OptoCOMM and SUNSET to enable large data offloading in Underwater Wireless Sensor Networks

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***Abstract*—In this paper we present the initial implementation of an integrated optical and acoustic system that can enable large data transfer between mobile and static nodes in Underwater Wireless Sensor Networks (UWSNs). The proposed system is based on the OptoCOMM optical modem and on the SUNSET Software Defined Communication Stack (S-SDCS) framework. The OptoCOMM modem allows to overcome the limits of maximum data rate and bandwidth imposed by the use of acoustic communication by providing a data rate of 10Mbps. SUNSET SDCS instead has been used to provide networking and fragmentation capabilities to efficiently offload large data in UWSNs. The performance of the proposed approach has been evaluated through in lab experiments where large files with arbitrary sizes have been optically transferred. The results achieved show that our system is able to transfer up to 1.5 GBytes of data in short time.**

***Index Terms*—Underwater Wireless Sensor Networks, OptoCOMM, SUNSET, Optical communication, data offloading**

I. Introduction

The interest of the community in the development of underwater communication systems able to wirelessly transfer high volumes of data has constantly increased in the recent years. The main motivation lies on the increasing diffusion of Unmanned Underwater Vehicles (UUVs) operating in survey tasks for environmental monitoring, off-shore industry investigation, search and rescue, etc. During these missions, the mobile platforms usually collect information on the environment, such as side-scan sonar images, bathymetry from multibeam instrumentation, cooperation algorithms and high-definition videos, that cannot be transmitted remotely in real time due to the limits of acoustic communications. In particular, the data rate and bandwidth limitations, the variation of channel quality in time and space, the high packet loss and small packet sizes make this technology unfeasible to transfer large amounts of data.

In the last years, high speed wireless communications have been enabled by underwater optical systems. The use of Optical Underwater Wireless Communication (OUWC) allows to increase the data rate from few Kbps, typical of acoustic modems, up to Mbps when considering short-range communications. Recently, the use of Light Emitting Diodes (LEDs) for such technologies has emerged thanks to its affordable price and the constant increment of their performance in terms of lumen per watt. One of the first OUWC based on LEDs has been presented by Woods Hole Oceanographic Institute (WHOI) in [1]. The use of OUWC overcomes the limits of acoustic communications, thus allowing data downloads from the autonomous survey platforms at close distances with very high data rate without requiring the UUV to resurface. The optical nodes can for instance be deployed over the sea bottom to cover the area where an AUV is operated to retrieve data from deep submerged observatories. An earlier example of such scenario can be found in [2] where a surface vessel was sent to offload data from a CORK (Circulation Obviation Retrofit Kit) installation. A tethered probe with optical communication capabilities was lowered from the vessel hovering above the CORK optical telemetry system (OTS) and transferring data using optical communication. In such scenario, 20MB of CTD-OTS data were transfered over a 5 Mbps link at a distance of 80m. More recently, the WHOI performed various demonstration evaluating the performance of the developed optical modem at different altitudes above the seafloor [3]. A fixed seafloor node was installed at a depth of 2400m while the "Sentry" AUV, equipped with the WHOI optical modem, performed several survey patterns at different altitudes (from 25m up to 150m) above the seafloor offloading data from the underwater node. The acoustic range and optical signal strength level was used as input to initiate the data offloading process between the AUV and the underwater node. Each data offloading process consisted on 100MB file transfer between the node and the AUV.

However, large data offloading in such scenarios requires not only a high data rate modem but also a framework for an efficient file transfer. Several aspects need to be carefully considered, including fragmentation and reassembling for files when their size exceeds the maximum packet size transmittable by the modem, reliable transmission in order to account for packet losses and duplicated information, combination of acoustic and optical communications for an efficient coordination in transmitting large files in mobile scenarios, etc.

In this paper we present the initial implementation of an advanced communication and networking solutions that can enable large data transfer between mobile and static nodes using both acoustic and optical communications. The proposed approach is based on the OptoCOMM optical underwater modem [4] and on the networking capabilities provided by the SUNSET framework [5], developed by the University of Rome “La Sapienza” and recently extended into SUNSET Software Defined Communication Stack (S-SDCS) [6]. A new user interface and a driver have been defined and implemented for the OptoCOMM modem. They have been fully integrated with SUNSET SDCS to allow the real-time and remote configuration of the optical modem parameters using both acoustic and optical links and to transmit data optically. Two new modules have been also designed and implemented in SUNSET SDCS to allow the transmission of large files underwater and to fragment and rebuild packets with arbitrary sizes. Such modules allow to overcome the limit of the maximum packet size of any commercial modem, both optical and acoustic, and therefore to enable application scenarios where there is the need to transmit very large data, such as videos and images.

The rest of the paper is organized as follows. Previous works on optical communication are summarized in Section II. In Section III we describe the OptoCOMM modem, the new driver, the user interface and the new features implemented in SUNSET SDCS, including the file transfer and fragmentation modules. The following Section IV illustrates the results of in lab experiments. Finally, Section V concludes the paper.

II. Related work

Several OUWC systems based on LED technologies have been proposed in literature to provide high data rate transmissions. Most of them operate in deep ocean where the optical transmission is easier since it is less subject to the environment interferences. In [1] the authors deployed optical nodes over the sea bottom to retrieve data from submerged observatories through an AUV, while in [3] the WHOI performed in field experiments to evaluate the performance of optical modems considering different depths. Further scenarios have been proposed in [7] where the OUWC systems were able to communicate in a range of 100-200 meters with 5 Mb/s data rate in very clear deep ocean water and 4 Mb/s at 20 meter in clear water near the surface. In laboratory other OUWC systems achieved a data rate of 5 Mb/s in 7 meters water tank pool [8] and 1 Gb/s with expensive laser diode set-up in a water pipe 2 meters long [9]. The AquaOptical and AquaOptical II prototype systems have been proposed in [10] and [11], respectively. The AquaOptical II modem is the evolution of AquaOptical I. It has been tested in an indoor pool where the modems were able to communicate bi-directionally in a range of 50 meters at 2 Mb/s data rate. In [12], the OptoCOMM authors tested their optical modem in an outdoor tank pool reaching a maximum data rate of 58 Mb/s using Discrete Multi-Tone (DMT) at a distance of 2.5 meters using a blue Light Emitting Diode (LED) based OUWC system. The evolution of this modem has been proposed in [13]. Commercial modems are also available on the market, such as [14] produced by the Blue Comm. The manufacturers states to offer good performance considering both shallow water or deep sea scenarios by transmitting data with a data rate of 4Mb/s at 20 meters of distance. In this paper we show how the optical modems can be used to actually transmit data with very large size underwater through in lab experiments.

III. System description

In this section, we describe the different components of the proposed systems that allow the optical offloading of large data files with high data rate.

A. Optical modems

The OptoCOMM optical modem has been developed during OptoCOMM project [4], a project performed through the support of the FP7-SUNRISE project [15]. The main goals of this project are the design and development of a new optical modem with a target data rate of 10 Mbps at a distance of about 10m and its integration in the SUNRISE LOON testbed [16]. The harbour shallow water, that characterize the LOON testbed, is the worst seawater scenario for optical communications. The turbidity and the presence of sunlight heavily affect the performance in terms of both data rate and communication range. In order to achieve the desired specifications, the modem transmitter is based on LED blue technology and the receiver is composed by an Avalanche PhotoDiode (APD). The companion paper [13] illustrates the alpha version development of the optical modem together with the first sea trials conducted in the same location of the LOON testbed. Despite the heavy summer sunlight and the depth of just 1 meter, the results successfully confirmed the choice of the proposed design. Moreover, the challenge is not limited to the physical limitation imposed by the natural mean of transmission, and the modem must be also integrated in the more general view proposed by the SUNRISE project. Other than the performance, the goal of the OptoCOMM project is to deliver such technology to the scientific community by means of the SUNSET SDCS framework. To do this, the software plays a fundamental role in the accomplishment of the integration. In what follows we describe the firmware and the user interface that have been designed and implemented to allow the interaction between the OptoCOMM modem and SUNSET SDCS.

OptoCOMM firmware. The firmware is developed on the National Instrument myRIO in [17], an embedded hardware device composed by an ARM Cortex A9 processor and a Xilinx FPGA. The operating system is a Real-Time Linux developed by the National Instrument, named NI Linux Real Time OS and it is instrumental in maximizing the throughput of the transmission and simultaneously offering a fluid user experience. A potential user can connect to the myRIO via Ethernet TCP/IP and communicate to the modem the commands via user interface.

OptoCOMM user interface. The user interface is based on simple ASCII command to allow the user to set/get the parameter of the modem, retrieve the health status, and of course send and receive data. In particular, the synchronous commands sent by user with the respective response are transmitted on a channel identified by a TCP/IP port and the asynchronous responses, i.e., acknowledgment and received data, are on an other port. In authors opinion this allow an easier management from the user program and an easier implementation for the developer. For a seamless integration with the SUNSET SDCS framework, the user interface was developed in accordance with the specifications provided by the University of Rome "La Sapienza". Regarding the network performance, the main advantage of using optical modems rather than the acoustic one lies on offering a reliable and high data rate communication medium. The very low packet loss and high data rate offer an experience similar to the physical Ethernet connection, but an ad-hoc optical communication protocol is necessary to guarantee at the same time high throughput and a reliable file transfer. The protocol is based on the Ethernet User Datagram Protocol (UDP), enhanced to overcome reliability limitations by means of an automated repeat request scheme to guarantee the integrity of the sent file. In addition, the user can set the parameters that characterize the retransmission method.

B. The SUNSET SDCS architecture

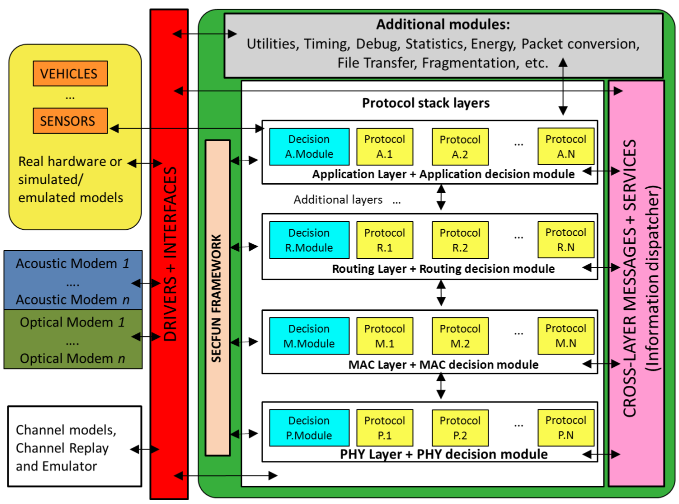

Figure 1: SUNSET SDCS architecture.

The Sapienza University Networking framework for underwater Simulation Emulation and real-life Testing framework [5] (SUNSET), and its extension SUNSET SDCS [6], is a framework that provides networking and communication capabilities to underwater nodes. It has been designed to allow an easy implementation of novel protocols and algorithms and to easily integrate external hardware, such as sensors, modems and mobile platforms. One of the most interesting feature of SUNSET is that the same code can be used in simulation, in lab emulation using real hardware and in field without any code rewriting. The architecture of SUNSET has recently been extended to support the innovative concept of Software Defined Communication Stack (SDCS) [6], where different network protocol stacks and modems (both acoustic and optical), can be dynamically and adaptively selected according to the network conditions, and applications requirements, see Figure 1. Several security solutions [18] and network protocols [19], [20], etc., are supported and tested in field.

SUNSET SDCS has been used to remotely and acoustically control different underwater vehicles [21], [22] by supporting several acoustic modems, including those produced by WHOI, Evologics, Kongsberg, Teledyne Benthos and Applicon.

A novel driver for the OptoCOMM modem has been designed and implemented as part of this work. In addition, two new modules have been designed and implemented in SUNSET SDCS to allow file transferring and payload fragmentation. The first one provides to the user multiple real-time and remote functionalities to handle files. The second one instead allows the fragmentation and reassembling of packets with arbitrary size thus overcoming the constraints of the limited packet sizes typical of the UWSNs. All the modules are described in what follows.

OptoCOMM driver. SUNSET SDCS has been extended to fully support the OptoCOMM modem operations by developing a new driver to control and reconfigure the modem, locally or remotely. The driver allows the users to set/get the modem parameters such for e.g., the number of attempts to resend data during an optical transmission (OPM), the number of the strobe light attempts during the handshake phase (CYC), specify the modem network address, etc. Using the fragmentation module together with this driver allows to send large amount of data with very high bitrate thus enabling new application scenarios for UWSNs.

File transfer module. This module has been designed to easily and wirelessly transmit and share files between underwater nodes. It provides several real-time and remote functionalities to the user, such as remote file transmission, request for file transmission, file listing, download and upload of any file type. Once the file is received, its integrity is checked by computing the related checksum. The user can also set the use of acknowledgments if needed. The interaction with this module can be performed either using acoustic or optical transmissions, according to the application scenario and user needs.

Fragmentation module. This module has been designed to allow SUNSET SDCS to transmit packets with arbitrary sizes without having to take into account the maximum packet size that a specific modem can transmit. The behavior of the module is completely transparent to both users and protocol stack. In addition, it can be placed at any level of the protocol stack, from the MAC to the application layer. On the transmitter side, once the fragmentation module receives a packet from the upper layer, it first checks its size. If it exceeds the maximum payload size allowed by the modem currently used, the module splits the data in smaller packets (*chunk*) and forward them to the lower layer(s) of the protocol stack. If instead the size of the packet is lower or equal to the maximum payload size, it is directly forwarded to the lower layer(s). On the receiver side, the fragmentation module reassembles the original packet once all the chunk packets are received. Then, the reconstructed packet is forwarded to the upper layer(s) of the protocol stack. Finally, the user can enable the use of

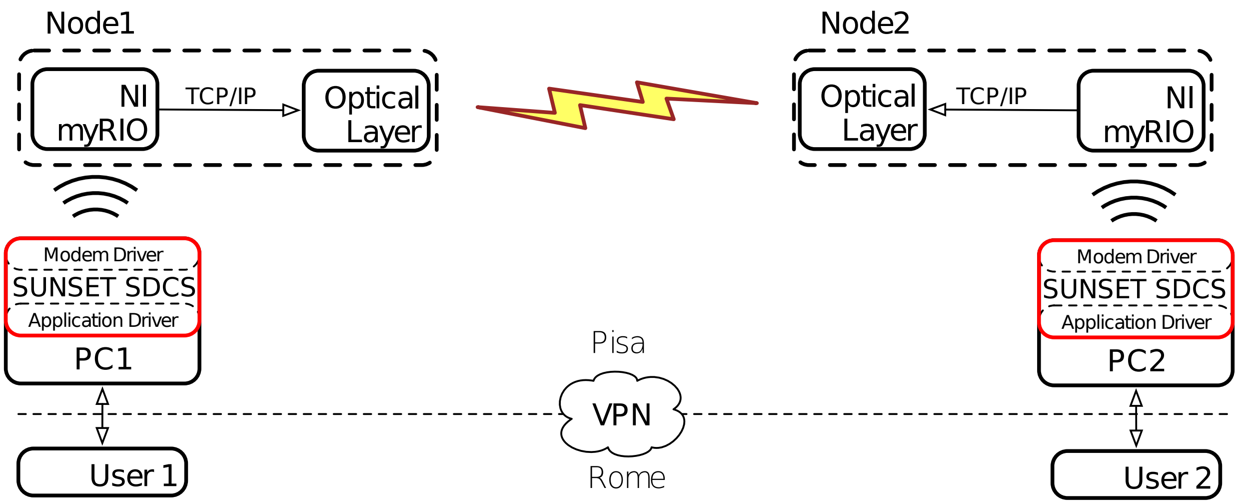

Figure 2: Schematic view of the experiments setup.

either per packet or cumulative acknowledgments to ensure the reception of all chunks.

IV. Experiments

The performance of the proposed system have been evaluated through in lab experiments. The main objective of these experiments is to prove the feasibility of the proposed approach to transmit arbitrary packet sizes in UWSNs. The experiment setup is presented in Figure 2. Two optical modems, Node 1 and Node 2, have been connected via Wi-Fi, using their myRIOs, to two instances of SUNSET SDCS running on two different PCs. A Virtual Private Network (VPN) connection between the university of Rome and Pisa has been used to allow the user access to SUNSET SDCS. The fragmentation module of SUNSET SDCS has been used to transmit large files overcoming the constraints of the maximum packet size of the optical modem. Several files with different sizes, ranging from 11 MBytes to 1.5 GBytes, have been optically transmitted (Figure 3). The maximum payload size for each packet has been set to 5 MBytes. Therefore the files with greater sizes have been fragmented by the SUNSET SDCS fragmentation module at the transmitter and then reassembled by the receiver. The bit-rate of the optical modem was about 10 Mbps. The Aloha protocol has been used at the MAC layer of the SUNSET SDCS protocol stack. Its header size has been set to 3 bytes.

The results of these experiments are shown in Table I where we report the size of the file transmitted, the number of chunks in which the files have been fragmented and the time needed to transfer them. The file sizes do not include the sizes of the different headers used by SUNSET SDCS for each layer of the protocol stack. The obtained time includes the amount of time needed to transmit the data from the first PC to the transmitter optical modem through the Wi-Fi connection, the actual optical transmission between the two modems and transmission from the receiver modem to the second PC via Wi-Fi. The final version of the modem will be provided with an Ethernet physical cable to communicate with the user, so the transmission time could benefit from the higher data rate. As expected, the latency increases according to the packet size and the number of chunks to be transmitted up to about 47 minutes when transmitting 1.5 GBytes of data. However, the latencies are in line with the typical delays of terrestrial networks confirming that the optical modems can be used to transmit large data size at high speed with very low latencies.

Figure 3: Laboratory experiments with two OptoCOMM modems during a file transmission.

File size	No. of Chunks	Time [s]
11 MBytes	3	18.7
46 MBytes	10	88.5
106 MBytes	22	198.5
354 MBytes	72	708.7
500 MBytes	101	929.6
750 MBytes	151	1402.5
1.25 GBytes	251	2316.4
1.5 GBytes	301	2816.3

Table I: Results from laboratory experiment.

Finally, authors want to highlight that even if the experiments were conducted with the optical system in air, the same setup has been successfully tested at sea and presented in the companion paper [13]. Therefore, the proposed system can be easily and seamlessly ported in field without any further changes.

V. Conclusions

In this paper we presented an innovative system for UWSNs based on the OptoCOMM modem and SUNSET SDCS to provide efficient large data offloading. A new driver and an user interface were designed and implemented in both the systems to allow optical data transfer with high data rate and to control remotely and in real-time the optical modems. Finally, two new modules were designed and implemented in SUNSET SDCS to allow the transfer of files with arbitrary size and the fragmentation/rebuilding of large data in underwater wireless sensor networks. During the tests, the OptoCOMM modems guaranteed an easy access to the their functionalities and a reliable transmission protocol by always delivering the sent file in its integrity. Results from in lab experiments confirm that the proposed system can be used to efficiently transfer very large data files.

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