect of the PS provides high performance advanced eytensible interface (AXI) ports to interface with the PL of the Zynq. The AXI4-Stream protocol is used in our case with a possible data rate of $400\,\mathrm{Mbit/s}$.

External interfaces: An Ethernet interface is used as external data interface for the development and demonstration. A SpaceWire interface is foreseen for the high speed data link onboard a spacecraft between the modem and the satellite bus. For the telemetry transmission and for commanding the modem, either a MilBus (with external space qualified application-specific integrated circuit (ASIC) or internally implemented in the PL), or a CAN bus (Zynq provides a built-in CAN controller) or a serial connection (e.g., RS485) is possible. A GPS puls-per-second (PPS) can be used for precise timekeeping in the modem.

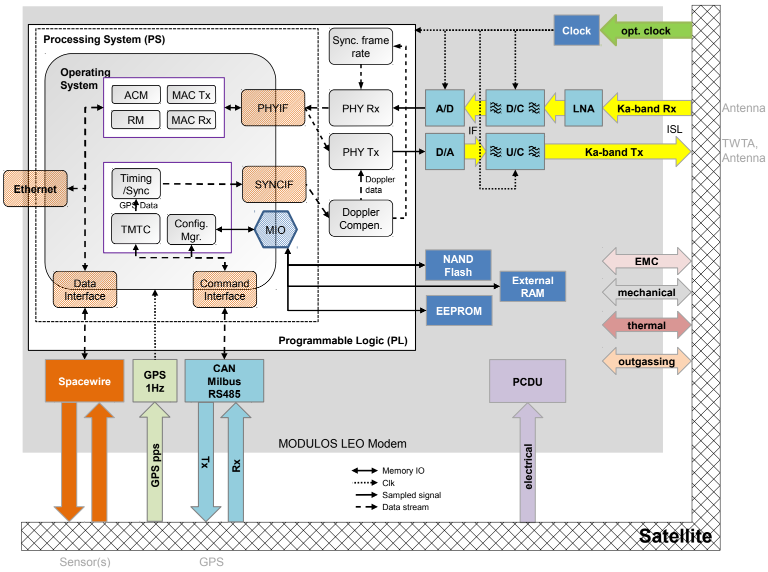

Figure 5. GeReLEO-MODULOS modem block diagram detailing the interfaces.

Figure 5 shows the block diagram of the modem, with focus on its internal and external interfaces. The internal interface "PHYIF" is using the AXI4-Stream protocol for the communication between the higher layer software in the PS and the physical layer firmware in the PL. The "SYNCIF" is using the AXI4-Stream protocol, too, to provide the precalculated Doppler shift and the synchronization frame rate to the physical layer.

6.2. Digital Signal Processing for RX and TX

The signal processing of the modem is almost fully digital: modulation, demodulation and filtering are all done in the PL.

TX signal path: The data frames provided by the PS are assembled to a PLD-frame according to the selected ModCod. After adding the PLS header using a barker code and appending LDPC codes, the resulting bit-stream is shaped with a root-raised-cosine filter (RRC), thus minimizing the inter-symbol interference (ISI) using matched filter techniques. Finally, the signal is digitally modulated on the intermediate frequency (IF) of $70\,\mathrm{MHz}$. The signal is then converted by the DAC with an output frequency of $186.66\,\mathrm{MHz}$ and up-converted to the required transmission frequency (e.g., $26\,\mathrm{GHz}$).

Synchronization frames are inserted into the signal before the first PLD-frame and at regular intervals at a configurable rate, if required.

TX based doppler compensation: To compensate for the signal doppler shift, the modulation frequency can be shifted in steps of $3\,\mathrm{kHz}$. The remaining Doppler shift is then compensated by the acquisition and tracking algorithm of the receiving side.

RX signal path: The down-converted signal is sampled with the ADC at a rate of $93.33\,\mathrm{MHz}$. The Nyquist criterion is not violated since we have a band limited signal. Therefore, the signal is band-pass filtered before sampling it. The signal is then demodulated using a least square (LQ) filter and additionally filtered a second time with a Berlett-Hann window to remove further disturbances.

The synchronization procedure is started, when a signal is discovered by an energy detection. Afterwards, an acquisition algorithm estimates the phase and frequency offset and the initial sampling point. The decoding is then started and the signal phase is corrected with the estimated parameter. The signal has then the correct phasing to be filtered with the matched RRC filter on the receiving side. The sample used for decoding is then interpolated between the samples of the oversampled signal with a piecewise polynomial interpolation.

The decoding of the signal starts with the detection of the start of the PLD-frame using the barker code in the PLS. In parallel the ModCod is decoded and the SNR of the signal is estimated. Afterwards, the payloads of the PLD-frame can be decoded according to the ModCod and are corrected by the LDPC decoder.

7. CONCLUSION

This paper provided a high level overview of the GeReLEO system concept, the LEO modem, and the applied novel physical layer techniques, which enable power and spectral efficient transmission with small complexity. The LEO modem developed in the GeReLEO-MODULOS project is capable to use adaptive coding and modulation (ACM) and variable coding and modulation (VCM) link adaptation techniques to adapt to the time varying channel conditions. Furthermore, we presented also the novel multiple access and multiplexing schemes that enable accessing several LEO satellites meeting physical layer requirements (e.g., satellite visibility) and higher layer requirements (service level agreements) at the same time. The presented LEO modem is especially useful for small LEO satellites with mass and power constraints allowing low to moderate data rates.

ACKNOWLEDGMENTS

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