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Moving JANUS forward: a look into the future of underwater communications interoperability

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CMRE conducts state-of-the-art scientific research and experimentation ranging from concept development to prototype demonstration in an operational environment and has produced leaders in ocean science, modelling and simulation, acoustics and other disciplines, as well as producing critical results and understanding that have been built into the operational concepts of NATO and the nations.

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***Abstract*—In the past 8 years, the Centre for Maritime Research and Experimentation (CMRE) has developed, tested and promoted JANUS - a robust and simple modulation and coding scheme to be used as the first standard to support interoperability in digital underwater communications. This document aims at reporting the current status of JANUS and a first look at possible routes for evolution of this soon-to-be standard.**

I. Introduction

Underwater (UW) communication capabilities are currently manufacturer-specific, generally using proprietary digital coding technologies and thus there exists no general interoperable capability between modems from different manufacturers. This introduces procurement and obsolescence management risks by imposing manufacturer dependence and prevents scalable and ad hoc underwater networking from being practicable. To fill this gap CMRE has developed JANUS, currently in the final steps before becoming an accepted NATO Standardization Agreement (STANAG). JANUS is, in a nutshell, a modulation and coding scheme (MCS), plus some additional mechanisms to render it practical in real use.

A very relevant feature is that JANUS is not intended to be limited to solely NATO military use, but also for civilian and international adoption. JANUS is unique in its open and public nature to ensure that academia, industry and governments may all benefit from its use. The specification of the signal encoding and message format is fully described in [1] and reference implementations are freely available online [2] so that anyone can construct a transmitter/receiver to communicate via JANUS with any other compliant platform. While JANUS is deliberately simple to allow easy adoption by legacy equipment, the protocol also anticipates the use of sophisticated decoders to allow significantly improved performance beyond what is achievable with the available simple, baseline receiver.

This document presents a summary view of the technical aspects, challenges and the future of JANUS. In Section II we review the key elements of JANUS. Section III presents some JANUS-based capabilities currently being implemented and tested while Section IV offers a look into what the next revisions of JANUS may look like. Section V finally concludes with a focus on the path to supporting JANUS adoption and evolution.

II. Key elements of JANUS

The full JANUS specification document is currently going through the STANAG approval process after a period of technical implementation, experimentation and validation documented in [3],[4],[5],[6],[7],[8],[9] and [10].

This section doesn't intend to offer a comprehensive description of JANUS (that can be found in its draft form in [1]) but rather to identify some of the key aspects that make it unique and (in our opinion) well-suited to be a standard.

A. Simple, robust design

The main design drives behind JANUS has always been a simplicity of implementation and a robustness to challenging channels. The simple implementation means that manufacturers willing to experiment or even implement JANUS in their hardware will not require latest generation DSPs or any type of advanced hardware, and in fact may deploy JANUS on existing hardware. The robustness aspect typically comes at the cost of reduced data throughput, something that can well be accommodated in JANUS. The motivation for JANUS was to provide a simple baseline mode that manufacturers could add to their modem products as an enabler for interoperability, where JANUS would be the *lingua franca* of underwater communications systems - nodes could use JANUS to establish a first contact, discover capabilities and eventually switch to another common and more performant MCS or "language". JANUS also offers basic data exchange capabilities for cases where no other common MCSs are present. A frequency hopping, frequency shift keying (FH-FSK) modulation scheme is employed as the base of JANUS.

B. Common frequency band(s)

Figure 1 shows a time-frequency representation of a generic JANUS packet. The JANUS waveform is fully parametrised based on centre frequency, providing flexibility in both definition and implementation details. For the initial JANUS specification, a centre frequency of 11520 Hz was chosen, resulting in a frequency band between 9400 and 13600 Hz.

The choice of the initial frequency band for JANUS comes partially from the attractiveness of the 9-14 kHz band for a range of typical communication operational scenarios [11]. Additionally the existence of a number of devices operating

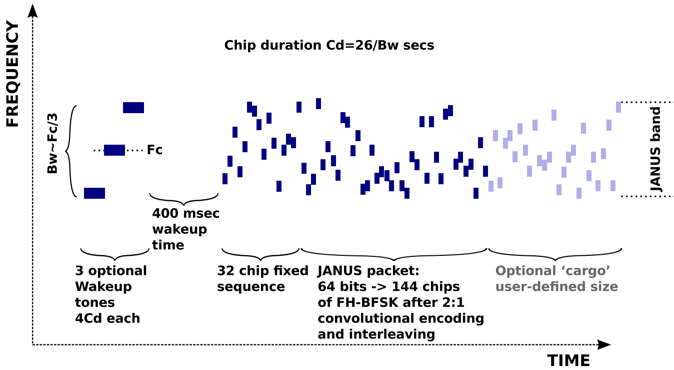

Fig. 1: the JANUS signal in a time-frequency plot

in the same frequency band opens the door for the use of "hardware of opportunity" and the possibility to explore the use of JANUS to achieve interoperability among several proprietary solutions.

There are two key mechanisms built in JANUS to hande the medium access – a channel reservation feature, and a built-in Medium Access Control (MAC). The channel reservation feature allows a JANUS node can issue a packet requesting "silence" from its neighbours for a defined period of time. The MAC component of JANUS was specifically introduced to minimise the risk of collisions between JANUS and legacy technologies operating in the same band (like the analogue underwater telephone - UT). The JANUS MAC simply measures energy in band while keeping track of the background noise level and always offers precedence to other energy sources occupying the band, where safety-critical UT communications may be found. An analysis of the impact of the JANUS MCS (without MAC) on underwater telephone intelligibility is presented in [8].

C. Openly available

JANUS is open and free to all. Even though born from the efforts of NATO and CMRE the requirement for global underwater interoperability was embraced from the outset and helped attract the broad international underwater communications community that has participated so strongly in JANUS's development.

The JANUS specification is available in its draft format in [1] while the full document moves up in the STANAG approval process,

In the JANUS wiki site [2], free reference implementations of a transmitter and receiver in both MATLAB and C++ can be found. After the promulgation of the JANUS standard, an additional document, produced by a NATO Industrial Advisory Group, offering a practical guide to implement JANUS systems will be made available. This guide focuses on practical questions not covered by the standard specification but of key importance to engineers and practitioners. These include considerations on the transducers to use, ideal sampling rates, etc.

D. Flexible packet definition

The JANUS specification defines a flexible, nested bit allocation scheme under which digital packets can be composed. A baseline JANUS Packet consists of 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. The initial JANUS specification defines a very sparse table of bit allocations for these fields, which is intended to be populated as the standard evolves and gets revised.

Additionally, a JANUS baseline packet can be complemented by a cargo section of arbitrary length.

E. Community engagement

JANUS was built on community consensus and its strength resides precisely in that community engagement. The fact that up to today there is no single adopted underwater digital communications standard is a testimony to the fact that consensus is not easy to reach. There are no technical limitations to the establishment on an underwater digital communications standard but the barriers can be immense if the different interests and requirements are not, at least, analysed and brought to the table for discussion. The first JANUS community workshop was held back 2008 and paved the way for the first implementation of JANUS. Subsequent meetings, joint sea trials and public discussions contributed to current evolution of JANUS and will surely continue to shape the future of the standard beyond initial promulgation. The UComms conference [12] has provided a wide and open discussion forum regarding JANUS-related issues since its first edition in 2012. In the third UComms edition (September 2016) a session dedicated to interoperability and standards was populated with 3 JANUS-specific manuscripts [8], [9], [10] with respective presentations and discussion.

III. Applications and JANUS-based capabilities

In the last couple of years, through the exploration of close connections with the operational community, CMRE has been able to exercise JANUS not only from a scientific perspective but also that of real end-users and operators in the field. JANUS-based services of relevance for the operational community, for example, are the so called "Underwater AIS" and the "Underwater METOC" services. These capabilities were developed and implemented with the support of the Portuguese Navy and their submarine squadron. Prototype hardware for JANUS transmission and reception was installed onboard the NRP Arpão, a state-of-the-art diesel-electric submarine during the REP16-Atlantic experiment that took place in Portuguese waters in July 2016. These 2 capabilities consist in delivering to a submerged submarine vital information to guarantee mission safety. Such information is usually not available unless the vessel navigates at periscope depth and becomes radio-capable. These transmissions from a buoy or other available asset (can be a surface ship) are depicted in Fig. 2 can be configured to be pre-scheduled, periodic or triggered depending on the mission profile of the submarine, in order to maintain its covertness when needed.

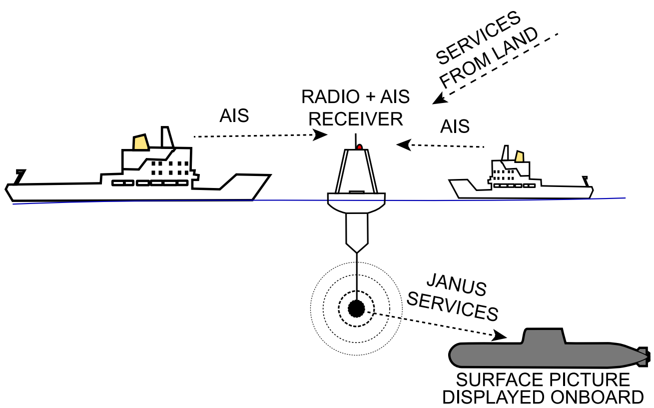

Fig. 2: JANUS-based services, delivered to underwater assets (manned or unmanned)

While, in technological terms, there has been nothing stopping such kind of developments and added capabilities to happen in the last couple of decades, being able to offer such a capability based on a consensus solution that is a prospect standard is a potential game changer.

A. Underwater AIS service

The Automatic Identification System (AIS) is a status-reporting service used to broadcast identification and localisation information to nearby vessels. It is mandatory for vessels above 300 tons and all passenger ships, and is electively deployed by many smaller vessels. The recent (July 2016) UK Astute-class nuclear submarine collision with a merchant vessel in Gibraltar highlighted once again the risks associated with water space management (or lack thereof). In CMRE's interactions with the operational community, such capability has been regarded as being of high value. The idea of using JANUS to transmit the AIS picture to submarines navigating at depth had been proposed in [13] as a mechanism to reduce the probability of accidents between surface ships and submerged assets.

In 2015, during the REP15-Atlantic trials, CMRE experimented with different packet configurations, using proxy hardware [14]. In July 2016, during the REP16-Atlantic experiment, CMRE was providing live AIS updates via JANUS transmissions issued by a gateway buoy. This data was used to display in real-time the received AIS picture in the combat room of the submarine.

B. Underwater METOC service

Another capability of extreme value for the planning and execution of maritime operations is the availability of updated military meteorological and oceanographic (METOC) data. During the REP16-Atlantic trials CMRE delivered, via JANUS, live wind maps to the same submerged submarine. This was implemented in close cooperation with the hydrographic office of the Portuguese Navy that currently provides (via radio waves) such information to support the operations of their assets around the world. Such matrices of wind speed and direction as shown in Fig. 3 are encoded in a total of 53 bytes, suitable for a JANUS cargo transmission. The packets were assembled and sent acoustically via JANUS between 2 deployed gateway buoys. This information was also decoded live onboard the submarine but no visualiser was added to the data chain for this proof-of-concept.

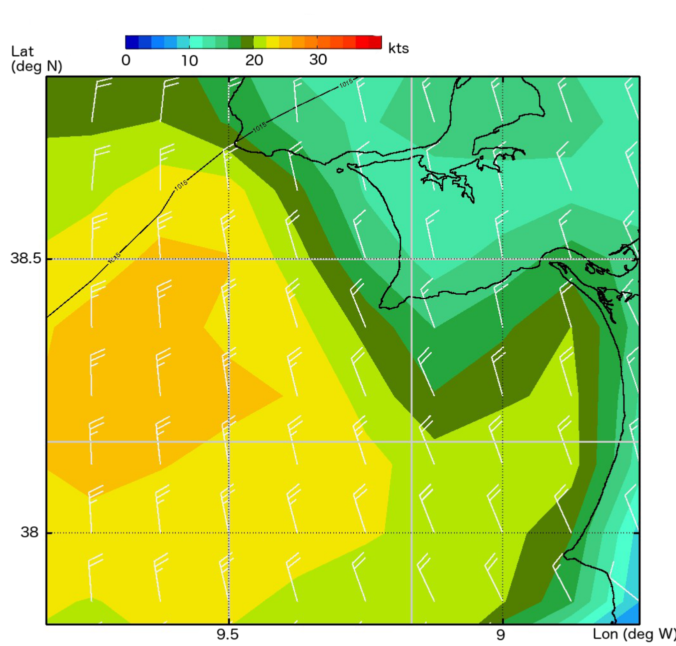

Fig. 3: Example wind map transmitted acoustically, via JANUS, during the REP16-Atlantic experiment

C. Support in distressed submarine operations

The prospect of employing JANUS for submarine search and rescue operations is a very attractive one. Currently, the doctrine of communications for search and rescue relies on the analogue underwater telephone and the usage of the phonetic codes *alpha* to *zulu*. This 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. Stress and language phonetic biases may also play a role in the success of the data exchange. By employing JANUS for search and rescue communications, the operator requirement may be removed with semi-automated systems transmitting critical data, and the confounding human factors may be removed altogether. As shown in [8] such operator-dependent factors play an important role in the ability to properly decode analogue underwater telephone communications.

During REP16-Atlantic one of the exercised scenarios was the one where a distressed situation is declared onboard a submarine and periodic packets with vital data are sent out via JANUS without the need for an operator. The data sent in a JANUS packet consisted of Latitude, Longitude, Depth, O_2, CO_2, CO, H_2, Pressure, Temperature and Number of survivors. The definition of such packet was iterated with the submarine Commanding Officer to guarantee maximum relevance. During the experiment, a live feed with all these data arrived in the control room installed onboard the research vessel NRV Alliance. The JANUS packet sent by the submarine was decoded on a deployed gateway buoy and then relayed via radio, following the inverse path of that shown in Fig. 2. For this proof-of-concept demonstration the data was artificially generated as there was no link present or necessary between the combat system and the JANUS equipment.

IV. Moving JANUS forward

The path to interoperability doesn't end in the promulgation of JANUS as an accepted standard. The promulgation of JANUS is a first step in demonstrating both the technical and organisational possibility of defining a real roadmap for underwater communications standards. In order to fully support JANUS and contribute to its future, the community of interest must continue its work and collaborate, and critically, engage in JANUS adoption.

Below we describe some candidate potential evolutions that may be proposed in future extensions of the standard.

A. JANUS fast modes

In the terrestrial domain, the ubiquitous IEEE 802.11 standard (our common WiFi) has been amended over time to support more Modulation schemes, coding schemes and spatial streams (for MIMO implementations) while maintaining backward compatibility with MAC and PHY layer protection mechanisms. This could be a possible way forward for JANUS with revisions to the standard including (standardised implementations of) more advanced modulation and coding schemes. The simplest way could be to define a table of such available schemes (as per revision n of JANUS) and have the application types include an index that specifies which is the MCS of the cargo packet, as depicted in Fig. 4.

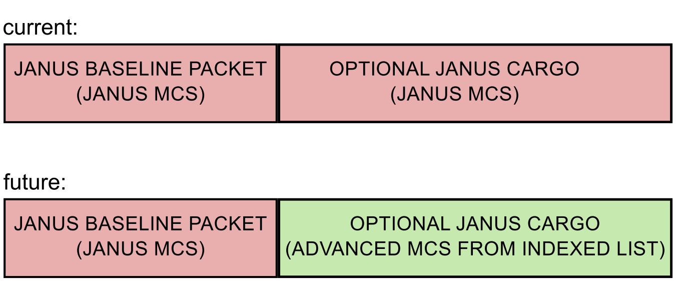

Fig. 4: Employing advanced MCSs in JANUS

CMRE has been testing candidate modulation and coding schemes at sea through different channels [15]. The modulations tested include 2, 4 and 8-PSK with different codes and bit rates varying form 2000 to 12000 bps.

B. Additional frequency bands

As described above, the JANUS waveform is fully scalable with all implementation parameters depending solely on centre frequency and bandwidth. For the initial JANUS specification a frequency band between 9400 to13600 Hz was established. Additional frequency bands will be adopted in future revisions of the standard. The definition of such new frequency bands was one of the key points of the mandate of a NATO Industrial Advisory Group (NIAG) created in May 2014. This study group recommended the adoption of the following bands: 5-7 kHz; 40-50 kHz and 50-70 kHz. These are likely to be the first ones to be considered for future adoption. Though the 20-30 kHz band was not mentioned in the study, it may also be an important extension in the future versions of JANUS as this is the regime where much existing acoustic hardware operates, typically in small AUV applications.

C. Security

Security in JANUS is supposed to be implemented from a low probability of exploitation (LPE) perspective. Since JANUS is not intended to implement covert underwater communications (*e.g.* low probably of detection, LPD), the different application types may or may not specify security mechanisms like encryption to protect the data being passed. For the time being, such mechanisms are viewed as upper-layer protocols that make use of JANUS like any other upper-layer protocol.

D. Standardising the language switching mechanism

The above mentioned concept of use of JANUS as the *lingua franca* of UW communications still requires one fundamental step to be fully realised: The discovery and language switching procedure needs to be standardised also. Different methods have been explored and reported, namely in [14] and [9]. This will certainly be one of the key aspects to settle upon promulgation of JANUS.

E. Establishing ID assignment mechanisms

Another case where standardisation is required for full interoperability is the allocation of addresses or IDs in a local underwater network. While in local applications with controlled assets this may not be an issue and IDs will simply be assigned statically, more evolved scenarios where teams of assets may join / leave a network at any given time will require a different approach. A recently published document, [16] proposes a fully distributed ID assignment mechanism that could be used in support of true ad hoc, interoperable JANUS communications.

F. Other applications and populating the User Class and Application Type fields

When imagining a world where JANUS is adopted and used in oceanographic buoys for underwater to surface (and vice versa) communications interface, one can't help to immediately think about bringing the above mentioned distresses submarine application one step further and apply it to aeroplanes to help in case of accident. The current black box devices equipping commercial airplanes include a "pinger" operating at 37.5 kHz. The French Bureau d'Enquêtes et d'Analyses pour la Sécurité de l'Aviation Civile (BEA) recently recommended the use of a lower frequency (8.5-9.5 kHz) for increased range. This could be a natural application for JANUS, employed to be used as a pinger and send some key information (*e.g.* depth from an integrated depth cell - in many cases enough to limit the search area) that could help making the search more efficient. An existing infrastructure supported on a widely used standard, would surely increase the chances of success.

Other applications can include JANUS beacons in submerged structures to provide obstacle signalling and navigation aids for underwater assets. The definition of new applications will be reflected by populating the User Class and Application Type fields in the standard specification.

G. Going beyond STANAG status

One of the ideas that has been ventilated in the past is the one of bringing JANUS outside of the STANAG realm and into a wider audience and propose it to be an IEEE standard. Given the open nature of JANUS, that could indeed be an attractive way forward, especially thinking in enlarging the community base that can have access to custodian activities. The first times of JANUS as a promulgated standard will surely help clarify to what extent that is desirable and even required.

V. What lies ahead

While in human-friendly environments the communication infrastructure required for machine interaction is inherited, in the underwater domain the reality is quite different. For its properties, acoustic signals have been the method of choice to implement underwater communications. The relatively small market for underwater communication systems (when compared to the mass consumption business of terrestrial communications) has so far been too small to trigger the creation of regulatory authorities. This has resulted in a void in standardisation and consequent lack of interoperability. As a NATO research institute that serves as a catalyst in a mixed environment of industry and academia, The Centre for Maritime Research and Experimentation is aware of this need and has been championing the effort of promoting standards for acoustic communications. JANUS provides a valuable first step towards communications and networking interoperability.

Through an inclusive approach, CMRE – with the help of industry, academia and governmental entities – managed to develop, test, validate and promote what we hope will be the first-ever widely adopted digital underwater communications standard. While breaking this interoperability barrier is a noteworthy achievement, a standard is only relevant if it is actually adopted. In the unique underwater domain, besides all the specific challenges, there are regulations neither for spectrum management nor interoperability. Adoption cannot be enforced nor controlled. For that reason, it is fundamental that a broad involvement of industry and academia is achieved so that interoperability in the underwater communications domain becomes a reality.

One of the key aspects is certification and compliance. The NIAG study mentioned in Section IV-B proposed a hybrid scheme of self-certification where vendors will check their implementations against test vectors to be provided by CMRE with varying levels of compliance depending on the performance obtained against such test vectors. In specific cases of equipment being used in rescue operations the suggestion is to request certification by an independent body to be identified (that could also be CMRE). This will surely be one area requiring clear definitions as JANUS moves forward.

Another point to be taken is how to define custodian activities that can continue beyond the NATO Nations, in the interest of a widely adopted standard. JANUS was built from its community of interest and it should remain as inclusive as possible.

A close interaction with the European Defence Agency (EDA) consortium behind the RACUN and SALSA projects will surely continue. Joining efforts towards the best and most interoperable future for underwater communications is without a doubt in the agenda of CMRE, NATO and EDA.

Lastly it may be important to underline that JANUS was never intended to replace existing industrial or even academic efforts. The fact that there is no "one-fits-all" solution to solve the underwater communications problem opens the door for multiple approaches that can and should be employed whenever best suited. JANUS could be the facilitator that provides the interoperability that is becoming a stringent requirement as the number of assets being deployed underwater increases and their concept of operation become more and more communications-dependent.

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