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A Balanced Energy Consumption Routing Using Channel Realization In Under Water Acoustic Sensor Networks

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Abstract: *Interest in Under Water Acoustic Sensor Networks (UW-ASNs) has rapidly increased with the desire to control the large fundamental differences in order to conceive a balanced routing strategy that overcomes the energy holes problem. Indeed, energy management is one of the major concerns in UW-ASNs due to the limited energy budget of the underwater sensor nodes. In this paper, we tackle the problem of energy holes in UW-ASNs while taking into consideration the unique characteristics of the underwater channel. The main contribution of this study is an in-depth analysis of the impact of these unique underwater characteristics on balancing the energy consumption among all underwater sensors. We prove that we can evenly distribute the transmission load among sensor nodes provided that sensors adjust their communication power when they send or forward the periodically generated data. In particular, we propose a balanced routing strategy along with the associated deployment pattern that meticulously determines the load weight for each possible next hop,that leads to fair energy consumption among all underwater sensors. Consequently, the energy holes problem is overcome and hence the network lifetime is improved.*

Indexterms: *UnderWater Acoustic Sensor Networks, routing,load management, energy management, performance analysis***.**

I. Introduction

AS an emerging area, underwater sensor network has attracted rapidly growing interest in the last several years. On the one hand, underwater sensor networks enable a wide range of aquatic applications, such as oceanographic data collection, pollution monitoring, offshore exploration, and tactical surveillance applications. On the other hand, the adverse underwater environments pose grand challenges for efficient communication and networking. In underwater environments, radio does not work well due to its quick attenuation in water. Thus, acoustic channels are usually employed. The propagation speed of acoustic signals in water is about m/s, which is five orders of magnitude lower than the radio propagation speed m/s . Moreover, underwater acoustic channels are affected by many factors such as path loss, noise, multipath fading, and Doppler spread. All these cause high error probability in acoustic channels.

In short, underwater acoustic channels feature long propagation delay and high error probability. In such harsh network scenarios, it is very challenging to provide energy-efficient reliable data transfer for time-critical applications (such as pollution monitoring and submarine detection). First, conventional retransmission-upon-failure approaches are hard to satisfy the delay requirements. To give a simple example, if two nodes are separated by 500 m, the propagation delay between them will roughly be s. Even one time retransmission upon failure will additionally introduce a delay of at least,1 which is quite large for some time-criticalapplications. Thus, to meet certain delay requirements, less or no retransmissions are preferred.

THE growing interest in the design of underwater networks is motivated by the wish to provide autonomous support for many activities such as offshore exploration, tsunami warning, and mine reconnaissance. Consequently, UnderWater Acoustic Sensor Networks (UW-ASNs) are gaining a remarkable momentum within the research community. Acoustic communication is deemed to be the enabling technology for underwater networks. Indeed, radio technology is unsuitable for underwater environments due to its poor propagation through water. Optical waves require the transmitter and receiver to be aligned in order to form a link and tend to be effective at very short range compared to the desired communication distances. Consequently, acoustic modems are the current technology of choice for underwater communications. Conceiving network protocols especially tailored for underwater acoustic networks faces serious challenges. Indeed, underwater channel imposes unique and harsh characteristics such as the high-attenuation, bandwidth-limited underwateracoustic channel and limited battery power. In fact, batteries of underwater sensors are not only limited in terms of budget but most importantly cannot be easily recharged, since for instance solar energy cannot be exploited. Moreover, acoustic underwater communications consume a larger amount of power compared to the terrestrial radio ones. Indeed, underwater communication is subject to transmission over higher distances and more complex signal processing techniques are required at receivers to compensate the impairments of the underwater channel. Due to the aforementioned reasons, UW-ASNs require protocols that make judicious use of the limited energy capacity of the underwater sensor nodes. To this end, one of the major characteristics of UW-ASNs that should be appropriately exploited in order to enhance the network management in terms of energy expenditure and transmission delay is their manual deployment. Underwater sensors are manually bottom anchored meaning that a prior knowledge of their locations can be acquired at deployment time. As such, we can take advantage of this feature in order to achieve a dedicated well studied deployment that satisfies our application requirements especially in terms of energy conservation. Once the target deployment is achieved, another crucial way that can be exploited to extend the lifespan of an UWASN is load management. The goal is that all the sensors consume their energy budget as smoothly and uniformly as possible. In terrestrial wireless sensor networks, it was shown that the closest sensors to the sink tend to deplete their provided amount of energy faster than other sensors [14]- [17]. This unbalanced energy consumption is liable to drastically reduce the lifetime of sensor networks; that is why it should be avoided to the largest possible extent. In fact, authors in [17] showed that by the time the nearest sensors to the sink drain their initially provided energy, sensors more distant still have up to 93% of their energy budget. Indeed, sensors in the vicinity of a static sink act as the traffic hot spots since they have significant packet load to relay. Those sensors which are 1-hop away from a static sink would suffer from a severe exhaustion of their battery power, which may cause energy holes resulting in possible network disconnection andconsequently preventing reports from reaching the sink.

In this paper, a balanced routing design for avoiding energy holes in UW-ASNs is proposed and thoroughly evaluated. Our ultimate aim is to balance the energy consumption among all underwater sensors which are manually deployed according to a defined deployment pattern such that network management is facilitated. Our balanced routing solution dictates that each underwater sensor can tune its transmission power among multiple possible levels. Each transmission power allows the sensor to reach possibly a specified next hop. We strive for deriving the optimal load weight for each possible power level that leads to fair energy consumption among all sensors in the network and hence the sink-hole problem is overcome.

Our proposed routing scheme is especially tailored for the underwater environment. Indeed, our routing solution takes into consideration the unique characteristics of the underwater channel through the use of the time-varying channel gain derived in [6].Our contributions can be summarized as follows. First, we propose a designed deployment pattern for UW-ASNs aimed at balancing the energy consumption and hence an improved overall energy management. Second, based on the proposed deployment, we prove that we can evenly distribute the transmission load among underwater sensors with constant data reporting provided that sensors adjust their transmission powers when they send or forward sensed data. In particular, we assume that each sensor can dynamically adjust its transmission power up to a predefined number of levels n. Consequently, at the routing layer, for each value of n, we determine the set of possible next hops with the associated load weight that lead to fair energy depletion among all sensors in the network. Third, we derive the optimal number of transmission power levels, n, that maximizes the network lifetime by overcoming the energy holes problem. In fact, there clearly exists a compromise between the number of transmission power levels (n) and the energy consumption [19], [21]. On one hand, as we increase n, we allow the traffic load to be much more distributed among all the upstream coronas and hence a balanced traffic load distribution is achieved resulting in a balanced energy consumption throughout the network. On the other hand, increasing n raises the energy consumption since the farthest coronas may be reached. Consequently, there clearly exists an optimal n value for which the network lifetime is maximized. Finally, we prove that our balanced routing design outperforms the nominal communication range based data forwarding [24] in terms of energy conservation and hence the network lifetime. Recall that our proposed routing

Solution is especially designed for the underwater environment since it takes into account the fundamental characteristics of the underwater acoustic propagation. That being said, it is worth pointing out that our proposed routing protocol is more suitable for collision-free MAC protocols like [4], [5].

This paper is organized as follows. Section II presents the state of the art related to the focus of this paper. Section III presents the system model to be studied. Section IV formulates and analytically solves the energy balancing problem. Specifically, we solve a linear optimization problem that leads to, an even energy depletion among all sensors. The results are provided in Section V, where we compare the performance of our proposal to the nominal transmission range based data forwarding scheme. This paper concludes with a summary of our conclusions and contributions.

II. Related Work

Geographical routing protocols seem appropriate for the underwater environment, where manually anchored nodes have knowledge of their coordinates at deployment time, and mobile nodes (such as AUVs) have local navigation systems. Several geographical routing protocols, especially devised for underwater channel have been proposed. In [19], the design of minimum energy routing protocols especially designed for the underwater environment is evaluated. The authors in [19] prove that, depending on the modem performance, in dense networks there is an optimal number of hops beyond which the system performance, especially in terms of energy consumption, does not improve. In [20], two distributed routing strategies are proposed for delay-insensitive and delay-sensitive applications. In [21], a new geographical routing strategy for underwater acoustic networks is introduced and joined with power control. The main contribution of this routing scheme called FBR is to dynamically establish routes on demand without damaging the network performance. In [22], the authors were mainly interested in providing a reliable routing solution especially dedicated for time-critical applications in underwater acoustic networks. To this end, they proposed a multipath routing scheme based on continuous power control aimed at minimizing the energy consumption without compromising the end-to-end delay. While providing a major improvement in terms of data reliability and error recovery, crucial issues such as energy consumption during reception of a packet were not taken into account in this analysis.

In [23], a mathematical framework for cross-layer optimization is stated along with an associated protocol. Based on the unique properties of the underwater environment, the proposed solution provides a joint optimization among different layers. In particular, the proposed strategy allow each underwater node to jointly select its best next relay, the optimal transmission power and the error correction technique that minimize energy consumption. However, the lack of an acoustic transceiver able to dynamically adapt its parameters to instantaneously fit the link conditions limits the applicability of this approach in practice.

In [25], the authors proposed a thorough analytical model for multipath propagation that evenly distributes the energy consumption among all sensors. Indeed, they show that sending the traffic generated by each sensor node through multiple paths instead of a single best path allows performance improvement especially in terms of energy consumption. Accordingly, they derive the set of paths to be used by each sensor node and the associated proportion of utilization that minimize the energy consumption.

In [28], event-driven applications in a non-uniform sensor distribution were considered. The authors proposed a blind algorithm that overcomes the energy-balancing problem without a prior knowledge of the occurrences of the events. In [29], authors proved that minimizing the total amount of energy along a path is only achieved when the coronas of a circular field have the same width. Unfortunately, such configuration would inevitably lead to uneven energy depletion among sensors. Consequently, they computed the optimal widths of coronas and their optimal number in order to achieve fair energy depletion of sensors.

In [30], authors revealed that up to 90% of the initially provided energy budget is unused especially in static WSN model where the sensors are uniformly distributed. For this reason, they proposed a non-uniform sensor distribution strategy and showed by simulation that it can increase the total amount of sensed data.

In [26] a protocol, called Variable Transmission Range Protocol (VTRP) was proposed with the aim to overcome the energy holes problem by varying the transmission power. Indeed, VTRP proposes to dynamically adapt the transmission range such that the closest sensors to the sink are bypassed and hence the network lifetime is increased. While VTRP assumes that the sink is static.

In [24] the proposed protocol considers sink mobility and energy heterogeneity among sensor nodes in order to overcome the sink-hole problem. Different from the contributions described in this section, in this paper, we present a routing solution dedicated for a specific underwater acoustic network deployment, which overcomes the energy holes problem by achieving a fair load distribution, balanced energy consumption, and better overall network management.

III. Model And Problem Definition

A. Time-varying underwater channel

1) The channel gain: In [6], an exhaustive mathematical analysis was conducted to describe the time-varying channel gain in underwater environment by taking into account most of the physical features of acoustic propagation such as frequency-dependent attenuation, the bottom surface reflections as well as the effects of inevitable random local displacements and its induced Doppler effect. The proposed analytical model was validated using experimental data and hence an underwater acoustic simulator was developed [7] to provide the instantaneous channel gain between a transmitter and a receiver, given their nominal coordinates and their displacement ranges. According to [6], underwater channel variations can be classified according to the size of the random displacement undergone by underwater sensors. Indeed, due to many phenomena (water current, transmitter/receiver drifting, surface waves...) underwater sensors may undergo displacement on the order of a few or many wavelengths. The former is referred to as small-scale variations and the latter as large-scale variations. Small-scale variations occur over short displacements and correspondingly short period of time during which the system geometry (especially in terms of nodes' locations) and environmental conditions do not go through remarkable change and hence are rather considered static. However, large-scale modeling takes into account variations caused by location shifting as well as varying environmental conditions. In other words, large-scale variations are modeled as a consequence of random system displacements spanning a given variation range leading thus to large-scale variation in the gains and delays of propagation paths. More precisely, in [6], transmitter/receiver within a nominal channel geometry have multiple propagation paths with different lengths and different angles of arrival. Large-scale variations cause each propagation path length to deviate randomly and considerably from the nominal. In addition to that, small-scale variations cause every propagation path to be further scattered into a number of micro-paths. Hence, small-scale variations influence the instantaneous channel response, and, consequently, the instantaneous signal-to-noise ratio (SNR).

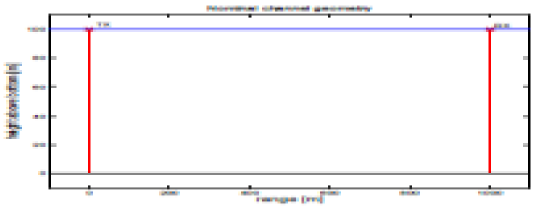

Fig.1. Nominal Channel Geometry: distance between the transmitter andreceiver

Therefore, small-scalechannel variations are to be considered during a few consecutive packet transmissions. In contrast, large-scale variations impact the average SNR over longer periods of time. That’s why, they are mostly significant for the study of top-level system functions such as power allocation. Accordingly, the authors define the instantaneous channel gain for a particular realization of the large-scale displacement and a particular realization of the small-scale variation for a system operating in the frequency range [fmin, fmin + B] as

$$\tilde{G}(t) = \frac{1}{B} \int_{f_{\min}}^{f_{\min}+B} |H(f,t)|^2 \, df \qquad (1)$$

$$G = E\{\tilde{G}(t)\} \qquad (2)$$

where H (f, t) represents the time-varying channel transfer function that was derived in [6]. Note that, in our work, we use the averaged instantaneous gain G to compute the needed transmission power to communicate a data packet between a pair of nodes in the network. While we rather use the instantaneous channel gain ˜G (t) to determine if a data packet was successfully received by the intended receiver. More details are provided in the next section. For illustration purposes, we focus on an acoustic channel example whose parameters are depicted in Fig. 1.

2) Power Allocation: In a time-varying channel, the power allocation can be either adaptive or invariant. In the latter case, where no power control mechanism is applied a fixed large margin is to be introduced to ensure that the SNR remains above a given threshold SNR0, regardless of the channel conditions. However, for energy efficiency reasons, the transmit power consumption can be minimized if the transmitter has at its disposal some knowledge of the channel gain as stated in [9]. Ideally, if the exact fading gain G is known, the transmit power ˆ PT can be rigorously tuned accordingly such that the SNR is kept at the value SNR0. In this ideal case, and as introduced in [9], ˆ PT can be simply adjusted to

$$\hat{P}_T = P_{T0}\tilde{G}/G \qquad (3)$$

$$P_{T0} = P_N \times SNR_0/\bar{G} \qquad (4)$$

where PN is the noise power over B. Note that, in such ideal case, adopting such value for ˆ PT will always guarantee the successful reception of a data packet. However, as explained in [9], deriving ˆ PT using G can be challenging as the channel cannot be fully known beforehand. Rather, an estimate ˆG is to be used in place of the true actual gain G. In this case, a margin K has to be introduced to guarantee to some extent that the gap between the estimated and the true channel gain does not lead to an outage. The transmit power is then adjusted according to

$$\hat{P}_T = K P_{T0}\bar{G}/\hat{G}. \qquad (5)$$

In our work, we suggest to consider ˆG such that the probability that, the actual exact fading gain G is less than ˆG, falls behind a given reliability level, Rper. Rper is to be decided by the network manager depending on the application requirements. In other words, we set ˆG such that

$$P(G < \hat{G}) \leq R_{per} \qquad (6)$$

It is worth noting that, in order to conceive a power allocation scheme, we rather consider G than ˆG (t). Indeed, as previously explained, since large-scale variations influence the average SNR over longer periods of time, it is rather more meaningful to consider the large-scale gain G to conceive a power allocation scheme. However, the instantaneous channel gain ˆG (t) is more convenient for deriving the instantaneous signal-to-noise ratio (SNR) and hence to determine if a packet was successfully received or has encountered a failure.

$$\tilde{P}_R(t)_{(i,j)} = \hat{P}_{T(i,j)}\tilde{G}(t)_{(i,j)} \qquad (7)$$

Note that, the average received signal power during the reception period of time will help us decide if a data packet was successfully received, as explained in the next section.

3) Probability of successful packet reception: In our work, in order to further take into account the time-variability of the underwater acoustic channel, we introduce a success probability Pi j over a link (i, j) which represents the probability of a successful reception by a node j for a transmission initiated by i using a transmission power ˆ PT (i,j) over a bandwidth B. In fact, a packet reception is considered successful by sensor j for a communication initiated by i during the time period [t1, t2] if and only if

$$\frac{1}{t_2 - t_1}\int_{t_1+D_{ij}}^{t_2+D_{ij}} \frac{\tilde{P}_R(t)_{(i,j)}}{P_N} dt \geq SNR_0 \qquad (8)$$

the total energy consumption will be affected. Given that our objective is to balance the energy consumption throughout the network, Pi j along with ˆ PT (i,j) will inevitably impact the load weights for every node in the network as detailed in section V.

B. Energy Sink-hole problem

In this paper, we investigate the energy sink-hole problem in underwater acoustic sensor networks, where ed always-on WSNs where the sensors periodically report their sensed data to a static sink using their nominal communication range [27]- [31]. For this reason, most of the already undertaken research on balancing the energy consumption is mainly on using adjustable transmission power. Indeed, by allowing each sensor to dynamically adjust its transmission power, the aim is to achieve a fair load distribution among sensors and thus the closest sensors to the sink are relieved from the relying task. Our study of the energy sink-hole problem in UW-ASNs is motivated by the manual static deployment of underwater sensors in real-world applications, and hence, efficient solutions should be provided to tackle this problem. Our goal is to balance the energy depletion of all sensors in terms of traffic forwarding (number of transmitted packets) in order to extend the network lifetime. To this end, our approach for tackling the energy sink-hole problem is twofold:

i) analyzing to what extent can perfect uniform energy depletion among all sensors in the network be assured such that the energy sink-hole problem in UW-ASNs is overcome and

ii) studying how can the energy sink-hole problem in manually deployed UW-ASNs be addressed. By thoroughly investigating these two issues, we aim at closely approaching the perfect uniform energy depletion among all underwater sensors in the network.

To address the first issue, we conceive a data forwarding strategy for transmitting the periodically generated data from underwater source sensors to the sink. The goal of this forwarding scheme is to appropriately distribute the total data dissemination load on the individual underwater sensors such that the energy depletion is balanced among all sensors in the network. To address the second issue, the set of the 1 hop away neighbors of the sink should change over time, thus allowing different subsets of sensors to act as forwarders to the sink. In other words by varying the transmission power of manually deployed sensors, the number of hops to reach the sink is continuously varying. For instance, suppose that a sensor U is 2r away from the sink S. If the underwater sensor U uses a transmission power to reach r then U is 2 hops away from S.

However, if U adopts a transmission power to reach 2r then U is 1-hop away from S. Consequently, we suggest that U sends a fraction of its total load using a transmission power to reach r and the remaining portion will be directly sent to the sink using the appropriate transmission power for 2r. To summarize, in our work, each sensor is responsible for deriving the appropriate load weight with the associated transmission power, namely potential next hop, that evenly distribute the energy consumption among underwater sensors. Moreover, we tackle the energy sink-hole problem by considering a static underwater sensor deployment strategy where underwater sensors are manually placed in a circular sensor field centered at one static sink.

C. Network and Energy model

The proposed deployment strategy considers a 2- dimensional shallow underwater sensor network. A set of sensors is anchored to the ocean bottom and endowed with a quite long rope along with a floating buoy to push the sensor towards the surface. Indeed, the buoy can be inflated by a pump in order to push the sensor towards the ocean surface. Note that in this work, we assume that the sensors will be all the time attached to their anchors through the cable which will severely restrict their displacement. Consequently, in such scenario, these surface sensors that are bottom anchored have a complete knowledge of their geographical position at deployment time. It is worth pointing out that our proposed deployment architecture targets especially shallow water which makes the deployment cost reasonable.

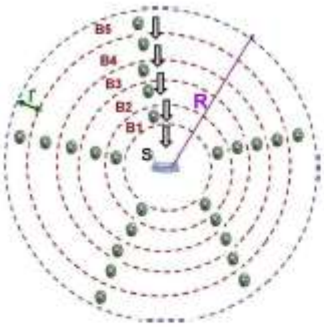

Fig. 2. Underwater Acoustic sensor network model.

In order to approach the uniform energy depletion, sensors are placed in a circular sensor field of radius R centered at the sink. The sensor field is virtually partitioned into disjoint concentric sets termed coronas of constant width r. The width of each corona is at most dtx−max, the maximum transmission range of an underwater acoustic sensor. Consider K to be the number of coronas around the sink.

$$K = \lfloor \frac{R}{r} \rfloor \qquad (9)$$

In the remainder of this paper, we consider a continuous reporting sensor application where the average number of reports generated per unit of time by each sensor node is denoted by A. Moreover, we assume that the energy consumption of sensors is due to data reception and transmission. In fact, since in underwater environment, the deployment is generally quite sparse, the energy depletion due to overhearing can be neglected. More precisely, the energy spent in transmitting one packet of length Pl bits over a distance d between two nodes i and j is given by

$$E_{tx}(d) = \hat{P}_{T(i,j)} \times \hat{T}_{tx(i,j)} \qquad (10)$$

$$\hat{T}_{tx(i,j)} = \frac{P_l}{\hat{C}(d)_{(i,j)}} \qquad (11)$$

we keep the dependance on (d) for the capacity in order to emphasize that the link capacity depends on distance through the SNR.

$$\hat{C}(d)_{(i,j)} = B \times \log_2 \left(1 + \frac{\hat{P}_{T(i,j)} \times \hat{G}_{(i,j)}}{P_{N(i,j)}}\right) \qquad (12)$$

Each packet is forwarded from the source to the sink by crossing adjacent coronas through the immediately adjacent sensors. Figure 5 illustrates a possible path along which a packet from one sensor in the outermost corona is routed to the sink. Notice that, in this example, each hop involves the immediately adjacent neighbor from the adjacent corona. More precisely, our sensor field can be seen as a set of wedges.

$$E_{rx(i,j)} = P_{rx}{}^{0} \times \hat{T}_{tx(i,j)} \qquad (13)$$

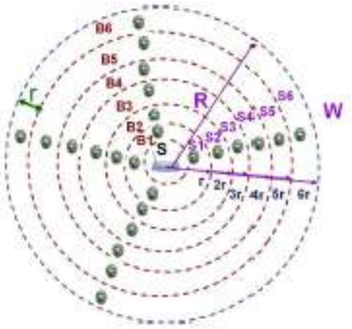

Fig. 3. A wedge W and the associated sectors.

Each sector contains exactly one sensor which has to forward the cumulative traffic coming from its predecessors to one of its possible successors. Specifically, in our study, we assume that each sensor is capable of adjusting its transmission power in order to send the appropriate fractions of packet load to one of its possible successors within its maximum transmission range dtx−max. More details are given in the next section.

IV. Energy Management

In our study, all the sensor nodes transmit periodically their reports to the sink node, denoted by S. The average number of reports generated per unit of time by each sensor node is denoted by A. In this section we turn to the task of evaluating the energy expenditure per sensor in an arbitrary corona Bi with i≥ 1. Observe that, according to our routing strategy, every node in a given wedge W and a generic corona Bi, (1 ≤ i≤ K), is called upon to serve two kinds of paths: • paths originating at an underwater sensor located in the same wedge W but in a different corona Bj with i< j ≤ K, and • paths emanating from the same sensor in Bi. It is easy to show that the total number of paths that may involve a specific node in a given wedge W and in corona Bi includes all possible paths in W except those originating in one of the coronas B1, B2, ... and Bi−1. For each sensor node located at corona Bi in a specific wedge W, the next hop to send generated reports to the sink S can be the sensor located in Bi−1 or Bi−2, ... or Bi−n, in the same wedge W where

$$n = \lfloor \frac{d_{tx-\max}}{r} \rfloor \qquad (14)$$

Considering a wedge W, we associate to each possible next hop located in Bi−1or Bi−2, ..., or Bi−n a respective weight _i1, _i2 , ..., _in and a respective probability of a successful reception Pi 1, Pi 2, ..., Pin such that Pn p=1 _ip = 1, ∀i,1 ≤ i≤ K. Consequently, the total number of packets per unit of time, Ai, handled by a sensor in corona Bi and wedge W can simply be expressed as follows

$$\begin{gathered} A_i = A + P_1^{i+1}\beta_1^{i+1}A_{i+1} \\ +\ldots + P_j^{i+j}\beta_j^{i+j}A_{i+j} + \ldots + P_n^{i+n}\beta_n^{i+n}A_{i+n} \qquad (15) \\ \text{if } \ i+j > K \ \text{ then } \beta_j^{i+j} = 0 \end{gathered}$$

It is worth pointing out that, the success probability is introduced to take into account the time-variability of the underwater channel. Recall that, every pair of nodes have their own success probability which reflects the probability of successful reception on their link, as introduced in section III.A.3. By doing so along with the adjusted transmission power ˆ PT , the time-variability of the acoustic channel is now considered in our analytical model aiming at offline deriving the optimal load weights balancing the energy consumption throughout the network which makes the derived load weights more realistic.

$$\begin{aligned} E_{TX}^{i} = \beta_1^i A_i E_{tx}(r) + \ldots + \beta_j^i A_i E_{tx}(jr) + \ldots + \\ \beta_n^i A_i E_{tx}(nr) \\ \text{if } \; i - j < 0 \text{ then } \beta_j^i = 0 \end{aligned} \tag{16}$$

Likewise, the average reception energy, Ei RX, consumed by a sensor in corona Bi and wedge W can be expressed as follows

$$\begin{aligned} E_{RX}^{i} = P_1^{i+1}\beta_1^{i+1}A_{i+1}E_{rx}(r) + \ldots + P_j^{i+j}\beta_j^{i+j}A_{i+j}E_{rx}(jr) \\ + \ldots + P_n^{i+n}\beta_n^{i+n}A_{i+n}E_{rx}(nr) \\ \text{if } \; i + j > K \text{ then } \beta_j^{i+j} = 0 \end{aligned} \tag{17}$$

Finally, the total energy consumed by a sensor in corona Bi and wedge W is

$$E^{i} = E_{TX}^{i} + E_{RX}^{i} \tag{18}$$

Recall that the goal of our work is to tailor the coronas in such a way that the energy expenditure is balanced across all the coronas. Consequently, our problem can be stated as follows:

$$\begin{aligned} & \text{Given } K, \; r, \; d_{tx-\max} \\ & \text{Find } \beta_1^i, \; \beta_j^i, \ldots, \beta_n^i \quad \forall i, 1 \le i \le K \\ & \text{such that } E^1 = E^2 = \ldots = E^K \\ & \text{subject to} \\ & \sum_{j=1}^{n} \beta_j^i = 1, \forall i, 1 \le i \le K \end{aligned} \tag{19}$$

It is worth noting that the perfect uniform energy depletion is impossible to achieve. Indeed, for the derived optimization problem of Eq. (19), the number of unknowns is much greater than the number of equations.

A. Iterative Process

We attempt to analytically approach the optimal uniform energy depletion using an iterative process. As it turns out the _is can be determined iteratively in a natural way. In the first iteration, we suppose that we only have the corona B1 of width r. In this case, the total traffic of each sensor in B1 is exclusively composed of the locally generated traffic A and clearly _1 1 is equal to 1. In the second iteration, we add corona B2 and knowing _1 1 we try to balance the energy expenditure between B1 and B2 by determining _2 1 and _2 2. More precisely, by adding B2, the total traffic of B1 increases since there is a newly received traffic from B2. Consequently, our previously established balance is perturbed. To re-arrange such imbalance we compute _2 1 and _2 2 . Note that _2 2 denotes the traffic weight that has to be sent directly from sensor in B2 to the sink. Generally speaking, suppose that we achieved iteration j and hence the energy consumption between j coronas is balanced. Adding corona Bj+1 will disturb the previously established balance since the total traffic in each corona will inevitably increase.

1) Calculation of the cumulative traffic: The cumulative traffic emanating from downstream coronas is a key variable that directly influences the energy consumption on every corona and hence the _i balancing vectors. For this reason, let us start by iteratively expressing the cumulative traffic at every corona.

Theorem 1:

$$\forall\, 1 \le j+1 \le K \;,\; A_{j+1} = A \text{ and } \forall\, 0 \le k \le j-1 \;;$$

$$A_{j-k} = \left[\alpha_{0k} + \textstyle\sum_{l=1}^{k+1} \alpha_{lk} P_l^{j+1} \beta_l^{j+1}\right] \times A$$

$$\text{where} \begin{cases} \beta_l^{j+1} = 0, \text{ if } l > \min(n, k+1) \\ \alpha_{00} = 1; \; \alpha_{0(-1)} = 1 \\ \alpha_{0k} = 1 + \sum_{m=1}^{k} \alpha_{0(k-m)} P_m^{j-(k-m)} \beta_m^{j-(k-m)}; \\ \alpha_{l(-1)} = 0; \\ \alpha_{lk} = 1, \text{ if } l = k+1 \\ \alpha_{lk} = \sum_{m=1}^{k+1-l} \alpha_{l(k-m)} P_m^{j-(k-m)} \beta_m^{j-(k-m)} \end{cases}$$

2) Calculation of energy consumption in transmission and reception:Recall that our objective is to determine _j+1 for each iteration j + 1 that balance the energy consumption between B1, B2,..., Bj+1. Consequently, at each iteration j + 1, we strive for deriving the unknown vector _j+1 of size j + 1. Recall that, as explained above, at iteration j + 1, all the _i, 1 ≤ i≤ j are already computed. As we newly add corona Bj+1, our previously established balance will be violated and hence _j+1 have to be computed such that our energy consumption balance is reinstated again.

$$E_{TX}^{j+1} = A \sum_{l=1}^{j+1} \beta_l^{j+1} E_{tx}^l \qquad (20)$$

where $\beta_l^{j+1} = 0$ if $l > \min(n, j+1)$.

$$E_{TX}^{j+1} = \sum_{l=1}^{j+1} TX_l^{j+1} \beta_l^{j+1} \qquad (21)$$

where $TX_l^{j+1} = AE_{tx}^l$.

$$E_{TX}^i = TX_0^i + \sum_{l=1}^{j-i+1} TX_l^{j-i} P_l^{j+1} \beta_l^{j+1} \qquad (22)$$

$$E_{RX}^i = RX_0^i + \sum_{l=1}^{j-i} RX_l^{j-i} P_l^{j+1} \beta_l^{j+1} + P_{j-i+1}^{j+1} \beta_{j-i+1}^{j+1} A E_{rx}^{j+1-i}$$

$$\forall 1 \le j+1 \le K$$
$$\forall 1 \le i < j+1$$
$$E_{TX}^{j+1} = E_{TX}^i + E_{RX}^i$$
$$TX_0^i + RX_0^i = \sum_{l=1}^{j+1} P_l^{j+1} TX_l^{j+1} \beta_l^{j+1} - \sum_{l=1}^{j-i} \left(TX_l^{j-i} + P_l^{j+1} RX_l^{j-i} \right) \beta_l^{j+1} - A \left[P_{j-i+1}^{j+1} E_{rx}^{j+1-i} + \sum_{q=1}^{i+1} \beta_q^i E_{tx}^q \right] \beta_{j-i+1}^{j+1} \qquad (24)$$

The proofs for Eqs. 22 and 23 are provided in Appendices B and C respectively

B. Problem Statement

Now that we succeed to linearly express Ej+1 TX ,Ei TX and EiRX, ∀1 ≤ i≤ j, as function of _j+1, we get our system of linear equations as expressed in Eq. 24. More concisely, our previously stated system can be written as follows

$$TX_{j+1} \beta^{j+1} = C \qquad (25)$$

$$TX_{i,l} = \begin{cases} P_l^{j+1} TX_l^{j+1} - TX_l^{j-i} - P_l^{j+1} RX_l^{j-i}, \\ \text{if } 1 \le l \le j-i \\ P_l^{j+1} TX_l^{j+1} - A \left[P_{j-i+1}^{j+1} E_{rx}^{j+1-i} + \sum_{q=1}^{i+1} \beta_q^i E_{tx}^q \right], \\ \text{if } l = j-i+1 \\ P_l^{j+1} TX_l^{j+1}, \text{ if } j-i+1 < l \le j+1 \end{cases} \qquad (26)$$

Consequently, we have much more equations than needed and hence achieving perfect uniform energy depletion is impossible. For this reason, we slightly deviate our goal to the one of minimizing the difference in energy consumption among different coronas. Consequently, in this case, we reformulate our problem as Follows

$$\begin{aligned} &\text{Given } K,\ r,\ d_{tx-\max} \\ &\text{Find } \beta^{j+1} \\ &\min_{\beta^{j+1}} \left\| TX_{j+1} \beta^{j+1} - C \right\| \\ &\text{subject to} \qquad\qquad\qquad\qquad (27) \\ &\sum_{l=1}^{j+1} \beta_l^{j+1} = 1 \\ &\beta_l^{j+1} \ge 0\ ,\ \forall 1 \le l \le j+1 \end{aligned}$$

Therefore, once the iteration number exceeds n, the previously stated optimization problem of Eq. 27 have to be solved instead of Eq. 25.

V. Performance Evaluation

According to our simulation model, the underwater sensor nodes perform continuous monitoring of the supervised circular area of radius R. Our circular sensor field centered at the sink is partitioned into disjoint concentric coronas of constant fixed width r. Recall that, we assume that underwater sensors are manually deployed according to the deployment pattern of Fig. 4. The proposed deployment strategy considers a 2-dimensional shallow underwater sensor network. A set of sparse sensors is anchored to the ocean bottom and endowed with a quite long rope along with a floating buoy to help the sensor reach the surface. Each underwater sensor periodically reports with rate A the locally generated data to the sink over several hops. At each hop, the traffic emanating from the local sensor must be merged with route-through traffic. Each packet is forwarded from the source to the sink by crossing coronas. the packets load should be evenly distributed among upstream coronas. Indeed, balancing the energy consumption among different coronas is a trade-off between two opposite requirements: the reception energy and the transmission energy which are the main two components of energy consumption. On one hand, since the reception energy is almost constant, hence sending over longer distance will reduce the total number of hops to reach the sink and thus the total energy consumption is minimized. On the other hand, the transmission energy is increasing with distance.

we consider the maximum consumed amount of energy among all coronas. Regarding network lifespan, we define the network lifetime *T* simply as the time for the first node in the network to drain its energy budget. In other words, the network lifetime is given by

$$T = \frac{E_{init}}{\max E(U)}$$

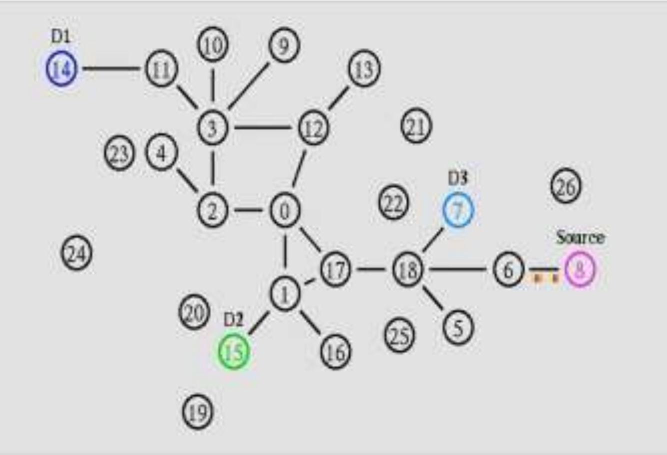

Fig. 4. The proposed deployment

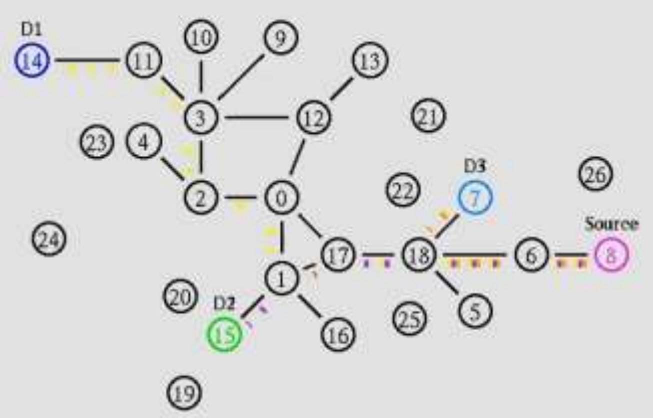

Fig. 5. The proposed network simulator

VI. Simulation Result

Simulation results are done by network simulator 2.Below shown the simulation of Throughput ,Energy Consumption, Monitoring Power, Network Utility, Successful Packets Delivered, Communication Over Head, Data Aggregation result.

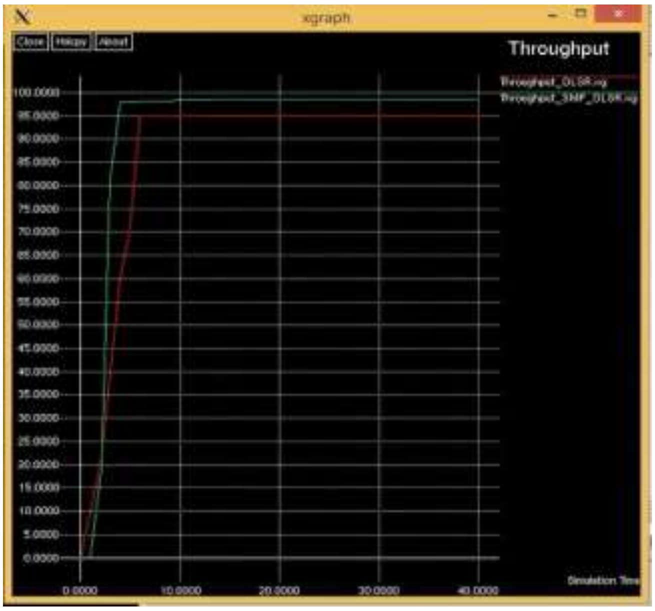

Fig. 6 Simulation of Throughput

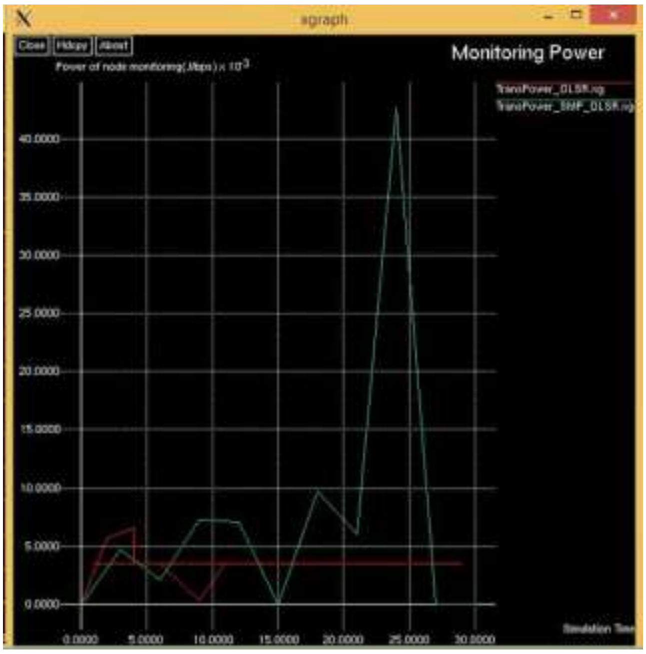

Fig. 7 Simulation of Power Monitoring

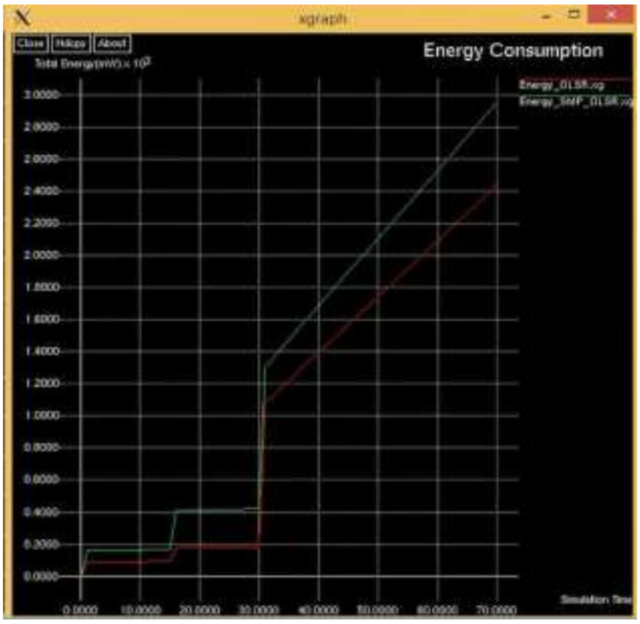

Fig. 8 Simulation of Energy consumption

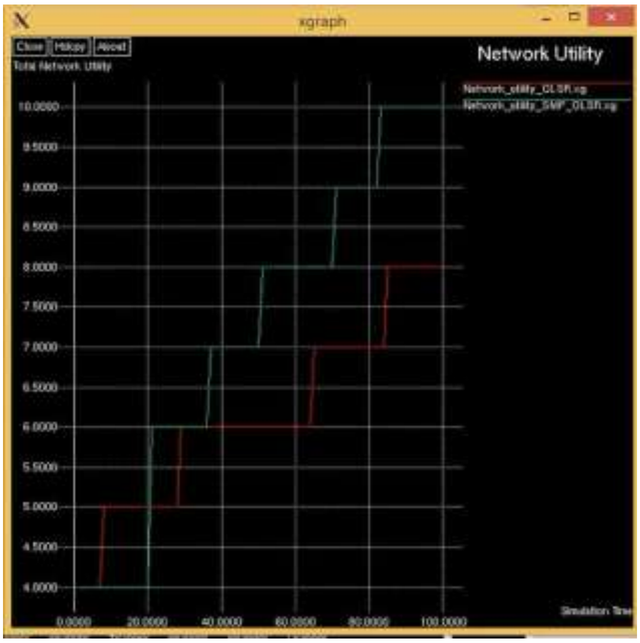

Fig. 9. Simulation of Network Utility

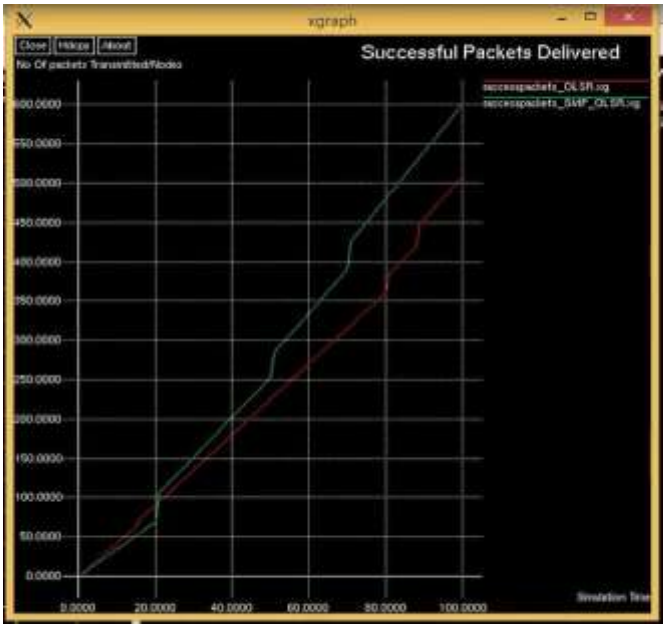

Fig. 10 Simultion of Successful Packets Delivered

Fig. 11. Simulation of Data Aggregation

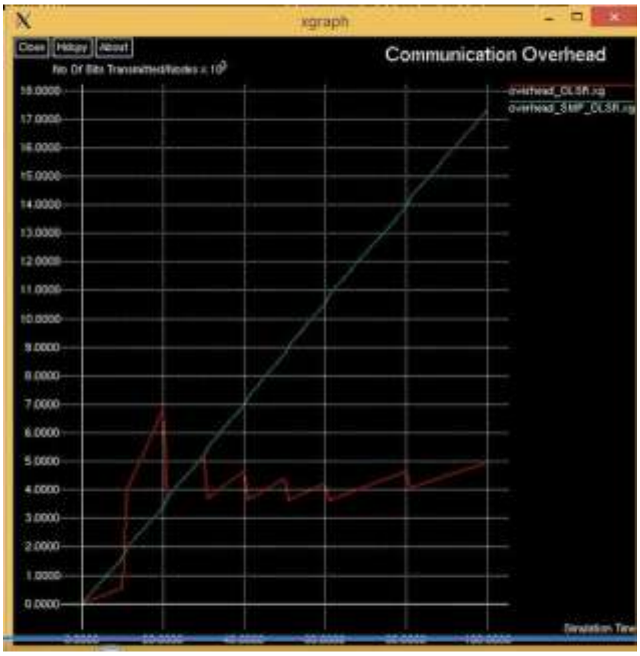

Fig.12. Simulation of Communication Over-Head

VII. Conclusion

In underwater environments, where solar energy cannot be exploited, operating on energy constrained underwater sensors imposes the design of energy-efficient protocols. These protocols should be carefully designed in order to deal with the dramatically different propagation characteristics of underwater acoustic signals, such as high attenuation and bandwidth limited channel. For these reasons, UW-ASNs require protocols that make judicious use of the limited battery budget while taking into account the unique features of the underwater channel. To this end, we proposed in this paper a routing strategy that leads to an even energy depletion among all sensors in the network and consequently an improved network lifespan. Accordingly, by allowing each underwater node to dynamically adjust its transmission power up to a predefined number of levels, we determined for each source sensor the set of possible next hops with the associated transmission power and associated load weight that lead to fair energy consumption and hence the energy sink-hole problem is overcome. To do so, we developed a comprehensive analytical model that iteratively derives for each source sensor the appropriate load weight along with the associated transmission power. Analytical results show that significant lifespan improvement is achieved by our balanced routing scheme compared to the nominal communication range based data forwarding.

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