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Mobile UW-ASN Framework with RSSI based Protocol Stack for Shallow River Monitoring

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Abstract: Approximately three-fourths of our planet's surface is covered by ocean and seas, a continuous body of water that is divided into several oceans and smaller seas. Water conditions determine climate that affects life on Earth. While fresh water in lakes and rivers cover less than 1%, its contamination significantly damages ecosystems. Within this research author propose a framework with a custom protocol stack for river monitoring with hybrid network topology. The main goal is to design and implement a distributed network of navigating and fixed sensors for the river that will collect monitoring information and transmit data to the central location. Proposed framework perfectly fits into the latest notion of Internet of Underwater Things architecture and in future can be utilized not only for the shallow river monitoring but also in such extended applications as pipeline surveillance, harbour security and fish farms monitoring. Critical challenges have been identified and addressed.

Keywords: data science, mac protocol, underwater sensor network, autonomous underwater vehicle, mobile nodes, routing, protocol, medium access control, river monitoring

1 Introduction

Underwater acoustic communication is a hot research topic nowadays, since it is clearly seen as the enabling technology to establish a network of fixed and mobile underwater sensors. Underwater Acoustic Sensor Networks' (UW-ASN) applications range from environmental, climate and pollution monitoring to patrol and surveillance in security systems. A range of scientific issues in underwater communication are investigated. Unlike terrestrial wireless networks that mainly rely on radio waves for communications, UW-ASN use acoustic wave which is possessed of quite narrow available bandwidth and high propagation delay [1]. Increased interest in ocean natural resources has resulted in a growing number of infrastructures located near the sea and rivers. About

71% of the Earth's surface is covered by the ocean [2], a continuous body of water that is customarily divided into several other oceans, smaller seas and rivers. Contamination, severe temperatures and bad condition of freshwater in lakes and rivers significantly affects various ecosystems and life on land. Therefore this problem should be addressed seriously.

The Internet of Underwater Things (IoUT) is defined as a world-wide network of smart interconnected underwater objects with a digital entity [3]. Autonomous Underwater Vehicle (AUV) is an integral part of IoUT and has been used by scientific laboratories, government agencies, militaries, and private companies for over 40 years. Since then, technology has progressed allowing AUVs to become dynamic platforms for a variety of imaging, chemical, biological, acoustic, and oceanic sensors that can be changed with ease based on the needs.

The goal of this thesis is to design and implement a network protocol stack for a distributed network of navigating and fixed sensors monitoring the river, which will collect information and transmit data to the surface. The solution is based on a custom flood type routing protocol and modified medium access (MAC) protocol. AUV-RM, unlike any other existing solutions, carefully couples the routing protocol that is based on the FLOOD algorithm [4], and generic MACA protocol that was significantly tailored exactly for the RSSI based river monitoring requirements. This architecture provides higher throughput and conserves more battery power at mobile nodes by significantly reducing the number of exchanged control messages and removing packet retransmissions. To make it possible such collision avoidance methods namely RTS/CTS will be denied as they are unfeasible in underwater sensor networks environment. Instead of the old techniques, a novel Received Signal Strength Indicator (RSSI) method to identify the closest sink node will be designed and implemented. Through an analytical study, author provides thoughtful examination of the proposed AUV-RM framework and justifies the selected protocol stack demonstrating their efficiency in both AUV based underwater communication and energy consumption. The performance of the proposed RSSI based UW-ASN scheme will be evaluated through simulation, and results will be confirmed through the analytical study.

The remainder of this paper is organized as follows. In Section 2 all the major related research studies are briefly reviewed. Section 3 introduces proposed framework for RSSI based mobile UW-ASN, called AUV-RM. In Section 4 author describes in detail custom protocol stack developed for this research study. Finally, Section 5 draws the conclusion and future work.

2 Related work

Recently, various research studies have been devoted to mobile UW-ASNs. Some of them were real world field experiments with use of AUVs and different applications.

The Internet of Underwater Things (IoUT) is a technological revolution of computing and communications [5]. Using acoustic and wireless sensor technology IoUT is able to connect underwater devices into a local or global network. These devices sense, interpret and react to the environment due to the combination of the Internet, powerful tracking technologies and embedded sensors. It is also possible to interconnect underwater with terrestrial things (e.g. base stations, science vessels, smartphones). Each underwater physical object is accompanied by a rich, globally accessible virtual object that contains both current and historical information on that object's physical properties, origin and sensory context. This information is ubiquitous, available in real-time using different ways of communication (Human to Thing (H2T) and Thing to Thing (T2T)) and streamlines dramatically how to maintain and manage underwater habitats and resources. Various research challenges if IoUT have been surveyed. However, there are many of them remain wide open for future investigation.

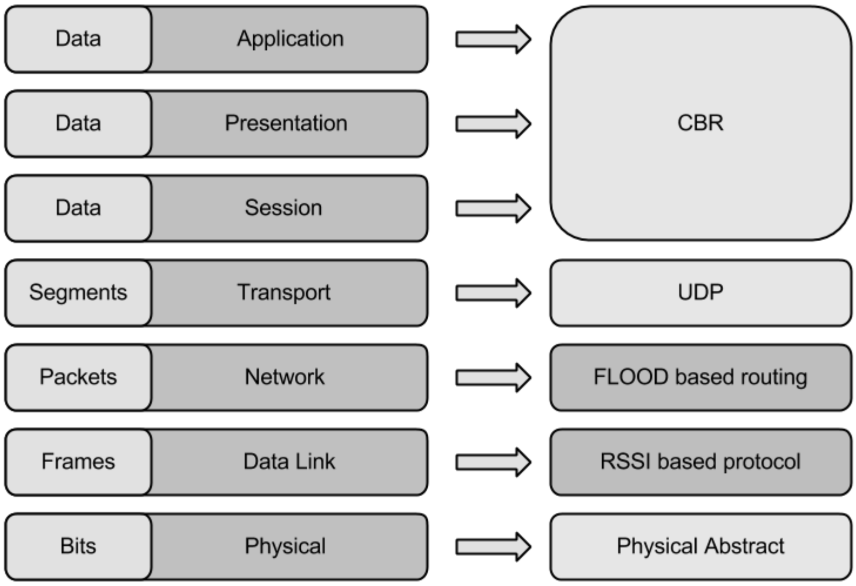
UAN10, a real world AUV based field experiment was conducted in [6]. Authors described the architectural design and implementation on AUVs of the Folaga class of a mission supervisor handling the communication, environmental sampling and decision-making tasks for the integration of the autonomous underwater vehicle as a mobile node of a wider underwater acoustic network. The main aim was to develop and test at sea an innovative and operational concept for integrating underwater and above-water sensors in a unique communication system to protect offshore and coastline critical infrastructures. the medium access was realized through a Carrier Sense Multiple Access/Collision avoidance (CSMA/CA) mechanism, while the routing protocol was based on the flood type algorithm. For underwater AUV based network communication the main focus was provide a solid network security mechanism to prevent spoofing attack (i.e., impersonation of a node) or a snooping attack (i.e., unauthorized eavesdropping of messages) may compromise the entire system's integrity and confidentiality. To equip the proposed architecture with network security features to guarantee the confidentiality, authenticity, and integrity of the exchanged messages, security overhead messages had to be implemented that has worsen the performance of the network.

Design aspects and the implementation of an acoustic network enabling underwater communications among multiple moving platforms were discussed by Nuno A. Cruz et al [7]. The SUNSET framework has been used to provide acoustic communication and networking capabilities to a set of robotic platforms. A CSMA protocol without acknowledgment packets has been used at the MAC layer on SUNSET.

3 AUV-RM framework

The proposed UW-ASN scheme for shallow river monitoring is essentially a new framework with specifically designed protocol stack, which includes flood based routing protocol and RSSI based media access control protocol. Constant Bit Rate (CBR) application is used to carry on sensing information, and abstract transmission method on a physical layer. On the Fig. 1 a particular contribution of this research paper from the Open Systems Interconnection (OSI) model point of view can be seen.

Figure 1 AUV-RM Framework as presented in OSI layer model



The following main priorities across affected media layers were identified for a new AUV-RM scheme:

- At Routing layer – as less control packets as possible, multiple short hops transmission instead if long links;
- At Mac layer – less collisions, less control packets overhead, less waiting time;
- Overall – less energy consumption.

All previously stated priorities for proposed protocol framework help to more or less overcome the most severe factors that affect performance of UW-ASN communication, such as transmission loss (1) and noise (2), which are defined as follows:

$$10logTL(d,f) = k \cdot 10log(d) + d \cdot \alpha(f) + A \qquad (1)$$

where k is the spreading factor, which describes the geometry of propagation, α(f)[dB/m] is the absorption coefficient and A [dB] is the so-called transmission anomaly which accounts for factors other than absorption including multipath propagation, refraction, diffraction and scattering [13]. The shallow water UW-A channel has higher values of attenuation than the deep water UW-A channel, while transmission loss increases with distance and frequency for both.

The signal-to-noise ratio (SNR) can be evaluated based on the transmission loss TL(d, f) and the noise power spectral density N(f). The narrowband SNR observed over a distance d when the transmitted signal has a frequency of f and power P, is given by [14]

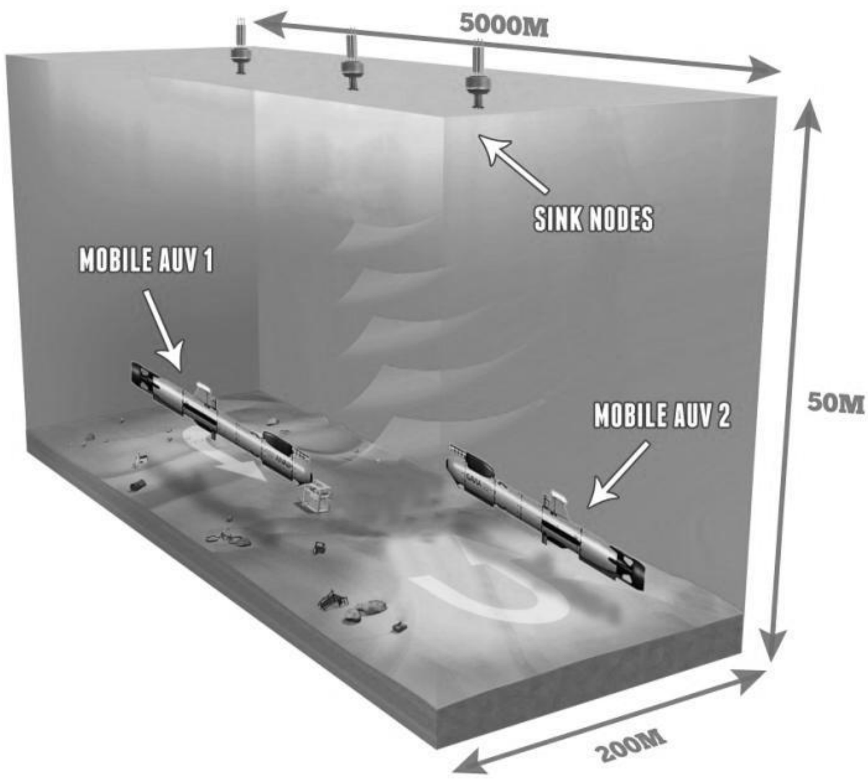
$$SNR(d, f) = \frac{P/TL(d,f)}{N(f)\Delta f} \quad (2)$$

where Δf is the receiver noise bandwidth (a narrow band around the frequency f).

We find that user scenario constraints are often neglected. In this research practical, technical and economic constraints are as important as theoretical performance. For this reason we have chosen a relatively simple MACA protocol as a basis for our MAC layer and very simple routing protocol. We intend to show that this choice will perform well in our network and traffic scenarios.

The utilized network configuration used for this research can be seen on Fig. 2. The general scenario is divided into two layers of nodes, mobile AUVs and fixed sink nodes.

Figure 2 River scenario of the proposed mobile AUV-RM architecture. Two mobile AUVs (Mobile AUV 1 and Mobile AUV 2) are navigating under the river surface in rounds while transmitting monitoring information to surface nodes (Sink Nodes).

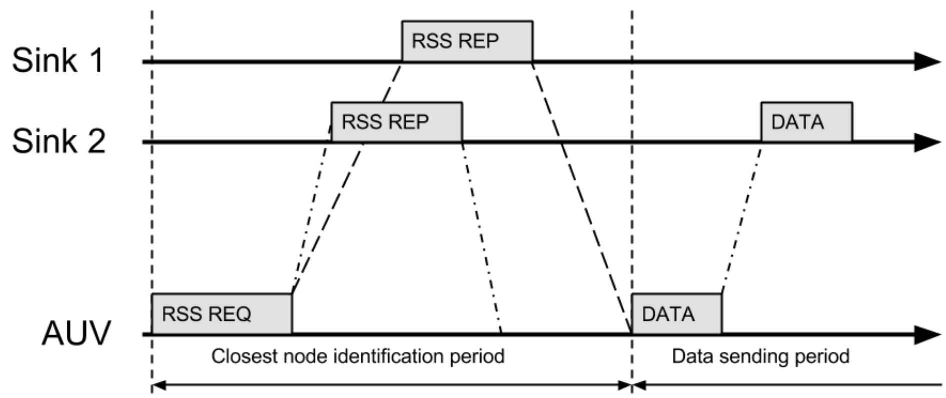


It is assumed that 2 AUVs are floating on the bottom of the river in circles and send monitoring information to sink nodes (surface stations) which in their turn pass sensing information to on-shore stations via wi-fi.

4 Protocol stack

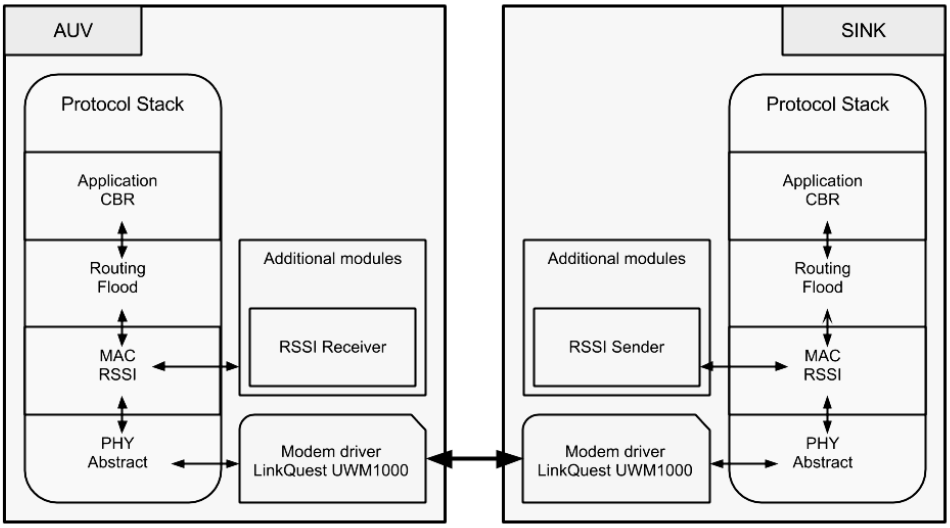
As can be seen from Fig. 2, there are two types of nodes: mobile AUV and Sink. Although they share the same protocol stack, their packet sending procedures have quite significant differences. A mobile AUV wishing to transmit the data first needs to acquire the intelligence on currently the nearest sink nodes. This functionality is achieved during the initial dialogue, where control packets are exchanged between mobile AUV and Sink nodes that are reachable by mobile AUV signal. After deciding which sink is the closest, mobile AUV sends actual data packets. Closest Sink node identification phase occurs in an interval according to slow speed of mobile AUV and distance between sink nodes, but usually it's no less than 5 minutes. This eliminates the asynchronous nature of underwater communication and the need for excessive long control packets before each data transmission, thus saving energy and improving throughput. On Fig. 3 it is shown how mobile AUV identified Sink 2 as closest because it sent reply with the stronger RSSI value information than Sink 1. Therefore, during the next long interval all the data packets will be sent to node Sink 2.

Figure 3 Closest sink node identification using RSSI before actual data transmission.



Sharing information between nodes in an UW-ASN involves a process called serialization: converting structured data information into a stream of bytes suitable for transmission over an digital acoustic communication link in a way that is efficient and can be unambiguously deserialized on the other end. However in order to transmit these bytes of data over the wireless acoustic channel, one need a PHY layer with functionalities like modulation and channel equalization for reliable transmission of digital bit streams. The key challenge underlying the PHY layer is to design spectrally efficient yet robust modulation schemes and receivers to exploit the limited bandwidth available in the underwater acoustic channel. And the purpose of AUV-RM framework is to seamlessly and in effective way integrate selected protocol stack with new MAC functional modules for underwater communication between mobile AUVs, fixed nodes and sinks. Fig. 4 depicts the overall AUV-RM architecture for AUV and sink communication.

Figure 4 AUV-RM protocol stack for mobile AUVs and Sink surface nodes.



Sharing absolutely the same proposed AUV-RM protocol stack AUV and sink node manage to perform different functionalities at the medium access control layer for sending and receiving RSSI information respectively, independently from application layer. In the next sections a closer look at MAC and routing layer implementation will be taken.

4.1 MAC protocol design

After thoughtful analysis of the current underwater MAC solutions, a generic MACA protocol was used as a foundation of the proposed protocol stack for AUV-RM scheme. The basic idea is to transmit frames without any control packets involved. In the challenging underwater environment exchanging traditional handshakes such as Request To Send / Clear To Send (RTS/CTS) packets before actual data transmission is not justified due to low propagation speed in the water, as well as spending too much of throughput and energy on overhead packets and not data packets.

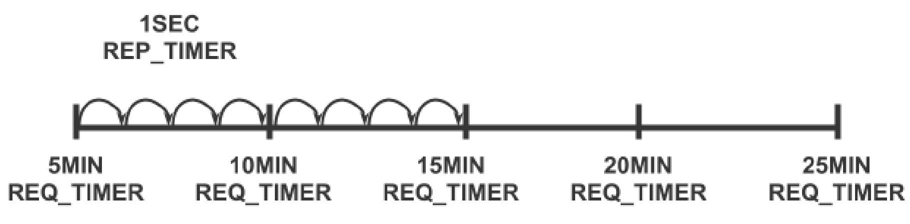
Basic MACA is not an optimal protocol regarding average delivery rate and medium utilization and several improvements of MACA for underwater communications have been proposed in the literature [8]. Author has chosen MACA as the foundation protocol mainly for its simplicity and has implemented some enhancements to it:

- RTS/CTS packets are not used to save energy and increase throughput.
- At MAC layer, the sending nodes know in advance the optimal destination node address, that was identified according to RSSI information received.
- No any retransmissions take place.

In common telecommunications, RSSI is a traditional measurement of the power present in a received RF signal by antenna. Therefore, the higher the RSSI value the stronger the acoustic signal. The same logic was applied to media access control for AUV-RM protocol stack. From the Physical layer of the proposed protocol stack *rxSensitivity* (*mW*) value is passed to the MAC layer that identifies the closest sink node destination address and unicasts a frame to this sink node. This way the proposed scheme is able to conserve more energy and reduce number of collisions. *mW* is one of the representations of a signal power that is easily converted into *dBm*, a more traditional expression of RSSI.

AUVs in proposed framework are assumed to broadcast a request of RSSI information from the sink nodes within a transmission range every 5 minutes. Taking into consideration of AUV speed of 1 meter per second, and distance between sink nodes on surface, this interval will be enough to find closest destination node every 300 meters and optimally use energy resources. Figure 5 shows two types of custom internal timers within proposed MAC protocol for sending and receiving RSSI information.

Figure 5 Timer intervals for sending and receiving RSSI information



A detailed Sending and Receiving a frame logic behind proposed MAC protocol algorithm is presented in form of call graph in Figure 6 and Figure 7.

Figure 6 Sending frames in RSSI based MAC protocol.

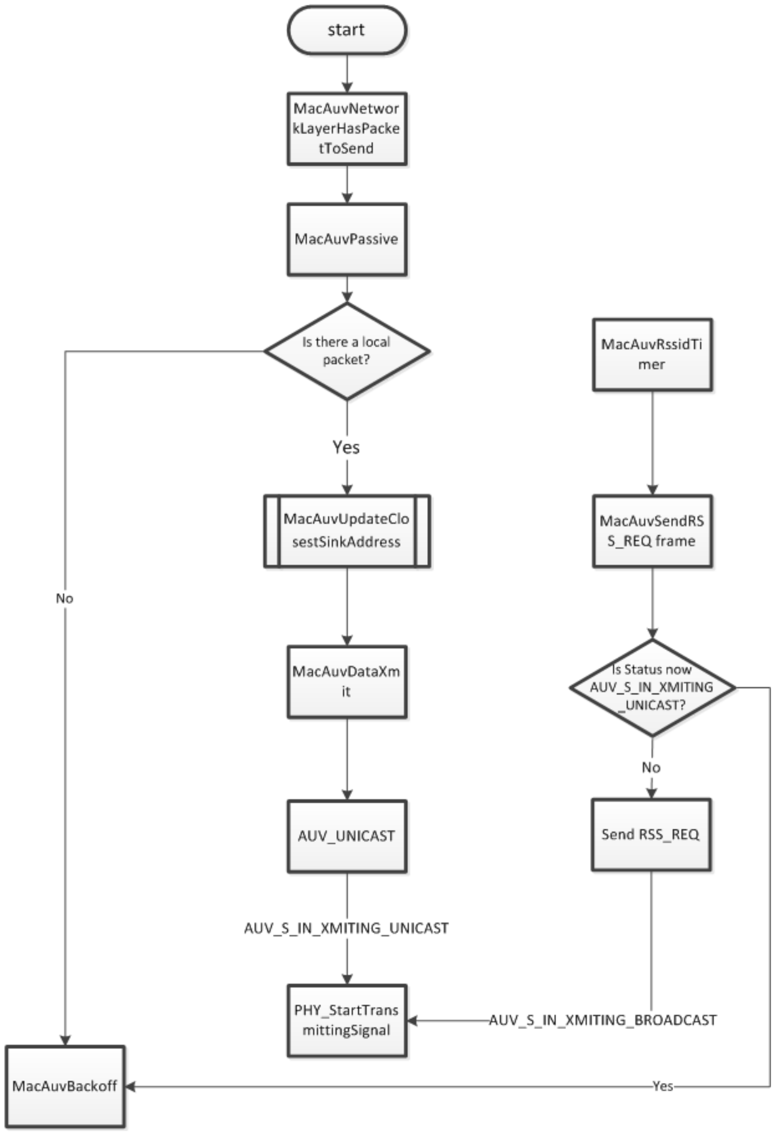
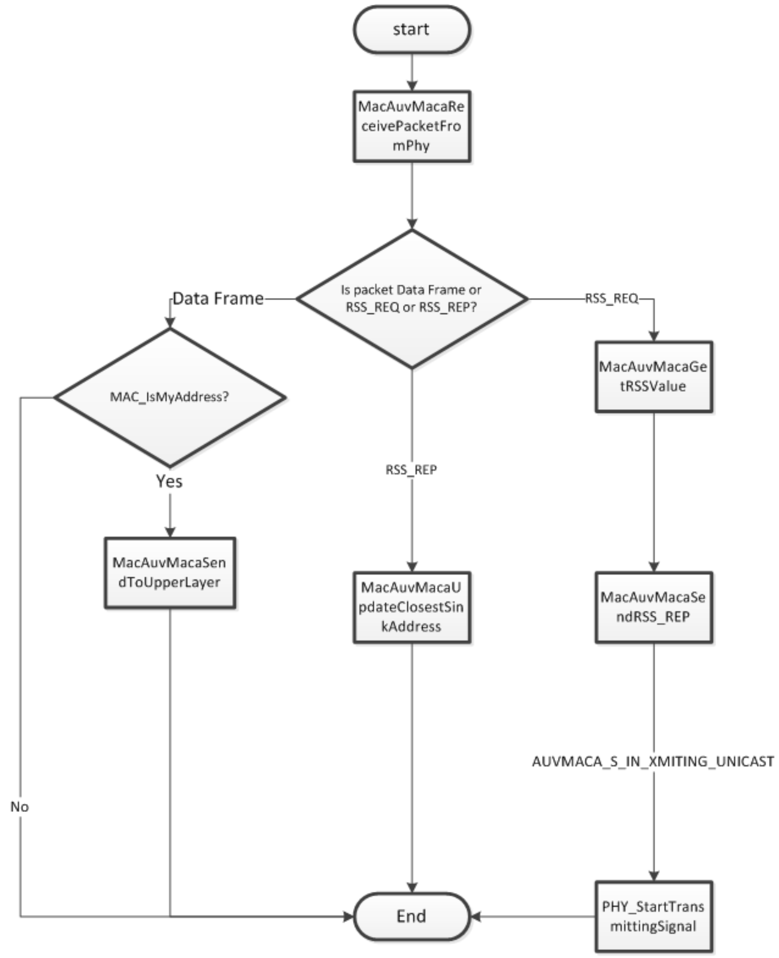


Figure 7 Receiving frames in RSSI based MAC protocol.



4.2 Routing protocol design

Routing is a fundamental issue for any network, and routing protocols are considered to be in charge for discovering and maintaining the routes. Most of the research works pertaining to underwater sensor networks have been on the issues related to physical layer [10,11], while issues related to network layer such as routing techniques are a relatively new area [12], thus providing an efficient routing algorithm, which becomes an important task. Although underwater acoustic has been studied for decades, underwater networking and routing protocols are still at the infant stage of research.

As was previously stated, the existing routing protocols proposed for terrestrial mobile and ad hoc networks usually fall into three main categories: proactive, reactive and geographical. Unfortunately, protocols belonging to all of these types are not suitable for underwater sensor networks. Proactive or table driven protocols require large signalling overhead in order to establish end-to-end routes, especially for the first time and every time when any change occur in the topology. For underwater sensor networks, it is already known that continuous node movement produces continuous topology changes. On the other hand, for reactive or on demand routing, the protocols belonging to this category are suitable for dynamic environments, but they face large delays as they require source initiated flooding of control packets for route discovery process.

AUV-RM's network discovery is based on the well-known flooding principle [3]. AUV node initiates the algorithm by sending a Flood packet. Every node hearing it repeats the Flood packet with a random delay. After a while every node will know its neighbours and the delay and signal quality parameters (attenuation) to each of them. Each node will transmit a Flood packet enough times for this information to be generated. After that every incoming packet from upper transport layer is sent on every outgoing line via broadcast (*ANY_DEST*).

The algorithm can easily be extended to handle new nodes entering the system. An algorithm like this is by nature non-deterministic. There is a chance that a link or node will not be detected due to collisions.

5 Simulation analysis

All experiments for AUV-RM framework were carried out in Qualnet 5.0 simulator. All the parameters are set to simulate river water environment, such as presented in Table 1. The simulation model itself can be referred from Figure 2.

Table 1 General simulation parameters

River dimensions	5000m x 200m
Below sea level	50m
Pathloss model	Underwater
Channel frequency	35KHz
Propagation speed	1500m/s
Applications	2 CBR with 150 bytes packet size
MAC Protocols	AUVRSS
Routing Protocols	Flood
Simulation time	160 min

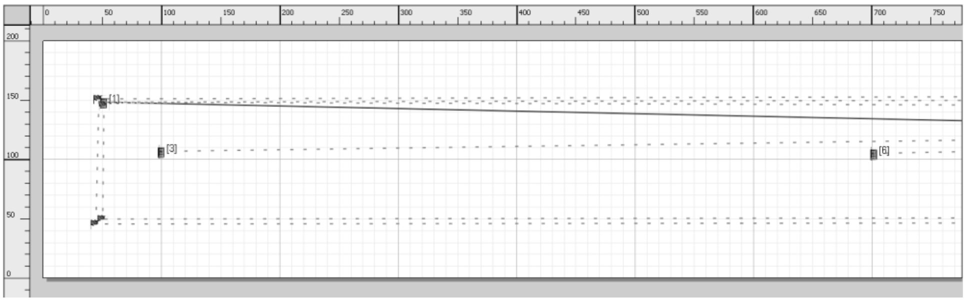
Energy consumption model is based on the commercial underwater acoustic modem LinkQuest UWM1000, a short range and low power modem for shallow water communications. Table 2 summarizes some of the acoustic characteristics of UWM1000 modem provided by LinkQuest [15].

Table 2 General simulation parameters

	Depth	Data Rate	Range	BER
UWM 1000	2000 m	960 - 19200 bit/s	0.35 km	$< 10^{-9}$

In order to test AUV-RM network performance, author, as shown on Figure 7, have created a simulation model that exactly replicate previously discussed general river scenario of the mobile AUV-RM architecture.

Figure 8 Scenario with 2 mobile AUVs and 9 fixed sink nodes on surface, partial view.



The network communication performance has been evaluated at the application level using three different metrics:

- Packet Loss (PL), computed as the number of packets sent by a client and received by the database, and viceversa. Note that the PL could differ from the packet loss at the physical level, as each acoustic packet can be transmitted up to three times by the modems, if a reception acknowledgment is not received.
- Average Delivery Ratio (ADR), defined as the average ratio between the number of received messages by a node and the number of sent messages to that node.
- Energy Consumption (EC), computed in mJoule metrics for a transmission mode.

During initial simulation of composed protocol stack it has been noticed that protocol stack of the AUV-RM framework outperforms original protocols in most of the important metrics. Absence of three way RTS/CTS control packets provides advantage with reducing collisions and therefore having more packets received. While RSSI closest node identification algorithm allows to send packets only to closest nodes. On Figure 9 the difference between comparing protocol stacks performing underwater can be seen, where *Average Delivery Ratio (ADR) = Packets Received / Packets Sent*. AUV-RM shows stable average delivery success rates even if AUVs are sending data packets every 5 or 25 seconds, whereas original protocols' performance dramatically decreases if data packet sending interval increased beyond 10 seconds.

Figure 9 Average delivery ratio (ADR)

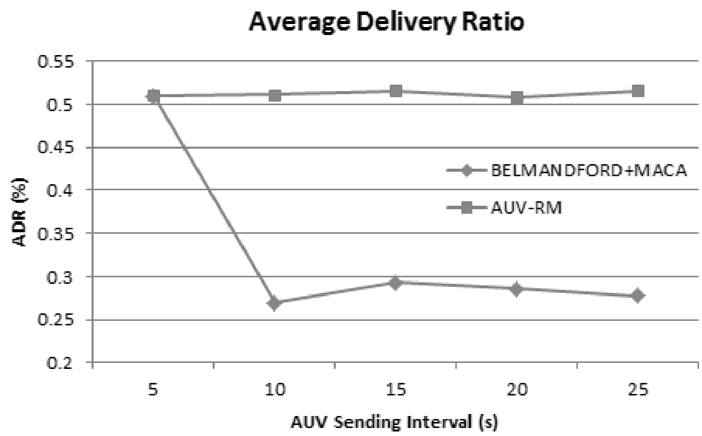
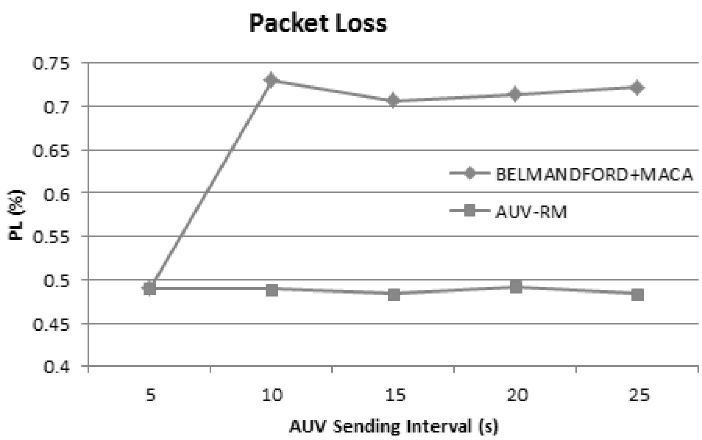


Figure 10 shows less packets were lost during transmission, where Packet Loss (PL) = Number of lost packet / (Number of lost packet + Number of packets received successfully).

Figure 10 Packet Loss (PL)



And finally, simulation has proven that some amount of energy was saved when using AUV-RM protocol stack. That is because AVUs were sending data packets only to the closest sink nodes and therefore spending less energy. Absence of RTS/CTS control overhead also reduces energy consumption. In receiver mode there were no changes in energy consumption. However, energy savings using AUV-RM were minimal.

After all, we can conclude as follows: In a given river scenario AUV based UW-ASN, instead of exchanging RTS/CTS control packets, due to mobile nature or network topology, it is better to find via RSSI information the closest destination node available and send data directly, thus obtaining better delivery rates and consume less energy.

6 Conclusion and future work

In this paper, author has proposed an RSSI based underwater sensor network framework for river monitoring. Proposed approach utilizes efficient custom routing and RSSI based MAC layer protocols in order to remove handshakes, reduce data retransmissions and conserve more battery power. Proposed algorithm first sends request for RSSI sensitivity information and after receiving replies from the nodes within a transmission range, decides which destination node will be the most optimal to send to. The simulation shows that this algorithm coupled with flood based routing in an AUV-RM protocol stack can achieve better results that the original protocols particularly in an underwater sensor network environment of the shallow river.

There are several directions for future work. AUV-RM network architecture should be extended to a wider configuration with bigger number of AUVs with subsurface and on-surface sink nodes. Performance of the proposed framework under more complex UW-ASN configuration must be thoroughly studied and evaluated using simulations to such metrics as throughput, end-to-end delay, collision rate and energy consumption.

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