Double Directional Channel Characterization on Board Ships

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Abstract— **Due to the metallic structure of decks, bulkheads and watertight (WT) doors, wireless communications are a serious challenge in the particular environment of ships. In order to deploy reliable shipboard wireless networks, wireless devices (access points, routers, sensor nodes, etc.) must be located at strategic locations ensuring full radio coverage and network connectivity. Strategic locations can be determined from the identification of the main propagation directions of electromagnetic (EM) waves within a ship. This paper presents the results of a radio propagation measurement campaign performed on board a ship. A dual-band Multiple-Input Multiple-Output (MIMO) channel sounder and antenna arrays have been used. Measurement data have been processed with a classic beamforming technique and a high resolution algorithm to extract dominant paths. A ray-tracing based simulation tool has been used to understand measurement results. Obtained results are used for optimal placement of radio devices when deploying shipboard wireless networks.**

Keywords-propagation; channel sounding; ray-tracing; ships

I. INTRODUCTION

Ships are an important part of modern systems, which are widely used in commercial and military purposes. Modern ships are equipped with automatic alarm and monitoring systems, which control and ensure safety and accuracy of the whole ship operation. Current shipboard monitoring systems use extensive lengths of cables to connect several thousands of sensors to control units. In addition to the high cost and weight due to wires installation during ships construction, vessels represent a complex and harsh environment in which extensive lengths of wires are vulnerable to heat, moisture and toxic agents [1]. Hence, applying wireless technologies such as Wireless Sensor Networks (WSN) to shipboard monitoring systems may be a cost-effective and survivable solution. Furthermore, wireless systems are easily and inexpensively reconfigured. Moreover, wireless communications can be used for other applications on board ships. Ferry companies, for example, aim to enhance their passengers' satisfaction by equipping their boats with WiFi networks. Cordless phones are very useful for communication between crew members.

However, wireless communications are a serious challenge in the particular harsh environment of ships. In fact, several factors may limit the performance of wireless systems on board ships [2]. Firstly, bulkheads and doors are made of metal, most often steel. Although the steel is not a perfect conductor, it can severely decrease the power of radio waves. Another limiting factor is the multipath propagation: a transmitted EM wave could be reflected, scattered or diffracted by different objects leading to several delayed copies to the receiver. The existence of multiple copies of the transmitted wave may cause disturbing interference signals at the receiver. In order to deploy reliable wireless networks on board a ship, wireless devices must be located at strategic locations ensuring optimal radio coverage and network connectivity. Strategic locations can be determined by identifying the main directions of EM waves within a ship.

Few works have studied the EM waves propagation on board ships [2-5]. However, spatio-temporal characterization of EM waves propagation within this particular environment has not been done yet. Existing studies have only considered the possibility of wireless communications without determining the directions of EM waves propagation. In [6], we have conducted Continuous Wave (CW) measurements on board several ferries to verify the possibility of intra-, inter-compartments and inter-decks radio communication. Measurement results helped us to determine the path loss exponents in different shipboard environments and different communication configurations. However, CW measurements cannot determine the Directions of Departure (DoD) and Directions of Arrivals (DoA) of EM waves. Double directional or MIMO measurements may be an efficient technique to estimate DoD and DoA by using antenna arrays at both link ends. In this paper, we present the results of a measurement campaign using a dual-band MIMO channel sounder [7]. This measurement system, developed in the IETR laboratory, was already used for outdoor, indoor and outdoor-to-indoor MIMO channel sounding [8]. The performed measurements provide a spatio-temporal characterization of the EM wave propagation within a ship. Collected data are analyzed using a classic beamforming technique and a high resolution algorithm. Obtained results are then compared to simulation results based on a ray-tracing tool. This comparison helps us to understand directions of propagation of EM waves in typical shipboard environments such as engine rooms, parking and passenger decks. Obtained results are used to ensure an optimal placement of radio devices when deploying shipboard wireless networks.

The remainder of this paper is organized as follows: Section II describes the methodology and measurement setup used in this study. Section III presents and analyzes the obtained measurement and simulation results. Finally, several conclusions are drawn in Section IV.

II. METHODOLOGY AND MEASUREMENT SETUP

The dual frequency band (2.2 and 3.5 GHz) used 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. Synchronization between the transmitter (Tx) and the receiver (Rx) is achieved with highly stable 10 MHz rubidium oscillators. Different impulse response lengths can be chosen from 1.27 to 81.84 µs, depending on the sounding bandwidth and the code length. As an example, for 100 MHz bandwidth and 1023 code length, the recorded impulse response length is 10.23 µs.

Different types of antenna arrays were developed for this sounder. At 2.2 GHz, a 4-element Uniform Linear antenna Array (ULA) and a 16-element Uniform Rectangular antenna Array (URA) are used respectively for the Tx and the Rx to characterize the double directional channel on a 120° beamwidth in the horizontal plan. At 3.5 GHz, a 4-element Uniform Circular Array (UCA) is used at Tx and a 16-element UCA is used at Rx. With this configuration, we can characterize 360° azimuthal double directional channel at both link sides. In order to improve the measurement dynamic range, power amplifiers have been directly integrated in the Tx antenna array, and low noise amplifiers have been placed directly behind the Rx antenna array.

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 were stored on a laptop for post-processing.

The measurement objective was to characterize the double directional channel impulse response h [9]. In the case of omnidirectional antennas at Tx location r_{Tx} and Rx location r_{Rx}, it could be expressed as:

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

where S is the number of multipath components, τ is the delay, Θ and Φ are the azimuth and elevation angles of DoD and DoA. With the plane wave assumption, the contribution of each multipath component s is:

$$\begin{aligned} &h_s(r_{Tx}, r_{Rx}, \tau, \theta_{DoD}, \theta_{DoA}, \phi_{DoD}, \phi_{DoA}) \\ &= |a_s| e^{j\varphi_s}.\delta(\tau - \tau_s).\delta(\theta_{DoD} - \theta_{DoD,s}).\delta(\theta_{DoA} - \theta_{DoAs}) \\ &\times \delta(\phi_{DoD} - \phi_{DoD,s}).\delta(\phi_{DoA} - \phi_{DoAs}) \end{aligned} \quad (2)$$

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

Analysis of collected data is performed with a classic beamforming technique [10] and the high resolution Space-Alternating Generalized Expectation-maximization (SAGE) algorithm [11], in order to determine dominant paths which propagate between Tx and Rx. We gave a special attention to the DoD and DoA, which are the most important parameters to determine the directions of propagations. In order to precisely determine these directions, a simulator of EM propagation [12] has been used. This simulator, based on a 3D ray tracing algorithm [13], computes successive EM 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 WT doors. A maximal number of 4 reflections and one diffraction are considered for each simulation scenario. When diffraction is involved, only one reflection can occur before and after it.

III. MEASUREMENT RESULTS AND ANALYSIS

This section presents and analyzes the obtained measurement and simulation results. Three typical environments have been studied on board the "Armorique" ferry: the engine rooms, the parking and the passenger deck. The engine rooms of "Armorique" include metallic engines, generators, valves and pumps arranged in a complex way. The common bulkheads of these rooms are metallic and include sliding metallic WT doors. The parking is a big hall with metallic walls. A metallic wall located in the middle of the parking divides it into two main parts. Vehicles of different types were parked in the parking (cars, buses, trucks, etc.) when performing measurements. The passenger deck is composed of passengers' cabins and corridors. In contrast with the two previous environments, corridor walls and cabin doors are not fully made of metals.

A. EM waves propagation within engine rooms

In spite of the fully metallic structure of bulkheads and WT doors in the lower decks areas of ferries, CW measurements have shown that wireless communications between adjacent rooms remain possible after closing WT doors [6]. A MIMO channel sounder and antenna arrays are used to identify the openings allowing EM waves leakage. The studied environment is the second deck of "Armorique", where sliding metallic WT doors are used between adjacent rooms. This environment is highly metallic and confined. It generates several propagation phenomena (reflection, diffraction, scattering). Measurements were carried out using the URA and ULA arrays at 2.2 GHz. The study was limited to a 120° characterization in the azimuthal plan. It is sufficient to characterize the propagation phenomena through the bulkheads doors between adjacent rooms. Fig. 1 shows the layout of the rooms, locations of Tx and Rx in the second deck of "Armorique".

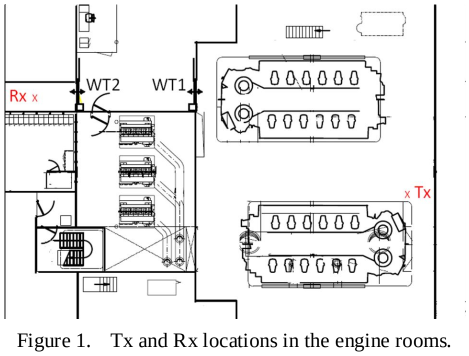
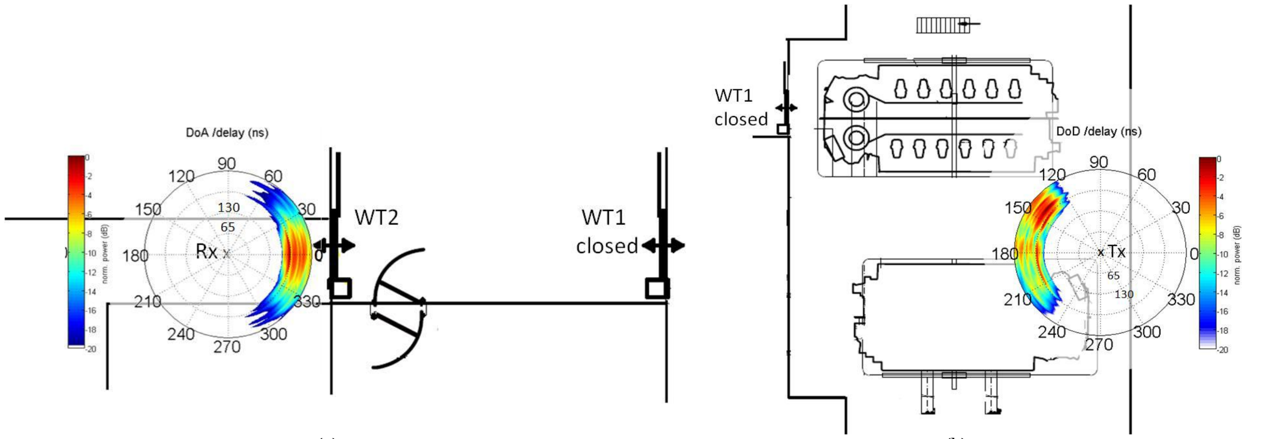


Figure 1. Tx and Rx locations in the engine rooms.

Two WT doors, called WT1 and WT2 on Fig. 1, are located on the propagation path between Tx and Rx, which are in No Line of Sight (NLoS) configuration. Measurements were carried out when WT1 was opened and when it was closed respectively, while WT2 was maintained closed. Measurement data were processed using the conventional beamforming. Fig. 2 and Fig. 3 present the normalized space-delay power graph for the two measured scenarios (radius scale of beamformer graph is in ns, and the color represents the normalized amplitude at each angle). These graphs represent the spatio-temporal channel response and allow identifying the main directions of energy propagation between Tx and Rx. It can be seen that the received energy is not homogeneously distributed on the 120° beamwidth. For the two scenarios, the angular distributions of energy are similar. It can be seen that a main beam of energy with about 20° beamwidth (between 125° and 145°) and other beams around 180° direction are formed at the Tx side. Moreover, a beam of 50° is formed around 0° at the Rx side. The main beams formed at the Tx and Rx sides correspond to the energy going to WT1 and coming from WT2 respectively. This similarity between the two scenarios (closed and open door) shows that the energy is propagating through the WT doors regardless their status. The other beams seen at 180° at the Tx side may be probably due to two respective reflections of EM waves on the bulkhead in front and behind the Tx, before penetration through WT1 and WT2 towards Rx. We have presented in [14] similar measurements for scenarios where the direct path between Tx and Rx is blocked by the WT door. Its results show that radio signals propagation is made through the openings on the edges of the metallic watertight doors.

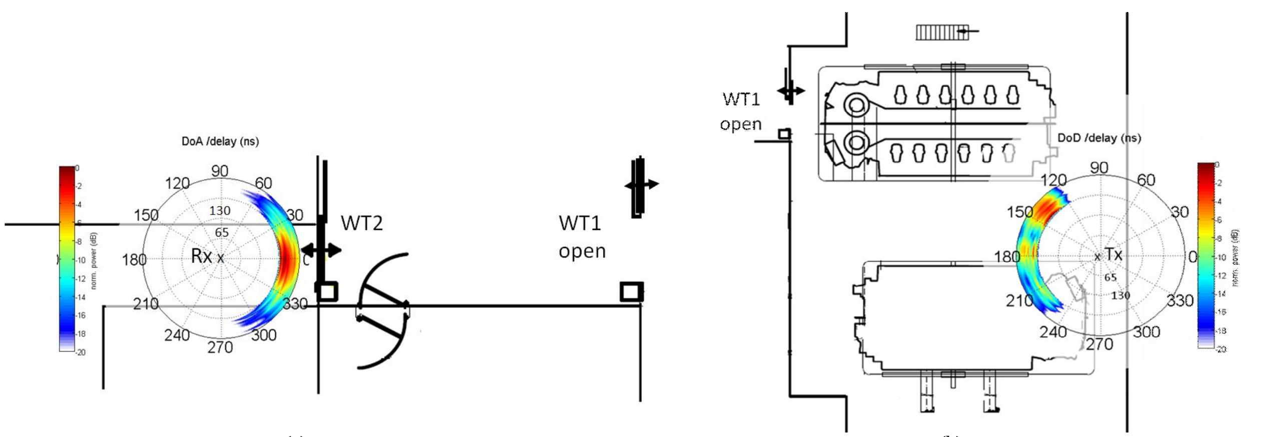
B. EM waves propagation within the parking

As stated before, the parking of "Armorique" is a big hall where all walls, ceiling and floor are totally metallic. A big bulkhead installed in the middle divides the parking into two parts (called lower part and upper part in the following). Two communication scenarios were considered. In the first one, Tx and Rx are both located in the lower part of the parking (Line of Sight LoS configuration). In the second scenario, Tx is located in the upper part of the parking and the Rx is located in the lower one. The middle bulkhead blocks the LoS between the Tx and Rx (NLoS configuration).



(a) (b)

Figure 2. Beamforming results when WT1 and WT2 are closed: (a) At Rx (DoA), (b) At Tx (DoD).



(a) (b)

Figure 3. Beamforming results when WT1 is opened and WT2 is closed: (a) At Rx (DoA), (b) At Tx (DoD).

The ULA and URA 2.2 GHz are used in these measurements. The results are processed using beamforming and compared to ray-tracing simulation results.

Fig. 4 shows the layout of the parking, locations of the Tx and Rx and ray tracing results for the LoS configuration. A guiding effect is clearly observed in the lower part of the parking due to the middle bulkhead; some other paths coming from the upper part can be detected. The middle bulkhead and the wall of the parking act as a waveguide between the Tx and Rx. Fig. 5 shows the comparison between beamforming results and ray-tracing simulation results at Tx and Rx. The comparison indicates also that main beams (in red) are formed in the lower part of the parking. A significant agreement between measurement and simulation results is found.

Fig. 6 shows the layout of the parking, locations of the Tx and Rx and beamforming and ray-tracing results for the NLoS configuration. In spite of the middle bulkhead, which blocks the direct path between Tx and Rx, EM waves are able to achieve the Rx through reflections on the parking walls and the middle bulkhead, and diffraction on the middle bulkhead edges. As in the LoS configuration, a significant agreement between measurement and simulation results is found. This agreement proves that the model of the parking used for simulation can be considered as realistic.

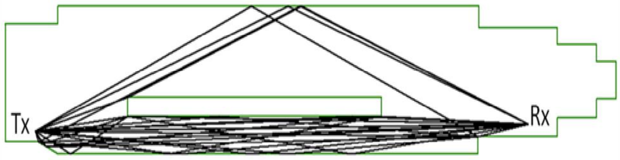
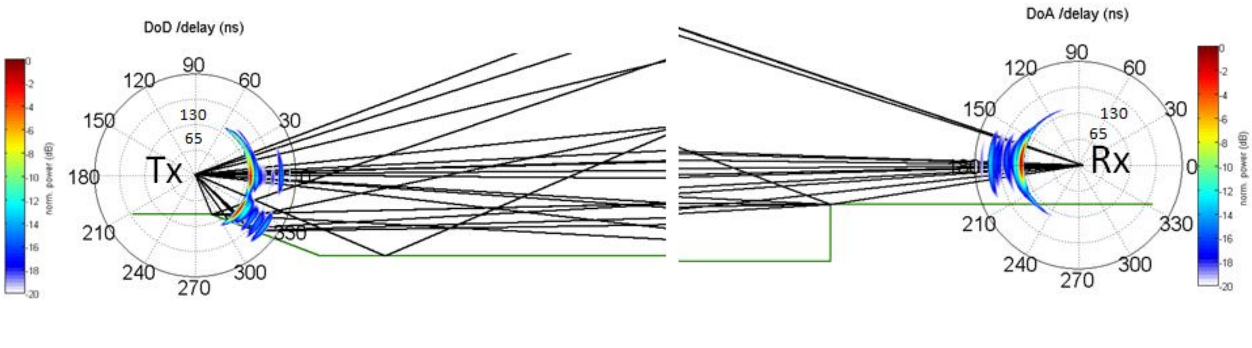


Figure 4. Ray-tracing results for the parking in LoS configuration.

C. *EM waves propagation on the passenger deck*

Fig. 7 shows the layout of the passenger deck and the locations of Tx and Rx. Rx is placed in the stairway located at the top left of this deck. The stairway door is opened. Tx is placed at three locations (Tx1, Tx2 and Tx3 in Fig.7).Tx is firstly located in a passenger cabin whose door is closed (location Tx1), then in a corridor in the middle of the deck (location Tx2) and finally at the bottom right corner of the deck (location Tx3). In all these measurement scenarios, Tx and Rx are in NLoS configuration. As this environment is not totally metallic like the parking and the engine rooms, no particular propagation directions can be excluded. Thus, the circular arrays have been used at the Tx and Rx to determine the directions of propagation in the 360° azimuth.



(a) (b)

Figure 5. Beamforming and ray-tracing simulation results for LoS configuration in the parking: (a) at Tx (DoD), (b) at Rx (DoA).

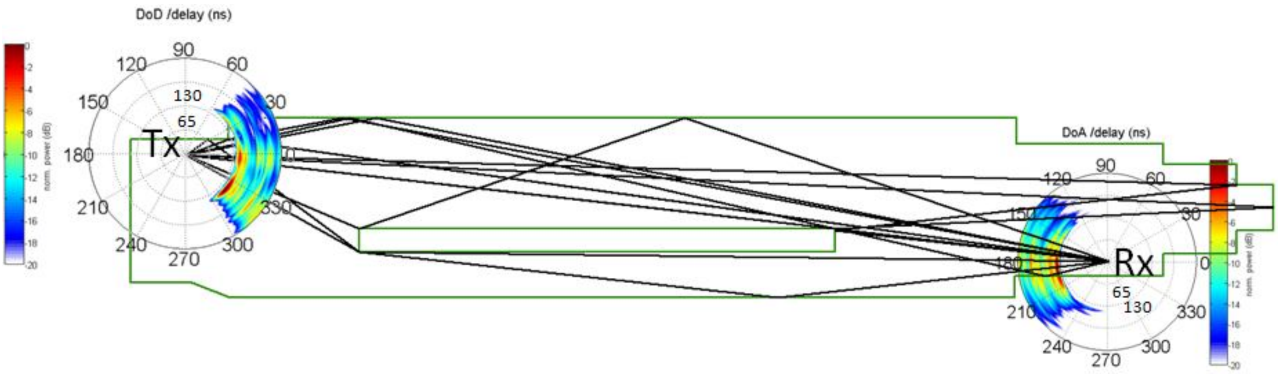


Figure 6. Beamforming and ray tracing results for the parking in NLoS configuration.

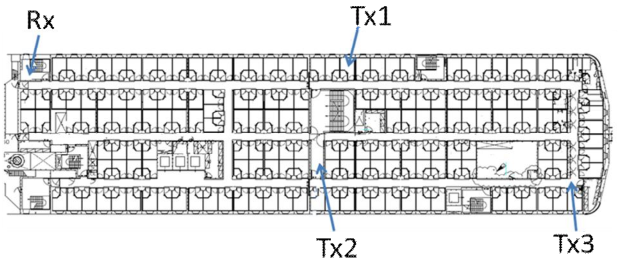


Figure 7. Layout of the passenger deck of "Armorique" with the locations of transmitter (Tx1, Tx2 and Tx3) and the receiver (Rx).

The propagation paths parameters are extracted using SAGE algorithm. Fig. 8 presents the normalized DoD and DoA results for all measurement positions. Black arrows indicate directions and the length of each one indicates its normalized amplitude (one tick interval corresponds to 10 dB). This overview shows that for the DoD, some privileged propagation directions can be easily identified. Concerning the DoA, for the three Tx locations, we notice that received energy directions are more equally distributed on 360°. This can be explained by the receiver location in the stairway. Due to its metallic walls, this environment is similar to a reverberant chamber. One can think that EM waves will arrive mainly through the entrance door of the stairway. After that, EM waves are reflected on the metallic walls of stairway and achieve the receiver from all 360° directions.

An adaptation of the ray-tracing based simulation tool was made at 3.5 GHz, mainly concerning the dielectric properties of materials constituting the passenger deck (used for the computation of the reflection, transmission and diffraction coefficients).

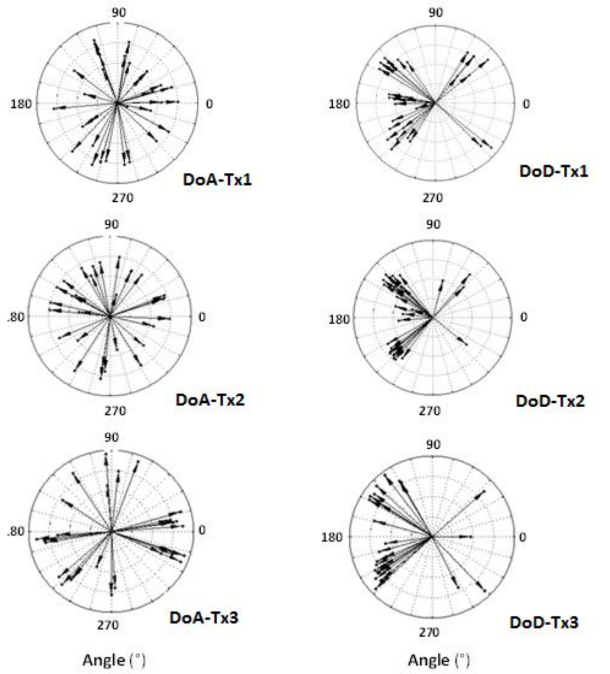


Figure 8. DoA and DoD for the three measurement scenarios on the passenger deck.

For the ray-tracing simulations, by assuming that the propagation is made through the corridors, and because of the current limitation of the RT simulator to compute complete paths from Tx to Rx, a virtual point of reception is located in the corridor near the Tx position. The idea is to visualize how the radio waves reach this point from the Tx. Fig. 9 presents the comparison between the DoD obtained from the measurements (black arrows) and ray-tracing tool (blue lines) for the Tx1 location. In this measurement scenario, Tx was located in a passenger cabin. The main directions of energy propagating from the passenger cabin to Rx position obtained from ray-tracing present a significant agreement with the measurement results. The obtained results validate our assumption that the propagation in this environment mainly occurs through the corridors. These directions show that EM waves penetrate through the thin walls of cabins (which are not metallic) before arriving to the corridor, and then they are guided to the Rx (through reflections). Note that the wall located at the left of the figure corresponds to a metallic structure.

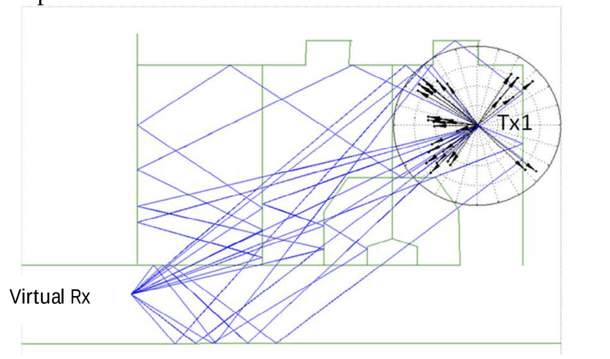


Figure 9. DoD results for the location Tx1.

Fig. 10 presents the comparison between DoD obtained from the measurements and ray-tracing tool for Tx3. As in the previous scenario, a significant agreement is observed between the main directions flows from the measurements and the ray-tracing simulation results. The obtained results also validate our assumption that the propagation in this environment mainly occurs through the corridors (but some waves can propagate through cabin walls). In this configuration, reflections are observed on the corridor walls surrounding the Tx3 location before arriving to the receiver.

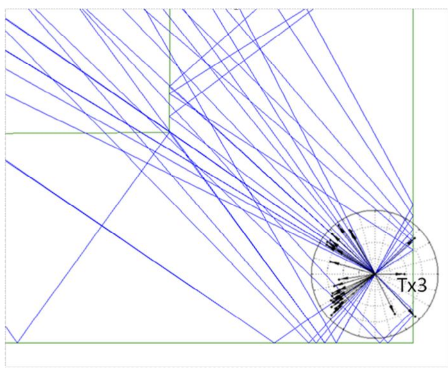


Figure 10. DoD results for the location Tx3.

D. Engineering rules for intermediate nodes placement

As mentioned in Section I, the main objective of these measurements is the optimization of wireless devices placement when deploying wireless networks on board a ship. This study is a part of SAPHIR project, which aims at applying WSN technologies to shipboard alarm and monitoring systems. Sensor nodes must be placed in all ship rooms and compartments to measure physical parameters such as tank level, water level, temperature, humidity, etc. and then send collected data to central control units located in the wheelhouse or the control room. As direct communications between sensor nodes and control units are impossible (due to large distances and metallic environments), intermediate nodes must be located to ensure the whole network connectivity. Results of these measurements are useful for placing intermediate nodes. Therefore, the following engineering rules are recommended. In the engine rooms, EM waves propagate mainly through watertight doors even when they are closed. It will be then recommended to place intermediate nodes in front of watertight doors to ensure connectivity between adjacent rooms. In the parking, the walls constitute a wave guide between communicating nodes. Intermediate nodes may be placed on the walls of the parking, including those of the middle bulkhead, to ensure the network connectivity of different nodes in the parking. In the passenger deck, EM waves propagate mainly through corridors. Intermediate nodes will may be located in the ceiling of corridors (to minimize the fluctuation due to passengers' movement).

IV. Conclusion

In this paper, a measurement campaign was conducted on board a ferry using a MIMO channel sounder. The objective of this measurement campaign was to determine the directions of propagation of EM waves in typical shipboard environments. In spite of the totally metallic structure of bulkheads and WT doors in the lowest decks of the ferry, obtained results show that closing WT doors does not block totally the radio waves propagation, which is made through the openings on the edges of the metallic WT doors. Moreover, the results show that parallel metallic bulkheads, such as in the parking, act as a waveguide between Tx and Rx. In spite of NLoS configuration, EM waves are guided through reflections on the metallic bulkheads and diffraction on the bulkheads edges, to the Rx. Measurement and simulation results on the passenger deck show that EM waves propagate mainly through corridors on the passenger deck. When the Tx is located in a passenger cabin, EM waves penetrate through the thin walls of cabins before arriving to the corridor, by which they are guided to the Rx. All these results are used to determine engineering rules for sensor nodes placement.

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