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Energy analysis of routing protocols for underwater wireless sensor networks

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Abstract

Underwater wireless sensor networks consist of a certain number of sensors and vehicles that interact to collect data and perform collaborative tasks.

Designing energy-efficient routing protocols for this type of networks is essential and challenging because sensor nodes are powered by batteries, which are difficult to replace or recharge, and because underwater communications are severely affected by network dynamics, large propagation delays and high error probability of acoustic channels.

The goal of this paper is to analyze the total energy consumption in underwater acoustic sensor networks considering two different scenarios: shallow water and deep water. We propose different basic functioning principles for routing protocols in underwater wireless sensor networks (relaying, direct transmission and clustering) and analyze the total energy consumption for each case, establishing a comparison between them.

Keywords: Acoustic communications; Routing; Energy efficiency; Underwater networking

1. Introduction

The sea is a fascinating large expanse of water that has always attracted people who wanted to solve its mysteries. For centuries the access of human beings to the sea was limited to the surface or the nearby water, because the researchers had to use wire-line instruments and sampling equipment located at the sea surface. This fact restricted the scientific research operations.

Nowadays there is a growing need of underwater monitoring (e.g. for exploration of natural undersea resources, gathering of scientific data or detection of marine incidents such as chemical pollution or oil spill) but the existing technologies do not measure up to the demanding requirements [1]. Small-scale underwater acoustic networks (UANs) [2,3] are associations of nodes that collect data using remote telemetry or assuming point-to-point communication. Remote telemetry with high precision is very expensive. With point-to-point communication a multi-access technique is not used because the nodes are sparsely deployed. Besides, UANs are usually fixed, either anchored in the sea floor or attached to buoys or GPS systems. Consequently, a new concept of low-cost more easily deployable underwater networks with less restricted conditions should be developed: underwater wireless sensor networks (UWSNs) [4]. This kind of networks must be scalable, mobile and capable of self-organization (by exchanging configuration, location and movement information). They eliminate the need for cables and do not interfere with shipping activity [5].

RF radio does not work well in the underwater environment because radio waves propagate only at extra low frequencies (30–300 Hz) and require large antennae and high

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transmitter powers; optical waves are severely affected by scattering, and, as a result, underwater networks are based on the propagation of acoustic waves [6].

UWSNs are very different from ground-based existing networks due to the intrinsic properties of the underwater environments. They suffer from:

- Large propagation delays:
  The propagation speed of acoustic signals in water is about 1.5×10^3 m/s, five orders of magnitude lower than the radio propagation speed (3×10^8 m/s) [7]. Consequently, the high resulting propagation delays will seriously damage localization and time synchronization [1].
- Node mobility:
  Underwater sensor networks move with water current (empirical observations suggest that water current moves at a speed of 3–6 km/h in a typical underwater condition [8]).
- High error probability of acoustic underwater channels:
  The underwater acoustic communication channel has a limited bandwidth capacity (of the order of KHz) that depends on transmission range and frequency, has variable delays and suffers high bit error rates, which are caused by noise, multi-path and Doppler spread. Consequently, temporary losses of connectivity can be experienced (shadow zones) [9].

Therefore, the stringent network operation conditions pose a motivation for doing research at each layer of the protocol stack [4,9,10].

Energy saving is a major concern in UWSNs because sensor nodes are powered by batteries and it could be difficult to replace or recharge batteries in aquatic environments. In acoustic networks the power required for transmitting is typically about 100 times more than the power required for receiving [11]. The design of robust, scalable and energy-efficient routing protocols in this type of networks is a fundamental research issue. Most existing data forwarding protocols proposed for ground-based sensor networks cannot be directly applied because they have been designed for stationary networks. The existing multi-hop ad hoc routing protocols are not adequate because they employ flooding techniques for packet routing (at least during the route discovery mechanism) that would lead an UWSN easily to energy exhaustion because in UWSNs the medium is highly variable and the routing overhead due to updates could be very high.

In this paper we have analyzed theoretically the total energy consumption in underwater acoustic sensor networks. To achieve this purpose, we have introduced the components of a general reference architecture for UWSNs and afterwards, we have described the different existing networking architectures. From here on, we have considered two different scenarios: deep and shallow water; shallow water refers to water with depth lower than 100 m, whereas deep water is used for deeper ocean. We have carefully studied the propagation of sound in the sea (deducing different equations for each scenario when necessary). The resulting equations (sound velocity in sea water, passive sonar equation, transmission loss) are necessary pieces to derive later a general expression of the energy consumption adapted to each scenario. We have proposed different basic functioning principles for routing protocols in UWSNs (relaying, direct transmission and clustering) and have analyzed the total energy consumption for each case, establishing a comparison between them. The analysis carried out proves that the routing protocols based on the clustering scheme save more energy and show a better performance in shallow water.

The paper is structured as follows: Section 2 explains related work about how to design routing protocols in UWSNs. Section 3 introduces a generic reference scheme and the different existing networking architectures; in addition, it shows a complete energy consumption study. Finally, Section 4 concludes this paper.

2. Related work

Since the nodes in an underwater wireless sensor network are powered by batteries, an important research issue is the design of robust, scalable and energy-efficient routing protocols.

Most existing data forwarding protocols proposed for ground-based sensor networks like Directed Diffusion [12], Rumor Routing [13], LEACH (Low-Energy Adaptive Clustering Hierarchy) [14], TTDD (Two-Tier Data Dissemination) [15] and GEAR (Geographic and Energy Aware Routing) [16], are unsuitable for UWSNs because they have been mainly designed for stationary networks and usually employ the flooding technique.

The existing multi-hop ad hoc routing protocols are not adequate because they apply a continuous exchange of overhead messages (proactive ad hoc routing [17,18]) or employ a route discovery process based on the flooding technique (reactive ad hoc routing [19,20]); these mechanisms are inefficient tools in large scale underwater networking because they consume excessive energy and bandwidth resources. On the other hand, geographical ad hoc routing protocols [21,22] could be applied to underwater environments if it is investigated how sensor nodes can obtain accurate localization information without much power consumption; the extended Global Positioning System (GPS) is not helpful to achieve this purpose because it uses radar waves in the 1.5 GHz band and those waves do not propagate in sea water; besides, GPS is greedy in data communications and data transmission using acoustic waves is very limited in range. Recently, significant efforts have been made to study and solve the localization problem in underwater wireless sensor networks [23–27].

On the other hand, some routing protocols have been designed for small-scale UANs. In [2] the authors propose a routing protocol where a master node collects the neighbour tables from all nodes in the network and uses this information to establish a routing tree and decide on the primary (and secondary) routes to each destination. The master node is responsible for sending the primary routes to all nodes. This routing protocol assumes that the nodes are static and can not be properly applied to large-scale mobile UWSNs because routes will break frequently due to mobility (consequently, the routing overhead will be increased considerably as well as the power consumption) and a centralized routing protocol is not an adequate solution (the master node concentrates all the routing traffic to a single point and is a possible unique element of failure); besides, the routes from the wireless sensors to the master node may be long or non-existent. In [3,28,29] other centralized routing schemes have been proposed, which have the same basic problems as previously described and thus are not appropriate for distributed UWSNs.

Finally, some routing protocols [30–35], [36,37] have been specifically designed for UWSNs. Some of them are location-based [30–32]; In [30,31] the authors use the concept of routing vector (defined as a vector from the source to the sink [30] or as a vector for each single forwarder (hop-by-hop vectors) [31]); In [32] the authors take into account the varying conditions of the underwater channel and the type of sensor network applications and design algorithms for delay-sensitive or delay-insensitive routing. Another routing protocol [33] tries to increase the probability of successful delivery forwarding data over more routes towards different local sinks which collectively form a virtual sink (multipath routing). In [34] the authors propose a dynamic proactive routing protocol that includes three steps, route discovery, route maintenance and route invalidity. In [35] a routing protocol has been proposed with no proactive routing message exchange and negligible amount of on-demand floods. Finally, a distributed adaptive clustering scheme that assumes random node mobility has been proposed for the shallow water scenario [36] as well as for the deep water scenario [37].

However, all these different protocols have some common characteristics: They assume GPS-free nodes; besides, they try to be adaptive, scalable and energy-efficient, some fundamental properties for the design of routing protocols in this type of networks.

In this paper we have analyzed theoretically the total energy consumption in underwater wireless sensor networks. A similar study has been done in [2], but the differences are the following ones:

In [2] the authors introduce only generic terms for the description of the shallow water scenario, whereas in this paper a complete analytical description for both scenarios (shallow water and deep water) is provided. Besides, the authors in [2] compare only direct transmission with packet relaying as functioning principles for routing protocols, whereas in this paper these functioning principles are studied in addition to the clustering scheme. The next section shows the results obtained.

3. Energy analysis of routing protocols for underwater wireless sensor networks

3.1. Different existing networking architectures for UWSNs

Fig. 1 illustrates the components of a reference architecture for UWSNs.

We can recognize some sensor nodes distributed over the ocean. They may be:

- Fixed:
  The fixed sensor nodes may be distributed on the water surface with the aid of buoys or on the water bottom anchored to the ocean [38]; although they are fixed with tethers, they may move due to anchor drift or disturbance from external effects.
- Mobile:
  Mobile sensor nodes are more flexible and enable the autonomous autoconfiguration of these ad hoc networks in an arbitrary location.

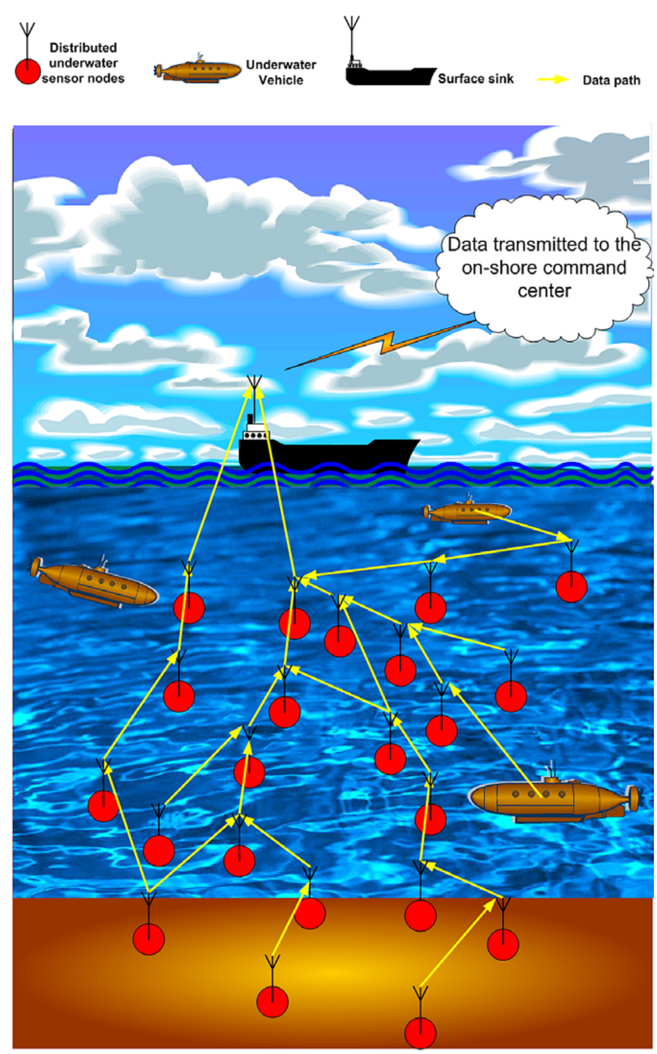

Fig. 1. Underwater wireless sensor networks (UWSNs).

All these sensor nodes communicate with each other using acoustic links and multihop routing; they relay data to the sinks via direct links or through multi-hop paths.

The sinks may be:

- Surface nodes (like the ship in Fig. 1):
  They can transmit data to the on-shore command center for example via radio or satellite.
- Underwater nodes:
  They can transmit data via multi-hop acoustic routes to a surface control center over the sea or to a surface station that retransmits them to the on-shore control center, for example via radio or satellite.

The control center should collect and process the data received to extract conclusions.

It is also possible that underwater sensors are able to communicate with a small number of autonomous underwater vehicles (AUVs) (see Fig. 1).

Based on this general description, some authors have classified UWSNs. In [10] the authors introduce the following architectures for underwater sensor networks:

- Static two-dimensional UWSNs for ocean bottom monitoring:
  They are constituted by sensor nodes that are anchored to the bottom of the ocean. They are interconnected to one or more underwater sinks by wireless acoustic links. These underwater sinks relay data from the ocean bottom network to a surface station. Typical applications may be environmental monitoring or monitoring of underwater plates in tectonics [39].
- Static three-dimensional UWSNs for ocean column monitoring:
  These include networks of sensors that float anchored at different depths. Typical applications are surveillance or monitoring of ocean phenomena (ocean bio-geochemical processes, water streams, pollution).
- Three-dimensional networks of autonomous underwater vehicles (AUVs): These networks include fixed portions composed of anchored sensors and mobile portions constituted by autonomous vehicles. Typical applications may be oceanography, environmental monitoring and underwater resource study.

In [4] the authors address "mobile" UWSNs instead of "static" and carry out the following classification:

- Mobile UWSNs for long-term non-time-critical aquatic monitoring:
  These include networks of local underwater sensors that collect data and relay them to intermediate underwater sensors; these nodes forward the packets to the surface nodes, which transmit data, for example via radio, to the on-shore command center. Typical applications may be oceanography, marine biology, deep-sea archaeology, seismic predictions, pollution detection and oil/gas field monitoring.
- Mobile UWSNs for short-term time-critical aquatic exploration:
  These include networks of underwater sensors that collect data and forward them to the surface control center via multi-hop acoustic routes. Typical applications may be underwater natural resource discovery, hurricane disaster recovery, anti-submarine military mission and loss treasure discovery.

The introduction of these networking architectures is the basis for the discussion of promising trends in the development of efficiently designed routing protocols. But first of all it is very valuable to study the principles of underwater sound as the necessary basis to introduce later a theoretical analysis.

3.2. Propagation of sound in the sea

3.2.1. The sound velocity in sea water

Sonar (Sound Navigation and Ranging) is a technique that uses sound propagation under water. Sonar operation is affected by sound speed, which is a function of temperature, pressure (or depth) and salinity of seawater and can be expressed by the following equation [40]:

$$\begin{aligned} c = {} & 1448.96 + 4.591T - 0.05304T^2 + 0.0002374T^3 \\ & + 1.340(S-35) + 0.0163D + 1.675 \times 10^{-7}D^2 \\ & - 0.01025T(S-35) - 7.139 \times 10^{-13}TD^3 \end{aligned} \tag{1}$$

where c represents the speed of sound in m/s, T symbolizes the temperature in degrees Celsius, S the salinity in parts per thousand and D the depth in meters. This equation is valid for $0 \leqslant T \leqslant 30°$, $30 \leqslant S \leqslant 40$ and $0 \leqslant D \leqslant 8000$. The sound velocity increases with temperature, salinity and depth.

3.2.2. The passive sonar equation

Active sonar creates a pulse of sound (often named "ping"), and then listens for reflections (echo) of the pulse. To measure the distance to an object, the time from emission of a pulse to reception is measured. Passive sonar listens without transmitting. This method consumes less energy and is therefore more suitable for underwater wireless sensor nodes.

The signal to noise ratio (SNR) of an emitted underwater signal at the receiver can be expressed by the passive sonar equation [41]:

$$\mathrm{SNR} = \mathrm{SL} - \mathrm{TL} - \mathrm{NL} + \mathrm{DI} \geqslant \mathrm{DT}, \tag{2}$$

where DT has been defined as the detection threshold, SL is the target source level or noise generated by the target, TL is the transmission loss due to the water environment, NL is the noise level (from the receiver + the environment) and DI is the directivity index (a function of the receiver's directional sensitivity or the ability of the sonar system (sensor node) to direct its hydrophone to avoid unwanted noise). This means that a node detects a target just listening to the noise generated by the target itself. The target noise received by the hydrophone (SNR) of a node that is sensing the medium equals the noise transmitted by the target (SL − TL) minus the noise that is lost (NL − DI).

If we consider that the value of SL is known or can be calculated, the value of NL can be measured, the value of DI is a function of the equipment and the value of DT can be measured experimentally, the value of TL is the parameter to be solved.

3.2.3. Transmission loss

The sonar parameter transmission loss, TL, can be defined as the accumulated decrease in acoustic intensity as an acoustic pressure wave propagates outwards from a source. Transmission loss is a magnitude that summarizes the effects of a variety of propagation phenomena in the sea. It can be estimated by adding the effects of geometrical spreading, absorption and scattering. Spreading loss refers to the energy distributed over an increasingly larger area due to the regular weakening of a sound signal as it spreads outwards from the source [41]; the energy per unit area is proportional to $\frac{1}{r^2}$, where r is the radio [41]. Absorption is a process that involves the conversion of acoustic energy into heat due to the internal friction at a molecular scale within the fluid. Energy is dissipated into the medium and the molecules of the medium absorb some of the energy as it passes through. At certain frequencies absorption is increased due to ionic relaxation of certain dissolved salts. Scattering refers to energy bouncing off suspended particles within the underwater medium.

If I_0 is the intensity at the reference point located 1 yard (1 yd = 0.9144 m) from the "acoustic center" of the source and I_1 is the intensity at a distant point in the sea, then it follows that [41]:

$$\mathrm{TL} = 10\log\frac{I_0}{I_1} = 10\log I_0 - 10\log I_1 \quad (3)$$

The source level SL can be defined as the intensity of the radiated sound in decibels related to the intensity of a plane wave of root mean square (rms) pressure 1 μPa, referred to a point 1 yd (0.9144 m) from the "acoustic center" of the source in the direction of the target [41]:

$$\mathrm{SL} = 10\log\frac{I_0}{I_{ref}} = 10\log\frac{I_0}{1\ \mu\mathrm{Pa}} \quad (4)$$

If we replace the value of SL in Eq. (3):

$$\mathrm{TL} = 10\log\frac{I_0}{I_1} = 10\log\frac{(10^{\frac{\mathrm{SL}}{10}})}{I_1} = \mathrm{SL} - 10\log I_1 \quad (5)$$

All the terms is Eq. (5) are given in dB re μPa, where the reference value 1μPa amounts to $0.67 \times 10^{-18}\,\frac{\mathrm{Watts}}{\mathrm{m}^2}$. In the rest of the paper we use the notation of dB to signify dB re μPa.

3.3. Energy consumption in shallow water

A major constraint in UWSNs is the limited energy supply because sensor nodes are powered by batteries, which cannot be easily replaced or recharged. Therefore, one important network design goal is to minimize the energy consumption of the sensor nodes. We have analyzed two different scenarios: shallow water and deep water; shallow water refers to water with depth lower than 100 m, whereas deep water is used for deeper ocean.

Now we introduce the shallow water scenario. We consider a linear network as shown in Fig. 2, where $N+1$ nodes are distributed along a stretch; the distance between two nodes is d.

We take into consideration that packets of K bits are transmitted from sensor nodes to the underwater sink. We wish to analyze the energy expense during this process. We consider that the nodes form a linear chain because it represents the worst-case scenario for network lifetime and applies to surveillance applications or monitoring of ocean phenomena.

We want to compare later this scenario with the deep water one; consequently we do not consider the last step (when the underwater sink transmits the packets to the on-shore command center).

We have defined spreading loss as the geometrical effect representing the regular weakening of a sound signal as it spreads outwards from the source. Acoustic signals in shallow water propagate with a cylinder bounded by the surface and the sea floor; as a result, cylindrical spreading appears (see Fig. 3).

In this case, the power P crossing cylindrical surfaces at range r_1 and r_2 is:

$$P = 2\pi r_1 H I_1 = 2\pi r_2 H I_2 = \ldots \quad (6)$$

where H is the height of the cylinder.

If r_1 is taken as 1 yd (≅1 m), the transmission loss to range r_2 (considering only spreading effects) is:

$$\mathrm{TL} = 10\log\frac{I_1}{I_2} = 10\log r_2 \quad (7)$$

Now we consider that in Fig. 2 the sensor node located at a distance Nd from the underwater sink needs to send information (K packets). The power level and energy consumed during transmission would be:

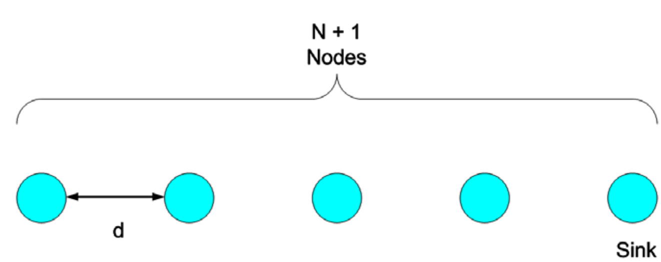

Fig. 2. Simple linear network for the shallow water scenario.

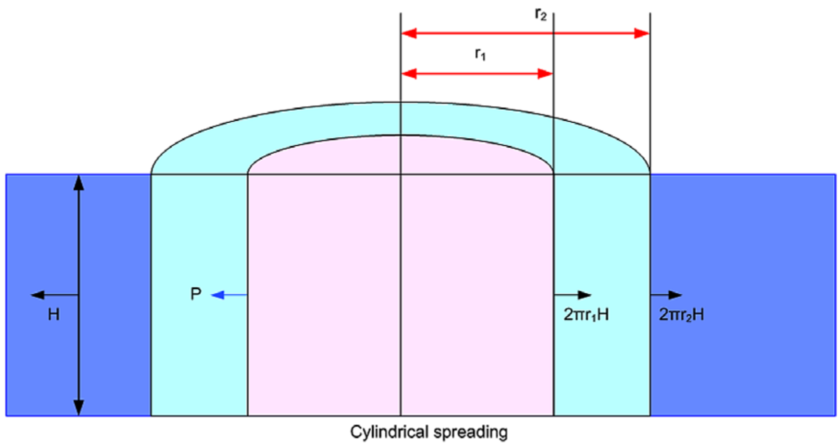

Fig. 3. Spreading in a medium between two parallel planes (cylindrical spreading).

$$P = 2\pi d H I_1 \tag{8}$$

$$E_{\text{total}} = NPT_{tx}K \tag{9}$$

where N represents the number of hops towards the surface sink, T_{tx} represents the transmission time for one packet and K represents the total number of packets sent by the source node.

When each node along the stretch has K packets to transmit, the consumed energy for packet relaying is [2]:

$$\begin{aligned} E_{\text{total}} &= NPT_{tx}K + (N-1)PT_{tx}K + (N-2)PT_{tx}K + \cdots + PT_{tx}K \\ &= \frac{N(N+1)PT_{tx}K}{2} \end{aligned} \tag{10}$$

On the other hand, if the sensor nodes communicate directly with the surface sink, the power level consumed by each node during transmission is calculated as:

$$P = 2\pi r_1 H I_1 \tag{11}$$

where r_1 equals the distance from each node to the underwater sink.

The total energy consumption when each node along the stretch has K packets to transmit using direct access, can be expressed as:

$$\begin{aligned} E_{\text{total}} = {} & P(r_1 = Nd)T_{tx}K + P(r_1 = (N-1)d)T_{tx}K \\ & + P(r_1 = (N-2)d)T_{tx}K + \cdots + P(r_1 = d)T_{tx}K \end{aligned} \tag{12}$$

$$E_{\text{total}} = KT_{tx}\sum_{i=1}^{N} P(r_1 = id) \tag{13}$$

We wish to represent the total energy consumed using both strategies. The total energy consumed is a function of power. Power is a function of intensity and intensity is related to transmission loss, in conformity with Eq. (5).

The transmission loss caused by cylindrical spreading and absorption (or attenuation) can be expressed as follows [42]:

$$\text{TL} = 10\log r + \alpha r \times 10^{-3} \tag{14}$$

where α represents the absorption coefficient and has the units dB/km and r is the range expressed in yards.

At low frequencies (100–3 KHz), the absorption coefficient can be calculated using Thorp's expression as [43]:

$$\alpha = \frac{0.1f^2}{1+f^2} + \frac{40f^2}{4100+f^2} + 2.75 \times 10^{-4} f^2 + 0.003 \tag{15}$$

where α is the absorption coefficient in dB per km and f is the frequency in kilohertz.

However, the expression of transmission loss in Eq. (14) is not complete. We must take into account the combined effects of other complicating factors such as:

- Multiple path propagation due to the variations of the speed with temperature, depth and salinity.
- Refraction effects.
- Diffraction and scattering of sound by particles, bubbles and plankton within the water column.

All of these factors just discussed can be lumped into a single term, A, called the transmission loss anomaly (expressed in dB). This term is artificial and is only used to write a complete equation for TL that combines all processes already discussed. The equation so written is:

$$\text{TL} = 10\log r + \alpha r \times 10^{-3} + A \tag{16}$$

From Eq. (5):

$$I_1 = 10^{\frac{\text{SL}-\text{TL}}{10}} = 10^{\frac{\text{SL}-10\log r_1 - \alpha r_1 10^{-3} - A}{10}} \tag{17}$$

Therefore, we can express Eq. (11) as:

$$P = 2\pi r_1 H I_1 = 2\pi r_1 H 10^{\frac{\text{SL}-10\log r_1 - \alpha r_1 10^{-3} - A}{10}} \tag{18}$$

Now we have calculated the total energy consumption when each node along the stretch in Fig. 2 transmits K packets via direct links or through multi-hop paths (relaying). We have examined several parameter values related to acoustic modems and hydrophones [44–46]. As a result, we consider a directivity index $\text{DI} = 3\text{dB}$ and a target $\text{SNR} = 20$ dB at the receiver. The value of NL is related to shipping activity, wind level, biological noise, seaquakes, etc. of a particular setting and we take the value of

$NL = 70$ dB because it is a representative shallow water case [41]. Besides, we consider a distance (height) between sea bottom and surface of $H = 75$ m and that 1000 packets are transmitted with a transmission time $T_{tx} = 40$ ms.

Fig. 4 represents the total energy consumption as a function of the distance between sensor nodes using direct transmission or packet relaying. For direct access as well as for relaying, the inclusion of additional nodes increases the energy consumption because for a fixed distance between nodes more sensor nodes will be far away from the underwater sink. In addition, for a fixed number of sensor nodes if the distance between sensor nodes is increased, the total energy consumed is increased, too, because the transmission power is related to the distance. However, we can not observe significant differences between direct transmission and relaying because in shallow water the transmission power is directly proportional to the distance between sensor nodes and not to the square of the distance.

Now we have decided to compare the relaying method with a routing protocol based on clustering. In the clustering scheme proposal (see Fig. 5), the nodes are distributed in a linear network and adjacent nodes are grouped into clusters (time division multiple access (TDMA) can be used in each cluster for communication [36]). As we can see in Fig. 5, a cluster head is selected every three nodes with exception of the neighbour of the sink, which delivers its packets directly. Sensor nodes should deliver the collected data to the nearest cluster head, which sends all the information from cluster head to cluster head until it reaches the underwater sink. As we can appreciate, the clustering method is a combined version of packet relaying and direct transmission methods.

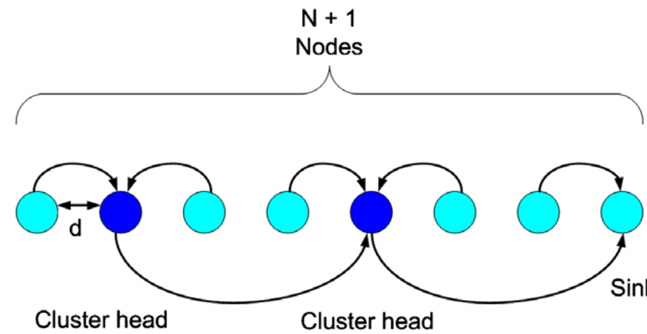

Fig. 5. Linear network for the shallow water scenario that applies clustering.

The comparison results between packet relaying and clustering are shown in Fig. 6. We can observe that using the clustering method the total energy consumed is less than with packet relaying for the same number of sensor nodes and the energy expense is increased with the distance between sensor nodes. Besides, the inclusion of additional nodes increases the energy consumption in both cases, although the clustering scheme always shows the best results.

3.4. Energy consumption in deep water

Now we are going to present a deep water scenario. We consider a linear network (see Fig. 7), where $N + 1$ nodes are distributed along a stretch; the distance between two nodes is d. We take into consideration that packets of K bits are transmitted from sensor nodes to the surface sink. We wish to analyze the energy expense in this process. We consider that the nodes form a linear chain because it rep-

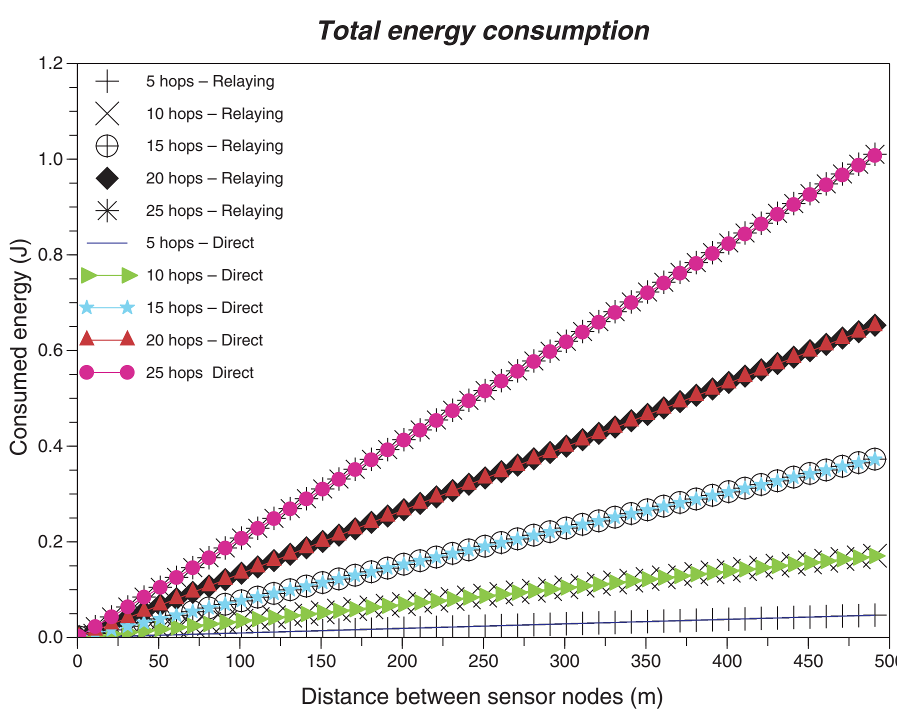

Fig. 4. Total energy consumption in shallow water via direct links or through multi-hop paths (relaying).

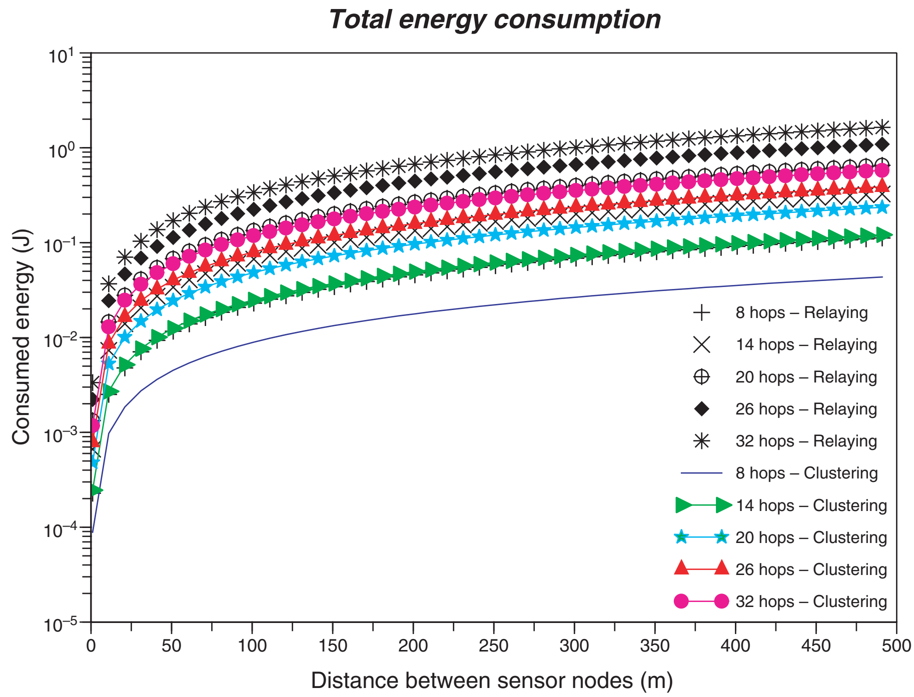

Fig. 6. Total energy consumption in shallow water through multi-hop paths (relaying) or clustering.

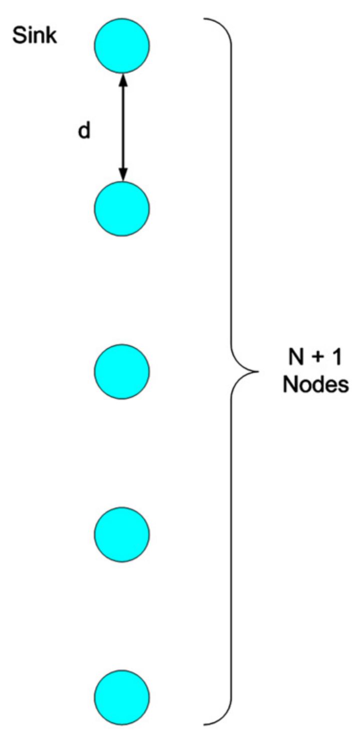

Fig. 7. Simple linear network for the deep water scenario.

resents the worst-case scenario for network lifetime and applies to surveillance applications or monitoring of ocean phenomena.

We have defined spreading loss as the geometrical effect representing the regular weakening of a sound signal as it spreads outwards from the source. Now we consider that the ocean is deep enough so that the propagation range is not bounded by the sea floor and the surface, so that spherical spreading applies.

Let us consider a small source that is located in a homogeneous unbounded medium, as it is shown in Fig. 8.

The power P generated by this source is radiated equally in all directions so as to be equally distributed over the surface of a sphere surrounding the source [41]:

$$P = 4\pi r_1^2 I_1 = 4\pi r_2^2 I_2 = \ldots \tag{19}$$

Then, if r_1 is taken as 1 yd ($\cong$ 1 m), the transmission loss to range r_2 (considering only spreading effects) has been defined as [41]:

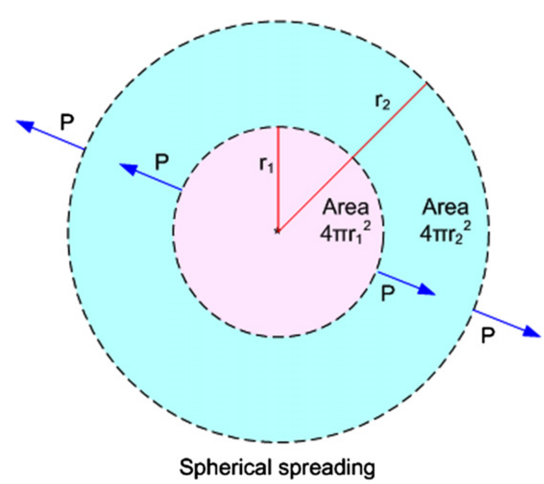

Fig. 8. Spreading in an unbounded medium (spherical spreading).

$$\mathrm{TL} = 10\log\frac{I_1}{I_2} = 10\log r_2^2 = 20\log r_2 \tag{20}$$

Now we consider that in Fig. 7 the sensor node located at a distance Nd from the surface sink needs to send information (K packets). The power level and energy consumed during transmission would be:

$$P = 4\pi d^2 I_1 \tag{21}$$

$$E_{\text{total}} = NPT_{tx}K \tag{22}$$

where N represents the number of hops towards the surface sink, T_{tx} represents the transmission time for one packet and K represents the total number of packets sent by the source node.

When each node along the stretch has K packets to transmit, the consumed energy for packet relaying is the same as in Eq. (10).

On the other hand, if the sensor nodes communicate directly with the surface sink, the power level consumed by each node during transmission is calculated as:

$$P = 4\pi r_1^2 I_1 \tag{23}$$

where r_1 is equal to the distance from each node to the surface sink.

The total energy consumption when each node along the stretch has K packets to transmit using direct access, can be expressed in the same way as in Eqs. (12) and (13).

In addition, the transmission loss caused by spherical spreading, attenuation and transmission loss anomaly, can be expressed as follows [41]:

$$\mathrm{TL} = 20\log r + \alpha r \times 10^{-3} + A \tag{24}$$

where α represents the absorption coefficient and has the units dB/km, A is the transmission loss anomaly expressed in dB and r is the range expressed in yards. Eq. (15) illustrates how to calculate the value of α.

From Eq. (5):

$$I_1 = 10^{\frac{\mathrm{SL}-\mathrm{TL}}{10}} = 10^{\frac{\mathrm{SL}-20\log r_1 - \alpha r_1 10^{-3} - A}{10}} \tag{25}$$

Therefore, we can express Eq. (23) as:

$$P = 4\pi r_1^2 I_1 = 4\pi r_1^2 10^{\frac{SL-20\log r_1 - \alpha r_1 10^{-3} - A}{10}} \tag{26}$$

Now we have calculated the total energy consumption when each node along the stretch in Fig. 7 transmits K packets via direct links or through multi-hop paths (relaying). We have examined several parameters related to acoustic modems and hydrophones [44–46]. As a result, we consider a directivity index $\mathrm{DI} = 3$ dB and a target $\mathrm{SNR} = 20$ dB at the receiver. The value of NL is related to shipping activity, wind level, biological noise, seaquakes, etc. of a particular setting and we take the value of $\mathrm{NL} = 70$ dB because it is a representative deep water case [41]. Besides, we consider that 1000 packets are transmitted with a transmission time $T_{tx} = 40$ ms.

Fig. 9 represents the energy consumption as a function of distance between sensor nodes using direct transmission or packet relaying. Packets are transmitted along a stretch via direct links or through multi-hop paths. In the first case, each sensor sends directly the gathered data to the surface sink. Although this is the simplest way to communicate sensors, it is not the most energy efficient. We can observe that the total consumed energy using packet relaying (instead of direct links) is reduced. In the packet

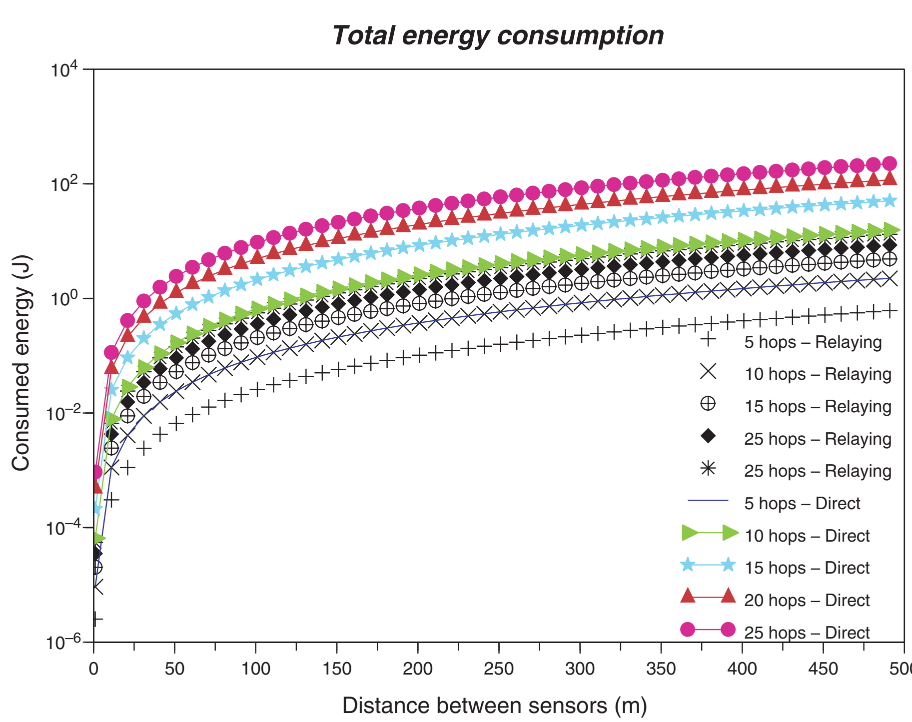

Fig. 9. Total energy consumption in deep water via direct links or through multi-hop paths (relaying).

relaying case, the data produced by a source sensor is forwarded through multi-hop paths by intermediate sensors until it reaches the surface sink. This technique results in energy savings. What is more, for a fixed distance between sensors, if the number of sensor nodes is increased, the total energy consumed is increased because more nodes are far away from the surface sink and the power necessary to transmit is proportional to the square of the distance. Finally, we can observe that for a fixed number of sensor nodes, if the distance between sensor nodes is increased, the total energy consumed is increased, too because the transmission power is related to the square of the distance.

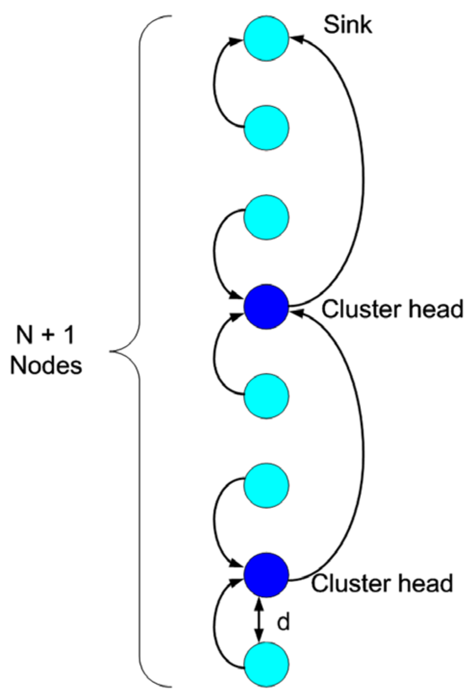

Fig. 10. Linear network for the deep water scenario that applies clustering.

Now we have decided to compare the relaying method, which shows the best results, with a routing protocol based on clustering. In the clustering scheme proposal (see Fig. 10), the nodes are distributed in a linear network and adjacent nodes are grouped into clusters (time division multiple access (TDMA) can be used in each cluster for communication [36]). As we can see in Fig. 10, a cluster head is selected every three nodes with exception of the neighbour of the sink, which delivers its packets directly. Sensor nodes should deliver the collected data to the nearest cluster head, which sends all the information from cluster head to cluster head until it reaches the underwater sink.

The results are shown in Fig. 11. We can observe that using the clustering method the total energy consumed is slightly less than with packet relaying for the same number of sensor nodes and the energy expense is increased with the distance between sensor nodes. Besides, the inclusion of additional nodes increases the energy consumption in both cases.

If we compare the results obtained with the shallow and with the deep water scenario, we can conclude that the routing protocols based on the clustering scheme save more energy and they show a better performance in shallow water.

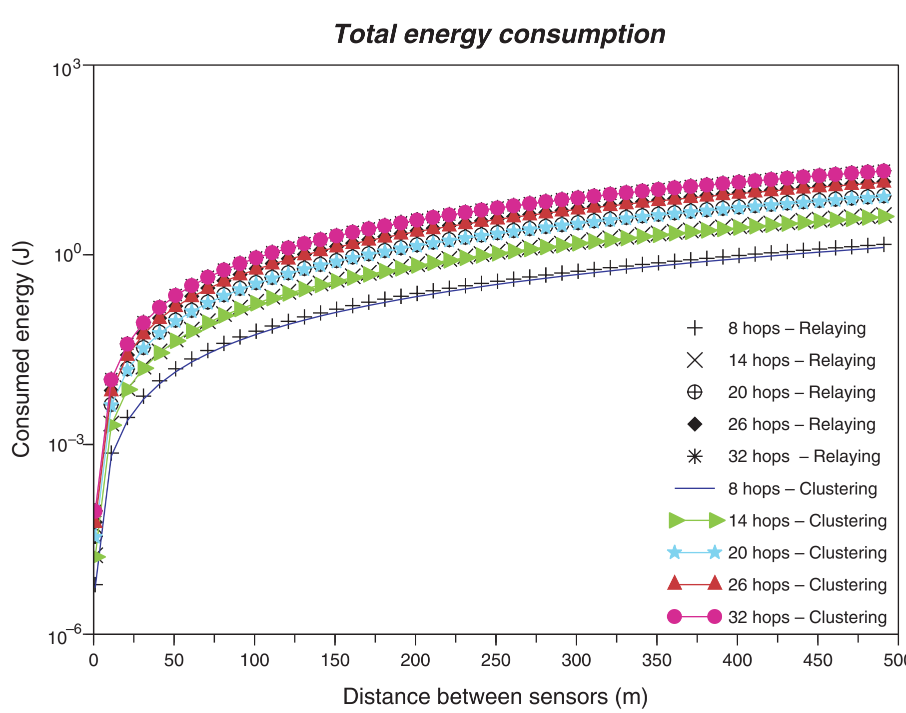

Fig. 11. Total energy consumption in shallow water through multi-hop paths (relaying) or clustering.

4. Conclusions

In this paper we have analyzed theoretically the total energy consumption in underwater acoustic sensor networks because UWSNs have a limited energy supply and consequently the energy required per transmission should be minimized. To achieve this purpose, we have introduced the components of a general reference architecture for UWSNs and have described the different existing networking architectures. From here on, we have considered two different scenarios (deep and shallow water) and have carefully studied the propagation of sound in the sea to derive later a general expression of energy consumption adapted to each scenario. We have proposed different functioning principles for routing protocols in UWSNs (packet relaying, direct transmission and clustering) and have analyzed the total energy consumption for each case, establishing a comparison between them.

The analysis carried out proves that the worst method is direct transmission, which shows bad results in the deep water scenario and is not recommended because it reduces the network throughput due to increased acoustic interference caused by high transmission power.

The packet relaying technique results in energy savings in the deep water scenario and increases the network capacity, although it increases the complexity of a routing protocol based on this method, as well, and results in increased end-to-end packet delay.

The analysis carried out proves that the routing protocols based on the clustering scheme save more energy and they show a better performance in shallow water. What is more, it has been demonstrated that the clustering scheme is scalable with respect to the number of sensor nodes and the distance between them.

As future work we are planning to design an energy-efficient routing protocol based on clustering that maximizes throughput and reliability while minimizing power consumption.

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