Enabling Cooperation and Networking in Heterogeneous Underwater Networks composed of Multi-Vendor Vehicles and Modems

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***Abstract*—The cooperation and networking in heterogeneous underwater networks composed of vehicles running different control software and multi-vendor modems are a key issue due to the lack of standard. Since the interaction between different and multiple assets is of paramount importance for several application scenarios, in this paper we first present the new SUNSET Software Defined Communication Stack (SDCS) framework architecture that enables the support of multiple and multi-vendor modems. These multi-modal features and new networking protocols allow the communication between assets equipped with different modems through nodes acting as bridge. Then we present the extension of the SSC protocol to support the ROS middleware thus enabling the cooperation between mobile underwater vehicles running different middleware. Such integration and the multi-modal bridging functionalities have been tested and validated through several in-lab and in-field experiments. In particular, SUNSET SDCS has been used to acoustically control in real-time the MARTA AUV running ROS by leveraging on the SSC protocol. In addition, MARTA has been used as a bridging gateway to allow the communication between nodes equipped with multi-vendor modems thanks to the SUNSET SDCS multi-modal capabilities. The results show how the proposed system allows the cooperation and communication in heterogeneous networks composed of different and multi-vendors assets.**

***Index Terms*—Underwater Wireless Sensor Networks, Multi-Modal communications, Autonomous Underwater Vehicle, Remote Control, DUNE, ROS, MOOS, SUNSET SDCS, S-SDCS, SUNRISE, MARTA AUV, Marine Robotics, Underwater Acoustics.**

I. Introduction

Underwater Wireless Sensor Networks (UWSNs) are a promising technology for sensing and monitoring the underwater world. Pervasive real-time monitoring of seas, oceans and waterways is required by emerging scientific and industrial underwater applications such as environmental monitoring, disaster prevention, archeological survey, coastline protection, etc. [1]. The use of heterogeneous Unmanned Maritime Vehicles (UMVs) and underwater modems offering different capabilities and features that cooperate and communicate through networking is crucial to support such application scenarios. In the last decades, the technology of Unmanned Underwater Vehicles (UUVs), Unmanned Surface Vehicles (USVs), acoustical and optical underwater modems has evolved to offer increasing capabilities. Unfortunately, the lack for standards in underwater digital communication and common interfaces for UMVs control is reducing the speed for the development and deployment of heterogeneous underwater network. In particular, underwater modems (both acoustic and optical) produced by different vendors are unable to communicate each other since using proprietary physical schemes. JANUS [2] is a first initiative to define a common language for underwater acoustic communication. Since it has been designed to be used for initial contact and emergency messages exchange between underwater nodes, the JANUS physical scheme is robust and reliable but at a toll of a very low data rate (80 bps). Unfortunately, even if heterogeneous mobile assets support a common physical coding scheme, the cooperation between heterogeneous robots is still unfeasible. This is because UMVs usually run different middleware platforms, such as MOOS [3], ROS [4] and DUNE [5], to control and interact with the hardware of the vehicle, to process the collected data and to determine the next course of action. Each vehicle encodes and decodes the messages used to communicate with such middleware or other vehicles in different way thus limiting the interaction between heterogeneous assets. Recently, University of Roma La Sapienza and its spinoff WSENSE srl [6] have presented an application protocol, named Software-to-Software Communication (SSC) [7], that enables the seamless cooperation between underwater heterogeneous assets.

In particular, the SSC protocol enables the communication and the interaction among underwater heterogeneous assets that use the SUNSET Software Defined Communication Stack (SDCS) networking framework [8] and a vehicle control software such as MOOS, ROS and DUNE. The authors show through several at-sea experiments, only the interaction between static underwater nodes and Autonomous Underwater Vehicles (AUVs) Noptilus [9] running the DUNE toolchain both equipped with EvoLogics S2CR 18/34 acoustic modems [10]. Both SUNSET SDCS and SSC have been engineered, extended and included in the smart underwater networking that is part of the offer of WSENSE srl.

In this paper we extend what the authors presented in [7] by enabling the communication between underwater nodes equipped with multi-vendor acoustic modems and showing in-field results related to the ROS integration in the SSC. In particular, the contribution of this paper is manifold. We extend and enhance the SUNSET Software Defined Communication Stack (S-SDCS) to support the use of multiple modems from different vendors at the same time. Two novel networking protocols have been also designed and developed to enable such multi-modal communication. Futhermore, ROS has been fully integrated in S-SDCS using the SSC protocol to allow the interaction with vehicles running such middleware. Finally, several in-field experiments have been performed to evaluate these new features involving the MARTA AUV [11] running the ROS and acting as a network bridge between nodes equipped with different acoustic modems. The results show that the SUNSET SDCS framework is able to support at the same time multi-vendors acoustic modems and vehicles to enable the communication, interaction and cooperation in heterogeneous networks.

The rest of the paper is organized as follows. In Section II we fully describe the considered system composed of MARTA AUV (Section II-A), SUNSET SDCS (Section II-B) and the ROS modules implemented to allow their interaction by leveraging on the SSC protocol (Section II-C). Simulation and in-field experiments are described in Section III and in Section IV. Finally, Section V concludes the paper.

II. System architecture

In what follows we deeply describe the architecture and all the different components of the considered system. In particular, we first describe the MARTA AUV [11] highlighting its features and capabilities. Then we describe the new architecture design of SUNSET SDCS [8] to support multi-modal communication and the ROS architecture. In order to support multi-modal communication, two novel multi-modal protocols are also presented. Finally, we describe the new modules designed and developed to enable the interaction between SUNSET SDCS and MARTA within the ROS system.

A. MARTA AUV

MARTA Autonomous Underwater Vehicle (AUV) is one of the main outcomes of the European ARROWS project [12]. It is an AUV prototype developed and built from scratch by the University of Florence and specifically designed to be used in archeological surveys. MARTA final version is shown in Figure 1 where the vehicle is navigating on surface. It is composed of many modules, each one dedicated to a particular task (e.g. propulsion, sensor payloads, power supply, etc.).

Thanks to its modularity and reconfiguration capability, MARTA AUV can be easily customized according to the archaeological mission to be performed. The vehicle has been designed to be deployable from a small boat. It has a total length of 3.7m (in its longest and complete configuration), an external diameter of 180mm and an in-air weight of 80kg. The maximum reachable depth is 120m and the maximum speed 3kn relates to an autonomy of about 4hours. The typical cruise speed is 1kn. MARTA, either on the surface or underwater, is able to perform hovering: It has 5 degrees of freedom (DOFs) fully controllable by means of 6 actuators (electric motors plus propellers). They include 2 rear propellers, 2 lateral thrusters and 2 vertical thrusters. MARTA can house both acoustic and optical payload.

Figure 1: MARTA AUV.

The software architecture of the vehicle is based on the Robot Operating System (ROS) [4], which yields a completely modular architecture where suitable software nodes (each of them related to a particular component or subsystem of the AUV) exchange data on dedicated topics. This pairs well with the modular nature of MARTA AUV, yielding an efficient and functional structure.

B. SUNSET SDCS

The Sapienza University Networking framework for underwater Simulation Emulation and real-life Testing framework [8] (SUNSET) 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. Recently SUNSET has been extended into SUNSET Software Defined Communications Stack (S-SDCS) [13], a smart underwater networking product of WSENSE srl, where different and multiple protocol stacks can run at the same time.

A decision module dynamically selects the communication technology, protocols and protocol parameters to use to optimize system performance. The S-SDCS has been designed by separating the protocol stack from the additional components handling the communications with external devices. This enable users to implement new protocol solutions in an easy and fast way, without affecting external hardware modules (see Figure 2) and makes very easy to interconnect the S-SDCS with different commercial hardware and navigation software. SUNSET SDCS has been used to remotely and acoustically

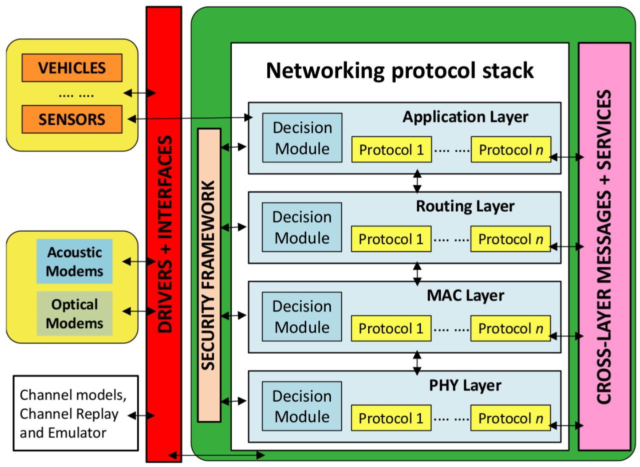

Figure 2: Simplified representation of S-SDCS architecture.

control several underwater vehicles [7], [14], [15] middleware platforms (such as MOOS [3], ROS [4] and DUNE [5]) thanks to the support of several acoustic modems, including those produced by WHOI, Evologics, Kongsberg, Teledyne Benthos and Applicon. All the solutions and features of SUNSET SDCS are currently commercialized by WSENSE srl.

The SUNSET SDCS framework has been extended to support multi-modal communication and the ROS architecture. In what follows, we describe these new features.

Concurrent multiple modems support. The S-SDCS architecture has been enhanced by adding the support for the use of multiple modems (acoustic or even optical) at the same time in the protocol stack. The new architecture is shown in Figure 2. Several modifications and improvements have been performed to the Core modules to properly support the use of multiple modems in a transparent way with respect to the networking protocol stack. In particular, the user can define which modem can be used in real-time. The reception of the data can occur at any modem and it will be simply forwarded at the upper layer. JANUS modulation scheme [16] has been also fully integrated in the S-SDCS protocol stack allowing the transmission and reception of data packets using this modulation scheme.

Multi-modal protocols. Since one of the goal is to make MARTA AUV act as a network bridge to transmit/receive information using multiple modems at the same time, two novel protocols have been implemented at the MAC and routing layers. Once the routing receives a data to transmit it selects which of the available modems to use for retransmission, signaling this information to the data link layer that will provide MAC capabilities and handle information exchange with each of the selected modems.

ROS support. The S-SDCS has been extended and enhanced to be fully integrated with the ROS system. A new module has been developed to allow the interaction between underwater vehicles running ROS and the S-SDCS. In what follows we deeply describe such integration.

C. SUNSET SDCS to MARTA interaction

Two ROS nodes have been developed to enable the interaction between SUNSET SDCS and underwater vehicles executing the ROS architecture: The SUNSET SDCS to ROS Vehicle Node (SRVN) and the ROS to SUNSET SDCS Vehicle Node (RSVN). The architecture is shown in Figure 3. The SRVN is an intermediary between ROS and S-SDCS according to the SSC protocol commands [7]. In particular, the role of the SRVN is twofold: 1) It manages the connection between ROS and S-SDCS receiving and sending SSC commands; 2) It translates SSC commands to ROS messages and vice-versa. As for the SSC protocol, the SRVN has been designed to be abstract and generic for any UUVs. The RSVN is instead the intermediary between the SRVN and the ROS architecture. This node is responsible to notify to the ROS system about the execution of S-SDCS commands according to the S-SDCS command definitions and semantics. Since the RSVN directly communicates with the vehicle, its design and implementation are specific to the considered vehicle.

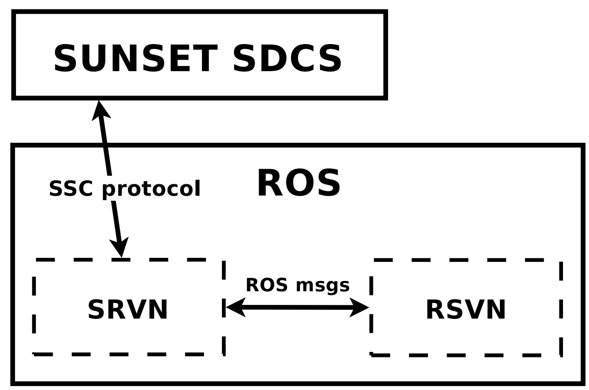

Figure 3: SUNSET SDCS to ROS communication scheme.

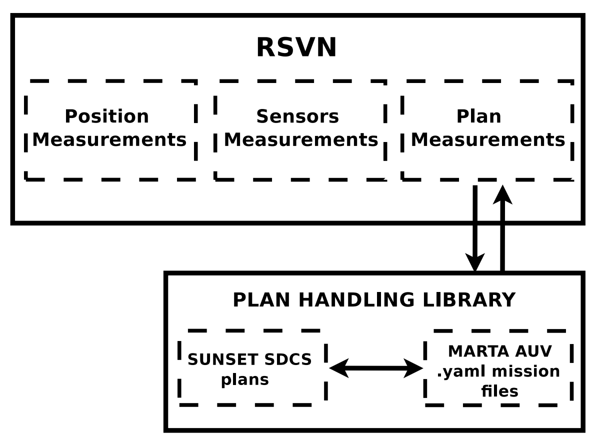

Figure 4: ROS to SUNSET SDCS Vehicle Node (RSVN).

The RSVN developed for MARTA AUV is in charge of translating each received SUNSET SDCS command into vehicle-specific format (Figure 4). Then accordingly, it indicates to the ROS system running on the vehicle which task has to be executed. In particular, the interpreter is a

ROS node, written in Python, which can be run in parallel with the whole MARTA software architecture. The node is split into two parts: 1) a low level plan handling library, which contains the methods used to convert vehicle plans defined according to the SSC into MARTA-readable format (i.e. .yaml mission files); 2) a high level interface, which exploits the former in order to actually perform operations on plans and additionally to handle the requests for position and sensor measurements on separate threads. The integration of the RSVN is completely transparent with respect to the vehicle: Since each SUNSET-related command is preliminarily "filtered" by it, no modification to the navigation and guidance system of MARTA AUV is needed, and SUNSET SDCS support can be easily added or removed with very little effort.

III. In-lab tests

By leveraging on the S-SDCS and ROS capabilities to run in simulation mode, we performed a preliminary set of in-lab tests to validate the integration. During these experiments we tested several SSC commands, such as *PlanAdd*, *PlanStart*, *PlanStop* and *PositionGet*. The S-SDCS channel emulator [8] has been used to emulate the underwater channel and acoustic modem behaviours by introducing realistic propagation delays and data transmission bitrate.

In Figure 5 we show the path followed by MARTA during one of the in-lab simulation tests. In particular, we added in the vehicle a new plan composed of two *Goto* maneuvers and a *Rows* maneuver, the latter consisting of a lawnmower path. In addition, after the mission starting, we requested the position of the vehicle with a frequency of 10 seconds in order to be aware in real-time about its path trajectory.

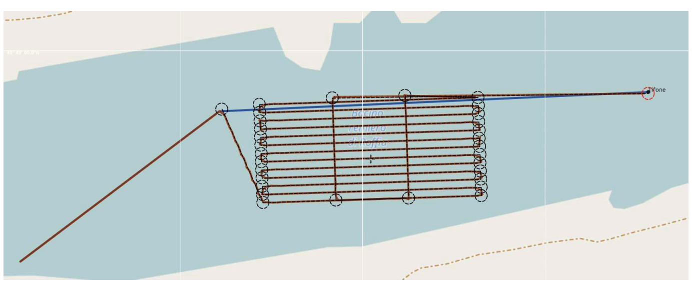

Figure 5: Path followed by MARTA during one of the in-lab simulation tests.

IV. In-field tests

The performance of the proposed system have been also evaluated in field during November 2016 at Roffia lake (Tuscany, center of Italy). Three sets of experiments have been carried out in this challenging scenario where the acoustic communications are severely affected by the limited depth of the lake (ranging from 1m to 3m). In the first one we tested the integration between the S-SDCS and ROS system to acoustically control in real-time MARTA. Then we tested the ranging estimation between a static node and the moving vehicle. Finally, we proved multi-modal communication using different acoustic modems and modulation schemes.

The topology used for all the considered experiments is shown in Figure 6. In particular, we deployed three heterogeneous nodes composed of two static underwater sensor nodes (with IDs 1 and 3) and the MARTA AUV (with ID 2). MARTA was equipped with two different acoustic modems, an EvoLogics S2CR 18/34 [10] and an AppliCon SeaModem [17]. Instead, static nodes 1 and 3 were equipped with an EvoLogics S2CR 18/34 and an AppliCon SeaModem, respectively. The AppliCon SeaModems have been configured to use both the FSK and JANUS [16] modulation schemes.

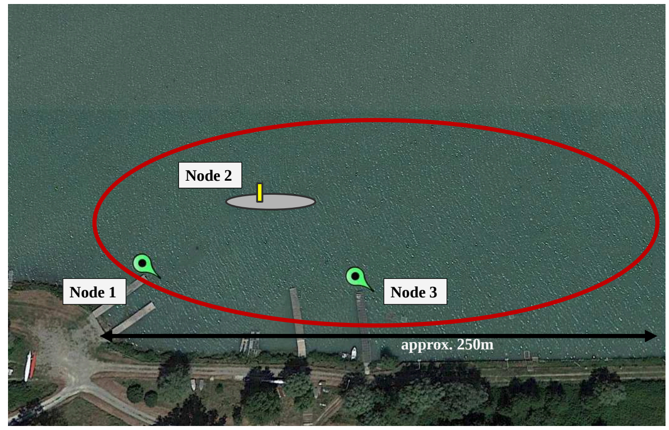

Figure 6: Network topology of Roffia lake experiments.

A. Remote and real-time control of MARTA

In the first set of experiments, we remotely and in real-time controlled MARTA using multiple acoustic modems thanks to the S-SDCS networking capabilities. We made the vehicle moving in the red area according to the user-specified maneuvers. In particular, we were able to remotely add, start, stop and abort different mission plans on the vehicles. Information about positions and sensor measurements collected by the AUV were also provided acoustically in real time. In Figure 7, we show the path followed by MARTA during one of the experiments. In particular, MARTA was executing a plan composed of two *Goto* maneuvers and a *Rows* maneuver. During the mission, we requested altitude measurements in real-time to the vehicle from the static nodes. The vehicle replied the estimated information using both the acoustic modems, namely the Evologics and SeaModem. In Figure 8 we report the aggregated altitude measurements that have been collected by node 1 and 3. Since the vehicle was moving, the static nodes were not always able to correctly receive the packets transmitted by the vehicle. In Figure 9, we show the packets containing the altitude measurements that have been successfully received by both the static nodes. In particular, each red triangle and blue circle represents a packet correctly received by node 1 (equipped with Evologics) and node 3 (equipped with SeaModem), respectively. It can be noticed that the relative distance (estimated with GPS) between them

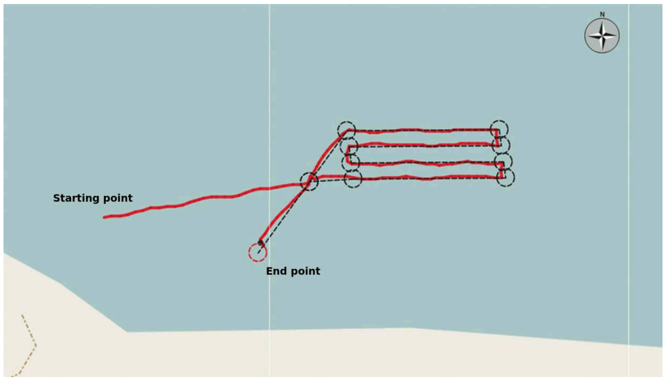

Figure 7: The path followed by MARTA during the in-field tests.

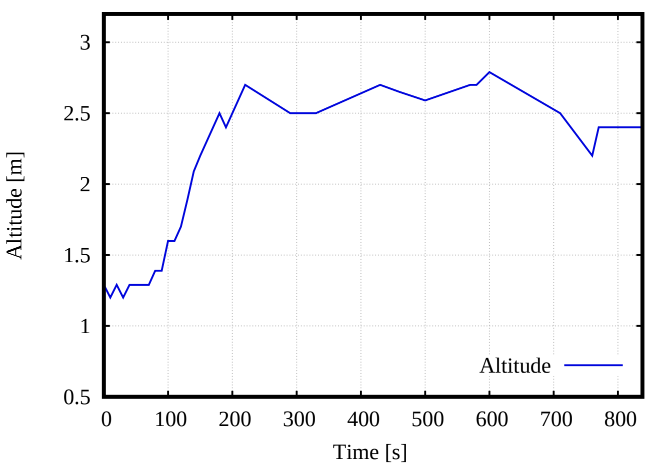

Figure 8: Altitude measurements collected using multiple modems.

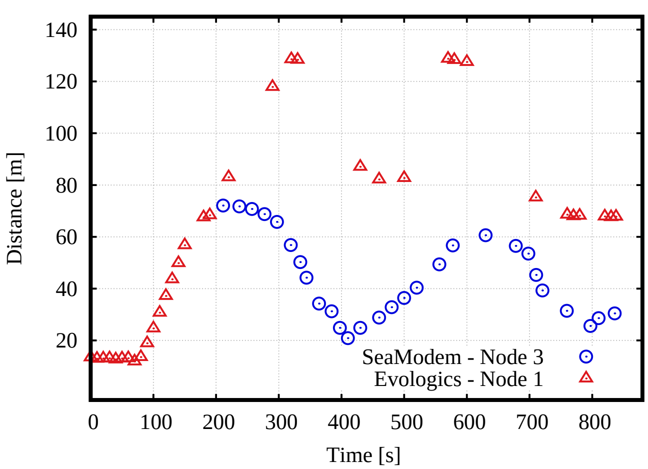

Figure 9: Relationship between packet reception w.r.t. MARTA and static nodes positions.

and the moving vehicle affects the successful reception of the data. That is, when the vehicle is close to node 1, it will be able to receive more packets than node 3 and vice versa.

B. Ranging experiments

In the second set of experiments, we estimated the relative distances between node 1 and the vehicle using the two-way ranging protocol implemented in S-SDCS [18]. During this test, the vehicle was executing a plan composed of two *Goto* maneuvers making the vehicle moving back and forth with respect to the static node 1 at about 2 knots. The GPS signal has been used as ground truth. The results of the ranging experiments are shown in Figure 10. Note that the precision

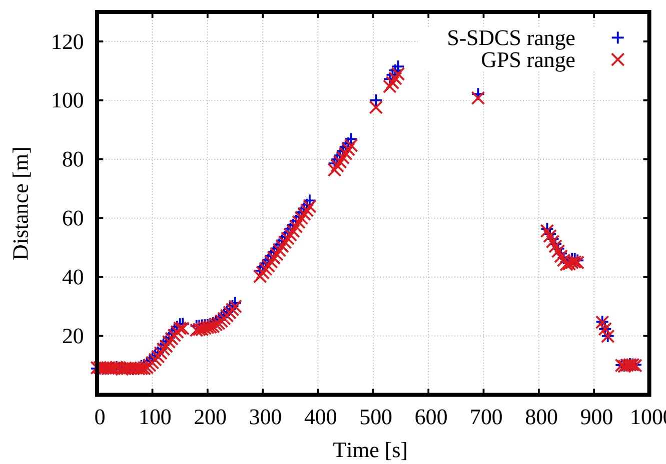

Figure 10: Range results using S-SDCS range protocol.

of the distance estimation is affected by both the very shallow water (limited direct paths) and the use of two-way ranging protocol involving a moving node. The corresponding range error is shown in Figure 11. It can be seen that the maximum

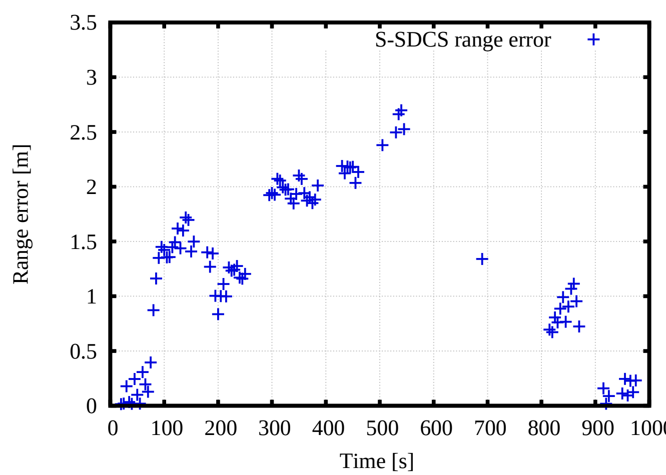

Figure 11: Range results using S-SDCS range protocol.

error is of about 2.7m that occurs when the vehicle reaches the greatest distance with respect to node 1.

C. Multi-modal experiments

In the third set of experiments, we performed communication between different modems using MARTA AUV as a network bridge. The main objectives of this test were to fully validate the routing and MAC multi-modal protocols designed and implemented in the S-SDCS and to check how different modulation schemes perform in the considered challenging scenario. For sake of clarity, the modulation schemes considered are the BPSK (EvoLogics), FSK (SeaModem) and FH-FSK (JANUS). In this experiment, the position of MARTA was fixed as shown in Figures 12 and 13 and several data packets have been transmitted from node 1 to 3 (and vice versa). The S-SDCS running on MARTA was able to bridge the packets from one modem to the other and therefore to forward the packets from one node to the other. More specifically, packets received from the EvoLogics modem were forwarded using first the SeaModem Frequency-Shift Keying (FSK) modulation and then the JANUS modulation.[1] Instead, packets received with the SeaModem FSK or JANUS modulation were forwarded using the EvoLogics modem. Figure 12 and Figure 13 show the network topology and the experiment results related to the Packet Delivery Ratio (PDR) associated with each link (and corresponding modulation scheme) of the deployed network. In particular, Figure 12 shows the PDR related to the first experiment in which packets are transmitted from node 1 to node 3. The PDR of the packets transmitted in the opposite direction is instead shown in Figure 13.

In the first experiment, 85% of the packets generated using the node 1 (EvoLogics) has been received by node 3 (Applicon SeaModem). In particular, MARTA (node 2) received the 90% of the packets transmitted with the Evologics. Then, 94% (81%) of these packets forwarded by MARTA using SeaModem JANUS (FSK) modulation has been received by the node 3. In the second experiment, the 73% of the packets

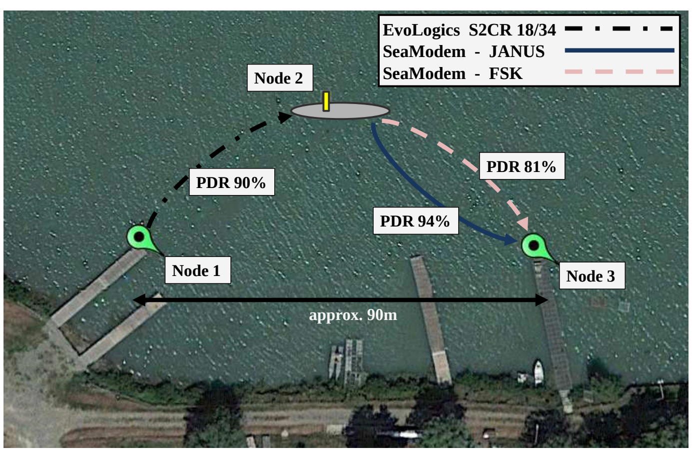

Figure 12: Acoustic bridge topology and PDR results on each link. Network bridge from node 1 to node 3.

generated by the node 3 using both the modulation schemes have been correctly received by node 1. In particular, MARTA received the 96% (20%) of such packets using the SeaModem JANUS (FSK) modulation scheme and forwarded them using the EvoLogics modem. The 76% of the forwarded packets have been instead received by node 1.

[1] JANUS was configured to use 10kHz bandwidth with and a center frequency of 30kHz.

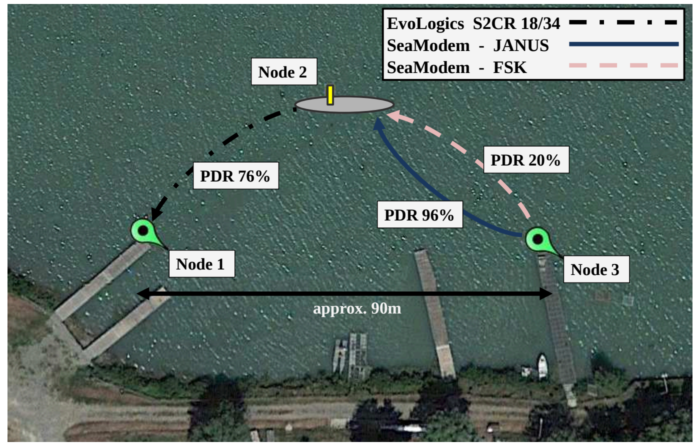

Figure 13: Acoustic bridge topology and PDR results on each link. Network bridge from node 3 to node 1.

As expected in such challenging scenario, the best results are achieved using JANUS that is the most robust modulation scheme between those considered.

V. Conclusions

In this paper we have presented the new architecture and features of the SUNSET SDCS framework to enable the communication between underwater networks using multi-vendor modems thanks to the use of bridging nodes. In addition, two new networking protocols have been also designed and developed in S-SDCS to enable such multi-modal communications. Finally, we have presented the integration between the SSC protocol and the ROS vehicle control software through S-SDCS and the MARTA AUV. The system integration has been evaluated and validated through in-lab tests and in-field experiments held at the Roffia lake (Tuscany, center of Italy). In these tests, we first evaluated the integration between S-SDCS and MARTA running ROS through the SSC protocol and then we tested the S-SDCS multi-modal capabilities using MARTA as a network bridge between nodes equipped with multi-vendor modems. The results achieved show how the cooperation and interaction in heterogeneous networks composed of multi-vendor vehicles and modems can be enabled by using the SSC protocol and the S-SDCS multi-modal capabilities.

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