Cooperative Anti-Submarine Warfare at NURC
Moving Towards a Net-Centric Capability

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***Abstract* - The NATO Undersea Research Centre (NURC) conducts research on off-board Low Frequency Active (LFA) sensors for use in Cooperative distributed ASW (CASW). The objective is to create a scalable and autonomous system that removes vulnerable personnel from the vicinity of high risk, is cheaper than conventional ship-based sonar and that potentially leverages the benefits of multi-static operations by creating an increased diversity of assets and spatial distribution. Such systems would also release personnel to perform tasks elsewhere. The NURC intends to prototype an open-architecture system with a high degree of interoperability in a concept demonstration in 2012.**

I. Introduction

The quietening of submarines over the last three decades has made passive detection at any significant range increasingly difficult. An extensive R&D investment into Low Frequency Active Sonar (LFAS) was made by several nations in the early 1990s, but the highly advanced systems that were developed were never really put to the test following the fall of the Berlin wall and the end of the cold-war conflict.

Furthermore, in the late 90's, a shift in operational requirements resulted in re-focusing on small and quiet diesel-electric submarines operating in littoral waters. As a result, today's geopolitical situation requires coalition forces to operate in very difficult underwater acoustic environments with high false alarm rates against small, quiet adversaries. In addition, the number of platforms with ASW capabilities has reduced considerably within NATO [1]. It has therefore become necessary to combine the NATO nations' efforts in ASW in the most efficient way possible.

The move towards multistatic ASW [2] has naturally led to the need for protocols and techniques that allow the exchange of information between assets. In particular, there is a need to exchange detailed information of the perceived battlespace in terms of individual detections and target tracks in order to develop multistatic active sonar networks with surface assets communicating above the water. As we move from surface-asset-based multistatic sonar to its submerged distributed AUV-based variant, the necessary communications must also transition to an underwater acoustic physical layer. The move to underwater networked communications is therefore included in the present Cooperative ASW (CASW) R&T effort begun in 2008, allowing us to leverage the many lessons learned during earlier phases.

Figure 1. One of NURC's Ocean Explorer (OEX) Autonomous Underwater Vehicles (AUV) with a NURC towed array.

Frigate cost and availability are driving the need for off-board ASW sensors that are persistent, scalable and cheap. The CASW concept is based on distributed heterogeneous sensing: i.e. multistatic active sonar complemented with non-acoustic sensors [3]. Distribution of tracking results and C2 is achieved both via in-air data links and underwater acoustic communications networking. The CASW approach takes personnel out of harm's way and holds the promise to leverage the benefits of multi-static operations by creating an increased diversity of assets and spatial distribution.

The CASW 'open-architecture' framework[1] is also suitable for application in other maritime domains such as Autonomous Mine Counter Measures (AMCM) and Non-Lethal Port Protection (NLPP), both on Autonomous Underwater Vehicles (AUVs) and Unmanned Surface Vehicles (USVs), with a focus on interoperability and standards.

There is also a need to link to standard NATO command and control systems in order to augment the Common Operational Picture (COP). A candidate technology is NC3A's NIRIS[2].

There is currently no commercial solution available for CASW. It is therefore necessary to investigate technologies and tools in order to support the NATO Nations in developing

[1] http://oceanai.mit.edu/moosivp/home.html
[2] http://tide.act.nato.int/mediawiki/index.php/NIRIS

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(specifications for) an off-board Intelligence, Surveillance and Reconnaissance (ISR) capability.

The NURC CASW project is creating a prototype multistatic active system that uses multiple sound sources and receiver arrays. The sources can be ship-based, fixed or drifting. The receivers may also be deployed in various forms, but the current focus is on arrays towed by AUVs.

The data from the towed arrays is processed on-board the AUV so that relevant information can be shared with other assets in the distributed system. The processing is performed locally, on board each AUV, rather than at a central processing node both to improve robustness to single-point failure and in recognition of the severely limited bandwidth and link intermittency of underwater acoustic communications. This architecture requires the AUV to display a high degree of autonomous processing and intelligent adaptive behavior.

The CASW project rationale is implemented in the following structure:

- *Concepts for Littoral Undersea Surveillance;*
- *Communications and Networking in the Maritime Domain* and
- *Decision Support.*

The *Concepts for Littoral Undersea Surveillance* task is investigating sensing technologies, real-time processing on embedded systems and distributed intelligence with autonomy. Some aspects of this latter research area are covered in an accompanying paper [4]. In this paper, however, we will discuss options for ASW sensing and the NURC design. We shall explain how, by means of a combination of detailed simulation, incorporating hydrophone level time series and vehicle dynamics, we have been able to test both the real-time signal processing which has been developed for our vehicles as well as ASW-relevant autonomous behaviors. We discuss how the software and techniques developed have then been validated by at-sea experimentation and discuss lessons learned.

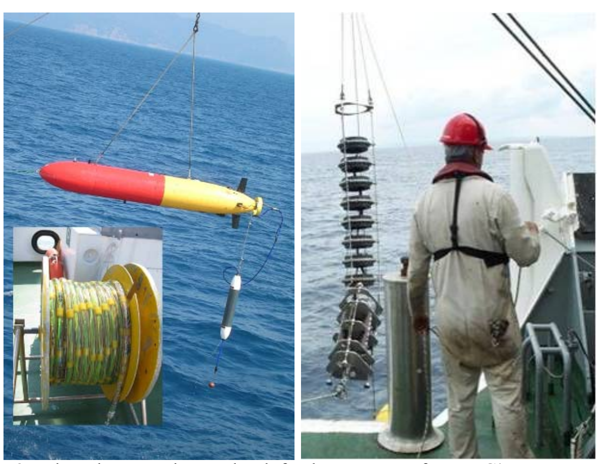

Figure 2. The photograph on the left shows one of NURC's autonomous underwater vehicles with its towed source (grey-white) which may also be used as a software defined modem transducer; in the bottom left corner the AUV's towed array can be seen on the winch. The photo on the right shows the moored sound source.

Communications and Networking in the Maritime Domain focuses on the development of open architectures that support adaptive, ad-hoc networking with a high degree of robustness and interoperability. Work has included developments on interoperability from the physical layer [5], Medium Access Control (MAC) [6] and Disruption Tolerant Networking (DTN) layers [7]. Our approach has been to begin with design, develop numerical simulation modules and then to test first in simulation and then with in-the-loop hardware, culminating in field trials of implemented software and hardware on AUVs and custom modem elements.

Our objective is not only to develop the necessary protocols to deal with the unique challenges of creating ad-hoc underwater networks (such as high latency, link intermittency, long reverberation and short channel coherence) but to choose and/or develop protocols that offer high performance on metrics such as network throughput, maximum/average delay and error rate for applications of interest.

For the CASW application, a hybrid networking solution is envisaged, providing high data-rate communications over short hops via inexpensive relay assets (possibly simple AUVs) with low data-rate but robust communications being provided over longer distances that are more aligned with tactical ranges by through-the-sensor software defined modems. The hybrid nature of this solution, both in terms of assets (combining high-value AUVs that can acquire and process acoustic data with inexpensive and simple AUVs that can relay messages) and communications protocols (sophisticated phase-encoded messaging over short hops combined with low bit-rate robust coding at low centre frequency for longer ranges) is a novel feature of the application solution.

The *Decision Support* task leverages a prototype MultiStatic Tactical Planning Aid (MSTPA) [8, 9], for the simulation of multistatic AUV missions, at a good accuracy level and quick response time. The tool considers the entire chain of events from an initial calculation of signal excess, the generation of a contact considering localization errors, followed by the subsequent tracking and classification processes. This methodology drives MSTPA towards its goal of becoming a tactical decision tool as opposed to a purely acoustic model, and allows for the determination of more operational metrics such as area coverage and time to classify.

In Sections II, III and IV we expand on each of the project tasks. In Section V we conclude and present our ideas on the way ahead.

II. CONCEPTS FOR LITTORAL UNDERSEA SURVEILLANCE

A. Introduction

The objective of this task is the examination of novel ideas for networked sensing with distributed intelligence currently considered for application to the problem of off-board reconnaissance and surveillance in littoral waters.

The vision of groups of networked unmanned vehicles swimming around independently, carrying out high-level processing and sharing information between other members of the submerged fleet, ultimately carrying out detection and classification of enemy assets and passing the information to a command and control (C2) centre, or carrying out their own prosecution, is seductive and enticing. Such a capability would, in effect, exhibit levels of flexibility which would be of great use in at least three of the arenas of interest as quoted in the US Navy's Unmanned Underwater Vehicle Master Plan (NUUVMP), cf. [10]:

- In transit / protected passage;
- Chokepoint / hold-at-risk;
- Sea-base / maritime shield.

All of these capabilities share a core set of requirements, among which 'Detection, Localisation, Classification and Tracking (DCLT) processing', 'autonomous adaptation of the AUV's path or trajectory' and 'intelligent task allocation'. It is this toolbox of tasks that we are researching within the CASW project; the next two sub-sections will provide more detailed information.

B. *Real-time Processing*

Real-time processing sits at the heart of the AUV-based system. It can be thought of as acting as the bridge between the sensors and the more complex adaptive vehicle behaviors which make decisions on the basis of the sonar world picture. The embedded processing chain we have implemented is constrained to run on relatively low-powered processing boards – this in order to limit power consumption within the vehicle – and is designed to be robust, obviously requiring no human intervention and able to cope with occasional data drop-outs and corrupted samples.

The approach is based heavily on the signal processing which has been developed at NURC for general array-based systems over several years [11]. The current version supports Frequency Modulated waveforms only. For speed and ease of implementation, beamforming and matched filtering are carried out in the frequency domain whilst the normalization, detection and contact forming are done in the time domain. Extensive testing of the processing chain has been carried out on the embedded system with an active sonar signal stimulator that generates hydrophone level data for a virtual multistatic active sonar scenario.

The generation of synthetic time-series at individual hydrophones is based on simple expressions for bistatic reverberation intensity developed at NURC for linear arrays [12], and on a more general theory for the target return on arrays of arbitrary geometry [13]. The overall consideration is one of the highest possible fidelity within the constraint of real-time simulation for the hydrophone elements.

At this time, the environment is assumed to be range-independent and iso-velocity, although the second assumption may be relaxed at relatively little computational cost. The bottom scattering is assumed to follow Lambert's law, a separable scattering kernel which lends itself to fast simulation. Similarly the target is assumed to be a point scatterer, another assumption which allows for fast implementation.

For the stimulation of reverberation at the element level, the assumption of a straight array allows the sampling of the product of the grazing-angle vs. azimuth reverberation intensity density developed in [13] with the array wavenumber response for the N+1 wavenumbers resolved by the array, where N is the number of elements, 32 in the case of the NURC array. The N+1 wavenumbers represent waves from forward end-fire through aft end-fire, at cosine angle spacing. The weights of the intensity observed by the array at each of these wavenumbers are obtained by taking the product of the array wavenumber response with the theoretical reverberation intensity. The pressure amplitudes at each wavenumber are simply the square root of this intensity, up-sampled to the sample frequency of the data acquisition system, randomized to have Rayleigh envelope statistics, and convolved with the source waveform.

For the stimulation of the target echoes on the individual hydrophones, the straight array assumption is relaxed, and a general propagation model is used to generate the one-way Greens functions from the source to the target and from the target to the hydrophone locations. These Greens functions are generated at the sample frequency of the data acquisition system, and are convolved with one other to obtain the impulse response of the target for each hydrophone. This impulse response is then convolved with the target impulse response and the source waveform to generate the required element level time series associated with the target response.

The simulated data on the hydrophones are the sum of the reverberation and target simulations which are then passed to the signal-processing module. This is an ***exact*** copy of the code which sits on the AUV. This exact replication of code and parameters is a crucial part of the checking and validation of ideas and algorithms before they are tested at sea. The configuration control at sea can become complex but is worth the effort to ensure well tested code is being used.

An exactly analogous approach is taken in terms of the code which controls the behavioral response of the AUV – in that the code used in simulation is that which is ultimately used on the vehicles. There is however a slight complication in that a model of the vehicle dynamics must be used.

Ultimately the work must be tested at-sea. At NURC we are involved in a program of development which includes a substantial sea-trial off the coast of Italy every summer. These trials – the GLINT trials - allow for the demonstration of progress in both signal processing and in the autonomous behaviour of the vehicles.

For the GLINT09 sea-trial, the processing chain was implemented on the Ocean Explorer (OEX) AUV (Figure 1) producing contacts and tracks. These data were passed via acoustic modem to the NRV Alliance where the information could be projected within the command and control centre on a screen which facilitated understanding of the geographical experimental space. Figure 3 shows a screenshot which was made during the trial.

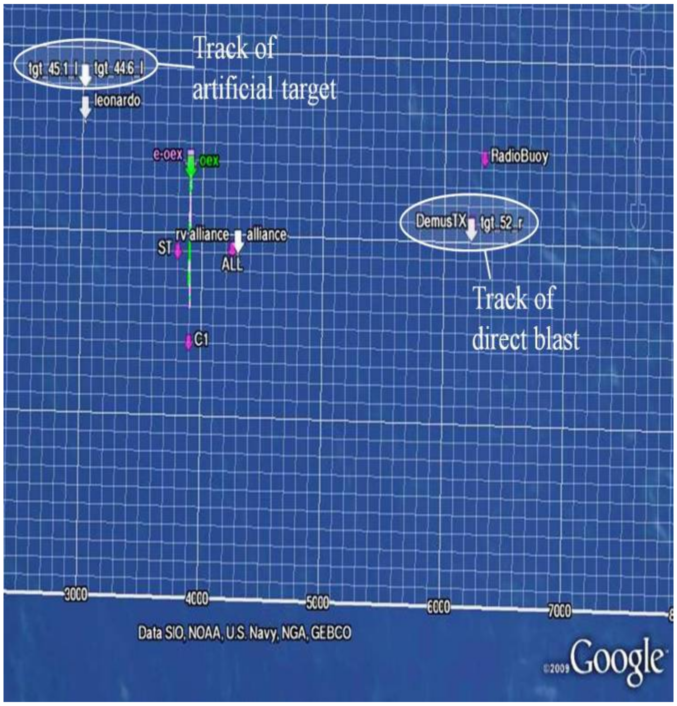

Figure 3. Screenshot, taken from command centre display produced during the *GLINT09* sea-trial. The display showed not only recent updates on the position of the AUV, shown in pink and green, but also the position of contacts, calculated on-board the AUV and passed back to the command centre by means of acoustic modems. AIS and radar information relative to the ships NRV Alliance and CRV Leonardo are also included.

The use of the linear SLIm Towed Array (SLITA) [14] means that an ambiguous return is created for every true detection and this replication is mirrored in the display where true contacts have an ambiguous 'ghost' The tracking was carried out using a simple baseline one-step ahead Kalman-filter based tracker which has been developed as part of NURC's Multistatic Tactical Planning Aid initiative [8].
An example track-level output obtained for one of the GLINT09 experiments is shown in Figure 4. The objective of this experiment was the investigation of expected sonar performance; during GLINT09, the (artificial) target could be tracked consistently over distances > 7km. For this experiment we have used the Deployable Multistatic System (DEMUS) bottomed source. DEMUS allows us to transmit up to 217 dB re. 1µPa at 1m and is reconfigurable either through a radio connection or through an acoustic modem – receiving, for instance a message from an AUV.

Several phenomena can be observed in the image: the 'second-time-around' returns of bathymetric features, and the ambiguous returns resulting from the use of a linear hydrophone array. The latter effect may be reduced by using ambiguity resolving arrays as mentioned in [15, 16]. NURC are investigating technological solutions as well as the possible merits of optimal maneuvering for ambiguity resolving.

Other approaches may include the introduction of a generic track labeling/ranking system, i.e. by giving each track a 'value' that reflects (1) the probability that it is the true track (as opposed to the ambiguous one), and (2) the probability that it is not a track corresponding to a bathymetric feature.

Although the latter seems more difficult, the long-term presence of CASW-type intelligence and surveillance systems may in future result in having detailed bathymetric charts available on-board the vehicle. Target classification clues and anomaly detection may help in estimating the possibility that a perceived track belongs to a bottom feature.

The obvious objective of the above algorithm is to lower the number of tracks that the AUV will have to deal with and, more importantly, to lower the number of tracks that will have to be exchanged with neighboring vehicles for data fusion. Although the message size per track is smaller than 50 bytes, it is of primary importance to keep underwater communications down to the minimum.

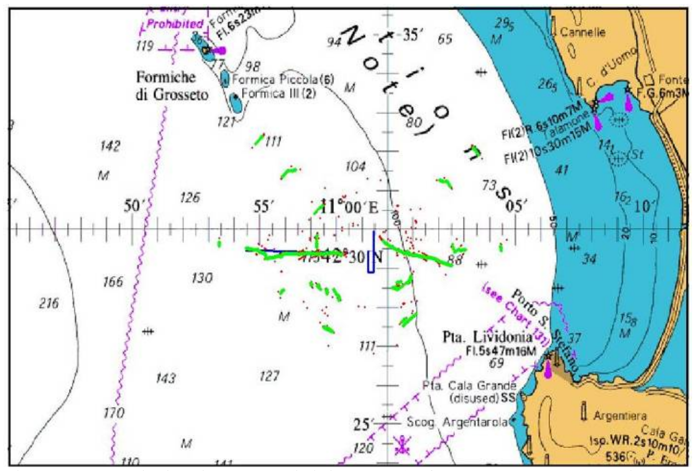

Figure 4. Track level output (bright green) for a *GLINT09* experiment. Multiple returns ('second-time-around') from the Formiche islands can be identified. Also the ambiguous track of the (west-bound) target can be identified east of the (blue) AUV race-track in the centre of the image.

For *GLINT10* the use of two (identical) OEX AUVs is foreseen, both operating identical embedded real-time systems. One of the OEXs is equipped with a towed sound source that will also be used as a software defined modem. One objective of the sea-trial is to show that one vehicle can process the data to track level and then send the 'best' track to the neighboring vehicle. The second vehicle will then use this track to improve its own target track solution and will adapt its course in order to autonomously improve the target track in the next ping: A first attempt to truly cooperative autonomous group behavior.

However, it will not be the first time that multiple vehicles have been used to collect multistatic data within the CASW project. During *GLINT08*, we experimented with two vehicles, a NURC OEX and an MIT *Bluefin* vehicle, both equipped with similar towed arrays and operating together with a NURC sound source towed behind a research vessel. At that time, real-time processing was not available so the processing was done off-line. Figure 5 depicts the results; here the more advanced Distributed Multiple Hypothesis Tracker (DMHT) was used [17]. Although this experiment was unrealistic in an ASW context – high SNR and short ranges – the output gives confidence for the upcoming sea-trial: the graph shows that the fused (red) track is of higher quality when compared to the (blue) single AUV track in terms of track fragmentation, false tracks and error with respect to the (green) ground truth trajectory of the artificial target.

It is the extension of this work to systems operating in real-time, carrying out the processing and tracking on-board, and then the passing of appropriate messages that we intend to investigate during 2010.

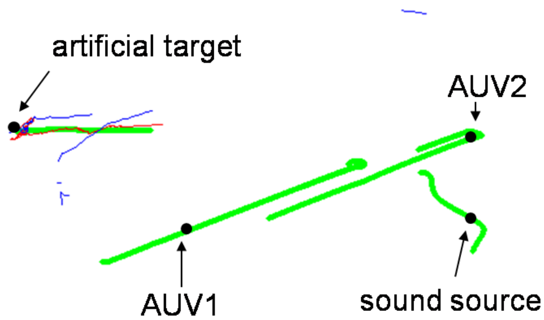

Figure 5. This *GLINT08* result shows the effect of fusing the data as received on two AUVs in a multistatic active sonar experiment: track fragmentation is reduced, the number of false tracks has gone down and the resulting (red) track is closer to the ground truth (green) track of the artificial target.

C. *Autonomous AUV behavior*

The 'autonomous' in AUV is a term which can lead to a great deal of confusion. For instance, a vehicle which is programmed to go out and execute a pre-defined lawn-mower pattern is called autonomous if there is no continuous updating of the vehicle's plan by an exterior source (by underwater acoustic communications or even a cable – as employed by a remotely operated vehicle). What we were interested in during the GLINT09 experiment was several steps of advancement from this baseline autonomy. For our demonstration we wanted to show how an AUV could monitor its environment based purely on its own sensors, and convert the data obtained into information which could be used to alter the trajectory of the AUV to exhibit some form of ASW-relevant behavior. As discussed in the previous section the observation and interpretation of the external world is carried out in the real-time processing. The output can be either contacts with associated latitudes, longitudes, bearing and SNR, or fully formed tracks, with associated position estimates and error-covariance estimates. The behavior, demonstrated successfully in the *GLINT09* [18] at-sea experiment, used only contacts. In an Oceans 2010 accompanying paper [4], tracker-based approaches are detailed that use measurement-error models [19,20] and autonomous behavior algorithms based on information theory [3,21] rather than the 'keep-target-in-broadside' behavior employed during *GLINT09*.

III. COMMUNICATION AND NETWORKING IN THE MARITIME DOMAIN

The objectives of this task are to provide the necessary communications links to support distributed processing, information transfer, command, control, telemetry, and seamless integration between sensor networks and NATO C2 networks, across the NATO Network Enabled Capabilities (NNEC) environment [22]. The focus is on interoperability, so that barriers to fielding co-operative distributed assets from different sources are minimised. This is being achieved through the standardisation of layers in the communication stack (physical layer upwards), open-architecture and creating software defined systems in place of hardware-locked implementations for systems such as underwater acoustic modems.

The general communications objective is illustrated in Figure 6 where clusters of sensing platforms, both fixed and mobile, are shown linked by gateway buoys to a C2 network that bridges tactical ranges and provides the necessary NNEC integration. Within each cluster there may be a heterogeneous mix of assets, including relatively expensive assets with sophisticated navigation and sensing capabilities in co-operation with inexpensive simple assets that may have little or no sensing or navigational capability. The synergy between such a mix of assets may be found in the ability of the inexpensive assets to act as high-bandwidth communication relay nodes for the expensive assets to communicate over longer ranges at higher frequencies than otherwise possible, while the inexpensive nodes inherit navigational fixes by using the sophisticated assets such as Long BaseLine (LBL) beacons.

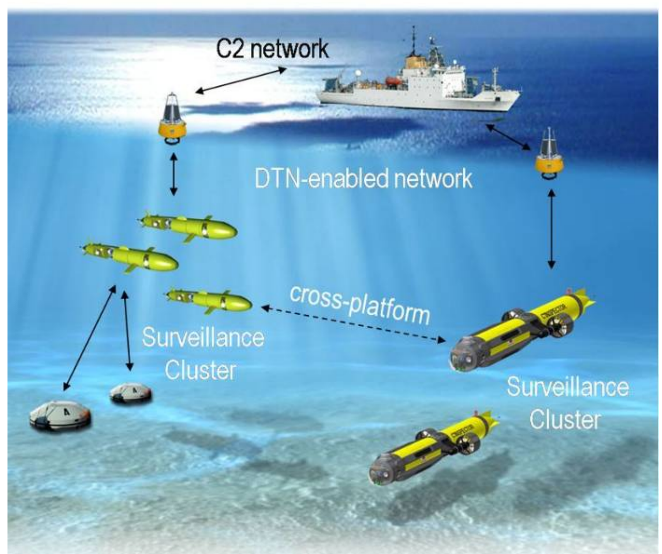

Figure 6. Illustrated goal of a heterogeneous network with gateways and NATO C2 integration.

One of the major hurdles in achieving the interoperability we need, is in having modems from different manufacturers be able to communicate with each other. This is currently impossible. Each modem manufacturer has its proprietary coding scheme and control and none can talk to a modem from another manufacturer. This is no longer a tenable situation if we are to move to distributed interoperable sensing networks.

The problem is being addressed in two ways. Firstly, NURC is striving to establish open-architecture standards for basic node discovery and low-level communication (JANUS [5]), MAC and Network protocols as an independent non-commercial body via NATO standards processes and eventually industry standards such as IEEE. Secondly, NURC is working with industry to develop a Software Defined Acoustic Modem (SDAM) that harvests benefits pioneered in Software Defined Radio to provide a flexible modem environment that can bridge across many coding schemes and protocols.

An additional advantage of an SDAM is the potential to dynamically negotiate coding schemes, MAC, packet lengths, etc., to locally (in space and time) optimize communications throughput for the environment and application currently in use. This addresses the need to escape from the inflexible 'one-size-fits-all' traditional trade-off between robustness (to environmental variation) and throughput efficiency [23,24].

The current implementation of this SDAM research initiative is illustrated in Figure 7, showing how the lower level functions are implemented on a traditional modem, with higher-level functions being run as processes under MOOS on a PC-104 [25]. MOOS adaptive control processes interact with the communications stack via direct control packets with each of the modem layers, indicated by the blue connecting lines on the left of the diagram.

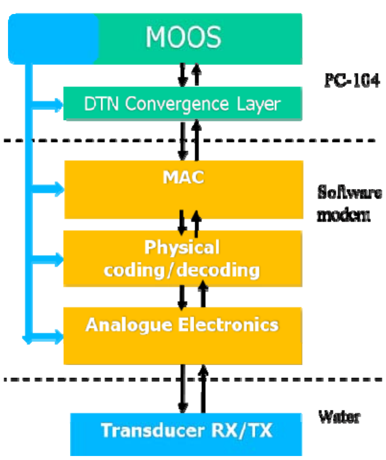

Figure 7. Current SDAM development environment with DTN implementation.

D. Physical layer

While differences in coding at the physical layer (most obviously the choice between incoherent and fully coherent modulation schemes) can be made adaptively and result in at least an order of magnitude change in communication throughput rates (provided the coherent coding is well tuned to the application and environment) there is usually no means to switch between very different centre frequencies. High frequencies offer higher bandwidth and hence throughput, at the cost of shorter ranges [26].

With a heterogeneous mix of assets providing an overlapping cluster of connectivity, longer ranges can be obtained by multi-hop transmissions with both high throughput and improved covertness, since the ranges over which high frequency transmissions may be eavesdropped are much shorter than for lower frequencies. In parallel, low frequency transmissions may be made through the CASW acoustic sources and received through the sensors, so that low-bandwidth tactical paging can be enabled over longer ranges without the need for additional hardware on the AUVs. This also provides a backup in case of failure of the multi-hop network connectivity.

E. MAC

A critical part of network communications is the Medium Access Control (MAC). The long latencies and short channel coherence times make MAC schemes developed for in-air electromagnetic networks unsuitable for UnderWater Acoustic Communications Networks (UWACommsNet).

NURC is working with several research groups from Universities in Europe, the US and Singapore to develop, simulate and test MAC protocols for CASW and other tasks [6]. Preliminary results suggest that simpler random access protocols may work better than sophisticated ones in many environments, with the best choices often lying somewhere between Carrier Sense Multiple Access (CSMA) and Medium Access with Collision Avoidance (MACA) variants [27].

Another feature of the problem is that accurate timing and navigational fixing is almost always a challenge for underwater assets, rarely the case in air. This suggests that we may wish to look at ways to integrate the exchange of estimated time and position as part of the communications stack tasking, affecting all layers of the communications stack from the MAC layer upward.

F. DTN

Delay and Disruption Tolerant Networking (DTN) [7], is being implemented on WHOI micromodems in co-operation with the University of Porto in Portugal. A convergence layer has now been written and tested that creates a reference DTN implementation, allowing our modem-equipped assets to cope with dropped links, lack of end-to-end connectivity at any time, data mule tasks, etc. NURC now has DTN running under LINUX on the PC-104 platform, permitting gateway functionality to wireless EM devices (including 802.11 and Android cellular phones) as demonstrator applications. The next step is to link into the NIRIS service from NC3A to provide the interface with NATO C2 networks.

G. OSI stack revisited – shoot the messenger

Returning to the idea of using a heterogeneous mix of simple/inexpensive and sophisticated assets, and the ubiquitous problem of accurate time and position estimation, it was earlier suggested that navigational information could be incorporated into the communications networking protocol so that position and time synchronization could be achieved as part of the network overhead. This is an extension of previous implementations that use modems to derive navigational information [28].

Navigational information is useful at the MAC layer upwards for a number of reasons, including the implementation of MAC protocols such as the Distance-Aware Collision Avoidance Protocol (DACAP) [29], updating routing tables, using acoustic transmission power control as a means to save power and simultaneously reduce collisions in the network, etc.

In our heterogeneous mix of assets, the simple (no navigation sensor) assets would then inherit position and timing information by passing the messages between the sophisticated assets (with high-quality position and timing estimates). This kind of integration would require a much more connected set of layers than the traditional OSI communications stack model allows. Until now, underwater communication systems have been designed using the OSI model as reference, according to practices that have served the research community in designing terrestrial communication networks.

To date, protocols for underwater communications have been developed primarily for the lower layers of the stack, to deliver point-to-point acoustic communication, where the physical layer is acoustic rather than electromagnetic and some adjustments need to be made to accommodate the long latency and short channel coherence of the underwater communications channel. We are now pushing the boundaries of this paradigm, however, as we seek to link a distributed network of autonomous assets. We propose therefore to replace the sequential structure of the OSI stack, with a collection of agents that have a high degree of inter-process communication, resembling more of a collection of parallel agent processes. The time and position of an asset could be embedded in the basic handshaking among the assets, to assist in the efficient set-up of the network, and to drive routing of messages and transmission power control. This approach can effectively shift the focus from the *messenger* to the *message*, to deliver new data-centric networking capabilities that are better adapted to the harsh underwater environment.

H. Simulation

An important step in maximizing the efficient use of seagoing trials resources and in de-risking experimentation is the simulation of performance of equipment and proposed protocols as an intermediate step between development and at-sea testing. For many years the network simulation package of choice has been an open-source simulator called Network Simulator 2 (NS2), see http://www.isi.edu/nsnam/ns. NS2 has been growing, both in terms of functionality and in popularity, making it one of the most used tools for reproducing the behavior of wireless and wired networks. While NS2 provides sufficient flexibility to simulate practically any kind of network and protocol, there is a lack of detailed channel models, especially for wireless links, and limited cross-layer interaction which, as we have seen, is a very desirable property for UWACommsNet. To address these limitations NURC has collaborated with the University of Padova to create an extension to NS2, the MultI-RAdio Cross-Layer Extensions (MIRACLE) module. NURC and the University of Padova are now running NS-MIRACLE to test the network performance of various proposed MAC protocols under different environments and applications prior to field testing in September 2010.

I. Experimentation

NURC is collaborating with the European Union Funded Underwater Acoustic Networks consortium and MIT to conduct a full-scale UWACommsNet experiment in September 2010 that will explore the real-time performance of various MAC schemes in several typical application scenarios. A low-cost AUV produced by Graaltech (Folaga) is being enhanced (eFolaga) as part of a collaborative development between Graaltech, ISME and NURC and will be used to carry the prototype SDAM currently under development. In addition, several modem nodes will be deployed on a bottom-mounted system that NURC has built for previous modem experiments known as the 'modem on a rope'. This system allows real-time communication with three modems mounted on tripods and connected to shore via fibre-optic cable.

Several candidate MAC schemes will be selected in collaboration with MIT, the University of Padova and the National University of Singapore. Candidates include CS-ALOHA [30] with random backoff, a MACA [31] variant, DACAP [29] and T-LOHI [32]. These will be used with two coding schemes, one robust but incoherent, the other coherent and high-throughput (FH-FSK and OFDM-based) to support two applications. In the first application, an eFolaga will transit back and forth through the field of fixed bottom-mounted modems, periodically transmitting data that is addressed to a gateway. The fixed modem distribution and AUV track are designed to ensure that links are not always up. DTN will be used to handle the intermittent links. In the second application, the same AUV and fixed assets will be used in the reverse flow of information. The eFolaga will be used as a data mule to collect data from the fixed assets and pass them on to the gateway.

By testing combinations of coding and MAC schemes under typical application scenarios we hope to be in a position to validate numerical and hardware-in-the-loop simulation tools and begin to map out the likely best choices for managing ad-hoc UWACommsNet.

IV. Decision support

The objective of this CASW task is sensor network simulation, the evaluation of Measures of Effectiveness (MoE) for ASW scenarios, the evaluation of autonomous behaviour modules and the development of CONcepts of USE (CONUSE) for networked sensors with distributed intelligence. The latter will be performed in close collaboration with the Centre of

Excellence for Confined and Shallow Waters (CoE CSW), based in Kiel, Germany.

The decision support task is developing a software tool that will allow users of a cooperative ASW network to deploy it most effectively. At the core of this decision support software there must be a module that is able to calculate a variety of mission specific performance metrics for given scenarios. Here, we build upon the Multistatic Tactical Planning Aid (MSTPA) developed at NURC to form the central modeling element of the decision support processing chain [8].

This chain begins with a data mining element to extract information from real time environmental measurements using fuzzy logic and rule based algorithms. The environmental data, and extracted information, are passed to the MSTPA model within an optimization engine that maximizes given mission metrics (e.g. area coverage). The optimization loop is combined with elements of decision and game theory in order to account for the behavior - tactical decisions - of an intelligent threat that is attempting to penetrate the cooperative network.

The premise behind MSTPA is to generate fast, sufficiently accurate, acoustic solutions which allow for subsequent calculations of operational metrics at the level of track and classification output. The model accounts for the entire chain of events from a signal excess calculation, through contact generation, to eventual tracking and classification processes.

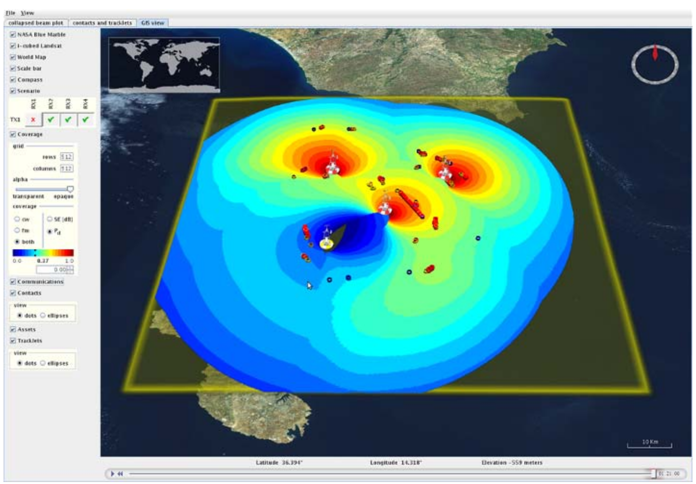

Figure 8. Example MSTPA output showing probability of detection for a Multistatic network of one source and three receivers. Note that a target track and additional false tracks have been generated.

Signal excess is determined using an implementation of the ARTEMIS model (Adiabatic Reverberation and Target Echo Mode Incoherent Sum) [33-36], which employs adiabatic mode theory and assumes a continuum of modes being equivalent to a continuum of ray angles. Inclusion of the ARTEMIS model allows MSTPA to account for fully range dependent sound speed profiles and bathymetry in the fastest way possible while maintaining high fidelity.

In order to add further realism to the model, and acknowledging the uncertainty of the environment, the calculated signal excess is assumed to be the mean value of a normal distribution with a user-defined standard deviation. A simulated lambda-sigma process is then used to perturb the calculated values in magnitude while taking into account the probability of inter-ping correlation over time.

When a final value of signal excess has been determined, an associated probability of detection is calculated and a contact generated according to that probability (this is especially useful within Monte Carlo simulations). The position of a contact, relative to the target that generated it, is determined taking into account user defined sensor errors in terms of the echo arrival time and bearing, array heading, and positional uncertainty of both receiver and source. The MSTPA tool samples these parameters, according to the user defined standard deviations, and generates a modified contact position accordingly.

Additional random contacts may be generated according to the statistics of the ambient noise level. Further development of the tool will add reverberation returns to the false contact background. All contacts, from targets, clutter, and noise, are sent to a Kalman filter to initiate the tracking process.

The contacts generated by all source-receiver combinations are sent to the tracker in a simulation of contact level fusion. Subsequently, any source receiver combination can be 'switched off' to examine the added value of individual nodes to the overall track consistency of the network. Additional false tracks may arise from noise and clutter contacts.

In the final stage of modeling, tracks are passed to a classifier to attempt to discriminate between target tracks, clutter tracks and other false tracks. The classification is based on a naïve Bayesian approach which is trained on the distribution of heading consistency within target and clutter tracks.

The completed process allows for an initial decibel value to be translated it into an eventual track classification of a target. This allows for more operationally relevant performance metrics to be determined such as track holding and time-to-classify. The fast acoustic calculation facilitates large Monte Carlo studies in which many targets may attempt to penetrate a barrier. The simulated localization uncertainty and lambda-sigma processes allow for probabilistic output to be investigated.

As already mentioned, the MSTPA tool will form the central modeling component of a decision support software chain to include elements of data mining, optimization, and decision/game theory.

The current version of MSTPA already implements genetic algorithms to optimize sensor placement according to a number of mission specific metrics. These include maximizing area coverage, cross-barrier detections and platform waypoints.

In terms of generating realistic target behavior a study was conducted [9] in which the A* path planning algorithm was used to model a worst case target attempting to penetrate a Multistatic network while minimizing either number of detections or track initiations. The study showed that the resulting target tracks provided a useful visual aid to assist a planner in positioning the sensors in the best way.

Further studies will be conducted in 2010 and 2011 to add decision and game theory components. For example, consider a target submarine entering a scenario area and counter detecting an active transmission. At this point the target must choose the strategy he believes gives him the best chance of completing his mission undetected. In one sense this is a decision under ignorance since, we assume, that he has no idea whether there are any multistatic receivers (perhaps sonobouys or AUVs) or indeed how many. His strategies will likely be independent of the presence of receivers such as, continue on present course, optimize against a monostatic sonar, transit at edge of scenario etc. We could assign a utility score for each of the targets tactics, assuming he has run an acoustic model to determine his likely probability of detection, and thereby reveal his best strategy and attempt to counter it.

Game theory assumes that the threat will make a decision based on the decisions made by the other player (he knows that we know etc). In this case the other player is the planner of the network who will have determined an optimum number of sensors to deploy. Consequently a two dimensional decision table can be generated in which the Pd of the target is generated for each of his strategies taking into account the strategies (network geometries) of the planner. An important assumption of game theory is that both players have complete knowledge of the others costs – we therefore assume that both the planner and the target have the MSTPA tool.

Further work to determine effective threat tactics will be investigated through the addition of a ‘man-in-the-loop’ component to the MSTPA tool. This will allow a human operator to drive a target through the MSTPA simulation making real time adjustments to his course, speed, and depth. The MSTPA simulation will reveal whether the target would have been detected, tracked, or classified. Work has begun on integrating the MSTPA tool within the *OpenSea* virtual world created at NURC.

V. Conclusions and Way Ahead

The modern push for frigate based multistatics for ASW is already more than twenty years old. Many lessons have been learned and many problems overcome. It remains however a complex and challenging area of technological development. At NURC we are investigating a conceptual sea-change on the whole concept. In this paper we have briefly discussed a large R&T program which we have broken into three strands of work.

Each of these strands, for the research considered in this paper, brings a high level of innovation based on the aforementioned lessons learned from ‘traditional’ multistatics. At NURC the main developmental push is towards a delay-tolerant underwater network based AUV-lead demonstration as early as 2012.

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