Experimental Analysis of a Wireless Sensor Network in a Multi-Chamber Metal Environment

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***Abstract*—Wireless sensor networks (WSN) are finding increasing use in all-metal marine environments such as ships, oil and gas rigs, freight container terminals, and marine energy platforms. However, wireless propagation in an all-metal environment is difficult to model and the use of sealed doors between compartments further complicates wireless network planning. This makes it necessary to characterise the physical wireless links performance in real environments to support the design and deployment of the network.**

In this paper, we report on the deployment of a 2.4 GHz network of 18 nodes distributed in three freight containers, with various obstacles inside and between them. Input variables included the placement of the nodes, antenna orientation, transmission power, and door openings while output variables included the key link quality indicators of packet delivery ratio (PDR), RSSI, and LQI for every possible link, as well as the performance of every node. We believe that this is the first time that this full range of physical link quality indicators has been measured in this type of application environment.

We found that, even with apparently fully sealed containers, sufficient propagation occurred through micro-openings to allow an 80.65% PDR sink connectivity. Providing as little as a 5 cm door opening increased sink connectivity to 96.92%. Average PDR sink connectivity over all the experiments was 91.97%, indicating that a WSN could operate in a multi-chamber metal structure under different conditions, and can be a viable alternative to reduce cost and complexity in these environments.

I. Introduction

Wireless sensor networks (WSN) can be used to optimise the operation, efficiency, and maintenance of all-metal marine environments such as ships, oil and gas rigs, freight container terminals, and marine energy platforms. However, the large amounts of metal and complex layouts make it very challenging to model the wireless propagation in these all-metal environments, and the use of sealed doors between compartments further complicates wireless planning. To be able to specify wireless network architectures and protocols, and to design applications for these metallic environments, it is therefore necessary to measure the link quality *in situ*, as it cannot be easily modelled and predicted.

In this paper, we describe a comprehensive methodology for fully characterising link quality at the physical level in metallic environments and verify it in practice by deploying a WSN in a testbed composed of three metal freight containers. In the methodology, we ran a series of experiments, changing input variables that influence link quality, and we recorded key link quality metrics. In contrast with other works done in related environments, we focus on physical link quality instead of application or network topology.

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The results of these experiments allowed us to classify the links reliability, asymmetry, and sink candidates, and to analyse the behaviour of the network at a high level of 3D detail. This is information that would be required in practice for the planning and design of higher-layer protocols and applications.

The remainder of the paper is structured as follows: Section II discusses related work and sets up the novelty and work in this paper. Section III describes the setup and design of the experiment, including the environment, variables, hardware, and software. In Section IV a detailed analysis of the results is given, providing an overview of the network performance as well as that of individual nodes. Section V presents the conclusions and plans for future experiments.

II. Related work

Several experiments have been done for monitoring shipping containers with WSN. In [2], a network was deployed on the outside of containers for location tracking, analysing application parameters such as the dynamics of routing, power consumption, and network topology, but not the link quality. Yuan et al. [3] tested a sensor network inside of food cargo containers, recording the RSSI and link quality indicator (LQI) besides the sensor data. However, the focus was primarily on the signal strength over distance, and the experiment was done with multi-hop and duty-cycling protocols.

A number of similar analyses have also been carried out using WSN on board ships, using simulations and practical measurements, with the objective of replacing current wired monitoring systems for a lower cost alternative [4], [5]. These studies show that communications between adjacent rooms and decks are possible due to signal leakage in watertight doors and stairways. In [6], [7], further tests are performed, accounting for realistic circumstances aboard the ship, such us opening and closing of doors, operating engines and machinery, and people movements. However, all of these experiments and analyses are built on top of the XMesh and Zigbee protocols, focusing on the network topology instead of the analysis of

Fig. 1. Outside view of the freight container testbed

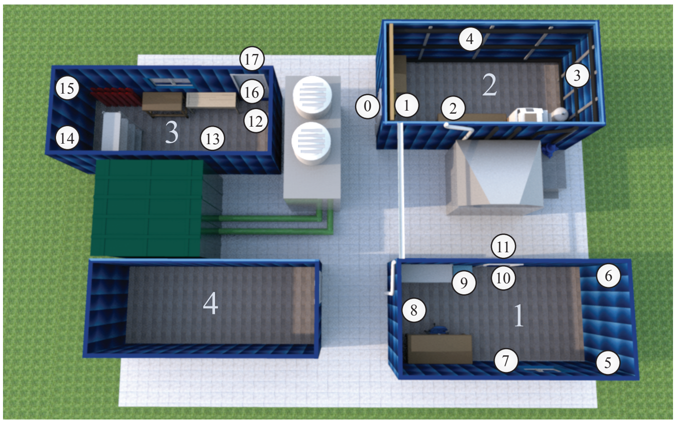


Fig. 2. Node distribution in the containers

physical links. Packet delivery ratio (PDR) and RSSI were measured, but they are not as representative in this case and do not provide a comprehensive understanding of the propagation environment, due to the use of upper-layer protocols that involve retransmissions and mesh network configuration.

Although the literature shows several of these WSN deployments in different metal environments, none of them use the methodology in this paper, which study the link quality between the nodes in an "all-to-all" fashion with probe synchronisation. This allows an accurate characterisation of the physical medium including the effects of varying conditions such as node position and orientation, door openings, and transmission power.

III. Experimental setup

A. Testbed environment

The experiments were carried out with nodes installed inside and outside three freight containers located in an outdoor yard and separated by 3 to 4 m, with various metal and concrete obstacles between them (Fig. 1). Containers 1 and 2 are 6 m x 3 m, while container 3 is slightly smaller at 6 m x 2.5 m. This constitutes a unique indoor/outdoor metal environment that more realistically replicates the real-world complex environments. The distribution of the containers and the nodes can be seen in Fig. 2. The containers contain several pieces of furniture such as tables and metal shelves, including a small metal box where node 9 is contained. It should be noted also that container 2 has a double door, a metal exterior door and a wooden interior door, but these were opened and closed as one door and not considered as separate variables.

B. Hardware and software tools

The hardware used for the experiments consisted of 18 TelosB [8] nodes, plus an extra gateway node connected to a laptop to configure the experiment and download the data. They are composed of a low-power microcontroller, a 2.4 GHz IEEE 802.15.4 radio chip, an on-board PCB antenna, and several integrated environmental sensors. These nodes were chosen for their wide use in research and good software support.

To conduct the tests, we used an open-source software tool called TRIDENT [9], which allowed us to configure and run the experiments without the need for a separate wired infrastructure, unlike other similar tools available. This expedites the work of changing the location of the nodes between different experiments, as well as retrieving the data via multi-hop wireless communication. The tool permits the configuration of every node as a sender and receiver, synchronising the senders in a round-robin fashion to avoid collisions and ensuring that there will not be more than one node transmitting at the same time. This feature, along with the ability to send probes without any MAC or upper-layer protocols, are key to acurate characterisation of the physical medium. The nodes acting as receivers log the number of received packets, RSSI and LQI, besides the noise floor sensed by the sender before transmission and environmental variables. This tool has been previously successfully used in different open field deployments, e.g. [10], [11].

C. Experiment design and variable selection

To understand how the links behave under the different conditions that the target environment could be subject to, we designed a full factorial experiment in which we varied one variable at a time. The set of variables and levels can be seen in Table I. An important issue in these multi-chamber environments can be the size of the openings between adjacent rooms. Therefore, we selected three different door openings for the containers to emulate this: fully closed, a minimum opening of 5 cm (approximately a half-wave for the frequency used), and a maximum opening of 40 cm, which corresponds to the size of an opening, such as a bulkhead door, that would allow a person to pass through. As sensor nodes will typically be used to monitor different parts of the structure and machinery, their height, position, and orientation will vary. We therefore selected two heights: middle height (1.7 m), and ground level (0 m); and, because the antenna is not isotropic, we selected the best and worst case: node attached horizontally

TABLE I
EXPERIMENT VARIABLES

Variable	Levels
Transmission power	0 dBm, -5 dBm
Node distance from ground	0 m, 1.7 m
Node antenna orientation	Horizontal, Vertical
Container door openings	Closed, Open 5 cm, Open 40 cm

and vertically. Finally, as the software tool allows us to interleave every round of packets with different transmission power levels, we set two levels of 0 dBm (maximum power) and -5 dBm, which would suppose around 20% reduction in power consumption. All combinations of these variables form a total of 24 experiments, organized in 12 different runs with two interleaved powers.

The nodes were placed inside containers 1 to 3, as shown in Fig. 2, to cover key points such as corners, doors, and problematic areas behind metal shelves or furniture. Container 4 could not be used due to restricted access. Three nodes (0, 11, and 17) were also attached to the outside of the doors, to allow connectivity through the doors' leakage. Since node 0 acts as the master node for synchronising and distributing the experiment to all the nodes, we choose its location to be at midpoint distance from the rest, and therefore the best candidate for the sink. This is not essential, as there are multi-hop capabilities for distributing the configuration, but nevertheless a good location of the master node can facilitate it.

All experiment runs were performed on the November 24th 2015, on a clear winter day. The experiment was designed to be completed in a single day, with the order of the runs randomized, to minimize the confounding effects of the environmental variables of humidity and temperature. For each run configuration, 4 rounds of probes per node were sent, 2 at high and 2 at low power, with every round composed of 10 probes with a 750 ms gap between them, and each probe with a burst of 10 messages with 50 ms separation. This forms a total of 200 messages per round and power level per node. The decision to perform burst experiments was made based on the target application, considering that machine and structural monitoring often require data bursts from accelerometers and other high sample rate sensors. The probes used channel 26, to avoid interference with Wi-Fi networks, and were configured not to use any MAC protocol. Each run configuration lasted for 10-15 min, accounting for the probe sending and the data writing to the memory which, along with changing the position of the nodes and data downloading, used the full day of experiments for the total set of 12 runs.

IV. Results & Analysis

A. Overall network analysis

A simple way to get a general understanding of the link quality of a wireless network is by looking at the RSSI,

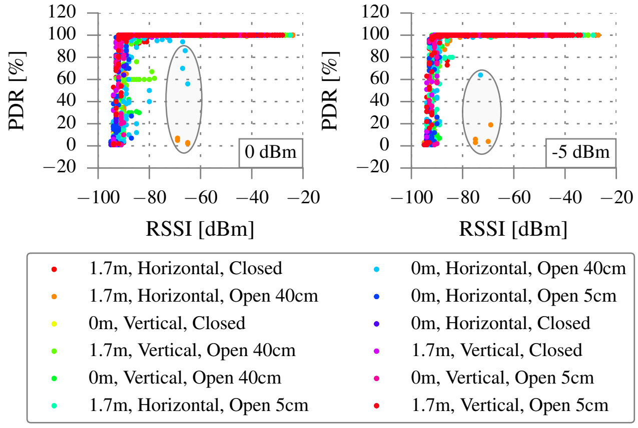


Fig. 3. PDR vs RSSI.

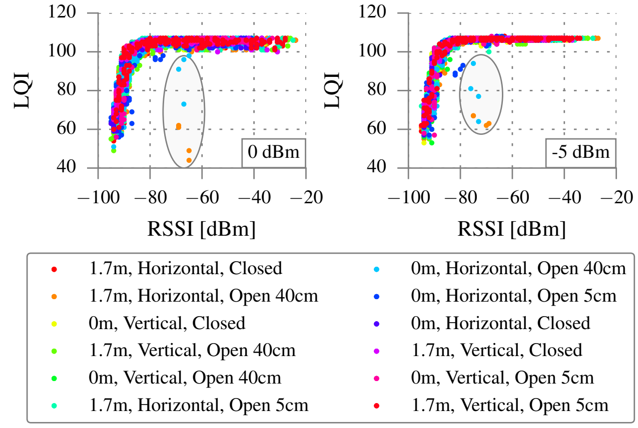


Fig. 4. LQI vs RSSI.

and its relationship with the PDR and LQI [12]. Although the presence of interfering signals can boost the RSSI levels while yielding a lower PDR [13], the setup of our experiment guarantees a lower chance of that occurring, due to channel selection and environment isolation.

In Fig. 3, we represent the PDR of each probe burst for the different combinations of rounds, for high (0 dBm) and low (-5 dBm) power, with respect to the mean RSSI. A total of $n(n-1) = 306$ links, with $n = 18$ nodes, were analysed for each round. We observe the typical overturned "L" shape found in the literature [14], [15], with disconnected, transitional, and connected areas. This can also be seen in Fig. 4, which shows how LQI relates to RSSI. However, we can perceive some outliers (circled) in both plots occurring in node 11, which is attached to the outside of the door in container 1, for the configurations with the doors open. Since external interference is unlikely, we speculate that this could be due to the multipath provoked by the amount of metal present in the environment. Moreover, the overall noise floor measured is fairly constant and close to the sensitivity of the radio chip, with an average of -96 dBm and $\sigma = 1.28$, which excludes the presence of other external elements that could affect the signal integrity.

In order to have a global view of the performance of each node, we show in Fig. 5 a 3D representation of the PDR per probe, accounting for each node being a sender or receiver. The first thing to notice is the high concentration of points near the 100% PDR plane, except for an empty rectangle between nodes 12-15 and 17, corresponding to the ones located in container 3, and with a concentration of points in a mirrored space on the 0% PDR plane. This could be due to two reasons: the door of this container faced away from the other two containers and the large metal block placed between container 2 and 3. This is more visible in the low power configuration. Further, we can observe the same empty block repeated, but rotated to the opposite side, suggesting a high degree of symmetry in the network. As asymmetry predicts the unreliability of a link, and has an impact on upper-layer protocols [16], we decided to have a closer look at the average link asymmetry of individual nodes. In Fig. 6, we represent the asymmetry as defined in [15], where a link is considered asymmetric if $|PDR_{n\rightarrow m} - PDR_{m\rightarrow n}| > 40\%$. It is shown that only links 11-13 and 15-17 exhibit a noticeable although small asymmetry ($< 10\%$), while most of the links are almost fully symmetrical.

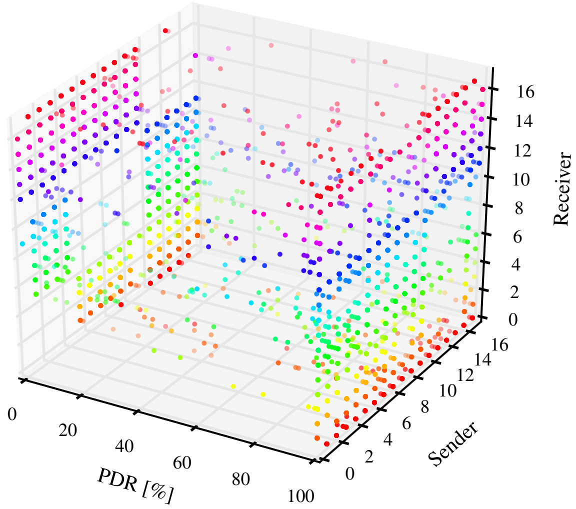
B. Effects of the variables in network performance

An interesting effect of the environment can be observed looking at the average PDR and RSSI for each of the different door combinations, shown in Table II. Although we could see a positive correlation between PDR and RSSI when representing all bursts of probes in Fig. 3, the average values per combination shown in the table seem to indicate the opposite. This is due to the fact that when any of the variables are set to have a negative effect on the signal range (e.g., closed doors), the average PDR computed over the whole network decreases; however, as the number of connected links also decreases, the average RSSI, which is calculated only over the remaining links, increases. This indicates that the network becomes more polarized, dropping links that were previously in the transitional region to the disconnected region. In Tables III and IV we can see that this is less noticeable for the node height and orientation variables, as they have less impact on the PDR.

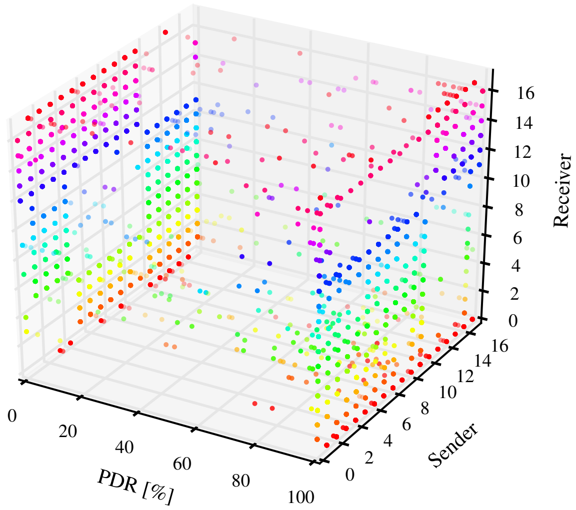
We observe an increase of over 50% in the total PDR from closed doors to fully open at full power, while for the node height and orientation it is much less. Therefore, the number and size of the openings will be the key variables to take into account when deploying wireless networks in these environments.

As expected, the best performance occurs when the nodes are transmitting at high power, located at 1.7 m in horizontal, and with the container doors fully open, yielding an overall PDR = 74.69% and mean RSSI = -69 dBm. On the other hand, the worst case is found at low power, nodes vertically oriented at ground level, and doors closed, with a resulting PDR = 37.25% and mean RSSI = -66 dBm.

Due to the season and geographical area, the environmental variables recorded during the tests did not undergo dramatic changes, with an average temperature of 13.44 °C, $\sigma = 1.63$, and relative humidity of 68.03%, $\sigma = 12.76$, outside the ranges that can affect significantly the performance of the wireless communications.



(a) Transmission power at 0 dBm



(b) Transmission power at -5 dBm

Fig. 5. PDR [%] between each node for all rounds at different transmission powers.

C. Link classification and sink selection

Although the previous 3D plots allow quick identification of problematic areas, we still need a way to quantify the link reliability to each specific node. For this we used the link classification described in [10], [15], which aggregates the links in five groups: *dead (PDR = 0%)*, *poor (PDR $<$ 10%)*, *intermediate (10% $\leq$ PDR $\leq$ 90%)*, *good (90% $<$ PDR $<$ 100%)*, and *perfect (PDR = 100%)*. Fig. 7 shows the number of links to each node distributed in each category, from a total of 17 possible links per node, for high and low power configurations.

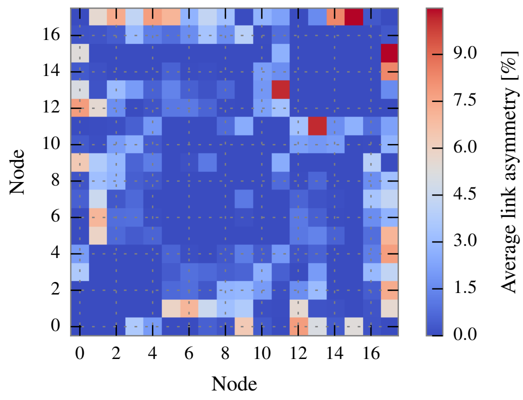


Fig. 6. Link asymmetry calculated as $|PDR_{n\to m} - PDR_{m\to n}|$.

TABLE II
AVERAGE PDR AND RSSI FOR DIFFERENT DOOR OPENINGS.

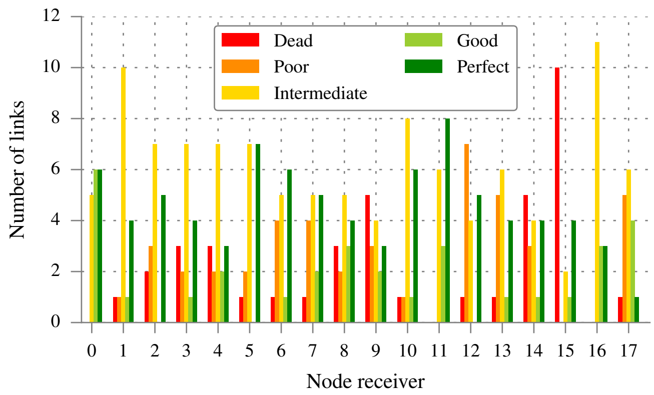
Transmission power	**Door state**	**PDR [%]**	**RSSI [dBm]**
0 dBm	Closed	41.13	-64
	Open 5 cm	47.83	-67
	Open 40 cm	64.21	-70
-5 dBm	Closed	38.03	-66
	Open 5 cm	42.35	-68
	Open 40 cm	55.66	-71

TABLE III
AVERAGE PDR AND RSSI FOR DIFFERENT NODE HEIGHTS

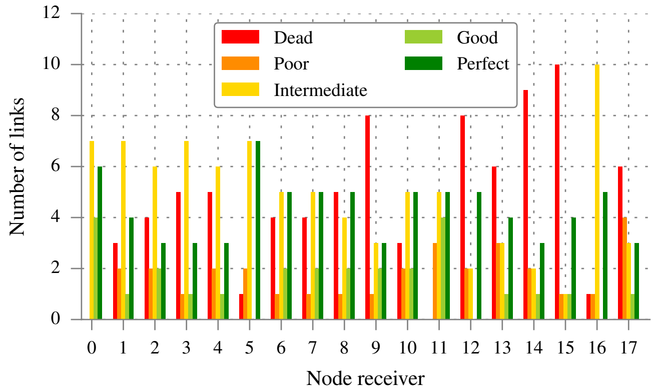
Transmission power	**Node height**	**PDR [%]**	**RSSI [dBm]**
0 dBm	1.7 m	53.49	-67
	0 m	48.61	-68
-5 dBm	1.7 m	47.06	-68
	0 m	43.63	-69

TABLE IV
AVERAGE PDR AND RSSI FOR DIFFERENT ANTENNA ORIENTATIONS

Transmission power	**Orientation**	**PDR [%]**	**RSSI [dBm]**
0 dBm	Horizontal	54.33	-67
	Vertical	47.78	-67
-5 dBm	Horizontal	48.17	-68
	Vertical	42.52	-69



(a) Transmission power at 0 dBm



(b) Transmission power at -5 dBm

Fig. 7. Number of *dead (PDR = 0%)*, *poor (PDR < 10%)*, *intermediate (10% ≤ PDR ≤ 90%)*, *good (90% < PDR < 100%)*, and *perfect (PDR = 100%)* links for each node.

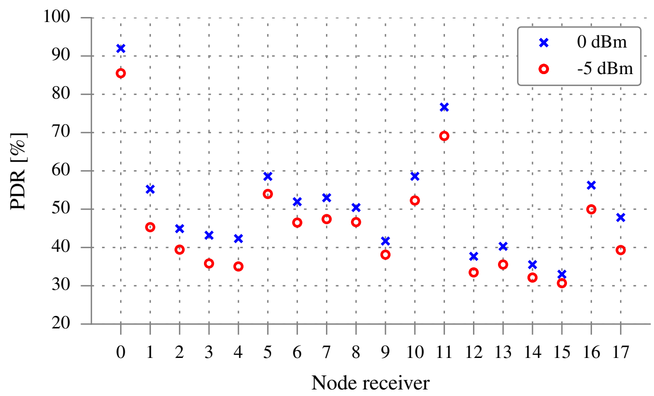


Fig. 8. Average total PDR [%] per individual node.

This representation, along with the average total PDR per node shown in Fig. 8, allow identification of the node with the best quality links that would be a good candidate for a sink in a one-hop network.

We notice that, even though the average PDR drop from high to low power per node is not large, the number of dead links increases considerably. This renders most of the nodes incapable of acting as a sink, with the exception of nodes 0 and 11, located outside containers 1 and 2, which keep all their links in the connected and transitional region, due to their strategic location. Looking at Fig. 8, we can confirm that our initial placement of the master node (node 0) as a sink candidate was correct, as it yields a better performance than the rest of the nodes, with an average PDR = 91.97% for all round combinations of high power.

TABLE V
AVERAGE PDR AND RSSI FOR DIFFERENT DOOR OPENINGS, FOR NODE 0

Transmission power	Door state	PDR [%]	RSSI [dBm]
0 dBm	Closed	80.65	-74
	Open 5 cm	96.92	-73
	Open 40 cm	98.33	-68
-5 dBm	Closed	70.04	-78
	Open 5 cm	88.69	-76
	Open 40 cm	97.77	-73

Since we established that the door openings are the most influential variable in our experiment, we show in Table V the average PDR and RSSI values for all the links to the sink candidate (node 0) for the different door configurations for both powers. In this case, unlike the previous case when we looked at the network links as a whole, we can see the expected increase in RSSI with the PDR, as a result of the links being stable under all different conditions. For the high power transmission, we observe a PDR = 80.65% for the closed door and a PDR = 98.33% for the open door case, with a 6 dB difference between both states, and a PDR = 96.92% is achieved with only a 5 cm door opening. Even at the worst case, with the doors closed and low power, we obtain an average PDR = 70.04% to the sink candidate.

V. CONCLUSIONS AND FUTURE WORK

In this paper, we studied through experimentation the physical link quality of a wireless sensor network in a multi-chamber metal environment. The results were obtained from a measurement campaign conducted during a full day using 18 nodes in three freight containers, in a randomized structured experiment accounting for the effects of node position and orientation, door openings, and transmission power. The PDR, RSSI, and LQI were recorded and analysed for all the possible links in the network, and an overview of the network behaviour was given as well as individual node performance.

From these results we observe that the best case is obtained when transmitting at high power with the doors fully open and nodes horizontal at 1.7 m, with a PDR = 74.69%, while the worst case is found at low power, doors closed and nodes vertical at ground level, yielding a PDR = 37.25%. We identify the door openings as the variable having the most impact on the overall network performance. The best sink candidate was selected, with an average PDR = 91.97% from the remaining nodes at a high transmission power (0 dBm), a PDR = 80.65% for the closed doors, and a PDR = 96.92% with just a 5 cm opening. This suggests that a wireless sensor network could be a feasible low-cost alternative to wired sensors under various conditions in all-metal environments. However, due to the difficulty in accurately modelling these metallic environments, a systematic practical study of the target environment will be necessary to identify areas of difficult connectivity and an optimal sink location. The methodology described in this paper is a verified one for performing this systematic practical study.

Further experiments will be carried out in different metal enclosed scenarios, to assess the effects of the wall thickness, chamber layout, and influence of electromagnetic noise on the communications, as this can be an important issue in off-shore deployments such as oil rigs, ships, and marine renewable energy platforms.

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