EDA-SALSA: Development of a self-reconfigurable protocol stack for robust underwater acoustic networking

Henry Dol
Acoustics & Sonar
TNO
The Hague, The Netherlands
Henry.Dol@tno.nl

Koen Blom
Acoustics & Sonar
TNO
The Hague, The Netherlands
Koen.Blom@tno.nl

Dimitri Sotnik
Communication Systems
Fraunhofer FKIE
Wachtberg, Germany
Dimitri.Sotnik@fkie.fraunhofer.de

Ivor Nissen
WTD 71 630
Bundeswehr
Kiel, Germany
IvorNissen@bundeswehr.org

Roald Otnes
Sensor and Surveillance Systems
FFI
Horten, Norway
Roald.Otnes@ffi.no

Arwid Komulainen
Robust Radio Communications
FOI
Linköping, Sweden
Arwid.Komulainen@foi.se

Filippo Campagnaro
Information Engineering
University of Padova
Padova, Italy
Filippo.Campagnaro@unipd.it

***Abstract*—This paper reports on the results achieved in the European Defence Agency (EDA) project Smart Adaptive Long- and Short-range underwater Acoustic network (SALSA), that was running from November 2018 to November 2022. SALSA was a European defence cooperation between The Netherlands (lead nation), Germany, Norway, Sweden and Finland. The objective was the development of a protocol stack for self-reconfigurable underwater acoustic networks that autonomously adapt to changing environmental conditions and operational needs.**

***Index Terms*—Robust underwater communications, adaptive modulation, cognitive network, protocol stack, standardization.**

I. Introduction

Smart underwater robots, such as Autonomous Underwater Vehicles (AUVs), have the potential to take over lengthy and labour-intensive missions in dangerous areas from navy ship crews and divers. In general, the role of mobile unmanned platforms in military scenarios (Rapid Environmental Assessment/REA, Mine Counter-Measures/MCM, Intelligence gathering Surveillance & Reconnaissance/ISR, Anti-Submarine Warfare/ASW) is becoming more important. However, crucial to their success is their seamless integration in the heterogeneous (mixed static/mobile) wireless network of surface ships, submarines, bottom/moored sensor nodes and surface gateway buoys (Fig. 1). This requires scalable underwater acoustic networks that allow ad-hoc joining, participating and leaving of allied mobile (surface/subsurface) platforms, as well as the capability to adapt autonomously to time-varying communication conditions. For example, by switching between frequency bands and data rates, such that network assets may remain connected for extensive (battery-limited) operation times without recovery and redeployment.

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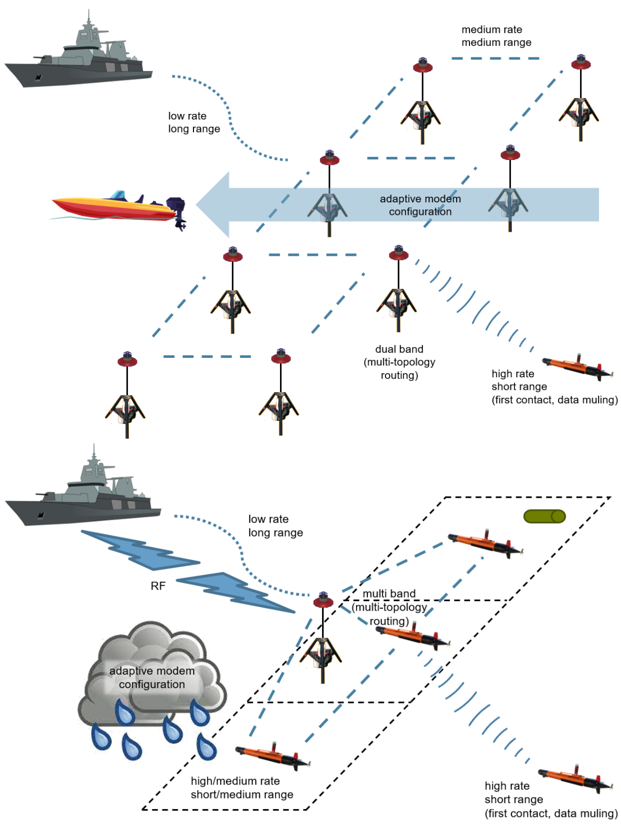

Fig. 1. A schematic ISR network scenario (top) for detecting mobile targets, consisting of mainly fixed barrier nodes and mobile reconnaissance node(s), and a schematic MCM/REA network scenario (bottom) for detecting stationary targets, consisting of mainly mobile survey nodes and fixed gateway node(s). Both networks may be operated from a mothership over the horizon. From an underwater-communications perspective, these can be considered as two "extreme" scenarios. Practical scenarios are likely to be more mixed static/mobile (heterogeneous network).

Flexible and self-reconfigurable underwater acoustic networks as described above require the development of a smart adaptive protocol stack, which was the objective of the SALSA project [1]. At the physical layer, where bits are converted into sound and vice versa, the JANUS standard [2] is applied for first contact, after which the more robust and flexible FRSS (Frequency Repetition Spread Spectrum) [3] modulation can be employed to enable the required heavy-duty communication in the military scenario at hand. At the network layer, the versatile GUWMANET (Gossiping in Underwater Acoustic Mobile Ad-hoc Networks) [4] flooding/routing protocol is being employed with the accompanying application-layer protocol GUWAL (Generic Underwater Application Language) [5]. The decisions for adaptations, and their synchronization within the network to maintain interoperability, are controlled by an adaptivity module inside the network layer [6].

After the “Europa-MoU” project UCAC (2005-2008; physical layer [7]) and the EDA-RACUN project (2010-2014; network layer [8], [9]), the adaptive underwater communication and networking capabilities of the SALSA project (2018-2022) have added a third stage of underwater cooperation and coordination. This robust interoperability is implementable on a wide range of underwater devices, such as mobile nodes (e.g., SeaCat AUV of ATLAS Elektronik, Hugin AUV of Kongsberg Maritime) and bottom nodes (e.g., NILUS nodes of FFI/TNO, Saab Sensor Nodes). In this way, it is possible to realize manned and unmanned teaming in poor environmental conditions using ad-hoc heterogeneous networks relayed within multi-hop distance to ship and land stations via underwater telephones (e.g., ELAC UT 3000) and gateway buoys (e.g., of Fraunhofer FKIE). The EDA-SALSA project has demonstrated European underwater connectivity.

II. Environmental characterization

A. Channel-sounding campaign

During the first sea trial (ST1) of the SALSA project in April/May 2019, an extensive channel-sounding campaign was performed, including simultaneous synchronized measurements of impulse-response evolutions and ambient noise levels at eight suitable bottom-node deployment locations in the Oslofjord, Norway (Breiangen area), as well as for two mobile nodes, see Fig. 2 for a trial impression. The channel soundings and noise measurements were performed in a low-frequency (LF) band of 4-8 kHz and a high-frequency (HF) band of 24-32 kHz, which were selected as the two underwater-acoustic frequency bands for the SALSA protocol stack. The measurements were performed continuously for several days, which included a change of weather conditions. The area and time of the year were deliberately chosen to be the same as that of the planned final demonstration in 2022, in order to increase the probability of comparable conditions. The measured impulse responses were subsequently used to support the adaptive modulation development (Sec. III-A) in the following years by performing channel-replay simulations.

Furthermore, both in-situ communication performance and a-posteriori channel-replay communication performance, as well as ambient-noise measurements, were used to derive so-called Look-Up Tables (LUTs) for the Packet Delivery Ratio (PDR) and (input and output) Signal-to-Noise Ratio (SNR) between the nodes at the ST1 positions, to account for the physical layer in the network simulations (Sec. IV). The network simulations were used to support adaptivity development at the network layer (Sec. III-B) in the following years, as well as to aid planning of the final demonstration and potentially also to validate simulation results with demonstration results in case of sufficiently comparable conditions. This made the ST1 measurement campaign a crucial event requiring careful planning and execution.

Fig. 2. Impression of SALSA’s first sea trial (ST1, 2019) in Horten’s inner harbour and the Oslofjord, Breiangen area (Norway).

B. Propagation loss

Using calibrated modem transmissions and receptions, propagation loss was measured between the eight deployed (NILUS) bottom nodes, as shown by the bottom-left graph of Fig. 3, reproduced from Ref. [10]. The measured propagation loss is higher than what would follow from spherical spreading and absorption because of a structural absence of direct paths, which was a direct consequence of the surface duct (checked by ray-tracing analysis), see the sound-speed profiles in the top-left graph of Fig. 3. Sound-speed profiles and bathymetry are not accounted for in the network simulations, where constant bottom depth and an empirical formula for the propagation loss were applied (Thiele formula [11], bottom-right graph in Fig. 3).

III. SALSA communication stack

The SALSA communication protocol stack is characterized by the following elements, where *italic font* marks elements that are newly developed in SALSA:

- application layer (operator, autonomous platform);
  - **GUWAL**, incl. *additional SALSA parcels*;
- network layer (multi-hop routing);
  - **GUWMANET**, incl. *modules for first contact, data muling, multi-topology routing (MTR)* and *adaptive modem configuration (AMC)*;
- physical layer (bits $\leftrightarrow$ acoustic waves);
  - **FRSS**, incl. *preamble encoding of profile*;
  - **JANUS** (NATO STANAG 4748) for *first contact*;
- *multiple bands*[1] *(multi-topology routing)*;

[1]The underwater acoustic frequency bands are slightly narrower for JANUS than for FRSS, see www.januswiki.com (forum post of 15 November 2019).

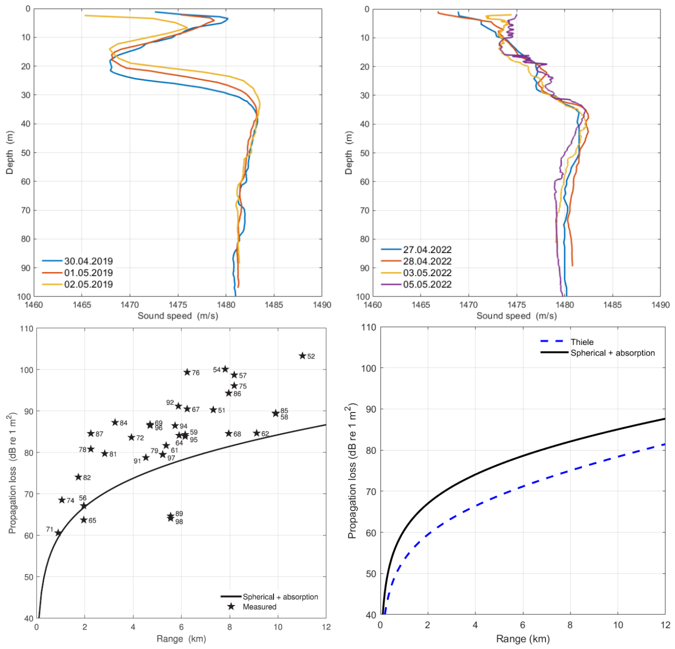

Fig. 3. Sound-speed profiles (top) as measured in the Oslofjord in April/May 2019 (left) [10] and 2022 (right), and propagation loss (bottom) in the 4-8 kHz band as measured in the Oslofjord in April/May 2019 (left) [10]. The indices of the propagation-loss measurements indicate the links between the (NILUS) bottom nodes (link N5→N6 is denoted by 56, etc.). For comparison, modelled propagation loss is also shown (bottom-right), using the (depth-independent) Thiele formula [11] of the network simulator (blue dashed line) and spherical spreading + absorption (solid black line) at $f_c = 6$ kHz.

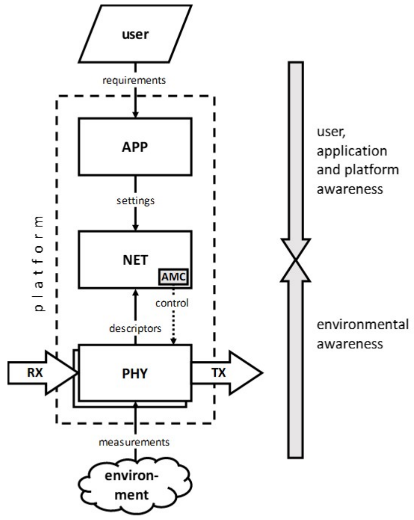

Fig. 4. SALSA network-communications protocol stack, indicating external influences (user, environment) and directions of information flow, the capabilities at each layer and their interrelations, and the 'NET-centric' Adaptive Modem Configuration (AMC) module.

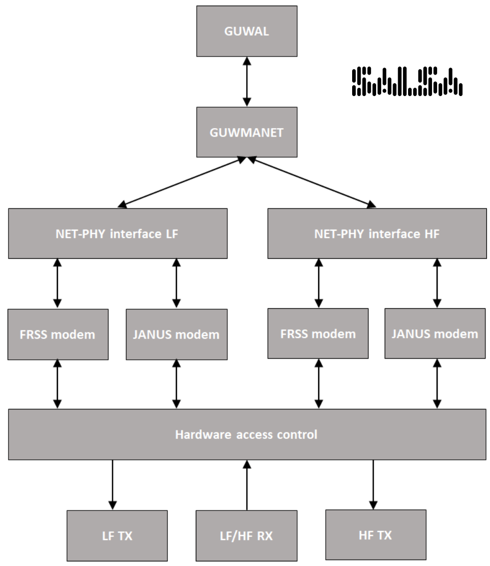

Fig. 5. SALSA software-defined modem architecture indicating the separate processes for the application layer (GUWAL), the network layer (GUWMANET), the low-frequency (LF) and high-frequency (HF) bands, and the FRSS-SALSA and JANUS modulations.

- underw. acoustic, LF: 4-8 kHz ("RACUN band");
- underw. acoustic, *HF: 24-32 kHz* ("SALSA band");
- above-water radio, RF (via gateway buoy, ship node).

See also Figs. 4 and 5. More information about the smart-adaptive physical-layer development (FRSS-SALSA) and cognitive network-layer development (GUWMANET modules) is provided in the following two subsections.

A. Smart-adaptive physical-layer development

The physical-layer (PHY) development in SALSA has been explained in detail in Ref. [3]. It concerned the development of an adaptive version of the FRSS modulation (FRSS-SALSA). The developed PHY adaptivity concerns self-reconfigurability of:

- data rate (four FRSS rates 1-4; 1 = highest data rate);
- message length (min. size 128 bits, ext. size 0-16 kbit);
- frequency band (LF, HF);
- modulation (FRSS, JANUS).

Specifically for the FRSS-SALSA modulation, the development consisted of the following parts:

- profile-encoded preamble (Fig. 6);
- frame header for minimum-length and extended-length PSDU (PHY Service Data Unit; Fig. 6);
- acoustic-descriptor computation (Fig. 4):
  - ambient noise level, for adapting the source level (transmit power);
  - output Signal-to-Noise Ratio ($\mathrm{SNR}_{\mathrm{out}}$, Eq. 46 in [10]), for adapting the FRSS rate;
  - degree of clipping, for adapting the gain;
  - delay spread: no added value over $\mathrm{SNR}_{\mathrm{out}}$; Doppler spread would have had added value, but cannot be computed accurately enough from the preamble.

B. Cognitive network-layer development

All different modem links (LF/HF acoustic, radio) are connected to the (C-coded) cross-platform network protocol GUWMANET (selected from EDA-RACUN). This network layer (NET) has the possibility to add new capabilities by

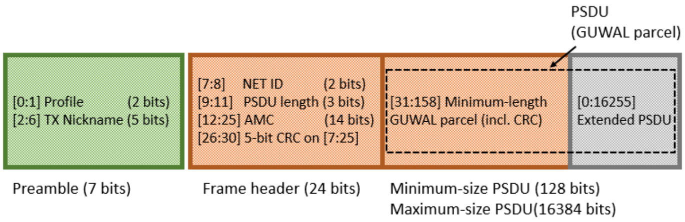

Fig. 6. Bit allocation for the coded preamble (green) and frame header with minimum-length packet size (orange) and with extended-length packet size (orange-gray). The "TX nickname" was included in the preamble to identify bad links.

means of plug-ins, also to allow other developers to adapt the protocol to their own needs by programming so-called modules. The network-layer (NET) development in SALSA consisted of the development of four adaptivity modules:

- *first-contact* module, using JANUS, and including dynamic address allocation;
- *data-muling* module, for buffered transfer of large messages by mobile nodes between disjoint clusters;
- *multi-topology-routing* (MTR) module, for message routing via all available bands and modalities (LF, HF, RF);
- *adaptive modem configuration* (AMC) module, for in-situ reconfiguration of transmit power (based on measured noise level) and modulation settings such as data rate (based on $\mathrm{SNR}_{\mathrm{out}}$).

The adaptivity at both PHY and NET levels is controlled by the adaptivity (AMC) module inside the network layer, which takes decisions using the acoustic descriptors as measured and computed at the PHY level (Sec. III-A). The AMC field in the bit-allocation table of Fig. 6 is further detailed in Table I for transmitted (generated) and forwarded (relayed) messages as visualized in Fig. 7. While in Step 1 of Fig. 7, the acoustic descriptors are obtained from the reception at node N2, in Step 2 these quality indicators, coded inside the AMC field, are spread to all neighbours in range, when forwarded. By overhearing these forwarded messages, node N1 can make adjustments for the next transmission [12].

TABLE I
FRAME HEADERS OF TRANSMITTED (GENERATED) AND FORWARDED (RELAYED) MESSAGES, WITH TAILORED AMC BIT ALLOCATIONS (POS. = BIT POSITIONS; L = NUMBER OF BITS).

AMC Generator bit scheme			AMC Relaying bit scheme		
Pos.	L	Type	Pos.	L	Type
12	1	Indicator Flag: 1 = Generator	12	1	Indicator Flag: 0 = Relaying
13-14	2	Repetition ID	13	1	Last frequency-band flag: 0 = LF band, 1 = HF band
15-16	2	Transmission signal power: 00 = 0-25%, 01 = 26-50%, 10 = 51-75%, 11 = 76-100%	14-18	5	Last-hop transmitter ID: 5-bit nickname of last transmitter
17-18	2	Signal to reverberation ratio: 00 = 0-25%, 01 = 26-50%, 10 = 51-75%, 11 = 76-100%			
19-21	3	Delay spread (0.001-0.06 s): 111 = $\geq$0.06 s, 110 = $>$0.04 s, 101 = $>$0.03 s, 100 = $>$0.02 s, 011 = $>$0.01 s, 010 = $>$0.005 s, 001 = $>$0.001 s, 000 = $\leq$0.001 s	19-22	4	Last-hop SNR: 0000 = <-9 dB, 0001 = -9 dB … 1110 = 6 dB, 1111 = $>$6 dB
22-24	3	Ambient noise: 000 = $<$0 dB, 001 = 0 dB … 110 = 5 dB, 111 = $>$5 dB	23-24	2	Repetition ID
25	1	Buffer-full flag	25	1	Repetition ID of prior reception: 0 if received first transmission, else 1

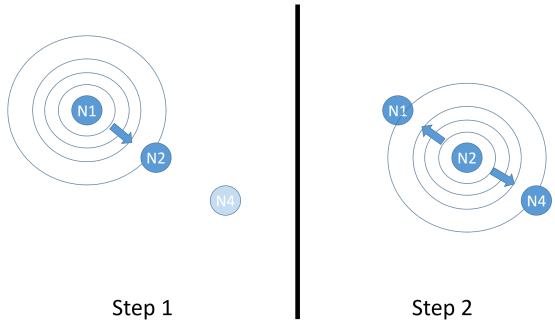

Fig. 7. Transmission (TX) and forwarding in GUWMANET.

IV. NETWORK SIMULATIONS

Network simulations have been performed using the NS2/DESERT simulation framework [13] to support the development of the adaptivity modules for the network layer. The physical-layer realism introduced by the LUTs, which relate PDR with input/output SNR as measured in the ST1 campaign (Sec. II), also aided planning of the final demonstration by enabling realistic estimations of the network communication performance in the Oslofjord. Unfortunately, the acoustic channel conditions during the final demo appeared to be quite different than during ST1 (see top-left vs. -right graphs in Fig. 3), which means that an a-posteriori comparison of simulations and measurements could not be made.

Nevertheless, the network simulations allowed evaluation of the correct functionality of the network protocol and all GUWMANET modules for non-trivial acoustic channels before the demonstration at sea, therefore permitting the identification of bugs and performing extensive tests of the network protocols and their implementation, also because the same protocol implementation was used both for simulations and the sea experiments. Actually, the fact that the conditions were different during the demonstration made that the system was tested in two different working conditions: ST1 of which the channel evolutions were mapped in the network simulator, and the final sea trials where the system was demonstrated.

Fig. 8 shows some simulation results of first-contact module tests, where the nodes are added to the network sequentially, from node 1.3 to node 2.2, in the order shown in the plot. After a node is added, it tries to join the network with the first-contact procedure. Due to imperfect channel conditions, the joining procedure is not always successful, especially for nodes 2.2 and 1.1 that have the lowest probability of successfully joining the network, highlighting that these nodes are the least connected to other nodes. The average number of transmissions in the network generally increases as more nodes are added to the network. The average time to join the network, instead, tends to be higher for nodes with a lower success rate.

Furthermore, Fig. 9 shows the functionality of the multi-topology routing module. Specifically, in the simulated scene, the gateway buoy (node 0.1) sends a status request to the AUV (node 2.2). Whereas these two nodes are only equipped with HF modems, other nodes can only transmit with LF modems, except for dual-band nodes 1.3 and 1.6 that are equipped with both LF and HF modems. In the figure, the red arrows symbolize HF transmissions and the blue ones LF transmissions. The simulation results show that all packets, for both the requests (Fig. 9, top) and responses (Fig. 9, bottom), reached their destination.

The HF status request from the gateway buoy (0.1) to the AUV (2.2) was, as expected, forwarded via a dual-band bottom node (1.3). From there, the packet was distributed throughout the network in the LF band, up to the second dual-band bottom node (1.6) where the packet could again be transmitted in the HF band to the AUV. In total, the network took 27 s to transmit the packet from the gateway buoy to the AUV, requiring three hops (HF-LF-HF). For the response of the AUV to the status request from the gateway buoy, the packet was first transmitted in the HF band to the nearest bottom node (1.6). Interestingly, this dual-band node (1.6) did not only distribute the packet in the LF band through the network, but was also able to establish a direct connection to the other dual-band node (1.3) in the HF band. At the last hop, the packet was also forwarded in the HF band to the gateway buoy.

Finally, Fig. 10 shows simulation results for the dynamic rate switching algorithm of the AMC module. The dynamic rate (p0) appears to be as robust as the most robust fixed data rate (p4), while consuming (on average) 16% less energy. The second-most robust fixed data rate (p3) is also quite robust, while consuming even less energy (36%), but not at all times (hours 10-16). This shows the importance of adaptive communications in time-varying channels.

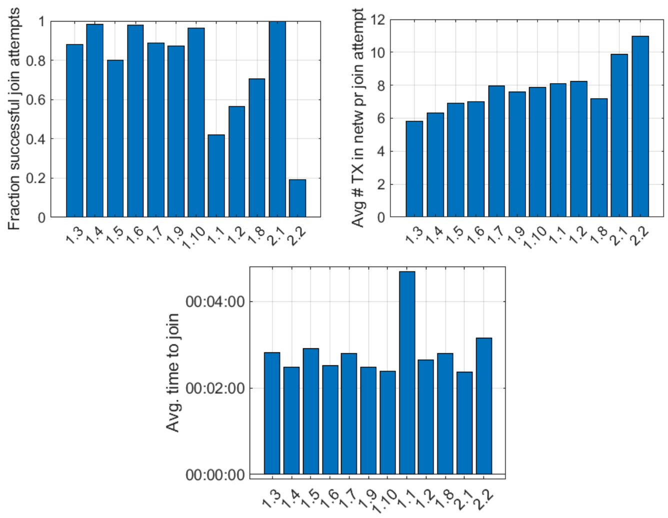

Fig. 8. Simulated first-contact protocol performance for each joining node, averaged over different time offsets in the Look-Up Tables (LUTs). [14]

V. Harbour tests

In the second full year of the SALSA project (2020), basic interoperability was successfully tested for the initial non-adaptive communication stack on all available modems: (original) FRSS, GUWMANET and GUWAL, on software-defined

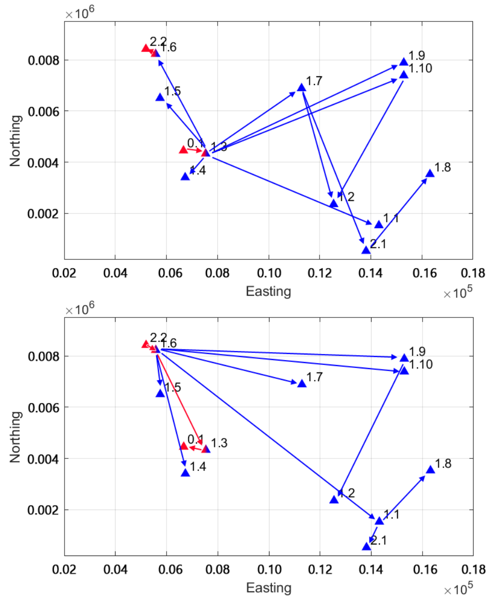

Fig. 9. Simulations of multi-topology routing, i.e., communication through LF (blue) and HF (red) frequency bands. Top: Request from gateway buoy 0.1 to AUV 2.2. Bottom: Reply from 2.2 to 0.1.

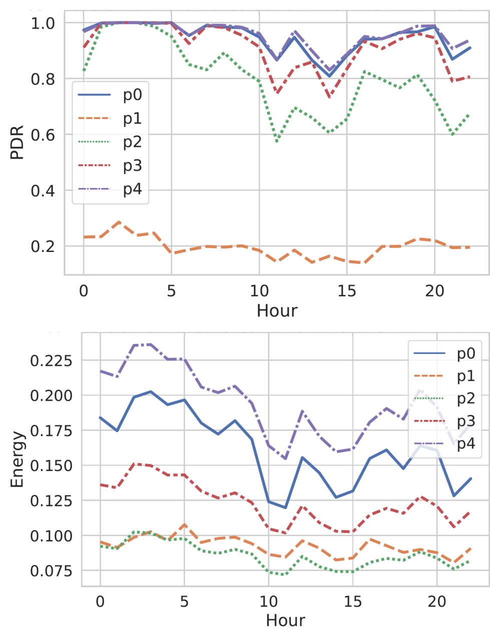

Fig. 10. Simulations of AMC PDR and energy performance: p1-p4 are fixed data rates (with p4 most robust), while p0 uses dynamic switching. [12]

modems of TNO/FFI, Saab and Patria, and on COTS modems of Kongsberg Maritime (cNode), ELAC Sonar (UT 3000 UWT) and Develogic. These initial tests took place in August 2020 in the harbours of Horten, Norway (FFI), and Kiel, Germany (all others), see Fig. 11. The separate testing at two locations was due to Covid19-related travel restrictions, and overall interoperability was ensured by having the software-defined NILUS modems of TNO/FFI [15] at both sides. These first harbour tests (HAT1) were very well prepared by a period of extensive ‘dry-testing’ (called “factory tests”, FAT1), consisting of demodulating each others wavefiles, exchanged via the project's collaborative software development platform (TNO GitLab). Without this online FAT testing, the one-week HAT period would probably needed to have been several times longer, so much costs were saved in this way and the trial planning with travel restrictions was made easier.

In the next year, in August 2021, after another extensive FAT phase (FAT2), joint harbour tests were again performed (HAT2), now in Kiel, Germany (all German partners), and Motala, Sweden (all others; Fig. 11). This time, the separate testing at two locations was due to logistic issues at the German side (combination with preparations for another trial), and again overall interoperability was ensured by having one of the modem systems at both sides, now a Develogic modem. A nice bonus was that the Develogic modems were also acting as internet gateways (LTE tunnels), thus connecting the two underwater acoustic networks in Kiel and Motala (Lake Vättern, Saab) with actual live communication between the two remote underwater networks. However, the most important achievement was that successful tests were performed with an intermediate version of the adaptive SALSA stack, including the adaptive FRSS-SALSA and the GUWMANET modules for first contact, multi-topology routing and data muling. As an example, Fig. 12 shows first-contact statistics from HAT2. It was observed that both the "time to join" and the "number of transmissions required to add a new node" increase as the network size increases. If the network had been less connected, e.g., when covering a larger physical area, this situation would have been different.

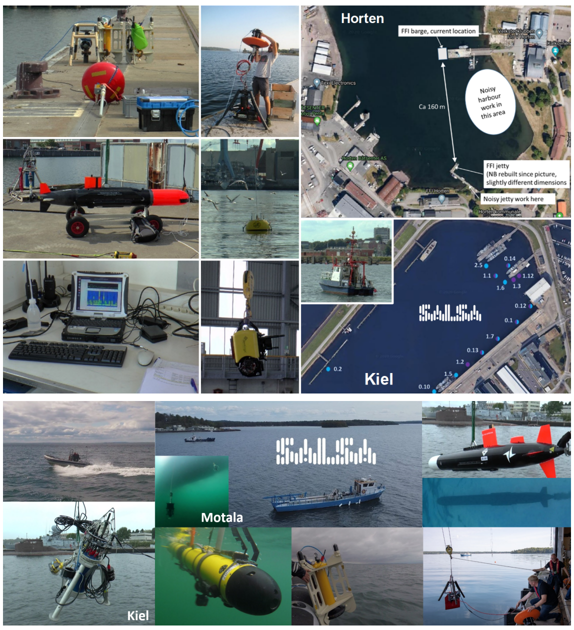

Fig. 11. Impression of the SALSA harbour tests in 2020 (Kiel/Horten; top) and 2021 (Motala/Kiel; bottom).

To conclude, the HAT activities allowed the SALSA consortium to verify the correct functionality of the first-contact and MTR modules, and to identify some issues of the data-muling module (addressing, CRC) that needed to be solved before the final demonstration in 2022, where also the AMC module was planned to be tested.

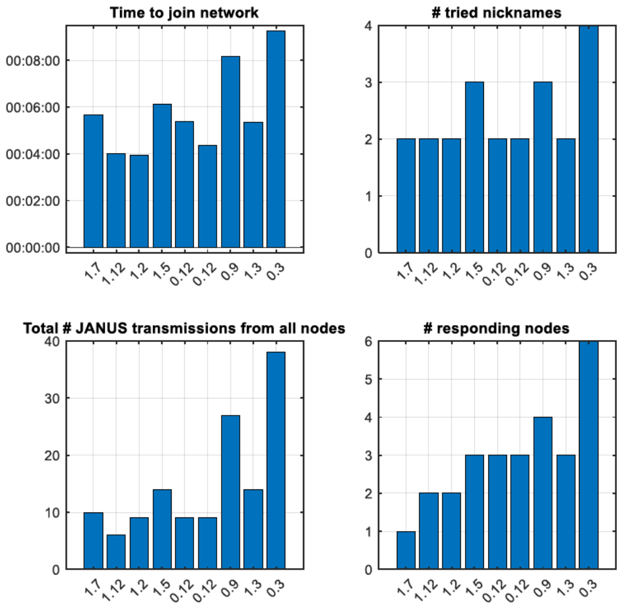

Fig. 12. Time to join the network, number of tried nicknames, total number of JANUS transmissions from all nodes and number of responding nodes, for a sequence of nodes using the first-contact mechanism during harbour tests in Motala (HAT2, 2021). The nodes are plotted in the order that they joined, from left to right.

VI. Demonstration at Sea

After extensive preparations using channel-replay and network simulations, and another round of FAT testing (FAT3), the EDA-SALSA consortium finally came together with all parties in April/May 2022 in Horten, Norway, to perform final harbour testing (HAT3), followed by a (rehearsed) demonstration for invited guests from the five SALSA nations. This final demonstration of a self-reconfigurable underwater acoustic network took place in the Oslofjord on 4 May 2022 (Fig. 13) and was very well received. Successfully demonstrated functionalities included ad-hoc network extension by AUVs joining the network using *first-contact* functionality (employing JANUS), *data muling* of a buffered image (request) by an AUV between two separated (clusters of) network nodes, *multi-band/topology routing* (GUWMANET) exploiting two distinct acoustic frequency bands (under water) and a radio link (above water), and *adaptive modem configuration* for in-situ optimization of transmission power and equalizer settings (data rate of FRSS) by measuring acoustic communication conditions (input/output signal-to-noise ratio) [12].

These functionalities were demonstrated in the context of surveillance/barrier (ISR/ASW) and mine-hunting (MCM) scenarios using up to 20 network nodes (6 ship nodes, 9 bottom nodes, 3 AUVs, 2 buoys; Fig. 14). About 20 'VIP guests' witnessed the demonstration from a ship and an on-shore operations centre, aided by a Situational Awareness (SA) plot

Fig. 13. Impression of the final harbour and sea trials of SALSA (April/May 2022).

showing the actual status of the network, i.e., positions of nodes (within one-hop distance) from which (relayed) messages were received by a gateway buoy. In the ISR scenario, bottom nodes were detecting[2] an intruder – a Rigid-Hull Inflatable Boat (RHIB) – and in the MCM scenario, AUVs were detecting bottom mines. The RHIB was also used to disturb the network on several occasions during the day by crossing the area at high speed, aimed at forcing automatic adaptations of the network communication.

Fig. 15 shows physical-layer connectivity maps for the LF and HF bands, as measured on the demo rehearsal day (3 May), where it can be seen clearly that more nodes are connected through LF than through HF. It also shows that there were many asymmetric links. Note that the moving nodes (red dots) are plotted in their nominal positions, making the visualization of those links somewhat misleading.

A. First contact

Fig. 16 again shows first-contact statistics, now for tests performed during HAT3. In the week after, in the Oslofjord, two moving nodes successfully joined the network after entering, but they needed considerably more time to join than in HAT3 due to an addressing bug. The bug was not discovered in the earlier tests (simulations, HAT2 and HAT3), which were all performed in series (sequential) and not in parallel as was the case in the demo week. This is a good example of the remaining necessity of including realistic sea trials in the development process.

B. Multi-topology routing

Multi-topology routing was used throughout the demonstration. There were several nodes that supported only the low-frequency band, such as 0.2, 0.3 and 1.5, while other nodes exclusively supported the high-frequency band, such as 0.4, 1.2 and 1.3. It was very often observed that also these nodes could communicate with each other. Fig. 17 shows an example of logged multi-topology routing behaviour in the heterogeneous SALSA network, where blue lines are LF connections and red lines are HF connections. The packet from

[2]Note that, as a consequence of the decoupling of communications and sensing (to keep the project unclassified), detection here means reception of 'signature messages'.

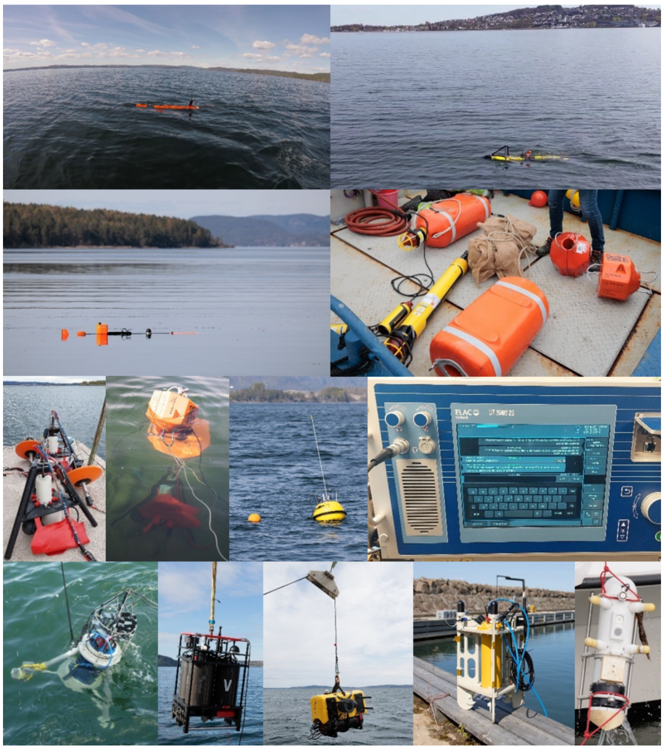

Fig. 14. Overview of network nodes deployed during the demonstration. Top-down/left-right: OceanScan LAUV (TNO), L3Harris Iver3 (Patria), SeaCat (ATLAS), cNode (Kongsberg), NILUS Mk2 (TNO), NILUS Mk2 with cNode (FFI), Gateway Buoy (FKIE), UT 3000 (ELAC), NEREUS Mk2 and Mk3 (WTD71), Bottom Lander (Develogic), Saab Sensor Node (Saab), and OnWeBSel (ATLAS). No ship nodes are shown.

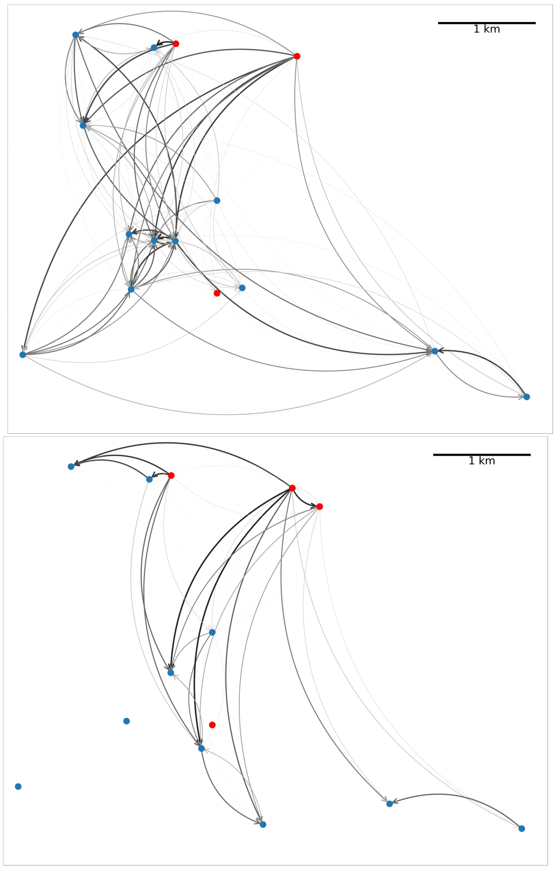

Fig. 15. Physical-layer connectivity maps for the LF band (top) and the HF band (bottom) in the Oslofjord on 3 May, 09:52-16:00 UTC (arrows pointing counter-clockwise, grayscale indicating PDR). Both panels show many asymmetric links and better LF connectivity than HF connectivity. Some long-range connections were with mobile nodes (red dots) plotted at their nominal positions.

0.4 (HF-only) is forwarded in the HF band to 1.3 (HF-only), but also to 1.12. Since 1.12 also has an LF band, the packet is now also routed in the LF band. However, 1.2 also has only an HF band and is not within direct communication range of 0.4. Therefore, the packet is retransmitted from LF to HF via 1.7, which supported both frequency bands, such that 1.2 is also reached. This example shows how packets were routed through the network using both bands, thus successfully demonstrating the MTR module's functionality.

C. Adaptive modem configuration

In Fig. 18, adaptive modem configuration (AMC) results for both the HAT3 week and the demo day are shown. Unlike the present (post-trial) algorithm, all incoming messages were then combined to obtain average descriptor values, regardless of their origin. This means that all available links were used to select the FRSS profile, which does not necessarily represent the data rate that reaches as many (direct) neighbours as possible, as desired from a (hopping) network perspective. As a consequence, the performance (PDR) on the demo day was much more robust than in the HAT3 week, at the expense of an overall lower data rate (throughput).

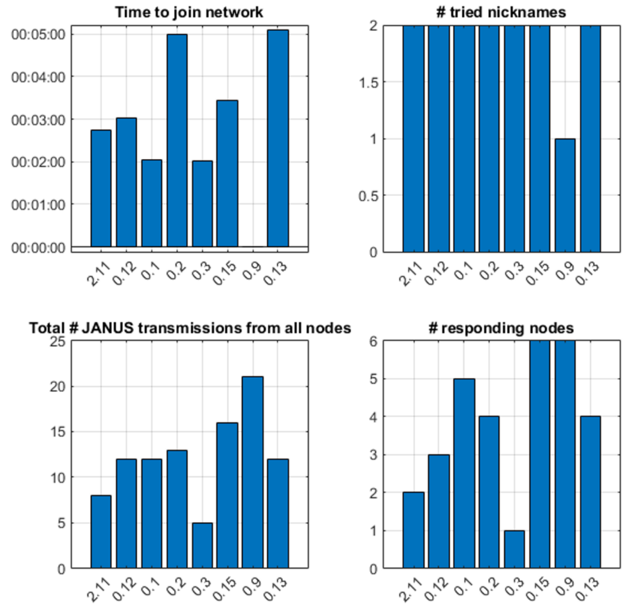

Fig. 16. Time to join the network, number of tried nicknames, total number of JANUS transmissions from all nodes and number of responding nodes, for a sequence of nodes using the first-contact mechanism during harbour tests in Horten (HAT3, 2022). The nodes are plotted in the order that they joined, from left to right.

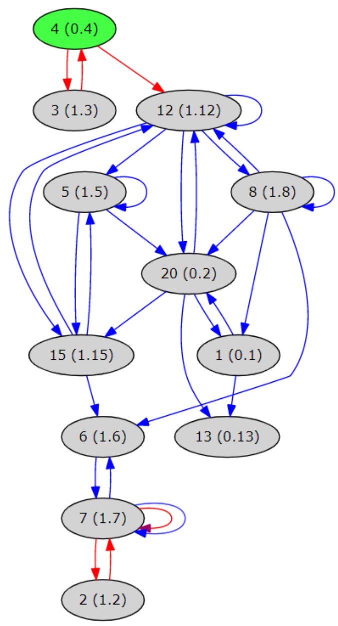

Fig. 17. Network connectivity analysis showing how nodes communicated with each other via LF/HF relay nodes in the Oslofjord (2022). Blue arrows indicate LF communication and red arrows indicate HF communication. The graph shows multi-topology routing of a broadcast packet. LF-only nodes are 0.2, 1.5 and 1.6; HF-only nodes are 0.4, 1.2 and 1.3; LF+HF nodes are 0.1, 0.13, 1.7, 1.8, 1.12 and 1.15.

Initially, after a first look through the logs of HAT3, there was the fear that some nodes would no longer be heard due to the selection of an insufficiently robust data rate and it was decided for the demo to add the fallback solution of checking the ratio of responding neighbours to all known neighbours and switch to a more robust data rate if too many neighbours were lost. However, in post-trial analysis, it appeared that this ratio was distorted by frequent false detections by the software-defined modems running the reference FRSS code (C++). This ratio was too low as the false detections had raised the number of known neighbours because of corrupt transmitter IDs on messages with incorrect CRCs.

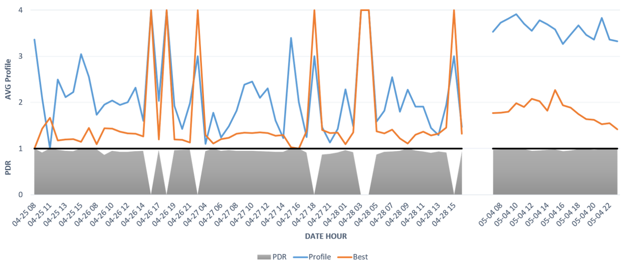

Fig. 18. AMC statistics (LF) for HAT3 (25-28 April 2022) and demo day (4 May 2022): Packet Delivery Ratio (PDR; gray), average selected FRSS profile (blue) and best profile (orange) for selected thresholds for the acoustic descriptors (as described in Sec. III-A).

D. Data muling

The data-muling tests during HAT3 proved difficult to perform successfully due to a number of reasons. HAT3 was performed in Horten's inner harbour, which is a smaller and shallower area than the demonstration area in the Oslofjord. It turned out that the AUV scheduled for the data-muling demonstration could not use its (top-mounted) HF modem in the shallow area where the gateway was positioned. Tests with the other available AUVs proved more successful but suffered from too benign channel conditions, making it difficult to achieve a (disconnected) network topology that made sense for the data-muling procedure. Some further improvements to the data-muling module were made during HAT3 to increase the chance of a successful demonstration.

During the final demonstration, a number of attempts at data muling were performed, though none were fully successful. The state machine governing the data-muling process worked as intended and the data mule managed to locate and offload the node that wanted to send the image, but the final offloading back to the requesting node did not succeed. An issue was that the transfer of the image was not guaranteed to happen on the HF band at a high rate, as this was determined by the adaptive modem configuration. For some combinations of frequency band and FRSS rate, the image transmission became too long and the packet was dropped by the sending modem. Being able to couple the communication and vehicle navigation, which was out of scope for this project, would be a way forward to be able to guarantee that data muling is performed at the higher data rates over short distances. Again, the need for realistic sea trials as part of development, to capture all effects from the channel and modem hardware, was made clear.

VII. Evaluation of Results

The successful SALSA demonstration was characterized by the following highlights:

- Robustness
  - The network was continuously ‘up and running’, as was shown to the SALSA crew and VIP guests on the live SA plot on the mothership and relayed to the on-shore operations centre by the gateway buoy. During the demo day, the weather conditions worsened somewhat (changed wind direction, higher waves) and a fast boat was crossing the network.
- Interoperability
  - Interoperability at physical, network and application layers between equipment of all partners, including commercial products (ELAC UT 3000 UWT, Develogic and KM-cNode modems) and two different physical layers: JANUS (STANAG 4748) and FRSS.
  - Equipment of one manufacturer was used to check the health of and send recovery messages to other manufacturer's nodes.
- First-contact mechanism
  - Success on a number of occasions. During the demo, it took longer due to parallel instead of serial execution, which was not tested before (fixed post-trial).
  - As the JANUS protocol was successfully and cooperatively integrated and applied by six industries, the SALSA demonstration was in fact also a successful “JANUS interoperability fest”.
- Multi-topology routing
  - Successful two-way communications between HF-only nodes and LF-only nodes through dual-band repeater(s).
  - Successful integration with internet (HAT2) and a radio network (gateway buoy, HAT3/demo), connecting separated sub-networks, ship and shore.
- Data muling
  - Partly successful, at least for the buffered image requests. The transfer of the actual images to the destination nodes was not entirely successful as this took too much time with the available bandwidth and the AUVs simply passing the bottom nodes (i.e., no loitering, which requires coupling of communication and vehicle navigation).
- Adaptive modem configuration
  - Partly successful, with evidence of rate switching between the harbour and fjord environments. Temporal and spatial data-rate/robustness optimizations per environment did not work as expected (as in simulations) due to frequent false detections by the software-defined modems running the reference FRSS code (C++), to be fixed in a follow-up project.

- Remote network monitoring and logging
  - A live RSS feed of GUWAL parcels from the radio gateway buoy enabled the SALSA crew to observe problems overnight (between the rehearsal and demo days) and take appropriate action in the early morning, thus saving the demo.
  - The Slack application (www.slack.com) was successfully used for communication within the team (at all vessels and on shore) and towards the VIP guests, and was also useful as a manual log of events for post-trial analysis. The network logs generated automatically on all nodes were parsed afterwards to generate plots as in Figs. 15–17.

VIII. Way forward

The five SALSA nations (NL, DE, NO, SE, FI), represented by their SALSA steering-board members and supported by their national research establishments (TNO, Fraunhofer FKIE, WTD71, FFI, FOI), have the intention to submit a proposal for a NATO Standardization Agreement (STANAG). The technical implementation of this standard in acoustic modems has the commitment of at least the six industries participating in SALSA (ELAC Sonar, ATLAS Elektronik, Develogic, Kongsberg Maritime, Saab, Patria).

From a systems perspective, SALSA intends to provide the navies with a very robust underwater acoustic network communication capability, suitable for both manned, unmanned and autonomous systems, at the sea floor, in the water column and at the surface, in networks consisting of tens of systems, and in diverse operational conditions. Even without optimal automatic data-rate adaptation (false-detection issue) and data muling (lack of bandwidth, no coupling between communication and navigation), the network was interconnected at all times, with status messages being received and displayed on a live map continuously while weather conditions were changing and noisy boats were crossing the network. Once the platform's sensor processing output also gets coupled with the communication, future collaborative underwater warfare scenarios, such as stand-off REA and MCM, and autonomous barriers for ISR and ASW, will get enabled by the robust and adaptive SALSA protocol stack that has potential for more functionalities and thus capabilities.

Looking back at the past four years and seeing what has been collectively developed by the SALSA group, it can only be concluded that a big step forward was made for robust and adaptive underwater acoustic communications and networking, but also that the field of adaptive underwater communication was only touched upon and that more work is thus to be done. Fortunately, this does not mean that the SALSA results cannot yet be standardized, as there is already a complete framework available and further improvements and added functionalities can be introduced in a modular way in periodic updates of the standard. Consequently, SALSA's standardization proposal, a deliverable of the project, will be used as input for the standardization process.

Additional capabilities/functionalities/modules may be added in a follow-up project, e.g., supported by the European Defence Fund (EDF). These improvements may include corridor routing, more advanced acoustic descriptors and decision-making algorithms, improved profile switching and coupling of communication with navigation and sensors, among others. Preferably, this follow-up project will no longer be a pure underwater communications project, but a project that will also use the SALSA stack as the underwater-communications backbone of a relevant military application (e.g., ASW barrier). Moreover, gateway communication and data-muling functionality may greatly benefit from modern high-bandwidth acoustic (or optical) transducer developments, as long as the AUV can loiter close enough near the gateway by its coupled navigation.

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