Data Link Layer Effect over Swarm Underwater Network Performance

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Abstract: The Underwater Swarm is a particular Underwater Network configuration characterized by nodes very close one to each other, with mobility capability. This type of network raises challenges for its effective design and development, for which the only use of acoustic communication as traditionally suggested in underwater communication could be not enough. A new emerging solution could be a hybrid solution that combines the use of acoustic and optical channel in order to overcome the acoustic channel limitations in underwater environment. In this work we want to investigate how the acoustic and optical communications influence the Underwater Swarm performance by considering the Data Link Layer effects over the two different propagation technologies. Performance simulations have been carried out to suggest how a new Underwater Swarm based on hybrid communication technology could be designed.

1 INTRODUCTION

Underwater communications have experimented a growing interest during the last years for different application fields from oceanography to undersea monitoring. Among different underwater networks, the swarm appears to have more interesting challenges for its effective design and development due to the typical limitation of the underwater environment, and the dependence of the topology configurations. To respond to these open issues, a new emerging solution could be a hybrid solution that combines the use of acoustic and optical channel, to take advantage by the two different technologies: the acoustic communications are characterized by low bandwidth and high power consumption, but they can cover long distance and are water condition independent; optical communications are able to provide higher bandwidth with lower energy consumption, but suffer from highly limited communication range and water conditions. Hence, the hybrid system could use optical channel or acoustic one according to the application (i.e. data rate required) and the environment (i.e. water conditions). This permits to have in the same device two alternative technologies according to the underwater services needs. Several research activities have been conducted in this direction to evaluate the different communication channels performance (Hon et al., 2014).

In this work, we are going to investigate how the acoustic and optical communications can influence the performance of the network. More deeply, we investigate the lower protocol layers (Physical Layer, Data Link Layer and Network Layer) effects over the Underwater Swarm for the different propagation technologies considered in order to suggest how the new hybrid system could be designed.

The article is organized as follows: a brief introduction of the Swarm Network with the corresponding lower layers challenges needed are provided in Section II. The main results are summarized in Section III, and finally in Section VI the main conclusions are drawn.

2 UNDERWATER SWARM

An Underwater Swarm is characterized by a set of AUV (Autonomous Underwater Vehicles) devices, i.e. nodes of the network, very close one to each

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other, with mobility capability. The structure of the network is that of a distributed network, in which the nodes, through the exchange of control information, will take decisions in collaborative manner. The applications and the corresponding performance are strictly related to the swarm configurations. In particular:

- **Alarm Detection** (*Pipeline Configuration*): the swarm detects an alarm occurrence, for instance a measured value of a specific parameter (e.g., oil in the water) is higher than a given threshold, and thus, it will be ready to coordinate itself and move towards the area, in which the anomalies have been detected. From a communication point of view, it means that each node is connected only to one next node and all the nodes are allocated in a linear manner. In this case a heavy data transmission is assumed in a directional way.
- **Data Processing and Report** (*Dense Swarm Configuration*)*:* the swarm needs to acquire and process complex data such as image, and thus, it will be ready to coordinate itself and move very close each to other towards the area, in which the anomalies need to be relevated. From a communication point of view, it means that each node is connected only to its closest neighbours and to forward information towards the collecting node (i.e. the *sink* node), a multi-hop paradigm is needed.
- **Periodical Monitoring** (*Swarm Configuration*): nodes perform periodical measurements of proper parameters. From a communication point of view, this configuration is a combination of the exemplary above described configurations: the number of hops needed to reach the collecting node is less than the *Pipeline* configuration and more than the *Dense Swarm* one.

2.1 Physical Layer Challenges

The swarm concept is based on the assumption that the network takes decision as a single entity through continuous information exchange among all nodes. The communication system, acoustic or optical, can provide advantages and disadvantages as described below.

2.1.1 Acoustic Technology

For the Physical layer based on acoustic technology, an isotropic transducer operating at 300 kHz has been considered for our analysis (Tabacchiera et al., 2012).

The acoustic technology suffers, due to the high latency of the acoustic signal in water (propagation speed ≈1500 m/s) of the "Doppler Spread" and the propagation effects may be time-variant, with an acoustic channel assumed as a Rayleigh Fading Channel, and only low data rates are supported. By these considerations, it is reasonable to consider an M-FSK modulation, with a bit error probability, P_e, expressed by (Proakis, 1989):

$$P_e = \frac{M/2}{M-1} \cdot \sum_{m_{MFSK}=1}^{M-1} \frac{(-1)^{(m_{MFSK}+1)} \cdot \binom{M-1}{m_{MFSK}}}{1 + m_{MFSK} + m_{MFSK} \cdot \gamma} \tag{1}$$

where M is the level number of the M-FSK modulation format, and γ the linear expression of the Signal-to-Noise Ratio (SNR).

2.1.2 Optical Technology

For the optical technology Physical layer, the optical communication system is based on LED technology.

Performance evaluation has been carried out starting from the SNR relative to the typical underwater optical link (Giles and Bankman, 2005):

$$SNR = \left[\frac{P_t \cdot e^{-3Kr} \cdot D^2 \cdot cos\Phi}{(tan^2\theta) \cdot 4r^2 \cdot NEP}\right]^2 \tag{2}$$

where the factors in the square brackets are referred respectively, to the transmitter, the communication channel, and the receiver. P_t is the transmitted power, θ the half angle transmitter beam width, $K=c/3$ the diffuse attenuation coefficient, which typically ranges from $0.02\ m^{-1}$ for the cleanest water, to $0.8m^{-1}$ for the more turbid coastal water, c being the beam attenuation coefficient, r is the optical link length, D the receiver aperture diameter, Φ the angle between the receiver optical axis and the line-of-sight between transmitter and receiver, NEP is the noise equivalent power. For a typical optical communication system, the modulation format is based on OOK, and the bit error probability P_e is water condition dependent, due to the strictly dependence of the SNR values to the different types of water.

2.2 Data Link Layer Challenges

The Bit Error Rate (BER) of an underwater link is often high and thus errors in the received bit stream are thus inevitable. To establish reliable communication over such a channel, a recovery strategy is needed. Generally, this procedure can be found in the data link layer, which is responsible of packet formatting and recovery procedure implementation.

Data link protocols for underwater systems needs to be efficient as possible, but simple to implement. Among of all, a good candidate for the underwater system seems to be the *Stop and Wait Automatic Repeat reQuest (S&W-ARQ*, or simply *S&W)* protocol (Xie and Gibson, 2001), because it does not explicitly require an FEC code. Error control is predominantly implemented by way of retransmissions, even if it would induce severe delay penalties on the acoustic systems. It represents a good compromise between performance and reliability, and thus we propose in our work its performance analysis.

2.2.1 S&W-Arq Protocol

In the S&W protocol, the transmitter sends a packet and waits for the acknowledgment (ACK). If the ACK does not arrive in a pre-specified amount of time, called the time-out, or a negative acknowledgment arrives, the packet is retransmitted. When the ACK arrives, the transmitter moves on to a new packet. Generally, the efficiency of an S&W protocol is measured by the time spent in waiting, and it can be improved if the idle interval between packet transmissions is used to transmit new packets, or by transmitting blocks of packets, rather than a single packet. More deeply, the sender transmits a group of m packets and waits for the acknowledgement. To evaluate the efficiency of S&W$_m$ (i.e. with blocks transmission of m packets), let assume that each packet consists of a total of $N = N_d + N_{oh}$ bits, where N_d is the number of data bits, and N_{oh} represents the packet overhead. Thus, the packet duration is $T_p = NT$, where $T = 1/R$ is the bit (symbol) duration and R is the bit (symbol) rate. Each group of packets (or each packet if transmitted alone) could be proceeded by a synchronization preamble of duration T_{sync}.

The communication link introduces a propagation delay $T_d = l/c$, where l is the distance between transmitter and receiver, and c is the nominal speed (i.e., for the acoustic channel is the sound speed $c=1500$ *m/s*). Thus, the total time needed for transmission of a group of m packets and reception of the corresponding group of acknowledgments is:

$$T(m) = m(T_p + T_{ack}) + T_w \tag{3}$$

where $T_w = 2(T_{sync}+T_d)$, is the total waiting time, and the duration of an acknowledgment is usually negligible with respect to the packet duration, $T_{ack} << T_p$.

For best efficiency, the time-out of an S&W$_m$ protocol should be equal to the round-trip time $T(m)$.

Hence, the Throughput Efficiency, η, of the S&W$_m$ is defined as the ratio of the packet data duration and the average time, T_m, needed to transmit m packets successfully.

$$\eta = \frac{m \cdot N_d T}{T_m} \tag{4}$$

If p is the Packet Error Probability, the average time needed to transmit *one* packet successfully is given by $T_1=T(1)/(1-p)$, (for the S&W$_1$ scheme), and T_m can be seen as the sum of m average times needed to successfully transmit *one* packet on one of m links, and thus $T_m = T(m)/(1-p)$, because m links operate in parallel. In other words, S&W$_m$ can be regarded as m S&W$_1$ protocols operating in parallel, where each S&W$_1$ has a time-out equal to $T(m)$ (Stojanovic, 2005). Hence, the resulting Throughput Efficiency is:

$$\eta = (1-p) \cdot \frac{m \cdot N_d T}{T(m)} \tag{5}$$

The Packet Error Probability is given in terms of the bit (symbol) error probability P_e as:

$$p = 1 - (1 - P_e)^N \tag{6}$$

By increasing the packet size, better utilization of the waiting time is achieved, but the chances of having a bit error in a packet are increased. Hence, there is an optimal packet size for which the Throughput Efficiency is maximized.

The efficiency, η, can be finally expressed according to the following manipulation:

$$\eta = (1-P_e)^{N_d+N_{oh}} \cdot \frac{N_d}{N_d+N_{oh}+\frac{R}{m}\left(2T_{sync}+2\frac{l}{c}\right)} \tag{7}$$

Hence, η depends on parameters such as packet size, link delay, and packet error rate in such a way that there exists an optimal packet size for which the efficiency is maximized.

2.2.2 MAC Protocol: Random Access Solution

Simple protocols based on random access, such as Aloha schemes, are considered in our analysis. They are widely studied in underwater network environment (Vieira et al., 2006), and by introducing a suitable guard time is possible to reach good performance (Chirdchoo et al., 2007) when low traffic is assumed, as in the monitoring applications considered in our test cases. The effect of other MAC schemes will be argument of future works:

Pure Aloha: we evaluate the collision probability P_c, assuming that the traffic rate of each node is λ and follows a Poisson process and thus:

$$P_c = 1 - e^{-2G} = 1 - e^{n\lambda(T_{sync}+T_P)} \tag{8}$$

where *n* is the number of node that could send packet at the same time.

Slotted Aloha: packets can be transmitted at the beginning of each slot. To obtain a collision probability as low as possible, the time slot may be greater than the propagation delay time T_d and a time guard needs to be taken into account:

$$T_s = T_P + T_{sync} + T_d + T_{guard} \tag{9}$$

Note that T_s is the expected service time per packet, and thus system utilization factor ρ can be obtained as $\rho=\lambda T_s$.

Furthermore, according to (Lipsky, 2008), the probability P_{ne} that a node's queue is not empty is $P_{ne} = min\{\rho ,1\}$.

In addition to P_{ne}, packet collision is also related to network topology due to spatial-temporal difference. However, according to our analysis, we consider T_d the time to reach next hop, and thus we can ignore the impact of network topology for the evaluation of the collision probability. The effect of the network topology will be considered in the performance evaluation at network level, as reported in the next section by considering their effect in the latency evaluation. Hence, a packet can be correctly received if only one packet is transmitted in a slot without collision. Based on this observation, the corresponding probability P_{succ} is:

$$P_{succ} = \binom{n}{1} P_{ne}(1-P_{ne})^{n-1} \tag{10}$$

If more than one packet is sent during the same slot, there would be a collision. Thus, excluding P_{succ} and the probability that no packet is sent in one slot from (2), the collision probability P_c can be expressed a follows (Zhu et al., 2013)

$$P_c = 1 - P_{succ} - (1-P_{ne})^n \tag{11}$$

where *n* is the sender neighbours.

2.3 Network Layer Challenges

To design a reasonable swarm two opposite constraints need to be taken into account: energy consumption and latency constraint. The first one is taken into account by considering appropriate solutions adopted at transmission level for both technologies; the second one by considering a multi-hop paradigm at network level to forward data from source to destination.

We investigate the Data Link Layer effects over the performance system in terms of retransmission packets and collision probability effects maximum tolerable, and how they can influence the network layer, by evaluating the different constraints of both technologies: the typical long propagation delay of acoustic communications on the side; the strong dependence of the water conditions and the short distance allowable of optical communications to the other side. This study is carried out in order to individuate a suitable trade-off between reliability and Quality of Service for different underwater applications.

In particular, the network performance can be evaluated by the End-to-End Frame Error Probability (FEP) (Stefanov and Stojanovic, 2011) where we introduce the effect of the MAC and we derive the following model in which we take into account collisions at the routing level, assuming that P_e, the bit error probability, and P_c , the collision probability, for a single node-to-node link are independent events:

$$FEP = 1 - \left((1-P_e)(1-P_c)\right)^{Nn_h} \tag{12}$$

where *N* is the frame size in bits, and n_h is the number of hops needed to forward data within the swarm. Obviously, we have different P_e for the two different propagation channels.

3 PERFORMANCE EVALUATION

For our analysis, we have simulated a Swarm Underwater Network composed by $N_{AUV} = 10$ AUVs, with a $r_{phy} = 3\ m$ and a coverage radius of each node of $r_{cov}=80\ m\ (20\ m)$ for the acoustic (optical) case. It means that two adjacent nodes may be at a distance no less than r_{phy}. We remind that, a swarm is characterized by a more complex communication protocol than a peer-to-peer paradigm often applied to AUV devices, and thus the performance of the network will be strictly related to the solutions taken into account at each design level. Hence, our evaluations want to be a starting point in the AUV communication module design, by considering a restricted number of nodes compounding the swarm and by investigating how different assumptions at different layers could impair the whole performance of the system. In particular, for network performance evaluation, it is important to take into account the effect of the swarm configuration, and thus we consider two exemplary situations: *Pipeline*, and *Dense Swarm* cases. The system parameters considered for the different propagation technologies are:

Acoustic Channel – The 16-FSK is considered with an $E_b/N_0=40$ *dB* to reach $P_e=10^{-4}$, according to the working parameters of the specific acoustic system, that is based on a Reson TC4034 transducer with operation frequency of 300 kHz (Tabacchiera et al., 2012). The bit error probability is assumed $P_e=10^{-4}$ in every water condition, because the acoustic channel is water turbidity independent. For this case, we have assumed different data rates as *1 kbit/s*, *10 kbit/s*, and *50 kbit/s*, because different performance could be experimented for different data rates. More deeply, the increase of the bit-rate leads to a decrease of the network performance due to the slow propagation characteristics of the acoustic channel in the underwater environment.

Optical Channel – For the optical case, the OOK modulation is considered with a transmitted power of *500 mW*. Three different water conditions, Clear Ocean, (k=0.0037), Coastal Ocean (K=0.22), and Turbid Harbour (K=0.8) are considered and the corresponding SNR values are evaluated according to (Giles, 2005). For the optical technology, there are not significant performance variations for different data rates, and thus we consider a typical data rate of *1 Mbit/s*. The bit error probability is assumed different for different water conditions, because optical propagation is strictly dependent on the water turbidity, and thus $P_e=10^{-6}$ for the Clear Ocean water, $P_e=10^{-4}$ for the Coastal Ocean water, $P_e=10^{-2}$ for the Turbid Harbpur brown water, respectively.

3.1 S&W Analysis

Throughput Efficiency, η, as a function of packet size has been investigated for the different types of scenario. Different maximum distances among the nodes of the swarm have been considered, *10 m,* and *200 m*. We remind that, for such a type of scenario the distances are very short, with high bit rates compared to the typical underwater network scenario. The parameters of the system are selected as $N_{oh}=8$, $T_{sync} = 16\ T$, and $m=16$. Obviously, at any distance considered for the analysis, the maximum η reachable for the optimum packet size has been investigated. By simulations we found that for the acoustic technology it is possible to delineate a region of packet sizes in which good performances are reachable (Figure 1), which is less than *500 bits*. As the packets dimension increases, the performance decreases, especially when long distances are considered (Figure 2) and high bit rate is assumed. On the contrary, optical technology is able to reach good performance regardless the maximum distance and the data rates considered when the swarm operates in clear water condition. When the turbidity of the water increases, the optical technology performances drastically decay up to communication drop. It suggests that the acoustic technology is not able to reach high data rates and thus is not able to send complex data in real-time, but at the same time is able to maintain communication among the swarm regardless water condition and thus suitable when optical communication is not applicable (i.e, brown water closest port region).

3.2 MAC & Network Analysis

Two different versions of the Aloha protocol have been considered and two different swarm configurations have been investigated for the MAC and Network analysis, respectively. In particular, we analysed MAC performance by Collision Probability evaluation versus different traffic loads, and Network performance by Frame Error Probability evaluation vs different packets dimension. For our analysis, we have assumed that different configurations correspond to different numbers of hops needed to forward information from nodes to the collecting node, i.e.: Pipeline: $n_h= N_{AUV}-1$; and Dense Swarm $n_h<N_{AUV}/2$.

Collision Probability - The collision probability, P_c, has been evaluated by varying the traffic load and by considering two exemplary packet dimensions that are, according to the S&W analysis, (especially for the acoustic case) less than *250bits*, and thus $Pk_1=100$ *bits* and $Pk_2=200$ *bits*. By the analysis, we have found that:

P_c Pure Aloha: traffic load no more than $\lambda=0.06$ *pkt/s* seems to be more appropriate for this type of network for the acoustic case, where the higher data rate and the lower packet dimension permit to reach suitable P_c levels (Figure 3). Also in this analysis clear water permits to reach better performance with the optical technology, while brown water experiments comparable performance with acoustic $R = 50$ *kbit/s* case (Figure 4). We remind that the effect of the water conditions in the optical case leads to communication impairments among distant nodes avoiding the participation of them to the medium access contention, and thus it appears as a

P_c reduction when low traffic loads are considered. This attitude is taken into account in the P_c equation (8) through n, the number of neighbour nodes that want to access to the communication channels and improve collision. Future works will consider a P_c model where the turbidity of water will be explicitly indicated.

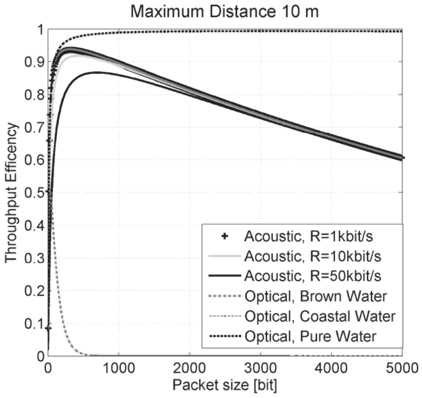

Figure 1: η of S&W vs packet size N_d for acoustic (different data rates) and optical (different water) technologies: at the maximum distance of *10 m*.

P_c Slotted Aloha: The collision probability has been evaluated in the same condition of the Pure Aloha by considering the Slotted scheme according to equation (11) and, as expected, performance improvement has been found for both technologies (Figures 5 and 6).

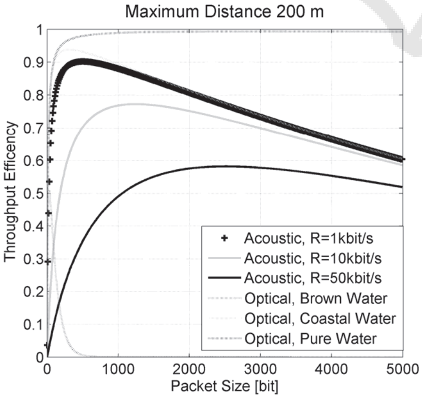

Figure 2: η of S&W vs packet size N_d for acoustic (different data rates) and optical (different water) technologies :at the maximum distance of *200 m*.

Frame Error Probability – The FEP evaluations have been performed for the two exemplary configuration cases, by varying the packets dimensions for two different traffic loads, $\lambda=0.02$ *pkt/s* (low traffic) and $\lambda=0.2$ *pkt/s* (high traffic) and different data rates, R. System simulations have been carried out for both Aloha schemes, Pure and Slotted. As expected, the trends are the same, but improvements are experimented for all cases under test in Slotted solution. For this reason, only Slotted Aloha evaluations are reported in this section. We found that:

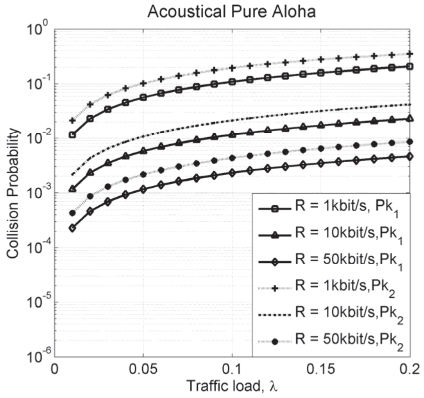

Figure 3: Collision Probability of Acoustic pure ALOHA with different traffic load λ and packet data dimensions.

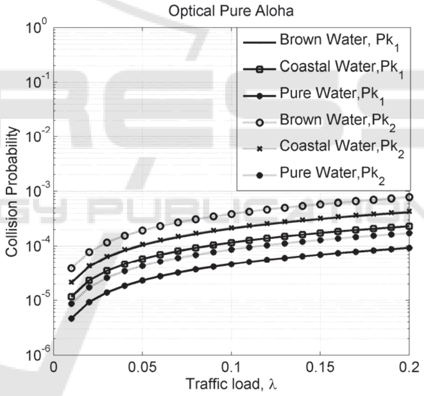

Figure 4: Collision Probability of Optical pure ALOHA with different traffic load λ. and packet data dimensions.

Pipeline Configuration - For the *Pipeline case* (Figure 7), where all nodes are involved in the forwarding scheme, we found that, with low traffic load, and low packets dimension (< *200 bits*), it is possible to reach suitable system performance level for the acoustic case ($FEP_{Acoustic} \approx 10^{-2}$), even if the optical technology shows better performance ($FEP_{Optic} \approx 10^{-3}$) when clear water condition is assumed regardless traffic load assumption (Figure 8). On the other hand, when brown water is assumed, the acoustic technology seems to respond better than the optical one ($FEP_{Optic} \approx 10^{-1}$). This attitude is more remarkable when low traffic, and very low packet size (< 1*00 bits*) is adopted.

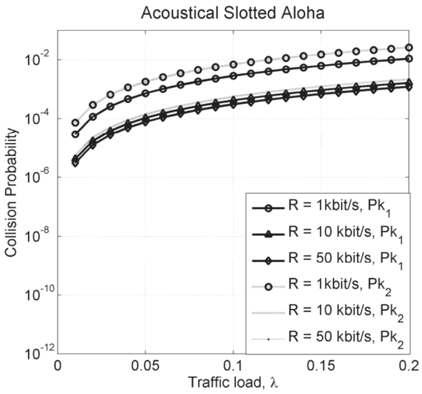

Figure 5: Collision Probability of Acoustic Slotted ALOHA with different traffic load *λ*. and packet data dimensions.

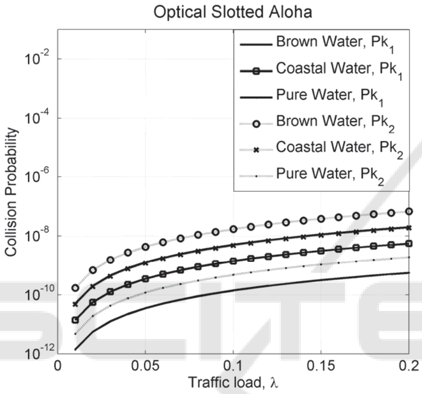

Figure 6: Collision Probability of Optical Slotted ALOHA with different traffic load *λ*. and packet data dimensions.

Dense Swarm Configuration - For the *Dense Swarm* case, we consider that only one hop is needed to reach source to destination. As expected in this case, the *FEP* is improved because the collision probability is reduced with respect to the *Pipeline* case. This trend becomes more evident with the optical technology thanks to the better performance of the optical channel ($FEP_{Optic} \approx 10^{-4}$) especially in clear water (Figures 9 and 10). Even in this case, in the brown water condition the enhancements of the acoustic technology ($FEP_{Acoustic} \approx 10^{-3}$) with respect to the optical one ($FEP_{Optic} \approx 10^{-1}$) become more evident when low traffic and low data rate are considered.

These evaluations suggest that, in the *Pipeline* case, acoustic technology experiments no more high performance, but it reaches a suitable level of affordability in every water condition; in *Dense Swarm* case, due to the reduced distance of the nodes, the optical technology overcomes the acoustic performance maintaining the minimum affordability threshold needed regardless water conditions. Finally, the performance investigated at Network Layer level, confirmed the results at Data Link Layer level: the optimum packet dimension appears no more than *200 bits* for every traffic load considered.

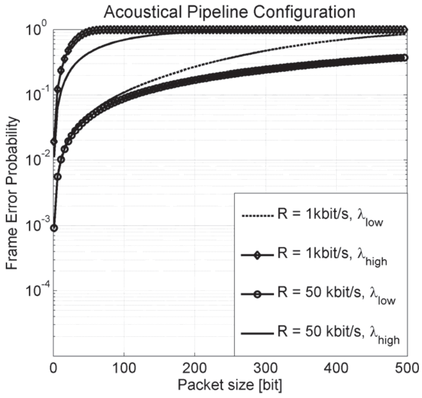

Figure 7: FEP versus packet size with acoustic channel and Slotted Aloha MAC (Pipeline Configuration).

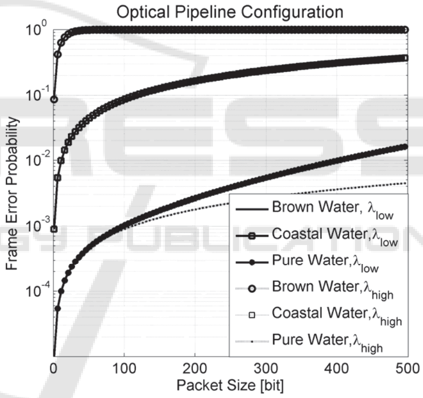

Figure 8: FEP versus packet size with optical channel and Slotted Aloha MAC (Pipeline).

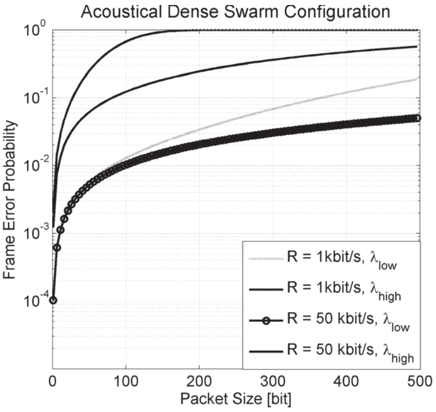

Figure 9: FEP versus packet size with Acoustic channel and Slotted Aloha MAC (Dense Swarm).

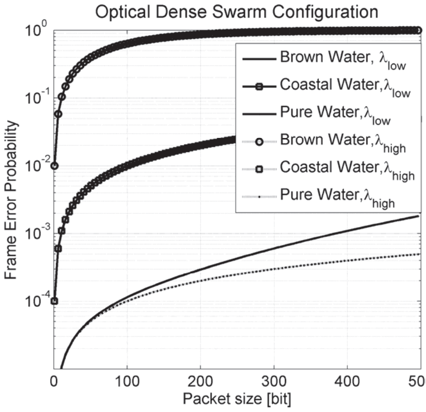

Figure 10: FEP versus packet size with Optical channel and Slotted Aloha MAC (Dense Swarm).

4 CONCLUSIONS

A hybrid Underwater Swarm based on both acoustic and optical technology has been investigated, taking special attention for lower layers protocols able to save energy, avoiding collisions and maximizing the throughput. For this scope, an improved S&W model, based on transmitting groups of packets for which selective acknowledgments are generated, has been investigated. Throughput Efficiency of these types of protocols can be maximized by selecting an optimal packet size as a function of the acoustic link and optic link parameters. In addition, network choices based on multi-hop solutions are investigated by taking into account MAC constraints in the network performance evaluation by considering two different schemes: the Pure and Slotted Aloha. Performance have been evaluated for different swarm configurations, and results have been investigated in terms of packet dimension and maximum traffic tolerable. The obtained results show that a packet size no more than *200 bits* permits to guarantee suitable system network performance at both Data Link layer and Network layer, for low traffic loads.

Actually, to fully utilize the limited resources of an acoustic channel and to respond in efficient manner to the optical water condition dependence, further improvements of the protocol layer should be taken into account by evaluating further MAC schemes. In addition, future works will also consider the scalability effect into network performance evaluation by drastically increasing the number of nodes in order to suggest useful indications for real AUVs communication module implementation.

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