Radio Channel Modelling in a Ship Hull: Path Loss at 868 MHz, 2.4 GHz, 5.25 GHz and 60 GHz

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Abstract—This paper presents the analysis of a channel sounding campaign in the hull of a bulk carrier vessel at sub-6 GHz frequencies 868 MHz, 2.4 GHz and 5.25 GHz as well as mmWave frequency 60.48 GHz. For the sub-6 GHz frequencies, path loss (PL) is measured using omnidirectional antennas. The measured PL is fitted to a one-slope PL model that takes into account attenuation due to engine room floor crossings, obstructions and walls. The fitted model has a reference PL lower than free space and a PL exponent around 1.2. For mmWave wireless communication high gain directive antennas are typically used. Therefore, the directive radio channel for Line-of-Sight (LOS) communication is measured using the Terragraph channel sounder and an antenna beam width dependent PL model is created. At mmWave frequencies, LOS PL in the vessel is close to PL in a free space environment, but angular spread values are lower compared to other indoor scenarios.

Index Terms— sub-6 GHz, mmWave, angular rms spread, beam width, channel modelling, engine room, vessel, path loss, ship hull.

I. INTRODUCTION

Even though wireless connectivity via WiFi, Long-Term Evolution (LTE) and satellite is omnipresent in our daily lives, many indoor industrial areas still lack coverage as the wireless channel in industrial environments is affected by the presence of large blocking metallic constructions [1]. One such environment where metallic constructions are present is the engine room of a vessel, which challenges the use of wireless communication. Therefore monitoring and maintenance tracking inside the vessel is currently a manual task. Enabling wireless connectivity inside the ship allows for automatic monitoring and controlling of devices and improves safety on board. During the last decade, most research focused on off-board marine communication [2], [3], [4], [5], [6], and existing papers about in-vessel wireless communication seem to focus on higher-layer measurements, e.g. deploying a sensor network and investigating packet error rate [7], [8], [9].

Radio channel experiments up to 2.6 GHz on board of a vessel were carried out in [10] and [11]. In [10] the distance-log relationship from (1) is derived for several rooms, with PL_0 the reference path loss (PL) at 1 m, d the distance in meter and n the PL exponent. The fitted PL exponent is less than 2 for propagation within a compartment.

$$PL(d) = PL_0 + 10 n \log_{10}(d) \quad (1)$$

Such a low PL exponent is seen in several industrial environments [1] and results in excellent network reliability when

testing higher layer protocols such as IEEE 802.15.4 based sensor networks on board of a vessel [9].

This paper investigates the indoor radio channel at different frequencies in the highly metallic environment of a vessel's engine room and proposes a generalized path loss model taking into account attenuation due to obstructions, as opposed to the distance model provided in [10]. We create a path loss model for frequencies 868 MHz, 2.4 GHz and 5.25 GHz. These frequencies are selected as they are already used by wireless technologies suitable for Internet-of-Things (IoT) or wireless local area networks. As an example, 868 MHz is used by LoRa, narrowband IoT and SigFox. 2.4 GHz is used by WiFi, ZigBee and Thread, and 5.25 GHz is used by WiFi. Apart from sub-6 GHz channel modelling, wireless communication at mmWave frequencies is considered, extending our previous research presented in [12] with antenna beam width dependence and a quantification of the angular profile. We compare 60 GHz angular spread in the vessel to outdoor [13] and indoor [14] environments.

The proposed PL models allow optimizing the wireless communication on board of the vessel. Section II provides the methodology description and results for the sub-6 GHz frequencies. The characterization of the 60 GHz directive radio channel via the Terragraph (TG) channel sounder is discussed in Section III and Section IV concludes this paper.

II. SUB-6 GHZ CHANNEL MODELLING

A. Methodology

We performed channel sounding measurements at 9 different transmit (TX) locations in 3 rooms inside the hull of the vessel, i.e. the engine room, the steering control room and the forecastle deck. A picture of each room is shown in Fig. 1. During the measurements, the ship was in the harbour and no workers were in the rooms. Therefore we assume the environment to be static. At every TX location, 3 tracks are measured during which a signal generator generates a sine

Figure 1. Measurement locations in the vessel

Figure 2. Channel sounding setup for sub-6 GHz frequencies

Table I
SUB-6 GHz CHANNEL SOUNDER PARAMETERS

Parameter	Value
TX and RX antenna type	Cobham XPO2V/1441
Antenna gain	2 dBi in freq. range 800 MHz - 6 GHz
Signal generator	R&S SMB 100A
Transmit power	15 dBm
Signal analyzer	R&S FSV30
Frequency span	100 kHz
Measurement points	691
Resolution bandwidth	1 kHz
Sweep time	1.896 ms

wave at respective center frequencies 868 MHz, 2.4 GHz and 5.25 GHz. The omnidirectional vertically polarized transmit and receive antennas are mounted at a height of 2 m. A signal analyzer is mounted on a mobile cart and records the power of the received signal. By pulling the cart away from the transmitter at a speed of 0.1 m/s and continuously recording received power and tachometer data, we get the received power as a function of distance. The received power is converted into path loss (PL) by taking into account transmit power, antenna gains and cable losses. For all tracks, the measured PL samples are averaged over 10 wavelengths. This results in 69 averaged samples at 868 MHz, 202 samples at 2.4 GHz and 471 samples at 5.25 GHz. A picture of the measurement setup is displayed in Fig. 2 and the measurement parameters are summarized in Table I.

The measurement tracks from the engine room are marked on the vessel's floor plan in Fig. 3 and are categorized into Line-of-Sight (LOS), obstructed LOS (OBS) and non LOS (NLOS). For the OBS scenarios, machinery (such as the rotary vane or an engine) obstructs the direct LOS path and a diffracted or reflected signal is received. For the NLOS scenarios, the TX and RX antennas were positioned at different floor levels or a metallic wall was obstructing the direct path. The minimum distance between the antennas and the closest surrounding metal is larger than the far field Fraunhofer distance of the used antennas, which is 0.4 m for frequency 5.25 GHz. The averaged PL samples of all tracks are combined and fitted to the log-distance model of Eq. (2) via a multiple

Figure 3. Engine room floor plan with 3 TX locations and LOS (full line), OBS and NLOS (dashed line) tracks

Figure 4. Measured LOS PL data for 868 MHz, averaged PL samples (LOS, OBS, wall crossing) and log-distance model

linear regression analysis.

$$PL(d, p, q, r) = PL_0 + 10 n \log_{10}(d) + p A_{Floor} + q A_{Obs} + r A_{Wall} + \chi \quad (2)$$

In this equation, d is the distance in m, $p \in \{0, 1, 2\}$ is the number of engine room floor crossings, $q \in \{0, 1\}$ indicates whether there is an obstruction present in the LOS path and $r \in \{0, 1\}$ indicates whether the LOS path crosses a wall. PL_0 is the path loss at a reference distance of 1 m (in dB), n (-) is the PL exponent, A_{Floor} , A_{Obs} and A_{Wall} are the floor, obstruction and wall attenuation in dB. The shadow fading term χ is based on the 95% percentile of a zero-mean normal distribution with standard deviation σ .

B. Results

The fitted PL model together with the calculated free space PL (FSPL) at 1 m for the different frequencies is listed in Table II. The largest pValue is $1.09e-4$ for parameter A_{floor} at frequency 868 MHz. The coefficient of determination R^2 ranges from 0.85 to 0.88. Fitting the combined LOS, OBS and NLOS samples results in a higher R^2 than fitting samples for each scenario separately. Figure 4 shows the LOS

Table II
FITTED LOG-DISTANCE PL MODEL FOR SUB-6 GHz FREQUENCIES

Frequency	FSPL	PL_0	n	A_{floor}	A_{obs}	A_{wall}	σ / χ	R^2
868 MHz	31.2 dB	30.5 dB	1.21	4.4 dB	6.3 dB	14.3 dB	3.0 / 5.9 dB	0.85
2.4 GHz	40.1 dB	35.9 dB	1.14	5.9 dB	3.4 dB	13.6 dB	2.9 / 5.7 dB	0.84
5.25 GHz	46.9 dB	34.3 dB	1.36	5.4 dB	3.3 dB	12.9 dB	2.5 / 4.9 dB	0.88

measurement data, together with the averaged PL samples for LOS, OBS and wall crossing NLOS for frequency 868 MHz, together with the fitted model for LOS ($p = q = r = 0$), OBS ($q = 1, p = r = 0$) and NLOS ($p = q = 0, r = 1$).

Compared to free space, both PL_0 and n are lower, which can intuitively be explained by the lower reflection loss for larger distances, similarly to radio propagation in the near region of tunnel environments [15], [16]. Indeed, for a larger distance the incident angle is larger and hence the reflection loss becomes smaller. Therefore, more reflected energy is received for larger distances, resulting in a lower PL. The fitted PL exponent is also lower than the values found in [10] where the model fitting was performed on individual tracks rather than a combined data set including LOS, OBS and NLOS measurement tracks. Floor and wall attenuation are similar for the different frequencies, whereas obstruction attenuation is higher for 868 MHz than for 2.4 and 5.25 GHz. The frequency independence of wall attenuation was also reported in [11], but our fitted attenuation due to wall crossings is lower.

III. 60 GHz DIRECTIONAL CHANNEL MODELLING

In this section, the directive channel at 60.48 GHz is characterized. We performed channel sounding via a pair of customized TG nodes.

A. Methodology

The TG nodes have a grid of 36x8 vertically polarized transmit/receive antennas with independently controlled phase shifters and are used to measure directional PL. The spacing of the antenna elements is 0.55λ . The sounder is capable of electrically scanning in the azimuth plane in a range from -45° to 45° using 64 beams with a beam width (BW) of 2.8° , by adjusting the phase of the antenna elements. The beams are spaced 1.4° apart. The sounder returns PL as a difference between equivalent isotropically radiated power (EIRP) and received power (PRX) for every TX-RX beam configuration. Figure 5 shows the angular measured PL as a function of TX (x-axis) and RX (y-axis) beam configuration for two different distances. For the two distances, the lowest PL is obtained for both TX and RX beams equal to zero, i.e. the direct LOS beam. For a larger distance, more reflections are received, e.g. for an RX angle of -15° and a TX angle of -30° .

Similar to the sub-6 GHz measurements detailed in Section II-A we performed measurements at five different TX locations inside the hull of the ship, but these locations are different from the sub-6 GHz measurement locations. For every TX location, multiple measurements are performed by moving the RX node away from the TX node. The distance ranges from 1.5 m to 15 m with a spacing of 25 cm between

Figure 5. Angular measured PL as a function of TX-RX beam configuration

Table III
60 GHz CHANNEL SOUNDER PARAMETERS

Parameter	Value
TX signal	802.11ad chirp, single carrier waveform
Signal recording	Time domain sampling 802.11ad waveforms
Sampling rate	1.76 Gsps
CIR repetition rate	3.52 Gsps
TX power	5 dBm, EIRP 45 dBm
Dynamic range	50 dB
TX, RX antenna	36 x 8 antenna array, 2.8° degree beam width
TX/RX synchronization	UTP

the measurements, which is a separation of 50 wavelengths. This spacing was selected as a trade-off between spatial resolution and required measurement time. Measurements with an obstructed LOS path showed that there is no distance relationship, as the reflected path showed lower attenuation than the direct obstructed path and the main reflected path was highly dependent on the exact placement of both the TX and RX nodes. Therefore only non-obstructed LOS measurements are considered for the fitting to a PL model, and the model from (2) can be simplified to p, q, r equal to zero. We calculate PL as a function of antenna BW, using the EIRP and PRX for every LOS measurement. In [12] we selected the TX-RX beam with the minimum PL to fit a PL model using a BW of 2.8° . To calculate PL corresponding to a BW ranging from 5.6° to 70° we sum PRX from the neighbouring beams, taking into account the beam spacing of 1.4° and antenna BW of 2.8° , and subtract this from the EIRP. As the beams overlap we sum the PRX of k^2 beams to get PL for a BW of $2.8k^\circ$. We also analyze specular multipath components (SMC) by determining local peaks in the angular measured PL at a BW of 2.8° and calculating angular spread.

Figure 6. Reference PL at 1 m and PL exponent as a function of beam width

B. Beam width dependent Line-of-Sight path loss model

In [12] we fitted the measured LOS PL values to a one slope PL model using a BW of 2.8° . Figure 6 presents the fitted reference PL (left axis) and PL exponent (right axis) as a function of BW. We see that the reference PL decreases with increasing BW. The reference PL at 1 m drops below the corresponding free space PL of 68.1 dB for a BW higher than 14° . The PL exponent is stable at around 1.9, except for BW 2.8° where it is clearly lower. We conclude that for increasing BW up to 20° , the PL decreases as more reflected energy is received. For higher BW, the fitted parameters do not differ much as the reflected energy is blocked by machinery.

C. Specular multipath components

The LOS PL model presented in [12] was based on the measured PL of the direct LOS beam between TX and RX. As the directional 60 GHz channel sounder is able to steer both the TX and RX antennas in the azimuth plane, we can analyze angular spread. From the angular measured PL of all locations and distances, we extract the specular multipath components (SMCs) by selecting local maxima in the angular measured PL. Figure 7 shows the angle of arrival (AoA) and angle of departure (AoD) of all SMCs as a function of distance.

In Fig. 8 the root-mean-square angular spread (RMS-AS) is visualized for both the AoA and AoD profiles. Similar to the RMS-AS analysis at THz frequencies in [17], the RMS-AS increases with distance. However, fitting the RMS-AS values to a second-order polynomial is not successful, with a root-mean squared error (RMSE) of 13.4 dB between the fit and RMS-AS values. As we only considered specular reflection and no diffuse scattering, these angular spread values are much smaller than the previously reported angular spread values for an outdoor environment (AoA spread of 10.5° and AoD spread of 15.4° for 73 GHz, [13]) or an indoor office environment (azimuth spread of 28° at 60 GHz [14]).

IV. CONCLUSIONS AND FUTURE WORK

In this work the results of a channel sounding campaign inside the hull of a large vessel are presented. Compared to previous research, a combined log-distance PL model is developed with additional loss terms for equipment and wall obstructions, as well as floor crossings. The floor and wall

Figure 7. AoA and AoD of SMCs as a function of distance

Figure 8. Root-mean-square angular spread (RMS-AS) for both AoA and AoD, with a polynomial fit

attenuation does not depend on frequency, and the PL exponent is lower than previous reports. We also created a beam width dependent path loss model at 60 GHz, which shows that propagation loss in the engine room is lower than in free space. As we only considered specular reflection, the angular spread is much lower than previous mmWave measurement campaigns. The path loss models will be implemented in a network planning tool which will be used for determining access point placement and configuration in order to guarantee full coverage in the engine room.

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