Energy Analysis of Routing Protocols for Underwater Wireless Sensor Networks

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Differences between Underwater Networks and Terrestrial Networks

- Large propagation delays: The propagation speed of acoustic signals in water is about $1.5 \times 10^3$ m/s.

- Node Mobility: Underwater sensor networks move with water current ($3 - 6$ km/h).

- Underwater networks consume more power than terrestrial networks due to the underwater channel characteristics.

- High error probability of acoustic underwater channels (noise, multi-path and Doppler spread).
Outline

1. Different Underwater Networks Architectures
2. The Signal-to-Noise Ratio (SNR) & Transmission Loss
3. Energy Consumption in Shallow Water
4. Energy Consumption in Deep Water
5. Conclusion
Outline

1 Different Underwater Networks Architectures

2 The Signal-to-Noise Ratio (SNR) & Transmission Loss

3 Energy Consumption in Shallow Water

4 Energy Consumption in Deep Water

5 Conclusion
Different Underwater Networks Architectures

- Static two-dimensional UWSNs for ocean bottom monitoring
- Static three-dimensional UWSNs for ocean column monitoring
- Three-dimensional networks of autonomous underwater vehicles (AUVs)
Underwater wireless sensor networks (UWSNs)

bour 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 cannot 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 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 have been specifically designed for UWSNs. Some of them are location-based; in the authors use the concept of routing vector (defined as a vector from the source to the sink or as a vector for each single forwarder (hop-by-hop vectors)); in 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 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 the authors propose a dynamic proactive routing protocol that includes three steps, route discovery, route maintenance and route invalidity. In 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 as well as for the deep water scenario.

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, but the differences are the following ones: In 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 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. Underwater wireless sensor networks (UWSNs).

Data transmitted to the on-shore command center
Outline

1. Different Underwater Networks Architectures
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The Signal-to-Noise Ratio (SNR)

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

\[
\text{SNR} = \text{SL} - \text{TL} - \text{NL} - \text{DI} + \text{P} \geq \text{DT}
\]

- **DT** is 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)
- **DI** is the directivity index
Transmission Loss

Transmission loss is defined as the accumulated decrease in acoustic intensity as an acoustic pressure wave propagates outwards from a source.

Transmission loss

\[ TL = 10 \log \frac{I_0}{I_1} = 10 \log I_0 - 10 \log I_1 \]

Transmission loss & source level

\[ TL = 10 \log \frac{I_0}{I_1} = 10 \log \left( \frac{10^{\frac{SL}{10}}}{I_1} \right) = SL - 10 \log I_1 \]
1. Different Underwater Networks Architectures

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The authors consider a linear network that includes $N + 1$ nodes and a distance $d$ between each two nodes.

This network transmits packets of $K$ bits from sensor nodes to the underwater sink.

The linear network represents the worst case scenario for network lifetime.
The spreading loss is cylindrical since the acoustic signals propagate with a cylinder bound by the surface and the sea floor.

The power level crossing the cylindrical surface at ranges \( r_1, r_2 \)

\[
P = 2 \pi r_1 H l_1 = 2\pi r_2 H l_2
\]

\( I \) is the intensity of the signal and \( H \) is the height between the bottom and the surface of the sea.

\[ \text{Cylindrical spreading} \]

\[ P \quad 2\pi r H l \]

\[ 2\pi r H l \]

\[ r_1 \]

\[ r_2 \]

\[ H \]

Fig. 3. Spreading in a medium between two parallel planes (cylindrical spreading).
Energy consumed during transmission for one node

\[ E_{\text{total}} = NPT_{tx}K \]

- \( N \) represents the number of hops towards the surface sink
- \( T_{tx} \) represents the transmission time for one packet
- \( K \) Represents the total number of the transmitted packets from the source node

Consumed energy for packet relaying

\[ E_{\text{total}} = NPT_{tx}K + (N - 1)PT_{tx}K + (N - 2)PT_{tx}K + \cdots + PT_{tx}K \]

\[ = \frac{N(N + 1)PT_{tx}K}{2} \]
The total energy consumption when each node along the stretch has $K$ packets to transmit using direct access is calculated as:

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

where:

- $E_{\text{total}}$ is the total energy consumption.
- $K$ is the number of packets.
- $T_{tx}$ is the transmission time.
- $N$ is the number of hops.
- $P(r_1 = id)$ is the probability of a particular packet distance.

The equation so written is:

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

where $N$ represents the number of hops towards the surface sink, $T_{tx}$ represents the transmission time, and $K$ represents the number of packets to transmit using direct access.
Represent the Power in Intensity and Transmission Loss

Transmission loss where \( r_1 = 1 \)

\[
TL = 10 \log \frac{I_1}{I_2} = 10 \log r_2
\]

The transmission loss caused by cylindrical spreading and absorption (or attenuation)

\[
TL = 10 \log r + \alpha r \times 10^{-3}
\]

Absorption coefficient

\[
\alpha = \frac{0.1 f^2}{1 + f^2} + \frac{40 f^2}{4100 + f^2} + 2.75 \times 10^{-4} f^2 + 0.003
\]
Represent the Power in Intensity and Transmission Loss (Cont.)

**Total transmission loss taking into account**

\[
TL = 10 \log r + \alpha r \times 10^{-3} + A
\]

- Multiple path propagation (speed, temperature, depth and salinity)
- Refraction effects
- Diffraction and scattering of sound by particles, bubbles and plankton within the water column

**Intensity**

\[
I_1 = 10^{\frac{SL-TL}{10}} = 10^{\frac{SL-10 \log r_1 - \alpha r_1 10^{-3} - A}{10}}
\]

**Total power**

\[
P = 2\pi r_1 HI_1 = 2\pi r_1 H 10^{\frac{SL-10 \log r_1 - \alpha r_1 10^{-3} - A}{10}}
\]
### Parameters Values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNR</td>
<td>$20dB$</td>
</tr>
<tr>
<td>NL</td>
<td>$70dB$</td>
</tr>
<tr>
<td>DI</td>
<td>$3dB$</td>
</tr>
<tr>
<td>H</td>
<td>$75m$</td>
</tr>
<tr>
<td>N. of Packets</td>
<td>$1000$</td>
</tr>
<tr>
<td>Ttx</td>
<td>$40ms$</td>
</tr>
</tbody>
</table>
Total Energy Consumption in Shallow Water via Direct Links or Through Multi-Hop Paths

**Total energy consumption**

- 5 hops – Relaying
- 10 hops – Relaying
- 15 hops – Relaying
- 20 hops – Relaying
- 25 hops – Relaying
- 5 hops – Direct
- 10 hops – Direct
- 15 hops – Direct
- 20 hops – Direct
- 25 hops – Direct

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

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

- NL = 70 dB because it is a representative shallow water case.
- 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.

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 represents a realistic deployment scenario.
Cluster head is selected every three nodes with exception of the neighbor of the sink, which delivers its packets directly.

Sensor nodes should deliver the collected data to the nearest cluster head.

This cluster head sends all the information to and other cluster head until it reaches the underwater sink.
Total Energy Consumption in Shallow Water Through Multi-Hop Paths (relaying) or Clustering

represents 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:

$$P = \frac{4\pi r^2 I}{1} = \frac{4\pi r^2 I_1}{2} = \ldots$$

Then, if $r_1$ is taken as 1 yd ($\frac{1}{3.048} m$), the transmission loss to range $r_2$ (considering only spreading effects) has been defined as:

![Graph showing total energy consumption in shallow water through multi-hop paths (relaying) or clustering.](image-url)
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The authors consider a linear network that includes \( N + 1 \) nodes and a distance \( d \) between each two nodes.

This network transmits packets of \( K \) bits from sensor nodes to the underwater sink.

The linear network represents the worst case scenario for network lifetime and applies to surveillance applications or monitoring of ocean phenomena.

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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]:

\[
P = \frac{4\pi r^2}{I_1} = \frac{4\pi r^2}{I_2} = \ldots
\]

Then, if \( r_1 \) is taken as 1 yd (\( \approx 1 \) 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).](image-url)
Spreading Loss in Deep Water

- In deep oceans, the propagation range is not bounded by the sea floor and the surface
- The spreading loss is spherical
- The power generated on the sphere surface is:

\[ P = 4\pi r_1^2 I_1 = 4\pi r_2^2 I_2 = \ldots \]
**Represent the Power in Intensity and Transmission Loss**

### Transmission loss where \( r_1 = 1 \)

\[
TL = 10 \log \frac{I_1}{I_2} = 10 \log r_2^2 = 20 \log r_2
\]

### Total transmission loss

\[
TL = 20 \log r + \alpha r \times 10^{-3} + A
\]

### Intensity

\[
I_1 = 10^{\frac{SL-TL}{10}} = 10^{\frac{SL-20 \log r_1 - \alpha r_1 10^{-3} - A}{10}}
\]

### Total power

\[
P = 4\pi r_1^2 I_1 = 4\pi r_1^2 10^{\frac{SL-20 \log r_1 - \alpha r_1 10^{-3} - A}{10}}
\]
Now we consider that in Fig. 7 the sensor node located at a distance $N_d$ from the surface sink, where $N_d$ 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 is:

$$P_{tx} = 10 \log \frac{I_1}{I_2} = 20 \log r_2$$

where $I_1$ and $I_2$ represent the power levels at the source and sink, respectively, $r_2$ is the range expressed in yards, and $a_b$ is the range expressed in units dB/km. Eq. (23) states how to calculate the value of $I_2$ etc. of a particular setting and we take the value of $A_{3}$ packets via direct links or through multi-hop paths (relaying). We have examined several parameters related to shipping activity, wind level, biological noise, seaquakes, etc. of acoustic modems and hydrophones. Therefore, we can express Eq. (24) as:

$$E_{relaying} = \sum_{i=1}^{K} P_{tx} \times T_{tx}$$

where $P_{tx}$ is the power level and energy consumed in transmitting a packet, $T_{tx}$ is the transmission time for one packet (in ms), and $K$ is the number of hops towards 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 communication, it is not the most energy efficient.

As a result, we consider a directivity index $DI = 3$ dB and a target SNR = 20 dB at the receiver. The value of $NL$ is related to spreading, attenuation and transmission loss anomaly, expressed in the same way as in Eqs. (12) and (13). We have derived a relation between the total energy consumption ($E_{total}$) and the consumed energy ($E_{relaying}$) in deep water via Direct Links or Through Multi-Hop Paths (relaying).
Apply Clustering in Deep Water

- Sensor nodes should deliver the collected data to the nearest cluster head.
- This cluster head sends all the information to and other cluster head until it reaches the underwater sink.

![Diagram of clustering in deep water](image-url)
Total Energy Consumption in Deep Water Through Multi-Hop Paths (relaying) or Clustering

In the 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.

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.
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Conclusions

- The paper analyzed theoretically the total energy consumption for two different scenarios (deep and shallow water) in underwater acoustic sensor networks.

- It proposed different functioning principles for routing protocols in UWSNs (packet relaying, direct transmission and clustering).

- There is no significant differences between direct transmission and relaying in shallow water.
Conclusions (Cont.)

- Direct transmission shows bad results in the deep water

- The packet relaying technique results in energy savings in the deep water scenario

- Clustering scheme save more energy and they show a better performance in shallow water
THANK YOU

Questions?