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JANUS-Based Services for Operationally Relevant Underwater Applications

Roberto Petroccia, *Member, IEEE*, João Alves, *Senior Member, IEEE*, and Giovanni Zappa

***Abstract*—This paper presents the design, test, and experimentation at sea of four JANUS-based services for operationally relevant underwater applications: 1) first contact and language switching; 2) transmission of automatic identification system data to submerged assets; 3) transmission of meteorological and oceanographic data to underwater vessels; and 4) support in distressed submarine operations. On March 24, 2017, JANUS was promulgated as a NATO standard (STANAG 4748) [1], marking the first time that a digital acoustic communications protocol is adopted at international level. JANUS is an open, simple, and robust modulation and coding scheme developed by the NATO STO Centre for Maritime Research and Experimentation, in collaboration with academia and industry. The implementation of the services presented in this paper is based on a standardized protocol and offers the potential to widely increase the safety and efficiency in maritime operations. The objective of this paper is to demonstrate that JANUS can be used in support of maritime operations, potentially increasing their efficiency. Such demonstration is achieved through experimentation at sea of four operationally relevant JANUS-based services. The four JANUS-based services discussed were validated during two different sea trials: REP15-Atlantic and REP16-Atlantic. During those trials, various heterogeneous configurations were considered, including the use of a state-of-the-art diesel-electric submarine, guaranteeing maximum relevance for validation and evaluation of the designed solutions. The collected results demonstrate that JANUS is a viable solution for operationally relevant underwater applications, thus validating the objective of this paper. Additionally, encouraging feedback has been provided by the operational community participating to the trials. The capabilities demonstrated served as an initial proof of concept and will certainly lead to newer requirements and eventually even more functionalities.**

***Index Terms*—First contact and language switching, interoperability, JANUS, support in distressed submarine (DISSUB) operations, underwater acoustic sensor networks, underwater applications, underwater automatic identification system (AIS), underwater digital communication standard, underwater meteorological and oceanographic (METOC).**

I. Introduction

THE interest in underwater acoustic networks (UANs) has largely increased in the past decade as an enabling technology to support a wide range of emerging applications. These include monitoring of the environment and critical infrastructures, coastline protection, and prediction of underwater seismic and volcanic events [2], [3]. To support these applications, novel, more reliable and performing devices have been developed in the recent past, including underwater acoustic modems, sensors, and unmanned maritime vehicles. However, there has been a main bottleneck imposing severe limitations on the effectiveness of such new developments in operationally relevant scenarios: The lack of standards and common interfaces for underwater digital communications and information sharing among heterogeneous network nodes. Given the impairments of optical and radio propagation in water, acoustic communication remains the most efficient way to communicate underwater over distances in the order of hundreds of meters and beyond. Among the several manufacturers of underwater digital modems, none is currently able to communicate with systems produced by different manufacturers. This imposes severe limitations on how cooperative networks of underwater assets can be effectively deployed.

To break this interoperability barrier, the NATO STO Centre for Maritime Research and Experimentation (CMRE) has developed, in collaboration with academia and industry, a simple and robust signaling mechanism to be used as the first standard for digital underwater communications. The proposed protocol, named JANUS (after the Roman God of transitions, gateways, and portals), has been iterated over close to ten years and has finally been promulgated as a NATO standard (STANAG 4748) on March 24, 2017. Its technical implementation, experimentation, and validation are documented in [4]–[12]. JANUS is the first internationally adopted digital underwater communications standard. It is, in a nutshell, a modulation and coding scheme (MCS) plus some additional mechanisms to render it practical in real use. JANUS is not intended to be limited to solely NATO military use, but also for civilian and international adoption. To promote the participation of industry and to make the standard usable and widely accepted, JANUS has been designed to minimize the changes required to bring existing underwater communications equipment into compliance. It is computationally simple and does not require power control nor flat frequency response in the transducers. During the final stages of the promulgation process, NATO sponsored an Industry Advisory Group (NIAG) study on JANUS (NIAG SG190) with the objective of gathering insight from industrial players on how to continue the development path of JANUS. Among the topics addressed by the group, there were:

1) additional frequency bands;

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2) new application classes;
3) protocol extensions;
4) how to define JANUS compliance.

The sponsored study has highlighted how the use of standardized methods may open the way to foster underwater node interoperability. This would catalyze the development of a wide range of underwater applications of operational relevance, including an underwater digital emergency channel (that can be seen as an underwater version of the "VHF Channel 16"), underwater automatic identification system (AIS), node discovery, and negotiation.

Until today, however, the use of JANUS in operationally relevant application scenarios has been limited. First attempts at investigating and testing the use of JANUS to implement a "bilingual" underwater acoustic modem were presented in [8] and [9]. Petroccia *et al.* [9] also explored various message formats to transmit AIS data underwater. In [10], the coexistence of JANUS and analog underwater telephone (UT) communication systems was studied. In [11], the performance of JANUS was investigated, while in [12] the definition of various operationally relevant services was presented.

The main objective of the field work behind this paper is to promote the use of JANUS among the operational community by demonstrating a new range of capabilities that may potentially increase the efficiency and safety of maritime operations. The four operational use cases, or application scenarios, originally introduced in [12] have been implemented, tested, and validated at sea to demonstrate the effective use of JANUS. These four JANUS-based services consist of the following:

1) first contact and language switching;
2) underwater AIS;
3) underwater meteorology and oceanography (METOC);
4) support in distressed submarine (DISSUB) operations.

Regarding the first contact and language switching application, the work presented in [8] used the JANUS specification transposed into a higher carrier frequency and bandwidth with respect to that specified by the standard [1]. This naturally resulted in a higher transmission rate. Additionally, no structured procedures were defined for the discovery of the network nodes and their communication capabilities. In [9] an initial design of the underwater AIS service was presented and different data formats for the transmission of AIS contacts were explored. These data formats were tested at sea in scenarios where up to three contacts were detected and transmitted acoustically. This paper expands these previous works by investigating the use of JANUS following the standard frequency and bandwidth definitions. A full implementation of the discovery procedure was achieved and an improved data format for the AIS service messaging was developed. Additionally, a new set of field experiments was conducted to evaluate the applicability of JANUS for delivering a large AIS picture (including several tens of contacts) to a submarine. Furthermore, two additional services relevant to the operational community have also been tested and demonstrated in field: the underwater METOC and the support in DISSUB operations, with the latter being validated during dedicated tests involving Portugal's NRP Arpão submarine.

Positive results have been collected during two sea trials conducted in Portuguese waters in cooperation with operational assets of the Portuguese Navy. During those campaigns, a very strong case was made for how JANUS can effectively contribute to the increase of safety in maritime operations. We believe that this work, with the presented services, results, and data formats, represents a promising starting point to foster underwater interoperability. The remainder of this paper is organized as follows. A description of JANUS is presented in Section II. In Section III, we describe the implemented JANUS-based services and the collected results. Finally, Section IV concludes this paper.

II. JANUS

In this section, we briefly describe the main features and characteristics of JANUS (readers familiar with the JANUS specification may choose to skip this section). The full technical specification can be found in [1].

JANUS is a simple robust signaling method for digital underwater communications that uses frequency-hopping binary frequency-shift keying to transmit digital data as a sequence of short duration tones. It was developed at CMRE with the collaboration of academia, industry, and government. The intention is for JANUS to become widely adopted as an enabler of interoperability between underwater NATO and non-NATO, military, and civilian maritime assets. The main design driver behind JANUS has always been a simplicity of implementation and robustness. The simplicity in the implementation is the key to enable the testing and adoption of JANUS by acoustic modem manufacturers. Not requiring latest generation digital signal processors or any type of advanced hardware, modem producers can implement and deploy JANUS on their existing commercial products. The robustness is required to cope with challenging underwater channels. This typically comes at the cost of reduced data throughput, something that can be well accommodated in JANUS, since it can easily scale to higher center frequencies and larger bandwidths (as described in Section II-A).

A. *Common Frequency Band(s)*

Fig. 1 shows a time–frequency representation of a generic JANUS packet. The JANUS packet may optionally be preceded by three "wake-up" tones that are intended for use in the cases where a modem needs to "wake-up" from a low power "sleep mode." The tones are followed by a short time to activate the receiver electronics, which precedes a fixed sequence of 32 chips. This sequence is used as a detection and synchronization preamble. Once the fixed preamble phase of the waveform is complete, we are into the message section, which is composed by the "baseline JANUS Packet" followed by an optional "Cargo" section, as described in Section II-B. The JANUS waveform has been designed to be scalable in frequency with all parameters being ratiometrically calculated from the center frequency. This provides flexibility in both definition and implementation details. Increasing the center frequency will increase the bandwidth and provide higher data rates. This will be achieved at the price of shorter communication range (due to frequency

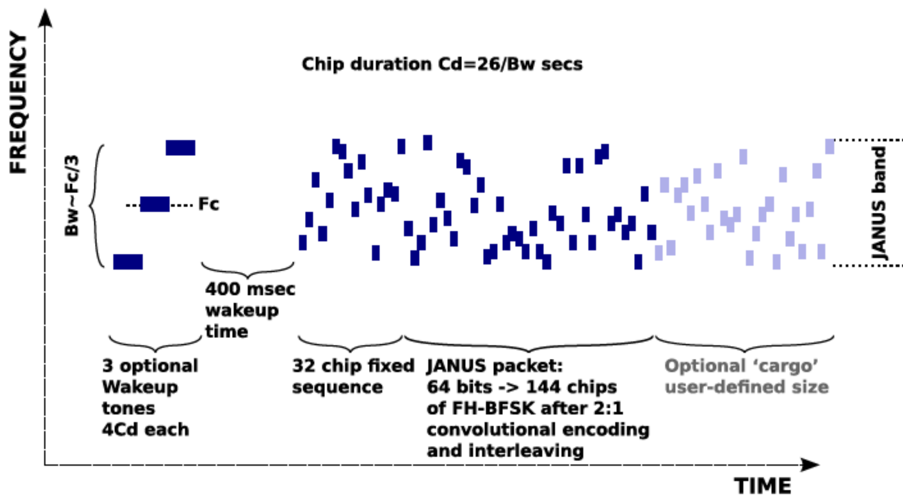


Fig. 1. JANUS signal in a time–frequency plot.

dependent absorption) and lower link reliability (due to smaller chip time).

For the initial JANUS specification, a center frequency of 11 520 Hz was chosen, resulting in a frequency band between 9400 and 13 600 Hz and in a bit rate of 80 b/s. The choice of the initial frequency band for JANUS is twofold: 1) The 9–14-kHz band is attractive for a range of typical communication operational scenarios [13]; and 2) there are many devices operating in this frequency band, thus opening the door for the use of "hardware of opportunity" and the possibility of exploring the use of JANUS to achieve interoperability among several existing proprietary solutions.

B. Flexible Packet Definition

The JANUS specification defines a flexible nested bit allocation scheme under which digital packets can be composed. A "baseline JANUS Packet" (see Fig. 2) consists of an acoustic waveform encoding 64 bits of information. Besides control and specification bits, the "core" of the packet is primarily defined by the user class ID, application type, and application data block. The logic behind this arrangement is that for each of the 256 available user class IDs (generic applications and nations), different application types can be specified along with their respective application data blocks. Depending on the application type, up to 34 bits can be defined by the user to include additional data. Additionally, a JANUS baseline packet can be complemented by a "Cargo" section of arbitrary length. This approach provides almost unlimited flexibility in the nature and extent of the data to be sent.

C. Medium Access in JANUS

There are two key built-in mechanisms in JANUS to handle the medium access: a channel reservation feature, and a built-in medium access control (MAC).

1) The channel reservation feature can be enabled by setting appropriate bits in the baseline JANUS packets, i.e., scheduling bit (Sch) and repetition bit (Rpt) in Fig. 2. By setting these bits, a JANUS node can request "silence" from its neighbors for a defined period of time.
2) The MAC component of JANUS was specifically introduced to minimize the risk of collisions between JANUS and legacy technologies operating in the same band (such as the analogue UT). The task of the JANUS MAC is to measure the energy in band while keeping track of the background noise level. In case other energy sources are detected in the occupied band, precedence is offered to these sources. This is mainly to avoid interfering with possible on-going safety-critical UT communications. An analysis of the impact of the JANUS MCS (without MAC) on UT intelligibility is presented in [10]. It shows that a good intelligibility could also be obtained when JANUS and UT transmissions overlap. This opens to new possible ways to use both JANUS and UT in support to maritime operations.

D. JANUS Plug-Ins

The usage of JANUS as a simple encoder/decoder of arbitrary payloads can be seen as the operation of an acoustic modem "talking" the JANUS language. JANUS, however, was designed to be something more, aiming at defining a standard for underwater digital communication that can coexist alongside proprietary solutions, providing the means for interoperability rather than trying to impose a new method that replaces the previous ones. To ensure interoperability in heterogeneous UANs, a baseline requirement is the ability to correctly read and write the content of JANUS messages. Therefore, the format of the information carried within each JANUS message needs to be specified as well. To support this capability while maintaining flexibility and modularity, the JANUS services have been developed using a design based on plug-ins. A plug-in is a software component that is in charge of properly formatting the JANUS data packet before the waveform is transmitted and correctly extracts its information after it is received. More specifically, each plug-in writes and reads the appropriate bit sequence to/from the application data block and cargo section. Each plug-in uses

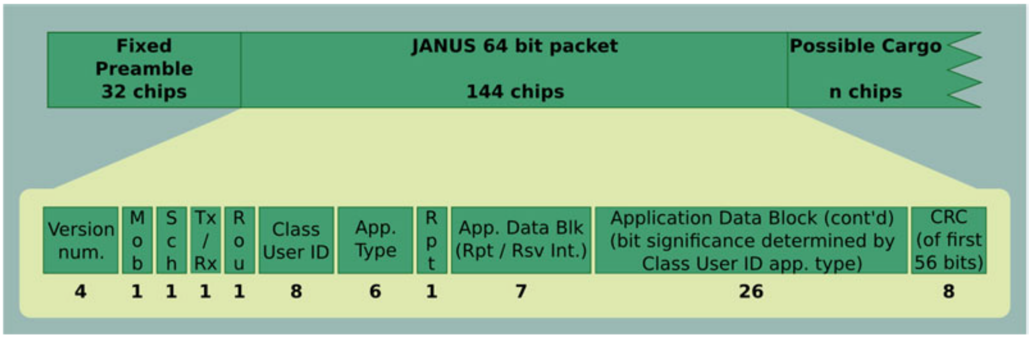


Fig. 2. Structure of a JANUS packet.

a specific combination of the "user class ID" and "application type" fields to implement the respective data field translation. It can be simply loaded on the JANUS system without the need to change or recompile the main code. For each of the JANUS-based services described in this paper, a specific plug-in and the corresponding data format have been defined and implemented.

III. JANUS-Based Services

In the recent past, CMRE has investigated the use of JANUS to support four different services to be used in maritime operations [9], [12]:

1) first contact and language switching;
2) underwater AIS;
3) underwater METOC;
4) support in DISSUB operations.

The main objective has always been to foster the usage of a standard MCS and standardized procedures to improve water space management, to transmit vital information to increase mission safety, and, in general, augment the capabilities available to the operators at sea. Information such as AIS and METOC is usually not available unless the submerged assets navigate at periscope depth and become radio capable, which is typically not a desirable operational condition. This limitation can be overcome with JANUS. The transmission of acoustic messages can be performed from a buoy, or other available assets [e.g., a surface ship or mobile autonomous surface vehicles (ASV)], bridging the radio and the underwater environment, as depicted in Fig. 3. For the information coming from the submerged asset, the inverse path is followed. Once the JANUS packet is decoded on a deployed gateway buoy or surface vehicle, it can then be relayed via radio to reach other platforms of interest. Acoustic transmissions can be configured to be prescheduled, periodic or triggered, depending on the mission profile of the submarine, to maintain its covertness, when needed. This concept is not limited to submarines and it can be applied to any manned or unmanned underwater asset.

It is important to notice that, in technological terms, there has been nothing stopping the development of these services to happen in the last couple of decades. However, being able to offer such capabilities based on a consensus solution that is now an accepted international standard is a potential game changer.

All the considered services have been designed and tested at sea during the REP15-Atlantic and REP16-Atlantic

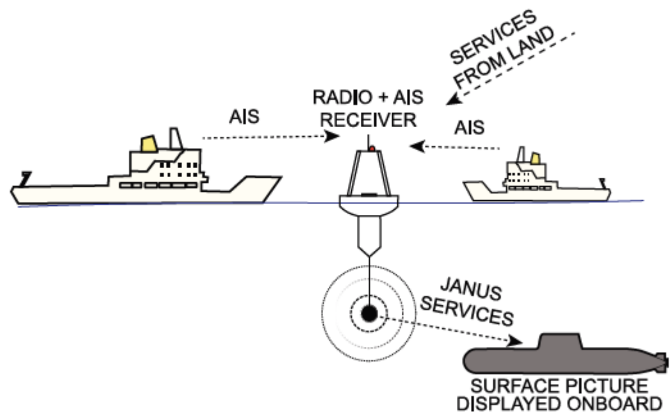


Fig. 3. JANUS-based services, delivered to underwater assets (manned or unmanned).

campaigns. During REP15-Atlantic, the "First contact and language switching" and the first version of the "Underwater AIS" have been tested and validated. In 2016, an enhanced version of the "Underwater AIS" has been developed for the REP16-Atlantic exercise, together with the testing and validation of two novel services: "underwater METOC" and "support in distress submarine operations."

All the services tested during REP16-Atlantic have been developed and implemented with the support of the Submarine Squadron of the Portuguese Navy. For that purpose, prototype hardware for JANUS transmissions and receptions was installed on board the NRP Arpão, a state-of-the-art diesel-electric submarine. Additionally, all these services have been implemented and integrated in the hybrid, cognitive, and secure underwater networking architecture developed by CMRE to provide a live feed of data to the system operator. In what follows, we describe the considered application scenarios and the conducted experiments presenting also the collected results.

A. First Contact and Language Switching Service

When planning and executing challenging cooperative tasks, such as underwater rescue operations, multiple surface and underwater assets can be employed. These devices may be equipped with heterogeneous communication capabilities, e.g., different acoustic modems, optical and radio interfaces, and various communication protocols with different settings. In such scenarios, JANUS can be used as the *lingua franca* to support the

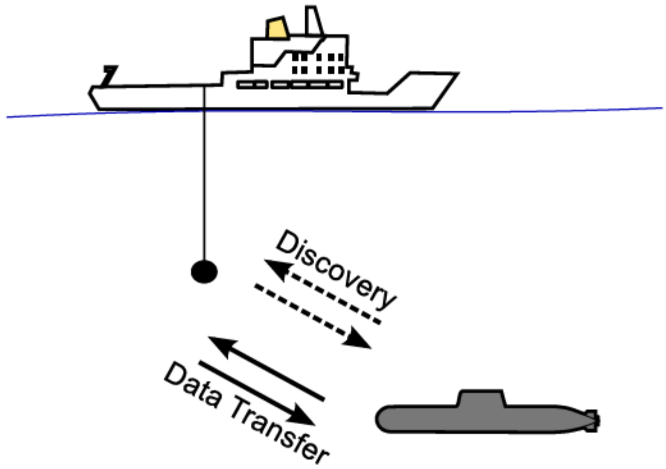


Fig. 4. First contact and language switching.

interaction and cooperation of the various devices. Through the use of a standardized MCS, discovery and language switching procedures[1] can be adopted to optimize the network operations and make better use of the underwater medium and node capabilities/resources (see Fig. 4).

1) Experimental Setting and Results: To implement and test the designed service, a new JANUS plug-in was designed. The NIAG SG190 has investigated this use case for JANUS with the definition of three phases:

1) node discovery;
2) communication capability discovery;
3) language switching.

For each phase, the use of an handshaking approach (request/response) has been suggested.

In designing and implementing the JANUS plug-in, the NIAG SG190 suggestions were considered with the addition of all the retransmission and recovery strategies that are necessary to cope with errors and packet losses.

The implemented proof-of-concept solution was tested and validated during the REP15-Atlantic experiments, conducted in cooperation with the Portuguese Navy and the Universities of Porto and Azores. The activity took place off the coast of Faial island, in the Azores archipelago, Portugal, in July 2015.

In what follows, we better detail these three phases.

1) *Node discovery:* During this phase, a node periodically broadcasts a discovery request to inform the others about its presence and to know about the other assets operating in the area. Upon reception of a node discovery request, a node can send back a reply to the requester to make it aware about its presence. Both discovery request and reply include the node type, possible node types are autonomous underwater vehicle (AUV), ASV, moored buoy, and ship. Each node introduces a random delay before transmitting its reply to avoid having overlapping receptions at the requesting node. The delay between two consecutive requests can be adapted over time. A shorter delay can be used when no other nodes are known. This delay can then be increased when other nodes are discovered and messages for the other two phases are exchanged in the network. Fig. 5 depicts an example of the node discovery phase where node A broadcasts the discovery request (D-Req), while node B and node C broadcast their responses (D-Resp). Each node overhears the discovery messages transmitted in the network. Therefore, node B is informed about the presence of node C when it receives the discovery reply transmitted by node C and vice versa.
2) *Communication capability discovery:* During this phase, a node sends a request to another node to be informed about the communication capabilities of that node. The requesting node adds its own communication capabilities in the request message. Once a node receives the request, it can check what are the communication capabilities of the other node and then reply with its own information. For this reply, the node may select to issue all or just a relevant subset of its capabilities (typically the ones in common).
Fig. 6 depicts an example of the communication capability discovery phase where node A requests the communication capability of node C. The modulation schemes supported by node A (MCS1, MCS2, and MCS3) are added in the request (C-Req). When node C receives the request, it decides to reply with a message (C-Resp) including only the modulation schemes in common with node A (MCS1 and MCS3). Fig. 6(a) shows the case where node A correctly receives the information transmitted by node C, while in Fig. 6(b) an error occurs and the request procedure has to be repeated.
3) *Language switching:* During this phase, the requesting node selects the MCS or "language" to be used in the com-

[1]To have the full system working, there is the need for a standardized MCS but also for standardized discovery and language switching procedures.

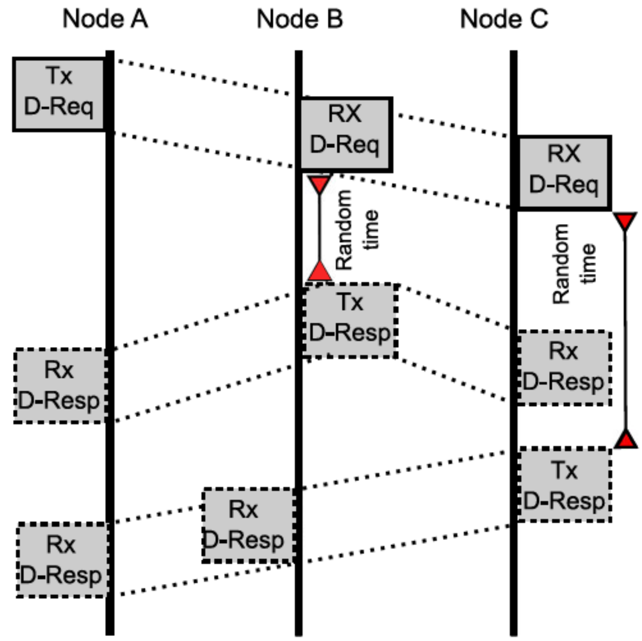


Fig. 5. JANUS node discovery.

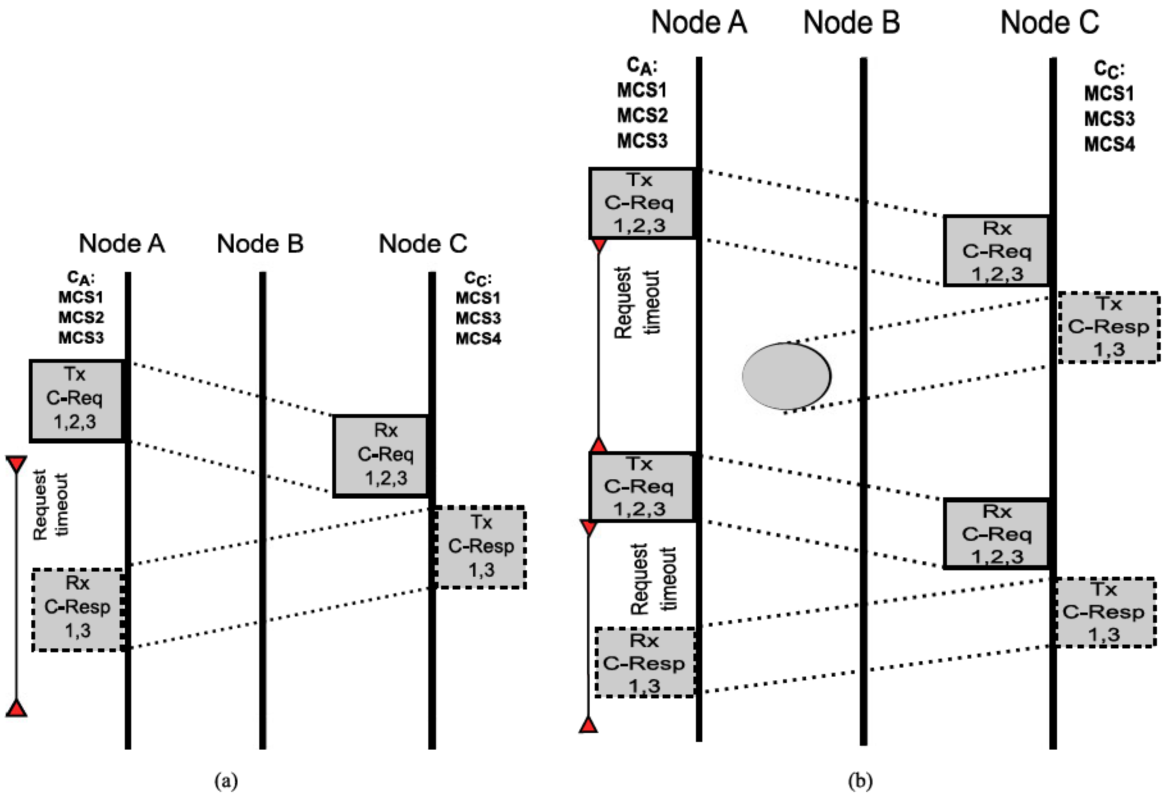


Fig. 6. JANUS communication capability discovery: Node A requests information to node C. (a) Node A correctly receives information from node C. (b) Error on response delivery with a request retransmission.

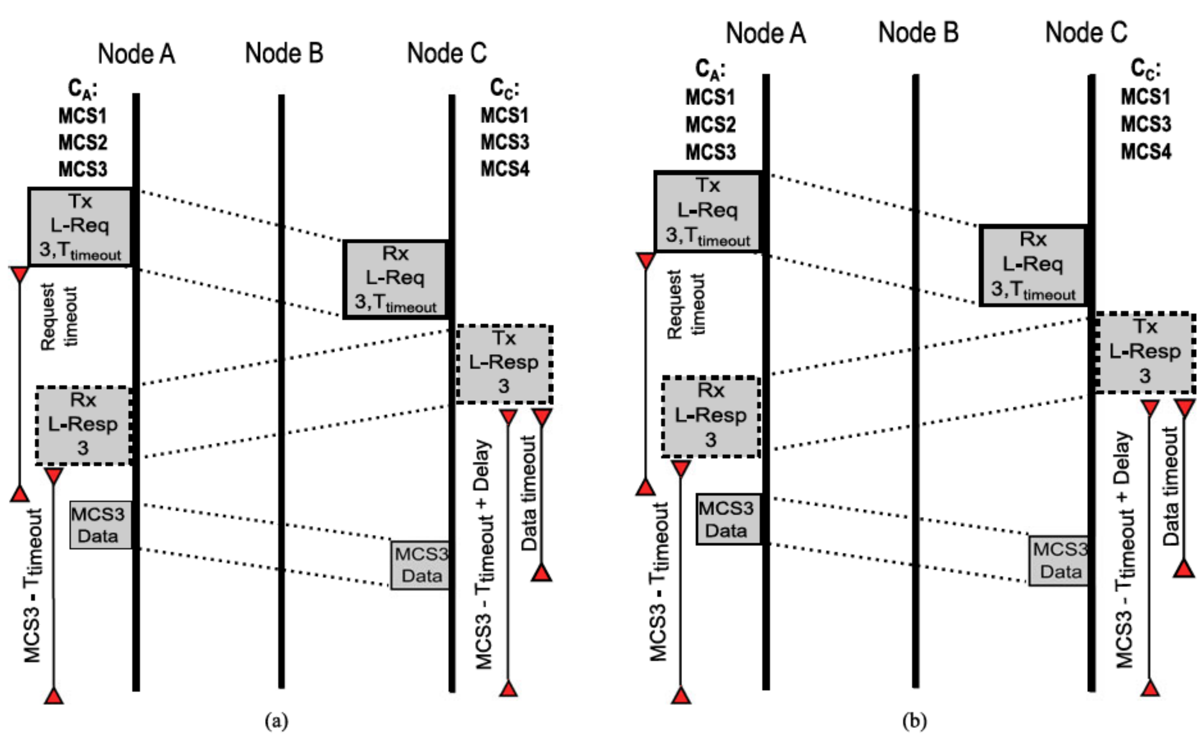


Fig. 7. JANUS language switching: Node A wants to use MCS3 with node C for a given time (T_{timeout}). (a) Node A correctly receives information from node C and they start using MCS3 for data exchange until T_{timeout} expires. (b) Error on response delivery, node A and node C stay on two different MCSs until the data timeout expires.

TABLE I
FIRST CONTACT AND LANGUAGE SWITCHING SERVICE RESULTS

Message type	Percentage of packets per handshaking type
Node discovery handshake	23%
Comms capability handshake	42%
Language switching handshake	35%

munications and the configuration parameters (e.g., for how long to stay on this non-JANUS language: T_{timeout}). This selection depends on the information obtained during the previous phase and on the switching strategy adopted by the node. When a language switching request is received, a node can accept or decline the request and a response is sent back to the requesting node. The following three timers are used:

a) *request timeout*, used to retransmit the request if no reply is received;
b) *data timeout*, used to switch back to JANUS if no data (transmitted with the selected modulation scheme) are received after the transmission of a response;
c) T_{timeout}, used to switch back to JANUS after the use of the selected modulation scheme.

Fig. 7 depicts an example of the language switching phase where node A wants to use the selected modulation scheme (MCS3) with node C for a given time T_{timeout}. Fig. 7(a) shows a correct negotiation between the two nodes. When node C receives the first message transmitted using MCS3, the data timeout is stopped. In Fig. 7(b), instead the response of node C is not delivered to node A and the two nodes stay configured on different modulation schemes for some time. When the data timeout expires and node C has not received any data message, it reverts back to JANUS to listen for possible request retransmissions or novel requests.

Given the small amount of data that needs to be exchanged to implement this service, only baseline JANUS packets (no cargo) have been employed. A language selection policy switching from JANUS to any language with a faster (higher bit rate) transmission parameter was considered. To validate this JANUS-based service, two nodes were employed and various configurations were considered. Three different communication interfaces were available on these two nodes: One had JANUS, Evologics modem [14] and a freewave radio (for communications when surfacing), while the second had JANUS and an Evologics modem. The Evologics S2C R18/34 acoustic modem provides an actual transmission rate of 480 b/s (in instant message mode, higher rates are achievable in burst mode), whereas the JANUS transmission rate is 80 b/s.

A total of 830 baseline JANUS packets were transmitted over the different days of testing. Table I summarizes the percentage of packets transmitted for each of the different phases, which sums up the weight of each phase in the process.

After the node discovery and communication discovery phases, the two nodes negotiated a switch to the Evologics language (the only faster language they had in common) to transmit a large amount of data at a higher speed. After that they reverted back to JANUS for further discovery and negotiation. Periodic transmissions of discovery requests were also triggered over time. This was done to check the presence of new nodes in the area and to monitor any change in the set of communication capabilities available at the node.[2]

After switching to Evologics, a transmission rate approximately six times faster was used to correctly deliver 1927 packets (~ 73 kB) between the two nodes. Due to the unreliable acoustic channel, an average packet error rate of ~ 0.3 was experienced. Various packets were lost during the different phases of the protocol, including 17% of the transmitted switch-over responses. This resulted in having the two nodes using different languages for some time before going back to JANUS via the built-in data timeout mechanism. It is clear that the development of an operational solution will require a more robust and sophisticated language selection policy and negotiation strategy to render the procedure more reliable and efficient. The selection of the communication hardware, MCS, and protocol solutions will surely needs to adapt over time, reacting to the status of the single node, the status and topology of the network, and the status of the underwater channel. Novel procedures based on protocols such as DIVE [15] could be standardized and adopted to discover the network and the capabilities of each node and to also assign short unique IDs to the nodes, thus, minimizing resource consumption and promoting truly ad hoc underwater networks.

2) JANUS Packets Employed: Table II presents the full specification of the JANUS packets employed. A currently open class user ID field (13) was used. It is hoped that experimental efforts such as this can contribute to populate the class user ID allocation table in future JANUS revisions.

B. Underwater Automatic Identification System Service

The AIS is a status-reporting service used to broadcast identification and localization information to nearby vessels. It is used as an automatic tracking system to avoid collisions between vessels operating at the sea surface. AIS is mandatory for vessels above 300 tons and all passenger ships, and is electively deployed by many smaller vessels. The recent (July 2016) U.K. Astute-class nuclear submarine collision with a merchant vessel in Gibraltar highlighted once again the risks associated with water space management (or lack thereof) between surface and underwater assets. The objective of this service is to use JANUS to broadcast to submerged assets, relevant AIS data collected above the water. The idea of using JANUS to transmit the AIS picture to submarines navigating at depth had been proposed in [16] as a mechanism to reduce the probability of accidents between surface ships and submerged assets.

[2]The set of communication capabilities available at a node can change over time due to various reasons, including: Possible failure in hardware/software related to a specific communication interface; enabling/disabling the use of a specific communication interface due to the energy constraints; deployment of new communication interfaces on the node.

TABLE II
SPECIFICATION OF THE JANUS PACKETS EMPLOYED IN FIRST CONTACT AND LANGUAGE SWITCHING

Field	Discovery Request	Discovery Response	Comms Request	Comms Response	Switch Request	Switch Response
Version num.	3	3	3	3	3	3
Mob.	1	1	1	1	1	1
Sch.	0	0	0	0	0	0
Tx/Rx	1	1	1	1	1	1
Rou.	1	1	1	1	1	1
Class User ID	13 (OPEN)	13 (OPEN)	13 (OPEN)	13 (OPEN)	13 (OPEN)	13 (OPEN)
App. Type	0	1	2	3	4	5
Rpt.	Not Used (Sch=0)	Not Used (Sch=0)	Not Used (Sch=0)	Not Used (Sch=0)	Not Used (Sch=0)	Not Used (Sch=0)
App Data Blk	<SRC ID>, 4 bits <DST ID>, 4 bits <TYPE>, 4 bits	<SRC ID>, 4 bits <DST ID>, 4 bits <TYPE>, 4 bits	<SRC ID>, 4 bits <DST ID>, 4 bits <COMMS INFO>, 24 bits	<SRC ID>, 4 bits <DST ID>, 4 bits <TYPE>, 24 bits	<SRC ID>, 4 bits <DST ID>, 4 bits <LANG INFO>, 24 bits	<SRC ID>, 4 bits <DST ID>, 4 bits <LANG INFO>, 24 bits
Cargo	Not Used	Not Used	Not Used	Not Used	Not Used	Not Used

In 2015, during the REP15-Atlantic trials, the first implementation of a JANUS-based underwater AIS service was investigated and different packet configurations were explored [9]. During REP16-Atlantic, this initial work was extended and improved in cooperation with the Portuguese Navy and their submarine squadron. The format and content of the JANUS messages was modified to include additional information and the full system was integrated with a graphical interface (Neptus [17]) ready to be used by an operator. A subset (filtered in space) of the available AIS data was compressed and transmitted using JANUS. While in regular AIS, a vessel will broadcast MMSI, latitude, longitude, heading, speed, and status, in our implementation two more fields were added: depth and type (i.e., AUV, ASV, moored buoy, etc.). The reason for this choice was to allow submerged nodes to broadcast their identification and localization data to any other vessels in communication range, above and below the surface. This contributes to reducing the probability of accidents between surface and submerged manned and unmanned assets.

1) Experimental Setting and Results: During this experiment, one gateway buoy (bridging the radio and the underwater environments) was used to collect and broadcast the AIS information to the other JANUS-capable assets operating in the area. Fig. 8 shows a subset of the AIS contacts transmitted by the gateway buoy and delivered to the NRP Arpão submarine via JANUS transmissions during REP16-Atlantic.

Two additional JANUS nodes were deployed to receive the AIS data: one on board the NRP Arpão submarine and one from the NRV Alliance at a depth ranging between 40 and 60 m. The node deployed from the NRV Alliance was used to mimic the operation of an additional underwater asset with no radio capability. All data exchanges were performed acoustically using JANUS messages. To reduce the number of acoustic messages transmitted in water, the AIS information was filtered in space and time. A large area[3] was selected to ensure the collection of multiple AIS contacts and to evaluate the usage of JANUS to deliver the obtained AIS picture. During one of the experiments that lasted approximately 2 h, 58 contacts were detected by the gateway buoy inside the target area. Overall, 861 JANUS messages were transmitted. The system was configured to encode the data of multiple contacts inside the one single acoustic packet, making use of the cargo section. Due to the unreliable acoustic channel, an average packet error rate of ~ 0.2 was experienced. The node on the NRV Alliance was able to correctly receive 483 messages and receive updates on 57 assets operating in the area. Some of the messages were also lost because Alliance moved out of the acoustic communication range of the gateway buoy for some time. Regarding the test system on board the submarine, a recurring hardware malfunction (identified during execution) resulted in an impaired reception capability. For this reason, only 207 messages were correctly received by the submarine. However, since the scheme incorporates redundancy, 53 contacts were correctly decoded. The implemented service provided live AIS updates (with a dedicated display in the combat room) to the NRP Arpão submarine via JANUS transmissions. A subset of the received contacts is displayed in Fig. 8. This capability was very welcomed by the submariners.

Fig. 8. Subset of the AIS contacts transmitted by the gateway buoy and delivered to the NRP Arpão submarine via JANUS transmissions.

[3]The size of the target area was $\sim$60 km $\times$ 30 km.

TABLE III
SPECIFICATION OF THE JANUS PACKETS EMPLOYED IN THE UNDERWATER AIS SCENARIO

Field	Underwater AIS
Version num.	3
Mob.	1
Sch.	0
Tx/Rx	1
Rou.	1
Class User ID	2 (Underwater AIS)
App. Type	8
Rpt.	Not Used (Sch=0)
App Data Blk	<SRC ID>, 8 bits
	<DST ID>, 8 bits
	<PAYLOAD SIZE>, 9 bits
Cargo	<MMSI>, 30 bits
	<TYPE>, 4 bits (vessel, AUV, ASV, buoy, bottom node, submarine)
	<LATITUDE>, 28 bits (decimal degrees)
	<LONGITUDE>, 28 bits (decimal degrees)
	<DEPTH>, 10 bits (metres)
	<SPEED>, 8 bits (knots)
	<HEADING>, 12 bits (degrees)
	<STATUS>, 4 bits (**0** = Under way, using engine; **1** = At anchor; **2** = Not under command; **3** = Restricted manoeuvrability; **4** = Constrained by draught; **5** = Moored; **6** = Aground; **7** = Engaged in fishing; **8** = Under way, sailing; **9** = For future use; **10** = For future use; **11** = Power-driven vessel towing astern; **12** = Power-driven vessel pushing ahead; **13** = For future use; **14** = AIS-SART; **16** = Undefined/default;)
	<NUM CONTACTS>, 3 bits (integer)
	for each of the contacts appended:
	<MMSI>, 30 bits
	<TYPE>, 4 bits (vessel, AUV, ASV, buoy, bottom node, submarine)
	<LATITUDE>, 22 bits (decimal degrees, relative to the first one)
	<LONGITUDE>, 22 bits (decimal degrees, relative to the first one)
	<DEPTH>, 10 bits (metres)
	<SPEED>, 8 bits (knots)
	<HEADING>, 12 bits (degrees)
	<STATUS>, 4 bits (as above)
	<CRC>, 8/16 bits depending on cargo length

2) JANUS Packets Employed: Table III presents the full specification of the JANUS packets employed for the underwater AIS scenario. The implementation uses class user ID 2, specifically defined for this application.

C. *Underwater METOC Service*

Another capability of great value for the planning and execution of maritime operations is the availability of updated military METOC data. METOC data can be used to assess the impact of the current and forecasted environmental picture on the mission, to adapt the various mission tasks, and to make go/no-go decisions, when needed. To date, this information is available to the underwater assets when they become radio capable navigating at periscope depth.

The use of JANUS could represent a viable solution to deliver METOC data to submerged assets in support to their activities, contributing to better planning and safety of operations. The possibility of supporting the delivery of such information to submarines navigating at depth provides extra flexibility to the Commanding Officer that may choose to remain at depth.

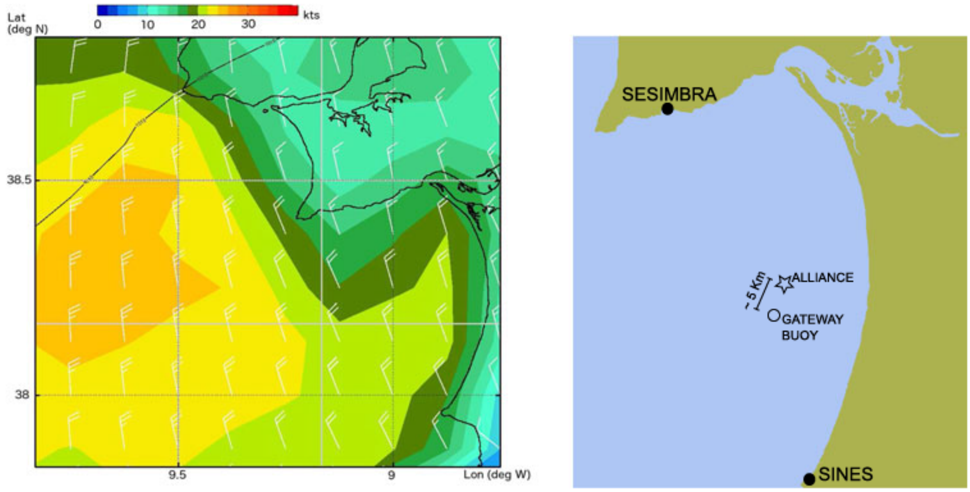
1) Experimental Setting and Results: During the REP16-Atlantic trials, the underwater METOC service was implemented in close cooperation with the hydrographic office of the Portuguese Navy (IH) and was fully integrated in the CMRE networking system.

Two JANUS-capable nodes were used for this test, one transmitter and one receiver. Wind maps generated by the METOC offices of the IH were transmitted acoustically. Matrices of wind speed and direction, as shown in Fig. 9(a), were encoded in a total of 53 bytes, suitable for a JANUS acoustic transmission with cargo section.

The packets were assembled at a gateway buoy and sent acoustically via JANUS to a node deployed from the NRV Alliance at a depth of $\sim$60 m. This node was mimicking the operations of an underwater asset operating at depth.

During this experiment, the distance between transmitter and receiver was between 5000 and 5500 m, as displayed in Fig. 9(b). Although a difficult downward refracting and spread channel produced an average packet error rate of ~ 0.25, the addition of redundancy at the transmitter always made possible the delivery of the intended wind maps, thus demonstrating the possibility of using JANUS to implement underwater METOC services.

2) JANUS Packets Employed: Table IV presents the specification of the JANUS packet employed for the underwater METOC scenario. This is an example of a specification that is pushed at national level, using the respective class user ID (in this case 234-Portugal).



(a) (b)

Fig. 9. Underwater METOC test. (a) Example wind map transmitted acoustically, via JANUS, during the REP16-Atlantic experiment. (b) Location of the nodes deployed for the underwater METOC test.

TABLE IV
SPECIFICATION OF THE JANUS PACKETS EMPLOYED IN THE UNDERWATER METOC SCENARIO

Field	Underwater METOC
Version num.	3
Mob.	1
Sch.	0
Tx/Rx	1
Rou.	1
Class User ID	234 (Portugal)
App. Type	0
Rpt.	Not Used (Sch=0)
App Data Blk	<SRC ID>, 8 bits <DST ID>, 8 bits <PAYLOAD SIZE>, 9 bits
Cargo	<METOC DATA>, 53 B, National format <CRC>, 16 bits

D. Support in Distressed Submarine Operations Service

The use of JANUS for submarine search and rescue operations has always been very attractive. Currently, the doctrine of communications for search and rescue relies on the analog UT and the usage of the phonetic codes *alpha* to *zulu*. The UT is a very simple standard (originally STANAG 1074, meanwhile superseded by STANAG 1475) specifying the modulation of voice into a carrier by upper single-sideband modulation with 2.7 kHz of analog bandwidth, approximately that offered by a regular telephone and sufficient to convey speech.

The use of the UT has the clear problem of needing an operator (that may be required for other equally critical tasks) to handle the communications on the submarine side. Additionally, it avoids the use of any data coding and other strategies, typical of digital information theory, to increase the reliability in decoding the received information. When employing human operators, stress and language phonetic biases may also play a role in the success of the data exchange. As shown in [10], operator-dependent factors play an important role in the ability to properly decode analog UT communications. Therefore, JANUS could be used to replace analog UT systems or in combination with these systems for search and rescue communications. The operator requirement may be removed and semiautomated systems transmitting critical data could be used. This would enable increasing the robustness, efficiency, and reliability in delivering and decoding critical information in DISSUB operations.

1) Experimental Setting and Results: One of the exercised scenarios during the REP16-Atlantic trials was a distressed situation on board the NRP Arpão. The scenario is described as follows. Once an alarm is raised on board,[4] periodic packets with vital data are automatically and periodically sent out via JANUS, without requiring the intervention of an operator (see Fig. 10). The data encoded in the JANUS packet included latitude, longitude, depth, O_2, CO_2, CO, H_2, pressure, temperature, and the number of survivors. The definition of such packet was iterated with the submarine Commanding Officer to guarantee maximum relevance and alignment with current practices covered by STANAG1390 and described in the ATP-57 document "The submarine search and rescue manual" [18]. The experiments performed during REP16-Atlantic were a proof-of-concept demonstration for this JANUS-based service. There was no interface with the systems on board the submarine and the data fed to the JANUS system was artificially generated.

As shown in Fig. 10, the objective is to deliver the vital submarine information to JANUS-capable surface stations, which can then relay the collected information via radio to any other relevant asset. For this experiment, a gateway buoy and the NRV Alliance were used as receivers. Using this setup, a live feed with position and status data was delivered to the control room installed on board the NRV Alliance.

Fig. 11 shows some of the live data provided to the system operator in the control room on the NRV Alliance for the DISSUB application scenario. The big circle marker represents

[4] To be validated positively or negatively with the intervention (or lack of it) of an operator. The operational concept of alarm validation was beyond the scope of the test.

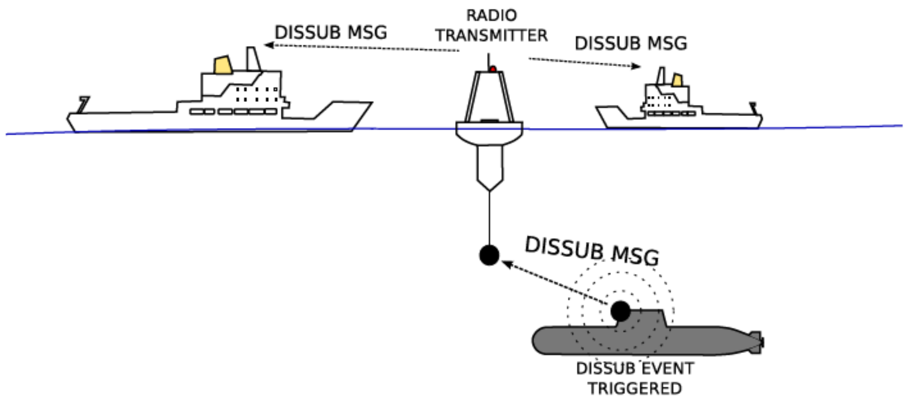


Fig. 10. Support in DISSUB operations.

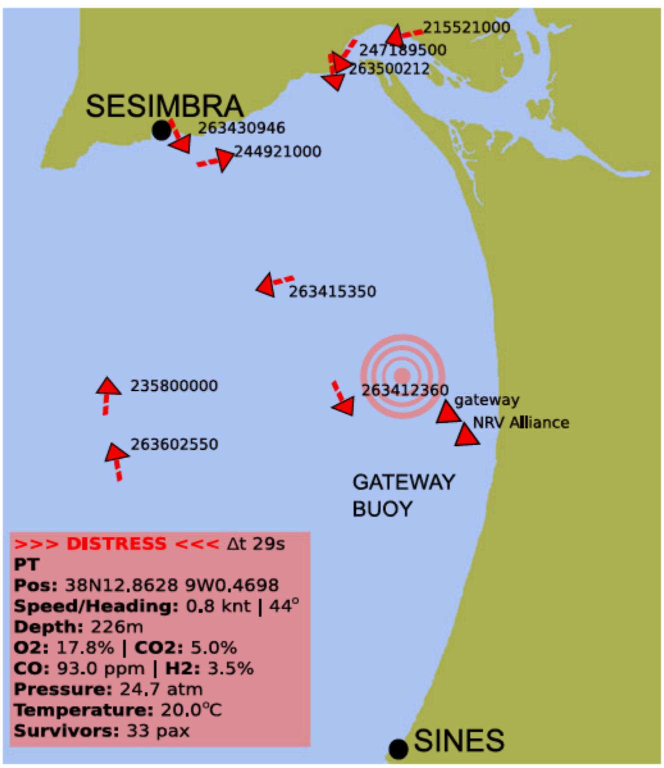


Fig. 11. Distress position and status information acoustically received in the control room on board the NRV Alliance. AIS contacts received via radio are also reported.

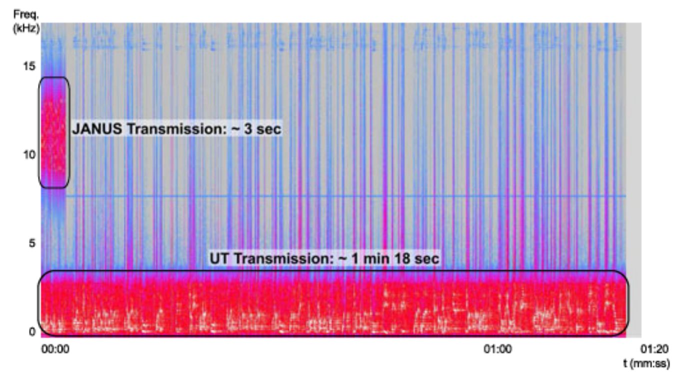


Fig. 12. Comparison of transmission duration for digital (JANUS) and analogue (UT) signals containing comparable information. Note that the frequency of the UT signal is shown as demodulated, as it is presented to the operator.

the submarine position, while the data shown in the small box on the left-bottom corner contain the latest position and status information received via JANUS.

AIS data (received through a conventional AIS receiver) are also displayed so that the vessels operating in the area (which may be used in support to search and rescue operations) are clearly identified.

To encode both position and status information, up to 22 B were used. This means that JANUS packets with cargo were transmitted. The overall transmission duration of such packets was about 3 s.[5] The established doctrine of data exchanges in case of a submarine in distress is published in the NATO ATP-57 document [18]. These exchanges are supported by analog UT transmissions. A comparison (made just for reference) of the channel time required by JANUS and UT to transmit the same information is shown in Fig. 12, where the efficiency of the digital method is evident. The UT transmission was acquired by employing an officer on board the Portuguese submarine NRP Arpão. Additionally, one can state that a digital system opens ways for automated operations when interfaced with the on board systems. Using JANUS, although some of the transmitted packets were lost (this was due to the unreliable acoustic underwater channel), the redundancy introduced by the automated transmission procedure made it possible to deliver the intended data in real time, meaning that the latest available position and the status of the submarine were available to all assets in communication range with negligible latency. Therefore, the collected results demonstrate that JANUS is a viable solution to support DISSUB operations.

2) *JANUS Packets Employed:* Table V presents the full specification of the JANUS packets employed in the DISSUB scenarios. Therefore, DISSUB is currently not one of the prespecified class user IDs and an open entry (in this case entry 11) was used. DISSUB applications are likely to be a strong catalyzer for JANUS and full message specifications are expected for the next revisions of the standard.

[5]The overall transmission duration accounts also for the 64 bits in the baseline JANUS packet.

TABLE V
SPECIFICATION OF THE JANUS PACKETS EMPLOYED IN DISSUB SCENARIOS

Field	DISSUB Position	DISSUB Status	DISSUB Position + Status
Version num.	3	3	3
Mob.	1	1	1
Sch.	0	0	0
Tx/Rx	1	1	1
Rou.	1	1	1
Class User ID	11 (OPEN)	11 (OPEN)	11 (OPEN)
App. Type	0	1	2
Rpt.	Not Used (Sch=0)	Not Used (Sch=0)	Not Used (Sch=0)
App Data Blk	<SRC ID>, 8 bits	<SRC ID>, 8 bits	<SRC ID>, 8 bits
	<DST ID>, 8 bits	<DST ID>, 8 bits	<DST ID>, 8 bits
	<PAYLOAD SIZE>, 9 bits	<PAYLOAD SIZE>, 9 bits	<PAYLOAD SIZE>, 9 bits
Cargo	<NATIONALITY>, 16 bits	<NATIONALITY>, 16 bits	<NATIONALITY>, 16 bits
	<LATITUDE>, 28 bits (decimal degrees)	<O2>, 6 bits (vol %)	<LATITUDE>, 28 bits (decimal degrees)
	<LONGITUDE>, 29 bits (decimal degrees)	<CO2>, 6 bits (vol %)	<LONGITUDE>, 29 bits (decimal degrees)
	<DEPTH>, 10 bits (metres)	<CO>, 8 bits (ppm)	<DEPTH>, 10 bits (metres)
	<SPEED>, 9 bits (knots)	<H2>, 6 bits (vol %)	<SPEED>, 9 bits (knots)
	<HEADING>, 12 bits (degrees)	<PRESSURE>, 10 bits (atm bar)	<HEADING>, 12 bits (knots)
	<CRC>, 8 bits	<TEMPERATURE>, 6 bits (deg. Celsius)	<O2>, 6 bits (vol %)
		<SURVIVORS>, 6 bits (pax)	<CO2>, 6 bits (vol %)
		<CRC>, 8 bits	<CO>, 8 bits (ppm)
			<H2>, 6 bits (vol %)
			<PRESSURE>, 10 bits (atm bar)
			<TEMPERATURE>, 6 bits (deg. Celsius)
			<SURVIVORS>, 6 bits (pax)
			<CRC>, 8 bits

IV. CONCLUSION

In this paper, we have investigated the use of four JANUS-based services for operationally relevant underwater applications. The collected results show that JANUS is a feasible solution to increase the maritime situational awareness in the underwater domain. Vital information can be transmitted to guarantee mission safety in support to operations at sea and to reduce the risk of collisions involving underwater assets. We have demonstrated that JANUS is a suitable solution for a first contact capability in a heterogeneous network where nodes may decide to switch to another common and more advanced MCSs for faster data transmission. Additionally, JANUS can be effectively used to deliver live AIS and METOC data, collected at the surface, to submerged assets. Similarly, JANUS is well adapted to transmit critical data from a submarine in distress. Therefore, JANUS could be used to replace the analog UT, or be used in combination with such a telephone, to increase the robustness, efficiency, and reliability in delivering and decoding critical information, avoiding the need to employ a human operator.

All the conducted experiments show that the use of a standard commonly agreed "language" for underwater digital communications is a long overdue key enabler of cooperation among heterogeneous underwater assets. Fostering the use of JANUS in relevant application scenarios is a key challenge to increase the safety and awareness in maritime operations and to make a better and more efficient use of underwater networks.

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Title

JANUS-based services for operationally relevant underwater applications.

Abstract

This paper presents the design, test, and experimentation at sea of four JANUS-based services for operationally relevant underwater applications: 1) first contact and language switching; 2) transmission of automatic identification system data to submerged assets; 3) transmission of meteorological and oceanographic data to underwater vessels; and 4) support in distressed submarine operations. On March 24, 2017, JANUS was promulgated as a NATO standard (STANAG 4748) [1], marking the first time that a digital acoustic communications protocol is adopted at international level. JANUS is an open, simple, and robust modulation and coding scheme developed by the NATO STO Centre for Maritime Research and Experimentation, in collaboration with academia and industry. The implementation of the services presented in this paper is based on a standardized protocol and offers the potential to widely increase the safety and efficiency in maritime operations. The objective of this paper is to demonstrate that JANUS can be used in support of maritime operations, potentially increasing their efficiency. Such demonstration is achieved through experimentation at sea of four operationally relevant JANUS-based services. The four JANUS-based services discussed were validated during two different sea trials: REP15- Atlantic and REP16-Atlantic. During those trials, various heterogeneous configurations were considered, including the use of a state-of-the-art diesel-electric submarine, guaranteeing maximum relevance for validation and evaluation of the designed solutions. The collected results demonstrate that JANUS is a viable solution for operationally relevant underwater applications, thus validating the objective of this paper. Additionally, encouraging feedback has been provided by the operational community participating to the trials. The capabilities demonstrated served as an initial proof of concept and will certainly lead to newer requirements and eventually even more functionalities.

Keywords

First contact and language switching, interoperability, JANUS, support in distressed submarine (DISSUB) operations, underwater acoustic sensor networks, underwater applications, underwater automatic identification system (AIS), underwater digital communication standard, underwater meteorological and oceanographic (METOC)

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