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ENERGY EFFICIENCY ANALYSIS OF ERROR CORRECTION TECHNIQUES IN UNDERWATER WIRELESS SENSOR NETWORKS

AMMAR ELYAS BABIKER*, M. NORDIN B. ZAKARIA

Computer and Information Science Department, Universiti Teknologi PETRONAS
P.O. Box 10, 31750 Tronoh, Perak, Malaysia
*Corresponding Author: ammaralyas@hotmail.com

Abstract

Research in underwater acoustic networks has been developed rapidly to support large variety of applications such as mining equipment and environmental monitoring. As in terrestrial sensor networks; reliable data transport is demanded in underwater sensor networks. The energy efficiency of error correction technique should be considered because of the severe energy constraints of underwater wireless sensor networks. Forward error correction (FEC) and automatic repeat request (ARQ) are the two main error correction techniques in underwater networks. In this paper, a mathematical energy efficiency analysis for FEC and ARQ techniques in underwater environment has been done based on communication distance and packet size. The effects of wind speed, and shipping factor are studied. A comparison between FEC and ARQ in terms of energy efficiency is performed; it is found that energy efficiency of both techniques increases with increasing packet size in short distances, but decreases in longer distances. There is also a cut-off distance below which ARQ is more energy efficient than FEC, and after which FEC is more energy efficient than ARQ. This cut-off distance decreases by increasing wind speed. Wind speed has great effect on energy efficiency where as shipping factor has unnoticeable effect on energy efficiency for both techniques.

Keywords: ARQ; FEC, Energy efficiency, Error correction techniques, Underwater communications.

1. Introduction

Underwater wireless sensor networks have been receiving growing interest since the last few decades [1-4]. As in terrestrial sensor networks; in most applications, reliable data transport is demanded in underwater sensor networks [5]. Forward

Nomenclatures

$a(f)$	Thorp's approximation function, dB/km
ack	Acknowledgment packet length, bit
d_{free}	Minimum hamming distance, km
E	Energy efficiency
E_{dec}	Decoding energy, J
E_{enc}	Encoding energy, J
E^{re}	Energy consumed by the sender, J
E^{tr}	Energy consumed by the receiver, J
f	Frequency for underwater communications, kHz
k	Spreading coefficient or Parity check, bits
l	Payload, bits
M	Number of phases
N	Overall noise, dB
n	Payload + Parity check, bit
N_s	Noise due to shipping, dB
N_t	Noise due to turbulence, dB
N_{th}	Thermal noise, dB
N_w	Noise due to wind, dB
P_b	Bit error probability
P_{re}	Receiving power, W
P_s	Symbol error probability
P_{tr}	Transmitting power, W
r	Packet acceptance rate
R_c	Code rate, kbps
s	Shipping variable
T_{tr}	Time of transmitting 1 bit, s
w	Wind speed variable, m/s
$w(d)$	Weight distribution function

Greek Symbols

α	Header field, bytes
γ_b	Received SNR
η	Energy efficiency
η_e	Energy throughput
τ	Frame check sequence, bytes

Abbreviations

AN factor	Attenuation noise factor
ARQ	Automatic repeat request
FCS	Frame check sequence
FEC	Forward error correction
PER	Packet error rate
PSK	Phase shift keying
SNR	Signal to noise ratio

error correction (FEC) and automatic repeat request (ARQ) are the two main error correction techniques that guarantee the reliability of data transmission in underwater acoustic links [2, 6, 7].

The traditional concern in designing a good reliable data transport protocol is energy efficiency, since many applications require nodes to operate underwater for long period without recharging their batteries. In addition, it is also difficult to recharge or replace batteries in some aquatic environments [5, 8].

There have been some studies concerning error control schemes in underwater sensor networks, and energy efficiency of error correction techniques in other networks. Harris et al. [9] designed and implemented a propagation model to calculate the signal to noise ratio for underwater acoustic channel. Sankarasubramaniam et al. proposed [10] an optimization metric for energy efficiency. This was used by Tian et al. [11] for energy efficiency calculations and they have proven that energy efficiency of ARQ techniques is independent of retransmission attempts; they compared ARQ and FEC techniques for terrestrials wireless sensor networks in terms of energy efficiency. Labrador et al. [12] studied modulation techniques for underwater communication system and it was found that 8-PSK is the best modulation for underwater systems. They argued that convolution coding achieves better coding gain in underwater environment. Hence, their modulation and decoding techniques are used in this study.

In this paper the energy efficiency of FEC and ARQ in underwater wireless sensor networks has been analyzed. A minimum attenuation noise factor (AN factor) is calculated first in terms of frequency, then a mathematical analysis for energy efficiency for ARQ and FEC in underwater is done for different distance, packet size, wind speed and shipping factor. ARQ is compared with FEC in terms of energy efficiency, and the status where each one outperforms the other is presented.

To the best of our knowledge, this is the first work in which a mathematical analysis for energy efficiency in the two main error correction techniques in underwater environment has been done. And based on this analysis a comparison between ARQ and FEC techniques in terms of energy efficiency in underwater environments using different variable parameters is presented.

The rest of the paper is organized as follows: underwater propagation model is given in Section 2, mathematical energy efficiency analysis for both error correction techniques is provided in Section 3 and Section 4 presents the results and analysis. In Section 5 the paper is concluded and some recommendations for future work are included.

2. Underwater Propagation Model

The propagation model is responsible for calculating the signal to noise ratio (SNR) at the receiver after attenuation and noise are taken into account. To calculate the SNR at the receiver, both the attenuation of the acoustic signal in water and the ambient noise need to be calculated. The total attenuation is calculated based on the spreading losses [9, 13], and Thorp approximation [9, 14] for the absorption loss.

2.1. Attenuation

To calculate the absorption loss at a given frequency, Thorp's approximation function for frequency greater than 400 Hz is as follows [9, 14]

$$10\log a(f) = 0.11\frac{f^2}{1+f^2} + 44\frac{f^2}{4200+f} + 2.75\times 10^{-4} f^2 + 0.003 \quad (1)$$

where $a(f)$ is given in dB/km and f in kHz for underwater communications. Combining absorption effects and spreading loss, the total attenuation is as follows [9, 13]:

$$10\log A(l,f) = k\log l + l\times 10\log a(f) \quad (2)$$

where the first term is the spreading loss and the second term is the absorption loss. The spreading coefficient, k, defines the geometry of the propagation, where k=1 for cylindrical propagation, k=2 for spherical, and k=1.5 for practical spreading [9, 13].

2.2. Noise

The calculation of ambient noise in underwater environment is divided into four major factors that contribute to the total noise: turbulence, shipping, wind and thermal. The following formulas give the power spectral density of the four noise components [9]

$$10\log N_t(f) = 17 - 30\log(f) \quad (3)$$

$$10\log N_s(f) = 40 + 20(s-0.5) + 26\log(f) - 60\log(f+-.03) \quad (4)$$

$$10\log N_w(f) = 50 + 7.5\times w^{0.5} + 20\log(f) - 40\log(f+0.4) \quad (5)$$

$$10\log N_{th}(f) = -15 + 20\log(f) \quad (6)$$

where N_t is the noise due to turbulence, N_s is the noise due to shipping (the shipping variable, s, takes the values between 0 and 1), N_w is the noise due to wind (the wind variable, w, represents wind speed in m/s), and N_{th} represents thermal noise. The overall noise power spectral density for a given frequency, f (kHz) is then

$$N(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f) \quad (7)$$

2.3. Signal to noise ratio (SNR)

Signal to noise ratio (SNR) is given by [9] as:

$$SNR = \frac{P_{tr}}{A(f)N(f)} \quad (8)$$

where $N(f)$ is given by Eq. (7), $A(l,f)$ is given by Eq. (2), and P_{tr} is the transmission power.

3. Energy Efficiency Analysis

The data packets in ARQ and FEC cases are presented as in Table 1. Data packet in ARQ case consists of a header field, α bits long, payload of size l bits and a frame check sequence (FCS) τ bits long. In forward error correction (FEC) case it consists of a payload of size (n-k) bits long, a parity check of k bits and a header field α bits long.

Table 1. Data Packets in ARQ and FCS Cases.

Case				
	ARQ	**Header**	**FCS**	**Payload**
		α	τ	l
	FEC	**Header**	**Parity check**	**Payload**
		α	k	n-k

3.1. Optimization metric

Energy efficiency, η, is defined as in [10, 11]

$$\eta = \eta_e r \tag{9}$$

where η_e is the energy throughput, r = (1-PER) is the packet acceptance rate, which accounts for data reliability.

3.2. Bit error rate calculation

Using 8-PSK scheme as the suitable modulation techniques for underwater acoustic communication [12], the symbol error probability P_s for ARQ is given by [12, 15]

$$P_s \approx 2Q(\sqrt{2\gamma_s}\sin(\frac{\pi}{M}) \tag{10}$$

where M = 8 for 8-PSK, and the bit error probability P_b is given by:

$$P_b = \frac{P_s}{3} \tag{11}$$

Whereas for FEC convolution code [16]

$$P_b = \frac{1}{k}\sum_{d=d_{free}}^{\infty} w(d)Q\sqrt{2dR_c\gamma_b} \tag{12}$$

where $w(d)$ is the weight distribution function, d_{free} is the minimum hamming distance, γ_b is the received SNR, and $R_c = k/(k+1)$ is the code rate.

3.3. ARQ energy efficiency analysis

For ARQ, energy efficiency is independent of retransmission attempts and is unchangeable with the number of retransmission [11]. The energy consumption of sensor node for communication in one hop is given by:

$$E_{ARQ} = E_{ARQ}^{tr} + E_{ARQ}^{re} \quad (13)$$

where E_{ARQ}^{tr} is the energy consumed by the sender in transmitting the data and receiving the acknowledgement, and E_{ARQ}^{re} is the energy consumed by the receiver in receiving the data and transmitting the acknowledgement as presented in the following equations:

$$E_{ARQ}^{tr} = E_{data}^{tr} + E_{Ack}^{re} = P_{tr} l_{data} T_{tr} + P_{re} l_{Ack} T_{tr} \quad (14)$$

$$E_{ARQ}^{re} = E_{data}^{re} + E_{Ack}^{tr} = P_{re} l_{data} T_{tr} + P_{tr} l_{ack} T_{tr} \quad (15)$$

where P_{tr}/P_{re} is the power consumed in transmitting/receiving, and $T_{tr} = 1/R$ is the time of transmitting 1 bit.

From Table 1 (for ARQ packet), using the bit error rate probability P_b in Eq. (11), the PER for ARQ can be derived as follows

$$PER_{ARQ} = 1 - (1 - P_b)^{l+\alpha+\tau} \quad (16)$$

From Eq. (9) energy efficiency of ARQ with or without retransmission strategy can hence be written as

$$Eff_{ARQ} = \frac{Eff_{ARQ}^{eff}}{Eff_{ARQ}^{tot}} \left(1 - PER\right)_{ARQ} = \frac{(P_{tr} + P_{re}) l T_{tr}}{(P_{tr} + P_{re})(l + \tau + \alpha + ack)} (1 - PER_{ARQ})$$

$$Eff_{ARQ} = \frac{l}{l + \tau + \alpha + ack} (1 - PER_{ARQ}) \quad (17)$$

where E_{ARQ}^{eff} is the energy consumed by the payload only, E_{ARQ}^{tot} is the total energy consumed.

3.4. FEC energy efficiency analysis

The energy consumption of FEC is given by:

$$E_{FEC} = E_{FEC}^{tr} + E_{FEC}^{re} + E_{dec} + E_{enc} \quad (18)$$

Using convolution turbo code as forward error correction techniques, encoding (E_{enc}) and decoding energy (E_{dec}) are considered to be negligibly small [10, 11], and from Table 1 (for FEC packet), the expression for the energy efficiency is defined as:

$$Eff_{FEC} = \frac{E_{FEC}^{eff}}{E_{FEC}^{tot}} (1 - PER_{FEC}) = \frac{(P_{tr} + P_{re})(n - k) T_{tr}}{(P_{tr} + P_{re})(n + \alpha) T_{tr}} (1 - PER_{FEC})$$

$$Eff_{FEC} = \frac{n - k}{n + \alpha} (1 - PER_{FEC}) \quad (19)$$

where PER_{FEC} is calculated using Eq. (12).

4. Results and Analysis

The results are obtained using a C++ program, with LinkQuest UWM2000 acoustic modem [17], and the parameters given in Table 2.

Table 2. Parameters Used in the Analysis.

Symbol	Parameters	
	Definition	**Quantity**
P_{tr}	**Transmitting Power**	2 W
P_{re}	**Receiving Power**	0.75 W
R	**Bit Data Rate**	10 kbps
l_{ack}	**Acknowledge packet length**	7 Byte
α	**Header + FCS length**	11 Byte

First, a suitable frequency range based on AN factor as shown in Fig. 1 was calculated; this frequency range corresponds to the minimum AN factor. A suitable range is found from 10 kHz up to 25 kHz, below and over this range the AN factor increases sharply.

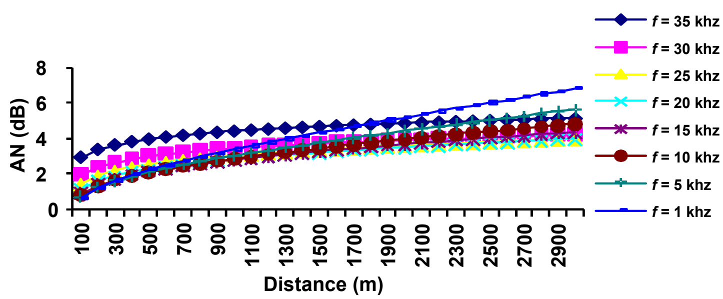
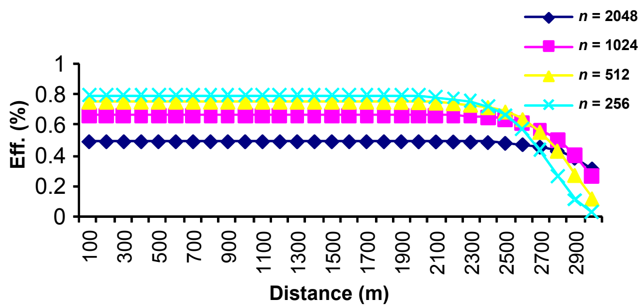


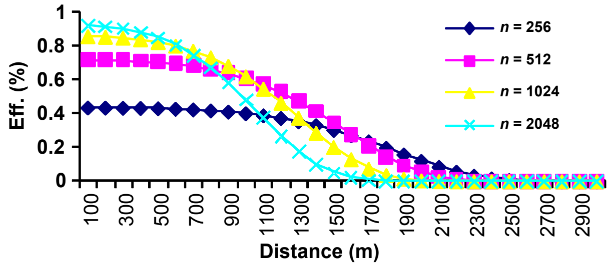
Fig. 1. AN Factor as a Function of Distance and Frequency.

From Figs. 2(a) and (b), it is clear that the energy efficiency of both techniques increases with increasing packet size in short distances, whereas decreases in long distances for both techniques.

In Fig. 3(a) for a packet length of 256 bit and when no wind exists, FEC is better than ARQ in terms of energy efficiency, and the effect of shipping is negligible. ARQ efficiency starts to decrease at 1700 m, where as FEC energy efficiency continues for longer distance. In Fig. 3(b) it is clearly that wind speed affects energy efficiency for both protocols, especially in longer distance. The effect of wind speed is more apparent in ARQ technique where the efficiency starts to decrease at 700 m than in FEC where it starts to decrease at 2400 m.

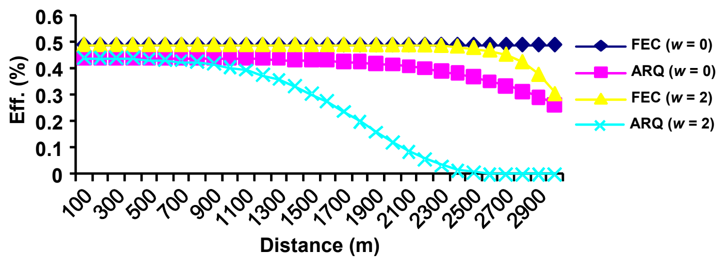


(a) FEC Technique (w = 2, s = 0)

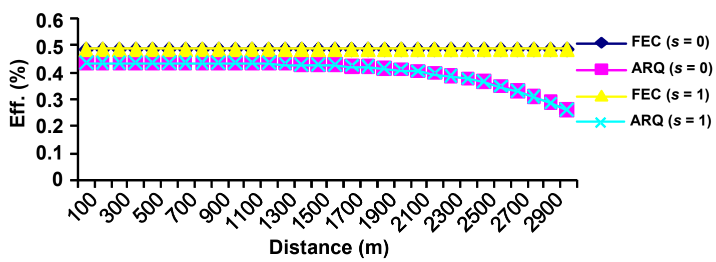


(b) ARQ Technique (w = 2, s = 0)

Fig. 2. Energy Effieicency as a Function of Distance and Packet Size.



(a) FEC and ARQ Techniques (w = 0 and 2)

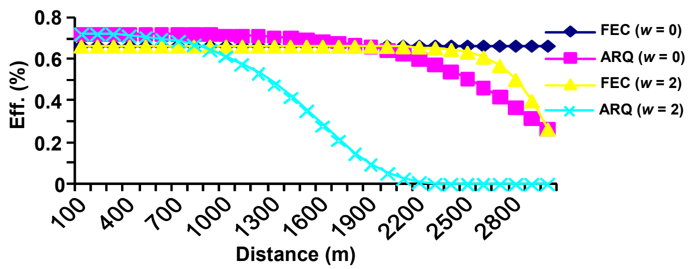


(b) FEC and ARQ Techniques (s = 0 and 2)

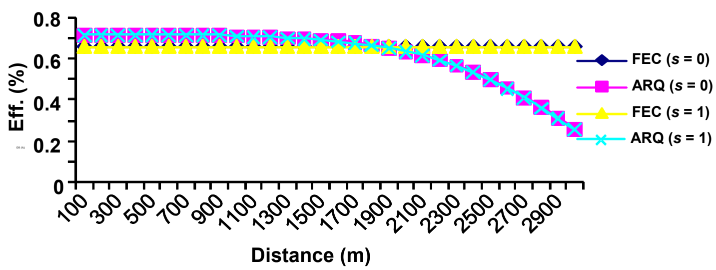
Fig. 3. FEC vs. ARQ Energy Efficiency (n = 256).

In Fig. 4(a) energy efficiency of ARQ and FEC for a packet length of 512 bit is shown. It is apparent that ARQ is more energy efficient than FEC below a specific distance (cut-off distance), and FEC is more energy efficient after this distance. The effect of shipping is unseen and can be neglected. In Fig. 4(b) the effect of wind is very clear, especially for ARQ, and the cut-off distance decreases from 2000 m when no wind exists to 1000 m only when the wind speed is 2 m/s. ARQ efficiency starts to decrease at 1400 m when no wind exists, and at 400 m when the wind speed is 2 m/s, whereas for FEC it starts to decrease at 2300 m when the wind speed is 2 m/s, and it continues for long distance when no wind exists.

The energy efficiency of both techniques increases in short distances (less than 2000 m); where-as it decreases in longer distances (more than 2000 m) compared to packet size of 256 bit. It is also apparent that ARQ is more energy efficient than FEC below a specific distance (cut-off distance), and FEC is more energy efficient after this distance. The effect of shipping is unseen and can be neglected.



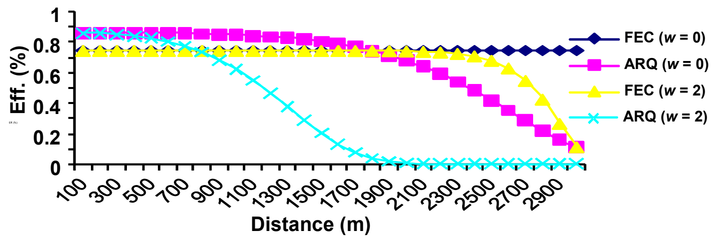
(a) FEC and ARQ Techniques (s = 0, w = 0 and 2)



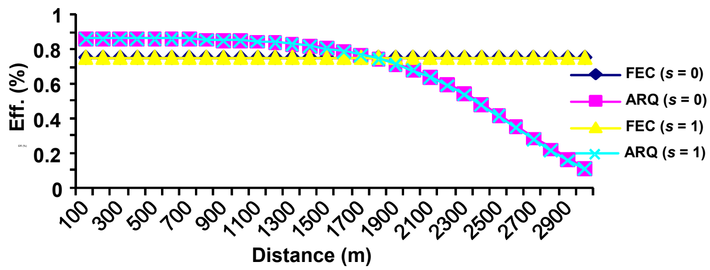
(b) FEC and ARQ Techniques (w = 0, s = 0 and 1)

Fig. 4. ARQ vs. FEC Energy Efficiency (n = 512).

In Figs. 5(a) and (b), energy efficiency for a packet size of 1024 bit is studied. It is shown that ARQ is more efficient than FEC below the cut-off distance and less efficient after that, this cut-off distance decreases from 1900 m when no wind exists to 900 m when wind speed of 2 m/s exists. It is also clear that ARQ efficiency starts to decrease at 1200 m when no wind exists-, and at 300 m when the wind speed is 2 m/s, where-as for FEC it starts to decrease at 2000 m in case of 2 m/s wind speed, and continues for long distance when no wind exists.



(a) FEC and ARQ Techniques (s = 0, w = 0 and 2)



(b) FEC and ARQ Techniques (w = 0, s = 0 and 1)

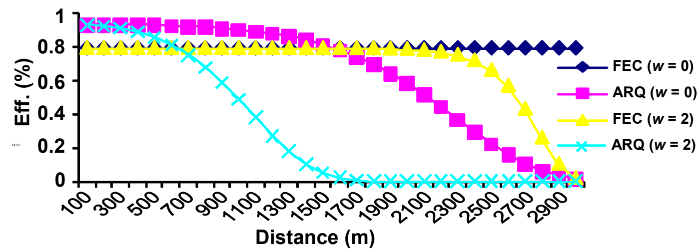
Fig. 5. ARQ vs. FEC Energy Efficiency (n = 1024).

In Figs. 6(a) and (b), for a packet size of 2048 bit the effect of shipping is negligible, whereas the effect of wind speed is clearly visible, and the cut-off distance decreases from 1600 m when no wind exists to 600 m when wind speed of 2 m/s exists. It is also clear that ARQ efficiency starts to decrease at 800 m when no wind exists, and when the wind speed is 2 m/s it starts to decrease at 200 m,; whereas for FEC it starts to decrease at 1900 m in case of 2 m/s wind speed, and it continues for long distance when no wind exists.

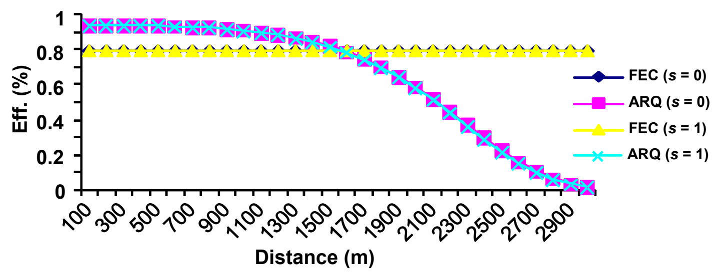
5. Conclusion and Future Work

In this paper a mathematical analysis for energy efficiencies of ARQ and FEC has been done, and a comparison between them in terms of energy efficiency in underwater environment is presented. It is found that energy efficiency in underwater increases with increasing packet size in short distances and decreases with packet size in longer distances. It is also found that ARQ is more energy efficient below a specific distance (cut-off distance), whereas FEC is more efficient after that distance. This cut-off distance is affected by the packet length and wind speed. Shipping factor has been found to have negligible effects on energy efficiency.

The results obtained from this analysis will be the basis for designing and implementing hybrid energy efficient error correction protocol for underwater wireless sensor networks in future.



(a) FEC and ARQ Techniques (*s* = 0, *w* = 0 and 2)



(b) FEC and ARQ Techniques (*w* = 0, *s* = 0 and 1)

Fig. 6. ARQ vs. FEC Energy Efficiency (*n* = 2048).

References

1. Heidemann, J.; Ye, W.; Wills, J.; Syed, A.; and Li, Y. (2006). Research challenges and applications for underwater sensor networking. *In proceeding of the IEEE Wireless Communications and Networking Conference, WCNC 2006,* 1, 228-235.
2. Proakis, J.G.; Sozer, E.M.; Rice, J.A.; and Stojanovic, M. (2001). Shallow water acoustic networks. *Communications Magazine, IEEE*, 39(11), 114-119.
3. Akyildiz, I.F.; Pompili, D.; and Melodia, T. (2004). Challenges for efficient communication in underwater acoustic sensor networks. *ACM SIGBED Review*, 1(2), 3-8.
4. Cui, J.H.; Kong, J.; Gerla, M.; and Zhou, S. (2006). Challenges: building scalable mobile underwater wireless sensor networks for aquatic applications. *Network, IEEE Publication,* 20(3), 12- 18.
5. Xie, P.; and Cui, J.H. (2007). An FEC-based Reliable data transport protocol for underwater sensor networks. In proceedings of the *16th International Conference on Computer Communications and Networks, ICCCN 2007*, 747-753.
6. Akyildiz, I.F.; Pompili, D.; and Melodia, T. (2007). State-of-the-art in protocol research for underwater acoustic sensor networks. *SIGMOBILE Mobile Computing and Communications Review*, 11(4), 11- 22.

7. Gao, M.; Soh, W.S.; and Tao, M. (2009). A Transmission scheme for continuous ARQ protocols over underwater acoustic channels. *IEEE International Conference on Communications*, ICC '09, 1–5.
8. Chan, C.Y.M.; and Motani, M. (2007). An integrated energy efficient data retrieval protocol for underwater delay tolerant networks. *OCEANS 2007 – Europe*, 1-6.
9. Harris, A.F.; and Zorzi, M. (2007). Modelling the underwater acoustic channel in ns2. In proceedings of *the 2nd international conference on Performance evaluation methodologies and tools,* 321(18).
10. Sankarasubramaniam, Y.; Akyildiz, I.F.; and McLaughlin, S.W. (2003). Energy efficiency based packet size optimization in wireless sensor networks. *In Proceedings of the First IEEE International Workshop on Sensor Network Protocols and Applications,* 1-8.
11. Tian, Z.; Yuan, D. ; and Liang, Q. (2008). Energy efficiency analysis of error control schemes in wireless sensor networks. In proceeding of *International Wireless Communications and Mobile Computing Conference, IWCMC '08*, 401-405.
12. Labrador, Y.; Karimi, M.; Pan, D. and Miller, J. (2009). Modulation and error correction in the underwater acoustic communication channel. *International Journal of Computer Science and Network Security*, 9(7), 123-130.
13. Urick, R. J. (1983). *Principles of underwater sound*. (3rd Ed.), McGraw-Hill, Inc.
14. Brekhovskikh, L.M.; and Lysanov, Y.P. (1982). *Fundamental of ocean acoustics*, Springer-Verlag, Berlin.
15. 8-PSK Modulation (http://en.wikipedia.org).
16. Daneshgaran, F.; Laddomada, M.; and Mondin, M. (2004). An extensive search for good punctured rate- k/(k+1) recursive convolution codes for serially concatenated convolution codes. *IEEE Transaction of Information Theory*, 50(1), 208-217
17. LinkQuest Inc.: Underwater acoustic modem models, (http://www.link-quest.com).