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AN OVERVIEW OF COMMUNICATION, APPLICATION AND CHALLENGES IN UNDERWATER ACOUSTIC WIRELESS SENSOR NETWORK (UWAWSN)

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Abstract. This paper seek to explain how underwater communication is achieved in Underwater Acoustic Wireless Sensor Network (UWAWSN), a survey on its application, challenges and mode of Communication was discussed based on existing literatures, facts about Underwater Communication where drawn from different works with various author developing ways out of solving the challenges, method of maximizing the acoustic channels where presented since the bandwidth is small in the region on 20-30khz, and low propagation speed of 1500 m/s, the multi-carrier is one of the most efficient method for optimum signal propagation, Orthogonal Frequency division Multiplexing (OFDM) is a very reliable modulation technique as it maximizes the bandwidth usage,adopting conventional RF based wireless sensor system for monitoring underwater faces a challenge of signal attenuation, based on the fact that the system operating frequency is 2.4 GHz and also experiences delay due to extreme limited propagation owing to the medium, UWAWSN propagation is best supported at low frequencies. Acoustic communication systems are inherently wideband.

Keywords: *under water, acoustic, satellite, wireless, frequency.*

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1. Introduction

Recently, there has been a huge interest in underwater acoustic communications simply because of its widespread application in marine research, oceanography, marine commercial operations, the offshore oil industry and defense. This interest has led to continuous research which has resulted in improved performance and robustness as compared to the initial communication systems [9,15].

Huge resources abound in underwater waiting to be explored and technology is the key to successful explorations of these resources. Accordingly, underwater sensor network (UWAWSN) is emerging as an enabling technology for underwater explorations. It is a fusion of wireless technology with extremely small micromechanical sensor technology having smart sensing, intelligent computing, and communication capabilities [1, 2, 11]. These sensor nodes are usually spatially distributed in underwater to sense water-related properties such as quality, temperature, and pressure. The sensed data can be utilized by variety of applications that are of benefit to humans. The sensor nodes, stationary or mobile, are connected wirelessly via communication modules to transfer various events of interest. Hence, underwater communication is mainly done with these set of nodes transmitting their data to buoyant gateway nodes that relay the data to nearest coastal monitoring and control station also called remote station.

Terrestrial and airborne Wireless Sensor Networks rely on radio frequencies as their communication medium for transmitting data and information; whereas in sub-sea environment, sensing and subsequent transmission requires all together a different approach for communication [11].The reason lies in the unpredictable conditions of water environment which creates serious constraints in the design and deployment of any network. The underwater acoustic channel is an unforgiving and complex wireless medium dominated by the ocean environment characteristics like significant delay, Double-side-spreading, Doppler- spreads, frequency-selective fading, and limited bandwidth [4, 7, 19]. Hence, efficient underwater communications would depend largely on human knowledge and understanding of the oceans, and the ability to collect information from these remote undersea locations using UWAWSN.

2. Underwater acoustic channels

Generally, acoustic communication is characterized by the following:

- Low Propagation speed (1500 m/s)
- Anisotropic Propagation in contrast to radio waves
- Frequency dependent Attenuated Noise
- Limited Frequency and Distant dependent

Hence, we review critically some parameters associated with underwater acoustic communication channels.

2.1. Underwater acoustic channel attenuation and noise

In a communication channel, Attenuation and Pathloss are important issues to be considered in determining the efficiency. Attenuation could be classified as follows:

i. large scale Attenuation
ii. Deterministic Attenuation
iii. Noise properties which is represented by the equation.

$$A(x,f) \approx x^k a^x(f) \text{..... Spreading + Absorption} \quad (1)$$

where x - distance , f – frequency, A – Attenuation, k =,spreading factor

A major difference between the radio wireless system and acoustic wireless system is that there is heavy dependence on the signal frequency and time.

2.2. Attenuation as a function of distance (x) and frequency(f)

In Underwater Acoustic Wireless Sensor Network there is a heavy dependency on Signal frequency of the attenuated signal. Note that the attenuation and noise defines the design while k denotes spreading factor, in radio frequency the attenuation given is in the range of d to higher powers like d^2 and so on, whereas k which is spreading factor is between 1 and 2.

Also note that $a(f)$ - Absorption is the transfer of Energy
Thus

$$A(f) = 10log\ a(f) \tag{2}$$

a = absorption loss

2.3. Absorption coefficient

Attenuation by absorption occurs due to the conversion of acoustic energy into heat in seawater. This process is frequency dependent since at higher frequencies more energy is absorbed. The attenuation by absorption models is considered for inclusion into the Thorp model [21]. Equation (3) provides the absorption coefficient in dB/km as a function in carrier frequency *cf*:

$$A = \frac{0.1f_c^2}{1+f_c^2} + \frac{40f_c^2}{400+f_c^2} + 2.75\ x\ 10^{-4}\ \ f_c^2 + 0.003 \tag{3}$$

2.4. Propagation loss

The transmitted acoustic signal in underwater acoustic communication reduces strength with increasing distance due to many factors such as absorption caused by magnesium sulphate and boric acid, particle motion and Geo- metrical spreading etc. Propagation loss is composed mainly of three aspects, namely, geometrical spreading, attenuation and the anomaly of propagation. The latter is nearly impossible to model. However, it is known that the signal attenuation, in dB, that occurs over a transmission distance l for a signal frequency f can be approximated as [21]:

$$10logA(1, f) = k.10logl + l.log\alpha \tag{4}$$

In equation 4, α is the absorption coefficient in dB/km which can be obtained from the particular models characterizing it, and *k* represents the geometrical spreading factor with its value between 1 - 2.

2.5. Noise property

i. ***Noise property in quiet, deep Sea***

Let's first consider a model for Noise property for quiet, deep Sea, which means no banging on the shores or human activity, then:

Noise = Turbulence + Shipping Activity + Surface + Thermal

ii. ***Noise property for Noisy deep sea:***

Noise = Turbulence + Shipping Activity + Surface + Thermal + Human Activity+ Banging on offshore noise + Biological Ice + Rain + Seismic

The number of ships causes the Background Noise, wind causes waves, the wave breaks and cause noise.

Power spectrum density of the noise is decaying with frequency which is in sharp contrast with that of the additive white Gaussian noise, so in the case of acoustics channels it is colored not white **[**14].

$N = 10logN(f)$ denotes Power Spectrum Density decaying with frequency, where N = Noise, f = frequency.

Noise is frequency dependent and in addition to the noise is a site specific noise, like ice cracking, banging near the shores that are busy with marine activity.

When we put the two together that is the path loss and the noise, we come up with a Signal to Noise ratio, which is dependent on the N product A, N Product that is the attenuation and power spectral Density of the noise. The- $10logA(x, f)\ N(f)$ is the inverse of the A, N Product which directly proportional to Signal to Noise ratio SNR which is a function of frequency in KHz.

2.6. Signal-to-noise ratio

In Underwater Acoustic Communication, signal-to-noise ratio can be calculated [16] based on signal attenuation and the noise power spectral density (p.s.d). Specifically, the SNR observed at the receiver can be calculated in μPa re dB per Hz using the following equation:

$$SNR(l, f) = \frac{P}{A(l, f)N(f)\Delta f} \quad (5)$$

where the *SNR(l,f)* is over a distance and a transmission centre frequency *f*, *P* is the signal transmission power and Δf represents the receiver noise bandwidth. Equation (5) clearly shows that the underwater acoustic channel SNR is a function of transmission frequency. As such we can find the optimal frequency for underwater acoustic communication to maximize SNR. The attenuation-noise (AN) factor, given by A(*l*,*f)* can be used to reflect the frequency dependent part of the SNR. By close analysis of this relationship, it can also be used to determine the optimal frequency at which the maximal narrow-band SNR is achieved for each transmission distance *l.* Since the SNR is inversely proportional to the attenuation-noise factor, the optimal frequency is that for which the value of 1/AN (represented in dB re μPa per Hz) is the highest over the combination of a certain distance, $f_{o.}$

In Figure 1 [21], frequency-dependent part of the narrowband SNR $1/A(l, f)N(f)$, is shown. In this plot the attenuation and noise parameters are selected as k = 1.5, S = 0.5, and to reflect the UWAC with moderate shipping activity and no wave noise. It can be seen that there is a frequency for which the narrowband SNR is maximized for a particular distance, for the given attenuation and noise constants. This optimal frequency, denoted $f_0(l)$ can be selected as the carrier frequency f_c for that particular transmission distance [20].

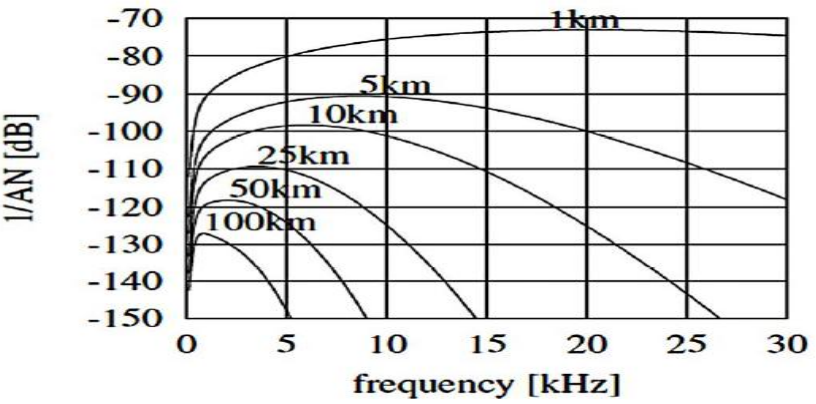

Figure 1. Narrowband SNR, $\frac{1}{A(l,f)N(f)}$; k = 1.5; s = 0; ω = 0 [20].

2.7. Ambient noise model

Ambient noise in the ocean can be described as Gaussian and having a continuous power spectral density (p.s.d.) [18]. The four most prominent sources for ambient noise are the turbulence, shipping, wind driven waves and thermal noise.

Their p.s.d. in dB re μPa per Hz are given by the formulae Equations (6)-(9) shown below, respectively [17]:

$$10\ log N_t(f) = 17 - 30 \log f \tag{6}$$

$$10 log N_s(f) = 40 + 20(s - 0.5) + 26\ log f - 60\ log\ (f + 0.03) \tag{7}$$

$$10\ log N_w(f) = 50 + 7.5\sqrt{w} + 20\ log f - 40\ log\ (f + 0.4) \tag{8}$$

$$10\ log\ N_{th}(f) = -15 + 20\ log f \tag{9}$$

The ambient noise in the ocean is affected by different factors in specific frequency ranges.

$N_t(f)$ represents the turbulence noise at frequency f, $N_t(f)$ the shipping noise (with s the shipping factor which lies between 0 and 1), $N_w(f)$ the wind driven wave noise (with ω as the wind speed in m/s), and as the wind speed in m/s), and $N_{th}(f)$ the thermal noise. The composite noise Power spectrum density p.s.d. can be obtained in μPa from

$$N(f) = N_t\ (f) + N_s(f) + N_w + N_{th}\ (f).$$

2.8. Doppler shift and under water acoustic communication multipath

In underwater communication, the relative movement between the transmitter and the receiver due to the constant motion of nodes results in Doppler shifts, which significantly distort received signals. It is required to estimate the Doppler shift and compensate it for all UWAC applications. Different from the case of terrestrial communication where the Doppler effect is modeled by a frequency shift, due to the slow sound speed in water, the effect of transceiver motion on the duration of the symbol cannot be neglected [16]. Doppler phase

α_d depending on the relative velocity v and the ratio between the carrier frequency *fc* and the symbol rate *R=1/T* [13] caused in the received signal as:

$$\alpha_d = 2\pi f T \frac{\Delta}{1+\Delta} = -2\pi \frac{fc}{R} \frac{v}{c-v} \tag{10}$$

From [14,17] UWAC multipath representation for multipath arrival p is characterized by its mean magnitude gains α_p and delay *tp*. These quantities are dependent on the path length l_p which in turn is a function of the given range *R*. The path magnitude gain is given by l_f

$$A(l_p, f_c) = \frac{\Gamma_p}{\sqrt{A(l_p, f_c)}} \tag{11}$$

where $\Gamma = \left(1/\sqrt{2}\right)^{rp}$ is the amount of loss due to reflection at the bottom and surface, and *rp* is the number of reflections for path p. From Equation (1), the acoustic propagation loss, represented by (l_p, f_c) resulting in the following equation.

$$A(l_p, f_c) = l_p^k [\alpha f_c]^{Lp} \tag{12}$$

The delay for path p , given is t_p =1/c (c = 1500 ms) is speed of sound in water) and l_p is the path length for path p [13]. r_p= 0,1,3,5,7 for each path respectively, the path lengths can be calculated using planar geometry.

2.9. Modulation

Multicarrier modulation has been tested and proven to be more efficient in underwater acoustic communication. However, Doppler effect is the major consideration in multi-carrier modulation. In a multi-carrier system, different data stream are put in parallel to each other over different carrier signal. These different data stream are sent on orthogonal carrier and due to time variation, the orthogonality between the carriers is lost resulting in inter-carrier interference (ICI). To solve this problem, one can either decrease the data rate, improve low complicity receivers that do not require a decrease in data rate or exploit the extra Doppler diversity. [4, 13, 16]

i.OFDM for Underwater Acoustic Channel

OFDM has a number of desirable features such as low complexity of implementation and mature technologies that keep it as the dominant technology for single-user (point-to-point) underwater communications. OFDM can be easily adopted for MIMO channels, however, the poor frequency spectra of subcarrier signals in OFDM are the main issue that limits the applicability of OFDM in some present and future development of broadband underwater communication systems [10].

Using OFDM as multi-carrier modulator, the input-output relation is given as

$$y_n = \sum_{l=0}^{L} h_{n,l}\ x_{n-1} + v_n, \tag{13}$$

where y_n is the output, h is finite impulse filter (note that h is dependent on n which shows that it is time dependent), x represents signal or data, v_n is noise at time instance n.

If a convolution is carried out and we assume all information bit are in the example here, we can then model the channel as finite impulse.

The Cyclic Prefix is transformed as circular convolution in this matrix format

$$[\![Y]\!]=[\![H]\!][\![X]\!]+[\![V]\!]= [\![H]\!][\![X]\!]+[\![V]\!]$$

If we consider applying Inverse Discrete Fourier Transform IDFT and Discrete Fourier Transform DFT at the transmitter and receiver we have a setup as shown in Figure 2

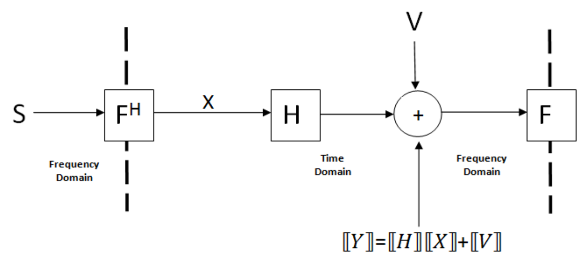

Figure 2. Interconnection showing Transform from Frequency-Time-Frequency domain

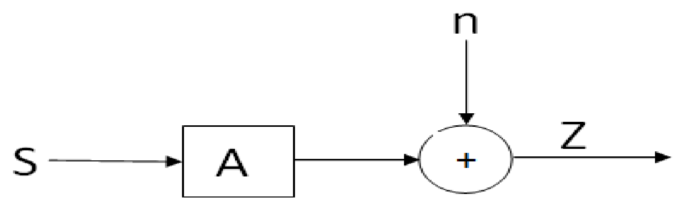

Figure 3. Z transform for A is what happens to H at the frequency domain

$$A= FHF^{H}$$

Therefore

$$Z =[\![A]\!][\![S]\!]+[\![n]\!]$$

Z is the frequency domain representation [15, 5, 12].

ii. MIMO for Underwater Acoustic Channel

Multi-input multi-output (MIMO) techniques is a more efficient method in underwater acoustic communications to overcome the bandwidth limitation of undersea channel [5]. Combined with OFDM modulation, the techniques provide substantial spectral efficiency and reasonable robustness against frequency fading while keeping simple equalizer structure. Long acoustic multipath, however, limits the applicability of MIMO channel estimation methods that require inversion of a matrix whose size is proportional to both the number of transmit elements and the multipath spread. Adaptive algorithm in used in overcoming this problem which does not require matrix inversion and operates in a decision directed manner, thus reducing both the computational complexity and the overhead. Reduction in complexity has been sought through selection of significant impulse response coefficients which results in a reduced-size matrix inversion. MIMO-OFDM design consists of the following key components:

1) Transmitter which are inserted with Null sub-carriers to facilitate the compensation of Doppler shifts at the receiver;

2) Pilot tones are used for MIMO channel estimation;

3) An iterative receiver structure is adopted that couples MIMO detection with channel decoding [10].

3. Applications

In this section, a survey of recent applications of UWASN is presented. Generally, UWASNs find their applications in fields like offshore oil and gas extraction, oil spills, military surveillance and reconnaissance, mine detection, pollution monitoring, natural calamities like tsunami and hurricane forecast, coral reef and habitat monitoring of marine life and fish farming to name a few. Figure 1 is an illustration of various application of the UWAWSN.

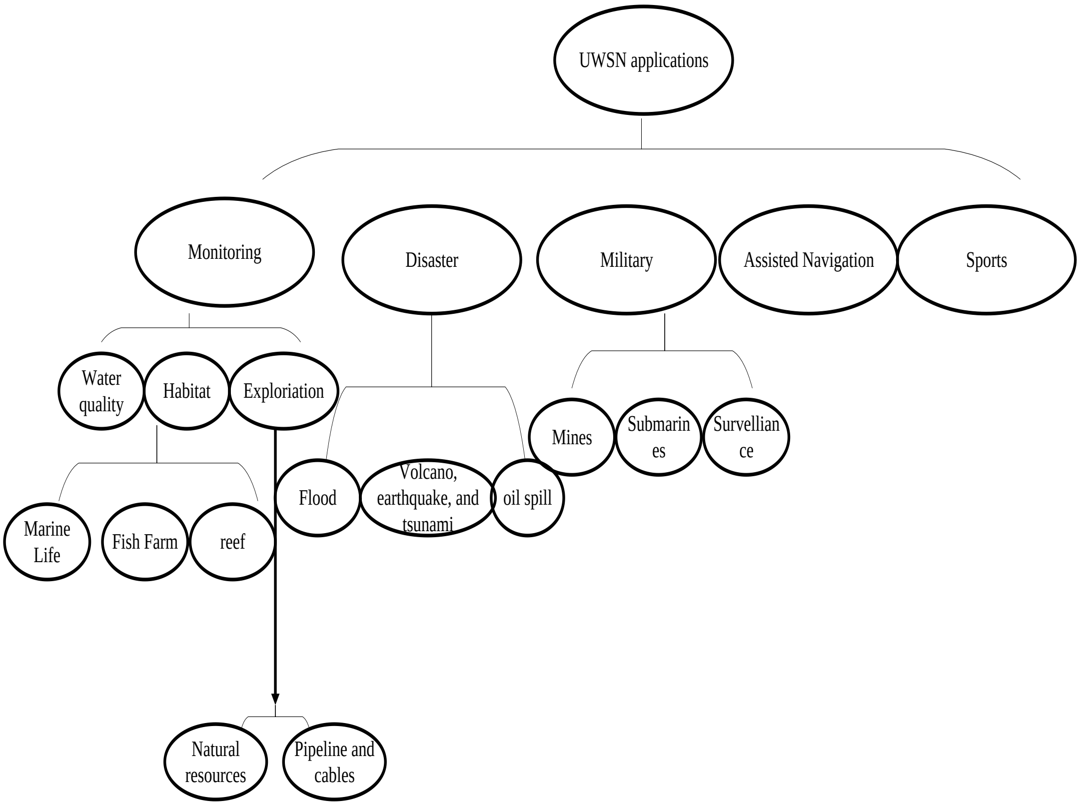

Figure 4. Different Classification of underwater wireless sensor network applications [9]

App.		Deployment		Sensors		Communication	Implementation
	Architecture	Salinity level	Operable depth	Type	Number	Type	
				Water quality			
[9]	1D	Pool	Few meters	O_2, NH_3-N, pH, EC	Few	RF	Real-time
[10]	3D, 4D	Reservoir	Few meters	T, EC, D, NO_3^-, Tur	Many	RF, acoustic	Real-time
[11]	1D	River	Few meters	Ph	Many	RF	Real-time
[12]	4D	Lake	Few kilometres	T, O_2, pH, EC	Many	Acoustic	Real-time
[13]	Static 2D	Shallow water	Few meters	T, pH, Tur	Many	RF	Nontime
[14]	3D	Ocean	Kilometers	n/a	Many	Acoustic	n/a
				Habitat			
				Marine life			
[15]	3D	Sea	75 Km	n/a	Few	Acoustic	Real-time
[16]	3D, 4D	Sea	Meters	T, P	Many	Acoustic	Real-time
[17]	3D	Shallow water	1–4 kilometers	T,P,S, Photo	Few	RF	Real-time
[18]	3D	Shallow water	Kilometers	T, P, S	Many	Acoustic	Real-time
[19]	3D	Sea	n/a	T, P, S, V	n/a	Acoustics	Real-time
[20]	3D	Sea	n/a	V	Few	Acoustic	Real-time
				Fish farms			
[21]	Static 2D	River	2–15 meters	T, S, Tur	Few	RF	Real-time
[9]	1D	Pool	Meters	O_2, NH_3-N, EC, pH	Many	RF	Real-time
[22]	Static 2D	n/a	n/a	T, pH, NH_4	n/a	RF	Real-time
[23]	Static 2D	Pool, pond	10 Km	T, L, H, O2, pH	Many	RF, acoustic	Real-time
[24]	3D	River	n/a	D, O_2, pH	Few	Acoustic	
				Reef			
[15]	4D	River	Few meters	T, C, pH	Few	Acoustic	Real-time
[16]	4D	River	200 meters	C, P, Comp, GPS	n/a	RF, acoustic	Real-time
[25]	1D	River	n/a	T	Few	Acoustic	Real-time
[26]	4D	River	n/a	T,P, pH	Few	Acoustic	Real-time
				Exploration			
				Natural resources			
[26]	4D	River	3 Km	T, S, P, D	Few	Acoustics	Real-time
[27]	4D	River	Meters	n/a	Few	Acoustics	Not deployed
[15]	3D	Oceans	Kilometers	n/a	Few	Acoustic	Real-time
				Pipelines and cables			
[28]	3D, 4D	Pool	Meters	n/a	Few	RF, acoustic	Not deployed
[29]	3D	Pool	Few meters	Vib, Cur	Few	RF, acoustic	Real-time
[30]	Static 2D	Pool	Few meters	n/a	Few	n/a	Lab environment
[31]	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Table 1. Comparison of UWSN monitoring Applications

C = camera, D= depth, H= humidity, L= water level, O_2 = oxygen, P= pressure, S= salinity, T= temperature, V= velocity, Cur = current, Comp = magnetic compass, EC = electrical conductivity, NH_3-N = ammonium nitrogen, NO_3^- = nitrate, NH_4 = ammonium, Photo = light, Tur = turbidity, Vib = vibration

Table 1 is a comprehensive detail of *Comparison* of UWSN monitoring applications
Source: Emad et al, (2015)

Underwater application can be viewed via satellite with Underwater Acoustic wireless sensor network (UWAWSN) which can be globally utilized for early warnings against natural calamities like floods, tsunamis, earthquakes and

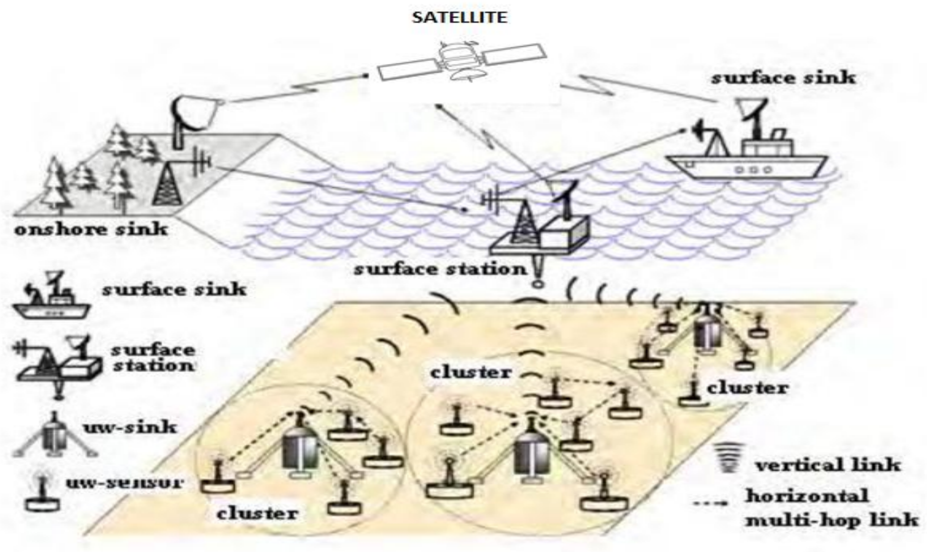

Figure 5. Network of Underwater Communication

Underwater Sensing and Communication Testbed

Generally, natural disasters are inevitable but water based natural disasters are more dangerous and produces huge destruction to the earth. The repercussions of flood and its increased frequency have pushed the researchers to find ways of timely flood alerts. Accordingly, disaster monitoring and preventive mechanisms are very necessary. Indicators such as seismic activity, variation in water turbulence, temperature and changes in the atmospheric densities can be measured by employing underwater sensor networks providing thorough information on any incoming disaster as early as a few days. UWSN monitoring strategies for disaster management and prevention can be formulated into a wide variety of applications such as floods, underwater volcanic eruptions, underwater earthquakes and their resulting tsunamis, and oil spills which lead to above-the-water and underwater ecological instabilities [3] proposed a three tier model (Figure 5) having a number of wireless nodes deployed at the sea bed having acoustic modems for communication. The nodes are organized in groups and a group head accumulates the data and relays it to the nearest surface station. In the second level, microwave communication is used to relay the information collected at the surface node to the land based data collection center. Once the data reaches the coastal collectioncenter, it can then be relayed to an international collectioncenter via satellite communication. Challenges that follow the model includes limited power, optimization of energy harvesting techniques, increased bit error rates (BER) and low signal to noise ratio (SNR) in case of low power nodes.

Frequent seismic monitoring is of importance in extraction from oil fields. And this is a promising application for underwater sensor networks since more concentration is now on offshore exploration. The monitoring of oil reservoir over time is useful for judging field performance and motivating intervention. Traditionally, seismic monitoring of underwater field is capital intensive and typically involves a ship with a towed array of hydrophones as sensors and an air cannon as the actuator, hence it is rarely done every 2 – 3 years. However, the use of underwater sensor network will alleviate the challenges being experienced in this regard [12].

Lastly, another important application of underwater sensor network is in equipment monitoring and control. Usually, long-term equipment monitoring in underwater is done with pre-installed infrastructure to see its efficacy. Temporary monitoring is most useful when equipment is first deployed, to confirm successful deployment during initial operation, or when problems arise. Hence, *temporary* monitoring would benefit from low-power, wireless communication.

4. Challenges

The following unique characteristics of the underwater acoustic communication channel as enumerated in this work poses a lot of challenge in the design of underwater acoustic networks such:

1. Severe limitation in bandwidth availability: Available bandwidth is severely limited because of the fact that attenuation of acoustic signal increases with frequency and range. Hence, the feasible bandwidth in underwater in the range of 20 and 30kHz is extremely small.
2. Severe impairment of the underwater channel due to multipath and fading problems
3. Extreme Propagation delay: This is very significant and has profound implications on localization and time synchronization of underwater sensor networks. This is due to the fact that propagation delay in underwater is five orders of magnitude higher than in radio frequency (RF) terrestrial channels, and extremely variable.
4. High bit error rates and temporary losses of connectivity (shadow zones) can be experienced, due to the extreme characteristics of the underwater channel.
5. Battery power is limited and usually batteries cannot be recharged, also because solar energy cannot be exploited.
6. Underwater sensors are prone to failures because of fouling and corrosion

5. Conclusion

In this work, an overview of the perculiarities of the underwater acoustic communication channel was carried out. Also, the applications and challenges for efficient communication in underwater acoustic sensor network with respect to channel utilization was highlighted and inferences drawn to encourage research effort in UWASN. It also shows that multicarrier modulation has been tested and proven to be more efficient in underwater acoustic communication. However, Doppler effect is the major consideration in multi-carrier modulation. In a multi-carrier system, different data stream are put in parallel to each other over different carrier signal. These different data stream are sent on orthogonal carrier and due to time variation, the orthogonality between the carriers is lost resulting in inter-carrier interference. It also show that OFDM has a number of desirable features such as low complexity of implementation and mature technologies that keep it as the dominant technology for single-user (point-to-point) underwater communications.

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