Deep-ocean Data Acquisition Using Underwater Sensor Networks

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ABSTRACT

The traditional approach of ocean data acquisition, based on the deployment of battery operated stations with sensors for data recording during some programmed time for later recovery, has several drawbacks that may be overcome with the use of Underwater Sensor Networks (UWSN). In this work we investigate the feasibility of UWSN for deep-ocean data acquisition. The limitations of acoustic channel are discussed and taken into account to analyze the feasibility of this class of network for one important application, deep-ocean current monitoring. Also, we propose a method for UWSN synchronization based on the tide variations.

KEY WORDS: Underwater; acoustic; sensor; network; synchronization; tide.

INTRODUCTION

There is an increasing interest in acquiring oceanographic data due to the importance of the ocean to different aspects of human life. Navigation, fishing, ecology, weather influence and support for petroleum offshore exploration are some of the examples of this importance. Nevertheless, although covering more than 70% of the Earth surface, the oceans are not well known due to their dimensions, difficulties of data acquisition and the high costs of maritime equipment and operations.

The traditional approach for data acquisition and ocean monitoring is based on several sensors gathered in one station operating on batteries. This station is left in the ocean in the place of interest and keeps recording data during some programmed time, which may last several days, weeks, or even months. At the end of the programmed time the station is recovered for data upload, processing, and analysis.

This kind of data acquisition has been used for long time but it has severe drawbacks: it is limited to one point of survey, it does not allow the monitoring of data quality during the mission, it has limited storage capacity and the acquisition parameters must be established at the beginning of operation and must remain unchanged until the end of the mission. Moreover, it is not possible to guarantee the sensors health during the mission. Frequently, we only discover at the end of the mission, that some sensors have failed and have recorded no data. For shallow waters, there are experiences connecting cables from the sensor station to a radio-equipped surface buoy to transmit sensors data to a land station in real time, but this solution is still limited to one point of survey. Furthermore, for deep-water there is the operational complication of long cable lengths.

The use of UWSN may overcome the drawbacks of this traditional way of ocean data acquisition but, although UWSN has been pointed out as solution for a lot of applications, some precautions must be taken in the analysis of its feasibility. To start with, there is a problem with the physical medium.

Although underwater communication may be accomplished through optic or electromagnetic waves, the effective technology for UWSN is acoustic. Therefore, the acoustic channel limitations must be taken into account on application feasibility analysis. In this work we discuss these limitations and show the feasibility of UWSN for sea current monitoring. Sea current monitoring is one of the most important underwater parameter, due to its influence on the weather and on the planning and execution of petroleum offshore exploration (Brown, Nicholas, Driver, 2005).

We also propose a method for nodes synchronization based on tide variations, even for deep-ocean scenarios. UWSN synchronization is challenging. The solutions known are based on periodical acoustic message exchanges between neighbor nodes, which consume energy. Tide variations may be passively monitored by all UWSN nodes to get a rough, yet reliable synchronization.

This work is organized as follows: Section UNDERWATER SENSOR NETWORKS describes those sensor networks, their possible topologies and a common architecture. Section UNDERWATER COMMUNICATIONS focuses on the underwater acoustic channel. In section APPLICATIONS REQUIREMENTS, we review important features to be observed, due to the acoustic channel limitations. In section SYNCHRONIZATION IN UWSN, we propose a method for UWSN synchronization based on tide variations and present some real data to support our proposal. In section UWSN APPLICATION: SEA CURRENT MONITORING we demonstrate the feasibility of this important application using UWSN. We summarize this work in CONCLUSIONS section.

UNDERWATER SENSOR NETWORKS

UWSN are based on battery-operated nodes equipped with sensors and communication resources. The nodes can wirelessly communicate with each other to exchange data and commands.

These networks may be composed of fixed nodes, mobile nodes or a mix of them. A good approach of these possibilities may be seen on Akiyldiz, Pompili, and Melodia (2005).

The nodes of UWSN may be arranged on a 2D topology, with all nodes resting at the sea bottom, or on a 3D topology, with nodes at different depths, each one anchored to the sea bottom through cables. In this case the nodes need a buoy to float and to keep the anchor cable stretched.

The UWSN may be used for real time data monitoring, with sensors communicating all the time with a control station. This type of operation spends too much energy with transmissions and, especially if the data packets are large and generated at high rate, it is applicable only to short-term cases. Another mode of operation is based on a DTN (*Delay and Disruption Tolerant Network)*. In this class of networks the nodes keep a stand alone operation of data acquisition until a mobile node comes to it, periodically, to retrieve their data. Due to the absence of long range transmissions this operation spends low energy and is suited to long-term data acquisition. Vasilescu, Kotay, Rus, Dunbain and Corke (2005) describe their experiments with this class of UWSN.

One of the possible architectures for an UWSN is shown in Figure 1. On this simple architecture the sensor nodes are fixed around a sink node and send the sensed data to this sink, if close enough, or forward to it data received from other nodes, farther from the sink. The sink node has two communication channels, one to communicate horizontally with the sensor nodes and the other to communicate vertically with a gateway on the sea surface. This gateway may be connected through a radio link to a land station, from which one may monitor and control the data acquisition of all nodes.

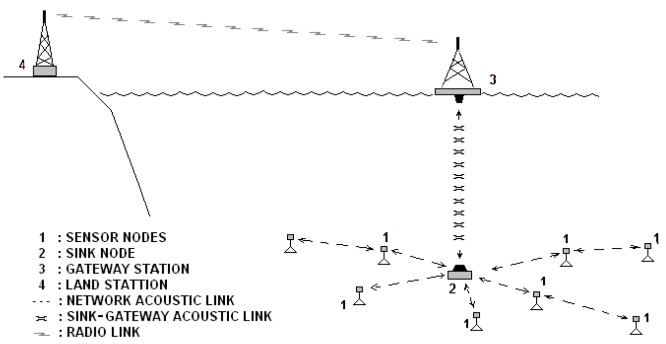

Figure 1. Architecture of a typical UWSN.

Although the nodes of UWSN may be connected trough copper wires or optical fibers, this solution is not suitable for most of applications, since it limits the architecture flexibility, restricts network topology to 2D and requires special connectors and insulations. In such a cabled UWSN it would be difficult to add or remove nodes dynamically, especially on sites with high exploration activities and obstructions. Optical fibers may be useful to make the link between the sink node and the gateway station, instead of the acoustic link (figure 1), or to supply an UWSN infrastructure to connect several sink nodes through a large regional area, as described by Freitag, Stojanovic, Grund and Singh (2002). Figure 2 shows an example of such infrastructure.

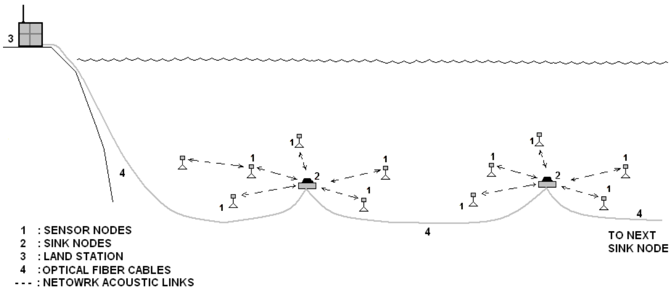

Figure 2. Fiber optics infrastructure to connect sink nodes to land station.

But even with this kind of infrastructure, an UWSN needs wireless communication, to be flexible and easy to implement and maintain.

UNDERWATER COMMUNICATIONS

Underwater wireless communications may be accomplished by means of optical, electromagnetic, or acoustic waves. Although possible, optical and electromagnetic communications in sea water have severe drawbacks that make them unfeasible for UWSN applications.

Electromagnetic

The main drawback of electromagnetic transmission in the sea water is attenuation due to the medium absorption. The absorption increases with the frequency and even at low frequencies the power necessary for electromagnetic transmissions turn them unfeasible for practical UWSN applications.

Optic

Although providing very high data rates and very low power consumption, optical transmission in sea water has the drawback of short-range achievable, due to the absorption and scattering of light. Depending on the water turbidity, the range achievable of optical transmission may be as short as one meter, and even into clear sea water the practical range of optical transmissions does not exceed a few meters. Furthermore, even at short distances a precise alignment is needed between transmitter and receiver to get efficient communication.

Because of these drawbacks, optical transmissions are suited only to UWSN applications that tolerate the limitations of DTN, as described in Vasilescu, Kotay, Rus, Dunbain, and Corke (2005).

Acoustic

Acoustic transmission is the practical method for underwater communication and, hence, the most used to implement UWSN.

Nevertheless, the acoustic channel still has characteristics that restrict its usage, such as low and variable propagation speed, low and distance-dependable bandwidth and high power consumption. These limitations must be taken into account when analysing the feasibility of UWSN applications. Moreover, due to the differences between acoustic transmissions in water and electromagnetic transmissions in the air, solutions issued from terrestrial wireless sensor networks may not be adequate for the underwater ones.

Liu, Zhou, and Cui (2008) review underwater communication using these three technologies.

Sound Speed in Sea Water

The sound speed in water is around 1,500 m/s, more than four times faster than the speed of sound in the air, but five orders of magnitude smaller than the speed of electromagnetic waves in the air. This characteristic imposes high latency to acoustic communications (approximately 0.67 s/km), which is one of the biggest challenge to UWSN implementation. Therefore, the design of UWSN communication protocols is difficult, especially in terms of Medium Access Control (MAC). Also, it imposes difficulties for building protocols which rely on time synchronization.

Apart from being low, the sound speed in water is variable: it depends on pressure (depth), density, temperature, and salinity (Urick, 1983). Due to the combination of these dependencies, the sound speed in sea water varies from the surface to the bottom according to a curve known as *sound speed profile,* as shown in Figure 3(a) (Brekhovskikh and Lysanov, 1991).

Due to this characteristic the sound in sea water may propagate through curved paths, due to sound wave refractions in continuously different-speed adjacent layers. Figure 3(b) (Brekhovskikh and Lysanov, 1991) shows the SOFAR (*Sound Fix and Ranging*) channel, formed around Z_m, due to the speed variation inversion in the sound speed profile. In Figure 3(a) "*C*" is speed whereas "*Z*" is depth. C_0 is the speed in the surface, C_h is the speed in the sea bottom, and C_m is the speed at a depth of Z_m. Z_m varies with the latitude.

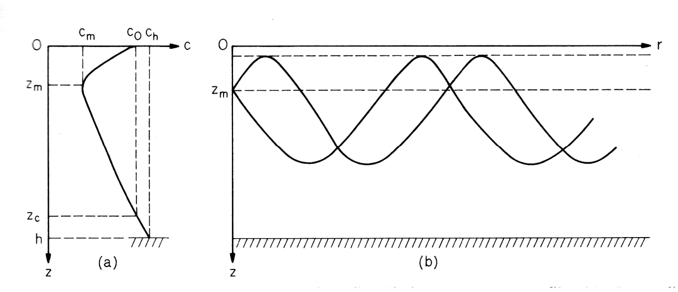

Figure 3. Sound speed profile (a), and the SOFAR channel (b).

Acoustic Channel Bandwidth

Mainly due to the sound transmission losses and noise at the receiver, the bandwidth available and the center frequency of the acoustic channel are variable, and decreasing with the distance.

Transmission loss is caused by energy spreading and sound absorption. The loss due to energy spreading depends on the transmitter-receiver distance, but absorption loss increases also with frequency.

Ambient noise is predominant in deep sea and its power spectral density is considered to decay at 20 dB/decade. The dependencies between bandwidth, transmitter-receiver range and SNR (Signal/Noise Ratio) at the receiver are illustrated in Figure 4 (Stojanovic, 2003).

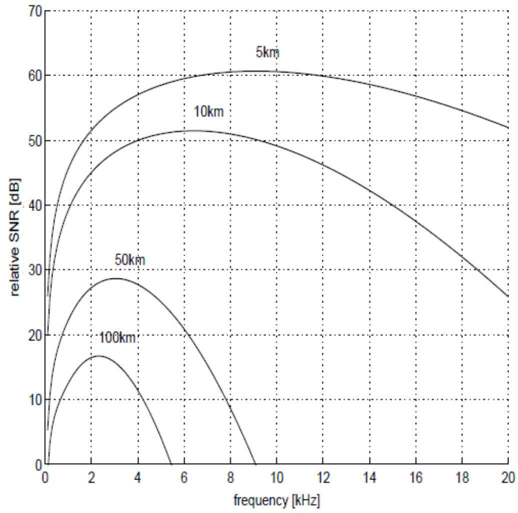

Figure 4. Frequency-dependent portion of SNR (Stojanovic, 2003).

Figure 4 shows the relationship between SNR and frequency to four different distances: 5 km, 10 km, 50 km, and 100 km. The longer is the transmitter–receiver distance, the narrower is the available bandwidth. Also, Figure 4 shows that the best communication frequency depends on the transmitter-receiver distance: the lower the distance, the higher the central frequency.
Table 1 (data from Stojanovic, 2003) shows a classification of systems based on the relationship between Range and Bandwidth.

This characteristic limits the useful source-destination distance to a few kilometers and the transmission frequencies to less than 30 kHz. This low frequency and the narrow bandwidth imply on very low practical transmission rates, typically lower than 10 kbps.

One interesting consequence of this characteristic is that for UWSN, short-range multihop transmissions become more energy efficient than long-range one-hop ones (Sozer, Stojanovic, and Proakis - 2000).

Table 1. Acoustic channel bandwidth as a function of the distance.

System	Range (km)	Bandwidth (kHz)
Very Long	1000	less than 1
Long	10 – 100	2 – 5
Medium	1 – 10	approximately 10
Short	0.1 - 1	20 – 50
Very Short	less than 0.1	larger than 100

Energy constraints

In underwater acoustic communication another important issue to take into account is energy consumption. Nodes of UWSN are battery operated and the power necessary for underwater acoustic transmissions is much higher than terrestrial radio ones. Acoustic signal is based on mechanical waves of alternating compressions and rarefactions of the water, requiring high power for transmissions. Kredo and Mohapatra (2007) made a comparison between acoustic and electromagnetic power, summarized in Table 2.

Table 2. Node power comparison.

State	Underwater	RF Sensor
TX	50 W	80 mW
RX	3 W	30 mW
Idle	80 mW	30 mW

Furthermore, a battery replacement or its recharge, which is a trivial operation in terrestrial sensor networks, is very difficult and expensive in UWSN. For this reason, it is crucial to avoid transmission losses caused by messages collisions, since this energy waste in this class of network is much more harmful than in terrestrial sensor ones.

There are several proposals dealing with Medium Access Control (MAC) protocols. Doukkali and Nuaymi (2005) did an analysis of some of them. A lot of these proposals try to adapt Radio Frequency (RF) Sensor MAC protocols to the underwater medium, but this approach is not ideal, since the RF and acoustic channels are quite different.

As a consequence, a method frequently used for medium access control in UWSN is TDMA (Time Division Multiple Access). TDMA is accomplished by cyclic assignment of a time slot for each network node transmission. During each time slot the channel is reserved to the transmission of only one node. Time slots must be separated from each other by a *time guard interval*, large enough to prevent transmissions overlapping. For the efficiency of this method, a minimal level of synchronization through the network must be guaranteed, and the *time guard interval* is defined based on the precision of this synchronization and on the maximum distance between nodes. Figure 5 shows a time representation of TDMA.

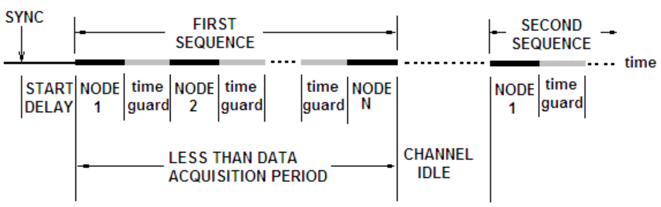

Figure 5. Time representation of TDMA.

APPLICATIONS REQUIREMENTS

Based on the exposed acoustic channel limitations one may list some requirements necessary for a data acquisition application to be securely implemented with an UWSN.

First, we must take into account that a 5 kbps data transmission rate, although conservative, is nowadays an upper limit for real acoustic modems. Higher data rates may be achieved, but under specials conditions and for short-range distances. Even the 5 kbps may not be achievable, depending on the scenario and the ambient conditions.

Mobile nodes communication in UWSN has been investigated but is a problem apart. They may be useful in DTN solutions, as proposed by Vasilescu, Kotay, Rus, Dunbain, and Corke (2005) but, for simplicity, applications with fixed nodes are more feasible with UWSN.

Due to the channel bandwidth dependence with source-receiver distance, the network node-to-node distance shall be kept under 5 km, or less if possible. Longer distances, further than implying in narrower bandwidth, require more transmission power and may expose the transmissions to medium interferences, which can compromise the communication efficiency.

Also due to bandwidth limitation and power conservation purpose, it is preferable to use multihop protocols to send data from farther network nodes to a sink node, than sending their data directly to it. This implies on the necessity of developing efficient routing protocols, but the benefit of power saving is worth. Furthermore, as we are considering fixed nodes, one may use static routing protocol, until a suited dynamic routing solution for this protocol is achieved.

We also have to consider that the amount of data to be transmitted shall not be large, to be compatible with the transmission rate available. Small packets are more likely to be successfully transmitted than larger ones. Data packets of one kbyte may carry a lot of useful information from network sensors and may be enough for several applications.

To have a good scalability in the number of possible nodes in the network, further than small packets, it is also desirable that they are generated at a periodicity as large as possible. A sampling period of one hour may be sufficient for many data acquisition purposes.
Small packets associated with low packet rate generation allow an efficient TDMA scheme with *time guard intervals* large enough to prevent transmissions overlapping and eliminating the possibility of packet collisions. Also, as larger the ratio of packet-interval and packet-size, as larger will be the network scalability in the number of simultaneous possible nodes in the UWSN.

SYNCHRONIZATION IN UWSN

Synchronization in UWSN is a very critical issue. As the nodes share the same transmission medium and due to the low bandwidth available, they shall not transmit at the same time, at least not in the same region, since this would cause messages collision and waste of the scarce energy.

To avoid collisions over an area with several nodes, a time reference common to all nodes is needed, as well as a method to organize the medium access. As discussed in the subsection ***Energy constraints***, the TDMA method may be used to avoid collisions, but its efficiency depends on minimal time synchronization.

Precise synchronization in UWSN based on the nodes' internal clocks is a challenge because, due to the harsh ambient conditions of the sea, the internal clock oscillators drift along the time and may not be used for long-term reliable synchronization. Drifts of some minutes along few months may be expected (Chirdchoo, Soh, and Chua, 2008; Heidemann, Ye, Wills, Syed and Li, 2006; "[Petroleo Brasileiro SA, private report]"). Furthermore, in the underwater environment there is no precise timing system reference, such as the Global Positioning System (GPS) which can be used for terrestrial sensor networks.

Many UWSN synchronization proposals are based on message exchanges between neighbor nodes. Syed and Heidemann (2006) expose their synchronization proposal for high latency acoustic networks and present a good review of these concepts. Although these methods may work satisfactorily, they have the drawback of spending a lot of energy with the necessity of periodical acoustic transmissions. They may be feasible for short-term missions, but, due to the costs involved in maritime operations, it is desirable that UWSN operations last as much as possible, which make the energy saving a crucial issue.

In this work, we argue that a rough yet reliable synchronization – since based on astronomical events – may be accomplished with the periodic ocean tides. Over a reasonably large area – tens or even hundreds of kilometers – one may consider that the cyclic tide variations effect is the same and may be observed with small delays from all nodes of a quite large UWSN, even at deep waters. The small delay is due to the *tidal wave* velocity – the tide in equator travels from East to West at a velocity of approximately 40,000 km/day. Within a range of 25 km along the equator line one may consider that this delay is less than one minute. Anyway, if we consider that the nodes are at fixed and known positions, one may compute those delays.

The tide variation may be monitored in real time by all nodes of an UWSN through a simple pressure measurement. It is possible to measure changes of 10 centimeters of tide variations at a depth of 1000 meters with existing equipment. As an example, Figures 6 and 7 show the locations and a graph of pressure measurements in 2 sites on the Brazilian coast during 16 days. Points N3 and S3 are at approximately 2,000 meters depth and are more than 130 kilometers apart from each other. Figure 7 shows the perfect synchronization between the tide variations on both sites. In this graph the two real curves had to be shifted by +/- 10 centimeters to make it possible to distinguish them from one another.

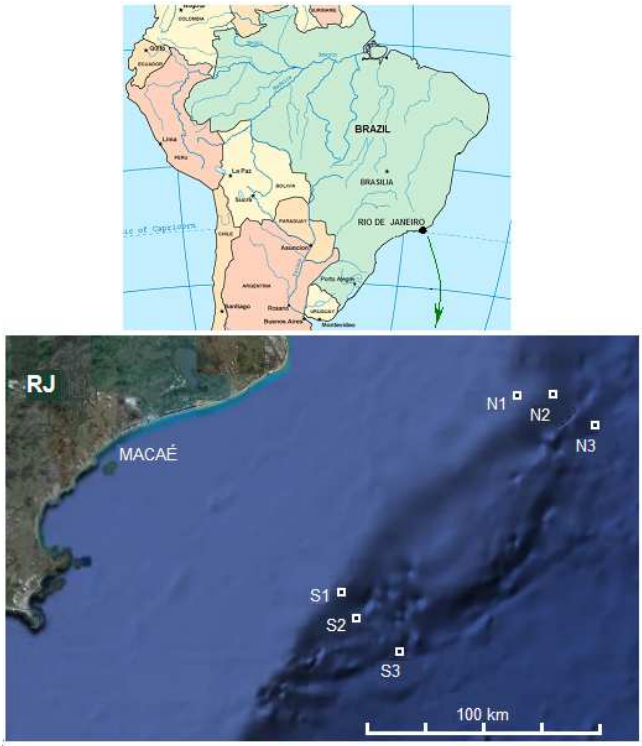

Figure 6. Location of tide measurements. The approximately depths are: N1/S1: 200 m; N2/S2: 1,000 m; and N3/S3 2,000 m.

The synchronization based on this effect may be done through the identification, by each UWSN node, of the maximum and minimum values of the tide "curve", which are periodical and regularly separated by approximately 6 hours.

Tides may be affected by sources other than astronomical ones, like atmosphere variations. Nevertheless, it does not prevent tide utilization as a reference of time, since this anomaly affects the underwater pressure in the UWSN nodes in the same way, simultaneously.

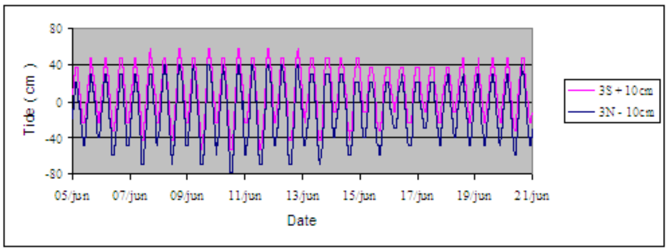

Figure 7. Tide variations on sites S3/N3 during 16 days. The curves had to be shifted by +/- 10 cm to be distinguishable

We can get a precision of one minute with the proposed tide-based synchronization scheme. This precision will be enough for many applications, since the underwater parameters do not change so quickly.

UWSN APPLICATION: SEA CURRENT MONITORING

Sea current measurement is accomplished with ADCP equipment (Acoustic Doppler Current Profiler). The method used to measure water currents is based on the analysis of sound reflections on suspended particles in moving water. The Doppler effect of these reflections allows precise measurements of water velocities over different layers of water crossing the acoustic beams emitted from the ADCP.

This equipment normally operates attached to the sea bottom, as shown in Figure 8, and is programmed to sample the sea currents above it at fixed intervals, until the ADCP is recovered to have its data uploaded to be processed and analyzed. A commonplace sampling interval for this data acquisition is one hour. Each of these samples is coded into a data packet, typically with less than one kbyte. These parameters comply with the requirements for a feasible UWSN discussed in the section APPLICATION REQUIREMENTS.

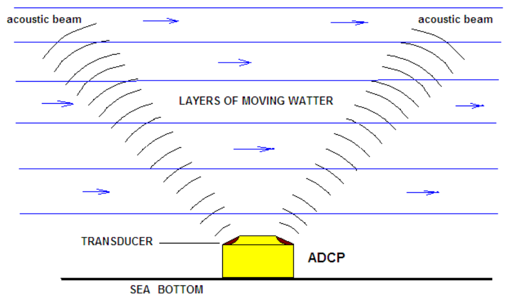

Figure 8. Sea bottom ADCP operation.

As an example, consider a scenario with 12 nodes, each one with an ADCP and an acoustic modem, arranged as shown in Figure 9. In this scenario the shortest distance between neighbor nodes is approximately 5 km. For a transmitter-receiver distance of 5 km, the channel bandwidth available is approximately 10 kHz, which leads to a transmission rate of up to 5 kbps.

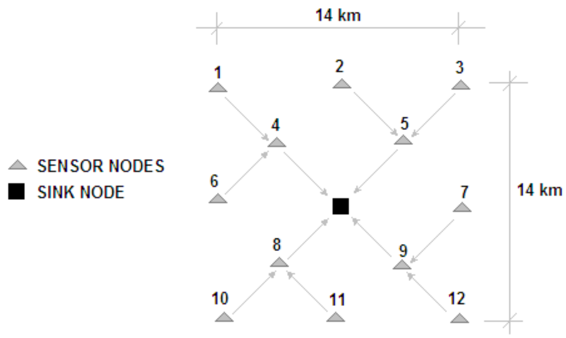

Figure 9. UWSN example scenario.

This scenario allows sea currents monitoring over a square area of 196 km^2, a quite real scenario. Nodes 4, 5, 8 and 9 are at one hop from the sink node whereas remaining nodes are at two hops from it. Considering data packets of one kbyte and a transmission rate of 5 kbps, we have that the Packet Transmission Time (PTT) is:

$$PTT = (1000 \times 8\, bits)/(5000\, bits/s) = 1.6\, s \quad (1)$$

As the nodes distances are 5 km, the Traveling Time (TT) will be:

$$TT = (5000\, m)/(1500\, m/s) \cong 3.33\, s \quad (2)$$

Thus, the Total Transmission Time (TTT) of one packet over one hop is:

$$TTT = PTT + TT = 1.6\, s + 3.33\, s \cong 5\, s \quad (3)$$

If we choose a security margin of 20% to define the TDMA time slot (TS) necessary for the transmission over one hop, then we have:

$$TS = TTT \times 1.2 = 6\, s \quad (4)$$

As we have nodes that are at two hops from the sink, we have to consider that the Total Time Slot (TTS) for all nodes in the UWSN must be the double of TS. This time may be considered as a *channel reservation time* for each node. Hence the TTS, considering a security margin of 20%, will be 12s.

Nevertheless, each time slot must be separated from each other by a *time guard interval* (TGI). Being conservative we set TGI to one minute, to be compatible with the tide synchronization described in section SYNCHRONIZATION IN UWSN. Then, we conclude that each node will need at maximum only 1 minute and 12 seconds to send their data to the sink node, directly or through two hops. As we have 12 nodes in this scenario, the total allocation channel time needed to send the data of all nodes to the sink node will be 14 minutes and 24 seconds.

At the end of the reception of the packets from all nodes, the sink node can gather these packets into a unique packet of 12 kbyte and send it to the gateway through the vertical acoustic channel. Again, considering a transmission rate of 5 kbps between sink node and gateway station, the Time from Sink to Gateway (TSG) transmission will be:

$$TSG = (12000 \times 8\, bits)/(5000\, bits/s) = 19.2\, s \quad (5)$$

Supposing that the Sink node is at 2,000 meters depth, the Travel Time from Sink to Gateway (TTSG) will be:

$$TTSG = (2000\, m)/(1500\, m/s) \cong 1.33\, s \quad (6)$$

Then, the total time spent to send the data of all nodes from Sink to Gateway is 20.52s.

As we need only 20.52 seconds and have more than 40 minutes to transmit those data to the gateway, we may slice this transmission into smaller packets to reduce the packet error probability.

Two time slots may be added at the beginning of each sequence, reserved for communication from Land Station to sink node and from sink node to any one of the UWSN nodes, to send commands and controls to the ADCPs.

Since the period of data acquisition is one hour, the channel will be idle most of the time, since we need less than 20 minutes for all transmissions, even with the large security margin for each node transmission and the conservative TGI chosen.

Even if we need to half the transmission rate to 2.5 kbps, the situation will still be similar, since we chose a TGI much greater than TTS.

This scheme has no feedback to the sending node about its transmission success. In noisy ambient we may incorporate an exchange of messages between sender and receiver nodes to improve the communication.

One improvement may be done with the implementation of a simple hand-shake: after sending a packet the sender waits an acknowledgement (ACK) from the receiver. If it does not receive the ACK until a specific timeout, it automatically tries up to two retransmissions, giving up after that. Figure 10 shows this hand-shake.

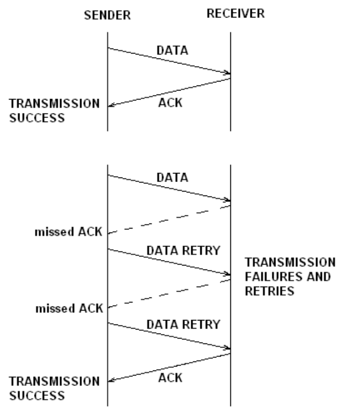

Figure 10. Reliable transmission hand-shake operation.

This additional hand-shake does not impact the feasibility of the application, since each ACK transmission adds only 3.33 seconds to each time slot. As the time guard interval is one minute, the increase is negligible. If the land station does not receive the data from a specific node or from a group of nodes during their time slots, this indicates a failure, which may generate a warning for maintenance purposes.

As an example, the application for scenario of Figure 9, supposing time slots of one minute (in the worst case, all nodes transmit each of their data tree times), the total channel allocation time will be increased to approximately 26 minutes, still well supported for the UWSN application under analysis.

Nevertheless, since one of the most important requirements of feasible UWSN is energy saving, this hand-shake shall be avoided and implemented only if necessary, since the transmission of ACKs for each received packet will consume energy of the UWSN nodes.

Routing in UWSN is still an open question. Most of the proposals need periodic message exchanges between all nodes of the UWSN to update routing tables and to monitor the links status. This consumes energy and compromise the network performance. Therefore, as for this application the nodes are at fixed positions, one may use static routing, as shown in Figure 7. For instance, node 4 is programmed to forward to the sink node the messages it receives from nodes 1 and 6. As one does not expect frequent changes in the scenario, static routes are acceptable.

CONCLUSIONS

In this work, we have analyzed important issues of the acoustic channel that must be taken into account when considering the use of UWSN for deep-ocean data acquisition. Fixed nodes, low data rates transmissions, up to 5 kbps, short node-to-node distances, as 5 km, small data packets, as 1 kbyte, and 1 hour of data acquisition periodicity are key features to pursuit when electing applications for feasible UWSN. We have demonstrated that deep-ocean current monitoring using ADCP equipment comply with those requirements and, hence, is a feasible application for UWSN. The high ratio between packet-interval generation and packet-size of this application allows the use of a secure TDMA scheme as method to multiple medium accesses, avoiding energy waste due to transmission collisions. This analysis is applicable to other deep-sea data acquisition with same characteristics. Also, we have proposed a method to get a rough but reliable synchronization method based on tide monitoring.

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