Deepwater Monitoring System Using Logistic-Support Vessels in Underwater Sensor Networks

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ABSTRACT

This paper proposes a deepwater monitoring system built with sensors distributed over the subsea pipelines which are responsible for transportation of oil production. Data transmission is undertaken by underwater acoustic modems installed on the sensors and vessels used for logistic support of the oil exploration. However, the vessels may not be within sensor range at all times, requiring the use of DTN (Delay/Disruption Tolerant Network). This work investigates the routing protocols Prophet and Epidemic, analyzing system behavior using ONE (Opportunistic Network Environment) simulator and compatible in the Campos Basin scenario in the Brazilian oil exploration area.

KEY WORDS: Underwater communications; acoustic; sensor networks; routing; protocols; deepwater monitoring.

INTRODUCTION

The last decades in Brazil were marked by the pursuit of self-sufficiency in oil production, which was successful, thanks to numerous discoveries in the oceanic continental shelf. The activities of this industry generate a production of gas and oil transported by an extensive network of subsea pipelines concentrated in a large area at 100 km off the coast with water depths ranging from 60 to 1000 m.

Operation and maintenance of these subsea pipelines are extremely complex due to the severe conditions of the underwater environment in Brazil, which at some points has an extreme tilt, subjecting these structures to great instability. Thus, it is necessary to implement a continuous monitoring, but the current approaches limit the observation of submerged points.

Underwater monitoring networks allow verification of the conditions to the full extent of submarine pipelines. However, communication in this environment is subjected to several limitations, leading to losses in the transmission channel that increases in media with high variability described by Fall (2004). For this reason, this system must tolerate failures and interference in order to cope with the medium characteristics.

The development of an architecture based on underwater communication with networks tolerant to delays and disconnections presented in Cerf et al. (2007) becomes a necessity due to the limitations imposed by that environment. Thus, monitoring applications in DTN networks (Delay/Disruption Tolerant Network) can be perfectly compatible with the delays and interruptions caused by interference and variability of the underwater environment. In this sense, communication architecture was adapted to the characteristics of the underwater environment, specifying scenarios for verification of system behavior to implement an effective monitoring application.

This paper investigates a deepwater monitoring system with acoustic sensors installed over the subsea pipelines which are responsible for the storage and transmission of information, and on logistic-support vessels from oil exploration. The objective is to analyze the viability and behavior of the system with routing protocols Epidemic (Mundur and Seligman, 2008) and Prophet (Lindgren, Doria and Schelén, 2004) which are representative of DTN-routing protocols. Those are analyzed using by the ONE (Opportunistic Network Environment) simulator (Keränen, Ott and Kärkkäinen, 2008), demonstrating that in scenarios compatible with the movement in an offshore area, logistic-support vessels can carry out data acquisition from sensors.

The remainder of this paper is organized as follows: Section 2 presents related works and Section 3, reviews the main characteristics of underwater communication. Section 4 introduces the proposed deepwater monitoring system. In Section 5 we show the analysis of the monitoring system. Section 6 presents the results, while Section 7 concludes the paper and present topics for future work.

RELATED WORK

Among other works on underwater monitoring systems, Vasilescu et al. (2005) present a sensor network for monitoring coral and reefs using AUVs (Autonomous Underwater Vehicle) to collect data, mixing short-range optical communication with acoustic communication. Penteado, Costa and Pedroza (2010) 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.

An analysis of the problems of underwater sensor networks is found in Liu, Zhou and Cui (2008). This paper presents the types of possible communications in the underwater environment, discussing the transmission alternatives: electromagnetic, optics and acoustics. An overview of underwater communication challenges can also be found in Heidemann, Ye, Wills, Syed and Li (2006), where the difficulties imposed by the media and the constraints of the acoustic channel, such as interference, bandwidth, reflections, error rate and range are highlighted. An architecture for underwater networks and its requirements was proposed in Akyildiz, Pompili and Melodia (2007). The study identifies different approaches for medium access control, network and transport layers, showing a very consistent evaluation of protocols of this architecture.

Some routing protocols have been proposed for underwater sensor networks. In Pompili, Melodia and Akyildiz (2006), the authors present a routing solution for monitoring applications with centralized planning of routes. Xie, Gibson and Diaz-Gonzalez (2006) present a cluster-based topology, where each node in a group will communicate with the gateway node, which is responsible for defining all routes of the network, managing the discovery of routes through test messages.

Delay tolerant networks (DTN) were used in the underwater environment, allowing communication through asynchronous messages, without the establishment of end to end path. Zhang (2006) examines some proposed protocols for DTN networks, such as Epidemic and Prophet. These protocols can be used in routing, depending on the desired message redundancy. Epidemic protocol uses a flood approach. Thus, each node sends the packet to all nodes found in order to increase a probability of packet delivery, consuming many network resources. The other extreme is the Prophet protocol, which uses the movement information to determine the most likely node to deliver the message, reducing the number of duplicate messages on the network.

Islam and Waldfogel (2008) analyze some routing methods for DTN networks like Direct Delivery and First Contact, showing that these simple strategies give good performance especially where only small bandwidths and low connectivity are available. Recently, Ribeiro, Pedroza and Costa (2010) proposed a hybrid routing protocol for underwater communication systems, which uses the mechanisms of the Prophet and Epidemic protocols for the routing of the messages according to the density of mobile nodes within the range of the sensors.

Unlike the works presented, we propose the integration of underwater sensors and mobile data collectors into a DTN network. Thus, it is considered the underwater monitoring system study using Epidemic and Prophet routing protocols. No reference was found in the available literature that addresses the provision of a monitoring system specific for subsea pipelines considering mobility and the constraints of the underwater environment.

UNDERWATER COMMUNICATIONS

Although underwater communication can be accomplished through electromagnetic and optics, acoustic waves method in practice is the most suitable. The electromagnetic transmission has high signal attenuation by water and requires large amounts of energy for transmission. Optical transmission has high transmission rate and low power consumption, but with the drawback of short range, caused by absorption and scattering of light. Applications are limited by the range of a few meters, even in clear water and perfect alignment (Vasilescu et al., 2005).

The most effective way to implement underwater communication is through acoustic waves (Liu, Zhou and Cui, 2008), even considering acoustic channel features, like sound speed in water that is about 1500 m/s, which is four times faster than sound speed in air, but still five orders of magnitude smaller than electromagnetic waves speed in the air. This feature implies latency of 0.67 s/km. Furthermore, the speed of sound in water is variable and dependent on pressure (depth), density, temperature and salinity (Urick, 1983). The combination of these dependencies makes sound speed in water vary from surface to the bottom according Brekhovskikh and Lysanov (1991), propagating in curved paths due to refraction caused by layers with different speeds.

Acoustic signal is based on mechanical waves of alternating compressions, requiring high power for transmission. Moreover, acoustic waves suffer interference from noises 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 for a few km with transmission frequencies below 30 kHz, implying in low transmission rates, usually around 5 kbps, as presented in Stojanovic (2006).

Control of medium access is difficult due to the high latency of communication channel. Thus, some proposals as FDMA (Frequency Division Multiple Access), TDMA (Time Division Multiple Access) and CDMA (Code Division Multiple Access) have become alternatives to underwater environments. The most used is TDMA due to the simple method of assignment of a cyclical time slot for transmission of each node in the network. During each time interval, the channel is reserved for the single node transmission. These intervals must be separated by a time guard to avoid overlapping transmissions.

Currently, acoustic modems can achieve underwater transmission rates of 5 kbps. In this case, distance between nodes must be up to 5 km. In greater distances, the bandwidth will decrease, increasing power consumption. Thus, to increase higher success rate and become compatible with high error rates, high latency and low data rates, the amount of data to be transmitted should be around 1 kbyte that is suitable for most applications.

DEEPWATER MONITORING SYSTEM

As presented, the use of acoustic monitoring networks in underwater environments was driven by the current acoustic modems that provided increased range up to 5 km with transmission rates of 5 kbps. Therefore, is possible to use underwater acoustic sensors installed over the submarine pipelines for monitoring pressure, temperature, flow and positioning control. This last option is especially important to monitoring the positioning during new lines launch of submarine pipelines (Solano et al., 2007).

The Campos Basin area is approximately 62,500 km^2 and can be divided into two regions, called transition and exploration regions (Fig. 1). Transition region is a transition area that logistic-support vessels moving between the coast and oil fields. Exploration region is the producing oil area composed by 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.

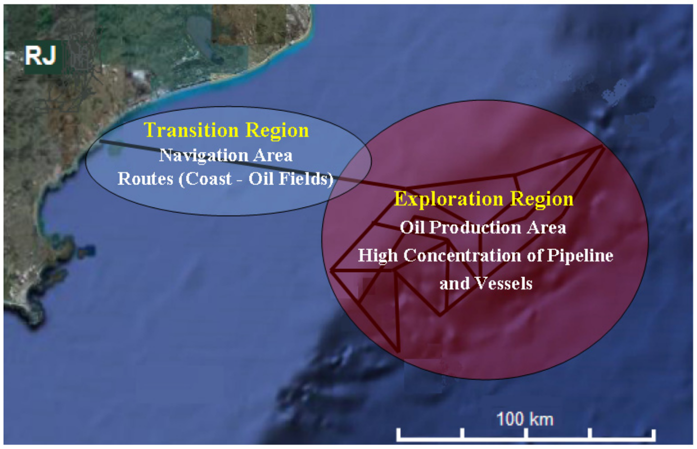

Fig. 1. Navigation area of logistic-support vessels.

Vessels have radio or satellite communication and their routes are coincident with subsea pipelines, becoming the most appropriate option to data sensors capture. The information is generated and stored on the sensors until some vessel is available for message reception, as shown in Fig. 2.

The long distances and dispersion of offshore installations affect the vessels density 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 of delays and interruptions perfectly fits the model of routing messages node to node, without establishing an end-to-end path.

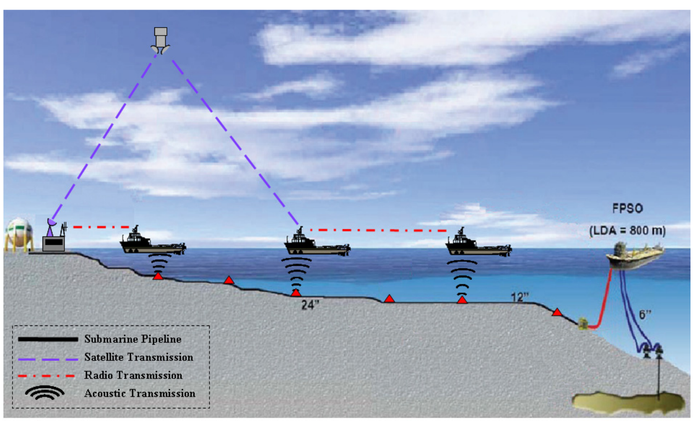

Fig. 2. Deepwater monitoring system.

Underwater Sensor Network

Underwater sensor network is based on nodes equipped with sensors and acoustic modems also used in Vasilescu et al. (2005). The nodes can communicate with other nodes to send their data and receive commands until it reaches a sink node. This edge node picks up the messages in underwater domain and forwards it to domain not underwater (Akyildiz, Pompili and Melodia, 2007). This network type, allows nodes maintaining an autonomous operation of data transmission, where sensors are responsible by the decision to transfer information when a mobile node is reachable. Thus, sensors can be used to monitor, even in real time, subsea pipeline conditions, but this operation must be planned to not spend too much energy with excessive data transmissions. The adjustment is necessary to ensure longer life of the sensors.

The proposed sensor network will not only have one sink, but all the mobile nodes may collect data in DTN (Delay/Disruption Tolerant Network) underwater domain. Sensors are installed over the subsea pipelines and programmed to generate information at fixed intervals, storing it until they are ready to forward them to the control center. Each of these samples is coded into a data packet, usually less than 1 kbyte. If deemed a transmission rate of 5 kbps, each node needs only 1.6 seconds of connection to transmit its packet. This feature is compatible with applications with low sampling rates like pipelines monitoring (Guo et al., 2010) and oceanographic data acquisition (Penteado, Costa and Pedroza, 2010).

The DTN network needs to forward messages without the establishment of an end-to-end path. This feature is related to the existing delays and disconnections. In underwater environments, these conditions are caused by constant changes in the acoustic medium, that affects the mobile node operation such as interferences, hibernation of sensors to energy conservation or maritime navigation conditions.

Underwater Communications Architecture

Communication architecture works through communication domains, defined by the type of communication and associated with device mobility. These domains are composed by acoustic sensors and mobile nodes that should be able to offer messages storage, which can be ensured with the use of the aggregation layer and storage units, implemented in the network architecture tolerant of delays and disconnections (Cerf et al., 2007). Moreover, acoustic sensors are responsible for determining the best form of communication that uses their resources.

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

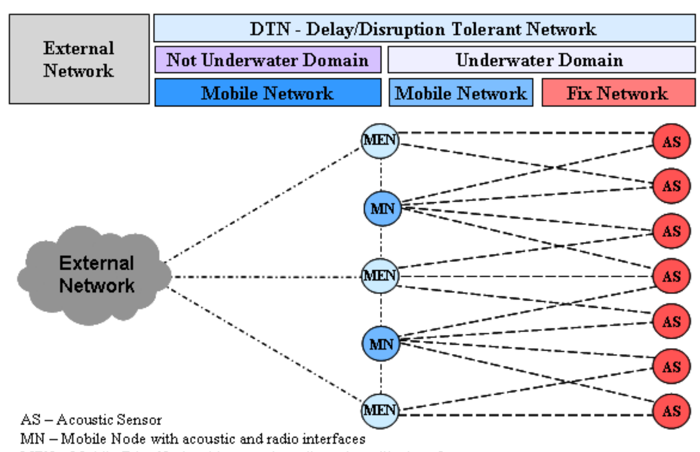

Fig. 3. Communication between mobile nodes and fixed sensors.

The mobile nodes (vessels) are entities present in the DTN network, which will be used to capture the sensors messages and the number of these devices depends on the vessels routes. All traffic must pass through the vessels before exiting the underwater domain. These vessels may have two kinds of functions: capture messages from sensors in underwater domain and retransmit these messages through not underwater domain. Some mobile nodes can be called edge nodes because they are also responsible for messages forwarding to the external network (Fig. 3).

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 the range of each sensor is an important parameter for the system and can be used to improve network performance. Thus, the routing protocol responsible for forwarding messages from the sensors can be based on Epidemic and Prophet algorithms in order to assert which of these protocols best fits the conditions of the monitoring system.

PERFORMANCE ANALYSIS

The analysis of the proposed monitoring system is done through a series of simulations designed to check the quality of the communication system during navigation of vessels in the transition and the exploration regions. The goal is to show the network behavior in each scenario to verify the communication system viability using the fleet of logistic-support vessels of oil exploration to capture data from sensors.

To evaluate and compare the monitoring system performance was used the ONE simulator proposed by Keränen, Ott and Kärkkäinen (2009). ONE uses a specific communication model to delays/disruption tolerant networks, where nodes make the reception, storage and forwarding of messages with different routing algorithms.

Due to the importance of the vessels displacements in this monitoring system, all simulations were based in the oil exploration area of Campos Basin in Brazil and real maritime routes to obtain a more realistic scenario. We used the mobility pattern "Shortest Path Map Based Movement", using Dijkstra's algorithm to find the shortest path to the destinations are randomly selected through the available routes.

The simulations consider a mobile network with 25 sensors and up to 200 mobile nodes (vessels) and a control center outside the DTN network. The mobile nodes are randomly distributed over the network and they move according to the mobility model. Nodes participate in the two 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:

- Transition Region: containing a total of 5 sensors over the submarine pipeline that connects the coast to the fields the production, this equals 1 sensor every 20 km. In this area, the vessels often travel great distances without stopping and at almost constant speeds;

- Exploration Region: containing a total of 20 sensors distributed in strategic points the submarine pipelines network. In this area, the vessels travel shorter distances with constant stoppages in the production units (fixed platforms, semi-submersible platforms and FPSOs - Floating Production Storage and Offloading), that may remain anchored the wait of new operational plans.

Currently, there are 254 ships operating for Petrobras, but the expectation is that this number will reach 465 by 2013. This information is based on the presentation of the Petrobras business plan 2010 - 2014 made by Gabrielli and Barbassa (2010). As the Campos Basin is currently working with nearly 80% of Petrobras vessels fleet, we chose to use this number in the simulations.

Another important characteristic of the movement model is the stop points executed during the vessels displacement. These points of interest represent offshore units and anchoring areas that are concentrated in the exploration region. The Fig. 4 presents the basic scenario of simulations where can be identified the points of interest, sensors and routes of vessels.

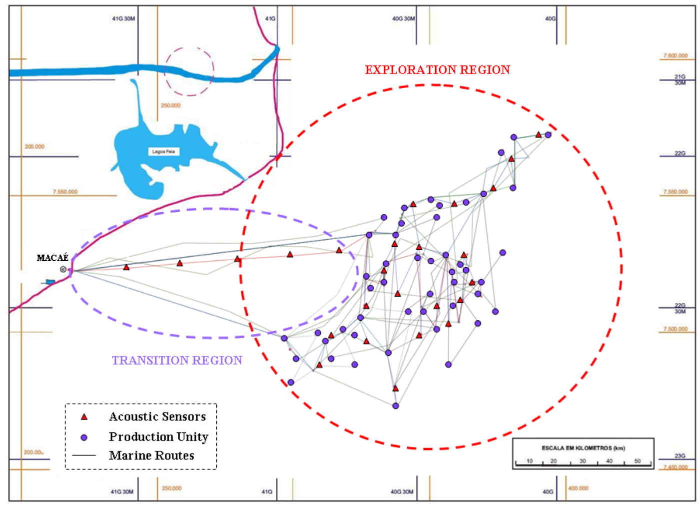

Fig. 4. Basic scenario of simulations.

Our evaluation focused on comparing the system behavior in the two regions using the protocols Epidemic (Mundur and Seligman, 2008) and Prophet (Lindgren, Doria and Schelén, 2004) to verify the message forwarding in communications domains.

The simulations are intended to verify the following system information:

- Percentage of sensors reached by vessels;
- Contacts made in the network;
- Average time until the transmission;
- Probability of message delivery;
- Network latency.

Scenario Configuration

To simulate a realistic monitoring scenario, we considered the specific characteristics the each region, which usually influences the type of movement and vessels density. Except for the sensors, mobile nodes (vessels) move according to pre-established navigation routes. In a typical operation, the vessels traverse the transition region staying for long times in the exploration region. During operation, vessels perform data acquisition whenever that a sensor is within range.

The parameters definition of the simulation was based on the area of oil exploration in the Campos Basin, the type the vessel movements and the transmission feature of acoustic and radio communications:

- Area of 250 km x 250 km (transition and exploration regions);
- 48 points of interest in the exploration region, representing the production units;
- The number of mobile nodes varies the 1 to 200 vessels;
- Vessels speed can vary between 5 and 14 knots;
- The range was defined as 5 km to underwater acoustic communication and 20 km to VHF radio communication. The connection is performed only if the sensor and the mobile node or both nodes are moving within the contact range;
- Data transmission speed was defined as 5 kbps to acoustic communication and 20 kbps to VHF radio communication;
- Message buffer was set to 10 Mbytes respecting the characteristics of acoustic modems;
- Messages were generated with uniform distribution between 60 s and 300 s;
- Message sizes were defined as 1 and 2 kbytes;
- Simulation period was 24 hours.

As the size of the message can be 1 and 2 kbytes may represent the exchange of text files with information on flow, pressure and temperature collected from the subsea pipelines.

SIMULATION RESULTS

The monitoring system should balance the availability of network resources with the use of the sensors. Therefore, the form of monitoring can also impact the amount of information and messages sent. Thus, it was possible to verify that even with the generation of messages every 60 seconds, the number of sent messages is much lower than the network capacity. Getting good results in two different situations that are complementary:

- Vessels in Transition Region: in this case, the availability of vessels is low, where the underwater monitoring can be compromised by a vessels shortage, but it is possible to increase the life of the sensors;

- Vessels in Exploration Region: in this case, the massive presence of vessels in the area of oil production, increase network availability, but shortens the life of the sensors.

Each simulation was performed to verify the ability of vessels to reach the sensors and capture messages. In this case, it was possible to determine the percentage the sensors contacted in each scenario, as shown in Fig. 5.

It can be observed that the system, even with few vessels (25), reached 96% of the network sensors. This is possible because the routes and subsea pipelines are coincident. All the sensors were only contacted from the scenario with 50 vessels. This was due to the large area and to the dispersed distribution of sensors used in the simulation.

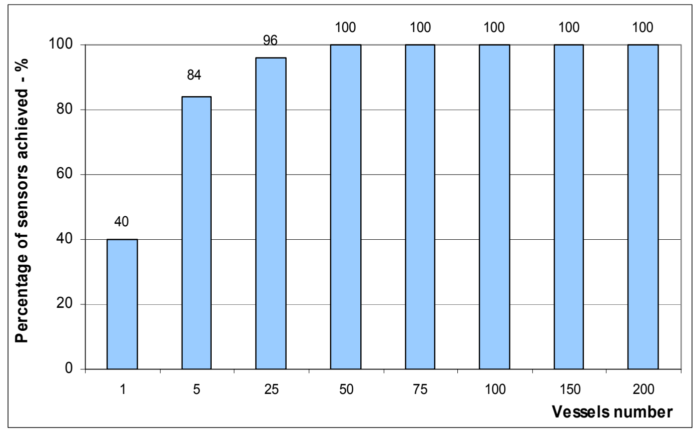

Fig. 5. Percentage of sensors contacted.

Another important aspect is the number of contacts made per hour (Fig. 6). This information shows the contacts growth with the number of vessels in the network that is also related with the average waiting time of the sensors to send messages, shown in Fig. 7. This time is crucial to define what kind of monitoring can be performed on the system with the available vessels.

The position monitoring of the ducts is a typical example; it varies very little and can be implemented with 25 or in the network. In these two cases, the sensors data are collected every 735 min (12 h and 15 min) on average.

The level needed to monitor flow, temperature and pressure of subsea pipelines is reached from 150 vessels obtaining an average wait interval of 29 min. In scenario with 200 vessels this time can reach 16 min becoming the monitoring system totally practicable.

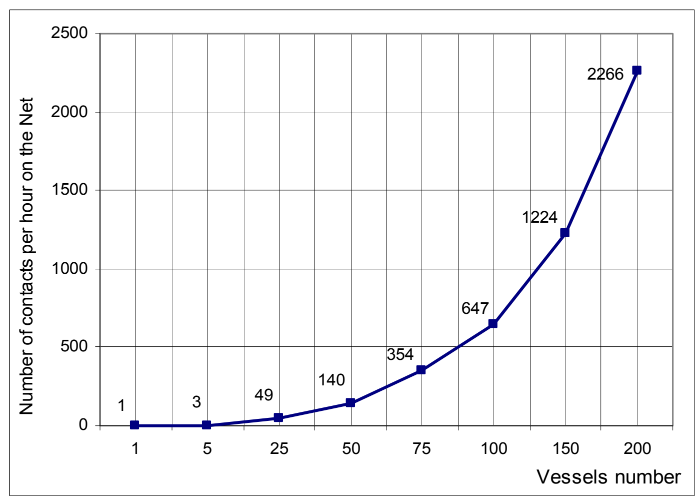

Fig. 6. Number of network contacts.

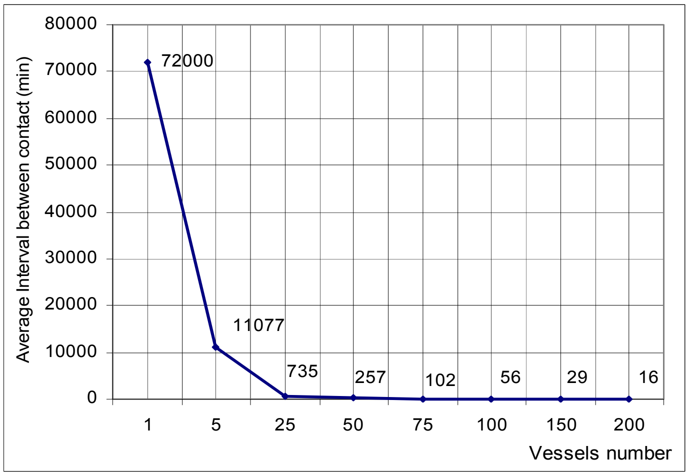

Fig. 7. Average interval for sending messages.

The results obtained with the monitoring system shown in Fig. 6~7, does not vary with the use of the Epidemic and Prophet protocols. These protocols have influence on messages delivery probability and on network latency, shown in Fig. 8~9.

The increase of vessels number in the network caused the increase of the probability of message delivery and the reducing of the latency on the network. This occurred due to the increase of the contacts and messages on the network that can lead to messages drop. This effect can be minimized by the size of the buffers (10 Mbytes) that could store up to 1250 messages of 1 kbyte.

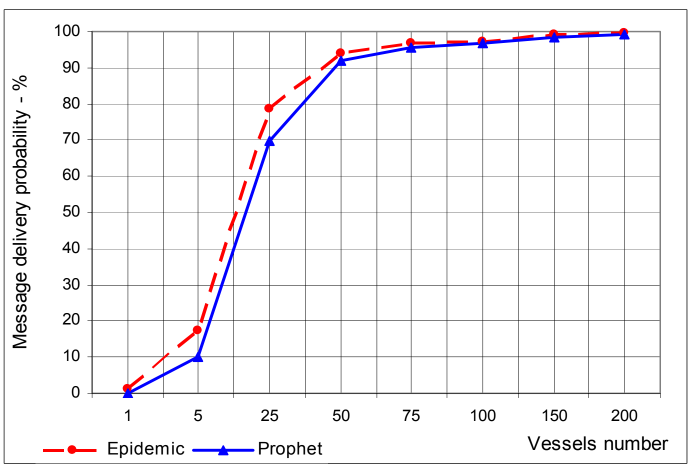

Fig. 8. Message delivery probability.

The probability of message delivery presents similar behavior for the Epidemic and the Prophet protocols. However there was only a small difference in the scenarios with few vessels, having the Epidemic protocol a little advantage, according to Fig. 8, due to the network flooding policy that tries to increase the number of messages in the destination.

As shown in Fig. 9, the network latency with Prophet protocol is smaller than with Epidemic protocol in scenarios with few vessels, due to the smaller number of messages in the network. This situation is reversed in scenario with 25 vessels. In this case, even using the network flooding, the network latency gets smaller due to the greater number of vessels, causing messages to be delivered faster.

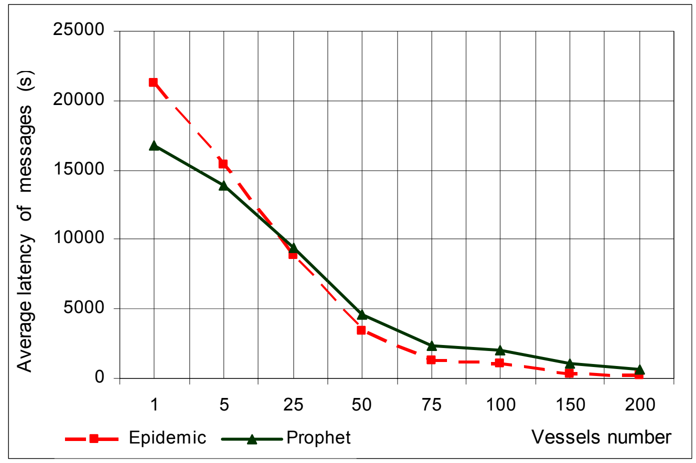

Fig. 9. Network latency.

The general behavior of the system was satisfactory, presenting results that demonstrate the feasibility of using the fleet of logistic support in underwater monitoring of the oil exploration area located in the Campos Basin.

CONCLUSIONS AND FUTURE WORKS

This work proposed a monitoring system for offshore pipelines in a delay/disruption tolerant network. The objective was to verify the system feasibility with the analysis of network behavior considering Epidemic and Prophet protocols. The mobility model was based on actual scenarios in the oil exploration area in Brazil. The system became feasible, with a longer number of vessels contributing to increase the number of messages sent from the sensors and to reduce the network latency.

The Epidemic and Prophet protocols presented very similar results, with small variations according to the number of available vessels. This suggests that the use of a protocol that exploits the differences in movement of vessels in the two regions (Ribeiro, Pedroza and Costa, 2010), can obtain better results in order to reduce the time of message collection.

Despite the unpredictable communication of system, it was found that fewer vessels are needed to implement monitoring applications that can tolerate a larger sampling period. Another important feature is that was done the contact with all sensors, achieved with a small number of vessels. The level that allows the monitoring of pressure, flow and temperature of submarine pipelines has been reached with a number of vessels that is totally consistent with the scenario currently found in the Campos Basin in Brazil.

As future work, we intend to investigate a hybrid protocol containing features of the Epidemic and the Prophet algorithms. This protocol can choose the best operation mode to increase performance of the underwater monitoring system.

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