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Energy Efficient Communication for Underwater Wireless Sensors Networks

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1. Introduction

Water covers more than 70% of the planet, contains much of its natural resources, and defines the greater territories of many nations. With the increasing use of underwater sensors for the exploitation and monitoring of vast underwater resources, underwater wireless sensor network (UWSN), mostly based on acoustic transmission technologies, have been developing steadily in terms of operation range and data throughput.

As in terrestrial sensor networks, various data transport protocols have been designed for UWSN (Pompili, 2007). However, as yet, there is no internationally accepted standard for underwater communication. The lack of standard is due to the technical challenges that still persist in establishing reliable underwater wireless data communication. Firstly, in underwater environment, electromagnetic wave is rarely of use, unlike in terrestrial space, as it can only travel a short distances due attenuation and absorptions effects. Optical signal suffers from scattering and absorption in underwater (Akyildiz, et al., 2005). Hence, to date acoustic energy is the most widely used type of signals used in underwater data transmission. Secondly, the fluctuating nature of ocean condition causes high bit error rate in acoustic transmission. Underwater acoustic transmission is also affected by path loss caused by spreading and absorption, noise which comes from many sources like water current, rain, wind, seismic and volcanic activities or biological phenomena (Pompili, 2007). Signal reflection and refraction from the surface and seabed, topographic sources like hills and hollows are some example error sources.

Hence in underwater environment, the two main issues of concern are namely: reliability and energy efficiency. These two issues are inter-twined. Reliability requires error-correction, and error-correction requires energy. More reliability tends to imply higher energy consumption, causing difficulty in applications that require nodes to be operated underwater for long periods of time without batteries recharging, and in aquatic environments that render hard the task of recharging or replacing batteries (Pompili, 2007; Preisig, 2007). Appropriate strategy must therefore be in-place to ensure reliable data transmission, while conserving energy.

In this chapter, we focus on the energy efficiency issue in UWSN. We develop a mathematical model of the efficiency of acoustic data communication in realistic underwater environment. We analyze existing error-correction techniques, and we then propose a new adaptive hybrid error correction technique that improves upon existing techniques.

We organize the rest of this chapter as follows: In section 2, we briefly review the basics of acoustic propagation. In section 3, we review the two most widely used underwater error correction techniques, ARQ and FEC. In section 4, we present mathematical and simulation analysis of the energy efficiency of the techniques. In section 5, an Adaptive Hybrid Energy Efficient Error Correction (AHEC) technique for Underwater Wireless Sensor Networks (UWSN) data transmission is presented. Finally, in section 6, we conclude the chapter.

2. Basics of acoustic propagation

Factors that characterized underwater acoustic propagation include path loss, noise, multipath, Doppler spread, and high and variable propagation delay. Those factors are the main reason for the variability in the acoustic channel. Bandwidth varies from a few KHz in a long range system which operates over several tens of kilometers to more than hundred KHz in a short-range system that operates over several tens of meters. UAC system are classified according to their communication ranges as shown in Table 1 (Akyildiz, et al., 2004, 2005):

	Range (Km)	Bandwidth (KHz)
Very long	1000	<1
Long	10-1000	2-5
Medium	1-10	=10
Short	0.1 -1	20-50
Very short	<0.1	>100

Table 1. Underwater Acoustic Communication System Ranges

Below are the factors that characterize underwater acoustic propagation (Colin et al., 2007; Joshy and Babu, 2010; Stojanovic and Preisig, 2009):

- Path loss: there are two main sources for path losses for underwater acoustic propagation:
 - Attenuation: this is the loss due to the conversion of acoustic energy into heat which known as absorption loss.
 - Spreading: this is the loss due to the expansion of the signal energy over a large area as the wave propagates forward.
- Noise: there are two kind of noise:
 - Man-made noise: it is caused by machinery (pumps, reduction gears, etc), shipping activities, etc.
 - Ambient noise: this is caused by the movement of water which includes tides, current, storms, wind, and rain. It is also caused by biological phenomena. Ambient noise depends mainly on frequency, so it must be considered when selecting frequency band in underwater communications systems (Preisig , 2007).
- Multipath: In most environments, the ocean can be modelled as a wave guide for communication signals. This waveguide is characterized by a reflecting surface and ocean bottom and a variant sound speed. Reflection, refraction and diffraction will occur with those surfaces resulting in multiple propagation paths from the source to the

receiver. Horizontal channel is characterized by long multipath spreads compared with vertical one. A multipath with varying impulse response tends to be subjected to an Inter Symbol Interference (ISI) that causes severe degradation in the acoustic signals.

- High delay and delay variance: underwater acoustic signal speed is just 1500 m/s, which is lower than electromagnetic signal by more than 5 orders of magnitude. The propagation delay is large too (about 0.67s/km).
- Doppler spread: it is significant in underwater acoustic channel, and cause degradation in the performance of digital communications..

Most of the factors mentioned above are caused by the chemical-physical properties of the sea water such as temperature, salinity and density, which these factors vary with depth, space and time.

3. Error correction techniques

Automatic Repeat reQuest (ARQ) and Forward Error Correction (FEC) are two commonly used strategies to combat error in underwater transmission (Bin et al, 2008). ARQ which proposes retransmission (Kunal et al., 2010), are widely used in data communications system for error control as they are simple and provide high reliability. However, the throughput is not constant and decreases rapidly in high bit error rate cases (Lin et al., 1984). In FEC, redundancy is added for error prevention. Redundant bits are encapsulated with data bits to form encoded information. However this increases the payload for transmission. Addition of redundant bit is known as channel coding. Error Correcting Codes (ECC) (block or convolutional) are used for this purpose. FEC codes have constant throughput which is equal to the code rate. However it has the drawback of using parity bit irrespective of the existence of errors. Reliability can be enhanced by combining FEC and ARQ, forming what is known as Hybrid-ARQ (HARQ) (Kunal et al., 2010).

3.1 Automatic repeat request

ARQ uses error detection codes, acknowledgement and/or negative acknowledgement messages, and time out to retransmit error packet. The basic idea is that the transmitter after sending the packet waits for specific time (time out) to receive an acknowledgement. If it receives positive acknowledgement (ACK), it sends the next packet. On the other hand, if it receives negative acknowledge (NAC) or timed out before receiving any acknowledgement, it then retransmits the same packet. The process repeats until an ACK has been received by the transmitter or a specific number of retransmission has been reached.

In (Tan et al., 2007), an opportunistic (hybrid implicit/explicit) acknowledgement scheme suitable for stop and wait protocols in underwater is proposed. The simple stop and wait (S &W) protocol is chosen as it is the most popular method in underwater acoustic communication due to the half-duplex property of acoustic modem. In the context of a multi hop channel, the work in (Tan et al., 2007) proposed that the acknowledgement can be achieved explicitly by transmitting an acknowledgement packet per successfully received packet, or implicitly by making use of the broadcast nature of the medium.

In (Lee et al., 2008), the channel sharing property inherent in underwater environment is utilized in proposing an efficient ARQ scheme. In this scheme packet size is controlled in such a way that transmission time becomes smaller than propagation delay. Collision free

transmission between multiple nodes is achieved by scheduling packets. In a multiple hop setup, the acknowledgement packet is replaced by overhearing packet transmitted from next hop. Overhearing as an acknowledgement method not only saves energy but it also minimizes overhead and transmission latency. The scheme is evaluated by comparing it with an existing stop and wait ARQ in term of the latency, and it shows a reduction in the latency. The latency and energy efficiency is still a problem in bad channel conditions cases though.

In (Gao et al., 2009), the authors make use of the long propagation delay in underwater environment to transmit and receive in a juggling manner. This juggling scheme enables a continuous ARQ to be implemented irrespective of the half-duplex property of the acoustic modem. This scheme decreases the propagation time by having more than one packet in the channel between transmitter and receiver. This leads to high throughput compared with the other variant ARQ schemes, but it is still unsuitable in bad channel conditions or in a longer distance ranges.

In (Valera et al. 2009), a modular and lightweight of an opportunistic multi-hop ARQ (Tan et al., 2007) was implemented for real system. An extensible network stack suitable for challenged underwater acoustic networks was designed and implemented in the work. Evaluation demonstrated that the opportunistic ARQ can provide significant improvement in terms of data delivery ratio. The disadvantage of this technique is an increase in end-to-end delay due to queuing and retransmissions.

3.2 Forward error correction technique

Forward Error Correction (FEC) or error control coding is a system for achieving reliable message transmission in a communication system by correcting errors in the receiver side (hence the name 'Forward').

Recent and major activities on error control coding can be summarized as follows:

- Research on good structural properties, and high error correcting performance.
- Efficient encoding and decoding strategies.
- Applicability of coding in various transmission system and channels.

Forward error correction can be used in two levels, namely at the bit and the byte level. Bit level correction is achieved by adding redundant bits to the data in the sender. At the packet level, additional check packets are transmitted to help recover lost packets. In the FEC, no back channel is needed, but high bandwidth is required. It is therefore suitable in cases where retransmission is costly or impossible, as in broadcasting. The numbers of errors which can be corrected depend on the code rate and the type of coding used. Therefore, different FEC codes are suitable for different conditions.

There are two main types of FEC; the first one is the block codes which work on a fixed-size blocks (packets of bits or symbols), the most famous block codes are Reed-Solomon, Golay, (Bose, Chandhuri and Hocquenghem) BCH code, multidimensional parity and Hamming codes. The other type of FEC is convolutional codes, which work on bit or symbol streams of arbitrary length. It is often decoded using Viterbi algorithm, and it can be turned into block code if desired.

Most telecommunication systems use fixed types of FEC code, which is designed for the expected worst case bit error rate. These codes will fail if the bit error rate ever gets worse.

In (Guo, 2006), error recovery through network coding was explored for underwater sensor networks. The computational power of underwater sensors along with the multiple routes provided by the broadcast nature of acoustic medium are the main reasons for applying network coding. In this technique the source and intermediate nodes encode packets and send them on multiple routes. The packets are then recovered in the destination by combining packets from different routes.

In (Xie and Cui, 2007), the Segmented Data Reliable Transport protocol (SDRT) is proposed. The protocol is a hybrid of FEC and ARQ. It sends data block by block and hop by hop. The sender encodes the packet using erasure codes, and sends it to an intermediate node. The intermediate node reconstructs the packet and encodes it and sends it to the next hop. The sender continues to send the data until it receive an acknowledgement from its next node, and this is the main problem with SDRT as it wastes energy. SDRT however improves channel utilization and simplify protocol management.

In (Liu et al., 2010; Bin et al., 2008), the Internode distance-based Redundancy Reliable Transport Protocol (ARRTP) is proposed. It is a hybrid of two types of error correction techniques which encode message on bit and/or packet level. ARRTP is based on distance as adaptation factor. For each range of distance, one or a hybrid of two techniques is used. The technique was also investigated in cooperation mode, making use of the broadcast nature of acoustic signal. ARRTP is found to have better probability of success and energy efficient in single and multi-transmission. This technique is based on fixed channel conditions analysis, so it is unsuitable in variable underwater channel conditions.

4. Transmission energy efficiency mathematical and simulation analysis

Underwater acoustic channel are characterized by variable channel conditions and variable distances between sensor nodes due to water currents. As said earlier in the chapter, in such situations, reliable and efficient communication data transport is needed. Reliability is usually achieved by using error correction techniques. However, energy consumption needs to be considered as it is difficult to recharge or even replace batteries for a large number and sparsely distributed sensors. This condition is even worse in underwater due to the harsh aquatic medium (Colin, 2007; Xie and Cui, 2007). Hence, the design of error correction techniques should take into consideration the energy conservation requirement.

In this section, we first develop a model for underwater propagation. A mathematical analysis for energy efficiency for FEC and ARQ techniques in underwater environment is then presented. The analysis is based on communication distance and packet size, and considers the effects of wind speed, and shipping factor. Simulation was done using MATLAB to validate the mathematical analysis results. Results depicting the energy efficiencies of transmission using ARQ and FEC for different packet size, different distances, and different channel conditions (wind speed and shipping factors) are presented.

4.1 Underwater propagation model

The propagation model is responsible for calculating the 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 and Thorp approximation for the absorption loss (Urick, 1983; Yang and Liu, 2009; Liu et al., 2010; Harris and Zorzi, 2007).

4.1.1 Attenuation

Attenuation consists of two parts, the first one is the absorption loss and the second part is the spreading loss. To calculate the absorption loss at a given frequency, Thorp's approximation function divides the frequencies into two groups; one group under 400 Hz and the other one over 400 Hz as follows:

$$\begin{aligned} 10\log a(f) &= 0.11 \frac{f^2}{1+f^2} + 44 \frac{f^2}{4200+f} + 2.75 \times 10^{-4} f^2 + 0.003 \quad f > 0.4 \\ &= 0.002 + 0.11 \times \left(\frac{f}{1+f} \right) + 0.011 f \quad f < 0.4 \end{aligned} \quad (1)$$

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:

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

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 (i.e., $k = 1$ for cylindrical propagation (shallow water), $k = 2$ for spherical propagation (deep water), and $k = 1.5$ for practical spreading) (Urick, 1983).

4.1.2 Noise

The background noise in ocean has many sources which vary with frequency and location (Wenz and Gordon, 1939). The following formulas give the power spectral density of the four noise components (Yang and Liu, 2009; Liu, 2010; Harris and Zorzi, 2007; Webb, 1992):

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

$$10\log N_s(f) = 40 + 20(s - 0.5) + 26\log(f) - 60\log(f + 0.03) \quad (4)$$

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

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

Where N_t is the noise due to turbulence, N_s is the noise due to shipping (the shipping variable s take the values between 0 and 1), N_w is the noise due to wind (the wind variables w represent 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:

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

4.1.3 Signal to noise ratio

It is well known that SNR of an emitted underwater signal at the receiver is given by (Yang and B. Liu, 2009; Harris and M. Zorzi, 2007; Brekhovskikh and Lysanov, L.1982)

$$SNR = SL - A(l, f) - N(f) - DI \quad (8)$$

where $N(f)$, $A(l, f)$ are in dBs given from equations (2) and (7). Assuming Omni-directional directivity, directivity index (DI) = 0. The source level $SL = 20 \log I / 1 \mu Pa'$, where I is the intensity at 1 m from the source in watt/m², given by:

$$I = \frac{P_t}{2\pi H} \quad (9)$$

Where P_t is the transmission power, and H is the water depth in m.

4.2 Energy efficiency mathematical analysis

The data packet format in ARQ case can be presented as in Figure 1 (a). It consists of a header field α bits long, payload of size n bits and a Frame Check Sequence (FCS) τ bits long. The acknowledgement packet length is ack.

In FEC case it can be presented as in Figure 1 (b). It consists of a payload of size $(n-k)$ bits long, a parity check of k bits and a header field α bits long.

Header	FCS	Payload
α	τ	n

Fig. 1. (a): ARQ Packet Format

Header	Parity check	Payload
α	k	$n-k$

Fig. 1. (b): FEC Packet Format

4.2.1 Optimization metric

Energy efficiency is the suitable metric which captures both energy and reliability constraints, and it is defined as (Sankarasubramaniam et al, 2003; Tian et al. , 2008):

$$\begin{aligned} \eta &= \eta_e (1 - PER) \\ &= \frac{E_{eff}}{E_{tot}} (1 - PER) \end{aligned} \quad (10)$$

Where η is the energy efficiency, η_e is the energy throughput, $r = (1 - PER)$ is the Packet Acceptance Rate (PAR), which accounts for data reliability, and $\frac{E_{eff}}{E_{tot}}$ denotes the energy

throughput. Therefore, the energy efficiency η represents the useful fraction of the total energy expenditure in a communication link between sensors.

4.2.2 Bit error rate calculation

Using 8-Phase Shift Keying (PSK) scheme as the suitable modulation techniques for underwater acoustic communication, the symbol error probability P_s for ARQ is given by (Labrador et al., 2009):

$$P_s \approx 2Q(\sqrt{2\gamma_s} \sin \frac{\pi}{M}) \quad (11)$$

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

$$P_b = \frac{P_s}{3} \quad (12)$$

Whereas for FEC convolution code (Lee et al., 2008):

$$P_b = \frac{1}{k} \sum_{d=d_{free}}^{\infty} w(d)Q(\sqrt{2dR_c\gamma_b}) \quad (13)$$

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

4.2.3 ARQ energy efficiency mathematical analysis

Energy consumption of sensor node for communication in one hop is given by:

$$E_{ARQ} = E_{ARQ}^{tr} + E_{ARQ}^{re} \quad (14)$$

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:

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

$$\begin{aligned} E_{ARQ}^{re} &= E_{data}^{re} + E_{ack}^{tr} \\ &= P_{re}l_{data}T_{tr} + P_{tr}l_{ack}T_{tr} \end{aligned} \quad (16)$$

Where $P_{tr/re}$ is the power consumed in transmitting/ receiving, and $T_{tr} = \frac{1}{R}$ is the time of transmitting 1 bit. From Figure 1 (a), using the bit error rate probability P_b in (12), and

assuming independent bit errors, the Packet Error Rate (PER) for ARQ can be derived as follows:

$$PER_{ARQ} = 1 - (1 - P_b)^{n+\alpha+\tau} \quad (17)$$

This expression closely approximates PER under bursty error conditions.

From equation (9) energy efficiency of ARQ without retransmission strategy can hence be written as:

$$\begin{aligned} Eff_{ARQ} &= \frac{E_{ARQ}^{eff}}{E_{ARQ}^{tot}} (1 - PER_{ARQ}) \\ &= \frac{(P_{tr} + P_{re})nT_{tr}}{(P_{tr} + P_{re})(n + \alpha + \tau + ack)T_{tr}} (1 - PER_{ARQ}) \\ &= \frac{n}{(n + \alpha + \tau + ack)} (1 - PER_{ARQ}) \end{aligned} \quad (18)$$

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

4.2.4 FEC energy efficiency mathematical derivation

The energy consumption of FEC is given by:

$$E_{FEC} = E_{FEC}^{tr} + E_{FEC}^{re} + E_{dec} + E_{enc} \quad (19)$$

Using convolution turbo code as forward error correction techniques, encoding (E_{enc}) and decoding energy (E_{dec}) are considered to be negligibly small (Sankarasubramaniam et al., 2003; Tian et al., 2008), and from Figure 1 (b), the expression for the energy efficiency is defined as:

$$\begin{aligned} Eff_{FEC} &= \frac{E_{FEC}^{eff}}{E_{FEC}^{tot}} (1 - PER_{FEC}) \\ &= \frac{(P_{tr} + P_{re})(n - k)T_{tr}}{(P_{tr} + P_{re})(n + \alpha)T_{tr}} (1 - PER_{FEC}) \\ &= \frac{(n - k)}{(n + \alpha)} (1 - PER_{FEC}) \end{aligned} \quad (20)$$

where PER_{FEC} is calculated using equation (13).

4.3 Simulation

Simulation offers a powerful tool to validate mathematical analysis. The simulation is carried out for a two system using different error correction techniques using MATLAB.

Two types of parameters are considered for design and configuration. Energy efficiency and packet probability of success (PAR) are taken as the main performance factors in comparing between the two systems.

4.3.1 Design parameters

The design parameters are the parameters that can be varied in order to study their effect on the system energy efficiency. In the first system ARQ technique is used as the error correction technique, where 8-PSK is used as the modulation technique as it is the best modulation technique in underwater channel as stated in the literature. In the second convolutional coding is used as the FEC error correction technique (Labrador et al., 2009).

The design parameters used are the distance, shipping factor and wind speed. Shipping factor and wind speed are taken as a representative for variable channel conditions; any other channel condition factor will have the same effect.

Modulation and encoding technique types and design parameters can be written as in Table 2. below:

Parameter	Description	Type or Value
Modulation	Modulation technique used in ARQ case	8-PSK
Encoding	Encoding technique used for error correction	Convolution coding
Distance	Communication distance	From 800 to 3000 m
Shipping factor	Factor describe the effect of shipping	From 0 to 1
Wind speed	Factor describe the effect of wind	Any value in m/s

Table 2. Modulation, Encoding Types and Design Parameters

4.3.2 Configuration parameters

The simulation is carried out using MATLAB.

In the transmitter a random bit generator is used with the parameters as follows:

- size of signal constellation $M = 8$;
- Number of bit per symbol $k = 3$,
- Number of bit processed $n = 3e^4$.

Binary data stream are created as a column vector using the function: $x = \text{randint}(n, 1)$;

A Bit-to-Symbol mapping which convert the bits in x into k -bit symbols is done using the following MATLAB function:

- $\text{xsym} = \text{bi2de}(\text{reshape}(x, k, \text{length}(x)/k) \text{, 'left-msb'})$;

Then an 8-PSK modulator is used to modulate the signal with the function:

- $y = \text{modulate}(\text{modem.pskmod}(M), \text{xsym})$;

The value of SNR in underwater channel is calculated as in section 2.1.3., and an AWGN function is used as:

- `y_noisy = awgn (y, snr, 'measured');`

In the receiver side 8-PSK demodulator is used to demodulate the signal using the function:

- `zsym = demodulate (modem.pskdemod (M), noisy);`

the Symbol-to-Bit mapping is done using the function:

- `z = de2bi (zsym,'left-msb');`

then BER is obtained by comparing the input x with the output z using the function:

- `[number_of_errors,bit_error_rate] = biterr (x, z);`

The energy efficiency is calculated from the BER as in section 2.2.3.

In the second system the 8-PSK is replaced by a convolutional encoder with the following:

Trellis is defined using the following function:

- `t = poly2trellis (3, [5 7]);`

Then puncturing is attained by the following function:

- `punctcode = convenc (x, t, [1 1 0 1 1 0 1 0 1 0]);`

This puncturing is for 5/6 code rate.

Then 0 bit is mapped to 1 and 1 bit to -1 using the function:

- `tcode = 1 - 2*punctcode;`

The value of SNR in underwater channel is written as in section 2.1.3., and an AWGN function is used as:

- `ncode = awgn(tcode, snr, 'measured');`

In the receiver side, the punctured code is decoded by viterbi using the function:

- `decoded = vitdec(ncode, t, 96, 'trunc', ...'unquant', [1 1 0 1 1 0 1 0 1 0]); % Decode.`

then BER is obtained by comparing the input x with the output decoded using the function:

- `[numErrPE, berPE] = biterr(decoded, x);`

The energy efficiency is calculated from the BER as in section 2.2.4

4.4 Results and analysis

The results are obtained using a MATLAB, assuming LinkQuest UWM2000 acoustic modem (LinQuest Inc., 2011), and the parameters as given in Table 3:

First, a suitable frequency range based on AN Factor as in Figure 2 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 above this range the AN Factor increases sharply.

From Figures 3 (a) and 3 (b), it is clear that transmission energy efficiency of both techniques increases with increasing packet size in short distances, whereas decreases in long distances

Symbol	Parameters	
	Definition	Quantity
P_t	Transmitting Power	2 W
P_{re}	Receiving Power	0.75
R	Bit Data Rate	10 kbps
l_{ack}	Acknowledge packet length	7 Byte
$\alpha + \tau$	Header + FCS length	11 Byte

Table 3. Simulation Parameters

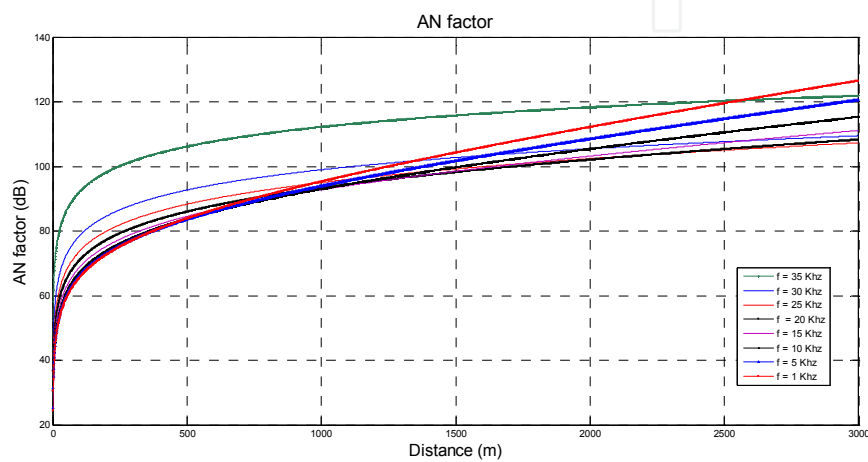


Fig. 2. AN Factor

for both techniques. It is also clear that there is only a slight differences between mathematical and simulation results which validate the results. This differences between mathematical and simulation results decreases as the number of bits transmitted in the simulation increases.

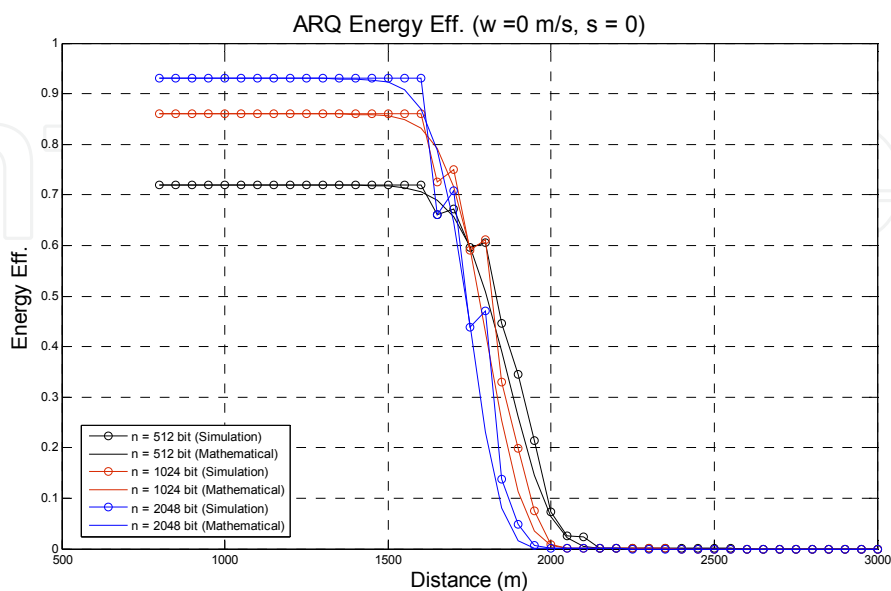


Fig. 3. (a): ARQ Transmission Energy Efficiency (Mathematical and Simulation Results)

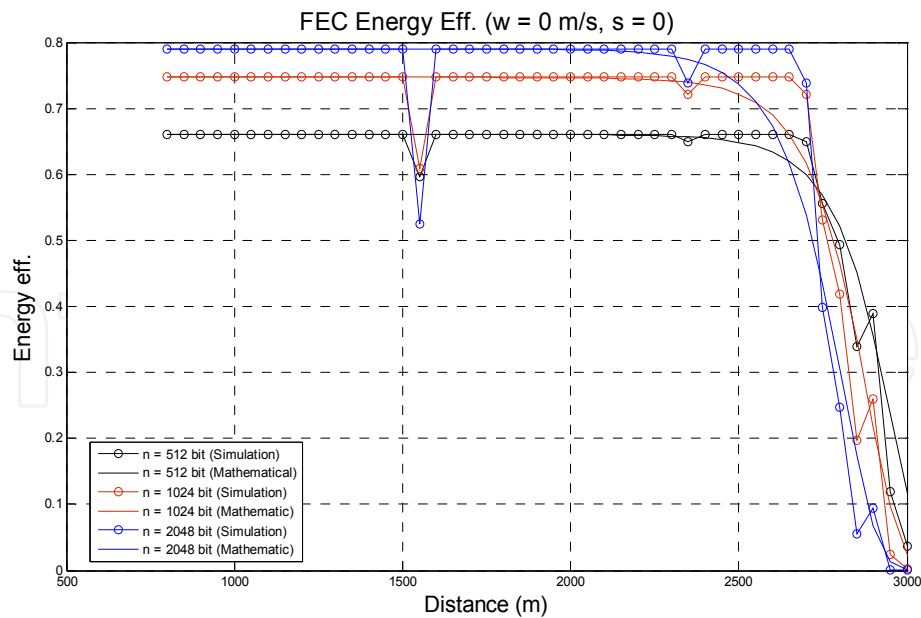


Fig. 3. (b): FEC Transmission Energy Efficiency (Mathematical and Simulation Results)

In Figure 4 (a) transmission energy efficiency of ARQ and FEC for a packet length of 512 bit is shown. It is apparent that transmission using ARQ is more energy efficient than using FEC below a specific distance (cut-off distance), and transmission using FEC is more energy efficient after this distance. The effect of shipping is unseen and can be neglected. In Figure 4 (b) the effect of wind is very clear, and the cut-off distance decreases from 1700 m when no wind exists to 1250 m when the wind speed is 1 m/s. ARQ efficiency starts to decrease at 1600 m when no wind exists, and at 1100 m when the wind speed is 1 m/s, whereas for FEC it starts to decrease at 2500 m when no wind exist and at 1800 m when the wind speed is 1 m/s.

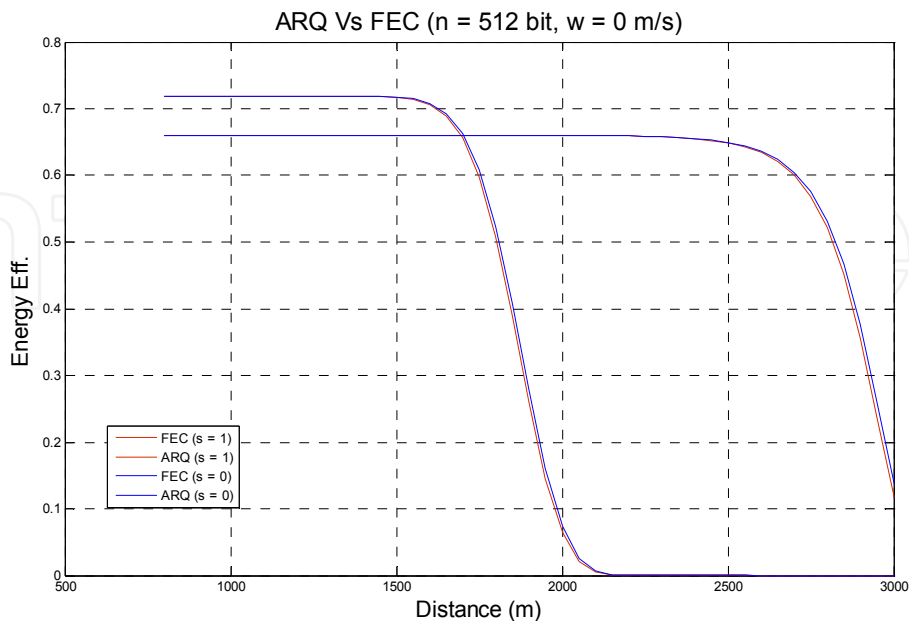


Fig. 4. (a): ARQ Vs FEC Transmission Energy Efficiency (n = 512 bit, Variable Shipping Factor)

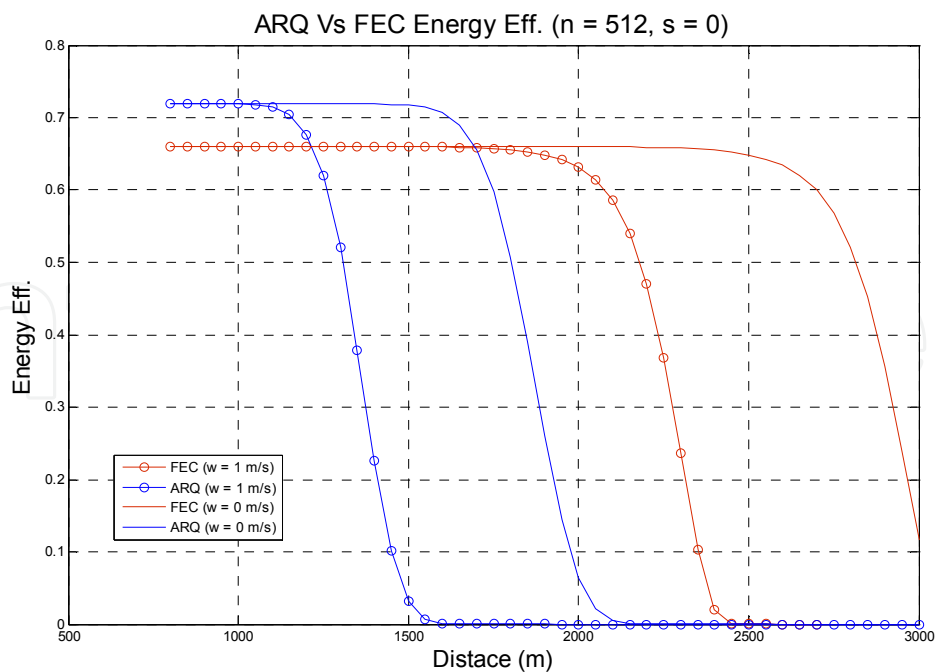


Fig. 4. (b): ARQ Vs FEC Transmission Energy Efficiency ($n = 512$ bit, Variable Wind Speed)

4.5 Discussion

A mathematical analysis for the energy efficiencies of ARQ and FEC data transmission has been presented. Simulation results validate the mathematical derivation results. It is found that transmission energy efficiency in underwater environment increases with increasing packet size in short distances and decreases with packet size in longer distances. It is also found that transmission using ARQ is more energy efficient below a specific distance (cut-off distance), whereas transmission using FEC is more efficient after that distance. This cut-off distance is affected by wind speed. Shipping factor has been found to have no effect on this frequency values. From those results we can say that variable distances and variable channel conditions which characterize underwater channel make it energy inefficient to use one or fixed type of error correction techniques in transmission.

The results obtained from this part will be the basis for designing and implementing a new adaptive hybrid energy efficient error correction protocol for underwater wireless sensor networks in the next part.

5. Adaptive hybrid energy efficient error correction technique for UWSN

As it is energy inefficient in transmission to use one or fixed type of error correction in realistic underwater conditions, it is important to consider hybrid error correction technique. This hybrid error correction technique must adapt to the variation in channel conditions and to the variation in distances between sensor nodes.

In this section, we propose an Adaptive Hybrid Energy Efficient Error Correction (AHEC) technique for Underwater Wireless Sensor Networks (UWSN) data transmission. The proposed technique depends on an adaptation algorithm which determines the most energy efficient error correction technique for the current channel conditions and distance. The

adaptation algorithm is based on the current Bit Error Rate (BER), current error correction technique, and a pre-calculated Packet Acceptance Rate (PAR) ranges look-up table which is pre-calculated using the energy efficiency derivation has been done in the previous section. Based on this, a periodical 3-bit feedback is added to the acknowledgement packet to tell the sender which error correction technique is most suitable for current channel conditions and distance. The error correction is chosen from a pure ARQ in a good channel conditions and short distances to a hybrid of ARQ and FEC with variable encoding rates in bad channel condition and over longer distance ranges.

This section is organized as follows: the in adaptive hybrid error correction technique is presented in section 5.1. In section 5.2 we show how the pre-calculated PAR ranges look-up table is calculated. Then in section 5.3, we compare the proposed AHEC technique with the techniques that use only ARQ or only FEC as the error correction technique in variable channel conditions and over variable distance ranges.

5.1 Adaptive hybrid error correction technique main concepts

The results of the derivations in the previous section state that transmission energy efficiency varies with the variation in transmission distances and channel conditions for both the ARQ and the FEC. Depending on the underwater network condition and the internode distances, one technique will be better than the other. The propose AHEC technique is designed to achieve high transmission energy efficiency in such conditions, by adaptively changing the error correction technique used.

The technique works like this: for variable distances and variable channel conditions, AHEC technique always search for the technique with the highest energy efficiency, and since reliability is one part in transmission energy efficiency calculation as stated in equation (10), it will also be a reliable technique. The technique depends on an adaptation algorithm which based on the current PAR, current encoding technique used, and a pre-calculated PAR ranges look-up table to determine which error correction technique is most suitable for the current distance and current channel conditions. AHEC technique can designed as in the diagram Figure 5.

In AHEC technique, only modulation technique (i.e. ARQ) is used in good channel conditions and short distances, which means low BER. In bad channel conditions and long distances a hybrid of ARQ and variable code rates convolutional encoding are used.

Variable code rates are obtained using puncturing technique by deleting a part of the bits of low-rate convolution code (Begin et al., 1990), as in Table 4., and it is represented in

Code rate	Puncturing Matrix
2/3	[1 1 0 1]
3/4	[1 1 0 1 1 0]
4/5	[1 1 0 1 1 0 1 0]
5/6	[1 1 0 1 1 0 1 0 1 0]
6/7	[1 1 0 1 1 0 1 0 1 0 1 0]

Table 4. Puncturing Matrix

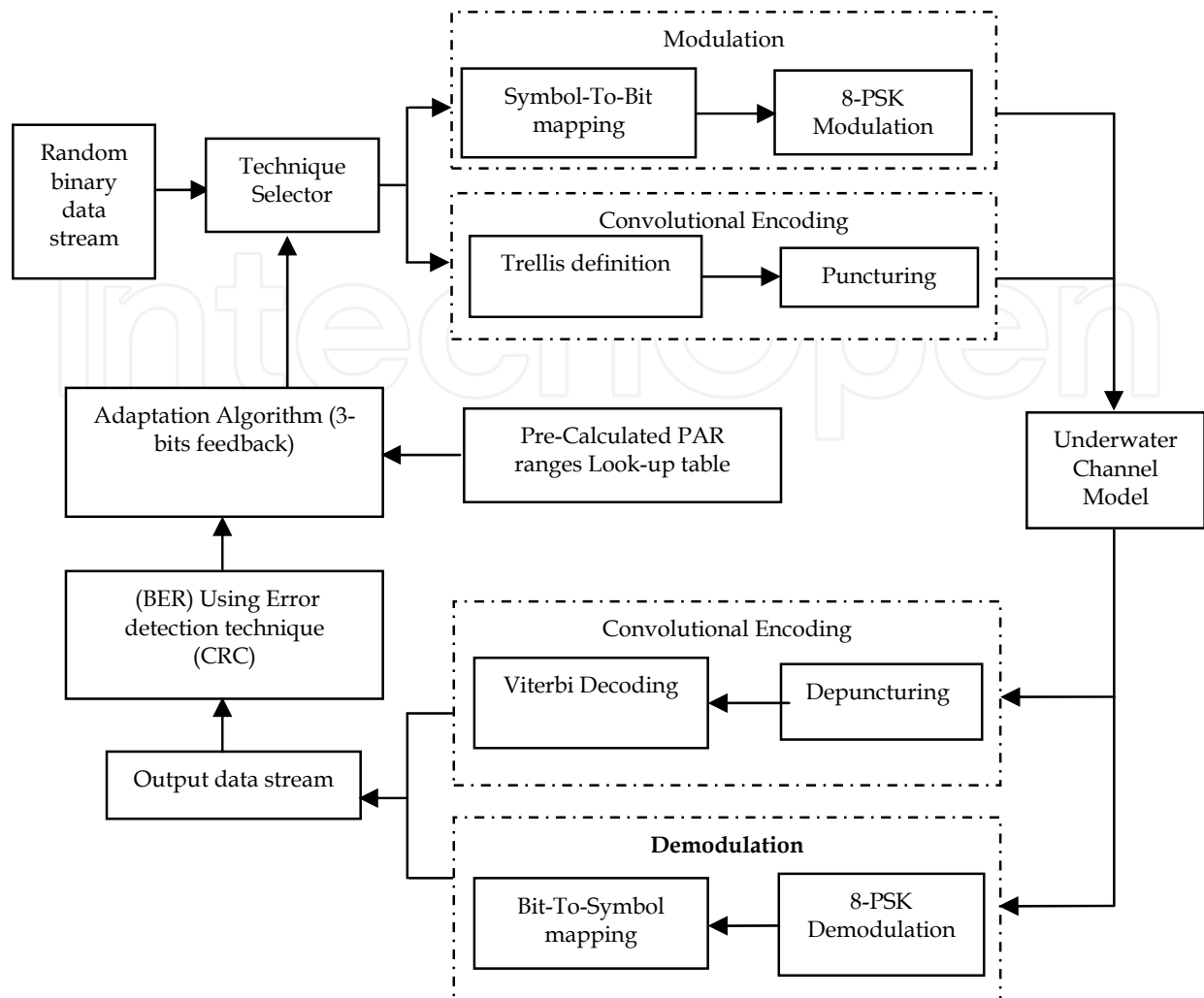


Fig. 5. AHEC Technique Design

MATLAB using systematic puncturing convolution codes with the parameters obtained from (Begin et al., 1990) as shown in Table 5.

R_c	2/3	3/4	4/5	5/6	6/7
d_{free}	3	3	2	2	2
W_{dfree}	1	15	1	2	5
$W_{dfree+1}$	10	104	36	111	186
$W_{dfree+2}$	54	540	309	974	1942
$W_{dfree+3}$	226	2520	2058	6815	16428
$W_{dfree+4}$	853	11048	12031	43598	124469
$W_{dfree+5}$	3038	46516	65754	263671	887512
$W_{dfree+6}$	10432	190448	344656	1536563	6088910
$W_{dfree+7}$	34836	763944	1755310	8724988	40664781
$W_{dfree+8}$	114197	3016844	8754128	46801477	266250132

Table 5. Minimum Hamming Distances (d_{free}) and Weight Distribution (w_{dfree}) for Variable Rate Convolutional Codes.

5.1.1 AHEC technique adaptation algorithm

The adaptation algorithm is as follows:

Using error detection technique in the receiver, BER is periodically calculated, and from the BER, PAR is calculated using the packet length n as:

$$PAR = (1 - BER)^n \quad (21)$$

Then the suitable error correction technique is calculated from the function:

$$J = f(PAR, I, PARMAX(I, J), PARMIN(I, J)) \quad (22)$$

where J is the suitable error correction technique required, PAR is the current packet acceptance rate, I is the current error correction technique used, and $PARMAX(I, J)$, $PARMIN(I, J)$ are the pre-calculated PAR ranges look-up.

We can mathematically model this function as in the following formula:

$$J = \sum_{n=1}^6 n \times I_{A_i^n}(PAR) \quad (23)$$

where A_i^n is a look-up table taken from the energy efficiency derivation of six error correction techniques (One ARQ and five varying code rates FEC), and

$$I_B(x) = \begin{cases} 1 \dots \text{if } x \in B \\ 0 \dots \text{otherwise} \end{cases} \quad (24)$$

From the value of J obtained, a 3-bit feedback is added to the acknowledgement to state which error correction technique to use as in Table 6. below:

Correction Technique	Consists of	FEC Code Rate	Feedback
1	Pure ARQ		000
2	Hybrid ARQ& FEC	6/7	001
3	Hybrid ARQ& FEC	5/6	010
4	Hybrid ARQ& FEC	4/5	011
5	Hybrid ARQ& FEC	3/4	100
6	Hybrid ARQ& FEC	2/3	101

Table 6. Error Correction Techniques Details

5.2 Pre-calculated PAR ranges look-up table calculations

The pre-calculated PAR ranges look-up table is calculated as follows:

1. Transmission energy efficiencies and PARs using six error correction techniques (One ARQ plus five variable code rates FECs) for variable values of SNR are found as in section 2.2.3 and section 2.2.4.
2. Starting with the SNR values which gives PAR values equal to 1 for all the techniques; at this SNR ARQ will have the maximum energy efficiency compared to the others, so the PAR for all those technique at this point is the maximum values in the ranges which makes the suitable technique is technique 1 (pure ARQ). This means $PAR_{MAX_{J,1}} = 1$, i.e. if the current technique is J and the current PAR is in the range that has 1 as the maximum value, then technique one is the most energy efficient technique.
3. Then decreasing SNR value until the energy efficiency of the first technique is less than the energy efficiency of the second technique; at this SNR the PAR for all technique will be the minimum values in the ranges which makes the suitable technique is technique 1 (pure ARQ). This means the PAR of any technique J at this point = $PAR_{MIN_{J,1}}$, i.e. if the PAR of the current technique J is in between $PAR_{MIN_{J,1}}$ and $PAR_{MAX_{J,1}}$, then technique one is the most energy efficient technique. As the minimum values in the first ranges equal the maximum values in the second range, then:

$$PAR_{MAX_{J,2}} = PAR_{MIN_{J,1}}$$

Then decreasing SNR value until the energy efficiency of the second technique is less than the energy efficiency of the third technique; at this SNR the PAR for all technique will be the minimum values in the ranges which makes the suitable technique is technique number two.

This means the PAR of any technique J at this point = $PAR_{MIN_{J,2}}$ i.e. if the PAR of the current technique J is in between $PAR_{MIN_{J,2}}$ and $PAR_{MAX_{J,2}}$, then technique number 2 is the most energy efficient technique.

As the minimum values in the second ranges equal the maximum values in the third range, then:

$$PAR_{MAX_{J,3}} = PAR_{MIN_{J,2}}$$

4. Then decreasing SNR value until the energy efficiency of the third technique is less than the energy efficiency of the fourth technique; at this SNR the PAR for all technique will be the minimum values in the ranges which makes the suitable technique is technique number 3.

This means the PAR of any technique J at this point = $PAR_{MIN_{J,3}}$ i.e. if the PAR of the current technique J is in between $PAR_{MIN_{J,3}}$ and $PAR_{MAX_{J,3}}$, then technique number 3 is the most energy efficient technique.

As the minimum values in the third ranges equal the maximum values in the fourth range, then:

$$PAR_{MAX_{J,4}} = PAR_{MIN_{J,3}}$$

5. Then decreasing SNR value until the energy efficiency of the fourth technique is less than the energy efficiency of the fifth technique; at this SNR the PAR for all technique

will be the minimum values in the ranges which makes the suitable technique is technique number 4.

This means the PAR of any technique J at this point = $PARMIN_{J,4}$ i.e. if the PAR of the current technique J is in between $PARMIN_{J,4}$ and $PARMAX_{J,4}$, then technique number 4 is the most energy efficient technique.

As the minimum values in the fourth ranges equal the maximum values in the fifth range, then:

$$PARMAX_{J,5} = PARMIN_{J,4}$$

6. Then decreasing SNR value until the energy efficiency of the fifth technique is less than the energy efficiency of the six technique; at this SNR the PAR for all technique will be the minimum values in the ranges which makes the suitable technique is technique 5.

This means the PAR of any technique J at this point = $PARMIN_{J,5}$ i.e. if the PAR of the current technique J is in between $PARMIN_{J,5}$ and $PARMAX_{J,5}$, then technique number 5 is the most energy efficient technique.

As the minimum values in the fifth ranges equal the maximum values in the sixth range, then:

$$PARMAX_{J,6} = PARMIN_{J,5}$$

7. At last zero will be the minimum values for the ranges that makes technique six is the most energy efficient technique ($PARMIN_{J,6} = 0$, for all techniques).

5.3 Results and discussion

In this section we first present how to calculate the pre-calculated PAR ranges look-up table, which is an essential part in our adaptation algorithm, then we will compare our AHEC technique with the previous works in the literature that depend on only ARQ or only FEC for error correction (Lee et al., 2008; Gao et al., 2009; Tan et al., 2003; Xie and Cui, 2007) in variable channel conditions and variable distances.

5.3.1 AHEC technique transmission energy efficiency calculations

To calculate the pre-calculated PAR ranges look-up table, energy efficiencies versus PARs for the six techniques are calculated as in section 2.2.3 for ARQ and in section 2.2.4 for the five variable code rate FEC, then the pre-calculated PAR ranges look-up table can be calculated as in section 3.3, and it can be displayed as in Table 7 below:

i \ j	1	2	3	4	5	6
1	0.95 -1.0	0.95 - 0.0				
2	1.0	0.89 - 1.0	0.84 -0.89	0.62-0.84	0.32-0.62	0.00-0.32
3	1.0	0.92 -1.0	0.89 -0.92	0.72 -0.89	0.45-0.72	0.00-0.45
4	1.0	0.96 -1.0	0.94 -0.96	0.85 - 0.94	0.68 -.85	0.00 - 0.68
5	1.0	0.98 - 1.0	0.97 - 0.98	0.92- 0.97	0.81-0.92	0.00 -0.81
6	1.0	0.995 - 1.0	0.992 -0.995	0.992 -0.98	0.95 - 0.98	0.00 - 0.95

Table 7. Pre-Calculated Look-Up PAR Ranges Table

From the Pre-calculated PAR ranges look-up table above, and from the current PAR, current encoding technique, AHECT energy efficiency can be calculated as in section 3.2

5.3.2 Transmission using AHEC technique versus the transmission using ARQ and FEC transmission energy efficiency

Figure 6 below gives a comparison between the energy efficiency of transmission using AHEC technique and the transmission using pure ARQ and pure FEC for varying distances.

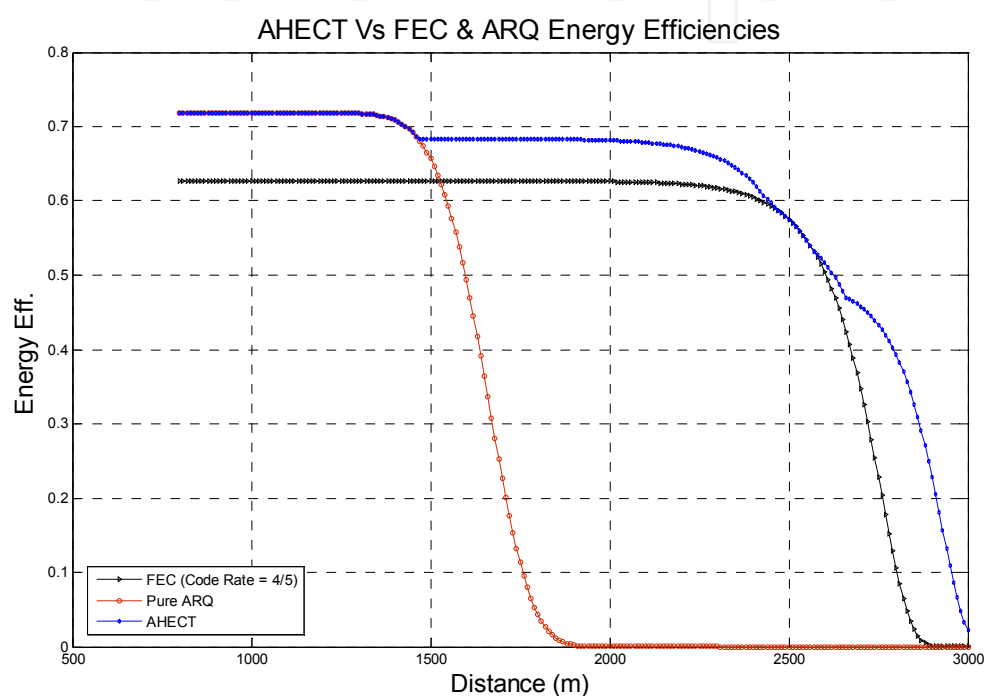


Fig. 6. AHEC Technique Vs ARQ & FEC Energy Efficiency (Variable Distances Case)

From this figure it is clear that transmission using AHEC technique is more energy efficient than using both ARQ and FEC in variable distances situation.

Compared with the pure ARQ, transmission using AHEC technique achieves 10 % increase in saving energy when the distance is around 1500 m and more than 60 % when the distance increases above 1700 m. When compared with transmission using FEC, it achieves around 10 % increase in energy saving when the distance is below 1500 m, and around 7 % saving when the distance goes above 1500 m.

In Figure 7; variable wind speed is taken as a measure for the variation in channel conditions. From this Figure it is clear that transmission using AHEC technique is more energy efficient than both techniques using ARQ and FEC for variable wind speed (i.e. variable channel conditions). Compared with the pure ARQ, and when the transmission distance is 1500 m, transmission using AHEC technique achieves 6 % increase in energy saving when wind speed is 0.5 m/s, more than 50 % energy saving when wind speed

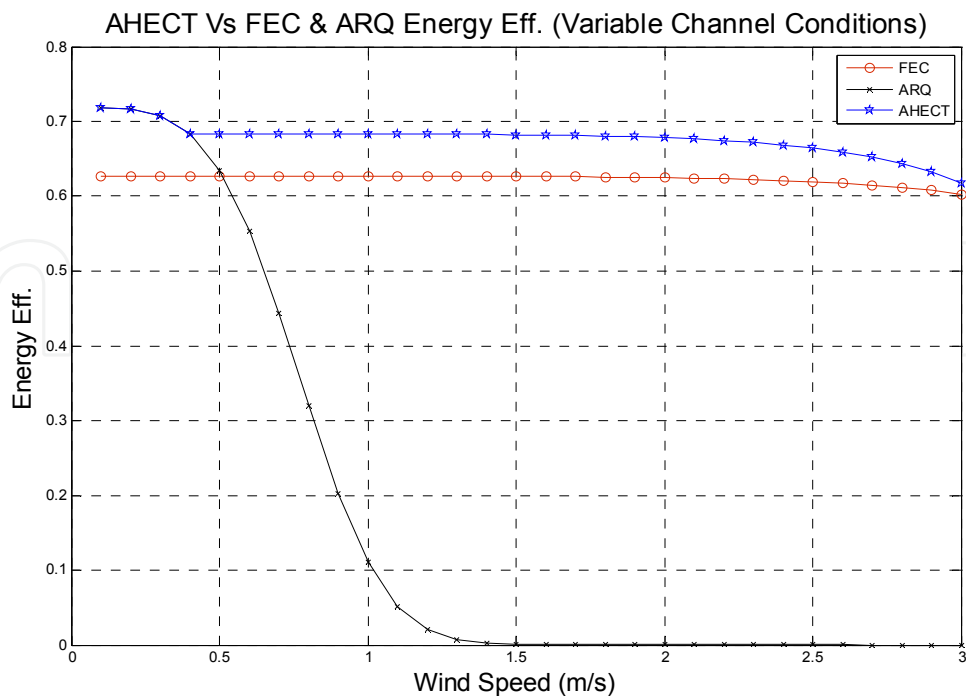


Fig. 7. AHEC Technique Vs ARQ & FEC Transmission Energy Efficiency (Variable Channel Conditions)

increases to 1 m/s, and more than 60 % when wind speed is greater than 1.5 m/s. When compared with transmission using FEC, transmission using AHEC technique achieves around 8 % increase in energy saving when wind speed is below 0.5 m/s and around 6 % when wind speed is more than 0.5 m/s.

6. Conclusions

Underwater wireless sensor network (UWSN) is a promising engineering endeavour which will ensure progress in monitoring and exploiting the ocean's vast resources. But until now it faces many challenges, the most important of which is the severe energy constraint of the batteries, which cannot be recharged or replaced in aquatic medium. Complicating the issue is the variability of the channel conditions and the distances between underwater sensors.

In this chapter, we have mathematically analyzed the transmission energy efficiency for two main error correction techniques, ARQ and FEC, in underwater environment. A simulation is done to validate the mathematical derivation results. Transmission using ARQ is found to be more energy efficient than transmission using FEC below specific distances, and transmission using FEC is found to be better after that. We call this specific distance the cut-off distance. We found that this cut-off distance is not fixed and varies with the variation in channel conditions and packet size.

Based on the mathematical analysis, we have proposed an energy efficient Adaptive Hybrid Error Correction (AHEC) technique for transmission. The proposed technique adaptively

changes the error correction technique to the technique with the highest transmission energy efficiency compared to the others. An adaptation algorithm which based on the current packet acceptance rate (PAR), current encoding technique, and a pre-calculated PAR ranges look-up table has been proposed. From the output of the adaptation algorithm, a periodic 3-bit feedback is sent to the sender indicating which error correction technique is most suitable given the current distance and channel conditions. The proposed technique has been compared with techniques that use only ARQ or FEC. The results show that our proposed technique is more energy efficient than either of them.

7. References

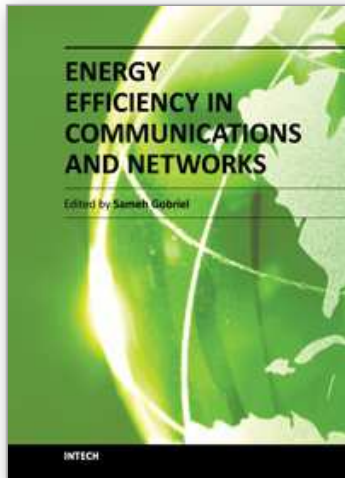
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