# CHAPTER 2

# REVIEW OF LITERATURE

## 2.1 Introduction

Literature review is one of the research phases adopted by the author of this dissertation on his research work. This phase allows him to conduct critical studies and analyses on concepts and ideas in UWA channel modeling and data packet size optimization from the related works accomplished by the UWA communities. These tasks are deemed essential for the author to build a strong foundation for his work. It is noted here that the bulk of the reviews would be on the optimization techniques or approaches rather than on the channel modeling, although channel modeling is needed to support the rest of the research works. The various optimization solutions proposed in the literatures are dealt with in depth in this chapter to explore their feasibilities to accommodate the UWA data packet size optimization algorithm to be proposed by the author. The findings in this chapter shall facilitate to formulate a preliminary framework for the intended algorithm that would be described in more details in the next chapter.

This chapter presents the review of various literatures related to the areas of research. In this chapter the author reviews some of the key papers and ideas relevant to the research presented in his dissertation. It begins with the review of the prior works found in underwater acoustic communications focused on data packet size optimization and then reviews the similar topics found elsewhere in the terrestrial wireless communications (TWC) counterparts. At the end of this chapter, a comparison of some issues related to data packet size optimization in underwater wireless communications (UWC) and TWC proposed in the reviewed literature is presented.

## 2.2 Data Packet Optimization in Underwater Wireless Communications

### 2.2.1 Data Packet Length with Maximum Throughput Efficiency

Basagni et al. [16] presented their findings in choosing the optimum packet size in multi-hop underwater networks in a simulated environment using ns-2 simulator. From their simulation, it is observed that an optimum packet size in UWA communications exists where the optimum size depends on the offered load and is highly influenced by the bit error rate (BER). The main contribution in this work is on choosing the length of data packet to achieve maximal *throughput efficiency* where this efficiency is generally defined as a ratio between the effective (delivered) and the offered (attempted) bit rate.

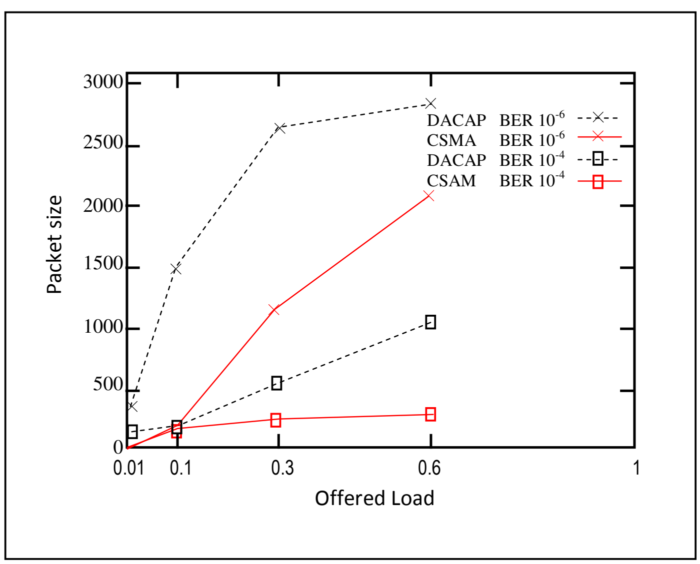
In their work, Bagsagni et al. used two realistically deployable MAC protocols – pure Carrier Sense Multiple Access (CSMA) protocol and the Distance-Aware Collision Avoidance Protocol (DACAP). Other realistic UWA channel characteristic parameters considered in their simulations include data bit rates, energy consumption models, and different BERs. An expected future underwater (UW) network deployment core scenario was additionally set up in their simulation works. Here, a relatively large number of nodes were randomly deployed over arbitrary shallow water where the data were generated with a rate corresponding to different application requirements. In more specific details, the setup of their experiment using the ns2 simulator was as follow:

- An N=100 of UW static nodes which were randomly and uniformly deployed over an area of 4km x 4km at a depth of 200m (shallow water environment).
- A centrally located common sink was placed at the sea surface to collect packets transmitted from the other nodes.
- Shortest path routing protocol.
- Sensor nodes were equipped with an acoustic modem with a transmission range of R = 1000m.
- Each data packet needed an average of 2.3 hops to reach the sink.

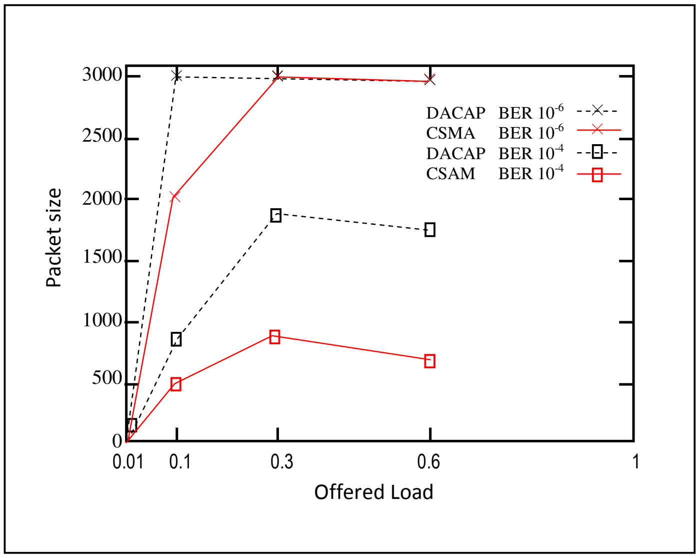
- Transmitting power was to achieve a SNR of 20dB at a receiver 1000m away in the presence of ambient noise and frequency-dependent acoustic path loss.
- Receiving power and idle power were set to 80mW.
- Carrier frequency used was 24 KHz.
- Data packet payloads ranged from 50 Bytes to 3000 Bytes.
- The acoustic modem raw bit rates were set to 200bps and 2000bps.
- Two different BERs of $10^{-4}$ and $10^{-6}$ were used.

There was no power control in this work. The total size of a packet comprised of the payload bits plus the header bits appended by the physical layer right through to the network layer. A minimum signal to inference ratio (SIR) of 15dB is required to correctly receive a packet.

In this research, the throughput efficiency was defined more technically as a ratio between the average bit rate delivered to the sink (correct bits) and the average bit rate offered by the network. The average bit rate offered by the network was given by $N_b\lambda$ where $N_b$ is the packet size in bits and $\lambda$ is packets per second. Figure 2.1(a) and (b) summarize their simulation findings. These results clearly show that there exist an optimum packet size to qualify optimum throughput efficiency. It is worth noted here that DACAP is more suitable for larger packets while CSMA is for smaller packets.




(a) 200 bps




(b) 2000 bps

Figure 2.1: Packet sizes that optimize throughput efficiency [16]

### 2.2.2 Optimal Packet Size and S&W Protocol Efficiency

The work by Stojanovic [17], focused on the design and analysis of data link protocols for underwater acoustic system, was accomplished with an aim to develop a protocol that is as efficient as possible at the data link layer for UW communications. In her research work the data link layer controlled the formatting of data packets with automatic request (ARQ) protocol. The ARQ protocol essentially is a *Stop-and-Wait* (S&W) protocol which unfortunately suffers from low throughput efficiency in UWA channel. The main causes of this low efficiency are due to the inherently high BER and long propagation delay (low speed of sound propagation) in most of the UWA channels.

Her work showed that the basic S&W protocol can be improved by transmitting packets in group and implementing a selective acknowledgement strategy. This improvement brings along a higher throughput efficiency which in turn can be maximized by selecting a proper optimal packet size. However the optimal size is somehow influenced by the bit rates, the range of transmission, and the error probability (the BER).

In general, the efficiency of the S&W protocol is a function of the data packet size, link delay, and packet error rate. This implies that there is an optimal packet size in obtaining a maximum efficiency [20]. The main contribution of Stojanovic's work is a statistical analysis of the S&W protocol efficiency that leads to the optimal packet size for a typical UWA channel. Her analysis involved three types of S&W protocols – the basic type called, S&W-1 and the other two modified protocols called S&W-2 and S&W-3 respectively. These protocols were for a group transmission of up to $M$ packets. The efficiency of these protocols is given respectively by the expressions below. It is claimed in her work that $\eta_2 \geq \eta_3 \geq \eta_1$.

S&W-1: $$\eta_1 = \frac{N_d T}{T_1} = (1-p)\frac{N_d T}{T(1)} \tag{2.1}$$

S&W-2: $$\eta_2 = (1-p)\frac{M N_d T}{T(M)} \tag{2.2}$$

S&W-3: $$\eta_3 = \frac{M N_d T}{T_M} \tag{2.3}$$

where,

- $Nd$ is the number of data bits.
- $T$ is the bit duration ($T$=1/$R$, and $R$ is bit rate).
- $p$ is the probability of packet error.
- $T(M)$ the total time to transmit and receive acknowledgement for a group of M packets.
- $T_M$ average time needed to transmit M packets successfully with probability of $p$.

The efficiency expressions shown above indicate that they are dependable on the probability of packet error rate $p$. By increasing the packet size with S&W protocol, it means a better utilization of the waiting time, but the chances of having more bit errors in the packet also increases. Hence there will be an optimal data packet size for obtaining maximal throughput efficiency or, in other words, the packet size can be varied to maximize the throughput efficiency. Further analysis on the efficiency expression of $\eta_2$ yielded the expression for optimal packet size as follow,

$$N_{d,opt} = \frac{\mu}{2}\left[\sqrt{1+\frac{4}{\mu\rho}} - 1\right] \tag{2.4}$$

of which,

$$\mu = \mu_o + \frac{2}{Mc} lR \tag{2.5}$$

where,

$\mu_o$ is the packet overhead

$M$ is packets transmitted

$c$ is speed of sound in water

$l$ is link distance

$R$ is the bit rate

and

$$\rho = \ln\frac{1}{1-P_e} \tag{2.6}$$

In which $P_e$ is the probability of bit error in the packet transmitted. Figure 2.2 shows one of the results obtained from the work of Stojanovic [17]. This graph depicts the optimal packet size plotted as a function of range-rate product ($lR$) for bit error probability ($P_e$) of $10^{-3}$ and $10^{-4}$. The plot is for S&W-1 and S&W-2 protocol. For a future system design, Stojanovic [17] suggested that an adaptive ARQ scheme should be used. Two worth considering aspects are: (1) adaptive adjustment of the time-out in accordance with the measured instantaneous round-trip time, and (2) adaptive adjustment of the packet size in accordance with the measured instantaneous error probability and link delay. It is the second aspect in his research works the author of this dissertation is focusing on.

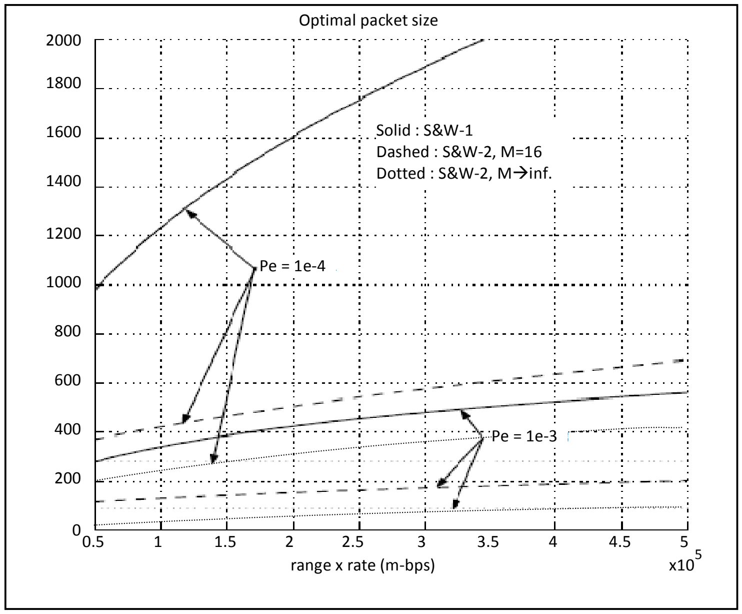



Figure 2.2: Optimal packet size $N_{d,opt}$ as a function of range-rate product [17]

### 2.2.3 Generic Cross-layer Optimization Framework

In the work of [18] the authors proposed a generic cross-layer optimization framework to determine the optimal packet size in terrestrial WSN. The framework however was extended to cater for the more challenging environment of UW and underground (UG) sensor networks. This work shows that a data packet optimization solution can be formalized using three different performance metrics – packet throughput, energy consumption per useful bit, and resource utilization. More specifically, the metrics also include the latency and reliability of the multiple hop link/path. The definition of the three performance metrics, according to [18] is as given below.

Definition 1: *Packet throughput*,

$$\frac{\quad}{\quad} \qquad (2.7)$$

where $l_D$ is the payload length, $PER_{e2e}$ is the end-to-end packet error rate, and $T_{flow}$ is the end-to-end latency.

Definition 2: *Energy per useful bit*,

$$U_{eng} = \frac{E_{flow}}{l_D(1-PER_{e2e})} \tag{2.8}$$

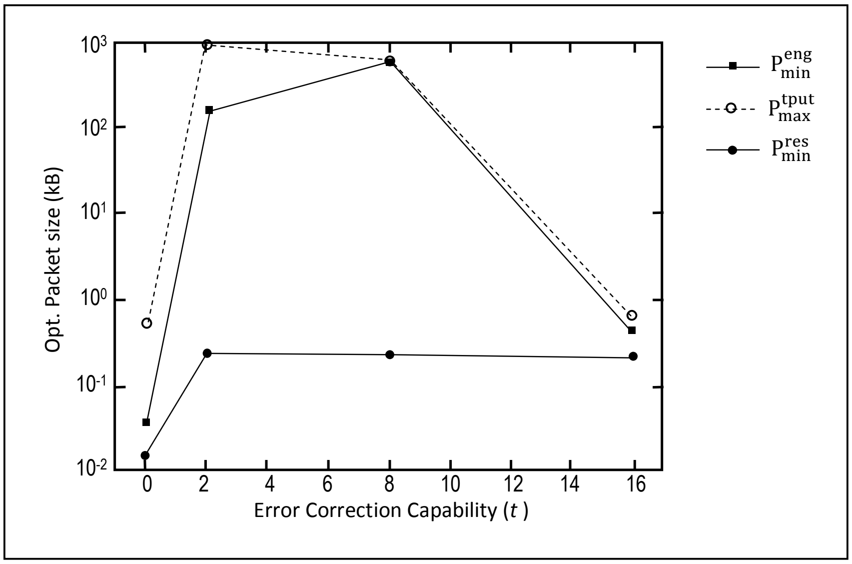
where $E_{flow}$ is the end-to-end energy consumption to transport a packet from a source to a sink.

Definition 3: *Resource utilization*,

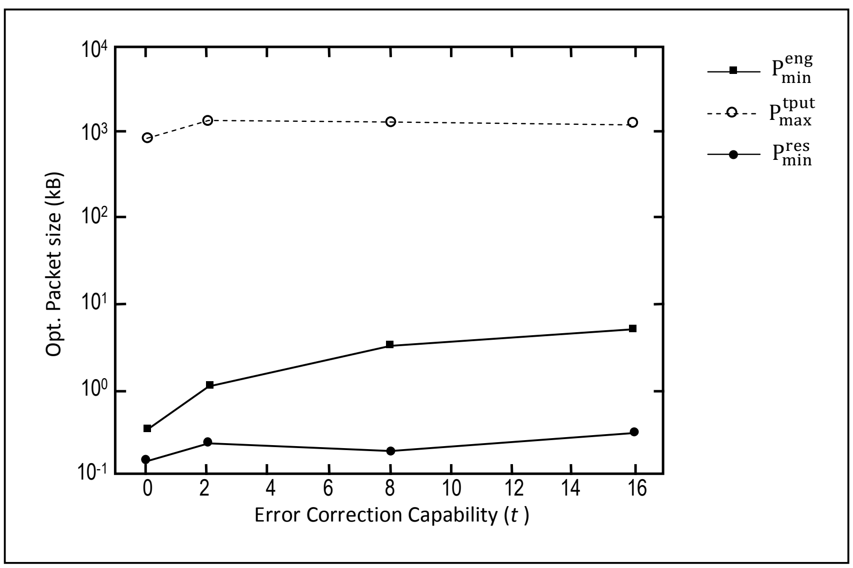
$$U_{res} = \frac{E_{flow}T_{flow}}{l_D(1-PER_{e2e})} \tag{2.9}$$

It was highlighted in their works that the energy consumption of a flow mainly is a function of packet size and the SNR threshold. In other words, the choice of the SNR threshold value may determine the optimum packet size. Moreover the packet size may also be affected by the routing decision.

For a given set of parameters ($D,\eta,\sigma,n,k,t$) maximum throughput can be computed using Definition 1, the minimum energy consumption per useful bit can be computed using Definition 2, and the resource utilization minimization can be computed using Definition 3. For that given set of parameters; $D$ is the distance between the transmitting node and the sink node, $\eta$ is the path loss component, $\sigma$ is the fading component, $n,k,t$ belong to a forward error correction (FEC) block code where $n$ is the block length, $k$ is the payload length, and $t$ is the error correcting capability in bits. The samples of the outcomes of the work by [18] are shown in Figure 2.3 (a) and (b) respectively. Take note that $P_{min}^{eng}$ is energy consumption per useful bit minimization, $P_{max}^{tput}$ is packet throughput maximization, and $P_{min}^{res}$ is utilization minimization.




(a) Deep water




(b) Shallow water

Figure 2.3: Optimum packet size for deep water and shallow water [18]

It is mentioned here that the results obtained from [18] were via the optimization toolbox in the MatLab application software. A significant difference in Figure 2.3 (a) and (b) shows that the propagation characteristic of deep water and shallow water would remarkably affect the optimum packet size.

## 2.3 Data Packet Optimization in Terrestrial Wireless Communications

### 2.3.1. Adaptive Frame Length Control Approach

A dynamic packet length control (DPLC) scheme for WSN was proposed by Wei Dong et al. [21]. In their work, a lightweight and accurate link quality estimation method adapted from [22] capturing both physical channel conditions (channel fading, mobility, or power degradation) and interferences to dynamically control the packet length were incorporated. The DPLC was to be implemented on the MAC layer but to facilitate upper-layer application programming it included two services – the aggregation service (AS) for small messages and the fragmentation service (FS) for large messages. The AS provides three distinct mechanisms: reliable transmissions, unreliable transmissions, and unreliable transmissions with fixed number of retrainsmissions. The FS meanwhile provides reliable bulk data transmissions as large messages are usually important for upper-layer applications. DPLC was validated by simulation on TOSSIM [23] and through indoor test-bed experiments via 20 TelosB motes running the CTP protocol [24].

DPLC used the metric of transmission efficiency ($\varepsilon$) for dynamic adaptation. In general the transmission efficiency is defined as, $\varepsilon = U_b / T_b$ where $U_b$ is the received useful bytes and $T_b$ is the overall transmitted bytes. Two variants of $\varepsilon$ were used in DPLC i.e. one for single-hop transmission and one for multi-hop transmission. For single-hop transmission the efficiency is given by [21],

$$\varepsilon_i = \frac{l.p(l)}{l + H + O} \tag{2.10}$$

where,

| | |
|---|---|
| $\varepsilon_i$ | equals $U_b$ received at node $n_{i+1}$ divided by $T_b$ from node $n_i$ |
| $l$ | is the payload length for MAC transmission |
| $p(l)$ | is the packet reception rate (PPR) from $n_i$ to $n_{i+1}$ |
| $H$ | is MAC header overhead and |
| $O$ | is DPLC overhead |

For single-hop transmission the $p(l)$ parameter was monitored to determine the packet length so that the metric is maximized. For multi-hop transmission the metric is given by [18],

$$\varepsilon_k = \frac{1}{\varepsilon_k^{-1}(l) + \varepsilon_{k-1}^{-1}\frac{1}{dr_k(l)}} \tag{2.11}$$

where,

| | |
|---|---|
| $\varepsilon_k$ | equals $U_b$ received at node $n_{k+1}$ divided by overall $T_b$ from $n_1$ to $n_{k+1}$ |
| $\varepsilon_k^{-1}(l)$ | is the normalized transmission overhead from $n_k$ to $n_{k+1}$ |
| $\varepsilon_{k-1}^{-1}$ | is the normalized transmission overhead from $n_1$ to $n_k$ and |
| $dr_k(l)$ | is data delivery rate from $n_k$ at packet payload length $l$ |

It is mentioned that for reliable multi-hop transmissions the strategy is equivalent to maximizing the $\varepsilon_i$ as in single-hop transmissions. However for unreliable multi-hop trans-missions with fixed number of retransmissions, the data delivery rate is related to PRR as,

$$dr_i = 1 - (1 - p_i)^{m+1} \tag{2.12}$$

where $p_i$ is the PRR from $n_i$ to $n_{i+1}$ ($1 \leq i \leq k$). Therefore, $dr_k(l)$ can be estimated from the PRR observed at $n_k$.

In this dynamic scheme, when the application in the sender node passes a message from application layer down to MAC layer for transmission, the DPLC module will determine whether AS or FS is to be used and the link estimator in DPLC will dynamically estimate the optimal packet length. At this point, the DPLC module decides how many messages shall be aggregated or fragmented. Initially the default packet size is sent through the link and the DPLC will monitor all packets by keeping a sliding window of size $w$. The DPLC computes the metrics when $w$ is full. Then based on a gradient variable that, can be positive or negative, decides to increase or decrease the packet length. The gradient variable is set to be positive by default. The outcomes of the TOSSIM simulation and the test-bed experiments by [21] showed that DPLC scheme reduced the transmission overhead by 13% and a 41.8% reduction in energy consumption as compared to the original protocol.

In a study of adaptive frame size predictor by Song Ci et al. [25], a different approach was used in comparison to the DPLC by using the Extended Kalman Filter (EKF) to predict the optimal frame size for better energy efficiency and goodput and, all at the same time to maintain the sensor node memory requirement. The advantages of EKF in its simplicity and ability to provide accurate estimation and prediction results were exploited by Song Ci et al. in their studies. The amount of data to be transmitted at any instant is dynamically well adjusted based on the link quality estimated by the EKF. In other words the frame size is dynamically optimized with respect to the channel quality predicted by an accurate predictor. They further proposed an algorithm capable of reducing the number of retransmissions due to frame errors, the rate of which is understandably sensitive to frame size. The algorithm, more specifically, was able to predict the optimal frame size based on the network parameters such as channel quality, frame length, protocol overheads, and data collisions. In brief, they used the EKF filtering characteristics coupled with the known present channel quality to keep track of the channel history and accordingly to predict the optimal frame size. The EKF has a unique capability of estimating the past, present, and future states of a system even without precise (exact) knowledge of the modeled system [26][27].

In the work of Song Ci et al. [25], in addition to find optimal packet size they also focused on how to maintain the network performance and to improve the energy efficiency of WSNs at the MAC layer. In order to use EKF this research team had developed two models namely, the *process model* and the *observation model* to fit into the EKF model. Channel throughput was chosen to be the main performance parameter in their developed models because their main goal is to maximize channel throughput $\rho$, at every transmission by predicting an optimal frame size considering the collision and frame errors. The *process model* developed was given by the following equations and provided the frame length $L$ at time $k$ and $k+1$ as,

$$L_{K+1} \begin{cases} = L_{max} & L_{k+1} > L_{max} \\ = L_{opt} & L_{min} < L_{k+1} < L_{max} \\ = L_{min} & L_{k+1} < L_{min} \end{cases} \tag{2.13}$$

where,

$L_{max}$ is the maximum frame size;

$L_{min}$ is the minimum frame size;

and,

$$L_{opt} = \frac{-u \pm \sqrt{(u^2 - 4L_k Pb_{k+1} \upsilon)}}{2L_k Pb_{k+1}} \qquad \text{(The optimal frame size)} \tag{2.14}$$

where,

$Pb$ is the bit error rate under a known channel quality;

with,

$$\begin{aligned} u = (&2L_k Pb_{k+1} H + L_k SR_k Pb_{k+1} - Pb_k L_k^2 - 2L_k Pb_k H \\ &-H - Pb_k H^2 - HN_k - SR_k - SR_k Pb_k L_k \\ &-SR_k Pb_k H - SR_k N_k - ACK(1 - Pb_k)^{-ACK} \\ &-OR_k (1 - Pb_k)^{-ACK} - N_k C_k) \end{aligned} \tag{2.15}$$

and,

$$\begin{aligned} \upsilon = (&L_k H + L_k Pb_{k+1} H^2 + L_k HN_k + L_k SR_k \\ &+L_k SR_k Pb_{k+1} H + L + kSR_k N_k \\ &+L_k ACK(1 - Pb_{k+1})^{-ACK} \\ &+L_k OR_k (1 - Pb_{k+1})^{-ACK} + L_k N_k C_k \end{aligned} \tag{2.16}$$

in which,

$L$: payload size of a frame
$R$: data transmission rate
$H$: MAC protocol header of a frame
$N$: average number of collisions occurred between two renewal points
$ACK$: frame length of an acknowledgment frame
$O$: overhead of ACK frame
$C$: average length of collisions
$S$: average number of random back-off time slots

The *observation model* is given by,

$$\rho_{k+1} = Q(L_{k+1}, Pb_{k+1}) \tag{2.17}$$

where,

$\rho_{k+1}$ is observation time at time $k+1$;

$Q$ is the observation function.

The proposed optimal frame size predictor algorithm was tested by integrating it into the MAC implementation of the Berkerly motes for performance evaluation under different channel quality conditions by modifying the PHY layer parameters. Four network scenarios were considered with 2, 5, 10, 20, and 50 nodes respectively. It was claimed that the algorithm achieved a 15% reduction in energy consumption, the goodput was doubled, and the delay was reduced by 20%.

E. Modiano [28] presented a work on adaptive algorithm for optimizing data packet size with wireless data link layer ARQ protocol focused on bit error rate (BER). His algorithm made use of the acknowledgment history to estimate the channel BER and allowed the ARQ protocol to dynamically optimize the packet size. It was claimed that this algorithm is particularly useful for wireless channel where BER tends to be high and time variable. He observed in his work that it was not necessary to have an accurate estimation of the channel BER by using the Selective Repeat Protocol (SRP), an optimal ARQ protocol, to choose a good packet size. Thus his algorithm was able to perform well with a short observation history of just 10,000 bits.

Modiano chose SRP to be an optimal ARQ protocol in a sense that SRP attempts to retransmit only packets containing errors [29]. An estimation of the channel BER can be made based on the acknowledgement history of the most recently transmitted packets. Hence, with a given number of packets that required retransmissions an optimal packet size can be chosen to maximize the expected efficiency of the data link protocol. In SRP, for a given channel BER $p$, the expected efficiency of the protocol using a packet size of $k$ is given by [30] as,

$$\eta = (\frac{k}{k+h})\frac{1}{(1-p)^{-(k+h)}} \tag{2.18}$$

where,

$k$ is the number of information bits;

$h$ is the number of header bits in the packet;

$p$ is the channel BER.

The first term of the expression above represents the ratio of information bits to the total bits in a packet, while the second term represents the average number of transmissions attempted per packet. If the number of retransmissions request $R$ out of the last $M$ packet transmissions is known, the expected efficiency of the protocol can be given as,

$$\eta_R(k) = \int_p \left[ \frac{k(1-p)^{k+h}}{(k+h)} \times \frac{\binom{M}{R} E^R (1-E)^{M-R}}{\int_p \binom{M}{R} E^R (1-E)^{M-R}} \right] \tag{2.19}$$

where $E$ is the probability that a packet contains errors and is given by

$$E = 1 - (1-p)^{k'+h} \tag{2.20}$$

Take note that the packet size used in the previous $M$ transmissions is given by $k'$. In this equation, it shows that the value of frame size $k$ can be chosen to maximize the protocol efficiency for a given value of $R$ out of the previous $M$ transmissions. Figure 2.4 shows the performance of the proposed algorithm for various bit observation histories. The results in Figure 2.5 is the evaluation of the steady state performance of the algorithm based on a Markov chain shown in Figure 2.4, which depicts the packet size of 200, 500, 1000, and 1500 bits.

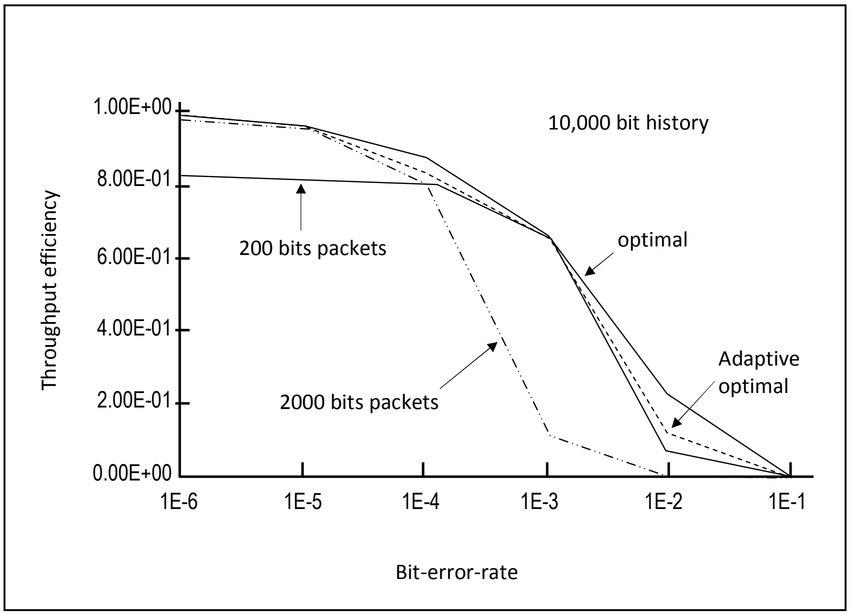



Figure 2.4: Performance of the adaptive algorithm [28]

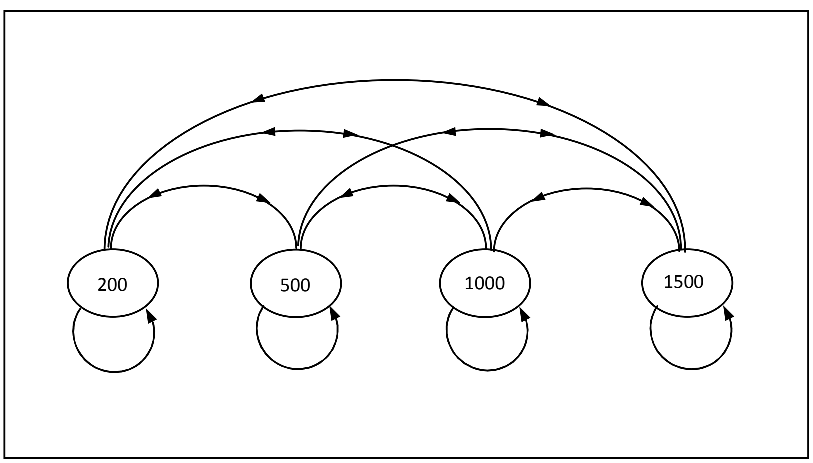



Figure 2.5: System Markov chain with 4 states [28]

### 2.3.2. Energy Efficiency Based Packet Size Optimization

By choosing energy efficiency as the optimization metric, Sankarasubramaniam et al. [31] aimed to determine the optimal data packet size for communications between neighboring nodes. They also examined the relationship among energy efficiencies based on the effect of retransmissions, error control parities and encoding/decoding energies. Based on the general data link layer packet format in Figure 2.6 and the energy model outlined in [32] the researchers in [31] have expressed the energy required to transmit and receive one bit of information across a single-hop as,

$$E_b = E_t + E_r + \frac{E_{dec}}{l} \tag{2.21}$$

where $E_t$ is energy consumed in transmitter, and $E_r$ is energy consumed in receiver with $E_{dec}$ as decoding energy per packet.


Figure 2.6: Data link layer packet format

It is further highlighted that $E_t$ and $E_r$ are respectively given by

$$E_t = \frac{\left( (P_{te} + p_o)\frac{(l + \alpha + \tau)}{R} + P_{tst}T_{tst} \right)}{l} \tag{2.22}$$

$$E_r = \frac{\left( P_{re}\frac{(l + \alpha + \tau)}{R} + P_{rst}T_{rst} \right)}{l} \tag{2.23}$$

where,

$P_{te/re}$ is power consumed in the transmitter/receiver electronics

$P_{tst/rst}$ is start-up power consumed in transmitter/receiver

$T_{tst/rst}$ is transmitter/receiver start-up time

$P_o$ is output transmit power

$R$ is data rate in bps

The expression for the energy required to transmit and receive one bit of information across a single-hop can then be written in terms of radio parameters $k_1$ and $k_2$ as,

$$E_b = k_1 + k_1 \frac{(\alpha + \tau)}{l} + \frac{k_2 + E_{dec}}{l} \tag{2.24}$$

where,

$$k_1 = \frac{(P_{te} + P_o) + P_{re}}{R} \quad \text{and} \quad k_2 = \left(P_{tst} T_{tst} + P_{rst} T_{rst}\right) \tag{2.25}$$

$k_1$ and $k_2$ are constants for a given transceiver and data rate $R$. Parameter $k_1$ can be the useful energy used to transmit and receive an information bit whereas $k_2$ represents the start-up energy consumption.

By observing the $E_b$ expression above, it can be noticed that if the $E_{dec}/l$ term is kept constant, then for a given value of $\alpha$ and $\tau$, $E_b$ is inversely proportional to the payload length $l$. It implies that $E_b$ shall become a constant $k_1$ if the length $l$ is allowed to increase to a large value. However, from practical experiences it is well understood that long packet sizes are always associated with greater loss rates, and on the other hand, shorter packets are more reliable but inefficient for energy. Therefore there will be an optimal packet size/length that can be chosen to balance these conflicting interests.

Sankarasubramaniam et al. [31] view that energy efficiency is the most suitable metric to capture the energy and reliability constraints. They then defined the energy efficiency as follow:

$$\eta = \frac{k_1 l}{k_1(l + \alpha + \tau) + k_2 + E_{dec}} \left(1 - PER\right) \tag{2.26}$$

where,

$(1 - PER)$ is the packet acceptance rate i.e. the data reliability rate and

$$\frac{k_1 l}{k_1(l+\alpha+\tau)+k_2+E_{dec}} \quad \text{is the energy throughput .} \tag{2.27}$$

The energy efficiency metric can be represented by the notion of energy channel in Figure 2.7 [31]. Thus for a given set of transceiver and channel parameters the optimal packet size can be determined by maximizing the energy efficiency metric ($\eta$) as defined above.

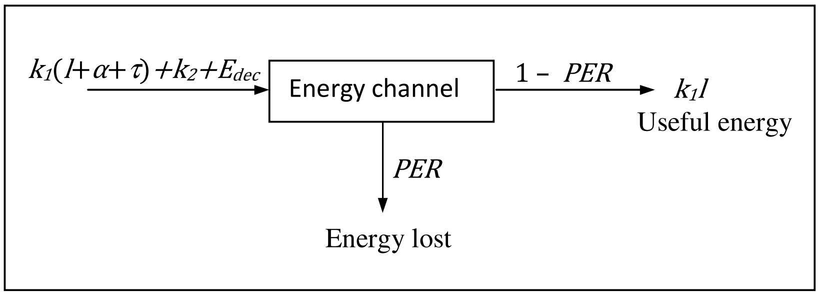



Figure 2.7: The notion of energy channel

It should be mentioned here that the proposed approach was for the optimization of fixed size packet based on the parameters estimated at the time of network design to give the maximal energy efficiency. It is thus not the same as those described in section 2.3.1 where the packet size is dynamically controlled based on the channel quality and other parameters. The additional computation and resource management overhead become the main reason why the researchers in [31] refrained from the dynamic control approach. The researchers had shown that significant improvement in $\eta$ can be achieved with forward error control (FEC) as compared to no error control i.e. with $\tau$ set to 0.

Inwhee Joe [33] proposed a method to improve energy efficiency in WSN using optimal packet length with channel coding capability without power management. His work showed that energy efficiency can be improved by using optimal packet length at the data link layer. He also showed that energy efficiency may not be maximized via power management approach in which the transceiver was turned off at idle state to conserve energy. He argued that since sensor nodes normally communicate using short packets that leads the energy efficiency in the nodes, due to the dominance of start-up energy, could actually be reduced.

However he emphasized that even though power management does not improve energy efficiency, it should be employed to minimize energy wastage. He defined the energy efficiency as,

$$\eta = E_{th} \cdot r \tag{2.28}$$

where,

$E_{th}$ is the energy throughput i.e. the ratio of energy consumed for actual data transmission to entire packet transmission

$r$ is the reliability i.e. the successful packet reception rate

In his work, Inwhee Joe [33] further expressed the energy efficiency as a function of packet length with and without power management as follows,

$$\eta = \frac{E_c l}{E_c(l+h)+E_s}(1-PER) \quad \text{: with power management} \tag{2.29}$$

$$\eta = \frac{l}{l+h}(1-PER) \quad \text{: without power management} \tag{2.30}$$

where,

$E_c$ is communication energy consumption;

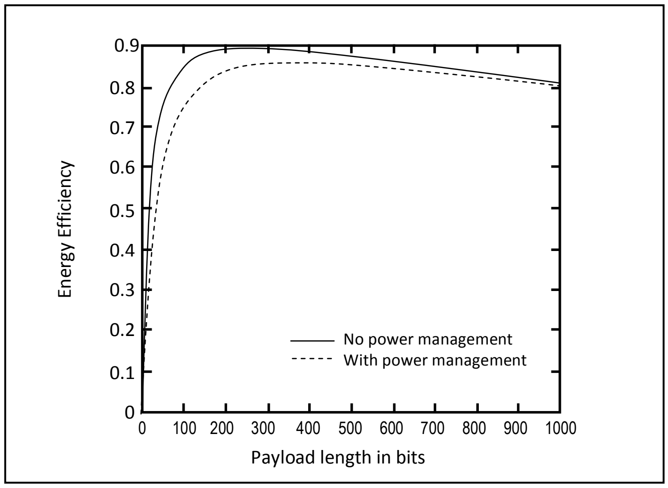
$E_s$ is the start- up energy consumption;

$l$ is the payload length;

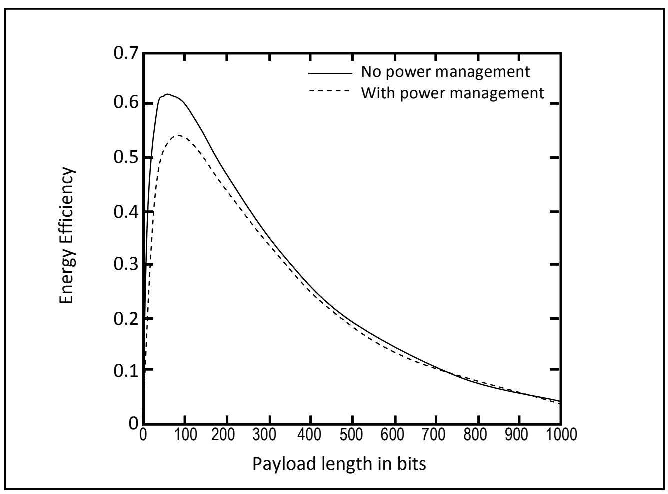
$h$ is the header length;

$PER$ is packet error rate.

From the work of E. Shih et al. [32] two important plots relating energy efficiency to payload length are shown in Figure 2.8 (a) and (b). These plots are for neighbor node distance, $d$ of 10m and 20m and header length, $h$ of 16 bits. The graphs compare the energy efficiency under power management and under no-power management.




(a) $d = 10$m




(b) $d = 20$m

Figure 2.8: Energy efficiency as function of payload length [32]

It is apparent from Figure 2.8 that there is approximately a 10% difference in peak energy efficiency between with and without power management. That is, as concluded by E. Shin et al. [32] that the use of power management cannot really improve energy efficiency. However the plots show that there is an optimal packet length in attaining maximal energy efficiency. For instance, with power management in place, when energy efficiency is at peak, the optimal payload length is 280 bits for 10m of neighbor distance and it is 60 bits for 20m of neighbor distance.

Inwhee [33] provides analysis in energy efficiency with optimal packet length in terms of channel coding i.e. with forward error correction (FEC). Channel coding is one of the most commonly used approaches in increasing the channel reliability. He attempted to find a relationship between FEC and energy efficiency by considering the Binary BCH coding and the rate ½ convolution coding. His analysis showed that with channel coding the energy efficiency can be improved significantly and BCH code is better than the convolution code by a factor of 2. The reason being that the redundancy bits in convolution code are almost double that of used in BCH coding. The energy efficiency equation with BCH coding with $t$ correction capability is given as below.

$$\eta = \frac{E_c(n-h-\tau)}{E_c n+E_s+E_{dec}} \cdot \sum_{j=0}^{t} \binom{n}{j} P_b^j (1-Pb)^{n-j} \tag{2.31}$$

Where, $n$ is the BCH code length of $h+l+\tau$ of which $h$ is the header, $l$ is payload length, $\tau$ is the trailer (parity bits), $E_c$ is the encoding energy, $E_{dec}$ is the decoder energy at the receiver side, and $P_b$ is the probability of bit error for BCH code. For completion purpose the energy efficiency equation with rate ½ convolution coding is given as,

$$\eta = \frac{E_c\left(\frac{n}{2}-h\right)}{E_c n+E_s+E_{dec}} \cdot (1-Pb)^n \tag{2.32}$$

Where $P_b$ is the convolution code probability of bit error, $n$ is the packet length and $h$ is the header length.

### 2.3.3. Packet Size Optimization for Goodput Enhancement

There are works done in investigating the relationship between optimal packet size and the goodput or throughput in WSN systems. One of the more recent works in this area can be found in [34] by Y. Zhang et al. They proposed a new analytical model to calculate the goodput and energy consumption with respect to packet size optimization for slotted IEEE 802.15.4 networks. The IEEE 802.15.4 standard [35] was released to regulate low-rate and low-cost short distance wireless personal area networks (LR-WPANs). They investigated the issue of how to optimize the packet size in terms of maximizing resource efficiency and energy efficiency by considering both MAC and PHY layer constraints with the assumption that the system under study is in saturation mode, which is every node in the system always has a packet to be transmitted at any moment. More specifically their research was to deduce the optimized packet size in terms of resource and energy efficiency maximization. System level simulation was used to verify their analytical model and the outcomes of the simulation were claimed to bring significant performance enhancement to IEEE 802.15.4 networks by more efficiently segmenting the data stream. Technically their new model takes into account of the protocol overhead, channel condition, CSMA-CA contention, resource efficiency, and energy efficiency. The protocol overhead can be illustrated by the standard IEEE 802.15.4 data frame format shown in Figure 2.9.

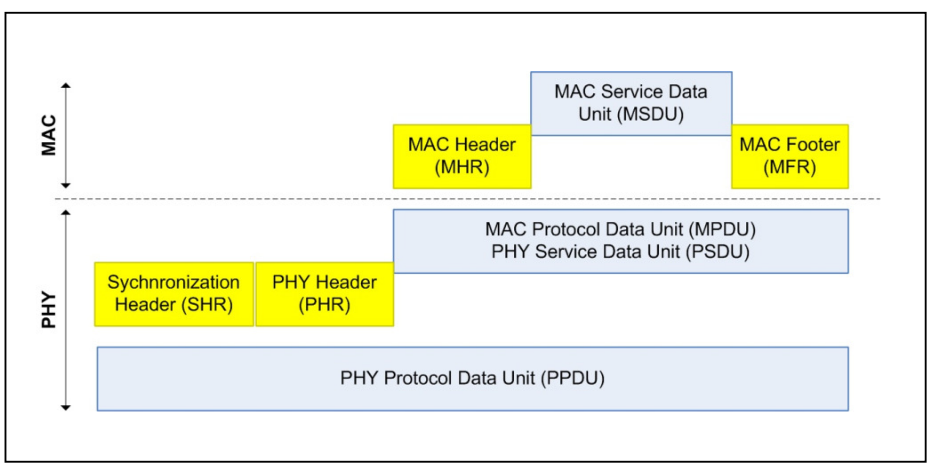



Figure 2.9: IEEE 802.15.4 data frame format

Note that in Figure 2.9 the only part in the data packet that carries the useful information i.e. user data is the MAC Service Data Unit (MSDU). The rest of the fields are simply overhead needed by the protocol. For the channel condition at PHY layer, the bite error rate (BER) is used as the indicator. For a given value of BER, the packet error rate can be deduced by,

$$PER = 1 - (1 - BER)^{l} \quad \text{;where } l \text{ is the packet length in bits} \qquad (2.33)$$

and $l$ can be computed by,

$$l = Lt_b R_{phy}$$

where,

$L$ is the number of back off period

$t_b$ is time interval of one back off period

$R_{phy}$ is the PHY layer bit rate

As for the CSMA-CA contention a Markov chain model in [36] was referred to derive the behavior of multiple access contention, accordingly to describe the transmission collisions. The new expression for packet collision probability is given below to denote that packet collision occurs when more than one users transmitting at the same exists.

$$P_{col} = 1 - (1 - p_{tr})^{Z} - Zp_{tr}(1 - p_{tr})^{Z-1} \qquad (2.34)$$

where,

$p_{tr}$ is the probability to transmission

$Z$ is the network size (number of nodes).

In terms of resource efficiency, Y. Zhang et al. [34] used goodput as the metric. It denotes the number of information bits, excluding protocol overhead and data retransmissions that have successfully been forwarded from the source to the targeted destination per unit of time. The goodput is defined as per the three constraints described above as,

$$G = \frac{(l-l_H)p_{tr}(1-p_{col})(1-PER)}{D_{tr}+D_{bk}} \tag{2.35}$$

where,

$l_H$ is the fixed protocol overhead

$D_{tr}$ is the expectation of time used for data transmission

$D_{bk}$ is the expected delay due to random backoff and channel sensing

In terms of energy efficiency, they used energy consumption per bit of goodput to do the measurement. The energy efficiency is given as,

$$E = \frac{LP_{TX}p_{tr}+D_{bk}P_{SL}+L_{CCA}(P_{RX}-P_{SL})}{(l-l_H)p_{tr}(1-p_{col})(1-PER)} \tag{2.36}$$

where,

$P_{TX}$ is energy consumptions per back off period in transmission state

$P_{RX}$ is energy consumptions per back off period in receiving state

$P_{SL}$ is energy consumptions per back off period in sleeping state

$L_{CCA}$ is the interval of channel sensing in both CCA1 and CCA2

A link adaptation scheme for multi-rate wireless networks which combines adaptive modulation and coding (AMC) at physical layer and with type-II hybrid ARQ (HARQ) at data link layer to enhance channel utilization and goodput was proposed by D. Wu et al. [37].

With reference to the goodput performance analysis of the scheme, they focused on goodput enhancement in delivering messages from the transport layer by optimizing packet sizes in a cross-layer fashion. An effective and efficient algorithm for searching (golden section search) optimal packet sizes was developed. In relating the goodput to optimal packet size search, D. Wu et al. began with a general goodput equation given by [38] as,

$$J_M = \frac{N}{T} \cdot (1 - P) \tag{2.37}$$

where,

- $N$ is the number of bits in a packet
- $T$ is the average time for transmitting a packet
- $P$ is the average PER of an N-bit information packet after the maximal possible $X^{th}$ transmission attempts

Then in general, in a transport layer session, each transport layer message is broken into MAC packets. In their work they assumed that a MAC packet consists of $N$ information bits. Thus each message is fragmented into multiple packets of size $N$. It follows that the last packet will contain the left-over bits. In other words, a transport layer message of length $l$ would be fragmented into $l/N$ packets with the final packet contains between 1 and $N$ bits. Their analysis showed that the goodput of transmitting a message can be given by [37],

$$J = \frac{l}{\left\lfloor \frac{l}{N} \right\rfloor \cdot T + t} \cdot (1 - P)^{\left\lfloor \frac{l}{N} \right\rfloor} \cdot (1 - p) \tag{2.38}$$

where $t$ and $p$ denote the average time and PER of transmitting a packet of leftover bits.

Based on the convexity property of the above goodput expression they have developed a one-dimension golden search algorithm to search for the optimal packet size. The search algorithm is listed as in Figure 2.10.

```
Step 1:  set x2 = a + 0.618(b−a),J2 = J(x2),
         go to step 2.
Step 2:  set x1 = a + 0.382(b−a),J1 = J(x1),
         go to step 3.
Step 3:  if |(b−a)| ≤ ε ,
            set x* = (a + b)/2 , stop.
         else,
         go to step 4.
Step 4:  if J1 < J2 ,
            a = x1 , x1 = x2 , J1 = J2 ,
            go to step 5.
         if J1 = J2 ,
            a = x1 , b = x2 ,
            go to step 1.
         if J1 > J2 ,
            b = x2 , x2 = x1 , J2 = J1 ,
            go to step 2.
Step 5:  set x2 = a + 0.618(b−a), J2 = J(x2),
         go to step 3.
```

Figure 2.10: The search algorithm [37]

This algorithm shall search for an optimal packet size, $x$ on an initial packet size interval $[a,b]$ for a given accuracy of $\varepsilon$. That is, the optimal packet size should have $x \in [a,b]$. Technically, the golden section algorithm requires an initial packet size interval $[a,b]$ on which the function $J(x)$ is a convex function of packet size $x$. It is claimed that this scheme does not incur much calculation complexity and computation overhead.

### 2.4 Data Packet Optimization in UWC against Optimization in TWC

Table 1.1 summarizes some of the important comparisons of data packet size optimization found in the literature reviewed and discussed above for underwater wireless communications and terrestrial wireless communications.

Table 2.1: Data packet size optimization in UWC and in TWC

| UWC | TWC |
|---|---|
| Packet size optimization in terms of energy efficiency, throughput, BER, and the types of protocol. | Packet size optimization in terms of energy efficiency, throughput, BER, and the types of protocol. |
| Dynamic control of packet size for each packet transmission is not very practical due to the slower speed of acoustic wave that brings along possible high propagation delay. | Dynamic control of packet size for each packet transmission is possible to be implemented at MAC layer and below especially at data link and physical layer. |
| Dynamic control of packet size involved link quality computation and some overhead resource utilizations. Due to slower transmission rate and high propagation delay, the computed link quality parameters may be out of date to support the required response time for adequate controlling of the packet size. Thus the next packet sent out may not be of optimal size. | Does involved link quality computation and overhead resource utilization however is possible to adjust the packet size dynamically with the proper selection of protocol and adaptive channel modulation and coding (AMC) at the PHY layer. |
| If dynamic or adaptive packet length control is not a good strategy then the fixed optimal packet size shall be determined at the network design stage with reference to the desired network parameters. | Has the luxury to use fixed size optimal packet or dynamically adaptive packet length. However fixed size packet transmission seems to be preferred in practice. |
| A more practical approach to optimize or increase the data rate, the efficiency, and the bandwidth of UWA transmission is the MIMO technique. | Not necessary to go into MIMO. New approaches are being investigated by many researchers. |

## 2.5 Chapter Conclusions

The literature reviewed in this chapter can be broadly categorized into two categories: data packet size optimization in underwater wireless communication and that in terrestrial wireless communications.

Optimization methods or approaches in the context of two main channel performance metrics of throughput efficiency and energy efficiency in each category were accurately explained. Take note that the optimization metrics are based on the BERs of the channel. Various essential parameters and equations were given here as quick references. Should the reader be interested to know in depth a particular equation, the cited references may be referred to. Table I serves as a quick reference for those who wish to know some important issues regarding data packet size optimization in UWC and in TWC respectively.

The author of this dissertation would like to emphasize here that some of the approaches highlighted in this chapter would be adopted into his research works and shall be recited in the various parts of the succeeding chapters.