ZigBee-Based Sensor Network for Shipboard Environments

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Abstract — **This paper studies the feasibility of deploying a ZigBee-based sensor network aboard ships. The objective is to verify if this network can be a suitable alternative of the actual shipboard wired monitoring system. Therefore, measurements campaigns have been conducted to evaluate the quality of ZigBee point-to-point communications aboard a ferry operating in the sea. Different configurations and environments were studied on each deck of the ferry. Experiments during the ship operation have been conducted to take into account the influence of crew's and passengers' movements, engines and machines on the quality of wireless transmission. In a second time, a full scale wireless sensor network was deployed aboard another ferry. Real time data such as temperature, humidity and pressure were sent from different ferry decks to a central base station located in the control room. This network has shown a very good connectivity, regardless of the metallic shipboard environments.**

I. Introduction

Shipboard monitoring system can contain several thousands of sensors and actuators. The reduction of extensive lengths of cables that are needed to connect these sensors with control units is an important technological challenge [1]. Routing these wires during construction increases the cost, the weight and the architecture complexity of the vessel. Therefore, a shipboard wireless sensor network (WSN) allows reducing wire installation and maintenance costs. However, a shipboard WSN operates in a very harsh environment. Many steel plates are cut or welded together to make a block, and then a ship is constructed by joining many of these blocks together. This means that a ship is a large structure made mainly of steel [2]. Therefore, shipboard wireless communications are strongly limited by the metallic structure of bulkheads and watertight doors. Hence, a propagation study must be carried out before the deployment of a wireless sensor network to study the feasibility of wireless solutions on board metallic ships.

The IEEE 802.15.4/ZigBee standard is assumed to be a very good solution for applications involving industrial control and monitoring, sensor networks, building automation, home control and control automation. This assumption is due to its ability to easily deploy large scale, reliable and self healing mesh networks with low cost and low power solutions [3].

A large number of papers have presented deployment or measurement campaigns using ZigBee equipments in indoor environments [4-6]. These studies have used the results of ZigBee experiments to determine empirical path loss models for several indoor environments. However, few papers have studied the wireless communication on board ships using ubiquitous technologies, especially the IEEE 802.15.4 and ZigBee standards. In [2], authors have conducted ZigBee measurements on the passenger deck of a ship and a small wireless sensor network has been deployed between the Main Engine Room (MER) and the control room. In [7], a star WSN has also been tested successfully in the MER of a ship. These experiments did not study all the shipboard environments, and measurements were limited to one or two decks. Moreover, all the measurements have been carried out when the ships where moored to the port. To date, experiments during ship operation have not been conducted. Since the main engine or other equipments and the passengers' movements can affect the quality of wireless communication, it would be necessary to conduct measurements with a ship operating in the sea.

In this article, we aim to make a more complete study of ZigBee feasibility for shipboard WSN, and in particular, to estimate the effect of closing watertight doors. Point-to-point measurements using ZigBee protocol analyzers have been performed aboard a ferry operating in the sea to evaluate the ZigBee link quality on different shipboard environments such as MER, parking, restaurant and entertainment spaces and passenger decks. These results have been compared with the empirical path loss model adopted for indoor measurements. In addition, an IEEE 802.15.4-based sensor network has been deployed aboard another ferry. This network covered all the vessel decks. Real-time data such as temperature, humidity, ambient light, acceleration and pressure from the different decks and rooms have been collected in a base station placed in the control room on the bottom deck.

The remainder of this paper is organized as follows: Section II describes the two ferries chosen for measurements. Section III shows the point-to-point communication tests performed aboard the first vessel and Section IV describes the WSN deployed aboard the second ship. Finally, Section V presents some concluding remarks.

II. Description of Measurements Environments

Point-to-point measurements were conducted on board Armorique [8], and a full scale WSN was tested on board Acadie [9].

The deckhouse of Armorique consists of the followings: the bottom deck which contains the main and the auxiliary engine rooms; the second deck which houses the control room; the third, the forth and the fifth decks which are vehicles parking; the sixth and the seventh decks which contain self service restaurants, shopping and entertainment areas; the eighth and

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the ninth decks which house the passengers cabins and finally the tenth deck which houses the crew cabins and the wheel house.

The deckhouse of the Acadie consists of the followings: the bottom deck which houses the engine room, the control room and the crew cabins; the main deck which is a vehicles parking; the passengers' deck and the bridge deck which contains the wheel house.

III. Point-To-Point Communication Tests

These measurements were realized during cruises between Roscoff (France) and Plymouth (United Kingdom). All the equipments in the engine room were being operated. Hundred of passengers were travelling aboard the ship and hundreds of vehicles were parked on decks 3 and 5.

Data transmission tests were carried out using two ZigBee protocol analyzers (ZPAs), one sending 100 packets and the other receiving those packets. The two nodes were maintained on a height of 1.80 m. 110 measurement positions were considered on all the ferry decks. Nodes antennas were omnidirectional, vertically polarized and with a gain of 1 dB. The received signal strength indication (RSSI), as well as the percentage of received packets with respect to the total number of sent packets (transmission ratio), were measured to evaluate the transmission quality.

Measurements were conducted on different decks of the ferry. On the two first decks, tests were done between the MER and its neighboring, and between the control room and its neighboring. We have evaluated the effect of closing watertight doors on the transmission quality between these two rooms. In the passenger decks and the restaurant decks, measurements were carried out when the WiFi used on the ferry was turned off and when it was turned on in order to verify the possibility of coexistence between the ZigBee and WiFi using the same 2.4 GHz ISM band. Measurements were also performed between two decks to verify the possibility of communication between floors.

A. Main Engine Room

Fig. 1 shows the locations of the measurements points in the MER of Armorique and the average of RSSI on each receiver location. The transmitter was placed at the position Tx in the tunnel and the receiver has been placed at 8 different locations in the pump room and the MER. The tunnel, the pump room and the MER are separated by watertight doors. Some crew members were moving between these two rooms. The standard deviations of RSSI values were ranged between 0.82 and 3.12 dB. The results of this test show a transmission ratio between 98% and 100% for the locations Rx1, Rx2, Rx3, Rx4 and Rx5 when the two watertight doors are opened. This ratio decreased to 73 % for the other locations in the MER. Closing the watertight door separating the tunnel and the pump room did not affect the transmission ratio for the locations Rx1, Rx2, Rx3 and Rx4, but the RSSI decreased of about 17 dB. However, the transmission ratio for other locations in the MER became null. Additional tests on the second deck which has a similar architecture (watertight doors, metallic bulkheads, rooms size, engines ...), have shown similar results.

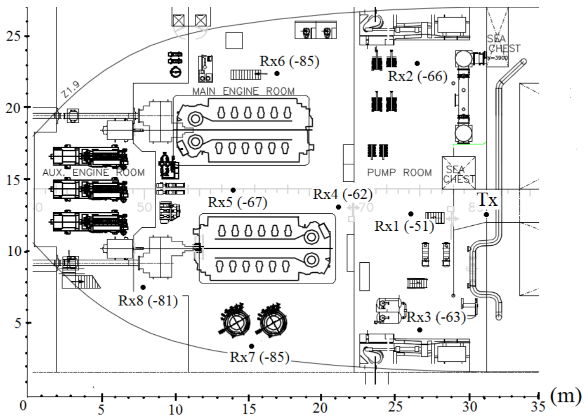

Figure 1. Measurement points in the bottom deck of Armorique

Communication is possible on these decks between two adjacent compartments even if the watertight door was closed. However, closing the door induces an attenuation of 17 to 20 dB. Therefore, to maintain the connectivity of a ZigBee-based sensor network in presence of a watertight door, we recommend placing nodes in the two sides of the door.

B. Parking

Tests in the parking have shown a very good connectivity. These decks are enormous metallic halls, similar to a waveguide between the transmitter and the receiver. Measurements were carried out when the parking was empty, when the vehicles were fixed and when vehicles were moving. Transmitter and receiver were in Line-of-Sight (NLOS), Obstructed Line-of-Sight (OLOS))and Non Line-of-Sight (NLOS) configurations. In all these cases and with a transmitter-receiver separation distance up to 100 meters, the transmission ratio exceeded 95 %. For the same positions of transmitter and receiver, the average of RSSI in the case of moving vehicles was higher than the average of RSSI in the case of fixed vehicles (the average difference is 12 dB). However, the standard deviation of RSSI was 8 dB for the first case and 3 dB for the second case. This difference is simply explained by the vehicles movement which randomly blocks or allows the direct visibility between the transmitter and the receiver.

C. Entertainment and Restaurant Decks

We have performed similar measurements on deck 6. Fig. 2 shows the transmitter and receiver locations, as well as the average of RSSI at each receiver position. The standard deviations of RSSI values were ranged between 0.78 and 4.78 dB. Hundreds of passengers were moving on this deck during the measurement campaign. This deck is also covered by a WiFi network already installed on the ferry for Internet access. The transmitter was placed at the position Tx and the receiver has been placed at 6 different locations. Tests were carried out when the WiFi was on and when it was off. When the WiFi was on, the results showed a transmission ratio of 100 % at Rx1, Rx2, Rx3 and Rx5, and a ratio of 65 % at Rx4 and a ratio of 47 % at Rx6.The low ratio of Rx4 is due to the non visibility between the transmitter and the receiver. However, the low ratio at Rx6 is due to the large separation distance between the transmitter and the receiver.

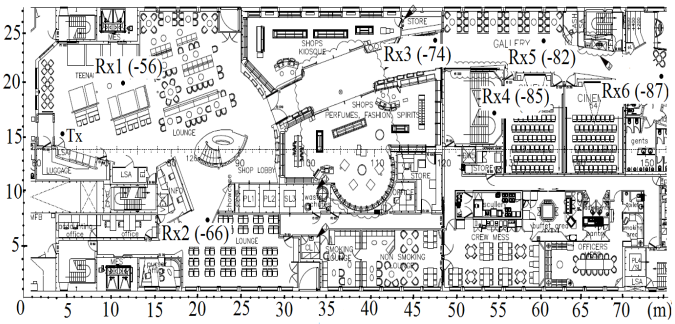

Figure 2. Measurement points in the restaurant deck of Armorique

However, when the WiFi was off, results show a transmission ratio of 100 % for the locations Rx1, Rx2, Rx3 and Rx5, a transmission ratio of 73 % for the location Rx4 and 87 % for the location Rx6. By comparing the two results, we can notice that the existence of WiFi has affected the ZigBee link quality in far positions only. Therefore, ZigBee and WiFi can coexist in this environments but the WiFi can reduce the radio coverage of ZigBee nodes. Using the direct sequence spread spectrum technique and the reduced channel occupancy of the ZigBee, allows it to coexist with other wireless standards using the same 2.4 GHz ISM band.

D. Passenger Deck

Fig.3 shows the locations of the measurement points on the passenger deck of Armorique, as well as the average of RSSI at each receiver position. The standard deviations of RSSI values were ranged between 0.94 and 4.48 dBm. The passengers' movement on this deck was less than that of the restaurant deck. The transmitter was placed within a cabin room and the receiver was placed at 10 different locations along the deck. The metallic door of the cabin was closed during all measurements.

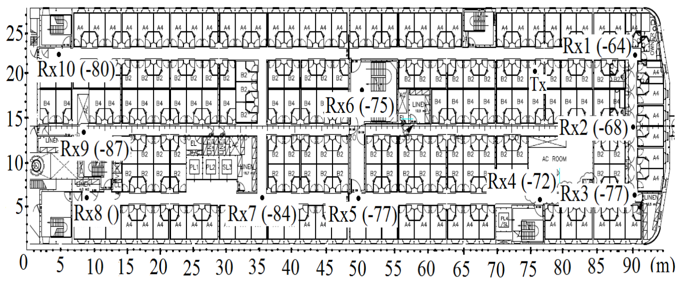

Figure 3. Measurement points in the passenger deck of Armorique

The obtained results show a transmission ration higher than 95 % for the locations Rx1, Rx2, Rx3, Rx4, Rx5, Rx6 and Rx10. This ratio decreases to 83 % at Rx9 and to less than 30 % at Rx7 and Rx8. Although, the transmitter was placed within a closed room, and the transmitter and the receiver were in NLOS for all these measurements, the ZigBee link quality was excellent for the most of locations. One ZigBee node can probably cover the half of the total surface of this deck.

E. Communication between decks

After testing the link quality on each deck, we have tested the link quality between decks. The transmitter was placed in one deck and the receiver was placed at several locations in the upper decks. These tests have shown a good connectivity between decks through stairways which guide the energy from the transmitter in the lower deck to the receiver in the upper deck. However, the communication was impossible when communicating nodes were placed far from stairways. Thus, to save network connectivity between decks, we highly recommend placing relaying nodes in stairways.

F. Path Loss Model

Many papers including measurements campaigns with ZigBee equipments in indoor environments have used the following path loss model [4-6]:

$$PL\,(d) = \overline{PL\,(d_0)} + 10n\log_{10}(d/d_0) + X_\sigma + FAF + \sum k_i L_i \quad (1)$$

where $\overline{PL\,(d_0)}$ is the average path loss at a given reference distance d_0 (1 m), n is the path loss exponent, d is the Tx-Rx separation distance, X_σ is a zero-mean Gaussian distributed random variable with standard deviation σ describing the random multipath effects, *FAF* is the floor attenuation for different floors, k_i is the number of obstacles of type i and L_i is the attenuation of an obstacle i.

Due to the metallic structure of the ferry, the communication between two decks is possible only when the transmitter and the receiver are placed near to the stairway connecting the two decks. Hence, the FAF term can be safely removed from (1) and we consider path loss models for one deck. Table 1 shows the parameters obtained by comparing RSSI measurements with (1) using a linear regression with minimum mean square error estimation. It includes the path loss exponent n, the average path loss at d_0, the standard deviation of X_σ and the coefficient of correlation r between the measurements and the model for three environments.

TABLEAU I. PATH LOSS PARAMETERS

Configuration	Parameters			
	n	σ	r	$\overline{PL\,(d_0)}$
Engine room	4.62	2	0.93	18.2
Restaurant deck	3.28	1.73	0.96	24
Passenger deck	2.1	1.79	0.93	45.7

The correlation coefficients for the three environments show a good fit between the measurement results and the path loss model. The only obstacle we have considered for shipboard environments is the watertight door with an attenuation L_1=20 dB. We remark from these results that the higher path loss coefficient is that of engine rooms (first and second decks). This result is explained by the architecture of these decks including lots of metallic bulkheads and watertight doors. Despite the non visibility between the transmitter and the receiver, the path loss exponent of the passenger deck is close to the path loss exponent of the free space (which is 2). In fact, the metallic walls of the corridors guide the signal to the receiver.

IV. WIRELESS SENSOR NETWORK ABOARD ACADIE

In order to verify the feasibility of a ZigBee-based sensor network aboard a ship, we have used the MICAz nodes from CrossBow Technology [10]. This test was conducted when Acadie was moored to the port. The network is constituted of 12

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sensor nodes and one gateway connected to a laptop PC via a USB cable. Each node is constituted of a processor, an internal memory, a 2.4 GHz radio antenna, two 2A batteries and a sensor board including temperature, humidity, barometric pressure, acceleration and ambient light sensing capabilities. The PC was running the MoteView 2.0 software which is a graphical user interface that allows visualizing the real time data sent by the wireless sensor network to the base station. In addition, it allows viewing the changes of network connections during the test. The base station was placed in the control room which is located near to the engine room in the bottom deck. Sensor nodes were distributed among the different ferry decks. Nodes 2, 3, 7 and 11 were placed in the stairways between decks in order to maintain connectivity between floors. All watertight doors were closed to simulate an emergency scenario. Each sensor node was periodically sending a packet data to the sink node every 3 seconds. The topology of the network deployed aboard Acadie is depicted in Fig. 4.

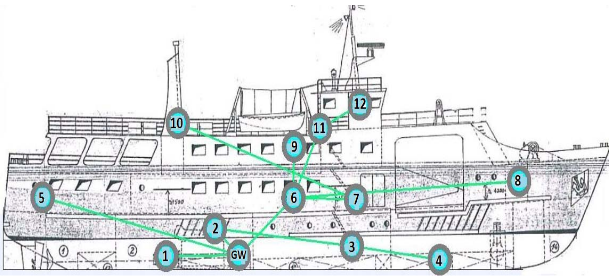

Figure 4. Network topology aboard Acadie

The nodes were turned on successively, and each one has joined the network autonomously. The results of this network test are resumed in Fig. 5 where "Forwarded packets" denotes the percentage of packets that the node has forwarded from other nodes and "Dropped packets" is the percentage of packets that the node has dropped. Packets are considered to have been dropped when 1 packet has been retransmitted 8 times without receiving the link-level acknowledgment. These results show that the network had a very good connectivity. The ratio of dropped packets is less than 2 % for all nodes except the node 12 which was located in the wheel house where the ratio was 7.57 %, which is also an acceptable value.

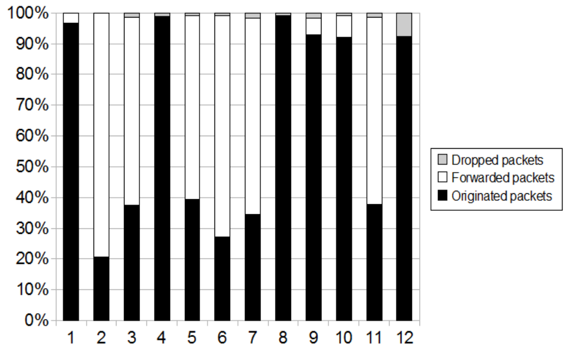

Figure 5. Wireless Sensor Network Results

This difference is due to the specific architecture of the Acadie where the wheel house is not linked to the passenger deck by stairs. The nodes 2, 3, 5, 6, 7 and 11 have high percentages of forwarded packets. These nodes played the role of router to data coming from the higher decks to the sink node placed in the control room. It is highly recommended to duplicate these nodes in case of a real deployment. Losing one of them may disconnect a large part of the network. The nodes connections have frequently changed during the network test, especially for nodes located in the upper decks. These nodes periodically scans their neighboring to choose the next hop taking into account the link quality and the shortest path to the sink node. These changes are due to the crew movement aboard the ship which affects the link quality between nodes.

V. CONCLUSION

In this paper, the results of measurements realized aboard two ships to test the ZigBee feasibility for shipboard wireless sensor networks have been presented. Different real shipboard environments have been studied such as the MER, the vehicles parking, restaurants and passenger decks. In addition, different configurations such as communication inside compartments, between compartments, and between decks have been studied. These measurements have showed that the wireless communications using the ZigBee standard are possible aboard ships despite the metallic architecture of the ferries. The results of these measurements campaigns helped us to test a full-scale wireless sensor network aboard another ferry. By placing nodes in sufficient locations carefully, we succeeded to deploy a self configurable, self healing multi hop sensor network aboard the ferry. This network has showed a good connectivity between different decks and different rooms. Precedent results showed that the ZigBee standard can be a good solution to deploy a future shipboard wireless sensor network replacing the actual wired monitoring system.

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