ENTWURF UND DURCHFÜHRUNG VON EXPERIMENTEN ZUR CHARAKTERISIERUNG DER KOMMUNIKATIONSVERBINDUNG VON UWE-1 MIT DER ANPASSUNG UND OPTIMIERUNG DER BENÖTIGTEN PROTOKOLLE

DESIGN AND IMPLEMENTATION OF EXPERIMENTS FOR THE CHARACTERIZATION OF THE COMMUNICATION LINK OF UWE-1 WITH ADAPTION AND OPTIMIZATION OF THE REQUIRED PROTOCOL STRUCTURE

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1. INTRODUCTION

Internet standards promise interesting application potential for telecommunication in space, but require adaptations with respect to the specific space environment. This way satellite data can be directly integrated and published within the terrestrial internet. Advantages of using standardized protocol stacks for spacecrafts benefit from the huge investments into the terrestrial developments with respect to reliability, safety, cost and work efficiency. International project cooperation takes advantage of a well defined, common interface of the internet protocol.
The first missions with standard Internet protocols in space have already been realized. Famous missions are the Operating Mission as Nodes on the Internet (OMNI) project from NASA/GFSC or investigations on standard Internet hardware in space (CISCO). The OMNI project tested in the last stage (CANDOS) the operation of different protocols like Mobile IP, MDP, or NTP [1]. These missions proved, that it is possible to use standardized terrestrial protocols on spacecrafts and that the space community could benefit from this development. Nevertheless drawbacks of this technology exist, which have to be considered. The typical problems of a satellite link are high bit error rates, delays due to the large distances, and asymmetric as well as intermittent communication links. While the Transmission Control Protocol (TCP) is in terrestrial links adapted to such effects, it can not directly be transferred to the space environment without significant performance degradation [2][3]. Therefore further investigation to optimize protocol parameters to thespace environment is very promising.
Pico satellites offer in this context interesting possibilities to operate and test new software and hardware components in space. The small satellites are ideal platforms for in-orbit experiments, because of their short development time and limited costs. Despite limitations in bandwidth pico-satellites offer an interesting approach to in orbit test and verification of innovative technologies.

The main scope of the presented work regards the design and implementation of different experiments for the characterization of the radio link of a pico satellite, as well as the optimization of the communication parameters. The optimization of the communication link should provide a basis for the usage of Internet Protocols (IP) in space in combination with pico-satellites. This task comprises subtasks, such as

- Design of experiments
- Implementation of experiments
- Execution of the experiments
- Experiment analysis
- Storage of experiment data
- Development of required tools
- Adaptation of the ground station

Preparatory work included analyses of the communication link (c.f. chapter 2), implementation of software tools and initial training for ground station operation.
The main topic of this work, the design and implementation of experiments for UWE-1 was divided in four major parts: Design, implementation, optimization, and simulation. In the design part, a detailed analysis of the requirements for each experiment was done and a theoretical consideration and design ideas were discussed. The implementation part deals with the practical implementation of the experiments tailored to the special UWE-1 architecture. The optimization of the experiments examines protocol parameters from different layers to enable the most efficient usage of the communication link. Therefore mathematic models of the communication link had to be developed to determine the influence of the protocol parameters. The last part, the simulation, focuses on hardware-in-the-loop simulations to guarantee a fault free operation of the experiments after launch of UWE-1.

The structure of the document is organized as follows: Chapter 2 describes the architecture of UWE-1 which affects the design of the experiments. This contains a general overview of the UWE-1 design and details of the UWE-1 telecommunication system. The third Chapter reviews design, implementation, optimization, and simulation aspects. Results from tests and a conclusion are presented in the last part.

2. PICO SATELLITE DESIGN

2.1. The pico satellite UWE-1

UWE-1, University of Wuerzburg´s Experimental Satellite was successfully launched on the 27th of October 2005. The small satellite was realized within the CubeSat standards [4][5]. UWE-1 is a research satellite of the pico-satellite class and is restricted to a cube of 10 cm side length and to a weight of 1 kg (c.f. Fig 1.). Nevertheless it is a fully functional satellite, composed of all the typical satellite subsystems.

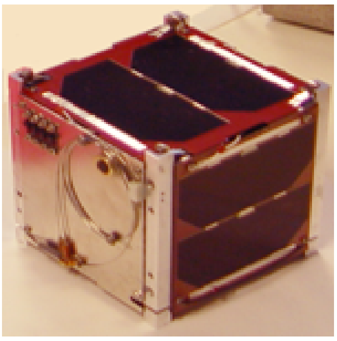

FIG 1. The UWE-1 pico satellite

The architecture of UWE-1 consists mainly of commercial-of-the-shelf (COTS) components and was developed at the computer science chair “Robotics and Telematics” in 1,5 years project time by an international team of students. There are two long term aims of the UWE project: The first one is the development of a flexible pico-satellite testbed to provide the base for a broad spectrum of technology experiments. The second objective is the integration of pico-satellites in a global IP network. Regarding the UWE-1 satellite as the first satellite in a series, two specific aims were focused: characterization of the radio link by telecommunication experiments and in-orbit test of technology developments with respect to miniaturisation techniques and high performance industrial solar cells.

2.2. Communication on UWE-1

Before designing the experiments for the UWE-1 mission, a study of the basic available communication was necessary. The UWE communication system is built from commercial-of-the-shelf (COTS) components, like amateur radio equipment or Terminal Node Controller (TNC). On Fig 2. the groundstation segment is depicted. It consists of a workstation with a Linux operating system (SuSe), which is connected via an AX.25 device to the TNC. The AX.25 Protocol is widely used in the radio amateur community for transferring data packets over huge distances. It is conforming to HDLC (ISO standard 3309) and follows recommendations Q.920 and Q921 (LAP-D) [6]. The name AX.25 is the short form of Amateur X.25, which expresses the origin X.25 extended with radio specific parameters. An AX.25 device is a network interface which enables the operator to communicate with the TNC like any other network interface, e.g. a standard Ethernet device. An AX.25 device is created with the KISS driver. KISS is a standard protocol used from radio amateurs for communication between PC and TNC. The TNC is in this project only used as a modem to modulate and demodulate the digital signals from the computer to the analogue signals of the radio equipment. It is possible to run the TNC with more “intelligence”, but to keep the control of the communication the protocol processing was shifted to the workstation. The radio equipment ICOM 910 is used to transmit the analogue signal from the TNC to the antenna.

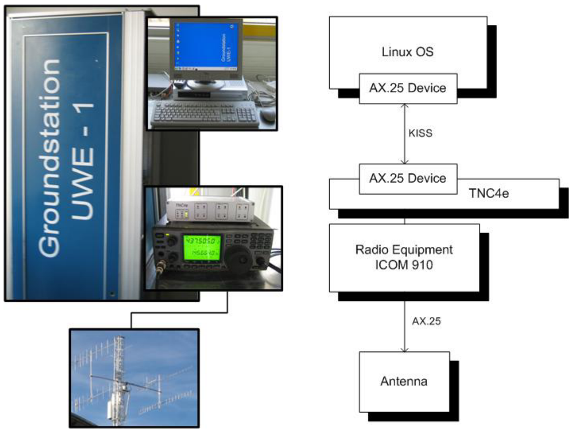

FIG 2. Groundstation Segment.

The communication on the space segment is almost identical. Of course, the size of the components is adapted to the limitations of UWE-1, but is in principle the same. Thus radio equipment, TNC and antenna are combined in one single component in UWE-1 (c.f. Fig 3). This device is called PR430 and is normally used from radio amateurs for establishing mobile radio connections. All parameters of the PR430 device can be configured by software. Therefore it is connected via an AX.25 device to the operating system. Of course it is not possible to include a whole workstation in UWE-1. For that reason a Hitachi H8 processor was integrated to provide the functionality of a full PC. The operating system on UWE-1 is also a Linux operating system, called uCLinux (pronounced micro-linux). This Linux OS was especially developed for processors without Memory Management Unit (MMU) and needs only a small amount of hardware resources. This architecture enables a basic communication over the AX.25 protocol on the data link layer (OSI reference model)

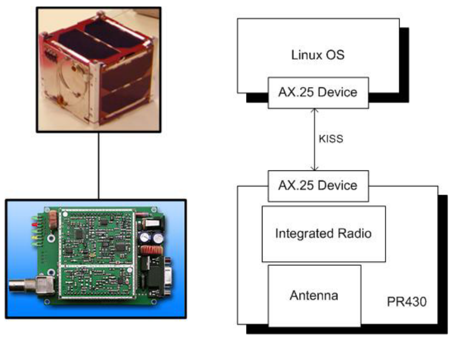

FIG 3. Satellite Segment.

As explained before, the AX.25 protocol is supported by the linux operating system and the source code is free available, which was for the UWE-1 project very important. To connect the operating system to the radio hardware, several drivers for AX.25 communication are available, e.g. KISS, 6pack, and Baycom. The AX.25 protocol operates on data link layer and therefore it is possible to use IP on top of AX.25 at the network layer. The abstraction of the different protocol layers makes it very easy to change the communication from ethernet to AX.25, as no modifications are necessary to use AX.25 instead of any other data link layer protocol. The main problem which occurs by this combination are the limitations of the satellite connection. The radio channel is limited by the bandwidth of 1200 Baud (9600 Baud respectively). This means the transmission of 150 bytes needs 1 second, which is not comparable to terrestrial internet, where response times close to milliseconds. Another crucial point is, that the connection to UWE-1 during one orbit pass is limited to approximately 12 minutes. When the pico satellite appears at the horizon the slant range is about 4000 km and it has a velocity of approximately 7 kilometers per second. At this range the signal has to cross a long distance influenced by atmospheric disturbances. When UWE-1 is directly over the ground station, the slant range is only 700 km. All these facts, like limited contact time and bandwidth or varying disturbances are influencing the design of the experiments. It was very important to take the restricted resources into account, which prevent experiments, where a huge amount of data has to be exchanged. With these considerations in mind, the experiments described in the next chapter have been implemented.

3. EXPERIMENTS WITH UWE-1

One of the central points of this work was the development of experiments for the UWE-1 project. This plan was organized as mentioned before in four major parts. The first part is the design of experiments, which build a theoretical preliminary consideration for reasonable experiments. The second part, the implementation of these experiments, handles the programming for the special UWE-1 architecture. To guarantee best performance and an operation without failures in orbit, an optimization part and a simulation part were also performed. The following subsections provide a short overview of each of these parts. Another significant aspect was the storage of the experiment data. To provide the whole cubesat team access to the gathered data, a database with a PHP frontend was implemented.

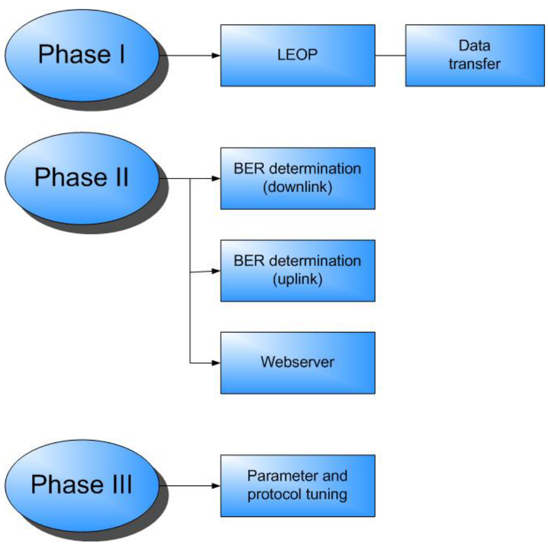

FIG 4. Experiments on UWE-1.

3.1. Design of experiments

The experiments planned with UWE-1 had two main goals: The first one was the characterization of the communication link. Therefore significant parameters like the Bit Error Ratio (BER) had to be determined and interactions with disturbances had to be examined. The second aim was the demonstration of internet protocols (IP) in space using a pico satellite. An overview of the designed experiments is displayed in Fig 4. The following sections describe the three main experiment phases.

3.1.1. Experiment phase I

Phase 1 started with the Low Earth and orbit Operations (LEOP) to get in first contact to UWE-1. In this period the Cubesat team worked 24 hours a day to activate the different subsystems of UWE-1 and to monitor the health of the pico satellite. Also a fine-tuning of the groundstation was performed in that time. Some time was spent to distinguish the orbit of UWE-1 from the other ejected flight objects, like NCube or SSETI Express. The LEOP phase was estimated with a duration of 2 - 4 weeks. After that, the first experiment began with a file transfer on UWE-1. For the transmission of a file, a simple file transfer protocol named Trivial File Transfer Protocol (TFTP) is used [7]. It is a very simple protocol basing on UDP. In this experiment the limitations like short contact times and restricted bandwidth were considered during the design to enable a reliable data upload. This means that the file transfer has to be finished in one single satellite pass. The upload of a file on UWE-1 shows the flexibility of the UWE architecture, where it is possible to update the software by uploading new applications.

3.1.2. Experiment phase II

The second phase is used to determine one of the most important values for the characterization of the communication link, namely the Bit Error Ratio (BER). This parameter is a very significant value for the communication and has to be determined separately for uplink and downlink. This means UWE-1 operates as a packet generator for determination of the BER on the downlink. To determine the BER on the uplink, the pico-satellite takes the function of a packet receiver. This is a very crucial point, as for the analysis of this experiment the recorded data in UWE-1 has to be transferred back to the ground station. During this experiment also influences like weather and position of the satellite should be considered.
The last experiment of this phase is the possibility of using UWE-1 as a webserver. Two different solutions are available here, the first one is an open source HTTP server called BOA, which has already been ported to the uClinux operating system. The second one is an own webserver implementation, which could be used without configuration effort to transmit the sensor values of UWE-1 as a HTML webpage. The transport layer connection of both webservers is established over a TCP version called TCP Westwood [8]. This TCP extension uses the “Faster Retransmit” algorithm to achieve a better performance on noisy links. The complete protocol stack available on UWE-1 is depicted in Fig 5.

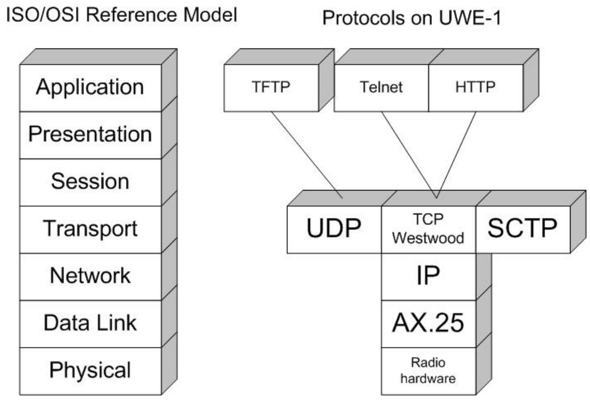

FIG 5. Protocols on UWE-1

3.1.3. Experiment phase III

The last experiment phase is called parameter and protocol tuning. This phase was planned to optimize the communication with the results obtained from the previous experiments. Especially regarding the BER, an additional Forward Error Correction (FEC) seems useful, but has to be applied to the characteristics of the radio link. From there, it is crucial to collect as much data as possible from the behaviour of radio link. As this experiment depends on the results from the former experiments, no detailed plan of this phase was worked out in advance.

3.2. Implementation of Experiments

All experiments mentioned in Section 3.1 had to be implemented for the special UWE-1 architecture. The CPU, a H8S Hitachi processor, runs uClinux as operating system (OS), therefore the implementation of the planned experiments had to be done in the C programming language. The use of Linux as OS provides great flexibility and offers a lot of free source code for a broad spectrum of applications.

The experiments are organized in separated programs. Each of these programs represents an experiment, which can be uploaded while UWE-1 is in orbit. This procedure shows the flexibility of the UWE-1 system architecture, which allows an easy experiment creation/update even after launch. To perform the file upload as simple and fast as possible, the file size of each application has to be kept very small. For the existing experiments, the source code was optimized to generate very small applications. Thus, the most comprehensive experiment - the BER determination on the uplink - has only a file size of about 17 KB. It is no problem to transfer this amount of data to UWE-1 in a single satellite pass. Another important limitation which influenced the implementation of the experiments are the restricted memory resources of the UWE processor board. As the Random Access Memory (RAM) has a size of 8 MB, the recordable experiment data is restricted by this upper bound. Thus it is significant for the applications to manage the amount of stored experiment results in an efficient manner.

3.3. Storing Experiment Data

To analyze the experiments regarding different disturbances, an extensive collection and storage of experiment related data had to be done. The aim was a consistent and clear recording of the experiments, to give all involved team members an easy access to analyze of the experiments.

The recorded data for each satellite pass of UWE-1 consists of the transmitted data-traffic, orbit data, weather situation and some additional helpful information like date, time, and description of the operating team member. All this data is stored in a MySQL data base. The access to this database was realized with an PHP frontend, which enables all team members to get specific information via a simple web browser. This mechanism is very useful to distribute the gathered experiment data to the whole Cubesat team, because it is accessible over the internet. The visualization of this data is depicted in Fig 6. The main window of the PHP frontend grants a general overview to the satellite pass, hyperlinks lead to further information like data traffic or orbit data.

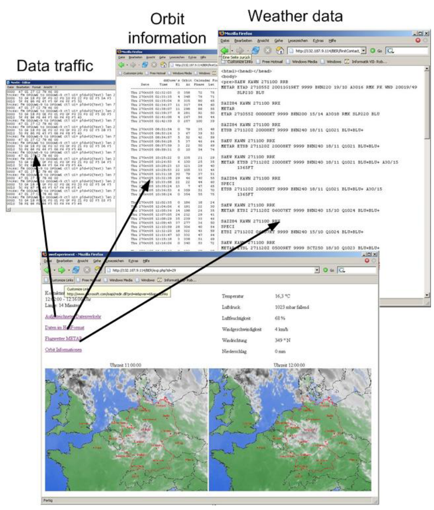

FIG 6. Stored experiment data

To facilitate the procedure of experiment recording, the ground station automatically gathers the most important information of each satellite pass. Scheduled from the operating system, the data traffic is stored every day in a separate folder to guarantee the consistence of the data. The orbit data (like position of the satellite, slant range, elevation, azimuth …) is calculated with the open software tool predict [9]. Information about the weather situation is collected according to flight weather standards. This automatic collection of data enables a simple and fast recording of the experiment for the operating team in the ground station.

3.4. Optimization of Experiments

To get the best performance of each experiment, different optimizations at the upper and lower layers of the ISO/OSI reference model have been performed. In this way a better behaviour of the protocols itself or the operation of the experiment should be achieved. On the lower layers, the channel access parameters of the data link layer have been optimized regarding the radio specific parameters. This is illustrated in Fig 7. where an optimal throughput depending on the parameters slottime and persistence was determined. Slottime describes a fixed time interval between two sending attempts. The parameter persistence describes the probability of a sending attempt.

The value of the throughput was then calculated with a mathematic model of the channel access algorithm especially developed for this purpose. Fig 7. shows that each graph has a unique maximum which can be reached with the correct parametrization.

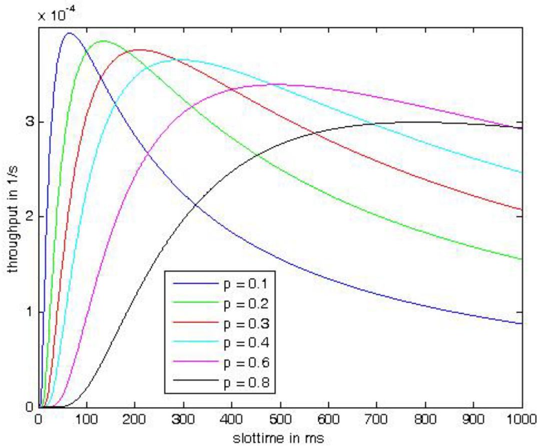

FIG 7. Determination of the optimal throughput

Another significant optimization was the tuning of the file transfer to UWE-1. As the file transfer has to be completed within one contact time of 12 – 14 minutes, the transferable amount of data is restricted. Therefore a mathematic description of the data transmission was modelled to find a trade-off between packet loss probability and packet size. If the value of the packet size is selected too short, too many packets have to be acknowledged, resulting in a bigger transmission time. Nevertheless it is not possible to use only big packet sizes, because of the growing packet loss probability according to raising packet sizes. The dependency between BER and transmission time for different packet sizes (128, 256, 512 Bytes) is depicted in Fig 8. These results can be used to adapt the packet size in case the BER is to high to transmit a file in one satellite pass.

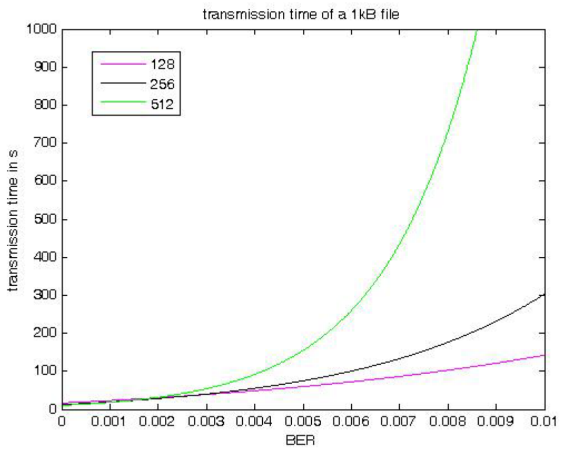

FIG 8. Theoretical file transmission time

3.5. Simulation

The hardware-in-the-loop simulation of the experiments was a important task after the implementation was finished. To prove the correct functionality of the implemented applications, each experiment was tested extensively to guarantee a fault free operation in orbit. The first performed simulation was the file transfer to UWE-1. The existing hardware was used in this test to transfer a file several times to the UWE-1 Cubesat. Afterwards average values for the transfer time have been calculated. The average transfer time of a 20 kB file is approximately 6 minutes. This time is short enough to transfer even under worst link quality condition a application to UWE-1. As mentioned in the previous chapter, all experiment applications are smaller than 20 kB.

The second simulation was the determination of the BER on the earth with the existing hardware. As it was no problem to exchange as much packets as the simulation needs, it was decided to use the batch means method for the evaluation of that experiment. These method divides a long simulation run in several batches and calculates confidence intervals for the average values of these batches. The results of the hardware-in-the-loop BER determination range between $3 \cdot 10^{-5}$ and $8 \cdot 10^{-5}$ with a probability of 90 %.

The third simulation was a “real flight test” where UWE-1 was brought to a small airplane to fly over Wuerzburg. This experiment was the first operational test to test the connection to the pico satellite. This showed the interaction of each component involved in the UWE project and was a kind of preparation for the first in-orbit contact to UWE-1.

4. EXPERIMENT RESULTS

After the first month of operation time first results could be reported. The Low and Early orbit Operations (LEOP) took about three weeks to determine the exact position of UWE-1.

The first surprising result was the influence of the weather on the communication link. The autumn in Germany is often very foggy in November, and it was complicated to get a stable connection to UWE-1 at that time. This was very hard, because it was at some days not possible to establish a single connection to the pico satellite. This behaviour can also be seen in the determination of the Packet Error Rate (PER). To compare the different positions of the satellite on his orbit, each overflight was divided into sectors of different elevation angles (c.f. Fig 9.).

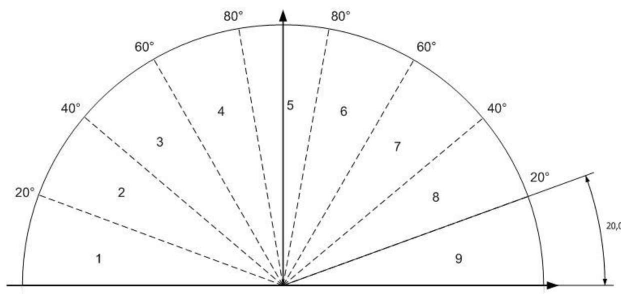

FIG 9. Sectors of a satellite pass

In Fig. 10 the measured PER values are shown in terms of confidence intervals. The x-axes describes the sector, in which the PER was determined. The slant ranges of the sectors vary between 700 and 3000 km. This is also expressed by the small values on the edges of the diagram. The variance is very high, due to the influence of the weather.

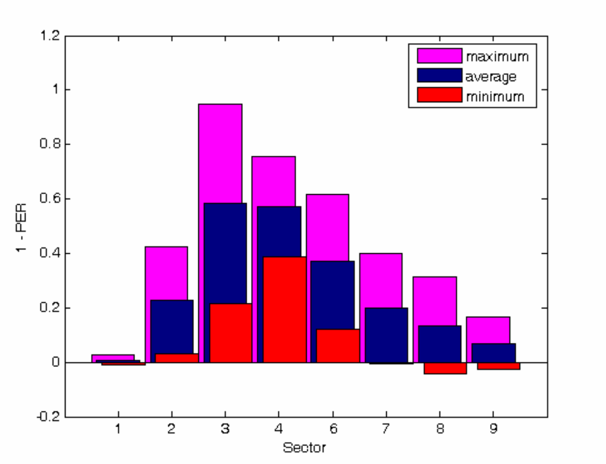

FIG 10. Measured packet error rate on downlink

The results from this experiment are very important, because they can be used for further improvement of the radio connection. The first important step is now to extend the communication on the data link layer with an additional forward error correction [10]. This strategy is very promising and should enable a better performance of the communication link. The second step is the adaption of different parameters on the hardware and software layers. This means a better finetuning of the radio amateur hardware and a dedicated usage of the software parameters when a high BER is detected.

The BER also influences the other experiments with UWE-1. Especially the data transmission is affected by the loss rate of data packets. The mathematic model for the file transfer developed in this work shows the interaction between packet loss and BER. The measured values of the PER therefore forces the packet size (the parameter blksize) to a small value, to prevent frequent packet corruption. This results in a higher transmission time, because of the bigger number of data chunks to transfer. As the data transfer is restricted by the contact time of 10 to 14 minutes, a trade-off between small data chunks and high PER has to be found. The experiments showed that it is possible to transfer a file of about 20 kB file size in 10 minutes with a chunk size of 128 Bytes. This satisfies all requirements.

5. CONCLUSIONS

The UWE-1 mission enabled characterization of the communication link. In particular the mathematical modelling of the communication link for a pico-satellite was performed including the identification of relevant communication parameters. On that basis the performance of Internet Protocols was analysed. The UWE-1 mission proved the potential of small satellites for investigation of new internet mechanisms. The usage of a microprocessor to run a complete Linux operating system on a pico-satellite emerged as an appropriate solution regarding flexibility and modularity.

In parallel UWE-1 also served the educational aim to practice system design methods at the motivating topic of spacecraft realisation [11]. Taking advantage of facilities from space industry, a team of international students implemented UWE-1 within 1.5 years.

Thus UWE-1 provides a good basis for future pico-satellites, addressing experiments on telecommunication, as well as and attitude determination and control technologies. It is planed to further develop the UWE platform into a flexible, stable and reliable testbed for future in-orbit experiments.

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