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Abstract

Understanding and characterizing millimeter wave (mmWave) communication in real-world scenarios is crucial to design reliable communication systems for Internet of Things (IoT) applications, including autonomous vessel 19s remote operation. To this aim, this research provides an empirical evaluation of large-scale fading for vessel-to-shore communication at 28 GHz. Specifically, we experimentally assess the path loss (PL) performance of short-range Line-of-Sight (LoS) links with low antenna heights. The measurements show trends that match well with the two-ray model PL predictions, yielding a root mean square error (RMSE) of 2.56 dB in the 10-100 m range.

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***Abstract*—Understanding and characterizing millimeter wave (mmWave) communication in real-world scenarios is crucial to design reliable communication systems for Internet of Things (IoT) applications, including autonomous vessel's remote operation. To this aim, this research provides an empirical evaluation of large-scale fading for vessel-to-shore communication at 28 GHz. Specifically, we experimentally assess the path loss (PL) performance of short-range Line-of-Sight (LoS) links with low antenna heights. The measurements show trends that match well with the two-ray model PL predictions, yielding a root mean square error (RMSE) of 2.56 dB in the 10-100 m range.**

***Index Terms*—mmWave, large-scale fading, path-loss, overwater communication, two-ray model.**

I. Introduction

The increasing demand for Internet of Things (IoT) applications operating in overwater conditions (e.g., coastal areas and offshore installations) stresses the need for reliable wireless communication in water environments [1]. These scenarios introduce unique challenges to signal propagation, including specular reflections that can compromise link performance [2] [3]. Understanding and mitigating the potential impact of detrimental propagation phenomena is critical to successfully provide reliable communication systems design.

In particular, understanding the real-world performance of millimeter wave (mmWave) in overwater scenarios is crucial to enabling robust future wireless communication systems toward 6G. Specifically, mmWave operating at 28 GHz has shown promise to establish high bandwidth communication links over water [4] and beyond [5], e.g., to support emerging real-time vessel-to-shore video transmission within the Internet-of-Things (IoT) umbrella [1]. However, as stated before, signal propagation in overwater scenarios suffers from distinguishing propagation phenomena, from strong reflections on the water surface to slow and rapid variations in the water level, e.g., due to tides [2] and sea waves, respectively.

Previous studies have highlighted the relevance of the two-ray model for predicting signal propagation over water, particularly in controlled or simulated settings [6] [7]. For instance, in [7], the authors examined the impact of different receiver heights on path loss (PL) at 28 GHz through simulations. However, empirical validation of these findings remains limited, especially in real-world mmWave scenarios. This study addresses this gap by empirically assessing large-scale fading through the two-ray model for overwater communication at 28 GHz. Using data collected from a vessel-to-shore scenario with low antenna heights, we evaluate the accuracy of the two-ray model in predicting PL while also using the free-space path loss (FSPL) model as a benchmark. Our findings provide preliminary yet promising PL validation for the two-ray model, offering valuable insights for designing and optimizing coverage for mmWave communication in overwater conditions.

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II. Experimental Setup

Location and setup. We built up a testbed to perform point-to-point vessel-to-shore measurements over "Embalse de la Luz," an artificial freshwater lake located in Curauma, Valparaíso Region, in Chile. The setup preparation involved a verification phase for the transmitter-receiver equipment inside an anechoic chamber. Moreover, before the experimental campaign, we used a short-range line-of-sight (LoS) test link to verify the received power matches FSPL predictions within 1 dB.

Transmitter side. We used a signal generator and a horn-type antenna to transmit the signals from a floating boat. The horn transmitter (Tx) antenna used has a directional 40° beamwidth in elevation and a 45° beamwidth in azimuth and was mounted at the bow of the boat at a low height near the surface.

Receiver side. We used a custom-built omnidirectional antenna mounted on receiver (Rx) platform on shore. The platform used is capable of rotating 360° in azimuth at 100 RPM. Note that the Rx antenna was placed at $r = 0.09$ meters

TABLE I
Measurement Campaign Parameters

Parameter	Symbol	Value
Frequency	f	28 GHz
Tx, Rx heights	h_{tx}, h_{rx}	0.45 m, 1.22 m
Tx, Rx gains	G_t, G_r	10 dBi, 48 dBi
Tx power	P_t	-7.1 dBm
Tx cable losses	L	1.7 dB
Distance range	d	[10, 100] m

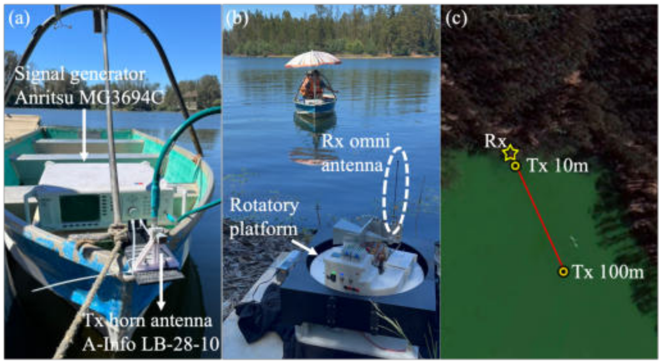

Fig. 1. Measurement scenario and equipment: (a) transmitter side, (b) receiver side, and (c) aerial view of the location and range of link distances.

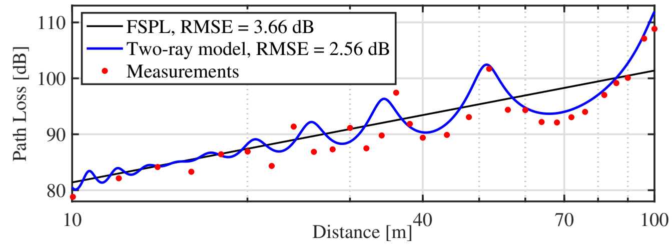

Fig. 2. Path loss of measurement campaign compared to two-ray model.

from the center of the rotating platform, which modifies the computation of the effective link distance. In addition, the platform has connected a low-noise amplifier, a mixer, and a power meter, with a 20 kHz receive bandwidth, which leads to a noise floor of -72 dBm. Power received measurements were recorded every half degree, yielding approximately 720 data points per rotation, with each measurement session lasting 16 seconds per point. Measurements were taken every 2 meters between 10 and 100 meters as shown in Fig 1. The rest of parameters are listed in Table I.

III. Channel Modeling

The averaged PL was calculated in decibels (dB) from the data collected using the classical link budget approach, which is expressed as $\overline{PL} = P_t + G_t + G_r - L - \overline{P_r}$, where $\overline{P_r}$ is the 360° averaged received power. In this way we ensure accurate path loss modeling, eliminating small-scale fading effects.

To analyze and model the data collected, the classical two-ray [8] propagation model expression was employed. Note this model assumes both Tx and Rx antennas as isotropic. At the same time, most signal energy is considered to arrive from two different yet dominant paths, directly from Tx to Rx, and indirectly, reflected from the water surface. For completeness, we formally present the two-ray model expression as follows:

$$P_r = P_t \left[\frac{\lambda}{4\pi}\right]^2 \left| \frac{\sqrt{G_l}}{l} + \frac{R\sqrt{G_r}e^{j\Delta\phi}}{x + x'} \right|^2, \tag{1}$$

where P_t is the transmission power, and G_l and G_r are the product of the Tx and Rx antenna radiation patterns in the LoS direction and in the direction of the reflected ray, respectively; l is the length of the direct ray, $x+x'$ the length of the reflected ray, and $\Delta\phi$ the phase difference between the two signals at the Rx side. R is the reflection coefficient for vertical polarization, considering the complex permittivity as in [7], assuming the permittivity and conductivity of freshwater as $\epsilon = 81$ and $\sigma = 0.01$ S/m, respectively [9]. Note P_r is 360°-averaged in the model at each d position, as described in [7].

Results. The measurements and theoretical PL model estimates are presented in Fig 2. It is observed that the two-ray model shows a clear visual match with the measurements along the whole distance path. The FSPL, despite not describing the typical peaks and fades predicted by the two-ray model, also shows a reasonably agreement regarding the average trend. Then, quantitatively comparing the results in terms of their root mean square error (RMSE), the two-ray model is still superior than FSPL, yielding 1.1 dB of lower RMSE when comparing the 2.56 dB of the two-ray model against the 3.66 dB of FSPL. These results represent a novel validation of the two-ray model for short-range vessel-to-shore path loss modeling at 28 GHz.

IV. Conclusion

This study analyzed the PL performance of short-range 28 GHz mmWave links in LoS conditions over a freshwater body. The results show that the empirical measurements are in good agreement with the classical two-ray propagation model, especially in terms of the model's ability to predict destructive and constructive interference while offering a reasonably low RMSE of 2.56 dB. In the future, we aim to comprehensively extend this study to links of longer distances and different heights, while considering additional details such as the impact of using directive antennas at the receiver.

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