Telecommun Syst (2015) 58:91–106
DOI 10.1007/s11235-014-9948-6

Underwater monitoring system for oil exploration using acoustic sensor networks

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Received: 28 August 2014 / Accepted: 8 December 2014 / Published online: 24 December 2014

Abstract This paper proposes an underwater monitoring system built with sensors distributed over a subsea infrastructure, which is responsible for operation and transportation of oil production. We consider the use of currently available equipment. Data is transmitted by underwater acoustic modems installed on the sensors, platforms and vessels used for logistic support of the oil exploration. These vessels are used to collect data and provide references for positioning the sensors. However, the vessels may not be within the sensor range at all times, requiring the use of Delay/Disruption Tolerant Network. This work performs an analysis of the behavior of the monitoring system, investigating the features that influence the underwater sensor network, using the Opportunistic Network Environment simulator. In this case, the displacement of logistic-support vessels on the maritime routes is very important, therefore we consider real-world scenarios based on the Brazilian offshore oil exploration area.

Keywords Monitoring system · Delay-Tolerant Network · Underwater communication · Sensor networks · Acoustic communication · Positioning

1 Introduction

The Last decades in Brazil were marked by the pursuit of self-sufficiency in oil production, which succeeded thanks to technological advances in oil exploration and operation in deep water. The development of this technology has enabled numerous discoveries in the oceanic continental shelf, in a large area 70 km of shore, with water depths ranging from 120 to 2,800 m, which generate a national production of oil and gas up to 2.376 million barrels daily.

The new frontier of oil exploration is located in a region 200 km off the coast called pre-salt which comprises an area of approximately 800 km in length and 200 km in width, encompassing three basins (Santos, Campos, and Espírito Santo) [1]. However, the exploration and operation in water depths up to 3,000 m is a challenge to be overcome, requiring the use of innovative technologies to support the operational control in this extreme environment. Therefore, new communication techniques should be used to obtain information of the subsea infrastructure.

Currently the production of oil and gas is concentrated in a large area of approximately 115,000 km^2 called Campos Basin [2]. This region contributes with about 70 % of national production that is transported by an infrastructure composed of pumping equipment and several submarine pipeline networks usually distributed by large areas.

The activities of this industry are complex and dangerous, requiring a robust and reliable infrastructure to withstand the harsh conditions of the underwater environment. Nevertheless, beyond the constraints imposed by operating in high seas, the submarine relief on the Brazilian coast is irregular in places presenting an extreme slope, which exposes the submerged structures to great instability. Thus, there is a constant need for underwater monitoring. Nevertheless, the methods

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currently used limit the observation points, excluding most of subsea equipment.

Underwater sensor networks can allow monitoring of the full extent of the subsea infrastructure and particularly in subsea pipelines, providing the operational control increase through constant equipment conditions and position checking. The accurate measurement of underwater position can allow the detection of seabed instability. Therefore, the use of sensor networks on seabed for underwater positioning monitoring enables verification of submarine displacements that can cause damage to structures in the marine environment. However, communication in these circumstances is subject to several limitations, including losses in the transmission channel, low bit rates, and large transmission delays [3].

As a consequence, the development of an architecture based on underwater communication with Delay/Disruption Tolerant Networks (DTN) [4] is a necessity. Monitoring applications based on DTN networks can cope with the delays and interruptions caused by interference and variability of the underwater environment.

The proposed underwater monitoring system consists of acoustic sensors, platforms, and logistic-support vessels. The acoustic sensors are responsible for calculating the position, storing and transmitting the information obtained from subsea equipment. The sensors are distributed over the submarine infrastructure and subsea pipelines. Logistic-support vessels of oil exploration are responsible for the collection of messages generated by these sensors and subsequent routing to the control center. However, these vessels, in conjunction with platforms, must provide at least three known coordinates to obtain the sensor position, through trilateration of acoustic signals received. The subsea mapping is obtained with references issued by units on the surface, which provide the location with geographic coordinates and depth.

The objective of this study is to investigate the feasibility and performance of the proposed monitoring system using the Epidemic routing protocol [5], reproducing the movement of vessels within scenarios consistent with the offshore environment to verify whether it is possible to implement an underwater monitoring and positioning subsystem. Generally the costs involved in offshore operations are significant. Thus the equipment and installation costs were checked to analyze the proposed system feasibility.

The performance analysis is done using the simulator Opportunistic Network Environment (ONE) [6], which was adapted to describe the conditions of underwater communication. In addition, scenarios were configured considering the specific features of the Campos Basin, Rio de Janeiro, Brazil, to check the conditions that the network provides for the calculation of positioning and for data acquisition, both directly influenced by the availability of logistic-support vessels within range of the underwater sensors.

An underwater monitoring system based on a DTN network is feasible, even considering an area of 115,000 km^2 and the dispersion of subsea equipment. Our results show that with increasing number of vessels the system becomes more efficient. There is a larger amount of information from the sensors, which results in smaller waiting time for the routing of messages and less storage needed. With more vessels, there is also higher probability of message delivery. As these vessels are not operating specifically for the monitoring system, the cost of implementing this system is relatively low compared to the values applied to oil exploration projects.

The remainder of this paper is organized as follows: Sect. 2 presents related work. Section 3 reviews the main characteristics of underwater communication. Section 4 introduces the proposed deep-water monitoring system and describes the method used for estimating underwater positioning. Section 5 presents the scenario and parameters of the undertaken simulation. Section 6 presents the results of the system performance analysis. In Sect. 7, we analyze realistic deployment costs, while Sect. 8 concludes the paper and presents future work.

2 Related work

The current status of underwater communications reflects the improvements achieved in data transmission in water. Urick [7] presents the basic principles of underwater acoustic transmission, emphasizing the characteristics that influence the speed of sound in water, such as the pressure (related to the depth), density, temperature, and salinity. The results presented by Sozer, Stojanovic, and Proakis [8] on underwater communication open the way for using networks of acoustic communications in the underwater environment. The study of underwater communication performed by Stojanovic [9] presents the features that influence the transmission of data on the underwater acoustic channel.

Underwater communication challenges are described by Heidemann *et al.* [6], where the difficulties imposed by the media and the constraints of the acoustic channel, such as interference, bandwidth, reflections, and consequent error rate are highlighted. The architectural requirements for underwater networks are proposed by Akyildiz et al. [10]. This study identifies different approaches for medium access control, network, and transport layers, showing an evaluation of different protocols. Another analysis of the problems of underwater sensor networks is also presented by Liu et al. [11]. The field experiments with software-driven underwater sensor networks are described by Jurdak et al. [12], presenting the technical and logistical challenges for deploying software-driven underwater sensor networks.

A spatially fair multiple access control protocol which explores the spatial-temporal uncertainty and focuses on spatial unfairness problem in Underwater Sensor Network (UWSN) is presented by Liao and Huang [13]. The proposal adopts a receiver based scheme and proposed a fairness MAC protocol to achieve the fair transmission, determining the earliest transmitter with a probability rule that compares with the first RTS. The protocol can operate in the large-scale networks as well as in the mobile sensor networks. A routing protocol based on the hydraulic pressure for underwater sensor networks proposed by Lee et al. [14] explores the levels of measured pressure to forward data to buoys on the surface.

Some routing protocols have been proposed for underwater sensor networks. Pompili et al. [15] present a two-phase resilient routing solution for long-term monitoring missions, with the objective of guaranteeing survivability of the network to node and link failures. The problem of data gathering for three-dimensional underwater sensor networks is investigated at the network layer by considering the interactions between the routing functions and the characteristics of the underwater acoustic channel. Xie et al. [16] present specific propagation models for underwater sensor networks, where each node in a group communicates with the gateway node, which collects statistics on the received packets. The gateway communicates with external entities through a special node equipped with both acoustic and RF systems.

The use of buoys is also an alternative for monitoring the oceans, even considering the increased complexity and cost of these solutions. A coastal observing system presented by Schneider [17] uses a network of buoys equipped with non-rechargeable batteries with radio communications of 1 km range and 800 bps rate. Rowley [18] presents a design of buoys for ocean measurements of biological and meteorological data to detection and monitoring of maritime risks. Taft et al. [19] present the application of acoustic windows in monitoring ocean currents using the Acoustic Doppler Current Profilers (ADCP). This study aims at reducing the distance from the buoy to ADCP to improve the measurements and eliminate mechanical stress and fatigue in electrical cables, which connect the transducers and other electronic components. Brown et al. [20] present a system for monitoring Great Lakes environmental conditions comprising low cost monitoring buoys.

The importance of the sensors distribution in the networks is presented by Xiao et al. [21], proposing a critical line based environment surveillance strategy. The proposed proactive routing method by Wenning et al. [22], adapts the routes before node failure, avoiding broken routes, delay and power consuming. This routing approach adapts the routes proactively based on information on node-threatening environment influences.

The power consumption is another important aspect, which is described by Dargie et al. [23] that proposed a comprehensive energy model for a fully functional sensor network that provides sufficient insight about the energy demand of the communication protocols. Garcia et al. [24] analyze cooperative group-based Wireless Sensor Networks (WSNs) to study the impact of these groups on energy saving and efficiency improvement in WSN communications. Thus, when a sensor detects a new event, the alert is sent to its group and it is distributed to an appropriate neighboring group based on the information shared between sensors.

A sensor network for coral reefs monitoring is presented by Vasilescu et al. [25]. This acoustic network utilizes Autonomous Underwater Vehicle (AUVs) to collect data, mixing short-range optical communication with acoustic communication. Penteado et al. [26] proposed a sensor network that obtains oceanographic data to monitor ocean currents. This network is composed of fixed acoustic sensors that communicate with a sink responsible for external communication.

Some proposals for location determination use the characteristics of the signals propagation to calculate the position. The Global Positioning System (GPS) is the best known example. This system is based on satellite radio navigation [27]. Other proposals may not use satellites for location. The proposal of Song [28] that performs the location using signals from the cellular system was the precursor for the study of location through GSM cellular system proposed by Varshavsky et al. [29]. Gunnarsson and Gustafsson [30] discuss the basic possibilities associated with mobile positioning in wireless networks with a model-based filtering. A tracking system for vehicular ad hoc networks is proposed by Boukerche et al. [31], showing how to combine the techniques of vehicle location by data fusion to provide a more robust tracking system.

Tan et al. [32] present an overview of techniques and challenges of localization in underwater sensor networks. The study compares the cost, speed, accuracy, and location coverage performed by acoustic communication using techniques based on reference nodes with known geographical position. A method that uses the GPS system and acoustic communication for the positioning of transponders on the seabed was presented by Wu et al. [33]. This method aims at monitoring crustal deformations due to the movement of tectonic plates. Thus, an acoustic transponder was developed in order to provide baselines that can be used to monitor the sensors position through a submarine mapping. The experimental study on the performance of a hybrid system proposed by Kerbkal et al. [34], allows simultaneous hydro-acoustic positioning of drifting underwater objects. This system enables hydro-acoustic communication between the node identifier of the underwater object and the nodes base in order to provide the determination of the position coordinates.

Unlike the works presented, we propose the integration of underwater sensors and mobile data collectors into a DTN network and to implement a monitoring system specifically designed for underwater oil exploration offshore in Brazil [35,36]. We introduce a monitoring system specific for the oil exploration subsea infrastructure, considering mobility and the constraints of the underwater environment of the Campos Basin, Rio de Janeiro, Brazil.

3 Underwater communications

Although underwater communication can be accomplished through electromagnetic and optic waves, acoustic waves are in practice the most suitable. The electromagnetic transmission has high signal attenuation in water and requires large amounts of energy for transmission. Optical transmission has high transmission rate and low power consumption, but with the drawback of very short range, caused by absorption and scattering of light. Applications are limited to the range of a few meters, even in clear water and perfect alignment [25].

The most effective way to implement underwater communication is through acoustic waves [11], despite its limitations. The sound speed in water is about 1,500 m/s, four times faster than sound speed in air, but still five orders of magnitude smaller than electromagnetic waves in the air. This feature implies latency of 0.67 s/km. Furthermore, the speed of sound in water is variable and dependent on the pressure (depth), density, temperature, and salinity [7]. The consequence is that the sound speed in water varies from surface to the bottom, propagating in curved paths due to refraction caused by layers with different speeds [37].

Acoustic signal is produced by mechanical waves of alternating compressions, requiring high power for transmission. Moreover, acoustic waves suffer interferences caused by reflections, obstacles, and turbulence. The loss caused by sound absorption is another important feature, making the bandwidth of the acoustic channel variable, decreasing with distance. This limitation restricts the useful range to a few km with transmission frequencies below 30 kHz, implying in low transmission rates, usually around 5 kbps [9].

Control of medium access is difficult due to the high latency of the communication channel. Different access methods such as Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA), and Code Division Multiple Access (CDMA) have been considered for underwater environments. The most used is TDMA, due to the simple method of assignment of a cyclical time transmission slot for each node in the network. During each time interval, the channel is reserved for a single node transmission. These intervals must be separated by a time guard to avoid transmission overlapping, which involves a heavy dependence of synchronization.

Most underwater sensors network applications require time synchronization services. Furthermore, time synchronization is indispensable in most localization algorithms, for both underwater [34] and terrestrial sensor networks [30,38]. However, the long propagation delays, jitter, mobility and the need of high energy efficiency poses a great challenge for time synchronization algorithms.

Time synchronization algorithms, such as TSHL [39], MU-Sync [40] and Mobi-Sync [41], have been proposed to improve the synchronization in underwater communication. These algorithms are able to deal with long propagation delays. The TSHL algorithm considers fixed nodes, being not suitable for mobile networks. The MU-Sync algorithm, designed for mobile underwater networks, is not able to be energy efficient. The Mobi-Sync algorithm is specifically designed for mobile underwater networks and provides high energy efficiency, using the spatial correlation of mobile sensor nodes to estimate the long dynamic propagation delays among nodes.

Due to the acoustic channel limitations, not all applications are suitable for underwater sensor networks. The dependence of the channel bandwidth on the distance is the main factor that limits the acoustic modems range. The impossibility of using acoustic modems at longer distances is caused by noise interference on the channel, compromising the bandwidth and consequently the communication efficiency [11].

The implementations of underwater sensor networks usually deal with transmission rates up to 5 kbps and range up to 5 km, a typical average value for acoustic modems. Higher transmission rates are possible, but under special conditions and short distances. The comparison among some market acoustic modems can be seen in Table 1.

The amount of transmitted data by the application must be compatible with the available transmission rate. Therefore, to increase the success rate and to be compatible with high error

Table 1 Underwater acoustics modems

Manufacturer	Model	Freq. (kHz)	Pot. (W) TX e RX	Range (km)	Rate (bps)
LinkQuest	UWM10000	7.5–12.5	40 and 0.3	7	5,000
EvoLogics	S2CM48/78	48–78	2.5–80 and 0.5	1	15,000
Teledyne Bentos	ATM885	16–21	28–84 and 0.7	2–6	15,360
Aquatec	AquaModem	8–16	20 and 0.6	10	2,000
TriTech	MicronModem	20–24	7.92 and 0.72	0.5	40
WHOI	MicroModem	25	50 and 0.23	1–10	5,400

rates, high latency, and low data rates, the amount of data to be transmitted should be around 1 kbyte [8]. Moreover, small packets are more likely to be successfully transmitted and monitoring applications of pipelines generate packets with 400 bytes in average with traffic around 5 kbps (real data obtained from measurements in the monitoring applications of onshore pipelines).

Delay/Disruption Tolerant Network networks are appropriate to operate with the limitations such as delays, bandwidth and power consumption found in underwater communications [25]. This leads to the necessity of developing efficient routing protocols which must consider the existence of mobile and fixed nodes in the underwater network, implying the adoption of solutions with dynamic routing for this kind of network.

Acoustic modems usually operate in underwater environment with energy supplied by batteries. Thus, an important issue is energy consumption, which is much higher than in radio transmissions [42]. The energy consumption of acoustic modems can lead to a greater need of battery replacement or its recharge. This operation is very difficult and expensive in underwater networks. Therefore, it is crucial to avoid transmission losses, since this energy waste in the network can decrease the sensor life.

4 Deepwater monitoring system

The use of acoustic monitoring networks in underwater environments was motivated by the most recent acoustic modems that provide increased range up to 5 km with transmission rates of 5 kbps. Underwater acoustic sensors can be installed over the submarine pipelines for monitor pressure, temperature, flow, and positioning control. This last option is especially important to monitor the positioning during new lines launching of submarine pipelines [43].

The Campos Basin area is approximately 115,000 km^2 and can be divided into two regions, called the transition and exploration regions (Fig. 1). The transition region is an area that logistic-support vessels cross when moving between the coast and the oil fields. The exploration region is the producing oil area, where there is an extensive pipeline network, several production units and a large number of vessels that are responsible for resource distribution, executing a specific routine of units supply and anchoring.

Vessels are equipped with a GPS system, radio communication, and in many cases, a satellite link and their routes match the subsea pipelines, becoming an appropriate option to capture sensed data. The information is generated and stored in the sensors until some vessel is available for message reception, as shown in Fig. 2.

The long distances and dispersion of offshore installations impact the number of vessels within sensors range. Thus, these vessels may not be reachable to sensors at all times, precluding the use of a conventional network architecture. In this case, a communication architecture based on underwater networks tolerant to delays and interruptions is needed to route messages node to node, without ever establishing an end-to-end path.

4.1 Underwater sensor networks

An underwater sensor network is based on nodes equipped with sensors and acoustic modems [5]. The nodes communicate with each other to send sensed data and receive commands. Sensed data is forwarded to a sink node. This edge

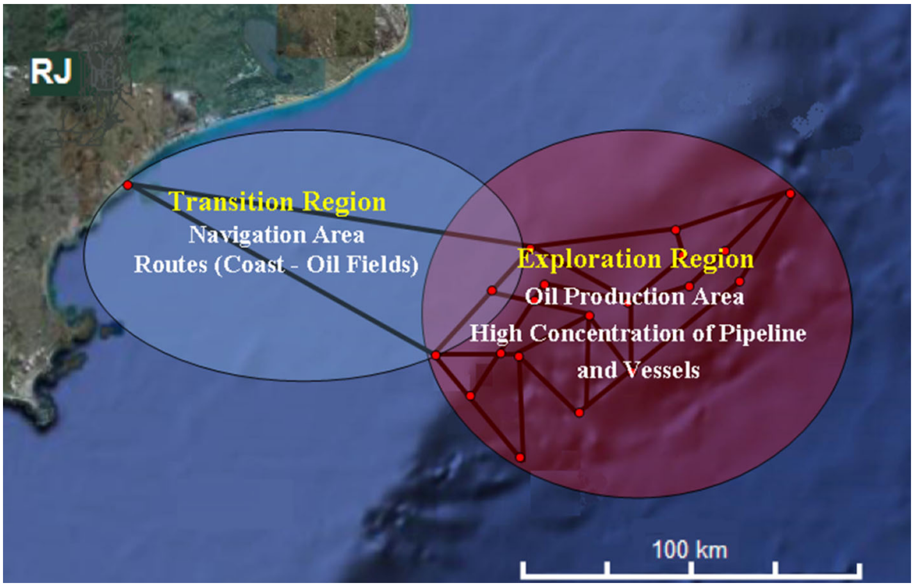


Fig. 1 Navigation area of logistic-support vessels

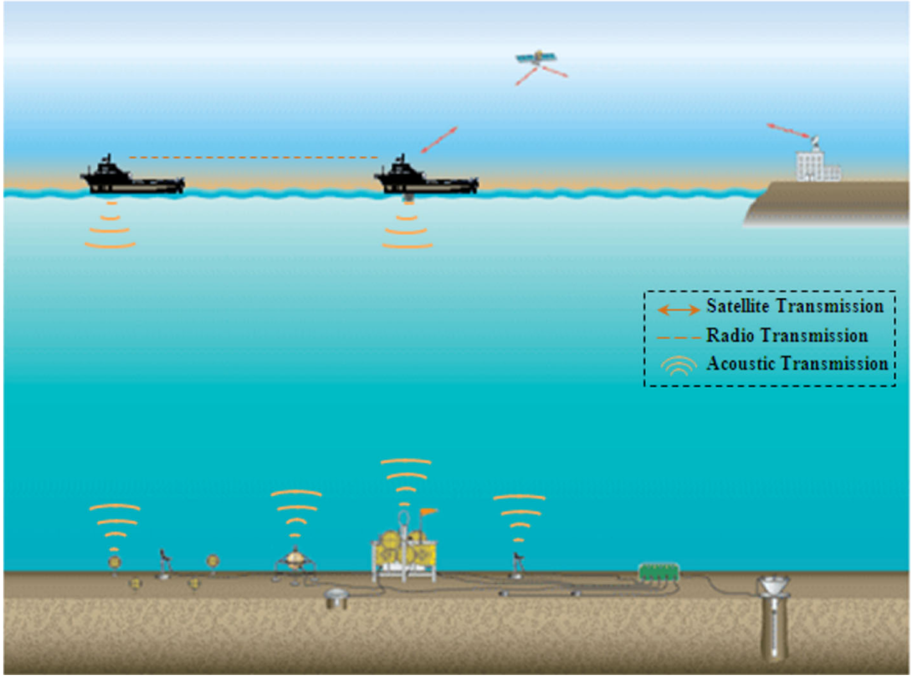


Fig. 2 Communication links in the deepwater monitoring system

node picks up the messages in underwater domain and forwards it to a not underwater domain [10]. This network type allows nodes maintaining an autonomous operation of data transmission, where sensors are responsible for the decision of transferring information when a mobile node is reachable. Thus, sensors can be used to monitor, even in real time, subsea pipeline conditions. Nevertheless, this operation must be planned, to avoid spending energy with excessive data transmissions since the sensors are battery-equipped. This adjustment is needed to ensure longer life to the sensors.

The proposed sensor network may have not only one sink, but all the mobile nodes may collect data in the DTN underwater domain. Sensors are installed on the subsea infrastructure and are programmed to generate information at fixed intervals, storing it until they are ready to forward it to the control center. Each of these samples is coded into a data packet, usually less than 1 kbyte long [2]. Considering a transmission rate of 5 kbps and a maximum range of 5 km, each node needs only 4.95 s of connection (1.6 of transmission delay and 3.35 of maximum propagation delay) to transmit its packet without errors. This feature is compatible with applications with low sampling rates like pipelines monitoring [44] and oceanographic data acquisition [26].

4.2 Communication architecture

The communication architecture of the monitoring system is divided in two domains, defined by the type of communication and associated with device mobility [45]. These domains are composed by acoustic sensors and mobile nodes that should be able to store messages, through the use of the aggregation layer and storage units, implemented in the DTN stack [4].

The network consists of underwater and not underwater domains. In the underwater domain, acoustic sensors generate messages to be captured by acoustic mobile nodes (vessels). These messages are forwarded in the not underwater domain, carried in the DTN until they reach the destination located in an external network, as shown in Fig. 3.

The mobile nodes, which are the vessels, are entities of the DTN that capture the sensor messages. The number of these devices depends on the vessel routes. All traffic must pass through the vessels before exiting the underwater domain. The vessels have two kinds of functions: capturing messages from sensors in underwater domain and retransmitting these messages through the not underwater domain. Some mobile nodes are named edge nodes because they are also responsible for messages forwarding to the external network (Fig. 3).

The not underwater domain takes advantage of the existing communication infrastructure in the vessels, which is comprised of radio/satellite communication systems. In this case the wireless network will be responsible for forwarding the packets collected from the sensors to the Control Center.

The vessels are identified according to the function and the type of available communication (VHF or VHF / Satellite) [36] forming two mobile nodes groups. In the communication architecture, the Mobile Node (MN) is a vessel with radio system responsible for forwarding messages until a vessel with satellite system is reached. This vessel, called Mobile Edge Node (MEN), sends packets to the external network.

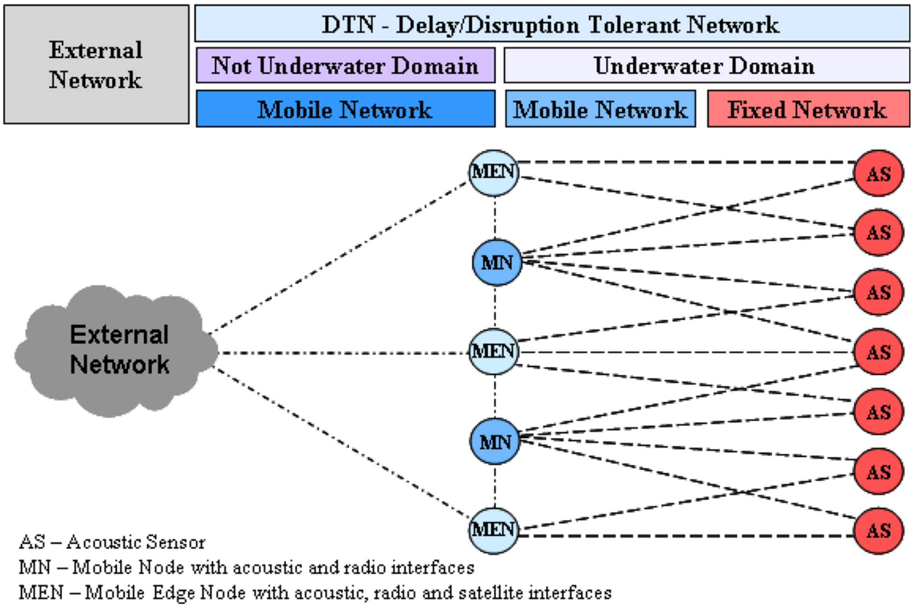


Fig. 3 Communication between mobile nodes and fixed sensors

The monitoring architecture should adapt to the underwater communication conditions and to the available network resources. Therefore, the variation in the quantity of mobile nodes within range of each sensor is an important parameter for the system and impacts the network performance. The routing protocol responsible for forwarding messages from the sensors can be based on several DTN routing algorithms, such as Epidemic [5] and Prophet [46] protocols, but the shortage of available vessels to capture messages from sensors makes the performance of these protocols equivalent [36].

The Epidemic protocol was chosen in order to ensure the best conditions in monitoring system due the controlled-flooding approach, which is based on the flooding of messages, where each node sends the packet to all nodes found in order to increase the probability of packet delivery, using the available network resources [36]. The difference of this routing protocol is the amount of information needed to make forwarding decisions, which in this case are minimal due to the simple routing model. This mechanism can be used to improve the routing of collected messages, influencing the behavior of the system and the feasibility of the monitoring application, since normally there will be no many vessels available for communication.

4.3 Underwater positioning

The position of a mobile or fixed element in a coordinate system can be computed by different methods. Whatever the coordinate system adopted, these methods require knowledge of location of at least three reference points in the system and the estimated distance of the unknown node to those reference points. Thus, the location methods generally have two basic components: an estimation of the distance and a calculation formula of the position.

The estimated distance is obtained from the characteristics of the transmitted signal between two nodes [47]. The distance can be estimated based on the Received Signal Strength Indicator (RSSI), Angle of Arrival (AOA), Time of Arrival (TOA), or a combination of these methods.

The method to estimate the distance by measuring the received signal strength (RSSI) is based on verification of the fading of the transmitted signal [48]. This indicator is therefore influenced by noises, obstacles, and the type of antenna, which makes it hard to model mathematically. The main source of error is the effect of shadowing and fading caused by multipath signal propagation. Moreover, the measurement can vary in systems where the power of underwater acoustic signal is controlled, to save the battery of the sensors [9].

The angle of arrival (AOA) of the received signal can also be used by location systems [38]. This angle is used to estimate the distance between the transmitter and receiver. The AOA estimation is done using directive antennas or a set of receivers arranged uniformly. The dispersion of the signal around the receiver and transmitter can change the measurement of the angle of arrival, limiting the range of the measuring devices. The need for additional hardware and interferences are drawbacks of this method. In underwater acoustic communication, transmissions are surrounded by sources of interference that affect the reception, making the AOA approach possibly impractical in this environment.

The last method of distance estimation uses the measurement of the signal propagation time (Time of Arrival—TOA) [48], which estimates the distance between the transmitter and receiver finding the unidirectional propagation time.

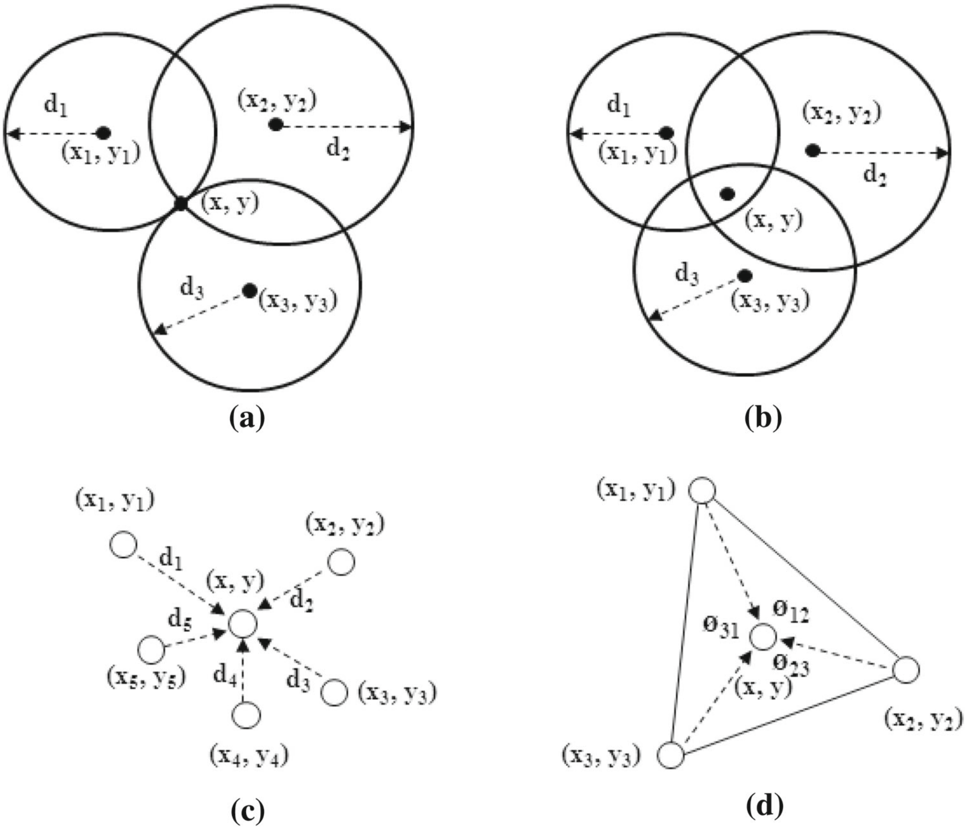


Fig. 4 **a** Hypothetical model of trilateration; **b** realistic model of trilateration; **c** multilateration; **d** triangulation

Geometrically, this produces a circle centered at the point of reference, where the receiver should be. In this case, the distance between two nodes is directly proportional to the time the signal takes to propagate from one point to another. Thus, if a signal was sent at time t_1 and reached the receiving node at the time t_2, the distance between the transmitter and receiver is $d = c\ (t_2 - t_1)$, where c is the speed of signal propagation and t_1 and t_2 are the times when the signal was sent and received. The accuracy of this estimation method depends on the synchronization between the nodes.

The location methods use the measures of distances performed by the node up to three or more reference points, running a series of calculations to define the position. The process of defining the position depends on the used method, which may be based on trilateration, multilateration, or triangulation.

The trilateration method is the most basic and intuitive. The position is calculated considering the geographical location of a node through the intersection of three circles. To estimate the position, at least three reference points associated with the respective distances to the node (d_1, d_2, d_3) are required [48]. The circles formed by the position and distance of each point of reference can be represented by the formula $(x - x_r)^2 + (y - y_r)^2 = d_r^2$, where (x, y) is the position to be computed, (x_r, y_r) is the position of the reference node r and d_r is the distance from the node to the reference point r. Thus, the location of the node is the point of intersection of three circles, considering no errors in the estimates of distances (Fig. 4a) or an area of intersection in the real case with measurement errors (Fig. 4b).

The multilateration is a generalization of trilateration [49], which can be used if more than three reference points exist (Fig. 4c). In this case, the calculation uses a system of equations for determining the location with greater accuracy. The number of operations is much higher, increasing the processing load on the node, which usually makes it difficult to use.

The triangulation is applied when the technique based on measuring the angle of arrival rather than distances is used [48]. The node estimates its angle to each of the three reference points and, based on these angles and the reference positions (which form a triangle), calculates its position using simple trigonometric relationships (Fig. 4d).

4.4 Sensor localization

The representation of the localization process performed by the underwater positioning system is shown in Fig. 5, where the references to positioning were given by a logistic-support vessel, a Floating Production Storage and Offloading (FPSO) and a platform. The point in the center of the triangle on the

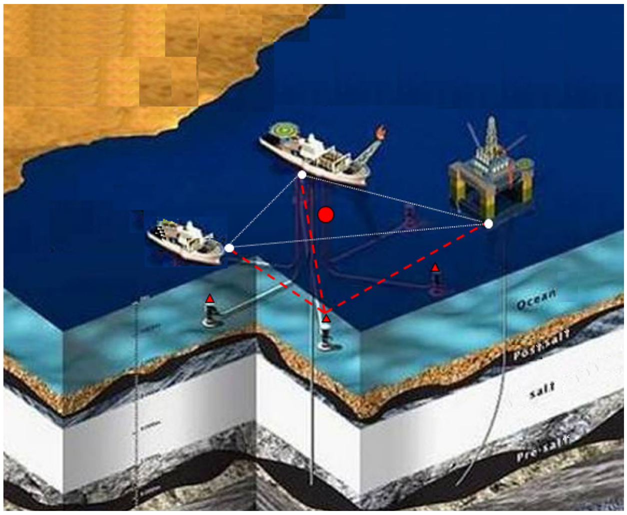


Fig. 5 Deepwater positioning system

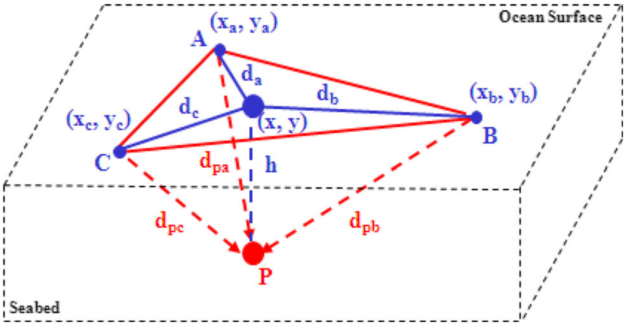


Fig. 6 Process definition of coordinates and depth

surface is the representation of the underwater sensor position in geographic coordinates. This representation, together with the depth information, allows mapping underwater objects by following a well-known location model.

The sensor can be activated with a control message that initiates the process of calculating the position. Once the sensor is activated, it estimates the distance and calculates the position with the coordinates of the reference points [50].

Estimates of the distances are performed by the Time of Arrival (TOA) method, due to the simplicity of measuring the propagation time of the acoustic signal in the underwater environment. According to Fig. 6, the underwater sensor P has estimated distances d_{pa}, d_{pb}, and d_{pc} from the references A, B, and C. This point can be represented on the surface through the decomposition of triangles and will be in the same plane of the reference points, making it possible to determine their coordinates (x, y) by trilateration.

The coordinates of points A, B, C, and P are respectively (x_a, y_a), (x_b, y_b), (x_c, y_c), and (x, y). The distances from the point on the surface for the three reference points A, B, and C are d_a, d_b, and d_c, and can be represented by Eqs. 1, 2, and 3.

$$(x - x_a)^2 + (y - y_a)^2 = d_a^2 \tag{1}$$

$$(x - x_b)^2 + (y - y_b)^2 = d_b^2 \tag{2}$$

$$(x - x_c)^2 + (y - y_c)^2 = d_c^2 \tag{3}$$

The distances d_a, d_b, and d_c are obtained by the decomposition of the triangles. As a consequence, we have three equations for two unknowns, making it feasible to obtain the position of point P on the surface with geographic coordinates and depth.

Generally, to estimate a position, a node uses at least three distance estimates, each with an associated error. Although desirable, the accuracy is not the only important feature in choosing the most appropriate method for the application. Other factors should be considered, such as cost, hardware, processing, and energy. Thus, the method to set the position depends on the application requirements.

Underwater positioning applications that work together with monitoring systems may use higher-precision techniques. For these applications, the precise location of the sensor in some cases is necessary. In these underwater activities such as the deployment of equipment at the head of oil wells, a specific positioning system fitted with close and dedicated reference points can be used to increase the measurement accuracy.

5 Simulation

The analysis of the proposed monitoring system is done through simulations. The objective is to check the viability of the communication system using the fleet of logistic-support vessels of oil exploration to capture data from sensors and the positioning system, using the fleet of logistic-support vessels and the production units as points of reference. The underwater sensors must be able to get their position through these references, with a sampling period appropriate to the needs of the operation of the Campos Basin.

5.1 Scenario

To evaluate and compare the monitoring system performance, the ONE simulator [51] was used. ONE uses a specific movement model that can be customized to represent the actual displacement of the vessels responsible for the logistical support of the Campos Basin oil exploration. These displacements depend on the navigation regions, namely the:

- Transition Region: containing a total of 5 sensors, this equals 1 sensor every 20 km over the subsea pipelines. In this area, the vessels often travel great distances without stopping and at almost constant speeds.

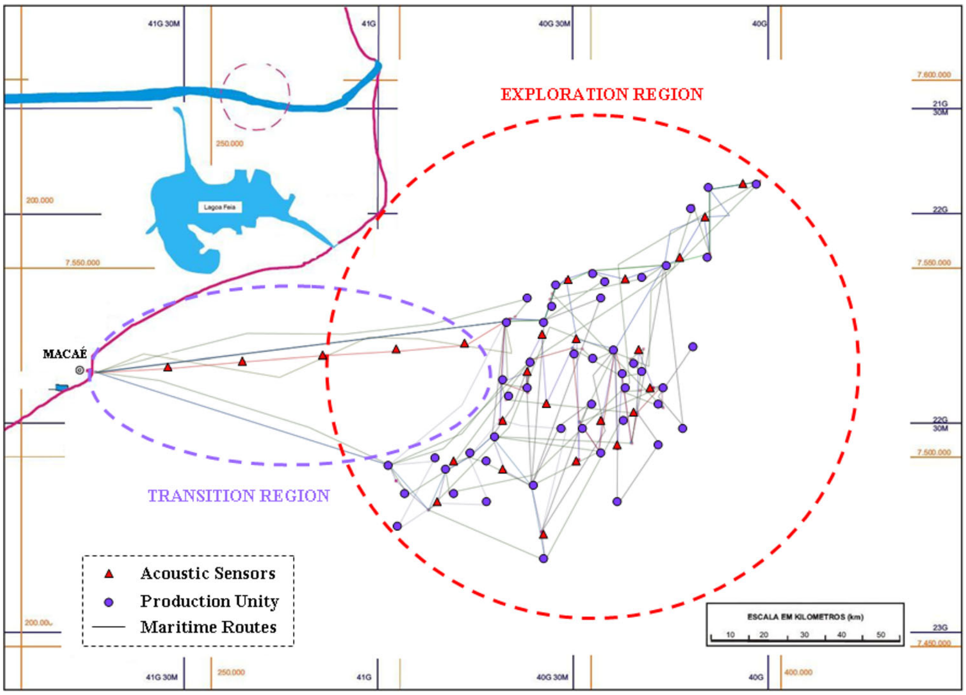


Fig. 7 Basic simulation scenario

- Exploration Region: containing a total of 20 sensors distributed in strategic points to take advantage of the production unit range, which in some cases already provides two reference points. In this area, the vessels travel shorter distances with constant stops in the production units (fixed platforms, semi-submersible platforms and FPSOs) and may remain anchored waiting for new operational plans.

The simulations consider a network with 25 sensors, 54 production units, and up to 400 mobile nodes (vessels) and a control center outside the network. The mobile nodes are randomly distributed over the network and they move according to the mobility model. Nodes participate in both groups that represent the types of logistic-support vessels according to the available type of communications (satellite or radio). Vessels execute specific movements according to each type of region. The sensors, production units, and routes for each region are shown in Fig. 7.

Currently, there are 254 logistical-support vessels operating for Petrobras, but the expectation is that this number will increase to 465 by the end of 2013, reaching a total of 504 vessels by 2020. This information is based on the presentation of the Petrobras business plan 2010–2014 made by Gabrielli and Barbassa [52]. As the Campos Basin is currently working with nearly 80 % of Petrobras vessels fleet, we use this number in the simulations.

The simulations aim to verify the following system information:

- Percentage of sensors reached by three references.
- Contacts made in the network.
- Average time to obtain a given position.
- Ratio between delivered and created messages.

5.2 Configuration

To simulate a realistic monitoring scenario, we considered the specific characteristics of each region, which usually influences the type of movement and the vessel density. Only production units (platforms), sensors, and mobile nodes (vessels) can move. The sensors have a very limited movement profile to represent displacements caused by movement of the seabed. In a typical operation, the vessels traverse the transition region staying for long times in the exploration region.

The definition of parameters for the simulation was based on the Campos Basin oil exploration area, including the movement of vessels and the characteristics of acoustic transmission. The simulations represent the supply process conducted by vessels during an operation of 24 h. Vessels move at variable speeds, covering an area of 250 × 250 km (transition and exploration regions). The range of the underwater communication was defined as 5 km, respecting the features of current acoustic modems, as shown in Table 2.

The connection is performed only if the sensor and the mobile node or both nodes are moving within the contact range. The range of the underwater communication was defined as 5 km, respecting the features of current acoustic

Table 2 Simulation scenario parameters

Parameter	Description	Value
Area	Transition and exploration regions	250 × 250 km
Points of interest	Representing the production units	48
Mobile nodes	Number of vessels	25–400
Vessel speed	Vary between	5–14 knots

Table 3 Communication simulation parameters

Parameter	Description	Value
Range	Underwater acoustic communication	5 km
Data transmission rate	Underwater acoustic communication	5 kbps
Range	VHF radio communication	20 km
Data transmission rate	VHF radio communication	20 kbps
Message buffer	Typical of acoustic modems	10 Mbytes
Messages generated	Uniform distribution	60–300 s
Message size	Underwater sensors	1 and 2 kbytes

modems. Thus, the behavior of the network depends on the features of acoustic and radio communications, buffer size, and message generation frequency, presented in Table 3.

The size of the message can be 1 and 2 kbytes, it may represent the exchange of text files with information collected by the sensors, according to data obtained from measurements made in the monitoring application of onshore pipelines.

6 Results

The performance of the positioning system depends on the availability of network resources (vessels). Therefore, the displacement of vessels can affect the calculation of the sensor position. Thus, simulations were performed to verify the system behavior in relation to the movement and to the number of logistic-support vessels.

The vessels provide a reference service to the positioning system. Nevertheless, they move according to the logistical-support activities. As a consequence, there is some level of unpredictability of contacts, an unavoidable condition in this system. Therefore, checking the availability of three references by the network may indicate the probability of obtaining the sensors positioning.

Each simulation was performed to verify the ability of vessels and production units to provide three references for the sensors. The evolution of percentage of sensors achieved (Sa) with the increasing number of vessels can be seen in Fig. 8. Note that the system allowed 100 % of the sensors to obtain at least three references in scenarios with 200 vessels, indicating the possibility of obtaining the positioning of all the sensors in the network. However, to be truly effective, this information must be provided with a frequency that allows the monitoring of real underwater conditions. Thus, the number of contacts and the average time to obtain the positioning are also important metrics.

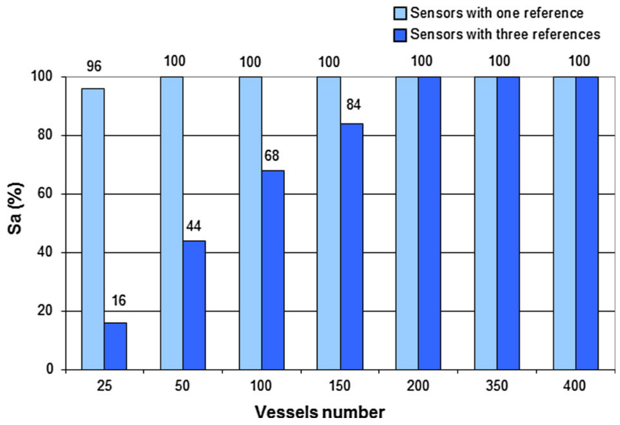


Fig. 8 Percentage of sensors achieved (Sa)

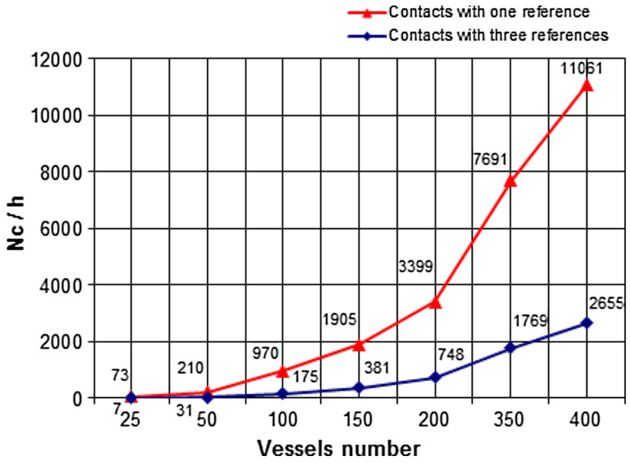


Fig. 9 Number of network contacts (Nc) per hour

The increasing number of vessels in the network caused the increasing number of network contacts (Nc), as shown in Fig. 9. This expected behavior indicates that the number of vessels affects the system ability to provide three references for sensors, allowing more sensors to be able to calculate their position. However, this information is only relevant if it is associated to the average time that a sensor waits to obtain these references.

The frequency with which the sensors are capable of transmitting their information and update their positioning is essential to define what kind of application will be sup-

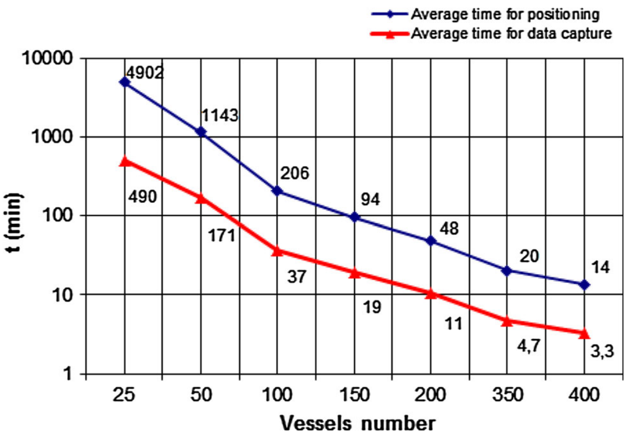


Fig. 10 Average time for positioning and data capture

ported by the system. Fig. 10 shows that, considering the scenario currently found in the Campos Basin (200 vessels), the sensors wait about 11 min to transmit data and 48 min to obtain three references, allowing to monitor the position of the underwater infrastructure. The condition for the position calculation may be improved reaching 20 min in 2013 (350 vessels) and 14 min in 2020 (400 vessels). The values are high compared with conventional systems, but represent the minimum response time to detect any deformation or sliding on the seabed that could affect the subsea infrastructure (e.g. submarine pipelines). In this case, it would be possible to activate the emergency maintenance service in a short time if there is any chance of oil spill, reducing the environmental damage.

The performance of the positioning system is affected by the availability of reference units within sensor range. Nevertheless, the use of fixed reference units (platforms) in certain areas allows sensors to be less dependent on vessels, requiring, in some cases, only a mobile reference point. In the case of the Campos Basin, we have verified that this behavior is exclusive of the exploration region, the transition region being dependent on vessels due to lack of fixed reference units.

The system ability to deliver the generated messages is an important feature to evaluate the behavior of the underwater communication network. The relationship of messages delivered/created is influenced by the number of vessels in the network.

The network behavior can be analyzed with the variation in the number of vessels available in the network. This information was obtained with the Epidemic DTN routing protocol (Fig. 11).

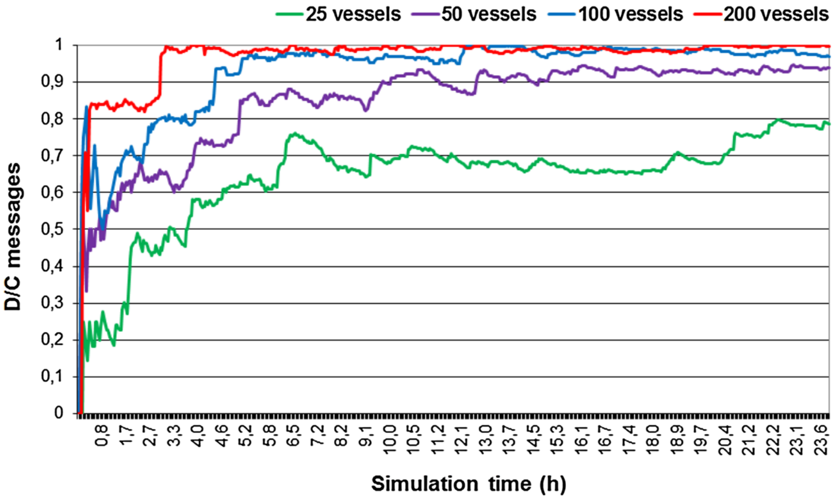
The results show that increasing the number of vessels positively influences the delivery of generated messages. It is possible to identify that the system obtains an acceptable behavior that emerges from the scenario with 100 vessels. Therefore, the system reaches average values very close to 1 with 200 vessels, which is the number of vessels currently in operation in the Campos Basin.

7 Deployment costs

To verify the feasibility of the proposed underwater monitoring system, we have gone beyond the analysis of the network behavior, and evaluated the costs of implementation of the monitoring system. The main goal is to make a survey of the business requirements in order to define the procedures for project execution. The results of this study aim to assist the deployment decision of this solution, based on estimates of costs and schedule related to the installation of modems and sensors in the subsea infrastructure, taking into account the costs of hiring specialized services to different depths in offshore environment.

The sensors will be installed on the subsea infrastructure (equipment and pipelines) which is distributed in a large area

Fig. 11 Ratio between delivered and created (D/C) messages.



that extends from the coast to the oil exploration region in the Campos Basin. The depth of the seabed ranges from 50 to 2,000 m. Thus, the installation of sensors will be the most critical time with respect to the cost of deployment, and can be performed in two basic scenarios:

- Sensor installation during deployment of new equipment or launching of pipelines. In this case, the sensor installation should not delay the installation of pipelines and / or equipment, avoiding additional costs from the longer utilization of the special vessel.
- Sensor installation in the ducts and / or subsea equipment that are in operation. In this case, the characteristics of the sensor location are of great relevance in the time and cost of deployment, being greater as the depth of operation increases.

Some characteristics of the sensors can influence the installation time, such as the type, positioning, and the way of "placing"/"fixing" sensors in the pipelines or equipment. Thus, the sensors should be adapted for each type of equipment/duct in order to avoid loss of time during installation and therefore reduce the cost of the project.

In all cases, the estimation of installation costs is obtained from a schedule containing only the main steps, which include the vessel mobilization, positioning on the location, sensor installation, and resource demobilization. Therefore, considering the characteristics of the Campos Basin and the service types offered by companies supporting oil exploration, it is possible to evaluate two scenarios that determine the basic cost of project deployment:

- Shallow waters, with water depths of up to 300 m. In this case, the sensor installation should be performed by divers, which are contracted jointly with the vessel which provides the specialized service for installation of 13 sensors positioned in these areas.
- Intermediary, deep, and ultra-deep waters, with a water depth above 300 m. In this case, the sensor installation can only be performed by remotely operated vehicles (ROV), being this service contracted together with the vessel for installation of 12 sensors positioned in these areas.

The estimation process defines the number of work periods that will be required to complete specific activities, taking into account the project scope, type, and quantity of available resources and their schedule. The estimated duration of each activity was based on the analysis of experts more familiar with the nature of work to be done, resulting from interviews conducted by the authors with Petrobras personnel.

The project budget accounts for the costs related to the acquisition of equipment (modems and sensors), modems installation on vessels, sensor installation, and the estimated time to perform each activity. The deployment costs are influenced by the location of the equipment that will be monitored, due to the different water depths of operation. We have listed the acquisition cost of equipment in Table 4 and the costs of installation in Table 5.

Table 4 Equipment costs

Equipment	Number	Cost (US$)	Total cost (US$)
Acoustic modem	200	10,000.00	2,000,000.00
Sensors <300 m	13	17,000.00	221,000.00
Sensors >300 m	7	26,000.00	182,000.00
Sensors >1,000 m	5	38,000.00	190,000.00
Total cost (US$)			2,593,000.00

Table 5 Installation costs

Installation	Time	Number	Cost (US$)	Total cost (US$)
Acoustic modem	12 h	200	6,000.00	1,200,000.00
Sensors <300 m	2.2 d	13	120,000.00	3,432,000.00
Sensors >300 m	3.2 d	12	90,000.00	3,456,000.00
Total cost (US$)				8,088,000.00

The total cost with the purchase of equipment for the project is US$ 2,593,000.00, and 77 % of this cost is related to the acquisition of 200 acoustic modems to be installed on logistic-support vessels.

The deployment of sensors and modems totalized US$ 8,088,000.00, representing the bulk of project costs. A large part of this budget is due to the necessity of using specialized vessels for sensors installation in different water depth.

The total cost to implement the monitoring system with 25 underwater sensors and 200 logistic-support vessels equipped with acoustic modems distributed in the oil exploration area of Campos Basin would be US$10,681,000.00.

8 Conclusions and future work

This work proposed an underwater monitoring system for the specific environment of the oil exploration area in Campos Basin, Rio de Janeiro, Brazil. The objective was to verify the system behavior and to analyze the feasibility of using the logistic-support vessels and platforms to capture information of sensors and provide the necessary references to obtaining the positioning of underwater sensors.

The mobility model was based on real scenarios of the Campos Basin. We have shown that the system is feasible. With the increasing number of vessels in the network, it becomes more efficient, leading to an adequate waiting time, and better ratio between delivered and created messages. Currently, the number of existing vessels at Campos Basin is consistent with the simulations, allowing reproduction of this scenario in practice.

Although vessels continue their normal operation, independent of the monitoring system, the study has shown that in conjunction with the production units (platforms) they can provide efficient delivery of sensed data and the needed references for each sensor calculating its position.

Despite the unpredictability inherent to the scenario, it was possible to achieve all sensors in the network with a sampling that allows the monitoring of pressure, flow, and temperature of submarine pipelines and displacements caused by the instability of the seabed in order to detect situations that may cause oil spill and consequently damage the submarine environment.

The general behavior of the system was satisfactory, with consistent results that demonstrate the feasibility of monitoring the underwater sensors in current and future scenario found in the oil exploration area of Campos Basin. Moreover, we have provided a study of the deployment costs further showing the monitoring system viability in practice.

As future work, we intend to apply a similar analysis in an extended exploration area, including the new pre-salt exploration regions. Those have specific operation characteristics, which influence the monitoring system due to new routes and new distribution of infrastructure.

Acknowledgments The authors would like to thank PETROBRAS, CAPES, CNPq, FAPERJ, and MCT/FINEP/FUNTTEL for partially funding this work.

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