Communication and Control of Autonomous Underwater Vehicles using Radio Frequency-Acoustic Hybrid MAC Schemes

by

Mehrullah Soomro

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APPROVED BY:

Assoc. Prof. Dr. Özgür Gürbüz ....Özgür Gürbüz....
(Thesis Advisor)

Assoc. Prof. Dr. Ahmet Onat ....
(Thesis Co-Advisor)

Assoc. Prof. Dr. Kemalettin Erbatur ....Kemalettin....
(Jury Member)

Assoc. Prof. Ayhan Bozkurt ....AyhanBozkurt....
(Jury Member)

Prof. Dr. Ece Olcay Güneş ....
(Jury Member İTÜ)

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to my family & my country

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Mehrullah Soomro

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Abstract

In shallow water subsea applications like control of AUVs, there is a growing demand of high-speed wireless communication links for transmitting data between AUVs and base station. Acoustic communication provide very low data rates and high propagation delays not suitable for high gain and high speed control of AUVs and on other hand radio communication is constrained by very high attenuation due to high conductivity and permittivity of water resulting in a very short working range. In this thesis, an Acoustic-RF hybrid communication system is proposed which uses acoustic link for long range communication and switches to Radio Frequency in close range. The system is tested on docking station model where AUVs get their location from transmitter at docking station and control the motors on AUVs to land on docking station. We show that this hybrid system solves the need of robust communication link as well as high data rate and low latency requirement of AUV communication. Three MAC schemes namely TDMA, Slotted ALOHA and Waiting Room are tested and compared in acoustic communication.

Otonom Sualtı Araçlarının Radyo Frekanslı Akustik Melez Orta Erişim Kontrollü Şemalar Kullanılarak İletişim ve Kontrolü

Mehrullah Soomro
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Özet

Günümüzde, otomatik sualtı robotları gibi sığ su altı uygulamalarında, baz istasyonları ve su altı cihazları arasında veri akışının sağlanabilmesi için yüksek hızlı kablosuz haberleşme hatlarına duyulan ihtiyaç giderek artmaktadır. Akustik haberleşme çok düşük veri hızlarında ve büyük gecikmelerle gerçekleşebildiğinden , su altı robotlarının yüksek kazanç ve yüksek hız gerektiren kontrolleri için uygun değildir. Diğer yandan suyun yüksek iletkenliği ve dielektrik sabitinin neden olduğu yüksek kayıplar nedeniyle radyo haberleşmesi de çok kısa mesafelerde sağlanabilmektedir. Bu tezde akustik-rf hibrit haberleşmesi yapılabileceği öngörülmektedir. Bu sistem uzun mesafelerde akustik haberleşmeyi daha kısa mesafelerde haberleşmenin radyo haberleşmesi olarak devam etmesini hedeflemektedir. Sistem, bir kalkış istasyonu modeli üzerinde test edilmektedir. Sualtı cihazları,lokasyonlarını bu kalkış istasyonu üzerinde bulunan bir vericiden almaktadır. Bu hibrit modelin, sualtı robotik haberleşmesi için ihtiyaç duyulan sağlam, güvenilir, yüksek hızlı ve düşük gecikmeli haberleşme kanalı ihtiyacını çözdüğü

gösterilmiştir. TDMA, Slotted ALOHA ve Waiting Room protokolleri test edilmiş ve akustik haberleşme ile karşılaştırılmıştır.

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Chapter 1

Introduction

1.1. Problem Definition

Underwater sensor networks and underwater networked control systems have gained lot of popularity in research field. Interest in understanding the hidden world beneath water and exploiting its resources have pushed researchers in developing applications and technologies for underwater environment. These applications require stable underwater communication links with high data rate and low latency.

Whenever communication in underwater is required, acoustic communication technology is considered because it provides stable links at long ranges. Acoustic technology uses hydrophones to send and receive acoustic or sound waves containing information. Sound waves are converted to electrical signals at receiver and information is extracted. Acoustic communication is proven technology for underwater scenario and it has been studied, experimented, standardized and implemented over decades of years because of its applications in submarines, oil and marine exploration and underwater wireless sensor networks [1, 2]. It is proven for deep underwater applications, but for shallow water applications, it is severely affected by time-varying multipath arrivals and high levels of ambient noise due to tidal waves and other movements [3, 4]. Additionally acoustic link provides very low data rates in range of around 10 kbps and acoustic wave propagation speed is also very slow, at 1500m/s [5]. This data rate and propagation speed is not enough for emerging applications like docking at underwater base and swarms of AUVs (Autonomous Underwater Vehicles) for the construction of offshore windmills. For control and coordination of AUVs large data rate and small sampling time is required [6]. So we have to look into other communication technologies.

Optical systems is an alternate that can offer very high data transmission rates in order of Gigabits per second (Gbps), at very high speed, however it requires line of sight(LOS) and very clean and clear water which is a problem in shallow waters where these are prone to backscatter from suspended matter and ambient light. Optical systems are therefore generally limited to extremely short distances typically less than 3 meters [7].

Another contender is RF (Radio Frequency) communication which provides high data rate and low propagation delay without the condition of LOS component like optical communication. Although it provides very stable and long range communication link in air, it suffers high, frequency dependent, absorption in water causing high path loss which limits the range of operation and require careful calibration of frequency, antenna design and transmission power [8]. Despite this, RF link is cheaper and more reliable than optical link and with proper calibration, it provides high speed connection fulfilling our requirements. For example the data rate of underwater RF link for range less than 10 meters in freshwater is around 10 Mbps.

Considering limitation of data rate in acoustic link and working range in RF link, this thesis suggests a hybrid communication model that uses acoustic link for long range communication and shifts to RF communication for short distance but high data rate communication. At short ranges, cooperation between AUVs require high bandwidth, whereas at long ranges, low bandwidth information exchange is tolerable.

1.2. Contributions

The contributions of this thesis are summarized as follows:

In this work, we have made a control system to model AUVs landing on a docking station. The AUV is modeled as a second order system. The distance of the AUV to the docking station is controlled by a PD controller which receives the distance measurement feedback from the docking station through a communication link. The output of the system i.e. position of the AUV is detected by the docking station which sends it back to the AUV using a communication link. This is an underwater networked control system model.

We have created the simulation environment as a simplified model to test the hybrid system. In this model, multiple AUVs track the error signal representing the distance to the docking station, and the docking station detects and sends the location information of AUVs using the communication link. AUVs use this information to calculate the control signal which they apply to their motors.

We have proposed a hybrid communication system which uses an acoustic link to send position feedback to the AUV at long distance and shifts to high speed RF link at short distance.

We implemented three Medium Access Control (MAC) schemes namely TDMA, Slotted Aloha and Waiting Room, in the AUV portion of acoustic link to compare their result and find the best one for this model.

We compared the three MAC schemes by looking at their performance for increasing number of AUVs from 1 to 10 under disturbance. We evaluated performance by looking at how smooth the trajectories of AUVs are and how long it takes to dock.

We also found the optimized MAC schemes for 3 AUVs and compared their result.

We compared the performance of hybrid communication system with acoustic only and RF only system for 3 MAC schemes under varying disturbance input and for different number of AUVs. We found the hybrid system better in control performance and more robust to disturbance as compared to acoustic only system and more practical than RF only system.

1.3. Organization

This thesis is arranged as follows. In Chapter 2, we provide detailed background of underwater acoustic communication technology and underwater RF communication. Chapter 3 details the system models, the 3 MAC protocols implemented and the hybrid communication system design and implementation. In chapter 4 we define the model setting and parameters and give simulation results. Chapter 5 concludes the main findings of this thesis and future work.

Chapter 2

Background

Underwater environments include deep oceans, shallow coastal waters, lakes and rivers. Application like remote control in off-shore oil industry, water quality monitoring in environmental systems, collection of data in deep sea exploration, data collection from sensor networks at seashores for measurement of soil erosion, voice link between divers, datalink between swarms of AUVs and others require underwater wireless communication. Most commonly used communication technology is acoustic technology but optical and RF technology is also being studied and tested in underwater environment. This chapter offers background knowledge of acoustic communication and radio frequency (RF) communication and lastly compares the two underwater wireless communication technologies.

2.1. Underwater Acoustic Communication

Acoustic technology is the primary form of communication technology in underwater environments. Acoustic technology uses acoustic or sound waves which are low frequency waves that offer small bandwidth but have long wavelengths. Thus, acoustic waves can travel long distances and are used for relaying information over kilometers [9]. The acoustic waves are transmitted and received using hydrophones which convert electric signals to acoustic waves using pressure oscillations and vice versa. Figure 1 represents a typical acoustic system.

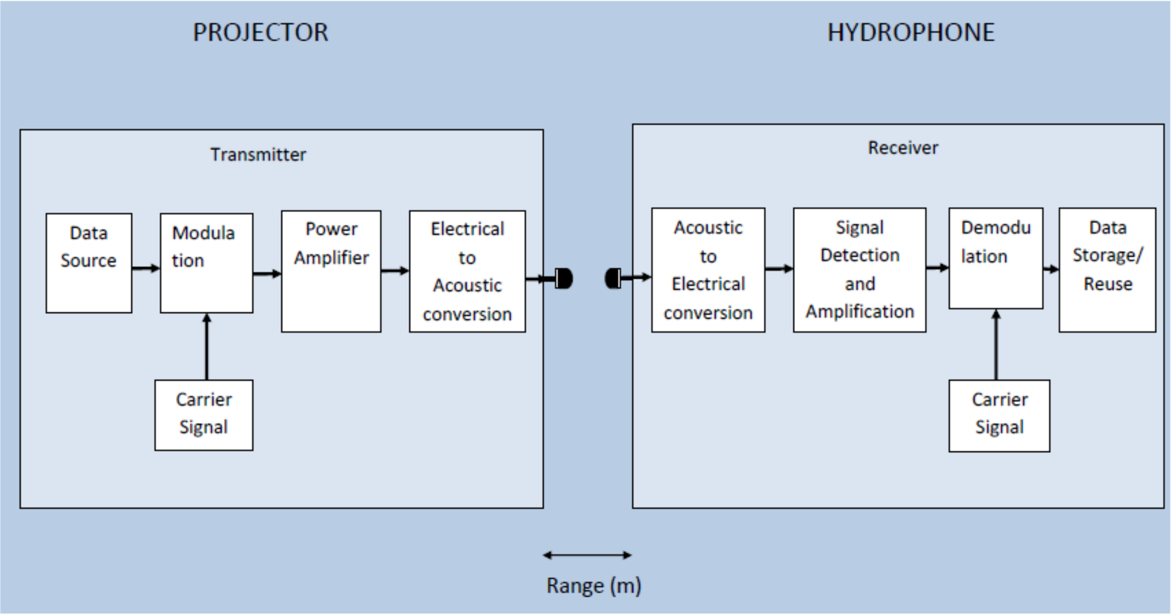


Figure 1: Block diagram of Projector and Hydrophone [5].

2.1.1. Evolution

The first recorded use of acoustic waves for underwater communication dates back to time of Leonardo Da Vinci, who discovered the possibility of detecting incoming ships from long distances by listening on a pipe submerged undersea. Two way underwater communication was first developed during first World war II for military purposes. USA in 1945 developed an underwater telephone as one of the first underwater communication systems for communicating with submarines [10]. This system used acoustic waves in 8-11 kHz frequency range, and was capable of sending acoustic signals over distances of several kilometers. The emergence of VLSI technology enabled the development of new generation of acoustic systems operating at moderate power levels and capable of implementing complex signal processing and data compression at submerged ends of an underwater communication link [11].

In last two decades, there have been significant advancements in the development of acoustic communication systems in many areas including throughput and operational range. Acoustic systems have been successfully used to control remotely operated vehicles (ROV) and Autonomous Underwater Vehicles (AUVs) [1]. There have been successful video transmissions from the bottom of ocean (6500m) to ship on surface using acoustic systems [12]. Successful experiments of acoustic communication at 50bps between moving nodes at depth 75m source and 200m depth destination at horizontal distance of 550km were conducted [13]. With the advancement of technology, new applications like Underwater Wireless Sensor Networks (UWSN) and swarms of AUVs have been developed [14]. But all the applications are constrained by low data rate and slow propagation speed of acoustic systems. There also have been studies about the adverse effect of acoustic technology on marine life [26].

Current research is focused on the development of efficient signal processing and communication algorithms, efficient coding and modulation schemes and MAC schemes. In underwater communication networking, work is well underway in design of protocols that are appropriate for long propagation delays and limited power available in the underwater environment [2, 15].

2.1.2. Acoustic Channel Characteristics

The Underwater acoustic communication channel arguably is one of the toughest environments for data communication. Its optimal channel capacity for long ranges is less than 50kbps for Signal to Noise Ratio (SNR) of 20dB with current modem capacities of less than 10kbps [5]. There are commercial products like Evologics S2C R 48/78 Underwater Acoustic Modem [16] that offers maximum 31.2kbps data rate at range of 1000m. To predict how the channel behaves becomes extremely difficult as conditions are constantly changing in underwater environment. The changing parameters include changing surface due to seasons and weather and changing physical surroundings of sea floor, depth, salinity and temperature. A good acoustic channel model must take into account all of these parameters to correctly mimic the channel behavior. On the other hand, we can ignore some of the parameters if we are considering controlled or constrained working environment. For example we can ignore depth of water and surface movement if we are working in a shallow lake.

2.1.2.1. Path loss model

Acoustic propagation in water is influenced by the frequency of the channel, the physical and chemical characteristics of the water and by the geometry of the environment. Path loss is the measure of loss of signal strength as it travels from projector to hydrophone. The Acoustic channel path loss model is as follows [5]:

The Path loss for underwater acoustic channel can be divided to two components; Spreading loss and Absorption loss.

Spreading loss is due to expanding area that the acoustic signal encompasses as it spreads outwards from the projector. Spreading loss is given by:

$$PL_{spreading}(r) = k \times 10 \log(r) \qquad dB \qquad (1)$$

Where r is distance in meters and *k* is the spreading factor.

The value of spreading factor depends upon the geometric shape of the communication channel. Spreading is spherical (*k*=2) when channel is unbounded because waves from source propagate out in all directions and is cylindrical (k=1) when channel is bounded. Spherical spreading is rare in oceans but it may exist in shallow waters and short range communication environment [17]. As we are dealing in the latter case, we will use k=1.5 Absorption loss is the loss of signal in form of heat energy due to friction and ionic relaxation as the acoustic wave makes it way from projector to hydrophone in the water medium as follows:

$$PL_{absorption}(r,f\,) = \; 10log\big(\alpha(\,f\,)\big) \times r \qquad dB \qquad (2)$$

Where r is distance is in kilometers and α is the absorption coefficient.

α is reasonably high in seawater as compared to lake or river water as it highly influenced by ionization relaxation factor. α is given by Thorp's expression as:

$$\alpha(f) = \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100+f^2} + 2.75 \times 10^{-4} f^2 + 0.0033 \qquad dB/km \qquad (3)$$

Where f is the frequency of acoustic signal in kHz.

Total path loss is given as sum of spreading and absorption losses as:

$$PL(r,f\,) = \; k \times 10log(r) + \alpha(\,f\,) \times r \times 10^{-3} \qquad dB \qquad (4)$$

For short ranges, spreading loss dominates over absorption loss, but in long ranges it can be ignored.

The path loss is subtracted from signal strength at source to get signal strength at receiver.

$$P_r(dB) = P_t(dB) - PL \qquad (5)$$

Then Rayleigh fading model is applied on received power to simulate the effect of shadow fading. Rayleigh fading is approximated by random exponential function.

Received power should be greater than receiver threshold and should be distinguishable from noise.

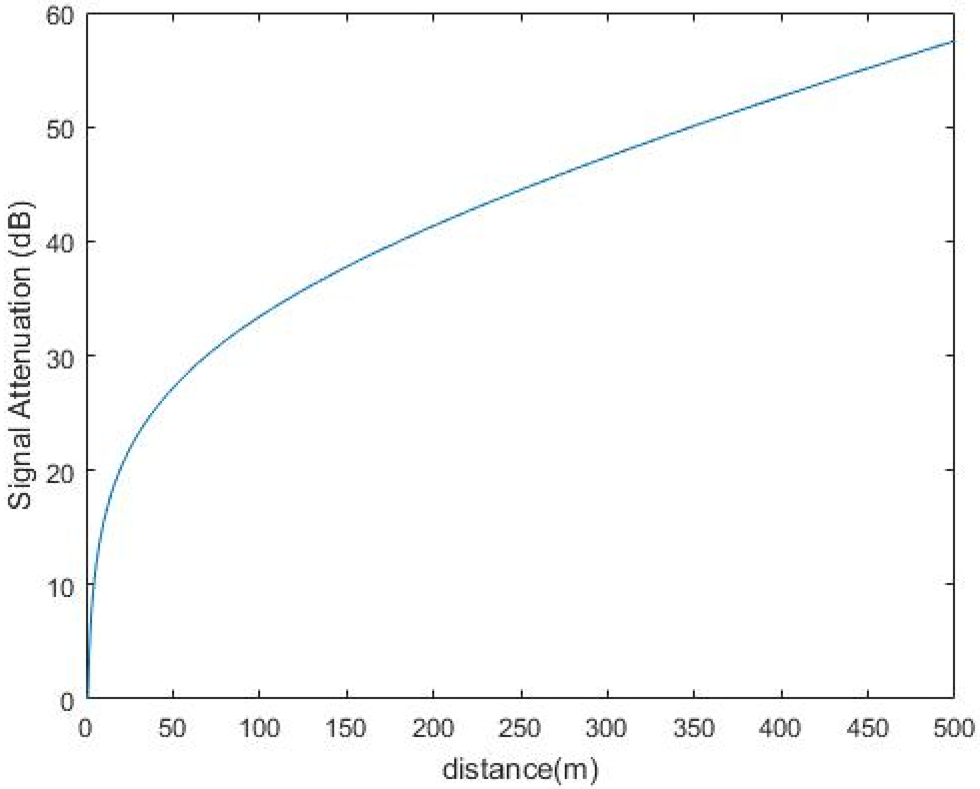


Figure 2: Path loss of 100 kHz acoustic signal

2.1.2.2. Multipath and Noise

Multipath and noise are big hurdles in acoustic signal transmission. Multipath is a phenomenon in wireless communication where multiple copies of the same signal with varying signal strength and propagation delay are received due to reflections and refractions of original signal at water surface and floor. Multipath's effect increases in shallow waters. These multipath signals are main cause of Inter Symbol Interference (ISI) in digital signals.

Acoustic noise in the water environment appears as a signal at the hydrophone. The actual received signal should be distinguishable from noise and hence should have higher power from noise intensity. There are three main sources of noise underwater; ambient noise which is represented as Gaussian noise, self-noise of the vehicle and intermittent noise which include biological noises. Figure 3 shows an underwater acoustic environment.

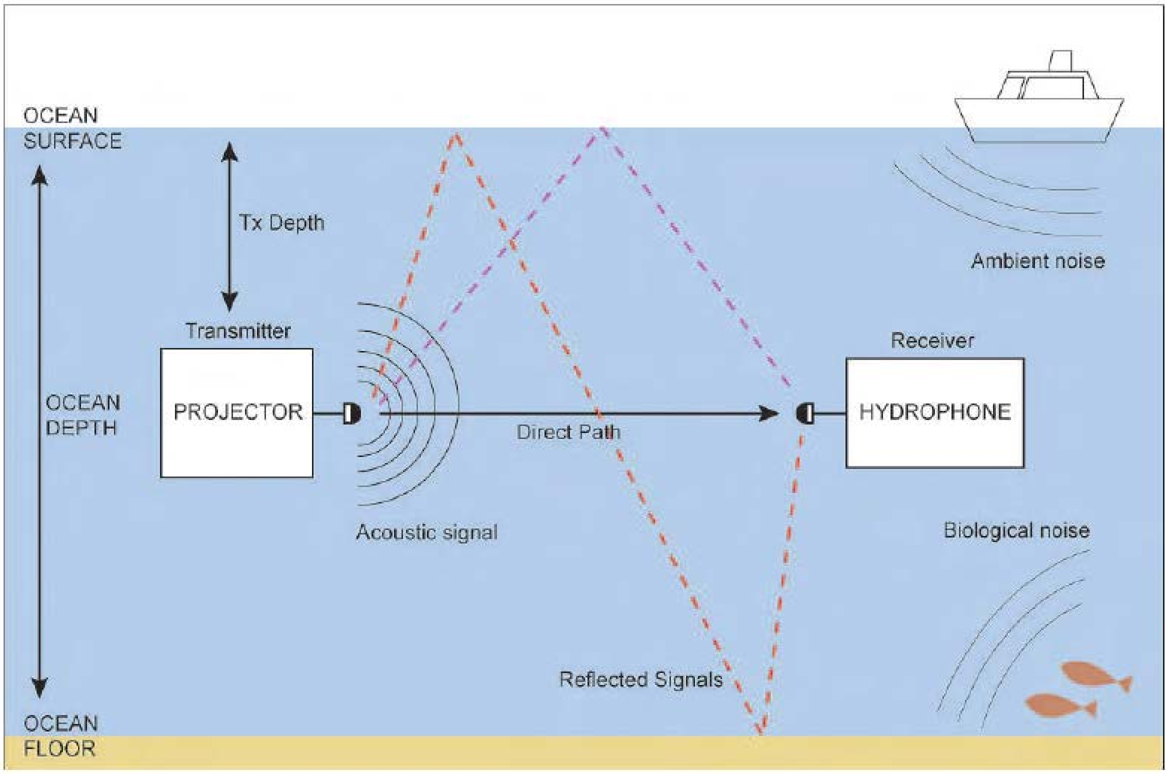


Figure 3: Underwater Acoustic Environment [5]

2.1.3. Medium Access Control Protocols

Medium Access Control (MAC) protocols are used to regulate and coordinate signal transmission from multiple sources or nodes using a shared communication channel. They are designed to optimize channel usage by minimizing chances of collision of signals and also have to deal with energy consumption, scalability and latency. There have been many MAC schemes suggested for acoustic communication and a lot of new work is being done to make more efficient MAC schemes. Table 1 by [2] gives a list of latest MAC protocols suggested by researchers working in underwater communication.

Table 1: Existing underwater acoustic MAC protocols [2]

Category	**Protocol**	**Year**	**TDMA**		**CDMA**	**Random**	**Cluster**	**Hand**	**Requires**	
			Fixed	**Adaptive**		**Access**		**Shaking**	**Sync**	**Prop. Time**
FDMA-based	Seaweb	1998	x						x	x
	UWAN-MAC	2009			x	x				
	UW-MAC	2010	x		x	x	x		x	x
CDMA-based	EDATA	2012	x		x		x		x	x
	HRMAC	2013		x	x	x	x		x	x
	ST-MAC	2009	x						x	x
Fixed	STUMP-WR	2010	x						x	x
TDMA	MDS-MAC	2012	x				x		x	x
	Distrib.Simplified	2011	x				x		x	x
	S-Aloha	1975		x		x			x	x
	PDT-Aloha	2011		x		x			x	x
Adaptive	S-FAMA	2007		x		x		x	x	x
TDMA	HRS-TDMA	2011		x					x	x
	UWAN-MAC	2007		x					x	x
	COD-TS	2013		x	x	x		x	x	
	Ordered CSMA	2007		x						x
	Aloha-CS	1970				x				
Direct	CSMA	1975				x				
	MACA-U	2008				x		x		
	PCAP	2007				x		x		x
Random	SF-MAC	2012				x		x		
Based	DACAP	2007				x		x		
	FAMA	1995				x		x		
Reservation	COPE-MAC	2010				x		x		x
	R-MAC	2007				x		x		x
	DOTS	2010				x		x	x	x
	RIPT	2008				x		x		x
	T-Lohi	2008				x				

MAC protocols can be divided into two main categories; contention-free and contention-based schemes. Contention free schemes make sure collision never occurs by assigning separate frequency slots (FDMA), time slots (TDMA) or codes (CDMA). Figure 4 [2] illustrates the concept.

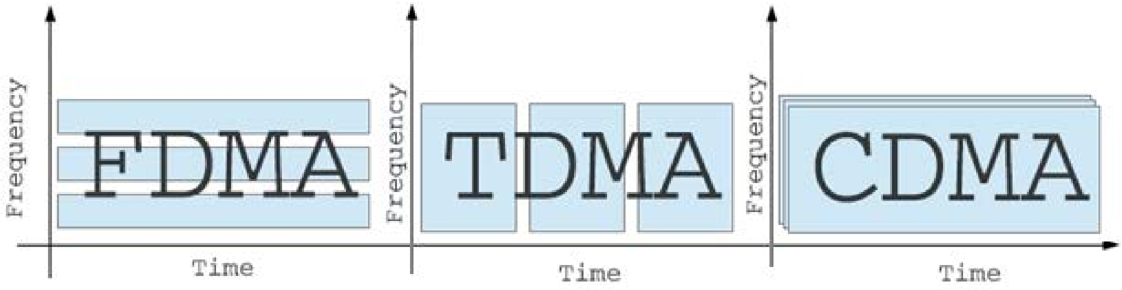


Figure 4: Contention free MACs

On the other hand, contention-based MAC protocols do not pre-allocate resources but rather allow nodes to contend with each other for acquiring the channel. This class of protocols use some form of random access to distribute the access by nodes and usually have some sort of mechanism for collision recovery.

There has been a lot of development in underwater acoustic MACs, and also in adopting of existing MACs for underwater acoustic networks for different applications. Some of them are described in [15, 18-22]. [2] provides a comprehensive study of existing underwater MAC protocols, which is summarized as follows:

Firstly in contention free protocols, FDMA was used for inter-cluster communication in early phases of seaweb project but was deemed impractical for underwater communication as it reduces the already small bandwidth of acoustic link and is vulnerable to multipath and fading. CDMA uses all the bandwidth available at all times and uses codes to distinguish between recipients of transmissions. Cross correlation however implies that long codes are used which reduces the data rate. CDMA has been successfully used in combination with other MAC protocols like Aloha and TDM, and is mostly used in inter-cluster communication, in cluster based networks. Fixed and adaptive TDMA assigns time slots for each node and require time synchronization and guard times which are comparatively difficult to implement in underwater acoustic networks and add more overhead due to long propagation delays. Nevertheless, TDMA has been implemented in many systems, especially short range ones like clusters, where propagation delay is less.

Researchers have used centralized and distributed time synchronization techniques and position based delay calculation for time synchronization and guard times respectively.

Moving to contention based protocols, slotted aloha protocol works similar to pure aloha, where nodes wait a random time before transmitting, except that in S-Aloha they can only transmit at the start of next slot. However in underwater acoustic communication, large propagation delay cause transmissions from different nodes to overlap, even though they are in different slots, resulting in degradation of performance to that of pure Aloha. Researchers tried to cope with this problem by adding some percentage of propagation delay time in the slot time. They observed 17-100 % improvement in performance in different conditions and slot times. Another contention based protocol is (CSMA) Carrier Sense Multiple Access, which senses the channel until it becomes free, then waits for a random time interval before transmitting.

2.2. Underwater Radio Frequency Communication

Electromagnetic waves are synchronized oscillations of electric and magnetic fields. These fields oscillate perpendicular to each other and to the direction of wave propagation. Visible light, infrared waves and ultra violet waves are all EM waves [23]. Radio Frequency (RF) waves are any EM wave in the frequency range 3kHz to 300 GHz [24] and are mostly used in communication. RF have been extensively researched, modelled, experimented, standardized and implemented in all forms of terrestrial communication throughout the world. But for underwater environment, it remains relatively untouched.

2.2.1. Evolution

Underwater radio communication was studied with great interest at the start of 20th century up until 1970s. Very low frequency (VLF) radio waves (3-30 kHz) were used in the early 1900's to communicate from station on land with submarine few tens of meters undersea. Because of low frequency, the data rate is very low. Medium and high frequency radio waves offer high data rate but undergo very high attenuation, consequently significant breakthroughs were not expected in submarine radio communication [25].

In present time, underwater applications requiring short-range, high data-rate and low latency are being extensively developed. Acoustic link is unable to fulfill these requirements which have brought forth the opportunity to re-evaluate RF EM capabilities in the underwater environment. With the advancement in digital technology and signal compression techniques, RF might be suitable for many short range underwater applications.

In recent times, there has been a lot of interest by the research community in the underwater RF communication. In [8], authors compare acoustic, optical and RF technology for underwater environment and suggest a Underwater Sensor Network with RF as communication link. In [27] models for RF path loss in different underwater conditions are created. [28] investigates EM waves propagation in sea water by experimentation. They were able to receive transmission at 5 MHz at 90 meters distance with a transmit power of 5W. [29] compares the experimental results of [28] with its own pathloss model. [30] investigates EM waves propagation from air into fresh water. They found that an optimum frequency range of 3 – 100 MHz for sending signal to 5m depth. [31] discusses the feasibility of RF waves in underwater sensor networks. They conclude that higher frequency signals suffer very high attenuation; hence providing very short range and low frequency RF communication require very large antennas. [32] models RF communication at 300-700 MHz range and [33] at 2.4 GHz. [34] experiments of multi carrier broadband RF communication underwater. [35] suggests a RF-Acoustic hybrid communication link. RF link is used to communicate from land to buoys at sea surface and vice versa then acoustic link to send from buoys to underwater nodes and vice versa.

2.2.2. RF channel characteristics

Underwater channel characteristics are a topic of debate in the research community and there is still not a single standardized pathloss model on which all agree upon. As seen in the previous section, there have been different pathloss models suggested by researchers, each have their own limitations, assumptions and constraints. Propagation speed of RF waves in freshwater is 3.35×10^7, about 9 times slower than RF speed in air but still about 22000 times faster than acoustic wave propagation speed. RF propagation speed in sea water is slower in sea water as it depends on conductivity [27].

2.2.2.1. Pathloss model

The RF channel is high bandwidth and high propagation speed channel but in underwater has high path loss. The data rate for less than 10m distance in freshwater at frequency 10 MHz is taken as 3Mbps [8].

The path loss model for RF link depends highly on frequency with contribution from conductivity, permittivity and permeability of water. It is given in [36] as:

$$PL = L_{\alpha,\varepsilon} + L_R \qquad dB \tag{6}$$

Where $L_{\alpha,\varepsilon}$ is the attenuation in water due to permittivity and conductivity of water and L_R is the reflection loss at water-air boundary.

$$PL = R(\gamma) \times \frac{20}{\ln(10)} \times D + 10\log(|T|^2 R\{\frac{\eta_o}{\eta_{water}}\}) \tag{7}$$

Where R means real part, D is distance. γ is propagation constant given by

$$\gamma = j\omega\sqrt{\mu\varepsilon - \mathrm{j}\frac{\sigma\mu}{\omega}} \tag{8}$$

Where $\omega = 2\pi f$,

$\varepsilon = \mathrm{permitivity} = \varepsilon_o\varepsilon_r = 80(freshwater) \times 8.854 \times 10^{-12}$

μ is permeability $= 4 \times \pi \times 10^{-7}$

T is transmission coefficient for normal impedance.

Relative permittivity is a complex number whose value depends upon salinity, temperature and operating frequency, but for freshwater it can be assumed a constant value of 80.

$$T = \frac{2\eta_0}{\eta_o + \eta_{water}} \tag{9}$$

Where η_0 is intrinsic impedance of air =377Ω

$$\eta_{water} = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\varepsilon}} \tag{10}$$

Where σ is conductivity of water. Fresh water conductivity is 0.01S/m. Seawater conductivity varies from 2 to 8 S/m depending upon presence of ions. Typically value of 4S/m is used for seawater. Conductivity plays a very important role in pathloss.

As we are not crossing the water-air boundary in this thesis, we will only use real part attenuation loss in water. So pathloss is:

$$PL = R(j\omega\sqrt{\mu\varepsilon - \mathrm{j}\frac{\sigma\mu}{\omega}}) \times \frac{20}{\ln(10)} \times D \qquad \text{dB} \tag{11}$$

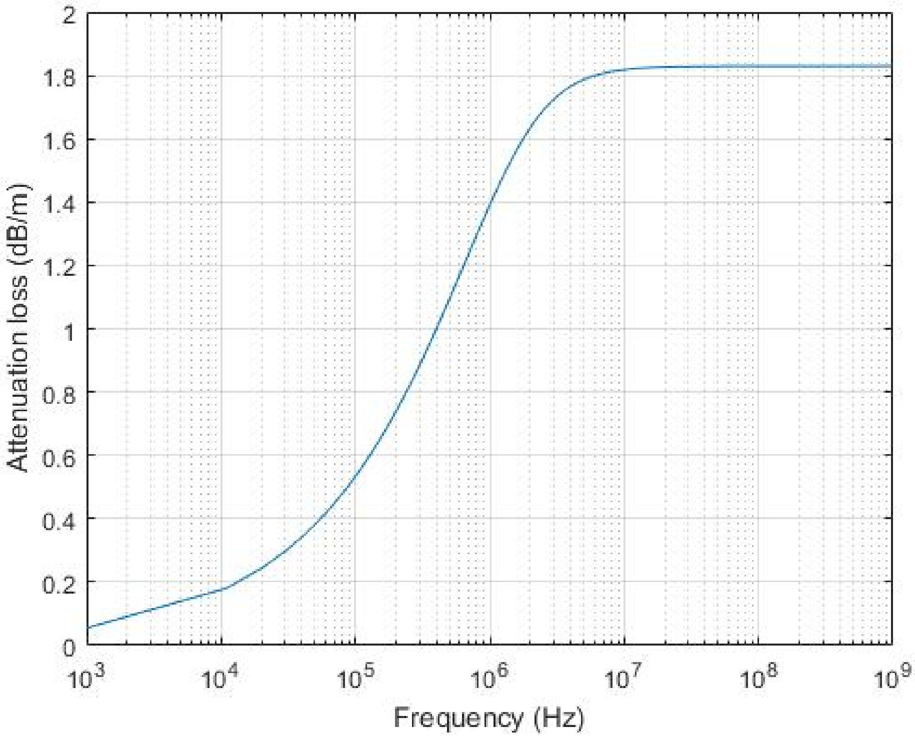


Figure 5: Attenuation loss per meter in Fresh water(σ=0.01S/m)

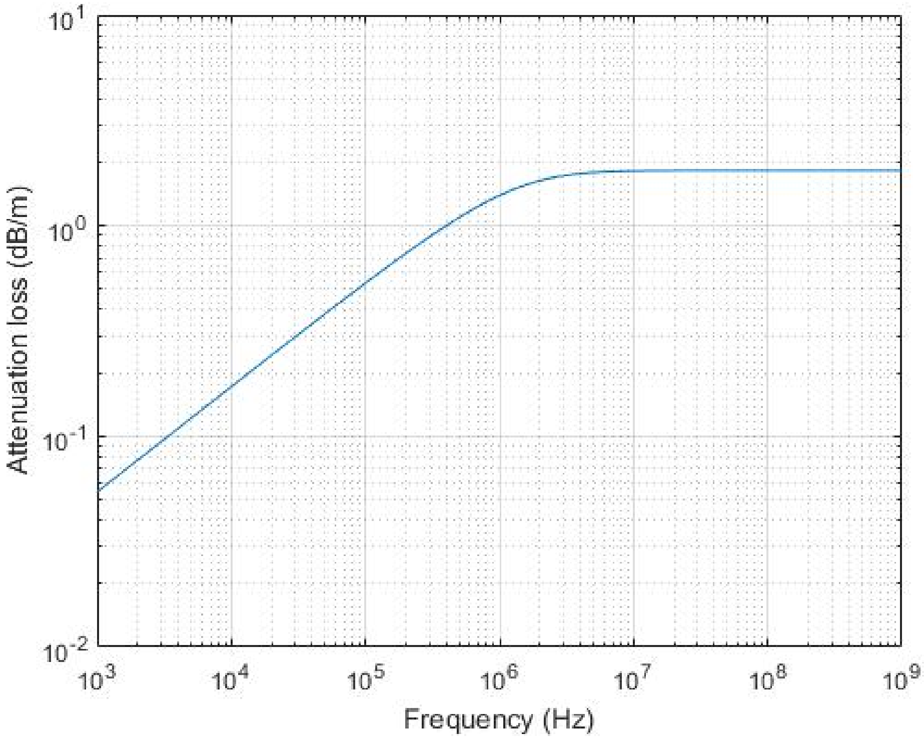


Figure 6: Attenuation loss in fresh water(σ=0.01S/m) in loglog scale

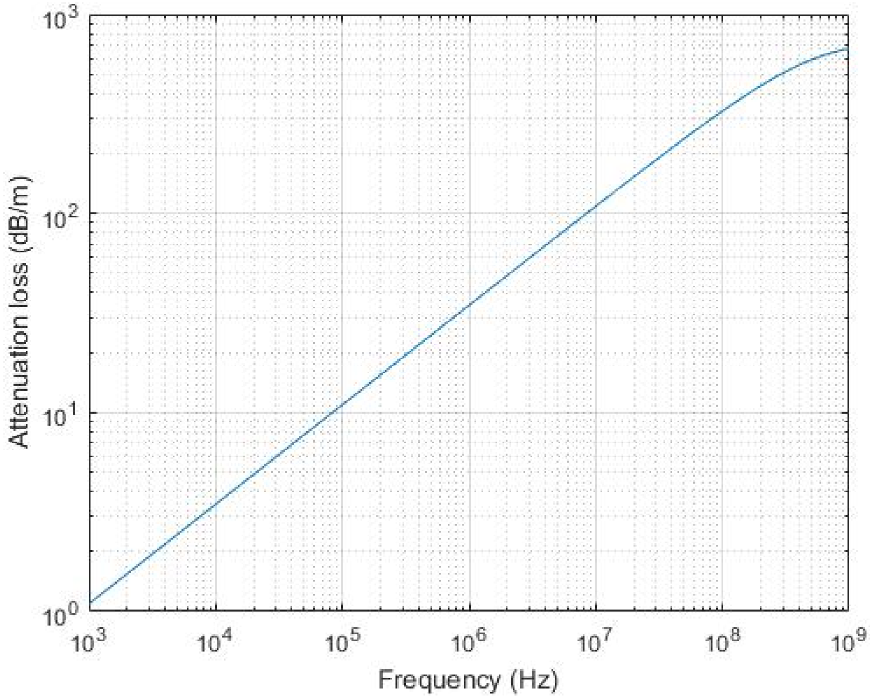


Figure 7: Attenuation loss in sea water.(σ=4S/m) loglog scale

After Pathloss is subtracted from transmitter power, shadow fading and Rayleigh fading are applied to get final value of received power.

2.2.2.2. Multipath and Noise

As we have seen in acoustic communication, multipath is a big hurdle in acoustic communication, in RF underwater communication on the other hand, can be used to our advantage. As we have already seen, RF waves are able to cross the water-air boundary with some signal strength loss, the air path can be used as an alternate path of communication between submerged nodes. Similarly, the sea/lake floor can also be used as an alternate low loss path. Figure 8 [8] illustrates the concept.

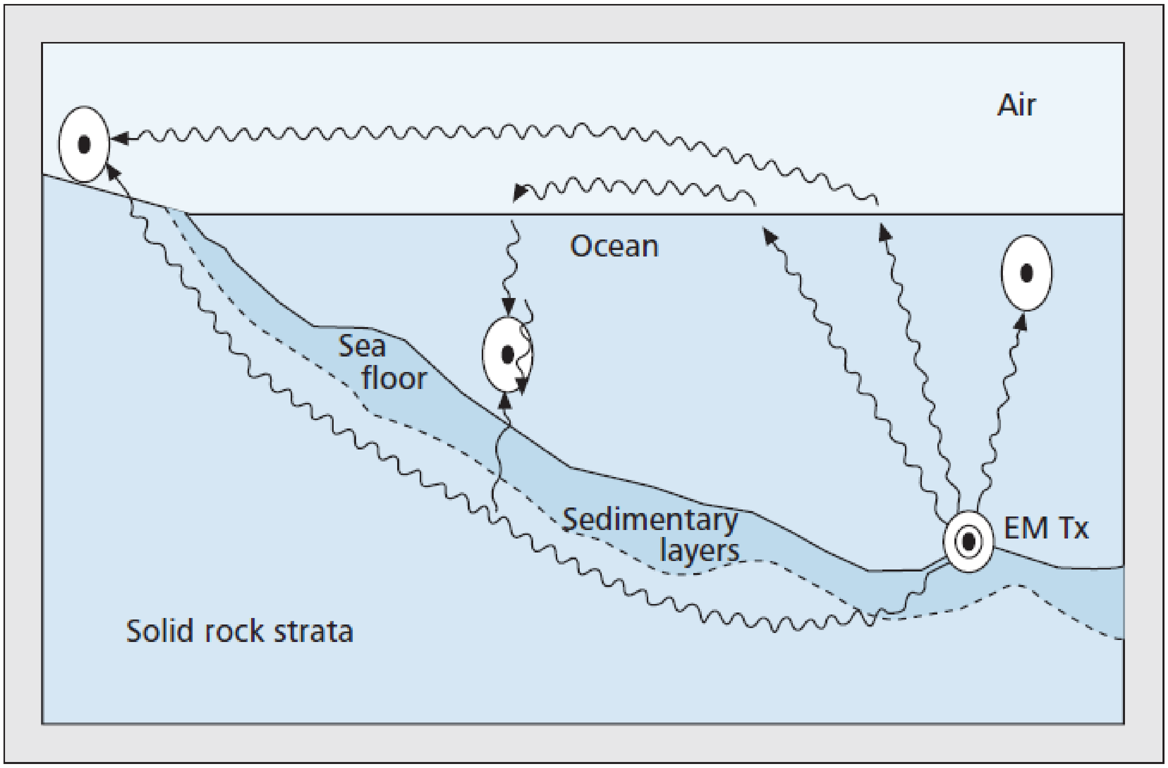


Figure 8: RF multi-path propagation underwater [8]

Also, as opposed to acoustic communication, the RF communication link is not affected by ambient noise or environment noise. It can however be effected by noise from other communication nodes, which is solved by MAC protocols and setting of SNR [8].

2.2.3. Medium Access Control Protocols

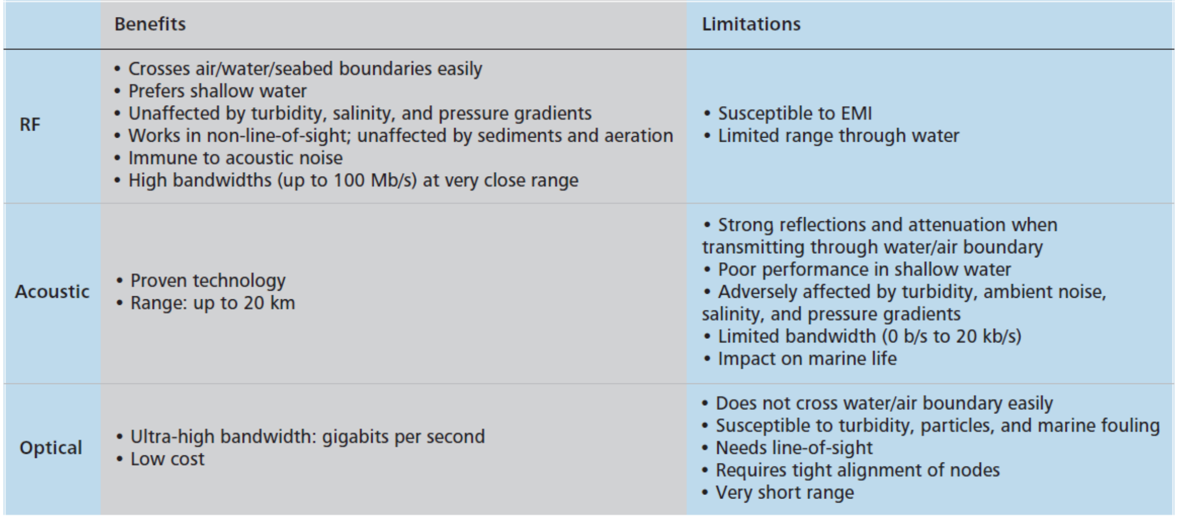
As research in underwater RF communication is still in its early stages, there are not many MAC designs for it. [37] designs a TDMA protocol for RF communication network and tests the performance in simulation and experiment. [38] provides a survey of underwater RF protocols and states Reservation based MAC (R-MAC), CDMA based MAC, OFDMA (orthogonal frequency division multiplexing multiple access) based MAC and energy efficient MAC protocol as existing MACs for RF underwater. [39] compares Aloha, MACA (Multiple Access with Collision Avoidance), CSMA without ack and CSMA with ack for RF underwater communication network and concludes CSMA without ack as most appropriate MAC for RF underwater network with slow traffic rate. A hybrid protocol is suggested in [40] by mixing scheduled access (TDMA) and unscheduled access protocols and concludes that the hybrid protocol performs better than either of the two protocols in certain cases.

2.3. Comparison

RF waves travel through air with very little signal attenuation, hence they can cover long distances and provide stable high speed communication link. Acoustic waves on other hand, have high attenuation in air, hence signal strength quickly diminishes in air. The roles are totally reversed in water where RF waves are attenuated very quickly while acoustic waves travel long distances.

Table 2[8] compares advantages and disadvantages of acoustic and RF communication in underwater environment.

Table 2: Benefits and limitations of RF, acoustic and optical communication links in underwater [2]



	Benefits	Limitations
RF	• Crosses air/water/seabed boundaries easily • Prefers shallow water • Unaffected by turbidity, salinity, and pressure gradients • Works in non-line-of-sight; unaffected by sediments and aeration • Immune to acoustic noise • High bandwidths (up to 100 Mb/s) at very close range	• Susceptible to EMI • Limited range through water
Acoustic	• Proven technology • Range: up to 20 km	• Strong reflections and attenuation when transmitting through water/air boundary • Poor performance in shallow water • Adversely affected by turbidity, ambient noise, salinity, and pressure gradients • Limited bandwidth (0 b/s to 20 kb/s) • Impact on marine life
Optical	• Ultra-high bandwidth: gigabits per second • Low cost	• Does not cross water/air boundary easily • Susceptible to turbidity, particles, and marine fouling • Needs line-of-sight • Requires tight alignment of nodes • Very short range

Chapter 3

Hybrid Communication Scheme design for underwater docking station

3.1. Docking station model

The system is comprised of a simplified underwater docking station and AUVs. The docking station is located at the bottom of sea and provides a safe place to park AUVs, AUV battery charging and wired data link facilities. AUVs sent on long missions use docking station to recharge their batteries and send collected data over high speed wired communication link. Docking of AUV in the small docking area of the docking station require a very reliable method to ensure AUV does not crash. In this thesis we assume docking station and AUVs as points. Figure 9 illustrates the idea of underwater docking station and AUVs landing on it. The docking station is at the base of a freshwater lake 50 meters deep. The AUVs are released on the surface of water and they use motor to propel towards docking station. For now the model considers only 1 degree of freedom (DoF) from the docking station. The docking station determines the location of AUVs using an underwater positioning technology like USBL (UltraShort BaseLine) acoustic positioning system and sends it through communication link to the AUV and AUV calculates and applies the control signal to the motor. Here we assume the location of the fixed docking station is known but the AUVs do not know their own location.

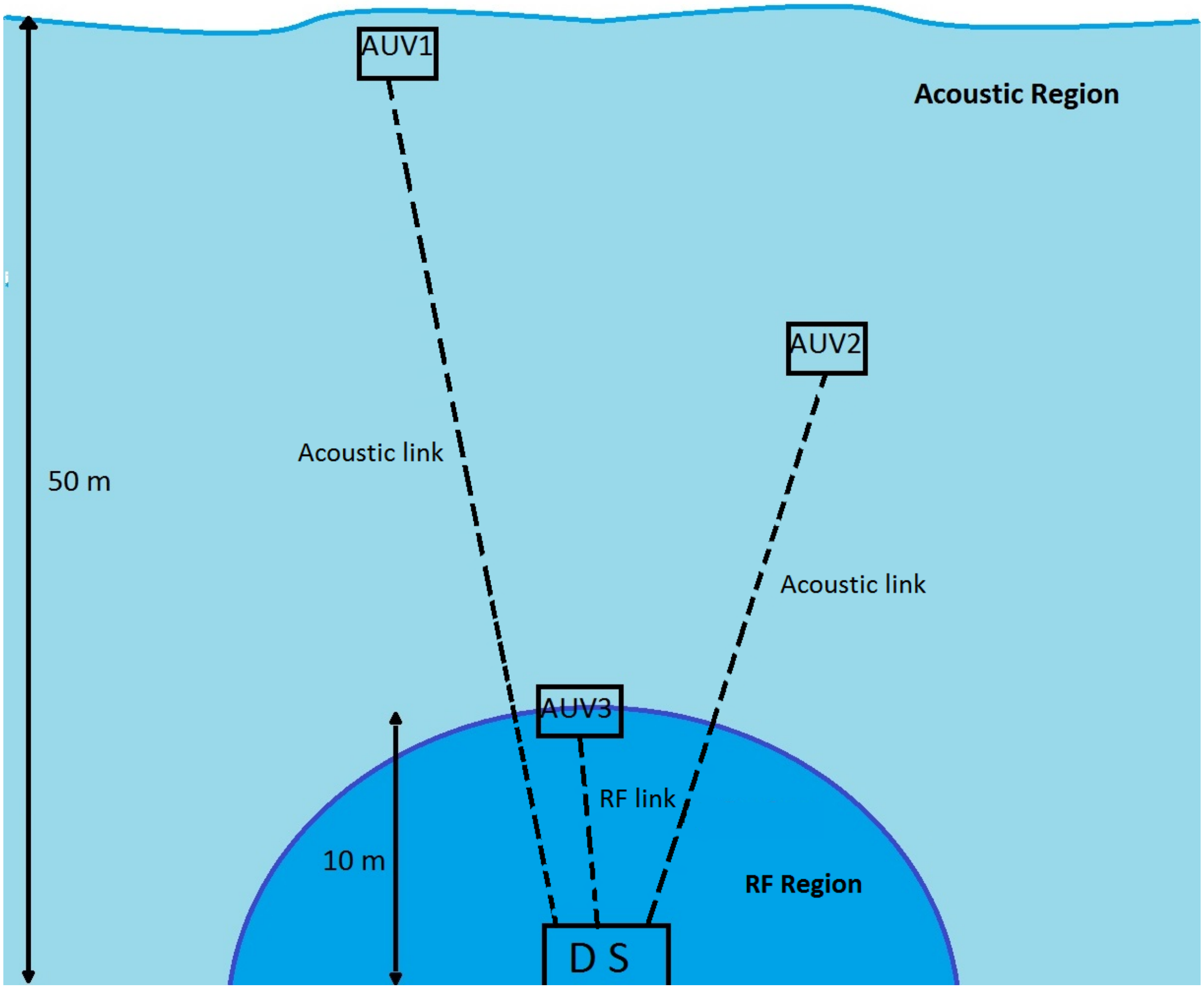


Figure 9: Proposed system

3.2. System model

AUV is considered as a point with 1 DoF. The AUV is a modelled as a second order system with transfer function:

$$\frac{X(s)}{F(s)} = \frac{10}{s^2+100s} \tag{11}$$

PD controller is used to control the system and its parameters are set to damp the response. The gains and sampling period of the digital controller are set according to the communication link used. The control signal comes from two controllers; one for acoustic link and other for RF link. At long distance of more than 10 meters, acoustic link is used to send location and due to slow propagation speed and low data rate, the controller gain must be set small to avoid instability due to delay. When distance is less than 10 meters, high data rate RF communication link can be used and controller gains set high. The controllers get the distance information via the communication links, sent by docking station. Figure 10 shows the block diagram of the system. Disturbance is added to the control output to mimic water currents as disturbance. The output of the plant is taken as the position of AUV which is fed back into the system using the communication links. The reference input, which is the position of fixed docking station, is taken as a constant number 50, i.e. the bottom of lake.

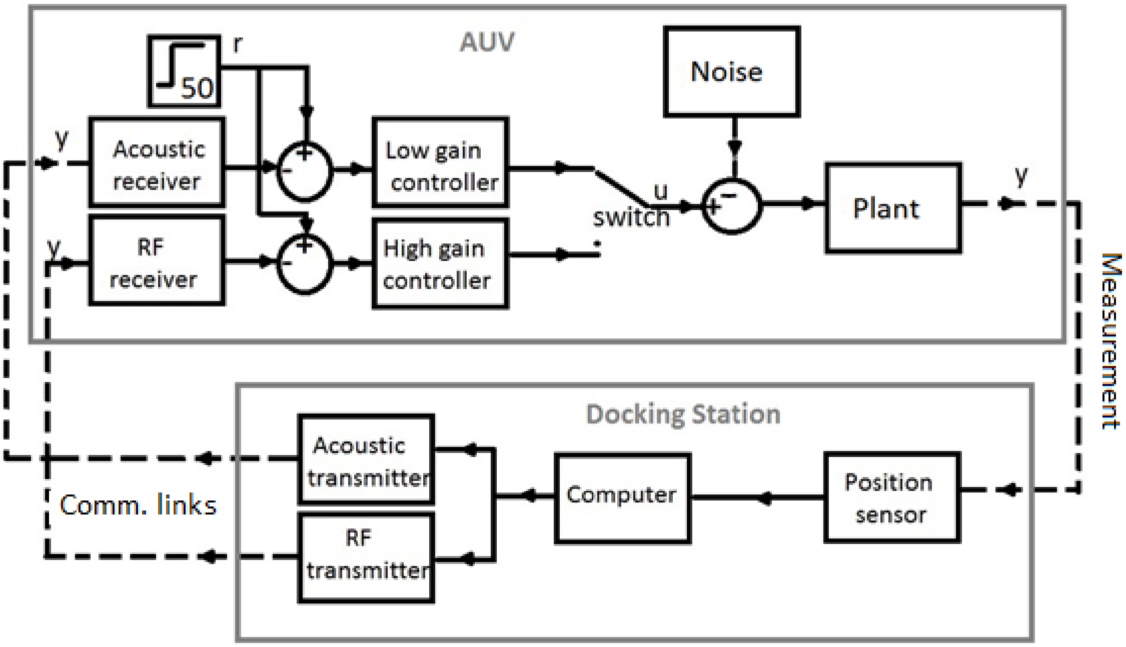


Figure 10: Block diagram of AUV and docking station systems

3.3. Hybrid Communication Framework

As we have seen in Chapter 2, the acoustic link provides long range and reliable link but low data rate and large propagation delay. On the hand, RF link work in very small range but provide high data rate and small propagation delay. In an attempt to combine best of both communication links, we propose a novel hybrid Acoustic RF communication scheme. This hybrid scheme uses acoustic link for long ranges and switches to RF link for short ranges.

We divide the communication frame into two parts, one belonging to docking station and other belonging to AUVs. As our thesis focuses on the docking station application, where docking station sends location information to AUVs one by one, it naturally follow a TDMA scheme, so we use a TDMA based MAC scheme where docking station periodically broadcasts AUV's location in packet to all the AUVs nodes that are going to land on it sequentially. This is a broadcast system so all nodes are able to receive all the packets and will decide to use the packet that have the same receiver id number as the node itself. So, first portion of the frame, which belongs to the docking station, will always follow TDMA scheme. There is no need to include propagation delay in time slots in the period because all messages are sent by a single node, so there is no possibility of message overlap or collision. Docking station simply transmits packets to each node one after the other. The docking station portion of the frame starts with the waiting time to allow packets from all AUVs to be received followed by transmission slots. The slot time in the first part of frame is 0.039 seconds.

The AUVs communicate with the docking station only when they have to send a "power control message" or a "start RF message". This will be the second portion of the communication frame, belonging to AUVs. A "power control message" is sent by the AUV when received packet power is lower than threshold level and message is not readable. Power control mechanism is described in section 3.4. A "start RF message" is sent by an AUV when it is 15 meters away from the docking station. It just contains the AUV id number. When docking station received this message, it establishes the RF link with that AUV and starts transmission. The packet size of the AUV message is made smaller than docking station packet size, hence the slot time in AUV portion of frame is also small. We suggest 3 MACs for this portion of frame:

Firstly TDMA, where slots are allotted to each AUV which they can use to send packets to the docking station, as seen in figure 11. Each time slot include propagation delay at the beginning of each slot, as each packet is transmitted from different node and without taking account propagation delay, the packets can overlap and collide. At 1500 m/s propagation speed, the maximum propagation delay for 50 meters is 0.033seconds. The total slot time is 0.034 seconds.

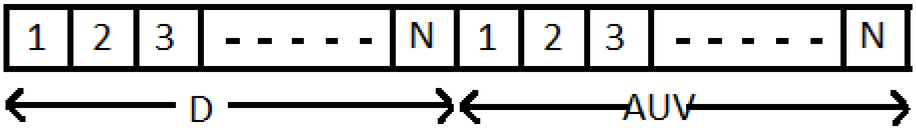


Figure 11: TDMA docking transmission period and TDMA AUV transmission period

Secondly, the AUV nodes have a contention based time like slotted ALOHA, where nodes will back-off for random multiples of slot time and send packet in the next slot. In case of collision there will be no re-transmission in the same frame and nodes will transmit again in the next frame. There is no acknowledge message by the docking station. The collided packets will simply be dropped. The S-Aloha portion of frame will start after a waiting time or guard time of 0.33 seconds, after docking TDMA portion of frame. As we have already discussed in Section 2.1.3, the slot time must include some percentage of propagation delay time. So, each slot contains 0.02 seconds or 60 % of propagation delay time. Total time slot is 0.03 seconds. A maximum of P<=N AUVs time slots are kept in this period as seen in figure 12.

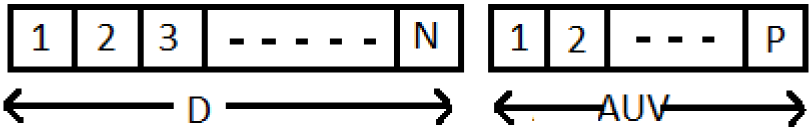


Figure 12: TDMA docking transmission period and S-Aloha AUV transmission period

Third method is the waiting room protocol. In waiting room, the nodes decide to send message during the Synchronization Gap (SG) which in our case would be the time when docking station is sending the messages. During SG each interested node is assigned a Terminal Gap (TG). It is different for every node and is assigned during design phase. Each node starts its timer and waits TG amount while listening on the channel for traffic. When TG of a node ends, it starts the transmission. Node with shortest SG transmits first. All other nodes listen to the channel and stops their timer and sleep for the transmission time known as Transmit Interval (TI). After TI, all remaining nodes start their timer again and wait for their TG to end. This goes on until all nodes have finished transmission then next frame starts with SG. If another request comes during this interval, it is added to next queue. In our thesis, we are considering control systems with fixed sampling time, so each frame time is always constant. As in S-Aloha, guard time is put between two portions of the frame. Each TG contains propagation delay. TI is 0.01 seconds and TGs are 0.03, 0.031, 0.032 and so on. Figure 13 demonstrates the TDMA, waiting room hybrid MAC.

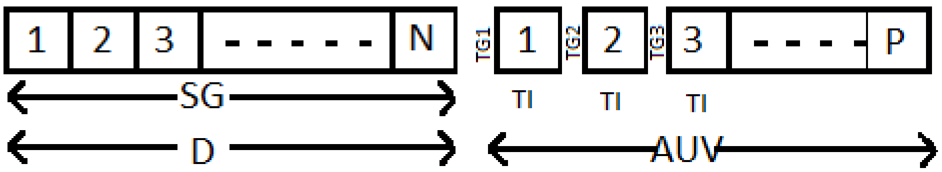


Figure 13: TDMA docking transmission period and Waiting room AUV transmission period

The broadcast packet, sent by docking station, is shown in figure 14.

sender id	receiver id	time stamp	packet number	data

Figure 14: Docking station message packet

The packet is 386 bits long. The node ids are predefined. The docking station send packet to specific node by giving their id. If the id the receiver id matches with the id of node, the packet is accepted, otherwise discarded. All AUVs can hear messages intended for a particular AUV and hence they can know the location of that AUV. AUVs can use this information to avoid physically colliding with other AUVs.

The data portion of the packet contains location information of the AUVs obtained from USBL. It is used by the AUVs to calculate the control signal for the motor defined in the previous section.

The AUV transmission packets are 64 bits long and only contain data field. AUVs can send two types of messages. “Power control message”, which contain the transmission power level and “Turn on RF message” which contain the id number of the AUV. AUVs recognize packets from other AUVs based on packet size and discard them. They only transmit and receive packets from the docking station.

When the distance between the docking station and AUVs is more than 10 meters, the AUVs use the acoustic channel. When the distance becomes less than 15 meters, the AUV send the “start RF message” to docking station. When the docking station receives the request, it initiates the RF link and start sending packets to AUV over the RF channel. The AUV sends power control messages and once the link is established and the distance between the nodes becomes less than 10 meters, the control is switched to RF link with higher gains. The acoustic link is still intact but the messages are ignored.

The RF link is high data rate and small propagation delay link. We will use the CSMA/CA scheme for RF, as number of nodes are changing and because of high data rate and small propagation delay, chances of collision are low. The packet size and description are same in both RF and acoustic links but packet transmission time will be different because of different data rates. The power control mechanism is also same in both links. Power control is described in the next section.

3.4. Power Control

The power control mechanism in both acoustic and RF link works the same way. The docking station sends the first packet with a predefined initial transmission power. The path loss and fading are calculated at the receiver node using the path loss models described in earlier section. The receiving node calculates the received power and compares it to a predefined threshold level. If the received power level is below the threshold level, the AUV node calculates a transmission power level using the pathloss model and sends a power increase message to the docking station with the new transmission power in the packet. The docking station receives the power control message and increases its transmission power to the power level sent in the packet.

Chapter 4

Performance analysis

4.1. System model and simulation details

The model is implemented in MATLAB Simulink and in Truetime which is a hybrid systems simulator, incorporating continuous domain dynamics, real time system and network simulator. It is an add-on for MATLAB developed by LUND University Sweden. The Simulink model showing Docking Station and 1 AUV is given in figure 15.

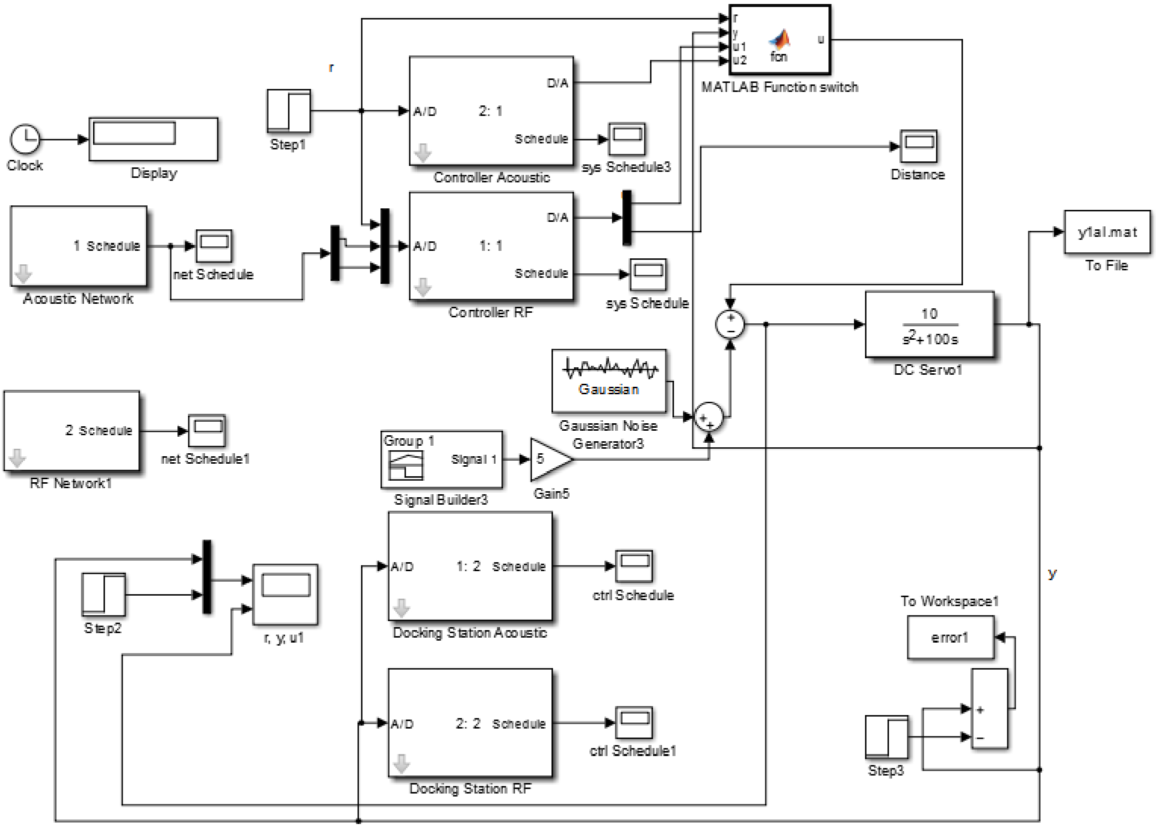


Figure 15: Simulink model for hybrid communication model

The two blocks on left are truetime (TT) network blocks. It allows to create networks with various parameters including, data rate, minimum frame size, network number and number of nodes. It also has some predefined MAC schemes. The acoustic link data rate is taken as 10 kbps and that of RF link is 3 Mbps. Freshwater parameters are used in all simulations. Acoustic link data rate is taken as 10 kbps and that of RF link as 3 Mbps. The acoustic channel frequency is 100 kHz and that of RF channel is 10 MHz. The 4 blocks in center are TT kernel blocks. All the control and MAC implementation are done inside these blocks. These work as network bocks and are attached with either of the two networks. The bottom two TT blocks are acoustic and RF docking station blocks. These blocks read the output data from the AUVs and transmit on the network which they are attached to. The top two blocks are acoustic and RF controller blocks and are attached with the AUV system. They read the reference value from the step signal and receive the AUV output signal from the network which they belong to. The PD controller and the AUV portion of

MAC schemes are implemented in these blocks. The top right MATLAB function block has the switch implementation which chooses the control signal source of either of the two controller blocks based on distance of AUV from docking station. There can be several AUV systems and each system contains once acoustic controller TT block, one RF controller TT block and one switch block. There is only one acoustic and RF docking station block each in every simulation.

Disturbance is added to control signal after multiplying by a gain and adding a Gaussian random signal. Disturbance is added to model water currents. The time dependent disturbance profile is shown in figure 16. The disturbance gain is increased in different experiments to test robustness of system.

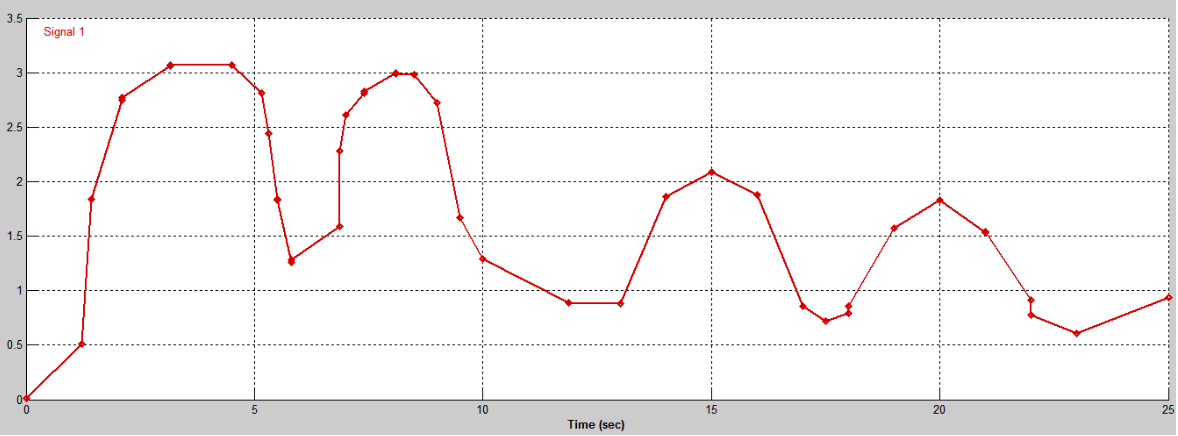


Figure 16: Disturbance profile signal

Each simulation runs for 25 seconds which is sufficient for AUVs to complete their maneuvers. First only acoustic link is active and RF link is inactive. Each acoustic frame has docking station TDMA phase followed by one of three MACs for AUV phase where AUVs send power control messages. When any AUV reaches 15 meter mark from docking station, it sends a “turn on RF” message which is just its node id number. All AUV packets are 64 bits long while docking station packets are 386 bits long as seen in section 3.3. When docking station receives turn on RF message, it turns on RF link and start sending packets to that AUV. The AUV and docking station exchange power control messages and establish a strong link. When AUV reaches 10 meter mark from docking station, the RF link takes over and the control is performed at the high gain controller. This is made possible by a switch which chooses control signal from high gain controller when distance become less than 10 meters. When the AUV reaches the docking station and distance is less than 0.6 meters, the maneuver is completed and the AUV sends message to turn off wireless. The RF computer of docking station receives this message and terminates link with that AUV. Figure 17 shows position of one AUV with respect to time and its control signal.

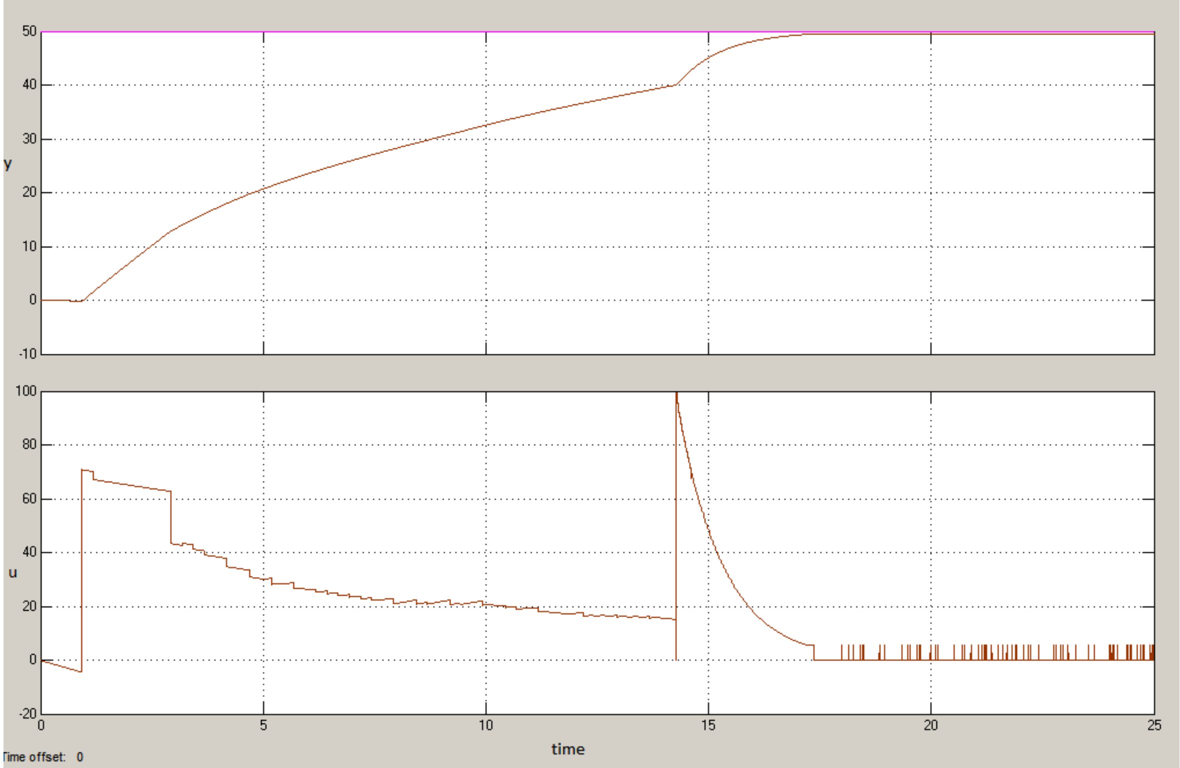


Figure 17: System output and control signal

It can be seen in Figure that AUV is using low gain controller until it reaches 10 meters when it shifts to high gain controller.

Figure 18 and 19 show acoustic and RF network traffic.

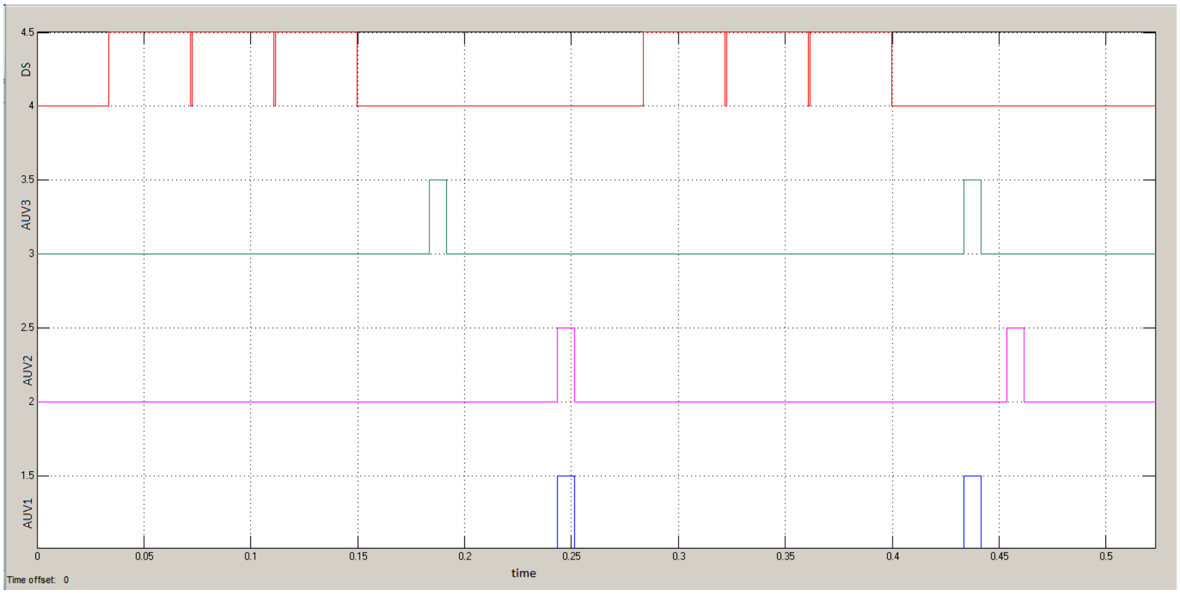


Figure 18: Zoomed Snapshot of Acoustic network traffic S-Aloha

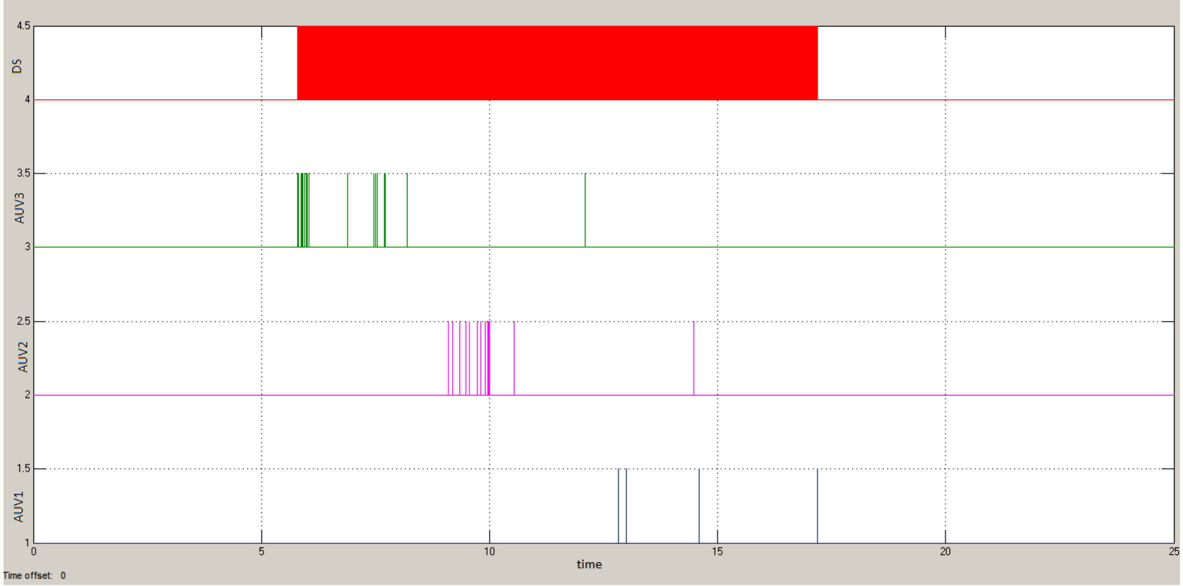


Figure 19: RF network traffic

The TDMA docking station phase and S-Aloha AUV phase can clearly be seen in the zoomed in snap shot in figure 18. And in figure 19, we can see that RF link becomes active when AUV3 crosses 35 meter mark at about 6 seconds. And RF link stops when AUV1 lands at about 17 seconds time. In this simulation, the AUVs had different control gains, hence their motion was different. AUV 3 establishes RF link at 6 seconds, AUV2 at about

9 seconds and AUV1 at about 13 seconds. Similarly AUV3 docks at 12 seconds, AUV2 at about 14.5 seconds and AUV1 at 17 seconds. After each AUV docks, RF link with that AUV is disconnected.

In all simulations, the RF link parameters remain the same. The frame time in RF link is 0.01 seconds. The proportional gain of PD controllers in RF link is 10 and sampling period is equal to frame time i.e. 0.01 seconds.

4.2. Comparison of MAC protocols

4.2.1. Load test

As we have designed 3 MAC protocols for AUV portion of communication frame, we compare their performances to find out the best scheme for our system for different number of AUVs. We designed the MAC schemes for 10 AUVs and kept the frame time fixed. Total frame time is 0.7635 seconds. The docking station portion of frame is 0.4235 seconds and AUV portion of frame is 0.34 seconds. Number of slots in S-Aloha are 10. We compared the performance of increasing number of AUVs from 1 to 10. The sampling period of PD controllers for all AUVs is equal to frame time. All AUVs have same proportional gain of 1.5 so that network traffic and movement of nodes remain fairly equal. The performance metric chosen for comparison is calculated as the time integral of the remaining distance to the docking station, i.e. the area between the reference curve and the distance curve of the AUV system. Lower value means the AUV reached the docking station quicker, hence better performance and vice versa. Each simulation is performed 20 times for increasing number of AUVs from 1 to 10, and average performance value is taken. Best and worst performance out of 20 simulation runs is also calculated. Performance varies in every simulation as low power messages from the docking station are dropped and power control is performed until receiver power is above threshold level. Figure 20 shows the performance graph.

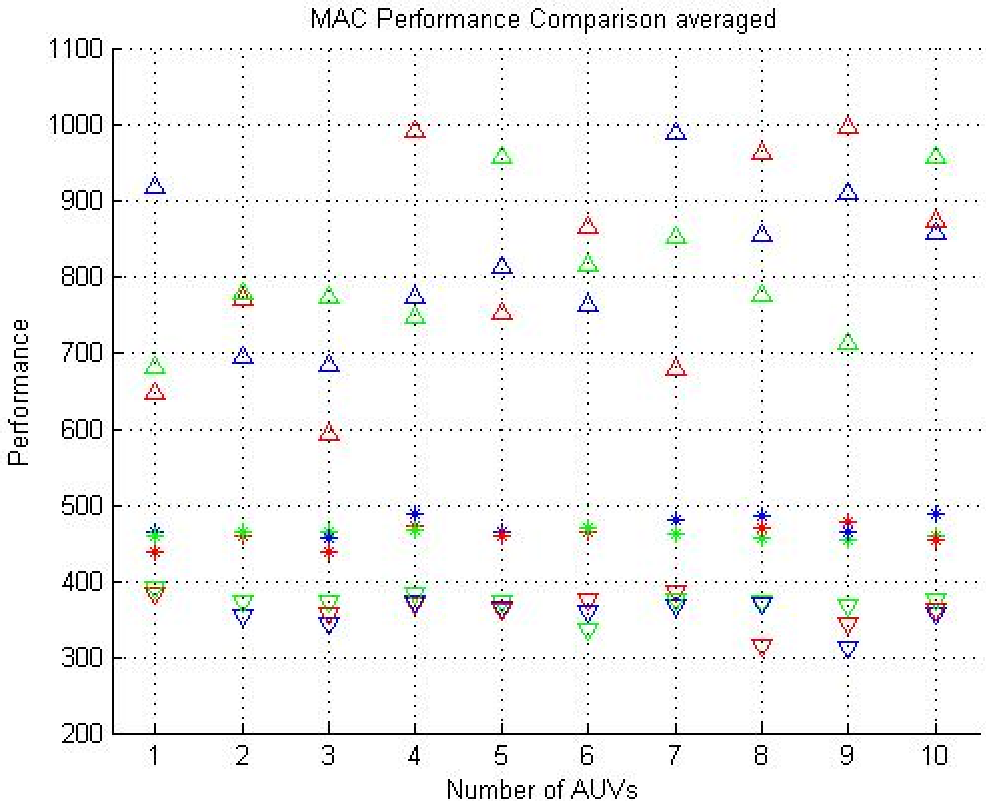


Figure 20: MAC Performance comparison

The star represents average value of 20 simulation runs. Each star is the average performance value of the number of AUVs. For example the star at 5 AUVs represents average performance of all 5 AUVs in 20 simulation runs. The up arrow represents worst performance in the 20 runs and down arrow shows the best performance in the 20 runs. Blue color represents S-Aloha, red color for TDMA and green color for Waiting room. Horizontal axis is the number of AUVs in the system and vertical axis is the performance of the MAC schemes for the number of AUVs. The color scheme and representation scheme for all result plots follow this structure unless otherwise specified.

The average performance of all protocols is not very different from each other as all 3 protocols have same data rate, frame time and packet size. TDMA and waiting room both have no collision, only in S-Aloha there is chance of collisions which is also greatly reduced due to 10 slots. Best performance for all AUVs is also very close as they represent simulation runs where power control was performed quickly.

Figure 21 shows percentage of error from the average of all 10 values for each number of AUVs.

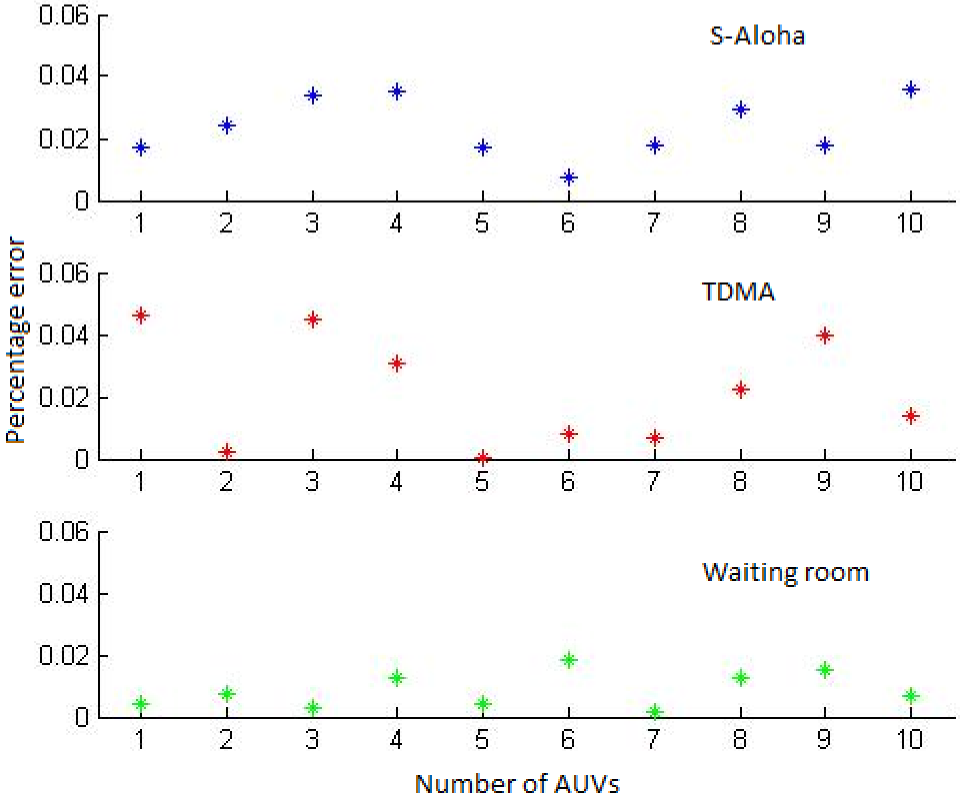


Figure 21: Percentage error. Deviation from average value

The average performance value of S-Aloha, TDMA and Waiting room are 471.8, 459.5 and 462. Although values are very close, TDMA gives the best average performance then waiting room then S-Aloha. Figure 21 shows that Waiting room has the least deviation from average value then S-Aloha, then TDMA. This suggests that Waiting room is more likely to give same performance over increasing number of nodes in network.

4.2.2. Robustness

For robustness we increased the disturbance gain to determine how the AUV output will behave in the 3 MAC schemes of the hybrid system. The system we tested was 10 slots system with 3 AUVs. We increased disturbance gain from 5 to 7.5 to 10. Each simulation was performed 20 times and average values were taken Figure 22 shows the performance of the 3 MAC schemes under increasing disturbance gain.

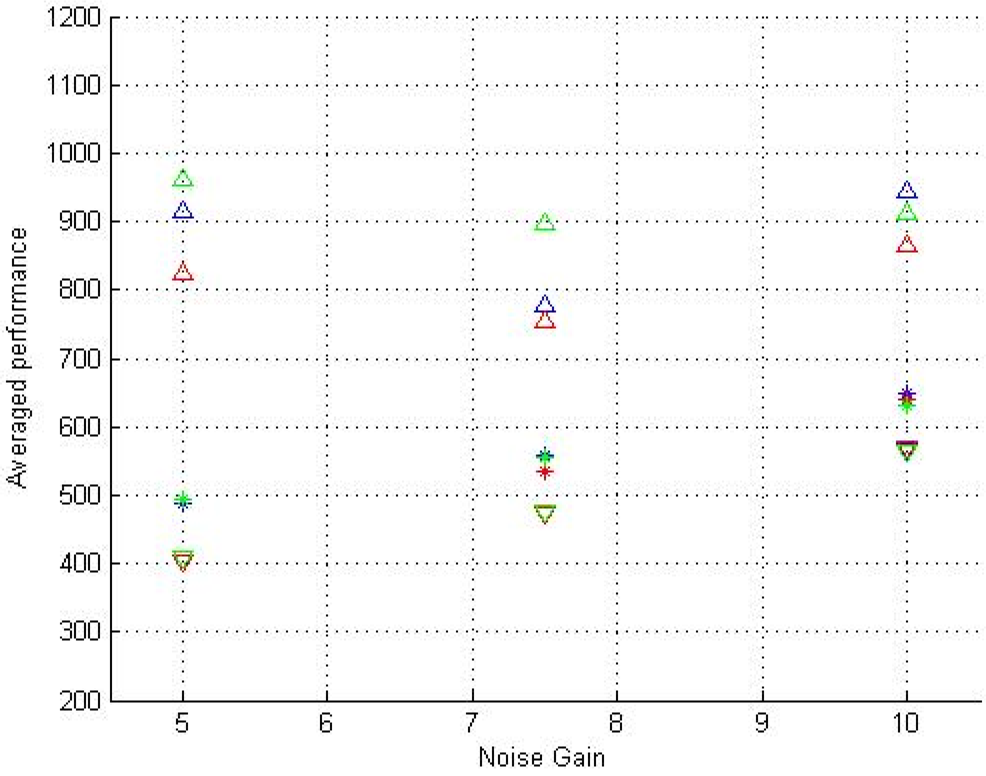


Figure 22: MAC performance with increasing disturbance gain

Performance of the three MAC schemes decreases with the increasing disturbance gain. The results are expected as the negative disturbance pushes the AUVs away from the docking station and the control system have to counter the negative disturbance. The performances of the three protocols are very similar to each other. System behaves in similar way in three protocols under increasing disturbance.

We then optimized the 3 protocols for 3 AUVs. For S-Aloha, the frame time is 0.25 seconds. Docking station portion of frame is 0.15 seconds and AUV portion of frame is 0.1 seconds. Number of slots in AUV portion of frame are 4. It is same for TDMA and for waiting room, the frame time is 0.3 seconds. Docking station portion and AUV portion of frame time are both 1.5 seconds. The proportional gains of PD controller of the 3 AUVs are 1.5, 2 and 3. The gains are set different to test if system performance would improve with higher gains without becoming unstable. We tested robustness of hybrid system MAC protocols optimized for three AUVs. Result is seen in figure 23. It is performance of 1 AUV with control gain=3.

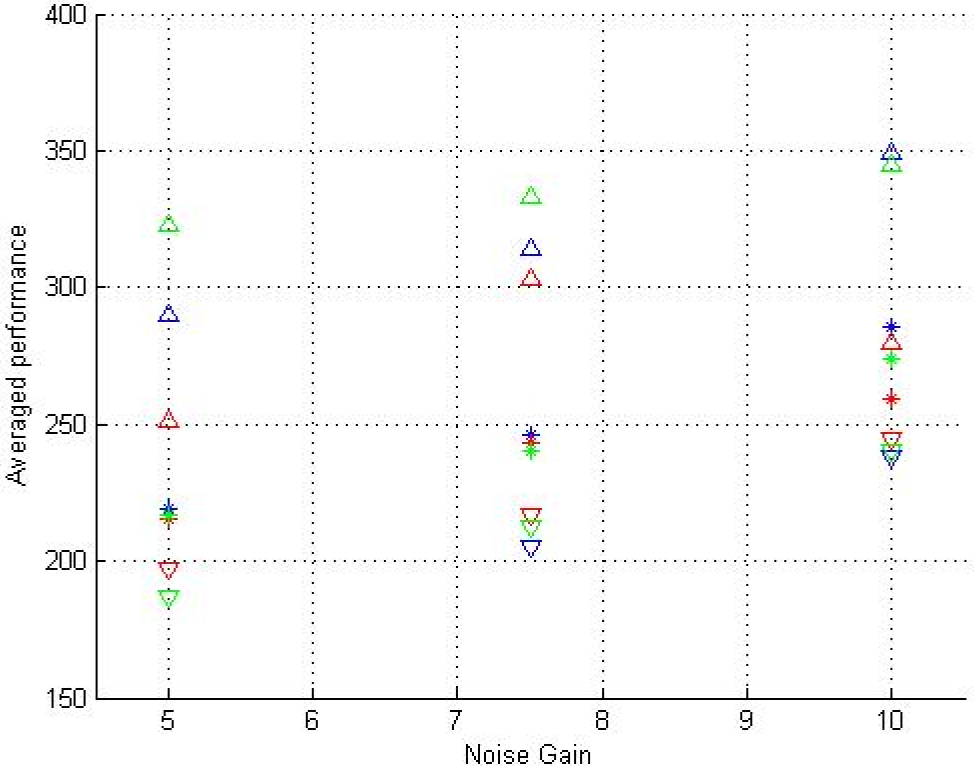


Figure 23: Optimized hybrid System Performance with increasing disturbance gain

We can see from Figure 23 that in systems with MAC schemes optimized for 3 AUVs, the performance at 5 and 7.5 disturbance gains, performance is similar for all MACs but at 10 disturbance gain, we see that S-Aloha gives comparatively lower performance and TDMA giving best. Performance of TDMA is 259.53. Performance of waiting room is 5.7

% less than TDMA and performance of S-Aloha is 9.95 % less than TDMA. The reason is the higher number of collisions in S-Aloha, resulting in degradation of performance.

4.3. Comparison with Acoustic only

We now compare our proposed RF-acoustic hybrid system with acoustic only system. We performed the robustness test on acoustic only system. Figure 24 shows the performance of Acoustic only system with 10 slots and 3 AUVs.

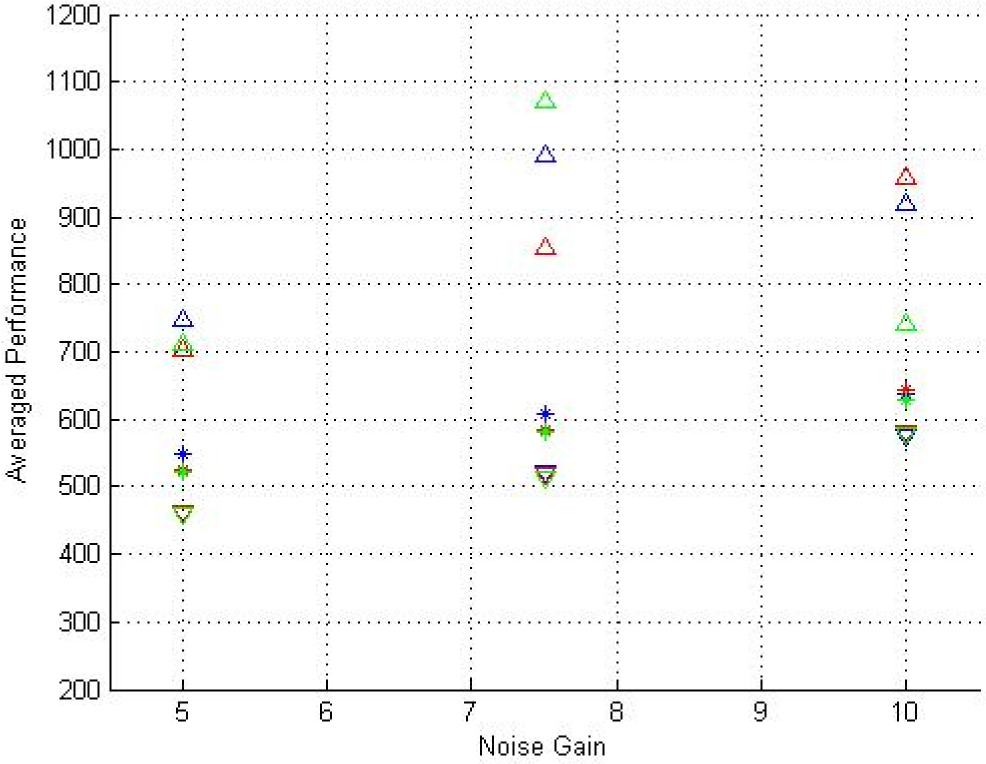


Figure 24: Acoustic only System performance with increasing disturbance

As we can see the performance gets worse with increasing disturbance gain. Also we can see that the performance is worse as compared to hybrid system in figure 22. The performance for acoustic only system is lowered by almost 12% compared to hybrid system at disturbance gain=5.

We also optimized the three MAC schemes for 3 AUVs in acoustic only system. The parameters are same as the optimized MAC schemes for hybrid systems.

Figure 25 shows the performance chart of optimized Acoustic only systems.

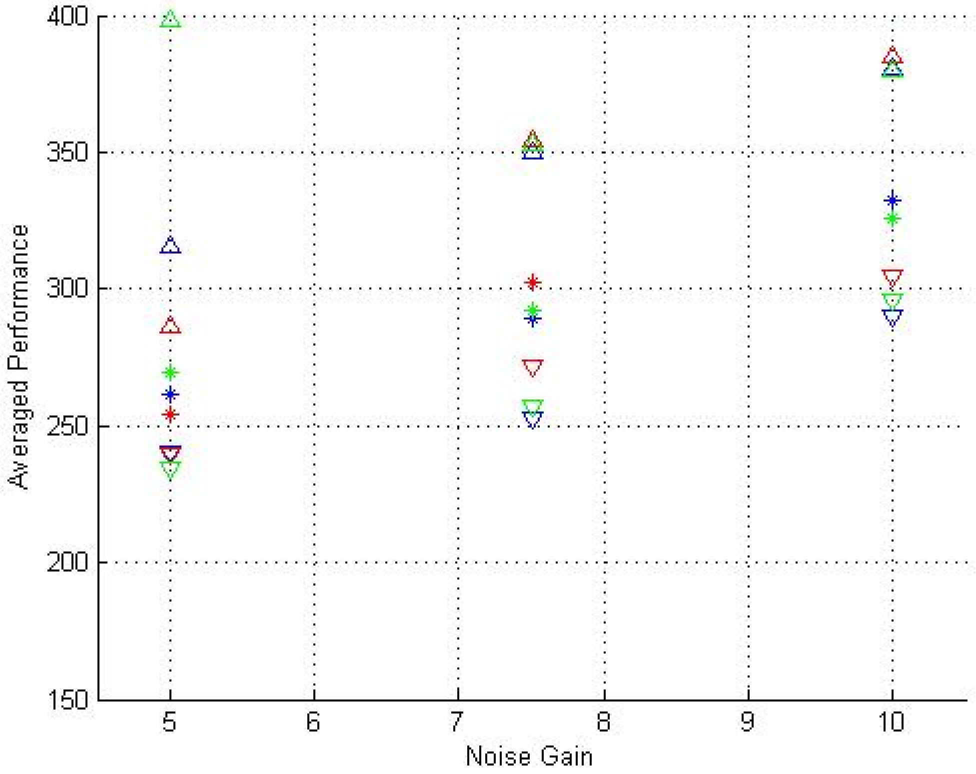


Figure 25: Optimized Acoustic only system Performance with increasing disturbance gain

We can see from figure 25 that performance of optimized acoustic systems decrease with increasing disturbance levels and that compared to optimized hybrid systems (fig 23), the performance is worse. For TDMA the performance decreased by 13.6 % compared to hybrid system at disturbance gain 5.

To get a better idea of hybrid system comparison with acoustic only system, see figure 26-28, which shows distance output graph of hybrid system overlapped with acoustic only system both using TDMA in acoustic link. In these figures MAC protocols are optimized for 3 AUVs and controller gain in acoustic region is set to 3.

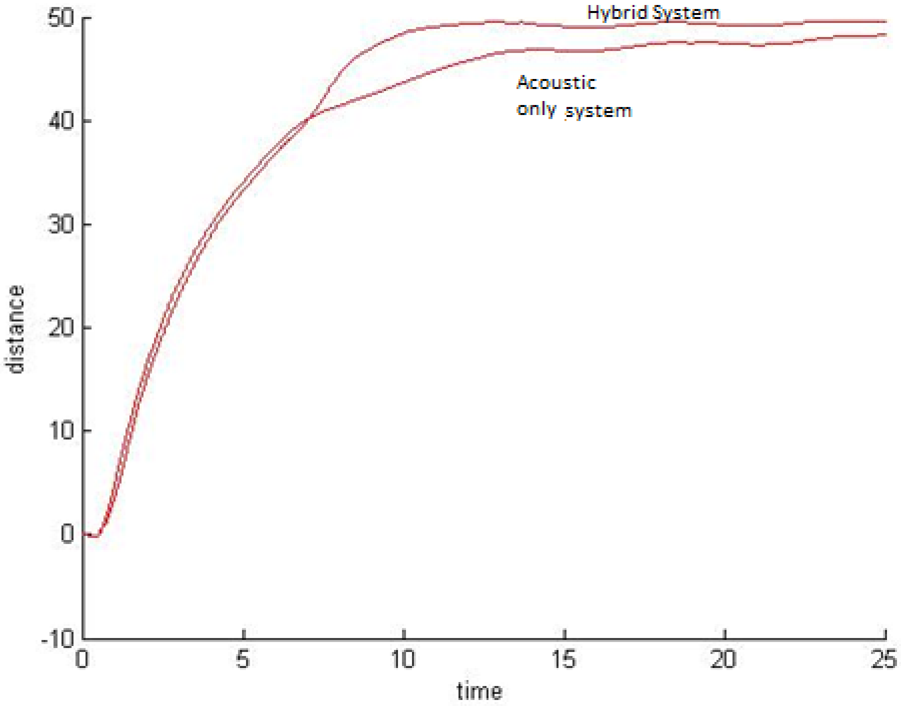


Figure 26: Hybrid and Acoustic only AUV output with disturbance gain=5

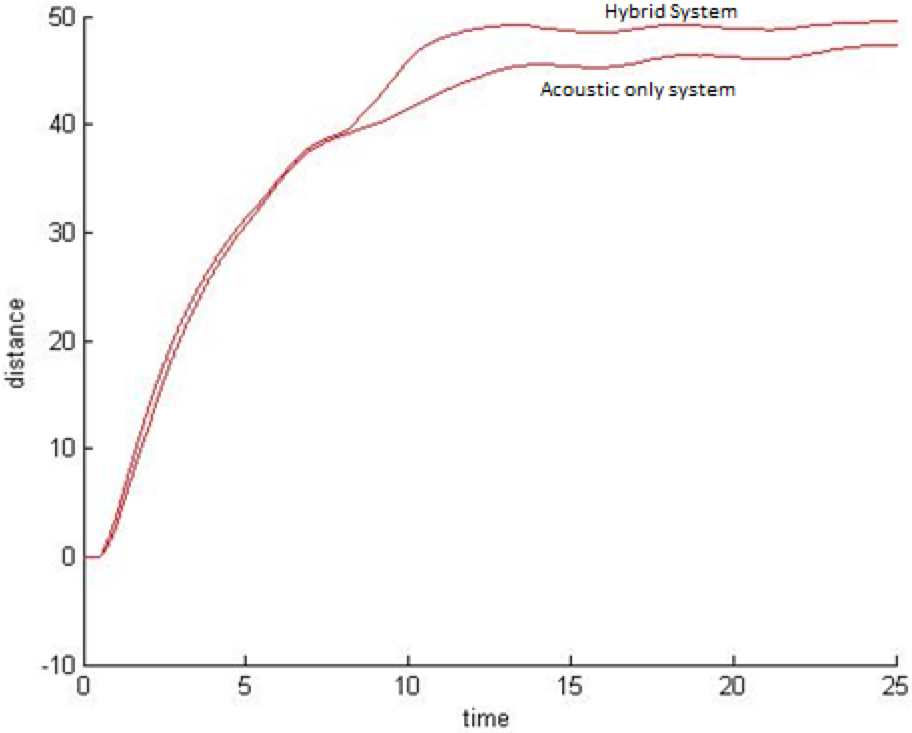


Figure 27: Hybrid and Acoustic only AUV output with disturbance gain=7.5

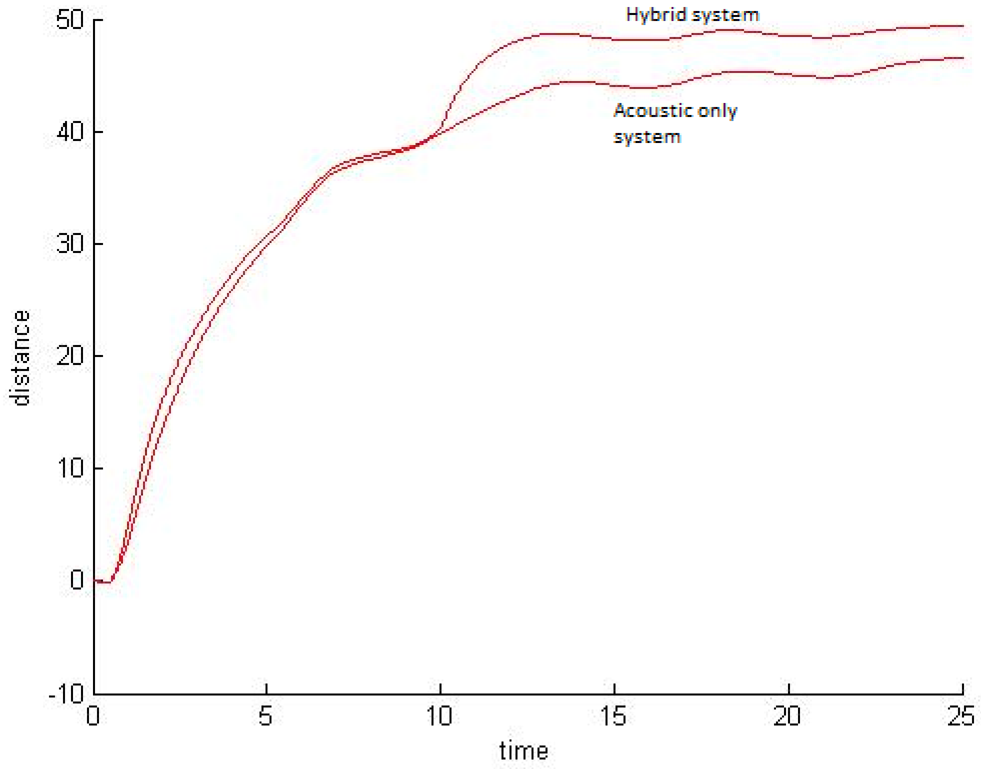


Figure 28: Hybrid and Acoustic only AUV output with disturbance gain=10

As we can see the RF region is smoother in all three disturbance gains and reach the docking station while the acoustic only system does not reach the docking station.

Next we compare the robustness of hybrid and acoustic systems with MAC schemes designed for 10 AUVs by adding location dependent disturbance near the docking station. Specifically, when distance between docking station and AUV is less than 10 meters. Disturbance signal is amplified by gain then Gaussian noise is added to the signal and the resultant disturbance signal is added to control signal. The disturbance profile is shown in figure 29 and the systems outputs are shown in figure 30.

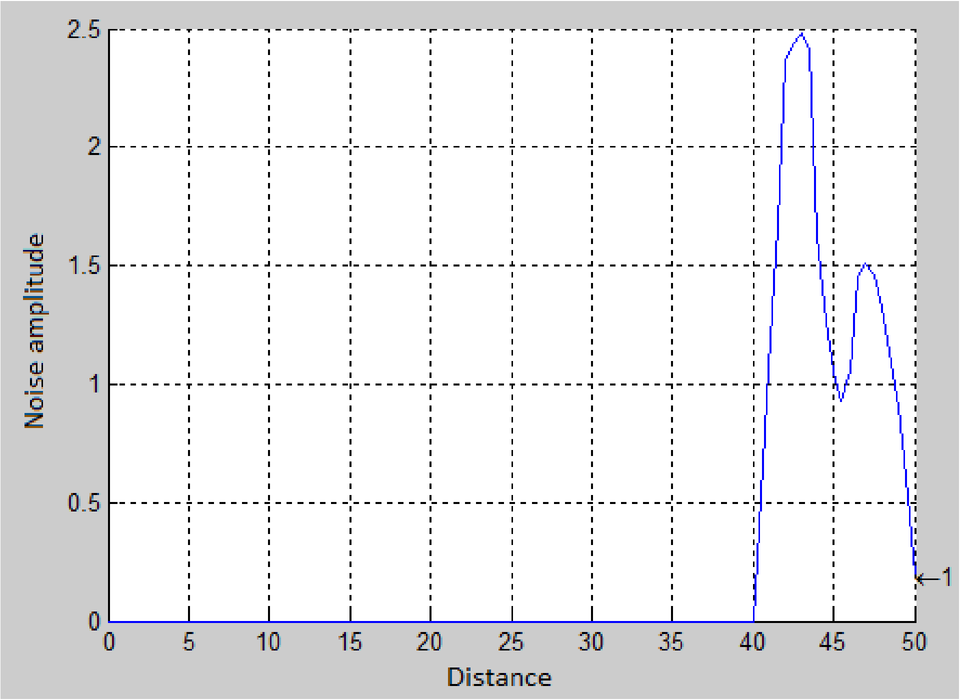


Figure 29: Location dependent disturbance profile

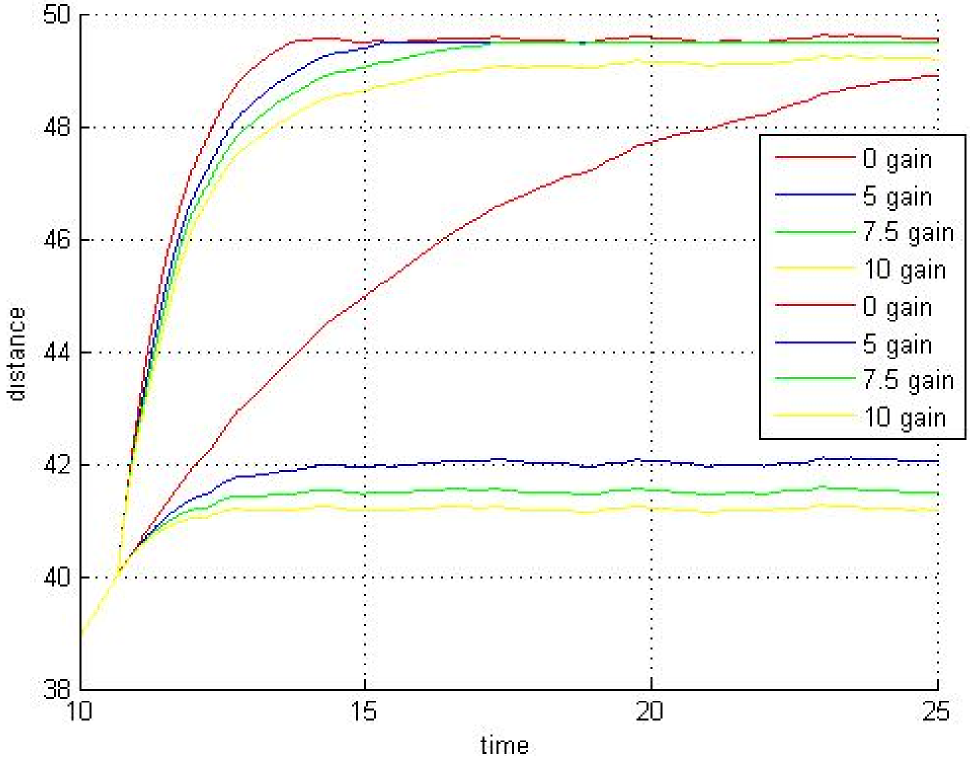


Figure 30: Comparison of AUV position vs time for hybrid TDMA and acoustic only TDMA for different amounts of disturbance

In figure 30, the upper 4 curves are positions of hybrid system while lower curves are positions of acoustic only system. We have chosen only TDMA MAC for this comparison. It can be seen from figure that hybrid system can work under high amplitude disturbance, while acoustic only system cannot counter the high amplitude disturbance. The reason for better performance of hybrid system is high gain controller in RF region. We cannot use high gain controller in acoustic link because it will make the system unstable due to large sampling period.

Table 3, shows the steady state errors of the two systems with respect to disturbance gain. It can be seen that acoustic only communication fails to reach the docking station.

Table 3: Steady state errors with respect to disturbance gains

System	**0 gain**	**5 gain**	**7.5 gain**	**10 gain**
Hybrid	0.45	0.501	0.501	0.812
Acoustic	1.1	7.95	8.5	8.81

4.4. Comparison with RF only

As RF link is high data rate and low latency link, it will outperform hybrid system but the limitation is signal power loss. As RF communication in water has high attenuation underwater, it will require very powerful source signal strength which is impractical. Power loss of 10 MHz RF signal in fresh water (conductivity 0.01S/m) is 1.81 dB/m and sea water(conductivity 4S/m) is 108.5 dB/m.

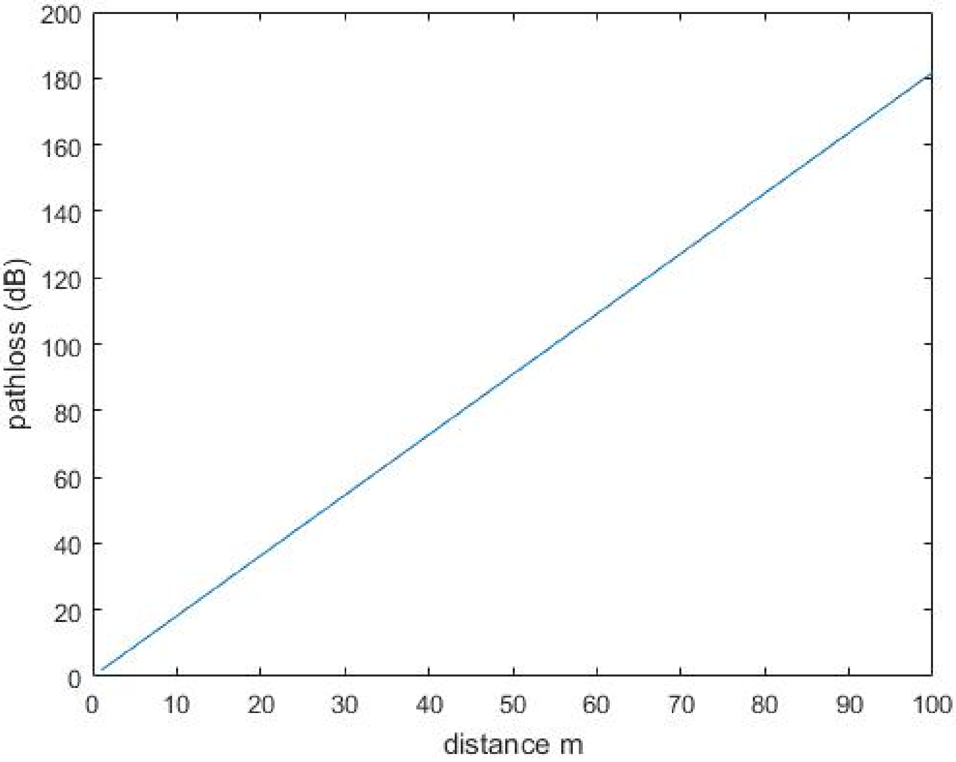


Figure 31: Freshwater RF pathloss at 10 MHz frequency

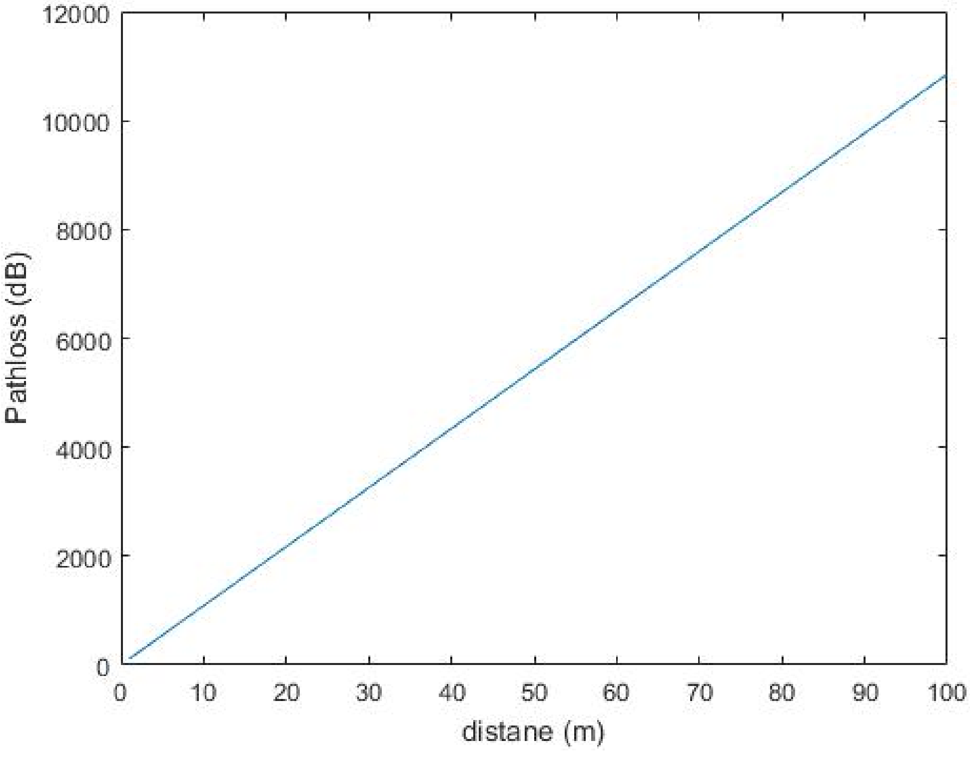


Figure 32: Seawater RF pathloss at 10 MHz frequency

Figure 29 shows RF signal at 100 m goes through 180 dB attenuation and 90 dB attenuation at 50 meters which are quite high. At 10 meter though, it suffers 19 dB attenuation, which is quite manageable. That is why we switch to RF link at 10 meter mark.

In sea water though, the attenuation is very high at 10 MHz frequency, but at lower frequencies, communication is possible at smaller distance and at lower data rate.

Chapter 5

Conclusion

We have shown the limitations of acoustic and RF communication link in underwater control application and developed a novel underwater radio frequency-acoustic hybrid networked control system that fulfills all requirements of underwater docking maneuver. To our knowledge this is the first attempt to combine acoustic and RF communication links in underwater environment for control of AUV system. We have implemented detailed models of acoustic and hybrid channel characteristics and designed a simplified model of underwater docking station and AUV system. We performed various simulations under varying parameters and conditions. We have shown that it is possible to use RF-acoustic hybrid communication scheme for control of underwater AUV systems.

We developed a hybrid MAC protocol to be used in the acoustic communication link that uses TDMA in the docking station portion of communication frame and used one of three schemes, namely S-Aloha, TDMA and waiting room protocol, in the AUV portion of communication frame. We compared performance of the three MAC schemes in the AUV portion of frame under varying load and varying disturbance and found waiting room protocol to be marginally better than other two in repeating the same performance across varying load.

We compared the RF-acoustic hybrid scheme with acoustic only communication scheme for increasing load and increasing disturbance and showed that the RF-acoustic hybrid framework performs better under increasing load and increasing disturbance than acoustic only system.

We have also shown that the RF-acoustic hybrid scheme is more practical than RF only communication link for underwater networked control systems.

We are currently in process of physically implementing RF communication link in underwater environment, after which we will be able to physically implement and experiment on our RF-acoustic hybrid communication scheme.

In future we can implement adaptive MAC schemes that can adapt to varying network traffic and design and implement adaptive controllers for AUV system that can adapt to changing data rate and sampling period.

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