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Manuscript for Review

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Double directional characterisation of radio wave propagation through metallic watertight doors on board ships

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The objective of this Letter is to characterise the electromagnetic wave propagation between adjacent rooms in lower deck areas of ships. A wideband MIMO (Multiple-Input Multiple-Output) channel sounder has been used to realize double directional propagation measurements at 2.2 GHz. The antenna configuration was a linear array at the transmission side and a rectangular one at the reception. The measurement data are first processed with a classic beamforming technique, then with a high resolution algorithm to extract the dominant paths. A ray-tracing based simulation tool is used to understand the measurement results. It is observed that, in spite of the metallic structure of watertight doors, wireless communication remains possible between adjacent rooms after door closure. Results show that electromagnetic waves mainly propagate through door edges openings.

Introduction: The shipboard monitoring system may contain several thousands of sensors connected to central control units via wires. Tens of kilometres of cables may be installed on board a ferry-type boat, increasing its weight, cost and architecture complexity. A possible solution to reduce the huge amount of cables is the use of the emerging Wireless Sensor Networks (WSN). However, the metallic structures of ships tend to severely limit the propagation of electromagnetic (EM)

waves between two points within the ships, especially in lower decks areas where the bulkheads and watertight doors are totally made of steel. A few works have verified the feasibility of wireless communications on board ships [1]. However, spatio-temporal characterisation of EM wave propagation between adjacent rooms separated by metallic watertight door has not been investigated yet. In [2], we have verified that wireless communications remain possible between adjacent rooms even when closing the watertight door. In fact, an excess path loss of 25 dB is measured when the closed door is located directly on the Line-of-Sight (LoS). Otherwise, the measured excess path loss is about 17 dB. This result proves the existence of openings that allow EM leakage between adjacent rooms. In this Letter, a measurement campaign is carried out at 2.2 GHz on board a ferry-type boat using a wideband MIMO channel sounder [3]. A linear antenna array is used at the transmission and a rectangular antenna array at the reception. The analysis of collected data is performed with a classic beamforming technique [4] and the high resolution SAGE (Space-Alternating Generalized Expectation-maximization) algorithm [5], in order to determine dominant paths which propagate between adjacent rooms after closing the door and verify if propagation through watertight door is possible. A comparison between the measurement and a ray-tracing simulation results is performed.

Measurement setup: The measurement campaign was carried out on board the “Armorique” ferry from the “Brittany Ferries” company. The studied environments are the two lowest decks of “Armorique”, where sliding metallic watertight doors are used between adjacent rooms (Fig. 1). One may notice the highly metallic and confined environment, which generates several propagation phenomena (reflection, diffraction, scattering). The channel sounder transmits a spread spectrum waveform using a periodic m-sequence. It has an 11.9 ns temporal resolution for 100 MHz sounding bandwidth. The dynamic range is 50 dB for the 1023 code length.

Synchronisation between the transmitter and the receiver is achieved with highly stable 10 MHz rubidium oscillators. A Uniform Linear antenna Array (ULA) and a Uniform Rectangular antenna Array (URA) have been used respectively for the transmitter (Tx) and the receiver (Rx) to characterise the double directional channel on a 120° beamwidth in the horizontal plan. The study was limited to a 120° characterisation which is sufficient to focus on the propagation phenomena through the bulkheads and watertight doors between adjacent rooms. The Tx array contains 4 active elements and the Rx array contains 16 active elements. In order to improve the measurement dynamic range, power amplifiers have been directly integrated in the Tx array, and low noise amplifiers have been placed directly behind the Rx array antennas. For this measurement campaign, Tx and Rx are located in two different adjacent rooms separated by a watertight door, in a Line-of-Sight (LoS) configuration when the door is opened. These experiments have been performed in two different locations. The Tx-Rx separation distance was 5.5 m for the first scenario and 9.5 m for the second one. In both scenarios, there were no visible openings or non-metallic windows on the common bulkhead of adjacent rooms. We assume a quasi time-invariant channel during the measurements. Attention was paid that no people were moving in the surrounding area. For each Rx location, several measurements were taken and averaged to reduce the noise effect. The collected channel data have been stored on a laptop for post processing. The measurement objective is to characterise the double directional channel impulse response h [6]. In the case of omnidirectional antennas at the transmitter location r_{Tx} and the receiver location r_{Rx} , it could be expressed as (1):

$$h(r_{Tx}, r_{Rx}, \tau, \theta_{DoD}, \theta_{DoA}, \phi_{DoD}, \phi_{DoA}) = \sum_{s=1}^S h_s(r_{Tx}, r_{Rx}, \tau, \theta_{DoD}, \theta_{DoA}, \phi_{DoD}, \phi_{DoA}) \quad (1)$$

where S is the MPC (Multipath Components) number, τ the delay, θ and ϕ the DoDs (Directions of Departure) and DoAs (Directions of Arrival) in the azimuth and

elevation. With the plane wave assumption, each MPC contribution “s” is defined by (2):

$$h_s(r_{Tx}, r_{Rx}, \tau, \theta_{DoD}, \theta_{DoA}, \phi_{DoD}, \phi_{DoA}) = |a_s| e^{j\varphi_s} \delta(\tau - \tau_s) \delta(\theta_{DoD} - \theta_{DoDs}) \delta(\theta_{DoA} - \theta_{DoAs}) \delta(\phi_{DoD} - \phi_{DoDs}) \delta(\phi_{DoA} - \phi_{DoAs}) \quad (2)$$

where $|a_s| e^{j\varphi_s}$ is the MPC complex amplitude of the component s.

Results and analysis: The measurements were collected from two different locations. We gave a special attention to the DoD, DoA and delays which are the most important parameters to determine the EM leakage through the metallic bulkhead. In order to understand the obtained directions, an EM wave propagation simulator [7] has been used. This simulator, based on a 3D ray tracing algorithm, computes successive electromagnetic interactions thanks to the Geometrical Optics (GO) or Uniform geometrical Theory of Diffraction (UTD). This computation is associated with a 3D geometrical description of the considered scene, including the structures and the positions of bulkheads, floors, ceilings and watertight doors. A maximal number of 4 reflections and 1 diffraction are considered for each simulation scenario. When diffraction is involved, only one reflection can occur before and after it. According with the experimental configurations, rays propagating out from the Tx and Rx 120° beam have been filtered. The door is represented by a metallic rectangular plate of which the lateral extremities are separated from walls by 3 cm. With this door model, we assume that propagation is possible mainly by the two lateral door edges.

Fig. 2a and 2b show the normalized space-delay power graph and ray paths for the two measured scenarios (radius scale of beamformer graph is in ns). They represent the spatio-temporal channel response and allow to identify the main directions of energy propagation between Tx and Rx. We can see that the received energy is not homogeneously distributed on the 120° beamwidth. In each scenario, highest power levels are concentrated in a 60° sector in front of the watertight door. Simulated paths have delays approximately bounded between 25 and 35 ns.

To improve the angular resolution, the ISI-SAGE (Initialisation and Search Improved) SAGE algorithm [8] has been used for channel parameters estimation. It divides the measured data into signal components and derives all the parameters of the path jointly. For parameter estimation, this algorithm is based on ML (Maximum Likelihood) technique. Fig. 3a and 3b present the dominant propagation paths obtained from measurement results and the ray-tracing tool (one tick interval = 10 dB). The black arrows represent the DoDs and DoAs obtained from measurements. Blue lines correspond to simulated ray-tracing propagation paths. These figures show that radio signals pass mainly through the two edges of the watertight doors. A part of signal penetrates directly through the edges of the door while another part undergo a reflexion on the surrounding metallic walls before penetrating through edges. The propagation phenomena related to the watertight door are clearer in the first scenario (Fig. 3a), where the antennas are closer to the door. These results show a significant agreement between measurements and ray-tracing simulation results. Thus, the door model used for simulations can be considered as realistic.

Conclusion: This Letter reports the experiments conducted on board a modern ferry to characterise the EM wave propagation between adjacent rooms through watertight doors. The results of double directional channel characterisation are presented and compared to ray-tracing simulation. A channel sounder has been used to determine the DoDs and DoAs of dominant propagation paths. In spite of the totally metallic structure of bulkheads and watertight doors in the lowest decks of the ferry, the obtained results have shown that closing watertight doors does not block totally the propagation of radio waves. Radio signals propagation is made through the openings on the edges of the metallic watertight doors. This observation brings interesting perspectives for WSN deployment in such a complex and challenging environment.

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Figure captions:

Fig. 1 Example of a studied watertight door

Fig. 2 Beamforming results and ray-tracing simulation

2a) First measurement scenario

2b) Second measurement scenario

Fig. 3 SAGE results and ray-tracing simulation

2a) First measurement scenario

2b) Second measurement scenario

Figure 1

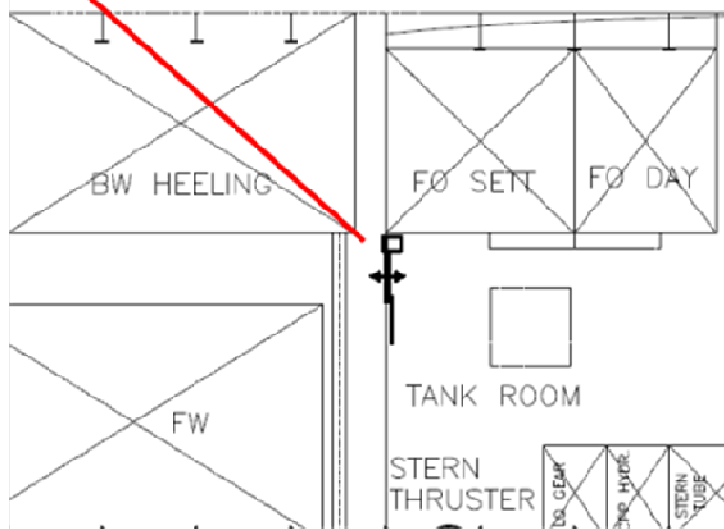
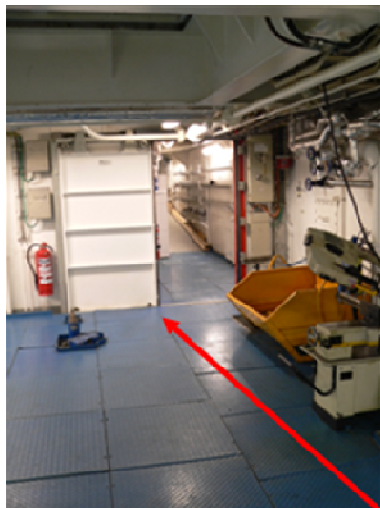


Figure 2

Fig. 2a

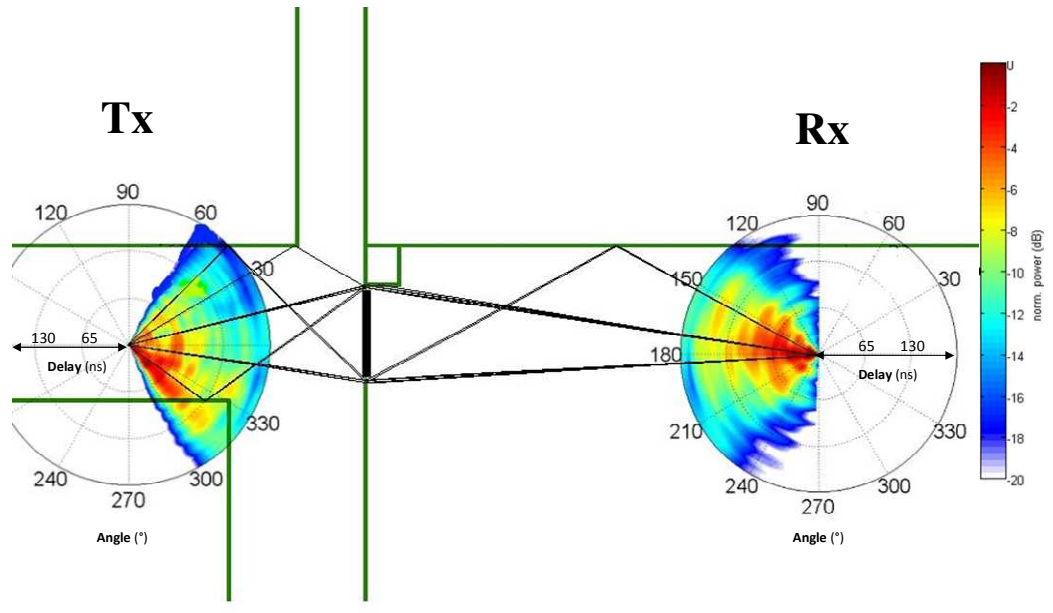


Fig. 2b

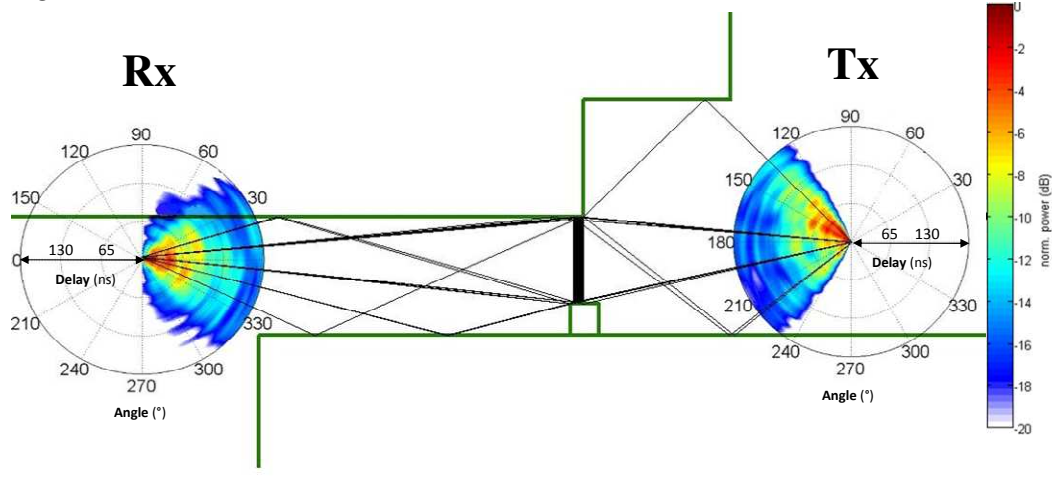


Figure 3

Fig. 3a

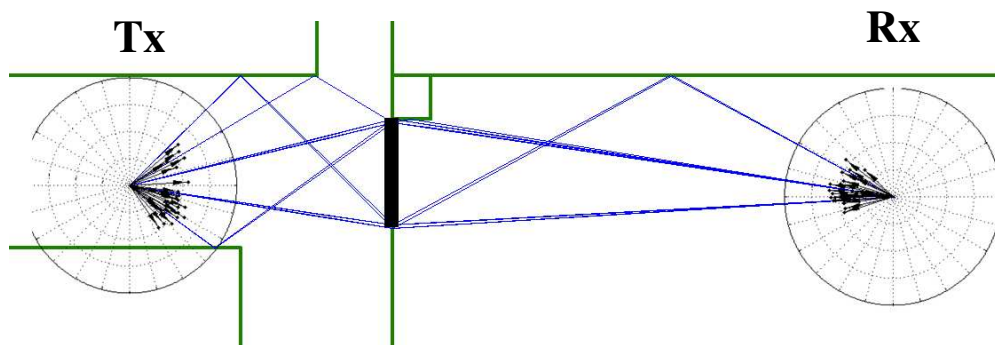


Fig. 3b

