SCIENCE AND TECHNOLOGY ORGANIZATION

CENTRE FOR MARITIME RESEARCH AND EXPERIMENTATION

Reprint Series **CMRE-PR-2019-114**

Underwater communications research and development at CMRE

João Alves, Kevin LePage, Piero Guerrini, John Potter, Giovanni Zappa, Andrea Munafò, Thomas Furfaro, Arjan Vermeij

June 2019

Originally published in:

Proceedings of the OCEANS 2015 MTS/IEEE Conference, 18-21 May 2015, Genoa, Italy, doi: 10.1109/OCEANS-Genova.2015.7271685

About CMRE

The Centre for Maritime Research and Experimentation (CMRE) is a world-class NATO scientific research and experimentation facility located in La Spezia, Italy.

The CMRE was established by the North Atlantic Council on 1 July 2012 as part of the NATO Science & Technology Organization. The CMRE and its predecessors have served NATO for over 50 years as the SACLANT Anti-Submarine Warfare Centre, SACLANT Undersea Research Centre, NATO Undersea Research Centre (NURC) and now as part of the Science & Technology Organization.

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.

CMRE conducts hands-on scientific and engineering research for the direct benefit of its NATO Customers. It operates two research vessels that enable science and technology solutions to be explored and exploited at sea. The largest of these vessels, the NRV Alliance, is a global class vessel that is acoustically extremely quiet.

CMRE is a leading example of enabling nations to work more effectively and efficiently together by prioritizing national needs, focusing on research and technology challenges, both in and out of the maritime environment, through the collective Power of its world-class scientists, engineers, and specialized laboratories in collaboration with the many partners in and out of the scientific domain.

NOTE: The CMRE Reprint series reprints papers and articles published by CMRE authors in the open literature as an effort to widely disseminate CMRE products. Users are encouraged to cite the original article where possible.

Underwater Communications Research and Development at CMRE

João Alves, Kevin LePage, Piero Guerrini, John Potter, Giovanni Zappa,
Thomas Furfaro, Andrea Munafó and Arjan Vermeij
NATO STO Centre for Maritime Research and Experimentation
Viale S. Bartolomeo 400, 19126 La Spezia, Italy
email: {joao.alves,kevin.lepage,piero.guerrini,john.potter,giovanni.zappa,
thomas.furfaro,andrea.munafo,arjan.vermeij}@cmre.nato.int

***Abstract*—A key to developing autonomous maritime systems for NATO is communication among data gathering platforms below and above the water. However, unlike the mature technologies that are used for terrestrial networks, underwater communications is still in an early stage. This paper provides an overview of CMRE's activities in the field of underwater communications where emphasis has been put in addressing the specific issues that may help accelerating the development of the state-of-the art. For its importance for NATO, interoperability is a key focus area for CMRE. Additionally, experimentation at sea and real-world data collection also play a crucial role as they represent the only viable means for science and technology validation.**

I. Introduction

The underwater (UW) world offers one of the most challenging media for wireless communications. Oceans are a key support system for life on our planet and despite the many impairments besetting UW communications, networking and systems, the development of effective technologies for sensing, monitoring and for controlling the UW world must be a priority.

The interest in UW communications has grown considerably in the last few decades as the ability to deploy assets at the sea with increased levels of autonomy has motivated the requirement to use them cooperatively. As Autonomous Underwater Vehicle (AUV) technology has matured, interest in using teams of such vehicles has emerged as a powerful paradigm. It has therefore become clear that sub-sea communications plays a critical enabling role for the marine technology community.

It's, however, important also to underline that a communication system *per se* makes little or no sense at all. The application and its environment dictate the requirements and drive the design. In our particular case, operators, roboticists, artificial intelligence scientists and system integrators among others play an important role in defining the directions for future developments that will hopefully bring additional capabilities and improved ways to explore the seas.

This document presents a summary view of the technical aspects, challenges and the future of UW communications under the light of CMRE's approach to the topic. In Section II we motivate the existence of this activity in CMRE, present the high-level challenges that actively drive the work and list some of the relevant activities. Section III specifically addresses the topic of standards and interoperability while section IV focuses on one of CMRE's flagship capabilities: at sea experimentation. Section V covers the topic of external engagements and the paper finalises with a view on future topics (Section VI) and conclusions.

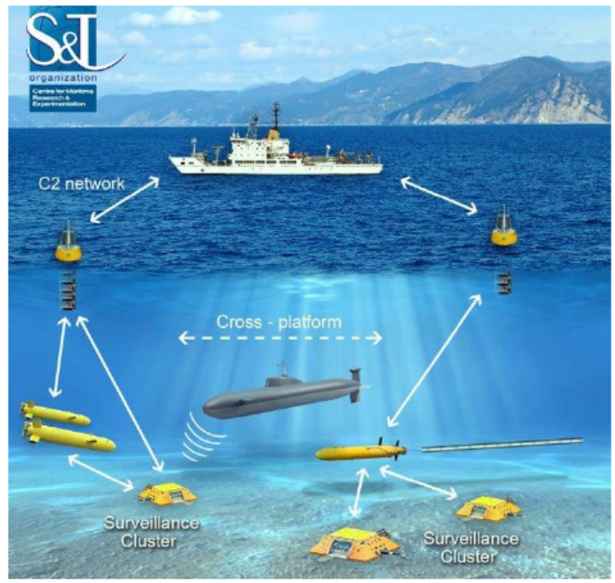

Fig. 1. Generic heterogeneous UW communications concept comprising manned and unmanned, static and mobile platforms interconnecting the UW world with command and control networks

II. Challenges and Technical Developments

UW communications is a key enabling capability to achieve sub-surface autonomous robotic collaboration and distributed sensing. The topic is deceptively broad in terms of required expertise and one that cannot afford to spare any efforts given the tough challenges posed by the medium. A future of seamless connectivity may not be near but important steps are being taken towards interoperability, system optimisation and persistent maritime presence.

UW communications research and development at CMRE is an activity born from the applications requirement of exploring the use of distributed autonomous systems in maritime surveillance scenarios.

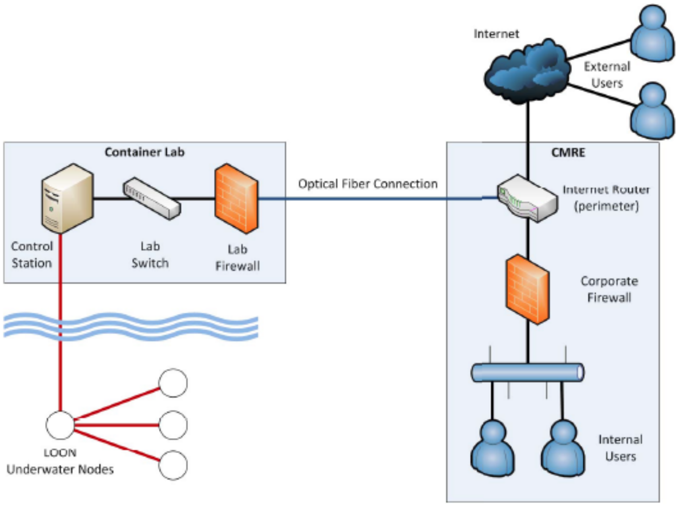

Fig. 2. The LOON concept diagram

Fig. 3. One of the LOON tripods during deployment

Several CMRE applications call for some degree of UW communications support as an enabler for advanced distributed autonomy solutions. The cooperative anti-submarine warfare (CASW) scenarios typically employ a small scale network spread over a wide area while for the autonomous naval mine countermeasures (ANMCM) programme the ranges tend to be shorter but with requirements to transfer images. Other applications like maritime security may explore multi-domain vehicles for extended persistence.

Figure 1 offers an overview vignette of an heterogeneous UW network, potentially comprising different clusters of manned, unmanned, static and mobile assets interfaced through command and control (C2) networks. The simplicity of the graphic, however, hides the magnitude of the undertaking.

Looking at some at the focal challenges currently faced by the UW communications community (developers and users), one can enumerate:

- **Physical layer signal processing:**
  Introduction of further enhancements and adoption of more aggressive modulation schemes may increase channel capacity.
- **Interoperability is nonexistent:**
  The relatively limited market for UW communication systems has so far been too small to trigger the creation of regulatory authorities or to generate the required critical mass to make a de-facto standard emerge. This has resulted in a void in standardisation and consequent lack of interoperability.
- **Typical software architectures fall short on providing cross-layer information:**
  The strict separation of typical communication implementations between physical layer, medium access layer, networking layer, etc. becomes excessively rigid when it comes to designing networking systems for the UW environment, characterised by a time-varying bandwidth limited channel that is severely impacted by conditions and subject to frequent disruptions. All available information at the different processing layers must be exchanged and used for joint protocol optimisations.
- **There is no single adopted way to simulate the acoustic channel:**
  Community consensus is nonexistent which means that different protocol solutions can't be tested and benchmarked in a standardised way for fair comparison, contributing to some degree of assessment bias.
- **Experimenting at sea is expensive:**
  Sea trials represent high costs in equipment, personnel and risks. Moreover such experiments are difficult to control and often impossible to replicate due to the high environment dependence.

Approaching such challenges is something that can hardly be done single handedly and indeed some environments may offer fertile grounds for specific breakthroughs. For example, physical layer developments are likely to emerge from the academia while interoperability is typically addressed at the industrial and multi-national level.

While CMRE's approach is without a doubt an holistic one, isolated aspects began to be investigated since 2008. Since then, CMRE has studied different aspects of the UW communications "puzzle". JANUS [1] [14] [5] [23] has been CMRE's first endeavour in this field addressing the problem of physical layer interoperability (more on this topic in Section III). From 2010 the work on the networking aspects of UW communications started. Medium Access Control evaluation was performed in simulation and at sea and is reported in [21]. Following the definition of a Delay and Disruption Tolerant (DTN) protocol [10] that attempts to deal with challenged environments (originally envisioned for space communications), an UW, lightweight version of DTN was successfully developed, implemented and tested at sea [16]. An UW routing scheme adapted to medium scale (10 to 20 nodes) deployments and well suited for the impairments of UW

Fig. 4. The NRV Alliance (top) and the CRV Leonardo (bottom) have been employed in UW communications experiments

communications has been developed and implemented [6] [7]. Localisation techniques based on UW networking operation have been explored [12] [11] [19] [24] and autonomous Long BaseLine constellation adaptation [18] implemented in recent sea trials. Through-the-water clock synchronisation services have also been embedded in the communications / localisation architecture [26].

III. Standards

For an organisation like NATO that relies on the collective strength of an alliance of 28 nations, interoperability is absolutely paramount. The relatively small market for UW 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, CMRE is in a privileged position to help promote interoperability in a field where it has been, up until now, absolutely nonexistent. Since 2008, CMRE has been developing and promoting JANUS. JANUS is a physical layer coding open-source and freely distributed under the GNU General Public License version 3. The two primary purposes for JANUS are to announce the presence of a node and to establish the initial contact between dissimilar nodes, establishing this way an UW “lingua franca”. Each JANUS packet includes a header of 64 bits (of which 34 bits may be user-defined according to their application) containing all the information to read and decode the message. In addition “cargo data” may be be appended to the header to carry extra information. A Frequency-Hopped Binary Frequency Shift Keying (FH-BFSK) modulation scheme has been selected for its known robustness in the harsh UW acoustic propagation environment and simplicity of implementation. Following the standard design, the frequency band allocation is 9440-13600 Hz and 11520 Hz is the central frequency. The chip-rate duration is 6.25 milliseconds with a nominal user bit rate of 80 bps after coding. Simplicity of implementation was one of the main design drives behind JANUS, targeting easy adoption by current hardware manufacturers.

As of April 2015 CMRE has made significant strides towards having JANUS adopted as a NATO standard. A draft STANAG has been submitted to the NATO Standardization Office to secure national ratification. If adopted JANUS will be the first UW digital communications standard for interoperability representing a significant contribution by CMRE to NATO networked enabled capability for the UW domain.

While one might be tempted to look at the interoperability problem purely from a physical layer perspective, there is an equally rich problem to be addressed: The one of establishing a common structure where communication protocols from the different layers, potentially developed by different interested parties, can be plugged to create a software-defined communication architecture. The current paradigm shift being observed in maritime robotics (increased number of autonomous assets and introduction of cooperation and teamwork between them) calls for re-configurable and re-usable solutions. Automatic adaptation to environmental conditions is a key feature to extract the maximum performance allowed by the channel at any time. In the specific case of the UW channel, cross-layer information (not available in typical software stacks) may be key to this optimisation. The current UW communications market is exclusively hardware-based. The lack of interoperability gives rise to bespoke solutions tailored to specific needs and typically lacking flexibility. The introduction of software-defined communications may open the door to a different approach: Manufacturers will be able to divide their business streams in hardware and software without the need to couple them tightly. Open architectures can support licensed solutions that keep key technological providers in business while users may tailor their system by software, instead of hardware.

CMRE has proposed a Software-Defined Open Architecture Modem (SDOAM) [22] that consists of an OSI-like stack, but with two important new features. Each layer of the traditional OSI stack is to be replaced by a wrapper, within which there are several modules, of equivalent function but that encode the various “languages” used in modems, presided over by a Policy Engine at each level that ensures a coherent choice of modules across all layers and consistency with application requirements. CMRE’s intention with the SDOAM proposal is to reach out over an extended network of international interests, spanning research organisations, commercial manufacturers and users and catalyse consensus towards developing and adopting useful standards that serve the maritime community. The aspiration is that these developments may lead from an Software Defined Radio-like architecture to a cognitive one.

IV. Experimentation

One of the undoubtable strengths of CMRE is the sea-going capability. Scientists and engineers conduct sea trials regularly as a means for testing equipment, validating new techniques and gathering data.

A. *Ship-based trials*

The experimental activities of CMRE are largely supported by the research Vessels CRV Leonardo and NRV Alliance, depicted in Fig. 4.

The NRV Alliance is a specially designed vessel, built for the purpose of conducting UW research and experimentation. The NRV Alliance is 93 meters long, offers 400 square meters of enclosed lab space and accommodates up to 25 scientists and engineers plus crew. The vessel is comprehensively equipped with a suite of deck handling A frames, multi-purpose winches, cranes and workboats as well as with extensive laboratory and working deck space. The CRV Leonardo on the other hand is the smallest research vessel in the world that is fitted with dynamic positioning and substantial deck handling equipment. The Leonardo is 28 meters long and can accommodate up to 10 people for multi-day cruises. For day-only cruises, the ship can handle up to 15 people.

These two vessel have given support to UW communications experiments at CMRE regularly since 2008. Periodically (typically every year), a major ship-based sea trial is conducted in support of CMRE's UW communications project. Since 2008 the main experimental activities have been CCLNet08, Glint08, SubNet09, Glint10, ACommsNet10, CommsNet12, CommsNet13 and REP14-Atlantic. These major sea-trials always were conducted with significant participation with external collaborators from academia and/or industry. The data sets acquired during those experiments have been used to test the feasibility of new concepts and to evaluate the performance of new solutions.

During REP14-Atlantic, CMRE expanded its spectrum of collaborators in the UW communications domain to the Portuguese Navy. The REP14-Atlantic trials [2] were jointly organised by CMRE, the Faculty of Engineering of the University of Porto (FEUP) and the Portuguese Navy. During this activity CMRE focused its efforts in JANUS experimentation, networking protocols testing and tests of new network-based services for AUVs.

Other activities carried out during REP14-Atlantic included further testing of networking protocols like the one in [7], evaluation of UW localisation techniques including dynamically relocatable Long BaseLine (LBL) beacons to support survey operations [18] and multi-domain communications testing with real-time bi-directional data exchanges between an AUV and an Unmanned Aerial Vehicle (UAV) using a Waveglider as a gateway device.

Figures 5,6 and 7 were taken during REP14-Atlantic and show some of the assets that were employed in the experiments.

Fig. 5. The NRP Arpão (left) and the NRV Alliance (right) during the REP14-Atlantic joint experiments on JANUS interoperability

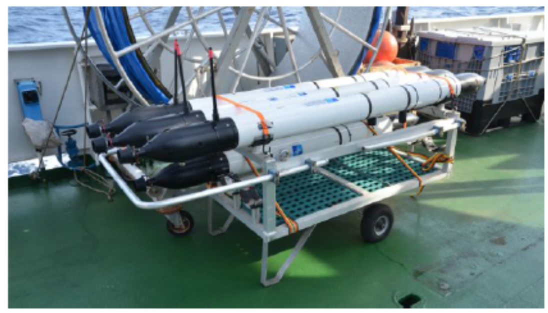

Fig. 6. The eFolaga hybrid vehicles used for UW communications development

Fig. 7. The LRI Waveglider vehicle was modified by CMRE to have a "backseat" driving computer. It is currently used as a mobile, self-relocatable gateway.

B. The Littoral Ocean Observatory Network

Back in 2009 CMRE (then NURC) identified the need to be able to take prototype communication schemes to sea with less cost and effort than is involved in traditional sea trials. CMRE developed a physical testbed, known as the Littoral Ocean Observatory Network (LOON) [4], [3], which consists of a set of small platforms that rest on the sea bed, each equipped with a variety of communication devices and linked to each other and the shore vie fibre optic cable. Most importantly, the LOON is connected (through a firewall and security measures) to the internet, where it can be directly accessed by authorised collaborators from their desks across the world. This dramatically lowers to cost of experimentation while still providing a real world scenario to test new communications technologies. This has provided the means to conduct long(er) term experiments, with equipment deployed in harbour or coastal areas, cabled to shore and interfaced to a control station connected to the internet. The main advantages of such a system are the reduction of the price per Megabyte of data acquired when compared to an experiment conducted from a research vessel, the longer time scales that are likely to be covered, the possibility to open the system for collaborators to run trials remotely and the increased flexibility to perform in situ system checks. The major drawbacks are the obvious logistic limitation of cabling and power that restrict the deployability of the system

Figure 2 presents a high level diagram of the LOON while Fig. 3 shows the detail of one of the tripods, equipped with UW communications equipment during deployment in 2011 for the AcommsNet11 trial.

V. External engagement

By its nature CMRE is naturally well positioned to working directly with academia, industry and national labs from NATO nations.

In 2009 CMRE established a strong link with the UW Acoustic Networks (UAN) project [9] funded by the EU. This led to joint experimental activities in 2010 that highly benefited from the co-location of personnel and assets for de-risking and further exploration of common interests.

Other stong ties were created with the academia during the past 5 years (Uni. Porto, Uni. Padova, Uni. Rome - La Sapienza, Uni. Pisa, ISME, Uni. Florence). These created a fruitful environment for development and experimentation of new solutions at sea.

In 2012 the UW communications team of CMRE started the participation in the MORPH project funded by the European Commission's (EC) seventh framework programme. MORPH [13] advances the novel concept of an UW robotic system composed of a number of spatially separated mobile robot-modules, carrying distinct and yet complementary resources. Instead of being physically coupled, the modules are connected via virtual links that rely on the flow of information among them, i.e. inter-module interactions are allowed by UW communication networks at distant and close ranges and supported by visual perception at very close range. The MORPH supra-vehicle (MSV) is thus in sharp contrast to classical monolithic vehicles or even cooperative groups of marine vehicles that operate safely away from each other. Without rigid links, the MSV can reconfigure itself and adapt in response to the shape of the terrain. This capability provides the foundation for efficient methods to map the UW environment with great accuracy especially in situations that defy existing technology: namely, UW surveys over rugged terrain and structures with full 3D complexity. CMRE contributes to this project with the UW communications network, based on commercial-off-the-shelf modems with a custom software layer that provides the networking and node localisation functionalities.

Late in 2013, CMRE engaged in another EC funded project - SUNRISE - this time with UW communications as the main research topic. SUNRISE [20] stands for Sensing, monitoring and actuating on the UW world through a federated Research Infrastructure Extending the Future Internet. CMRE is part of the consortium of partners which work together to develop a federation of UW testing infrastructures for marine and ocean monitoring, exploitation and control. The SUNRISE concept stems from the experience of existing European UW testbeds operating at the partner sites, and especially from the experience of the LOON permanent installation mentioned above. Five versions of the LOON throughout Europe and the USA are scheduled to be deployed and federated within the SUNRISE project. SUNRISE integrates physical systems with software development aiming at creating the Internet of UW Things. It is the first project that develops this concept, based on joint research performed in this direction by the consortium partners, in the last few years.

Additionally, CMRE has been organising the UW Communications and Networking conference (UComms) since 2012 (2 editions so far). This conference aims to bring together key people in UW communications networking to review the state-of-the-art and share understanding of performance constraints and trade-offs with a view to catalysing consensus on standards for interoperability. The conference has enjoyed great success, naturally granted by the quality of the participants. The 2016 edition is currently being prepared.

VI. Moving forward

A field where CMRE is particularly well positioned to provide a unique contribution is the one of standardisation. While the discussion between what is to be standardised and open *versus* what should be kept for a limited audience goes beyond the scope of this communication, it's important to state that open and restricted are not two "orthogonal spaces" of the communications domain. Standardisation has the potential to offer interoperability and promote co-existence of open and restricted systems and can offer the foundation for secure UW networks from a perspective of low probabilities of interception, detection and exploitation (LPI/LPD/LPE). Standardisation needs to be supported through adequate custodian programs for the developed standards. For this, involvement of all stakeholders is crucial.

Other areas CMRE will explore (or continue exploring) are listed below:

A. Physical layer

The physical layer will always be the foundation of the communications system and, in case of acoustic communications, its main bottleneck. Advanced signal processing techniques and "smart" receivers will play a key role in increasing channel capacity. Future extensions of JANUS may include advanced modulation schemes to support high(er) bandwidth communication.

Parallel physical layer advances will include additional modalities, like optical or electromagnetic. Optical communications, in particular, offer powerful, complementary attributes of shorter ranges but very high throughput. Additionally, typical characteristics of optical systems (potential compact size and low power consumption) are well aligned with the requirements of some applications, namely the ones that specify short distances between nodes. The currently immature state of the optical-based UW networking solutions offer interesting ground for evolution. An obvious solution, fitting the current SDOAM paradigm is the development of hybrid intelligent systems capable of routing certain streams of data through different modalities depending on the environmental conditions for each channel, individual stream requirements and energy budget. Within the EC project MORPH, CMRE has started to address multi-modality for sub-surface communications. While multi-modality is currently already supported in CMRE's Software-Defined architecture implementation ([22],[25]) with automatic radio / acoustic modem switching, new smart switching algorithms (policy engines in SDOAM nomenclature) will need to be developed to achieve true hybrid UW systems.

B. Networking

Continued investigation on networking protocols is foreseen, from layer 2 MAC schemes to higher level routing and transport protocols. CMRE is particularly interested in side-by-side protocol comparisons under application-relevant conditions. The availability of test beds like the LOON allows enables long term data collection of channel characteristics that can be converted into traces for channel replay [8].

C. Security

Security for UW communications will be tackled both from a physical and networking perspective. The implementation of unmanned UW wireless networks raises a myriad of interesting and challenging problems: With the objective of securing the data (potentially sensitive) being gathered by the unmanned platform different layers of protection will need to be put in place depending on the application requirements: in terms of LPD/LPI/LPE. Since the application of cryptography tends to increase message size [15], one must balance carefully the threat risk against the performance degradation imposed by the additional overhead. Integrity of communications in critical operations, protection against denial-of-service attacks, detection of malicious behaviours through trust and reputation models [17] and identification of compromised nodes are also areas of interest for CMRE.

D. Network-enabled services

Network-enabled services are an integral and important part of an autonomous system. CMRE has been working on localisation and clock synchronisation schemes that are embedded in the communication operation. Currently such modes of operation are tightly integrated additional envisioned network-enabled services include a communications analytics module that aggregates all available communications events and makes that information available for protocol adaptation and neighbourhood confidence models for network-based security.

E. System co-design and integrated simulations

A valuable lesson learnt during the last few years of UW communications at CMRE is that current AUV technology is still not fully compatible with UW networking. It's common to come across vehicles that are simply too noisy (from both an acoustic and electromagnetic perspective) to be effective in scenarios where they need to rely permanently on UW communications. Some critical components are the power drivers of the thrusters, the actuators or fins and the propellers. System co-design means that not only the communication system must be designed for a specific application and vehicle but also the vehicle design needs accommodate the communication system. Additionally, mission simulations must include full acoustic and electromagnetic profiles of the AUVs so that realistic performance assessments can be made before employing the vehicles in the real application. Such profiles must include radiated noise at different propeller regimes, flow noise at different speeds and the communication system mapping function, *i.e.* how those values impair the ability to communicate.

Cross-domain integration is also likely to become a reality and a push for interoperability. Combined UW, surface and aerial presence has the potential to augment the maritime picture and offer higher quality real-time and offline products. It has also the obvious potential advantage of bringing a part of the UW scenario up to the surface world where a less demanding channel can be explored.

VII. Conclusions

Due to its position as a hub and catalyst of scientific development for 28 nations the CMRE can be seen as a small model of a near future where wide spread academic and industrial cooperation and collaboration is key to the rational use of resources. The UW communications domain is currently shifting its focus from the purely technical challenges of developing effective digital coding schemes to the much broader domain of systems architecture and implementation that supports intelligent adaptive ad-hoc networking and connectivity with above surface systems. The current global economic struggles are underlining the need to promote multi-use technologies and system interoperability and expandability. Standards are essential not only to achieve such goals but also play an important role in obsolescence management and replacement of parts or software blocks. The current UW communications market is exclusively hardware-based. The lack of interoperability gives rise to bespoke solutions tailored to specific needs and typically lacking flexibility. The introduction of software-defined communications may open the door to a different approach where manufacturers will be able to divide their business streams between hardware and software without the need to couple them tightly. Being that acoustic, optical and electromagnetic waves are affected differently by the aquatic medium, multi-modality systems will likely offer significant benefits for UW network throughput, robustness and connectiveity to above water networks. In a way there is a parallel with current handheld device use where we have our mobile systems automatically switching between WiFi, 3G and LTE depending on the specific signal conditions under conditional rules of stream assignment (*e.g.*) large volumes downloadable only via WiFi).

CMRE has been an active player in the UW communications domain and expects to continue its contributions and joint work with academia and industry contributing toward a future of seamless UW connectivity.

ACKNOWLEDGEMENT

The authors would like to thank all CMRE colleagues (present and past) that made all activities described in this document possible.

REFERENCES

[1] Janus wiki: http://www.januswiki.org. [Online]. Available: http://www.januswiki.org

[2] J. Alves, J. Borges de Sousa, J. Pereira, M. Galocha, B. Pereira, and c. Loureno, "Experiments in multi-vehicle operations: the rapid environmental picture atlantic exercise 2014," in *MTS/IEEE OCEANS 2015*, May 2015.

[3] J. Alves, J. Potter, P. Guerrini, G. Zappa, and K. LePage, "The LOON in 2014: Test bed description," in *IEEE OES Underwater Communications Networking Conference, UCOMMS 2014*, September 2014.

[4] J. Alves, J. Potter, G. Zappa, P. Guerrini, and R. Been, "A testbed for collaborative development of underwater communications and networking," in *Military Communications Conference, 2012 - MILCOM 2012*, Oct 2012, pp. 1–8.

[5] J. Alves, A. Vermeij, D. Hughes, and G. Zappa, "Software-defined JANUS communication support for AUVs," in *Proceedings of the fourth International Conference and Exhibition on Underwater Acoustic measurements: Technologies and Results*, 2011.

[6] J. Alves and G. Zappa, "A low overhead message routing protocol for underwater acoustic networks," in *OCEANS, 2011 IEEE - Spain*, june 2011, pp. 1–10.

[7] J. Alves, R. Petroccia, and J. R. Potter, "MPR: Multi-Point Relay protocol for Underwater Acoustic Networks," in *Proceedings of the Nineth ACM International Conference on Underwater Networks and Systems*, ser. WUWNet '14, Rome, Italy, November 12–14 2014.

[8] S. Basagni, C. Petrioli, R. Petroccia, and D. Spaccini, "Channel replay-based performance evaluation of protocols for underwater routing," in *Proceedings of MTS/IEEE OCEANS 2014*, St. John's, Canada, September, 14–19 2014, pp. 1–7.

[9] A. Caiti, P. Felisberto, T. Husoy, S. Jesus, I. Karasalo, R. Massimelli, T. Reinen, and A. Silva, "Uan - underwater acoustic network," in *OCEANS, 2011 IEEE - Spain*, june 2011.

[10] K. Fall, "A delay-tolerant network architecture for challenged internets," in *Proceedings of the 2003 Conference on Applications, Technologies, Architectures, and Protocols for Computer Communications*, ser. SIGCOMM '03. New York, NY, USA: ACM, 2003, pp. 27–34. [Online]. Available: http://doi.acm.org/10.1145/863955.863960

[11] T. Furfaro and J. Alves, "An application of distributed long baseline node ranging in an underwater network," in *IEEE OES Underwater Communications Networking Conference, UCOMMS 2014*, September 2014.

[12] J. Gomes, E. Zamanizadeh, J. Bioucas-Dias, J. Alves, and T. Furfaro, "Building location awareness into acoustic communication links and networks through channel delay estimation," in *Proceedings of the 7th ACM International Conference on Underwater Networks and Systems.* Los Angeles, CA, USA: ACM, 2012.

[13] J. Kalwa, A. Pascoal, P. Ridao, A. Birk, M. Eichhorn, L. Brignone, M. Caccia, J. Alves, and R. Santos, "The european r&d-project morph: Marine robotic systems of self-organizing, logically linked physical nodes," in *9th IFAC Conference on Manoeuvring and Control of Marine Craft*, September 2012.

[14] K. McCoy, "JANUS: From primitive signal to orthodox networks," in *Underwater Acoustic Measurements: Technologies and Results, Nafplion, greece*, 2009.

[15] A. J. Menezes, S. A. Vanstone, and P. C. V. Oorschot, *Handbook of Applied Cryptography*, 1st ed. Boca Raton, FL, USA: CRC Press, Inc., 1996.

[16] D. Merani, A. Berni, J. Potter, and R. Martins, "An underwater convergence layer for disruption tolerant networking," in *Internet Communications (BCFIC Riga), 2011 Baltic Congress on Future*, feb. 2011, pp. 103–108.

[17] L. Mui, M. Mohtashemi, and A. Halberstadt, "A computational model of trust and reputation for e-businesses," in *Proceedings of the 35th Annual Hawaii International Conference on System Sciences (HICSS'02)-Volume 7 - Volume 7*, ser. HICSS '02. Washington, DC, USA: IEEE Computer Society, 2002, pp. 188–. [Online]. Available: http://dl.acm.org/citation.cfm?id=820745.821158

[18] A. Munafo, J. Sliwka, and J. Alves, "Dynamic placement of a constellation of surface buoys for enhanced underwater positioning," in *MTS/IEEE OCEANS 2015*, May 2015.

[19] A. Munafo, J. Sliwka, G. Ferri, A. Vermeij, R. Goldhahn, K. Lepage, J. Alves, and J. Potter, "Enhancing auv localization using underwater acoustic sensor networks: Results in long baseline navigation from the collab13 sea trial," in *Oceans - St. John's, 2014*, Sept 2014, pp. 1–7.

[20] C. Petrioli, J. Potter, and R. Petroccia, "Sunrise - sensing, monitoring and actuating on the underwater world through a federated research infrastructure extending the future internet," in *Proceedings of EMSO 2013*, Rome, Italy, November, 17 2013.

[21] C. Petrioli, R. Petroccia, and J. Potter, "Performance evaluation of underwater mac protocols: From simulation to at sea testing," in *Proceedings of the IEEE/OES Oceans Europe*, 2011.

[22] J. Potter, J. Alves, T. Furfaro, A. Vermeij, N. Jourden, G. Zappa, A. Berni, and D. Merani, "Software defined open architecture modem development at CMRE," in *IEEE OES Underwater Communications Networking Conference, UCOMMS 2014*, September 2014.

[23] J. Potter, J. Alves, D. Green, G. Zappa, I. Nissen, and K. McCoy, "The JANUS underwater communications standard," in *IEEE OES Underwater Communications Networking Conference, UCOMMS 2014*, September 2014.

[24] J. Sliwka, A. Munafo, G. Ferri, and J. Alves, "Interval methods based auv localization in the context of an acoustic network with experimental results," in *Oceans - St. John's, 2014*, Sept 2014, pp. 1–6.

[25] A. Vermeij, J. Alves, T. Furfaro, and G. Zappa, "CMREs software-defined communications architecture for the maritime domain," in *MTS/IEEE OCEANS 2015*, May 2015.

[26] A. Vermeij and A. Munafo, "Clock synchronisation in underwater acoustic networks," in *Underwater Communications and Networking (UComms), 2014*, Sept 2014, pp. 1–5.

Document Data Sheet

Security Classification		Project No.

Document Serial No.	Date of Issue	Total Pages
CMRE-PR-2019-114	June 2019	7 pp.

Author(s)

João Alves, Kevin LePage, Piero Guerrini, John Potter, Giovanni Zappa, Andrea Munafò, Thomas Furfaro, Arjan Vermeij

Title

Underwater communications research and development at CMRE

Abstract

A key to developing autonomous maritime systems for NATO is communication among data gathering platforms below and above the water. However, unlike the mature technologies that are used for terrestrial networks, underwater communications is still in an early stage. This paper provides an overview of CMRE's activities in the field of underwater communications where emphasis has been put in addressing the specific issues that may help accelerating the development of the state-of-the-art. For its importance for NATO, interoperability is a key focus area for CMRE. Additionally, experimentation at sea and real-world data collection also play a crucial role as they represent the only viable means for science and technology validation.

Keywords

Interoperability, standards, vehicles, physical layer, protocols, software, robot sensing systems

Issuing Organization

NATO Science and Technology Organization
Centre for Maritime Research and Experimentation

Viale San Bartolomeo 400, 19126 La Spezia, Italy

[From N. America:
STO CMRE
Unit 31318, Box 19, APO AE 09613-1318]

Tel: +39 0187 527 361
Fax:+39 0187 527 700

E-mail: library@cmre.nato.int