Exploring Cognitive Techniques for Bandwidth Management in Integrated Underwater Acoustic Systems

Hwee-Pink Tan[*], Winston K. G. Seah[†] and Linda Doyle[*]
[*]Center for Telecommunications Value-chain Research (Republic of Ireland)
[†]Networking Protocols Department, Institute for Infocomm Research (Singapore)
Email: {tanhp@tcd.ie, winston@i2r.a-star.edu.sg and ledoyle@tcd.ie}

Abstract—**The richness in the largely unexplored ocean is increasingly fueling research in underwater networks. Unlike their terrestrial counterparts, underwater networks are likely to remain sparse and mobile due to prohibitive costs and extremely harsh underwater environment. It remains a challenge to coordinate access (i) between navigation and data signals and (ii) between Autonomous Underwater Vehicles (AUV) and sensor nodes due to the limited underwater bandwidth. In this paper, we explore how dynamic spectrum sharing concepts inspired by the advance in cognitive radio technology can be used for spectrum management to achieve integrated communication and navigation in Integrated Underwater Acoustic Systems.**

I. INTRODUCTION

Over two-thirds of the Earth's surface is covered by the ocean, which is rich in natural resources (e.g., oil and natural gas) and largely unexplored by human beings. Presently, there is great interest in exploring the ocean for scientific, environmental, commercial and military purposes. Examples of applications envisaged for such advanced communication systems include oceanographic data collection, pollution monitoring, offshore exploration, disaster prevention, assisted navigation and tactical surveillance.

The traditional approach to ocean monitoring follows the cycle of *deploy*, *record* and *recover*. The drawbacks of such an approach are that it (i) is restricted to non time-critical data, (ii) is limited to capacity of onboard storage devices and (iii) does not support on-the-fly configuration of the system and detection of failures. These limitations may be overcome by underwater (wire-*less*) networking using an Integrated Underwater System [1] of sensor nodes and Autonomous Underwater Vehicles (AUV)s that combine *navigation*, *communications* and *sensor* capabilities. An example subsystem that embeds these capabilities is the WHOI Micro-Modem [2], a compact, low-power acoustic transceiver that can provide both acoustic telemetry and navigation, and up to 16 such units can be supported in a polled or random-access mode.

While many design principles and tools for ongoing, ground-based terrestrial wireless networks may be borrowed, they have to be adapted for the underwater environment since there exist fundamental differences in the *physical channel* as well as *operating regime*. Acoustic communication is seen as the primary candidate for underwater communications at typical transmission ranges and in typical water salinity [3] as radio frequency (RF) waves are severely attenuated and light waves are strongly scattered in water. However, the underwater acoustic channel is characterized by (a) long and variable propagation delay (the acoustic propagation speed is about 1500m/s, which results in delay approximately 2×10^5 times higher than in RF terrestrial channels), (b) limited range-bandwidth performance (see Table I), (c) multipath and fading due to the temporal variations of the channel, and (d) shadow zones (where very little energy can be transmitted from a given location) due to sound speed variations, driven by temperature and salinity variation.

While terrestrial wireless networks are characterized by dense and fixed deployments of low-cost *homogeneous* RF nodes (around €70 [4]), the temporal and spatial variance of the underwater environment and the prohibitive costs of sensor nodes and AUVs (about €5k and €40k to €1M respectively to fabricate) and their deployment will drive integrated underwater acoustic systems to be *sparse* and *heterogeneous* [5].

Channel (depth)	Range (km)	Centre frequency (kHz)
200m shelf	3.2	10
2200m offshore	3.6	15
10m very shallow water	2	25
3m surf zone	0.8	25

TABLE I
OBSERVED PERFORMANCE OF WHOI MICRO-MODEM WITH DEFAULT BANDWIDTH OF 4KHZ AND DATA RATE OF 80 BPS [2].

While most research consider the implications of the physical channel on the design of underwater networking architecture and communication protocols, we focus on the impact of the *new* network operating regime. Although several protocols have been presented, e.g., [6], [7], for integrated communication and navigation in a (homogeneous) network of AUVs, we explore how dynamic spectrum sharing etiquettes proposed recently for cognitive radio networks may be borrowed to address the challenging task of networking in a heterogeneous integrated underwater acoustic system.

II. DYNAMIC SPECTRUM SHARING IN CR NETWORKS

The majority of today's terrestrial radio systems e.g., cellular telephony such as GSM and UMTS, broadcast TV such as Digital Television Broadcast - Terrestrial (DVB-T), radar systems and IEEE 802.16 WiMax, are not *aware* of their radio spectrum environment, and operate in specific frequency band(s) licensed by a regulator on a long-term basis for their *exclusive* use. Various investigations of spectrum utilization indicate that (i) spectrum usage varies dynamically and (ii) not all spectrum is used, in space and/or time by these licensed users. For example, recent measurements [8] indicate that the average usage within the 30 MHz to 3 GHz band is only 14%. This inefficient use of scarce wireless radio spectrum, along with a dramatic increase in spectrum access for mobile services, have been the driving forces towards new dynamic spectrum access (DSA) paradigms [9], which can be abstracted into the (i) *Dynamic Exclusive Use*, (ii) *Open Sharing* and (iii) *Hierarchical Access* models. One of the main enabling technologies driving research in this area is Cognitive Radio (CR) [10], [11].

A CR can be viewed as an amalgamation of a software reconfigurable radio and a cognitive engine. Combining the facets of radio *flexibility*, *intelligence* and *spectral awareness*, a CR will adapt itself to changes in the environment, its users' requirements and the requirements of other radio users sharing the spectrum (in time and space). To illustrate, a CR that wishes to access spectrum undergoes the following cycle, which is illustrated in Fig. 1.

- *sense*: It senses its local environment, e.g., transmission activities and QoS requirements of other users sharing the spectrum;
- *analyze*: It analyzes the sensed information e.g., to evaluate spectrum occupancy and transmission levels within occupied spectrum, location of transmitters, users' willingness to share etc;
- *decide*: It decides on the optimal transmission parameters e.g., channel, power level;
- *act*: It acts on the decision through software reconfiguration;
- *learn*: It uses long-term analysis to learn about its environment and its own behavior.

Since CRs are very flexible and have the potential to interfere with other users, their behavior must be controlled or agreed through software-based spectrum policies defined by regulators or other third parties. Examples of such policies include the definition of CR users' rights, development and deployment of spectrum monitoring systems, enforcement of DSA policies and standardization of interfaces between radios to support heterogeneous networks and services.

To realize the full benefits of cognition, intelligent signal processing across all layers of the OSI architecture (cross-layer optimization) is required. This level of complexity, coupled with full software defined radio technologies, is unlikely to be achieved in the next 20 years, and may never be necessary. However, achievable forms of intelligent reconfigurable CR-enabled devices are realizable within the next 5 years [12], and they have the potential to provide high bandwidth services, increased spectrum efficiency and minimize the need for centralized spectrum management.

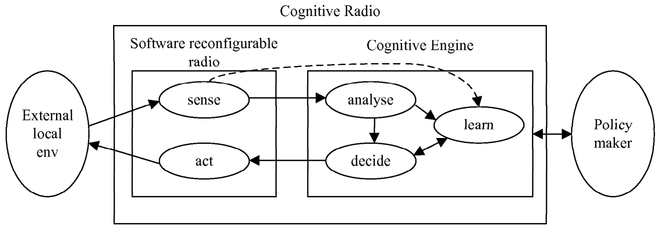


Fig. 1. Components of a Cognitive Radio.

III. SPECTRUM MANAGEMENT IN INTEGRATED UNDERWATER ACOUSTIC SYSTEMS

We consider two common communications architecture for Integrated Underwater Acoustic Systems (IUAS)s as shown in Fig. 2.

The 2-D architecture in the LHS of Fig. 2 is useful for undersea explorations by deploying a group of sensor nodes anchored to the seabed. In shallow water (typically <100m depth), sensed data is forwarded directly via wireless links to the surface station. On the other hand, in deep water (up to 4km depth), the sensed data is first forwarded horizontally via wireless links to one or more underwater gateways, which then relay the data vertically to the surface station. The surface station, in turn, communicates with an offshore or surface sink via RF communication.

The 3-D architecture in the RHS of Fig. 2 offers a more flexible means to detect and observe phenomena that cannot be adequately observed by the 2-D architecture. In this architecture, each sensor anchored to the seabed is additionally equipped with a floating buoy that can be inflated by a pump to regulate the depth, so as to offer 3-D coverage for ocean monitoring and exploration. In addition, since sensor nodes are prone to failure due to fouling, corrosion, disturbance due to marine life and depletion of battery life, such nodes can float to the surface for replacement or recharging using solar energy, thus reducing the operational costs and prolonging the lifetime of the network. On the other hand, some of these sensor nodes can be moored to the sea-floor and position-calibrated to serve as a navigation net for active and passive navigation [6].

While AUVs extend the sensing coverage of the sensor network, they may also serve as (i) collection points for time-critical data from, and (ii) links between partitioned segments [13] of, the sensor network. Since *navigation* signals from GPS satellites cannot reach AUVs underwater, they navigate (without cables) using (i) locally acquired position references evaluated based on the navigation net and (ii) control strategies for autonomous coordination, obstacle avoidance and steering.

Due to the frequency- and range-dependent attenuation of the acoustic channel, high-resolution navigation systems and

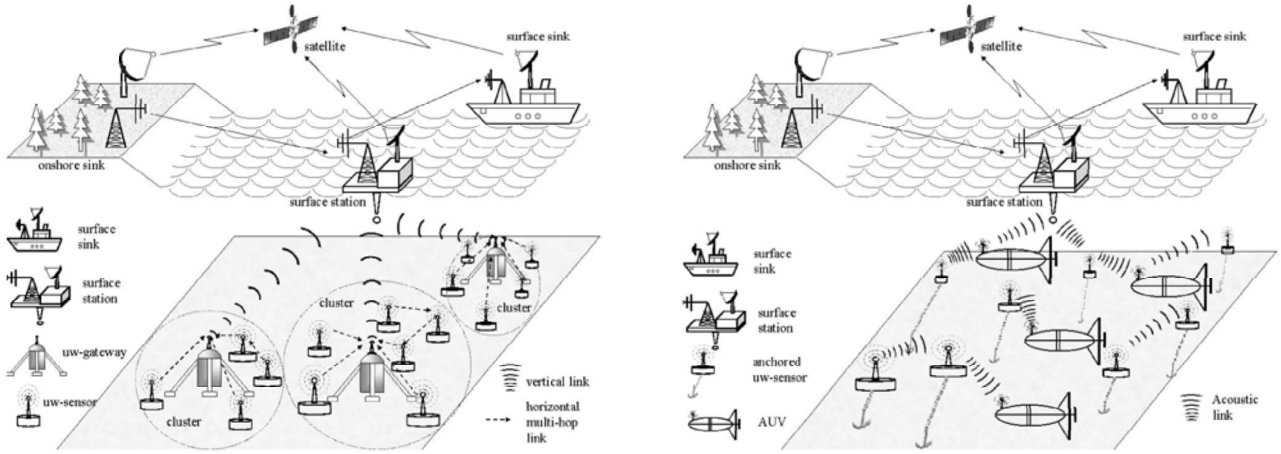


Fig. 2. A 2-D (left) and 3-D (right) communications architecture for an integrated underwater acoustic system [3].

high-throughput communication systems covering a region of a given size (e.g., in [6]) generally use similar centre frequencies and have to share the same limited acoustic bandwidth. Therefore, it is challenging to manage the acoustic spectrum such that timely and accurate navigation information is available (which is critical for proper operation of AUVs) while maintaining adequate data rates for the desired sensing application. In addition, the unreliable underwater environment renders the access coordination in such a heterogeneous network an important but challenging task.

While DSA concepts have been extensively researched recently to improve spectrum utilization in terrestrial wireless systems, we believe that they can extend to spectrum sharing amongst non time-critical applications in heterogeneous systems with limited bandwidth operating in a dynamic environment. In fact, DSA can be applied to manage the acoustic spectrum in the integrated underwater systems shown in Fig. 2 since:

- underwater acoustic links are characterized by limited available bandwidth (see Table I) and suffer from high spatial and temporal variations [3];
- it is a heterogeneous network comprising fixed and mobile devices with different physical characteristics such as size and mobility levels, and diverse communication needs;
- it supports non time-critical applications such as oceanographic data collection.

In fact, compared to terrestrial radio networks, IUASs are particularly suited for implementing DSA because the underwater nodes (sensors and AUVs) are:

- *large*, with ample physical space, memory and computational capacity for housing cognitive capabilities;
- *sparsely deployed*, facilitating effective and tractable collaborative processing.

In the following, we illustrate how DSA models can be applied to spectrum sharing scenarios in IUASs in Fig. 2.

IV. OPEN SHARING IN 2-D UNDERWATER NETWORKS

Let us consider a variant of the 2-D network in the LHS of Fig. 2, which comprises several clusters of sensors for deepsea monitoring seismic movements of the seabed. We consider one particular cluster as shown in Fig. 3, where the *master* node (gateway) serves as the data collection point or sink and, along with (up to) 4 *secondary* nodes form the navigation map [6] for the network. While all sensor nodes are assumed to be within communication range from the navigation map, each sensor node can only communicate with each of its nearest neighbour. Instead of direct links with the surface station from the master nodes, a single AUV supports the 2-D network by serving as the *link* (i) with the surface station, (ii) between partitioned segments of the cluster, (iii) between different clusters etc. Each underwater device is assumed to be equipped with cognitive components as shown in Fig. 1.

A list of the main networking activities is given as follows:

- Downlink of monitoring instructions, control strategies for the AUV etc, from master node to other devices;
- Uplink of data from master node to AUV;
- Uplink of data from other nodes to master node;
- Node-to-node communication;
- Active navigation by the AUV.

A. Open Sharing Model for DSA

A suitable DSA paradigm for supporting the above activities is Open Sharing, also referred to as *spectrum commons* [14]. Its advocates draw support from the phenomenal success of wireless services operating in the unlicensed ISM band (e.g., WiFi). With this paradigm, no user has absolute priority for spectrum access or full protection from interference; instead, mutually-interfering *peer* users negotiate and share spectrum dynamically according to their individual QoS requirement and interference limits, usually based on constraint-based optimization techniques [15] and game theory [16]. We illustrate

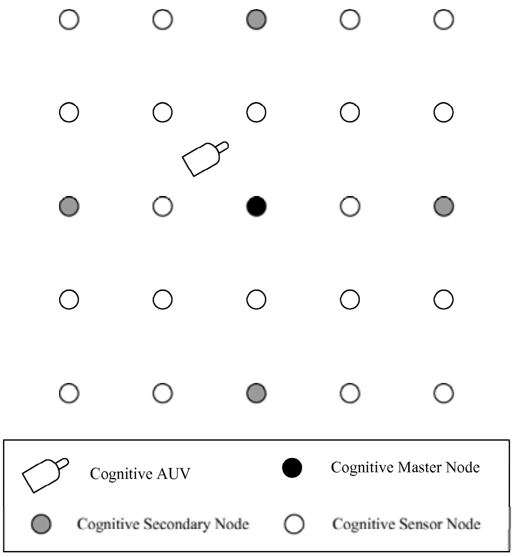


Fig. 3. A 2-D underwater network with a single AUV to illustrate Open Sharing DSA.

the mechanism of open sharing DSA in 2-D underwater networks in the following sections.

B. Network Disconnectivity

Recall that the harsh and highly variable undersea environment may cause partitioning of the sensor network by shadow zones or zones of temporal disconnectivity. We consider two such scenarios here: a *weakly-connected* and *disconnected* network, as shown in Fig. 4(a) and (b) respectively.

In Fig. 4(a), the direction of data flow is towards the top left corner, where the master node is located. Due to node failure and poor links, the network becomes weakly-connected, where link A-B becomes the bottleneck link. To mitigate this, the following cognition cycle is initiated:

- *sense*: Nodes A and B sense a reduction in the node degree due to node failure or poor links in their neighbourhood;
- *analyze and decide*: The node degree information, along with higher data volumes received, may indicate node and link failures. Link A-B is identified as the bottleneck link in the weakly-connected network;
- *act*: The master node is notified of the bottleneck link and broadcasts the assignment of more bandwidth to nodes A and B for prioritized access. The parameters for the MAC protocol are appropriately adjusted;
- *learn*: The nodes may learn from the decision to respond quicker to network disconnectivity in future.

Fig. 4(b) represents a disconnected network, where the lower-right partition is disconnected from the upper-left partition, where the master node is located. In this case, the AUV is required to serve as the temporary link between the partitions until network recovery. To activate this, the following cognition cycle is initiated:

- *sense*: Node C senses that there is no data arriving from the lower partition;
- *analyze and decide*: Based on the characteristics of arriving data, node C concludes that the lower partition of the network is disconnected;
- *act*: The master node is notified of the presence and locality of the disconnectivity. It may broadcast an instruction to the AUV to manoeuvre to the locality of nodes C and D to serve as link or data collection point, and to assign the AUV, nodes C and D more bandwidth for prioritized access;
- *learn*: The nodes may learn from the decision to respond quicker to network disconnectivity in future.

The approach proposed here complements our earlier work described in [13].

C. Uplink of Data to Surface Station

To activate the uplink of data to the surface station via the AUV, the following cognition cycle is initiated:

- *sense*: The master node monitors the data volume received and current location of the AUV;
- *analyze and decide*: Based on sensed information, the master node determines and decides when to uplink data;
- *act*: The master node broadcasts, through the instruction command, an instruction to the AUV to manoeuvre towards it and/or to commence uplink. It assigns itself and the AUV more bandwidth for prioritized access;
- *learn*: The nodes may learn from the decision for more efficient data uplink in future.

V. HIERARCHICAL ACCESS IN 3-D UNDERWATER NETWORKS

Next, let us consider the 3-D heterogeneous network as shown in the RHS of Fig. 2 for monitoring of ocean pollution. Each underwater device is assumed to be equipped with cognitive components as shown in Fig. 1. We assume that the network overlays a navigation map that comprises a master node with up to 4 secondary nodes moored to the seabed (similar to Fig. 3).

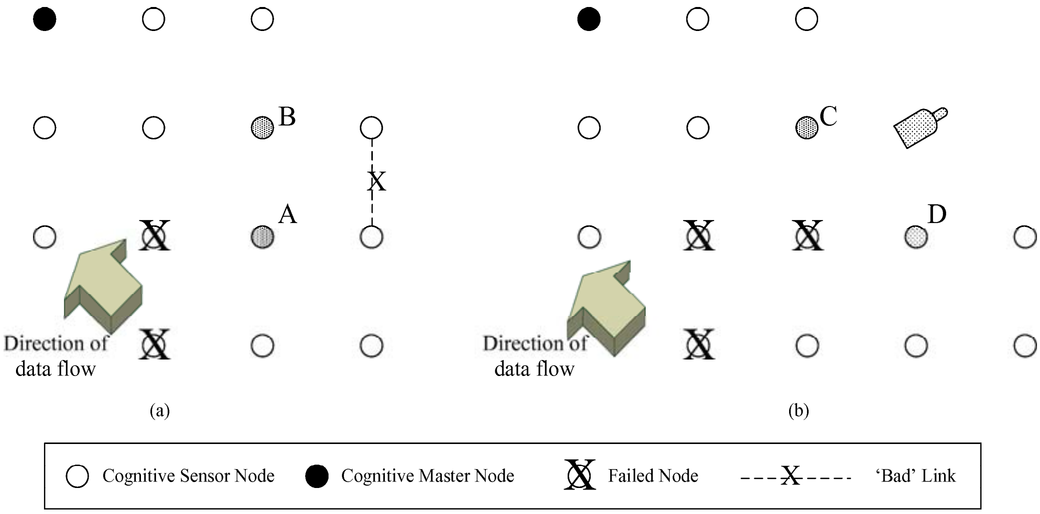
A list of the main networking activities is given as follows:

- Active and passive navigation of underwater devices;
- Uplink of data from underwater devices to surface station;
- Node-to-node communication.

Accurate and timely navigational information is crucial for the proper operation of the 3-D network. In particular, the information is vital for the prevention of collisions (i) amongst AUVs and (ii) between an AUV and the sensor node infrastructure, which will be costly to fabricate and replace. Since navigation signals have to share bandwidth with data communication signals in general, they should (i) have priority access and (ii) be protected from interference.

A. Hierarchical Access Model for DSA

A suitable DSA paradigm for spectrum management in 3-D heterogeneous networks is Hierarchical Access. Built upon a hierarchical structure with *primary* and *secondary* users, the



(a) (b)

Fig. 4. Application of Open Sharing DSA to a (a) weakly-connected and (b) disconnected network.

basic idea is to open *licensed* spectrum to secondary users and limit the interference perceived by the primary users (licensees). Hierarchical access can take the form of a spectrum *overlay* [17], [18], *underlay* [19], [20] or a combination of both [21], [22].

With spectrum overlay, each CR-enabled secondary user senses *unused* primary users' spectrum. It may then, independently or in cooperation with other secondary users, reconfigure its transmission frequency accordingly to the sensed unused spectrum. Since primary users have priority access to the spectrum, overlay users must vacate the bands when a primary user requires the spectrum. With spectrum underlay, each CR-enabled secondary user senses if primary users' spectrum is *under-used*; if so, it reconfigures its transmission power to be spectrally coincident with, while inducing tolerable interference to, primary users. The level of tolerable interference can be quantified by the interference temperature metric [23] suggested by the FCC in 2003.

The vision for this kind of opportunistic approach to spectrum access is one in which overlay and underlay techniques will allow secondary users to fit in around existing primary user regimes, using whatever technologies are suitable, and in doing so, make optimal use of the spectrum. Recently, a soft decision CR approach was proposed [24], where the transmitted power spectral density can be adapted according to the spectrum usage using spectrally modulated, spectrally encoded waveforms [25], thus simultaneously exploiting both unused and under-used spectral regions. This concept is illustrated in Fig. 5.

In the absence of a regulator to allocate underwater acoustic bandwidth, the notion of legacy users in terrestrial systems does not currently exist in the underwater environment. Hence, we re-define the notion of *primary* and *secondary* users in the underwater environment as users of *primary* and *secondary* importance at any instance, where, depending on the scenario, users may be *promoted* or *demoted*. We illustrate the mechanism of Hierarchical Access in 3-D underwater networks in the following section.

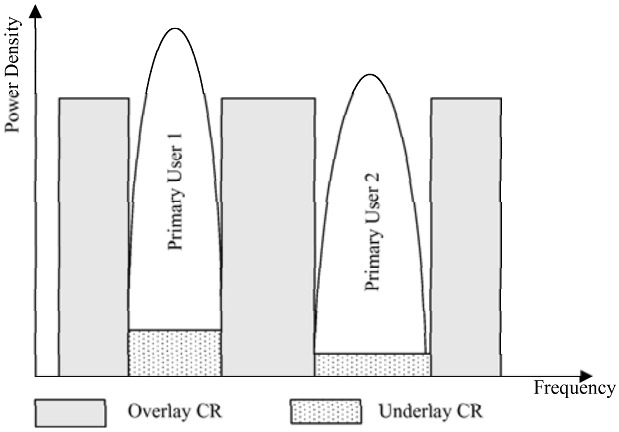


Fig. 5. Illustration of Overlay and Underlay spectrum sharing.

B. Spectrum Sharing between Navigation and Data

For the purpose of the discussion here, we assume that the system operates as a centrally-controlled time and code-division multiplexed network, as in [6]. Time is partitioned into individual frames, and the master node broadcasts an *initialization* command at the beginning of each frame to initiate all acoustic transactions. This command triggers all remaining network components to respond with individual CDMA code sequences, e.g., Kasami sequences [26]. The difference in times of arrivals are used to compute a passive navigation fix at each frame. We apply hierarchical access DSA over the remaining duration of the frame to support networking activities. This is illustrated in Fig. 6.

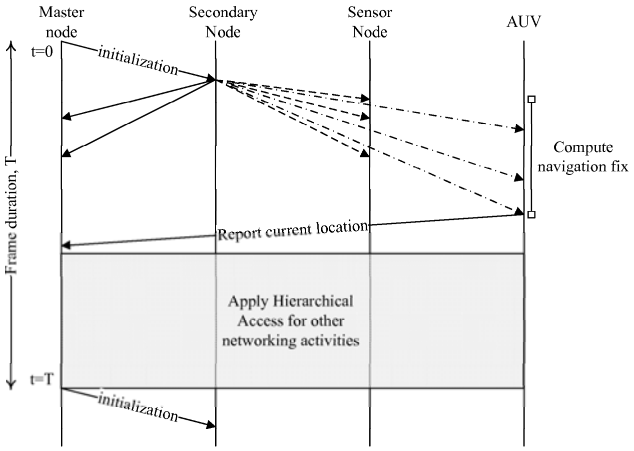


Fig. 6. Timing diagram to illustrate system operation of 3-D underwater network.

Since (active) navigation signals should (i) have priority access and (ii) be protected from interference, the master node allocates non-overlapping channels to AUVs for exchange of signals between the navigation map and AUVs for active navigation. Since not all AUVs will perform active navigation in every frame, underwater devices that wish to engage in other networking activities may do so opportunistically by initiating the following cognition cycle:

- *sense*: Each device senses the entire acoustic bandwidth in its local environment for unused and under-used spectrum, as well as other devices' requirement;
- *analyze and decide*: Devices exchange sensed information over a common control channel and determine a global channel map. Together with the user requirements, devices are allocated spectrum that overlays/underlays the primary signals;
- *act*: Devices reconfigure their transmission activities according to the allocation;
- *learn*: The nodes may learn from the decision to derive a transmission pattern for active navigation signals.

VI. DYNAMIC EXCLUSIVE USE MODEL FOR IUASS

Although a wide range of applications have been envisaged for IUASs, the ocean and seafloor of our planet remains largely unexplored. However, various initiatives have been created by national bodies to further the sustained study of the ocean. For example, the National Science Foundation (NSF) has created the Ocean Observatories Initiative in 2003 [1] with an initial infrastructure investment (of USD 200M) comprising three elements: (i) a coarse global array of buoys, (ii) a regional cabled observatory and (iii) enhanced coastal observatories. Meanwhile, on the other side of the world, the European Sea Floor Observatory Network (ESONET) consortium [27] is exploring the possibility of rigging up the Atlantic and Mediterranean coasts, and the subsea network infrastructure is likely to cost €130-220M. It is hoped that these investments, as well as others, will lead to concomitant large science investments in developing IUASs.

Such infrastructure elements are expected to span much *larger* spatial and temporal scales than the coverage of individual IUASs. We can envisage the infrastructure owner to assume the role of a regulator (as in terrestrial radio systems) that owns the acoustic spectrum over its entire coverage region. A suitable DSA paradigm to allocate spectrum to end-users who wish to deploy an IUAS within that region for scientific, military or commercial applications is Dynamic Exclusive Use.

The Dynamic Exclusive Use model retains the basic structure of current spectrum regulation policies in terrestrial radio systems, but introduces *flexibility* to improve spectrum efficiency. There are two main approaches proposed: *spectrum property rights* and *dynamic spectrum allocation*.

With the former approach, licensees are permitted to sell and trade spectrum and to freely choose technology, allowing the economy and market forces to lead to the most profitable use of spectrum. Instead of static spectrum allotment policy, dynamic spectrum allocation allocates, at a given time and region, a portion of the spectrum to a network for its exclusive use, taking into account the spatial and temporal traffic statistics of the services it carries.

VII. CONCLUSIONS AND FUTURE DIRECTIONS

The richness in the largely unexplored ocean is increasingly fueling research in integrated underwater acoustic systems (IUAS)s. Such systems comprise sensor nodes and AUVs and combine navigation, wire-less communications and acoustic sensing capabilities. While many design principles and tools for ongoing, ground-based terrestrial wireless networks may be borrowed, they have to be adapted for the underwater environment since there exist fundamental differences in the physical channel and operating regime. While terrestrial wireless networks are characterized by dense and fixed deployments of low-cost homogeneous RF nodes, the temporal and spatial variance of the underwater environment and the prohibitive costs of sensor nodes and AUVs and their deployment will drive IUASs to be sparse and heterogeneous. It is a challenging task to manage the acoustic spectrum in this new regime.

While CR-inspired dynamic spectrum access (DSA) concepts have been extensively researched recently to improve spectrum utilization in terrestrial wireless systems, they lend themselves well to our acoustic spectrum management problem. In fact, IUASs are particularly suited for implementing DSA because the underwater environment is highly dynamic and underwater devices are (i) large, with ample capacity to house cognitive capabilities and (ii) sparsely deployed, facilitating tractable collaborative processing. We illustrate how various DSA models can be applied to different spectrum sharing scenarios in IUASs.

Although CR-inspired DSA approaches potentially offer significant benefits, there are a number of key challenges (some of which are spill-overs from terrestrial radio spectrum, but exemplified in underwater environments) that need to be addressed:

- *Power* : A full CR-enabled device that actively monitors its local conditions and responds dynamically to them is expected to be power-hungry. Since underwater devices run on battery, they may have to adapt their behavior and operate as simple intelligent devices;
- *Security* : CR-enabled devices are expected to suffer from the same security problems as software defined radios such as malicious use, leading to unexpected or problematic behavior of individual devices or potentially the entire system;
- *Control* : The autonomous and adaptive nature of CR-enabled devices mean that it could be difficult to predict and control the behavior of some devices.

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