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Application of Wireless Sensor Network for the Monitoring Systems of Vessels

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1. Introduction

Wireless Sensor Networks (WSNs) have gained worldwide attention in recent years, particularly with the proliferation of Micro-Electro-Mechanical Systems (MEMS) technology which has facilitated the development of smart sensors. Smart sensors are small devices composed of one or more sensors, a memory, a processor, a power supply and a radio unit. They can sense the environment, measure and send data wirelessly to control unit for further processing and decisions. WSNs have great potential for many applications such as habitat monitoring (Polastre et al., 2004), intrusion detection and target tracking and surveillance (Arora et al., 2004), oceanography (Tateson et al., 2005), environmental monitoring (Barrenetxea et al., 2008a, 2008b; Padhy et al., 2005; Selavo et al., 2007), structural health monitoring (Paek et al., 2005), infrastructure monitoring (Stoianov et al., 2007), precision agriculture (Langendoen et al., 2006), biomedical health monitoring (Gao et al., 2005), and hazardous environment exploration and seismic sensing (Werner-Allen et al., 2006).

Structures, including bridges, buildings, dams, pipelines, aircraft, ships, among others, are complex engineered systems that ensure society's economic and industrial prosperity. Monitoring systems have been implemented for these structures to monitor their operation and behaviour against incidents. The monitoring system is primarily responsible for collecting the measurement output from sensors installed in the structure and storing the measurement data within a central data repository. To guarantee that measurement data are reliably collected, structural monitoring systems employ wires for communication between sensors and the repository. While wires provide a very reliable communication link, their installation in structures can be expensive and labour-intensive. With the emergence of wireless sensor technologies, industrial and academic groups have started to investigate the feasibility of WSN

to replace the current wired monitoring systems (Lynch et al., 2006). Ships constitute an important part of modern systems widely used in armed conflicts and commercial purposes such as fishing and transporting passengers and cargos. Ships manufacturers and navy companies aim to use automation on board ships as much as possible in order to improve security and reduce the number of crew members. Modern ships are equipped with automatic monitoring systems which control and ensure the safety and accuracy of the whole ship operation. Current shipboard monitoring systems use extensive lengths of cables to connect several thousands of sensors to central control units. Tens of kilometres of cables may be installed on board a ferry-boat, increasing its cost, weight and architecture complexity. In addition to the high cost of wires installation during ships construction, vessels represent a complex and harsh environment in which extensive lengths of wires are vulnerable to detriments such as heat, moisture and toxic agents. Hence, using wireless communication between sensors and control units on board ships presents several advantages over wired solution. Radio waves travel through space, i.e. the additional cost, weight and complexity produced by the routing of cables through the structure of a vessel, are eliminated. Moreover, wireless systems are easily and inexpensively reconfigured. Therefore, using the WSN technology for shipboard monitoring systems can be a cost-effective and survivable solution. Wireless sensor nodes are capable to form a large scale (up to thousands), self-organising and self configurable ad hoc network with low cost and low power consumption devices.

However, electromagnetic waves propagation on board a vessel is a serious challenge. Several factors decrease the performance of wireless networks in this particular environment. Metallic bulkheads, made often of steel, can severely decrease the power of received signals. Moreover, multipath effects leading to multiple delayed copies of the transmitted signal at the receiver may also decrease the radio communication data rate. A propagation study must be carried out in this harsh environment to ensure the reliability of radio links and the WSN feasibility.

This chapter studies the feasibility of WSN on board ships. Several measurement campaigns are conducted on board a ferry-boat to verify the possibility of wireless communications between ship parts and to analyse the performance of WSN on board. These measurements aim at determining path loss models for typical shipboard environments and testing the possibility of wireless communication between adjacent rooms or adjacent decks. Using the results of these experiments, a WSN is tested on board the ferry. The results obtained from the measurement campaigns are then used to propose an architecture for a large-scale shipboard WSN. As the network test uses a limited number of nodes, the full monitoring system based on the proposed architecture is simulated using a network simulator.

2. Related works

Several research teams have investigated the possibility of using of wireless sensors on board vessels.

In (Mokole et al., 2000), a feasibility study of wireless communications using Commercial Off-The-Shelf (COTS) wireless modems that communicate at radio frequencies from 800

MHz up to 3 GHz was conducted on board vessels. Authors have verified that radio communications are possible between adjacent rooms even when watertight doors are closed.

In (Estes et al., 2001), measurement campaigns were carried out on board various naval vessels to verify the feasibility of intra- and inter-compartment radio communications. The measurement results have shown that ship bulkheads severely decrease the power of received signals of about 20–30 dB but communication through two or three bulkheads is found to be still possible. They explain this result by the presence of a number of non-steel elements in the bulkheads (e.g. hatch seals, ducts, cable transits) that allow radio signals to penetrate.

In (Schwartz, 2002), a new shipboard monitoring system using wireless sensors interfacing to a ship Local Area Network (LAN) through 802.11 Wireless Access Points (WAPs) was proposed. The system has been validated successfully on numerous naval vessels including the USS Monterey and the ex-USS Shadwell.

Authors in (Brown et al., 2003) presented a process template to assist the information and process control technologist in successfully deploying today's COTS WLAN systems. The process focuses on an eight-step process that balances analytical modelling requirements with empirical surveys to qualify below deck noise, signal propagation and realistic connectivity expectations.

Authors in (Ploeger et al., 2003) proposed a wireless shipboard monitoring system constituted of wireless data acquisition nodes, called Intelligent Components Health Monitor (ICHM), that are capable to collect sensor data from analog sensors and communicate these data via Bluetooth wireless radios to a centralized data repository, called Compartment Health Monitor (CHM).

Authors in (Li et al., 2003; Ou & Li, 2003) studied the feasibility of using wireless sensors for monitoring the health of offshore oil platforms. The proposed WSN is constituted of multiple sensor nodes wirelessly connected to a base station which collects the data for processing and distribution through a LAN or the Internet.

(Takahashi, 2004) reported on the use of wireless sensors for wireless monitoring of oil tankers. Wireless sensors manufactured by Dust Networks are being installed throughout various oil tankers, especially in critical regions where structural or mechanical problems could potentially occur.

Authors in (Krishnamurthy et al., 2005) focused on the preventive equipment maintenance in which vibrations signatures are gathered to predict equipment failure. Based on application requirements and site surveys, they have proposed and tested an architecture for this type of application on board an oil tanker in the North Sea. The sensor network including 150 accelerometers, 26 sensor nodes, 4 Stargates and 1 PC has been deployed and tested during four months on board the ship.

Authors in (Park et al., 2008) carried out some experiments using ZigBee devices on board a ship. Their communication tests have shown that intra-compartment wireless communications are possible and inter-compartments wireless communications are almost

impossible. Based on these results, they have successfully tested a hybrid WSN using ZigBee for intra-compartment communications and Power Line communications (PLC) for inter-compartment communications.

Moreover, authors in (Paik et al., 2009) carried out some transmission tests using two ZigBee protocol analyzers to evaluate the performance of wireless communications on the passenger deck of a ship. Four scenarios including communication between a cabin and the corridor, in the corridor and between adjacent decks with and without entrance door closure, have been considered. In addition, a ZigBee-based WSN has been successfully tested in the engine room of the ship.

Authors in (Pilsak et al., 2009) investigated the propagation conditions of 2.4 GHz RF waves on a bridge of a modern cruise vessel which is important for evaluation of the ElectroMagnetic Compatibility (EMC) behaviour of the electronic bridge equipment. The intention of such an evaluation is to ensure that electronic equipment, as well as the wireless transmission line, is not disturbed. The bridge has been simulated with a 3D model which includes the material data of the different objects on the bridge. A ray tracing algorithm has been applied to this model and the maximum data rate of a 2.4 GHz wireless LAN system has been simulated. In addition, measurements on the bridge have been performed to back up the simulation results and to investigate the real case.

Authors in (Kang et al., 2011) proposed a new method of tracking the crew member location using ZigBee tags and routers. Their method was tested and proved its viability on board steel-structured ships. The authors think that this method may assist the onboard training organizer and commanding officer by providing complete information to base its decisions.

Finally, authors in (Kdouh et al., 2011a, 2011b, 2011c, 2012) reported on the feasibility of WSN on board ships. Several measurement campaigns have been conducted on board several ferries to verify the possibility of intra-, inter-compartment and inter-decks radio communication. A WSN has been tested successfully on board a ferry. The obtained results of these works will be detailed in the remaining of this chapter.

3. Measurement sites

'Acadie' is the ship used for this study. It is a ferry boat from the 'Compagnie Océane'. The 'Acadie' is constituted of the following decks, arranged vertically from bottom to top: the bottom deck which houses the main engine room, the control room and the crew's cabins; the main deck which is a parking; the passenger deck, and the bridge deck which contains the wheel house. Four typical environments are considered for the propagation measurements: the engine room, the parking, the passenger deck and the crew's cabins.

The engine room of 'Acadie' is composed of the main engine room and the control room. These two rooms are separated by a bulkhead and a watertight door which have both a big glass window. The engine room contains engines, pumps, generators and valves. The other part of the bottom deck houses the crew's cabins. This part is separated from the engine room by a thick metallic bulkhead. The cabins doors are made of wood.

The parking of 'Acadie' is constituted of a big hall with metallic walls including some glass windows and some small rooms (in the front section) with metallic watertight doors. Measurements were carried out on board the ferry when it was moored to the harbour. There were no vehicles parked in the parking. The parking is connected to upper and lower decks by stairways that have a metallic watertight door on the parking side.

The passenger deck of 'Acadie' is a big hall with metallic walls including glass windows. It is composed of passengers' seats and tables. This environment is composite and constituted of several types of materials such as wood, glass and steel.

4. Propagation measurements

This section describes the propagation measurement campaign conducted on board 'Acadie'. It includes the measurement procedure, results and analysis.

4.1. Measurement procedure

Due to the low data rate of a shipboard WSN, Continuous Wave (CW) measurements are sufficient to characterize the propagation effects related to a WSN deployment because the bandwidth of the transmitted signal is much less than the coherence bandwidth of the propagation channel. The transmission system is composed of a signal generator, an omnidirectional conical monopole antenna and some connecting cables. The signal generator delivers 0 dBm sinusoidal signal at a frequency of 2.45 GHz (ISM radio band - Industrial Scientific and Medical). This ISM frequency band has been selected as it is used by most existing standards dedicated to WSN (Yick et al., 2008). The receiver is composed of a spectrum analyzer operating in a zero-span mode, a laptop to collect and save measurements data, an antenna positioner and connecting cables.

Each shipboard environment was measured using a standard procedure. The transmitting (Tx) antenna, which has a height of 1.80 m, is placed at a fixed location. Path loss measurements are performed using a receiver (Rx) with a 1.80 m antenna height. The receiver is placed at different locations in each shipboard environment. Tx and Rx locations are marked on a digital map to calculate the Tx-Rx separation distance. These experiments rely on narrowband measurements of a CW signal at 2.45 GHz performed to determine the path loss. The received power varies over a small area due to multipath-induced fading. However, averaging the received power values along 20 wavelength circular track using 250 power samples, yields a reliable estimation of the local average power independent of signal bandwidth (Durgin et al., 1998). The average of the received power values in Watts is used for all path loss estimations.

4.2. Measurement scenarios

Fig. 1 shows the transmitter locations (Tx1 to Tx4), the receiver locations (blue squares), the layout of the ship and the measured path loss for all environments considered on board 'Acadie'. In the passenger deck, the transmitter was placed at the Tx1 location and the

receiver was placed at 16 different locations. In the parking, the transmitter was placed at the Tx2 location and the receiver was placed at 21 different locations. In the engine room, the transmitter was placed in the control room (Tx3 location) and the receiver was placed at 14 different locations in the main engine room. To characterize the communication between decks, the transmitter was placed at the location Tx4 in the parking (2 m in front of the watertight door) and the receiver was placed at 11 different locations in the crew cabins. These two decks are connected by metallic stairs. The entrance watertight door to the stairway in the parking was closed during these experiments. The other three stairways connecting the parking to the engine room and the passenger deck have the same architecture. The results of this experiment can be generalized to characterize the communication between decks.

4.3. Results analysis

The main configurations of communication between nodes in a future shipboard WSN are:

- communication between nodes placed in the same room
- communication between nodes placed in different rooms
- communication between nodes placed in different decks

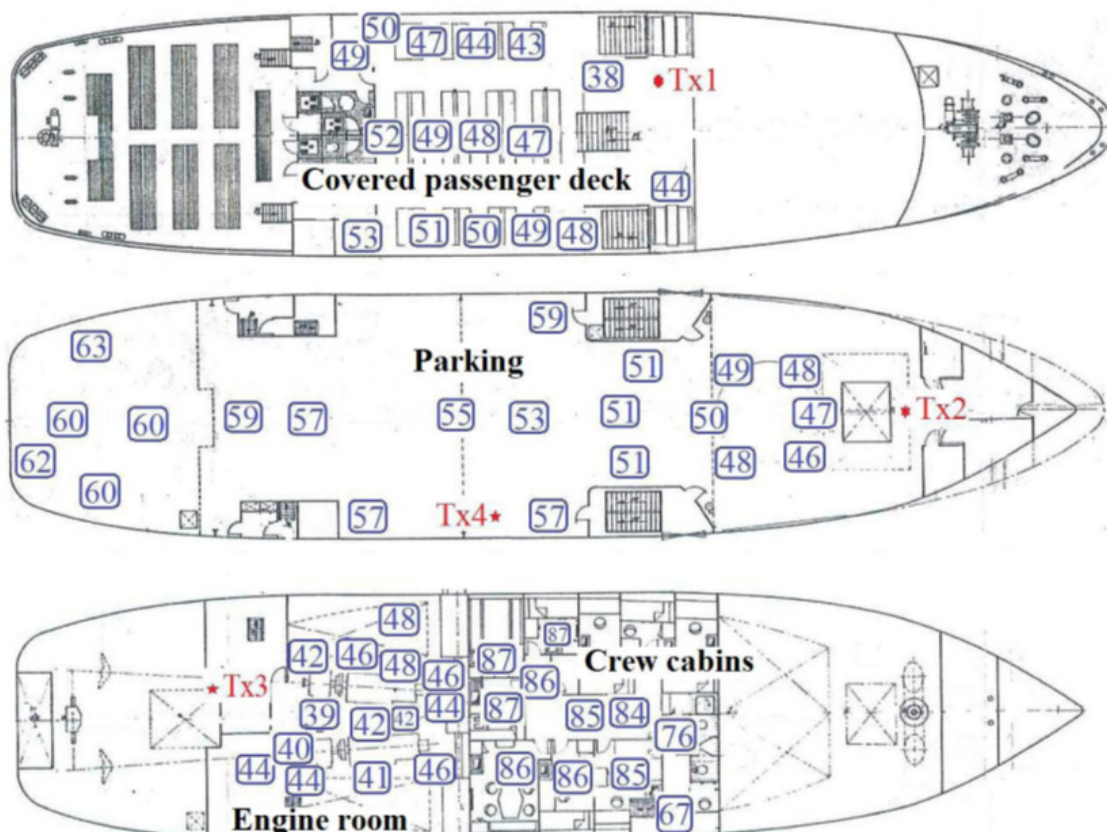


Figure 1. Layout of different parts of the 'Acadie' vessel, and locations of the transmitter Tx1, Tx2, Tx3 and Tx4 (in red), and the receivers (blue squares). Values in the blue squares are the path loss in dB

A communication is considered as possible when the received power is higher than -85 dBm. This threshold is related to the receiving sensitivity of sensor nodes that will be used later in the WSN experiment (Memsic Technology, 2007a).

4.3.1. Communication between nodes within the same room

The three considered environments in this case are: the engine room, the parking and the passenger deck. Measurement results are used to determine the relation between the path loss and the distance between nodes in each environment. Average path loss for a separation distance d between the transmitter and the receiver is expressed as a function of distance by using the following expression (Rappaport, 2002):

$$\overline{PL(d)} = \overline{PL(d_0)} + 10n\log_{10}(d/d_0) \quad (1)$$

where n is the path loss exponent which indicates the rate at which the path loss increases with distance and $d_0 = 1$ m is the reference distance. This model does not consider different surrounding configurations for the same Tx-Rx separation distance d . Measurements have shown that at any value of d , the path loss $PL(d)$ for a particular location is random and has a log-normal distribution around its mean distance-dependant value. Hence, path loss can be expressed as:

$$PL(d) = \overline{PL(d_0)} + 10n\log_{10}(d/d_0) + X_\sigma \quad (2)$$

where X_σ is a zero-mean Gaussian distributed random variable (in dB) with standard deviation σ (also in dB). The log-normal distribution describes random effects of shadowing or multipath propagation which occur over a large number of measurement locations having the same separation distance but with different levels of clutter on the propagation paths (Rappaport, 2002).

The results of measurements performed on board the 'Acadie' vessel have shown a significant correlation with model (1). Fig. 2 shows path loss values as a function of distance for all environments. Shadowing effects have been taken into account by the Gaussian distributed random variable with σ computed as the standard deviation of the error between the measurements and the model (1) results.

The values of $\overline{PL(d_0)}$, n , and σ have been computed from measured data using linear regression (Minimum Mean Square Error MMSE estimation). The parameters obtained for the three environments are given in Table 1 where ρ is the correlation coefficient between measurements and model results. The large values of ρ show a significant correlation between measurement results and the path loss model. Nevertheless, the value of ρ in the engine room is lower than that in other environments. This difference may be explained by the complex arrangement of metallic machines and tubes in this environment, which randomly scatters, reflects and diffracts the radio waves. The arrangement is more homogenous in the passenger deck and the parking.

Some preliminary conclusions may be drawn from the values of n . The path loss exponent is equal to 1 in the engine room of 'Acadie'. This result can be explained by the presence of metallic walls and ceiling and the absence of significant radio leakage between the engine room and the neighbourhood (the access between the engine room and the parking was closed during measurements). The transmitted energy is then kept within the engine room. The engine room is then similar to a reverberant chamber. Moreover, the path loss exponent in the parking is equal to 1.61 which is lower than the free space path loss exponent. This result is explained by the guiding effect of metallic walls and ceiling. However, the difference between the engine room and the parking exponents is explained by the presence of glass windows in the parking walls which allow EM leakage for radio waves. The transmitted energy is not kept inside the parking like in the engine room where the walls are completely metallic. Furniture obstructing the visibility between Tx and Rx explains the larger value of n in the covered passenger deck.

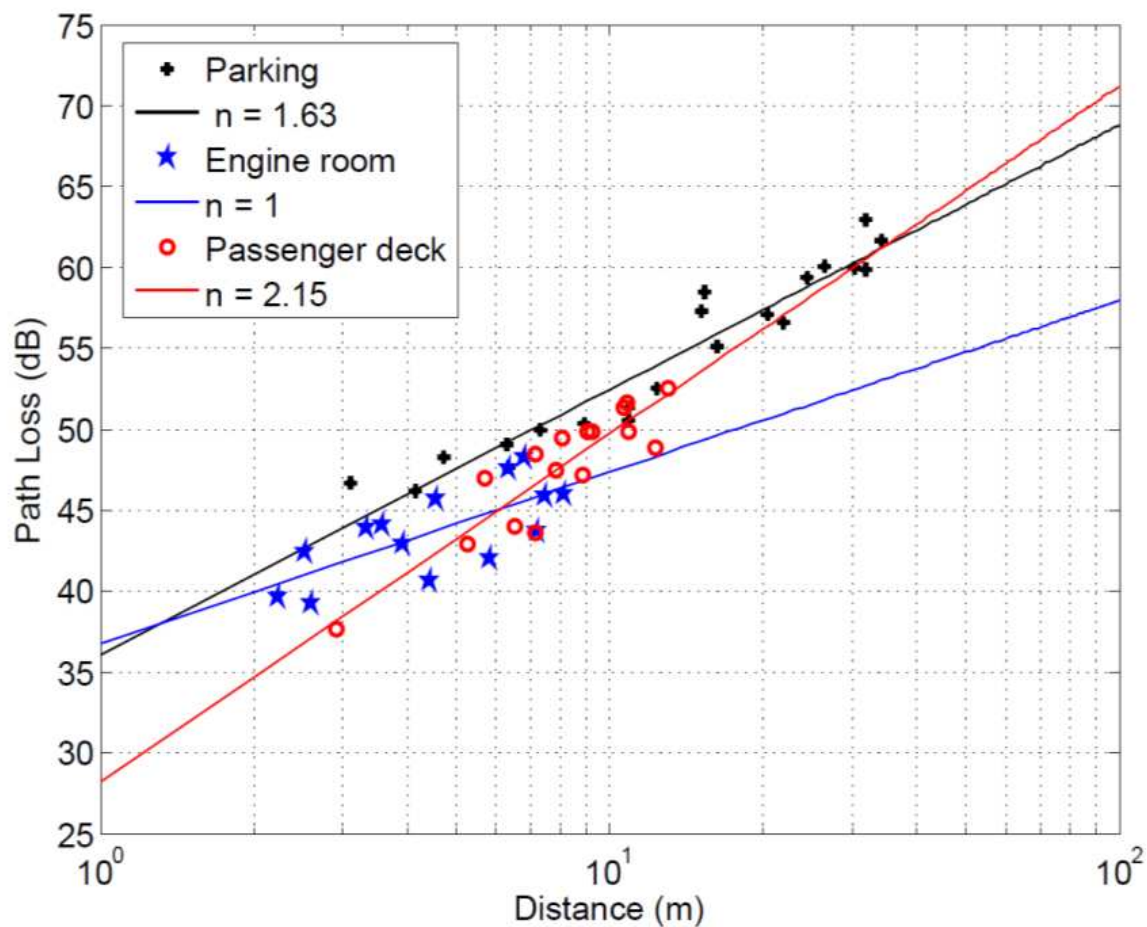


Figure 2. Scatter plot of path loss versus Tx-Rx distance within the same room

Environment	n	$\overline{PL(d_0)}$ (dB)	σ (dB)	q
Engine room	1	36.76	1.37	0.72
Parking	1.63	36.10	1.21	0.96
Passenger deck	2.15	28.19	1.25	0.90

Table 1. Path loss parameters

4.3.2. Communication between nodes placed in different rooms

The second studied configuration is the communication between nodes placed in different rooms of the same deck. EM waves propagation is considered in the bottom deck and the parking which contain several rooms. In this case, the propagation path between Tx and Rx is obstructed by bulkheads and doors.

The first scenario is the communication between the crew's cabins and the engine room. As stated before, these two parts are separated by a thick totally metallic bulkhead. The transmitter is located in the corridor between crew cabins and the receiver is moved in the engine room. No signal has been received, in spite of the small Tx-Rx separation distance. This is explained by the huge attenuation of the thick metallic bulkhead and the absence of openings allowing EM leakage between these two adjacent areas.

The second scenario is the communication between nodes located in two adjacent rooms with a common door. Two types of doors may be considered on board 'Acadie': the metallic watertight doors that are mainly used at the entrance of stairways connecting the parking to other decks, and between small rooms located in the front section of the parking; and the wooden doors of the crew's cabins. Several experiments have been conducted to determine the excess path loss due to closing a door between two nodes, using the following experimental protocol. Tx and Rx are located in the two sides of the door and path loss is measured when the door is opened and when it is closed (with the same locations of Tx and Rx for both cases). Excess path loss due to the door closure is determined as the difference between the two measured values. The results have shown that the closure of a metallic watertight door decreases the received signal by an average value of 20 dB (with a standard deviation of 3 dB). However, the effect of wooden doors was negligible (no more than 0.5 dB of attenuation).

Several conclusions may be drawn from these experiments regarding the configuration between two nodes placed in adjacent rooms. If the common bulkhead between rooms is totally metallic and does not support a door, the communication is impossible. Otherwise, in the presence of a door, the communication is always possible (door opened or closed). Closing a watertight door on the propagation path between nodes decreases the transmitted signal level by up to 25 dB. However, the presence of the two closed watertight doors between two nodes makes their connectivity impossible.

4.3.3. Communication between nodes in different decks

Path loss levels of measurements between the parking and the passenger deck (Fig. 1) show that the transmitter located in front of the watertight door in the parking is not able to cover

the total area of the crew's cabins deck. The maximum acceptable path loss is 85 dB, which is less than most of the values found in this deck. The variation of path loss values in this configuration does not depend directly of the Tx-Rx separation distance. It depends on the closeness of the Rx and Tx to the stairway. This variation indicates that stairways are the main sources of EM leakage between adjacent decks. Hence, placing intermediate sensor nodes in the stairways is necessary to maintain the connectivity of shipboard WSN.

5. Wireless sensor network test

This section describes the deployment of a WSN based on the conclusions drawn from the propagation study. Firstly, the technology used in the experiment is described and then, in the second part, the deployment procedure is presented. Finally, the obtained results are presented and discussed.

5.1. Technology used for WSN test

The shipboard WSN test was carried out using Crossbow's MICAz wireless sensor nodes (motest) (Memsic Technology, 2007a). MicaZ, which is IEEE 802.15.4 compliant, is a tiny wireless measurement system designed specifically for deeply embedded sensor networks. Each node is composed of a processor, an internal memory, a 2.4 GHz radio transceiver, two AA batteries and a sensor board. It has a maximum data rate of 250 kbps. Embedded sensors can measure temperature, humidity, barometric pressure, ambient light and acceleration. The Crossbow's XMesh routing protocol, which is a link-quality based dynamic routing protocol that uses periodic route update messages from each node to estimate link quality, has been used in this experiment. Each node listens to the radio traffic in the neighborhood and selects the parent that would be the least costly in terms of transmissions number to reach the base station (Memsic Technology, 2007b). The network is composed of 12 sensor nodes and one gateway connected to a laptop via a USB cable. The laptop runs the MoteView 2.0 software which is a graphical user interface that allows visualizing the real time data sent by the WSN to the base station and the network topology evolution during the test.

5.2. Deployment procedure

The choice of the locations of nodes is based on the results obtained from the propagation study. Previous results have shown that EM waves propagation is possible between decks through stairways. To ensure the connectivity between the four decks of the shipboard WSN, relay nodes are first installed in the stairways. Hence, the deployment procedure has continued by installing the following nodes in stairways (Fig. 3):

- Node 3 between the crew's deck and the parking (the watertight door is closed)
- Node 2 between the engine room and the parking (the watertight door is open)
- Node 7 between the parking and the passenger deck (the watertight door is open)
- Node 11 between the covered passenger deck and the non-covered passenger deck (this stairway has a wooden door which was closed during the test).

The base station is installed in the control room (same location of Tx3 in Fig. 1). Node 1 is installed on one of the two main engines in the engine room, node 4 is installed in the crew's deck and node 9, in the covered passenger deck. Node's installation is different in the parking where several cases have been distinguished as a function of the number of watertight doors between the transmitter and the receiver. Node 8 is installed in the small room located in the front section of the parking. The watertight door of this room is closed during the test. Node 6 is installed in the middle of the parking and node 5 is installed in front of the second stairway located between the engine room and the parking. Node 12 is used to collect data from the wheel house. There are no stairs between the wheel house and the lower decks. Thus, node 10 is installed on the bridge deck as an intermediate node between node 12 located in the wheel house and node 11 located in the stairways between the covered and the non covered passenger deck.

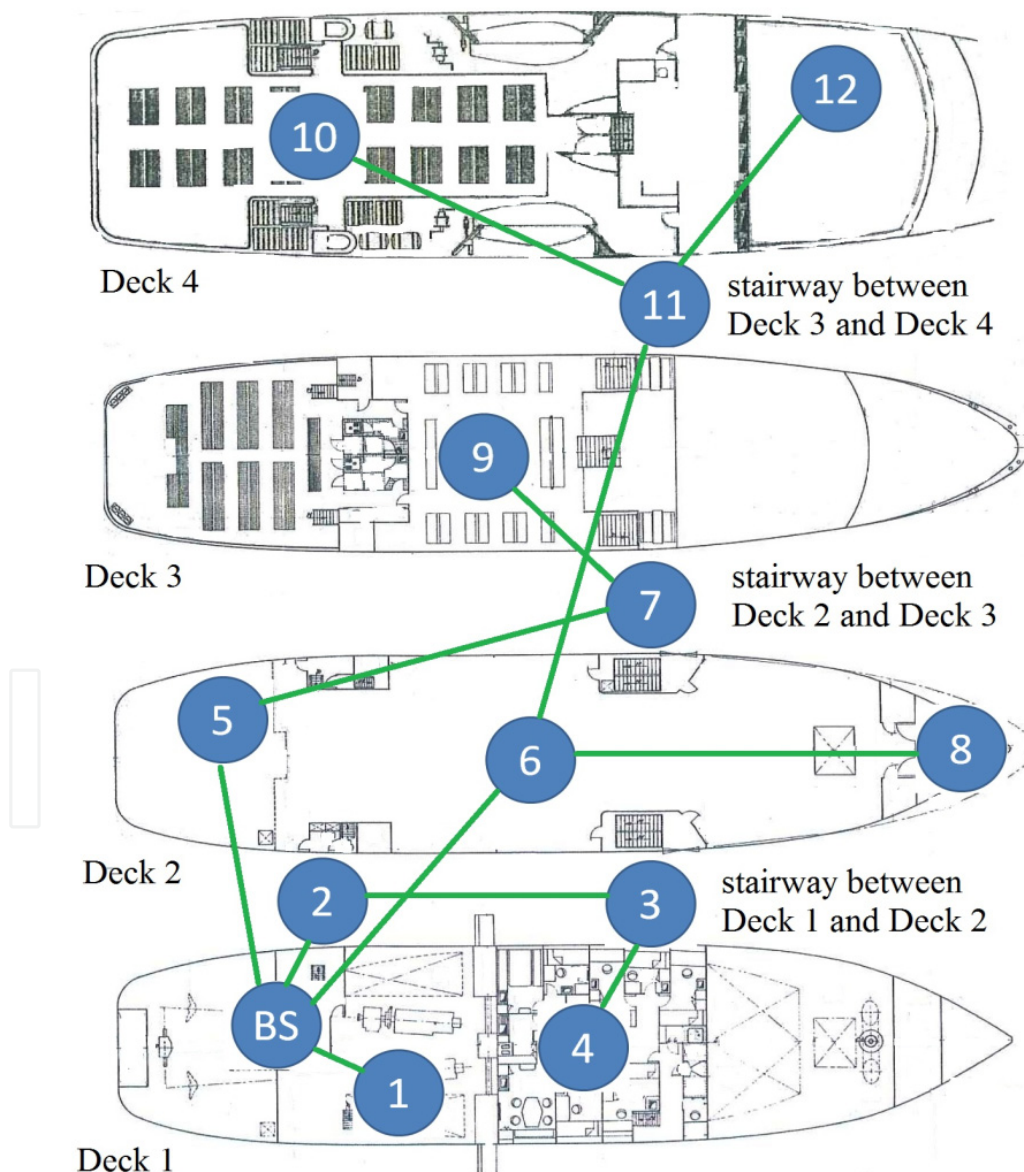


Figure 3. Locations of sensor nodes on board 'Acadie'

5.3. Network results

Analysis of the performance of the network has begun with the statistics of the packets sent by all the nodes during the experiment. Fig. 4 presents the percentage of originated, forwarded and dropped packets of the 12 nodes in the WSN. 'Originated' packets include all data, node health, neighbour health and route update packets originated at the node. 'Forwarded' packets are the packets that the node has received from other nodes and forwarded to other nodes. 'Dropped' packets are the packets that the node has dropped. Packets are considered dropped when 1 packet has been retransmitted 8 times without receiving the link-level acknowledgement.

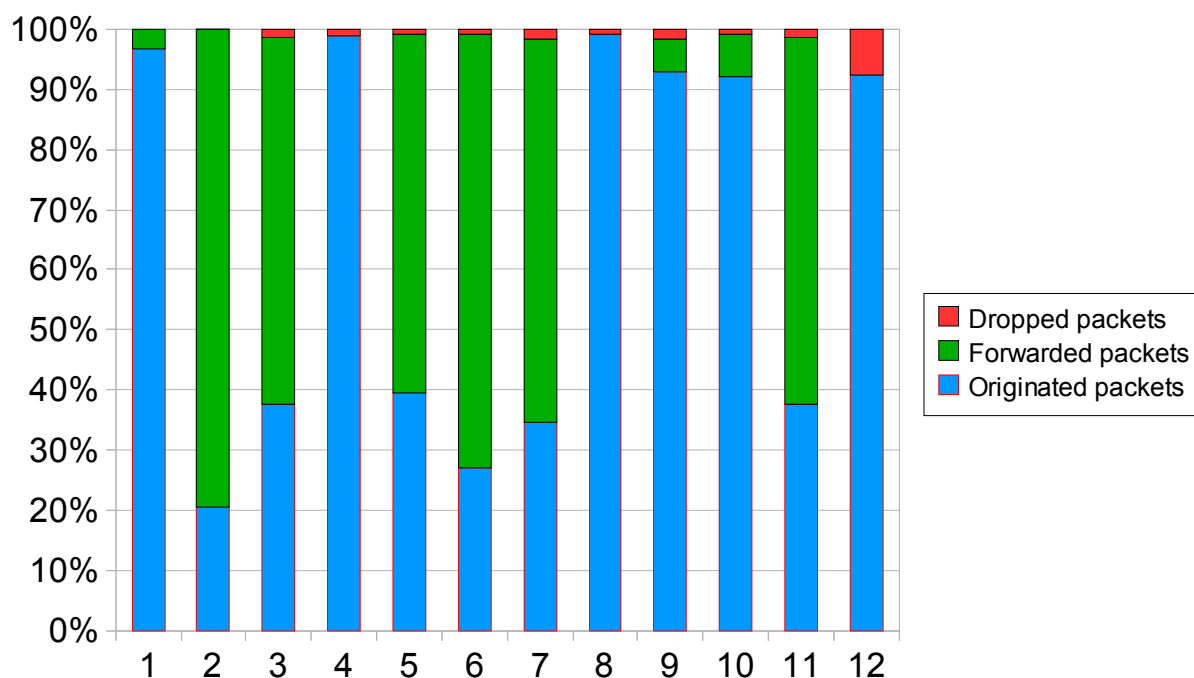


Figure 4. Percentage of dropped, forwarded and originated of all sensor nodes

The obtained results (Fig. 4) show that less than 2 % of packets have been dropped for most of nodes (only node 12 has 7 % of dropped packets due to its particular location in the wheel house, separated from other ship parts). The small percentage of dropped packets reflects significant efficiency of the XMesh routing protocol in such hostile environments. It can be also noticed that the huge amount of forwarded packets comes from the nodes 2, 3, 5, 6, 7 and 11, due to the location of these nodes in the stairways. The whole network connectivity is based on the convenient location of these nodes. Nodes in upper decks route their data mainly through stairway nodes, as the radio signal penetration is impossible through metallic ceiling and floors.

In order to improve knowledge about radio propagation inside the vessel, the paths followed by packets from source nodes towards the base station have been studied. As previously stated, the sensor nodes are pre-programmed by the Crossbow XMesh routing protocol. Therefore, a sensor node selects the next hop which minimizes the number of

transmissions required to send a packet to the base station. The selected parent node (next hop node) is then characterized by its closeness to the base station (in term of number of hops) and its good link quality with the source node. Hence, the choice of the next hop may be an indicator of the quality of links between a sensor node and its one-hop neighbours. Table 2 shows the parent nodes of each sensor node and the percentage for each one during the test.

NodeID	GW	1	2	3	4	5	6	7	8	9	10	11	12
1	100												
2	100												
3			56			34	9	1					
4				100									
5	65		35										
6	65		35										
7			33	10		42	15						
8						1	99						
9							45	43				12	
10								49				51	
11							70	27		3			
12											18	82	

Table 2. Percentage of selected parents for each sensor node of the network

Several remarks may be drawn from this table. It can be noticed that node 8 has never selected node 3 (or node 7) as parent node despite the small distance between them. This behaviour is in agreement with the statement that two nodes separated by two closed watertight doors cannot be connected in the parking (nodes 3 and 7 are located in two stairways with closed doors). However, this connection remains possible when only one closed watertight door separates the two nodes (which is the case of nodes 6 and 8). Furthermore, it can be noticed that nodes 1 and 2 were directly connected to the base station (GW = Gateway) during the test. This was expected, as these three nodes are located in the engine room where the probability of outage between two nodes is very low (due to the low path loss exponent). Node 4 has always node 3 as parent node. Connection between the crew's deck and the parking is not possible because the watertight door in the entrance of the parking is closed. In spite of the small distance between nodes 4 and 1, the connection between them is impossible since the engine room and the crew's deck are separated by a thick metallic bulkhead. However, it can be noticed that node 6, located in the middle of the parking, is directly connected to the base station GW for 65 % of of the forwarded packets (as well as node 5) and node 9 is connected to node 6 for 45% of the time. This can be explained by the fact that the two watertight doors of the first stairway between the engine room and the parking and the first stairway between the parking and the passenger deck are opened. These two nodes used the intermediate nodes located in the stairways (nodes 7 and 2) for the remaining time when the direct connection becomes impossible. Finally, node 12

located in the wheel house has node 11 (82 %) and node 10 (18 %) as parent nodes. The direct connection between nodes 12 and 11 is probably provided by the signal reflection on the metallic tour upside the non-covered passenger deck.

6. Hierarchical architecture for large-scale shipboard WSN

The following concluding remarks can be drawn from the measurement campaigns:

- Ships (especially ferry-type) are built of metallic blocks that constitute decks and rooms.
- Wireless communications between adjacent rooms are possible in the presence of non-conductive materials in the common bulkhead.
- Watertight doors are the main source of radio leakage between adjacent rooms. Closing a watertight door induces an attenuation up to 25 dB.
- Stairways are the main source of radio leakage between adjacent decks.
- Wireless communication between spaced nodes is possible through multi-hop communications.

These conclusions are used in this section to propose an architecture for a large-scale shipboard WSN.

6.1. Proposed architecture

As previously stated, the shipboard monitoring system may contain several thousands of sensors located in all compartments. Some rooms, such as the engine rooms, may contain hundreds of sensors. Using the previously stated concluding remarks, a hierarchical WSN architecture adapted to the particular characteristics of the shipboard environments is proposed. In this architecture, the network will be divided into groups and different nodes levels are defined, based on the functions and resources of nodes. The radio propagation study has shown that the metallic structure of ships makes each room (which is similar to a metallic cube) quasi isolated (from a wireless propagation point of view). Therefore, it has been decided to divide the network into zones where each metallic room is a zone. Three types of nodes may be found in this architecture: Sensor Nodes (SN) which collect sensing data from the environment, Border Nodes (BN) which collect data from SNs, and Gateway Nodes (GN) which collect data from the BNs and send them through a wired connection to the central processing units. Two types of wireless communications are distinguished: the intra-zone communications and the inter-zone communications.

6.1.1. Sensor nodes

This level is constituted of SNs distributed in all ship rooms. Different data may be measured by these nodes such as temperature, pressure, humidity, fire, tank level, water level, etc. depending on the application. One SN may be connected to several sensors if their locations are close (case of the engine room where hundreds of sensors are located in a small area). If SNs are powered by batteries, their power consumption must be optimized. As the

radio unit (Tx and Rx) consumes the most of the energy, it must be in the sleep mode as much as possible. Therefore, the number of transmissions must be optimized. In the confined metallic rooms, one-hop communication is sufficient between any nodes placed in the same room. Sensor nodes will not be intended to forward data from other nodes, which can greatly reduce their power consumption. Radio units are then turned on only when sensor nodes want to send their sensing data to the border node. These data may be periodic or event driven. In order to minimize the number of transmissions, a Hard Threshold (HT) and a Soft Threshold (ST) may be predefined for each application. It is not necessary that a SN sends its data continuously to its BN. Instead, it saves the last sent data and continues to sense its environment. Measured values will be compared firstly to HT. If it exceeds this value (higher or lower depending on the application), the data will be sent. If not, the difference between the last value and the measured value will be compared to ST. If the difference exceeds ST, the value will be sent. This procedure reduces the number of transmissions to only urgent cases (exceeding HT) or to important value changes (exceeding ST). A careful attention must be given to the Medium Access Control (MAC) layer in order to minimize collisions. As the IEEE 802.15.4 standard is adopted for this study, the used MAC algorithm is CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance). Another contention free mechanism is possible in this standard for critical applications.

6.1.2. Border nodes

Border Nodes (BNs) are the second level of the proposed architecture. Each BN is responsible of all or a part of the sensor nodes in a metallic room. BNs are placed in front of doors borders of each room. More than one BN may be placed in a room if it has several doors, giving multiple choices for SNs to join the network. SNs send their data to BNs via one-hop intra-zone communication. BNs query and gather sensed measurements from SNs, and aggregate collected data (eliminate redundancy) before sending to the base station via multi-hop inter-zone communication. Different routing protocols may be adopted for inter-zone communication. Regarding the critical role of a BN (it is responsible of a cluster of sensor nodes), it must be always powered on. BNs may be powered by the mains supply of the ship. Therefore, the inter-zone routing protocol does not have to optimize the energy consumption of these nodes. Instead, the link quality and the number of hops to the base station must be optimized. XMesh, the used protocol in the network test, or other routing protocols existing in the literature, may be used for inter-zone communications.

6.1.3. Gateway nodes and central data repository

Gateway Nodes (GNs) aggregate data from the network, interface to the host, the Ethernet or the Internet (through satellites connections). Gateways form bridges to send and receive data between the central repository and the sensor network. Similarly to BNs, gateways play a vital role in the network. Hence, they are always powered by the mains supply of the ship. Depending on the network size on board the ship and the technology adopted, one or more gateways may be used. In case of multiple gateways, each gateway will form a sub-network using a frequency sub-band and all gateways will be connected to an Ethernet installed on the ship. This mechanism increases the network scalability and decreases the collisions rate.

Data aggregated by the gateways are sent to a central repository located usually in the control room or in the wheel house of the ship. Data are analyzed and conclusions concerning the current state of each room are drawn. Central data repository is equipped with a user visualization software and a graphical interface for managing the network and showing measured data.

6.2. Performance analysis

This section presents the performance analysis of the proposed architecture. It includes the network simulator description, the used standard and the simulation scenarios.

6.2.1. Network simulator

OPNET Modeler 16.0 (OPNET Technologies, n.d.) is used to simulate and evaluate the performance of the proposed shipboard WSN architecture. OPNET is a discrete-event and object-oriented simulator. Strength of OPNET in wireless network simulations is the accurate modelling of the radio propagation. Different characteristics of physical-link transceivers, antennas and antenna patterns are modeled in detail. In OPNET, the possibility of wireless link between a transmitter and a receiver depends on many physical characteristics of the involved components, as well as time varying parameters, which are modeled in the Transceiver Pipeline Stages. Parameters such as frequency band, modulation type, transmitter power, distance and antenna pattern are common factors that determine whether a wireless link exists at a particular time or can ever exist.

However, OPNET does not take into account the physical obstacles between Tx and Rx in indoor environments. Studying the performance of the shipboard WSN architecture must be preceded by a realistic modelling of the shipboard environments. Therefore, several objects and functions have been developed in the simulator to take into account the propagation challenges. Firstly, the log-normal path loss model determined from the propagation measurement campaign is not supported by the “Terrain Modeling” module of OPNET. Therefore, this model has been integrated in the “Received Power Pipeline Stage”. The parameters of the model depend on the Tx and Rx locations. Secondly, a wall object has been developed to simulate the ship bulkheads. A “path loss” attribute has been given to each wall to indicate its structure (totally metallic, metallic with openings, wooden wall, etc). The excess path loss due to the existence of a wall between Tx and Rx is also taken into account when determining the path loss in the “Received Power Pipeline Stage”. Finally, the ship has been modelled using its real dimensions.

6.2.2. ZigBee standard

ZigBee (ZigBee Alliance, 2005) is one of the most used standards for WSNs. It is based on the IEEE 802.15.4 standard with a theoretical transmission data rate equal to 250 kbps in a wireless link. ZigBee defines three types of nodes: end devices, routers and coordinators. The coordinator creates the network, exchanges the parameters used by the other nodes to

communicate, relays packets received from remote nodes towards the correct destination, and collects data from the sensors. Only a single coordinator can be used in a network. A router relays the received packets and the control messages, manages the routing tables and can also collect data from a sensor. Routers and coordinators are referred to as Full Function Devices (FFDs). On the other hand, end devices, also referred to as Reduced Function Devices (RFDs), can act only as remote peripherals, which collect values from sensors and send them to the coordinator or other remote nodes. However, RFDs are not involved in network management, and therefore, cannot send or relay control messages.

According to the ZigBee standard, three different kinds of network topologies are possible: star, cluster-tree, and mesh. In a star network, there are a coordinator and one or more RFDs (end nodes) or FFDs (routers) which send messages directly to the coordinator (up to 65536 RFDs or FFDs). In a cluster-tree topology, instead, there are a coordinator which acts as a root and either RFDs or routers connected to it, in order to increase the network dimension. The RFDs can only be the leaves of the tree, whereas the routers can also act as branches. In a mesh network, any source node can talk directly to any destination. The routers and the coordinator, in fact, are connected to each other, within their transmission ranges, in order to facilitate packet routing. The radio receivers at the coordinator and routers must be “on” all the time. In the mesh network, the ZigBee standard employs a simplified version of the Ad-hoc On-demand Distance Vector (AODV) routing protocol (Perkins et al., 1999).

Due to previous features, the ZigBee standard has been chosen to test the proposed architecture. SNs will be formed by ZigBee end devices, BNs will be ZigBee routers and the GN will be a ZigBee coordinator. As it is impossible to cover all the ship by a star topology (due to metallic obstacles), mesh and tree topologies have been only considered.

6.2.3. Simulation scenarios

Table 3 summarizes the parameters used for simulation.

Parameter	Value
Maximum number of router or end devices per router	200
Route discovery timeout (s)	10
Maximum depth	10
Acknowledge wait duration (s)	0.05
Minimum value of the back-off exponent in the CSMA/CA	3
Maximum number of back-offs	4
Channel sense duration (s)	0.1
Data rate (kbps)	250
Receiver sensitivity (dBm)	-95
Frequency band (GHz)	2.4
Transmission power (W)	0.001
Packet inter-arrival time (s)	1
Packet size (bits)	120

Table 3. Simulation parameters

The sensor nodes have been deployed on the simulation model of the four decks of the ship as shown in Fig. 5. The network is constituted of 100 sensor nodes (routers and end devices) and one coordinator located in the bottom deck. As previously stated, in each room where end devices are located, routers have been placed in front of watertight doors and windows. The number of sensor nodes in each room is related to the real placement of sensors in the current monitoring system, which contains hundreds of sensors. The engine room (bottom deck) contains 150 sensors. The packets size sent by each sensor is 2 bytes. As the rooms on board ships are not large, it would be possible to connect several sensors to one node. It is supposed that each sensor node is equipped with 5 sensors (similar to MicaZ nodes used in the measurement campaign). Hence, the data packet size is equal to 120 bits (8 bits for the sensor ID and 16 bits for the measured data). Therefore, this scenario simulates a WSN with 500 sensors.

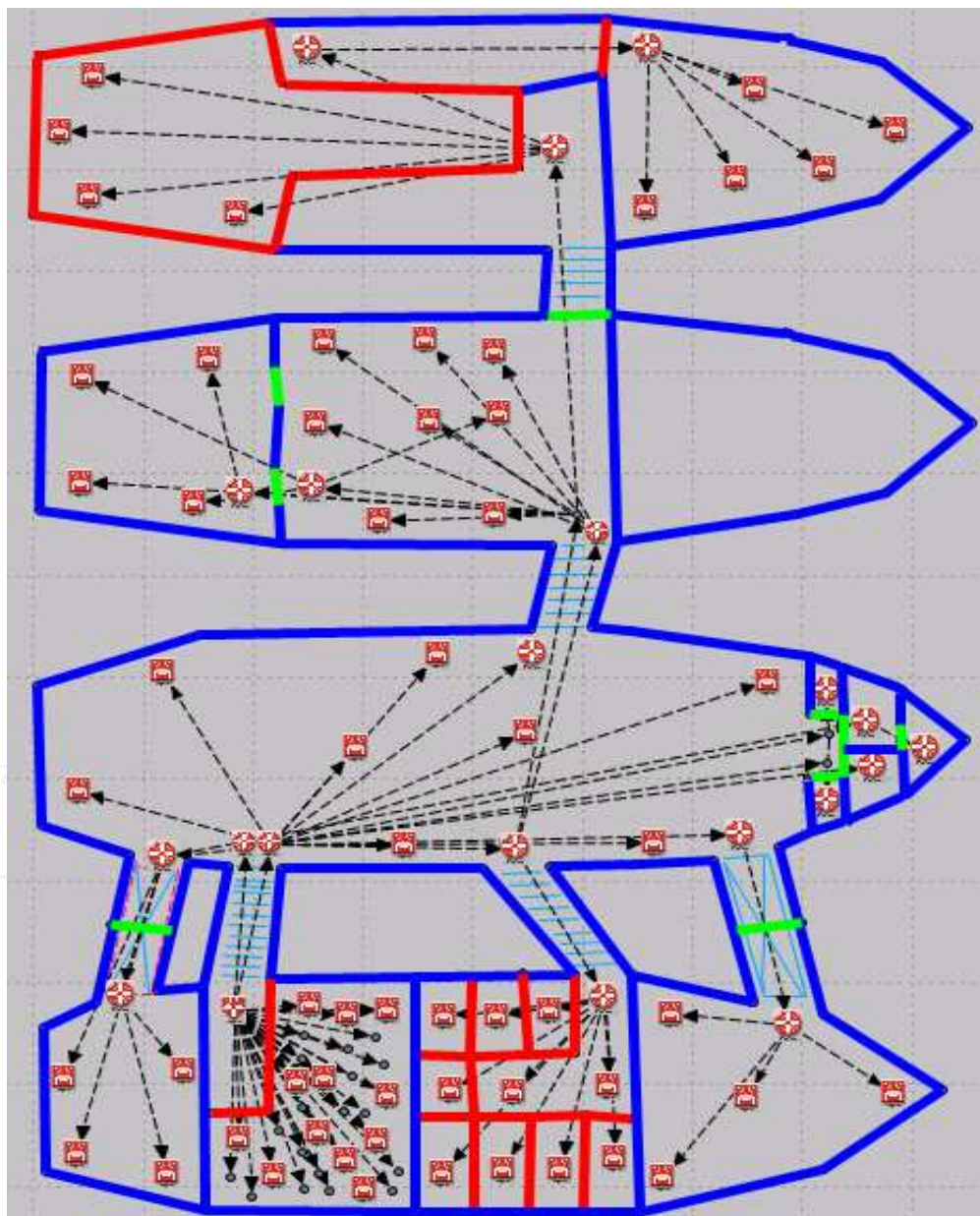


Figure 5. Layout of simulation model of Acadie and ZigBee WSN topology

6.2.4. Results and analysis

The objective of this study is to propose a reliable shipboard monitoring system based on wireless technologies. In spite of the important reduction of cost and complexity, this solution must provide a Quality-of-Service (QoS) similar to that provided by the current wired system. A monitoring system has hard requirements in terms of reliability and delays. All critical sensed data (fire alarm or water-level data) must arrive successfully to the data repository. The maximum acceptable delay for considered data is 1 second.

IEEE 802.15.4 offers the possibility of retransmitting a packet if the source node does not receive an acknowledgment from the destination node. In a network with a huge number of nodes (similar to a shipboard WSN), the number of retransmissions has an important impact on the global performance of the network, including the packet delivery ratio, the end-to-end delay, the energy consumption of nodes and the network load.

Fig. 6 shows the evolution of the packet delivery ratio of the network with respect to the maximum number of retransmissions for the tree and mesh topologies. For the tree topology, the packet delivery ratio increases with the number of permitted retransmissions. It reaches 100 % when the retransmissions number is equal or higher than 10. It can be concluded from this curve that a maximum number of 10 retransmissions is sufficient to have a maximum packet delivery for the considered network. Otherwise, for the mesh topology, the packet delivery ratio increases rapidly until the number of retransmissions becomes 10 and decreases slowly for higher values. This may be explained by the collisions that can cause the retransmissions of failed packets. Therefore, a maximum value of 10 retransmissions is an optimal value for the two topologies.

It can be noticed in this figure that the packet delivery ratio achieves 99% for 8 retransmissions, which is equal to the average packet delivery found in the network test (8 retransmissions in the XMesh protocol). It is also seen in the figure that the packet delivery ratio is slightly higher for the tree topology. The particular ship environment makes this advantage of the tree topology.

Fig. 7 shows the variations of the average end-to-end delay with respect to the maximum number of retransmissions for the tree and mesh topology of ZigBee network. End-to-end delay is defined as the total delay between creation and reception of an application packet. This figure shows that the average delay increases when the maximum number of retransmissions increases. For the tree topology, the delay increases rapidly for a maximum retransmissions number lower than 10.

For larger values of the maximum number of retransmissions, its variations become small. This result is coherent with the packet delivery and confirms that 10 retransmissions are sufficient to have a reliable tree-topology network. The value of delay achieved is 0.1 second which is acceptable for the shipboard monitoring system that supports a maximum delay of 1 second. Otherwise, the delay keeps increasing in the case of mesh topology. It is slightly higher than the delay of tree topology. This is basically due to the differences in the routing techniques and the size of routing tables in the mesh topology where the route discovery procedure induces additional delays.

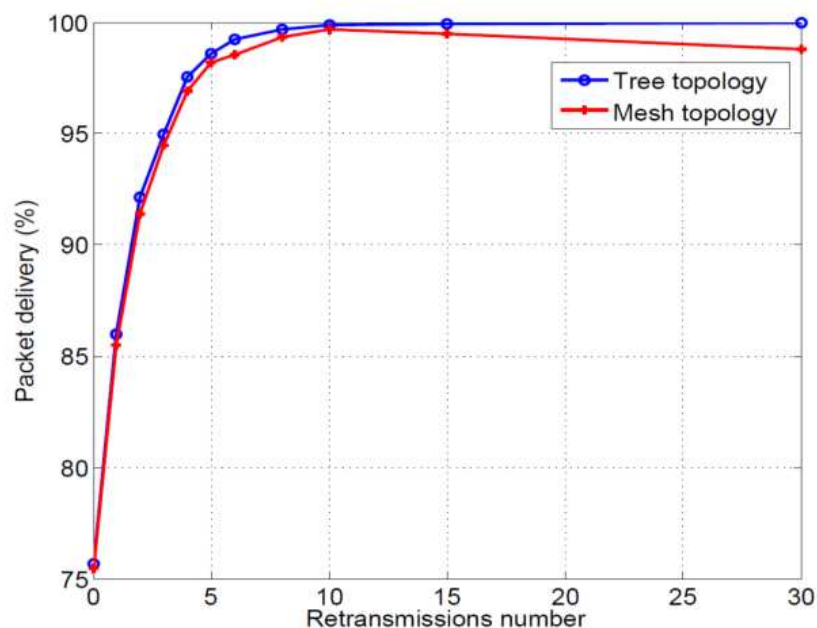


Figure 6. Packet delivery ratio versus the number of retransmissions

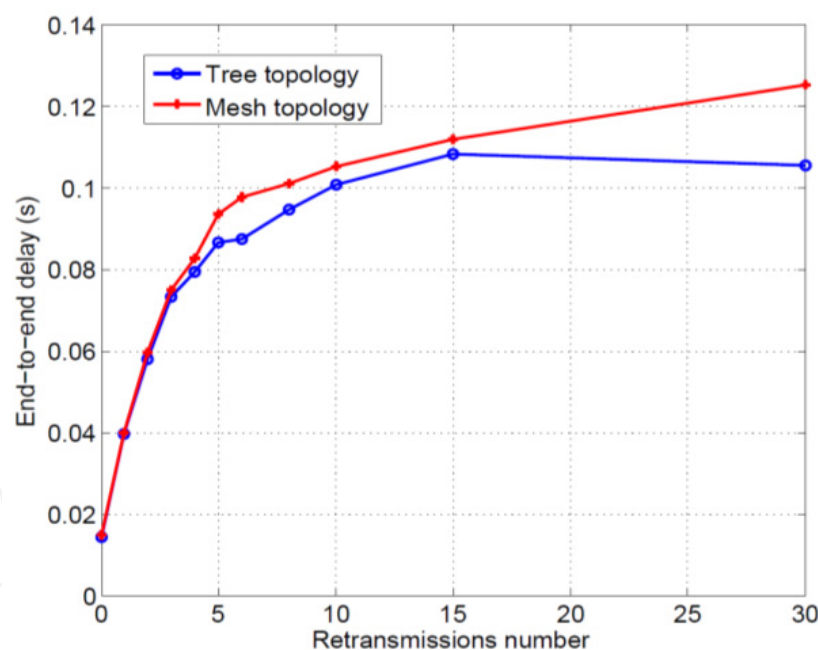


Figure 7. End-to-end delay versus the number of retransmissions

7. Conclusion

In this chapter, the application of wireless technologies to the shipboard monitoring system has been studied. A measurement campaign has been carried out on board a ferry to determine path loss models. An IEEE 802.15.4 compliant WSN has been tested successfully on board the same ferry. Based on the measurement results and the particularities of the

environment, a hierarchical zone-based architecture has been proposed for a large shipboard WSN. The performance of this architecture has been evaluated using ZigBee standard. In order to obtain a reliable and representative simulation, the path loss models obtained from the measurement campaign have been integrated into the simulator. The obtained delay and packet delivery ratio meet the difficult requirements of the shipboard monitoring system. These results have also shown that ZigBee may be an appropriate technology for the proposed architecture.

In spite the successful tests in verifying the WSN's feasibility onboard ships, the introduction of wireless solutions in the shipboard monitoring system is not likely to happen quickly. Special attention must be given to the development of shipboard sensor nodes: this equipment must resist against hostile environmental conditions in the engine rooms such as temperature, humidity, vibration, etc. Additionally, several steps including testing, regulation and standardization will be necessary before deployment.

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