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Abstract

Modeling Tidal Fading with the Two-Ray Model for Short-Range WiFi Overwater Communication

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***Abstract*—This research evaluates the two-ray propagation model as a tool for predicting tidal fading over short-range overwater WiFi links. We compare the accuracy of the i) full version of the two-ray model, which considers a material (e.g., relative permittivity) and polarization-dependent reflection coefficient, against the ii) simplified —yet widespread— two-ray model with a reflection coefficient magnitude of one. The evaluation is done resorting to a real-world dataset of a Shore-to-Shore (S2S) WiFi communication link operating in the 2.4 GHz band over an intertidal zone during an ebb period of about 2.5 h. The results show a clear agreement between received signal strength measurements and the full two-ray model, achieving a root mean square error below 1 dB. Overall, the work stresses the importance of using the complete two-ray model incorporating relative permittivity and antenna polarization in overwater communication modeling.**

***Index Terms*—RSSI, tidal fading, two-ray model, Wi-Fi.**

I. Introduction

Tidal fading is a common yet barely explored propagation phenomenon affecting Radio-Frequency (RF) based communication links deployed over tidal waters. Although having a long-standing history [1], most works reported kilometer-scale RF links, including long-range WiFi and LoRa overwater communications [2], [3]. This phenomenon is induced by the rise and fall of tidal water levels that alter the propagation environment, primarily due to *time-varying* interference between direct and reflected signal paths. While tidal fading has been studied for long-range links, its impact on short-range WiFi links —such as those used for Internet-of-Things (IoT) coastal and offshore applications— remains less investigated.

Short-range WiFi overwater communications enable several emerging IoT applications, including environmental monitoring and remotely controlled or autonomous vessel operations. Even though recent works have reported the influence of tides on WiFi Shore-to-Shore (S2S) [4] and Shore-to-Vessel (S2V) [5], [6] communication, its channel modeling remains to be done. This research evaluates the efficacy of the two-ray propagation model for predicting tidal fading in short-range S2S overwater WiFi links. Specifically, we compare two versions of the two-ray model: i) complete model [7] incorporating a reflection coefficient that depends on the relative permittivity of the reflective medium (e.g. water, mud or soil) and the antenna polarization (vertical or horizontal), and ii) simplified model [8] with a reflection coefficient magnitude of one. To assess the accuracy of both models, we analyze real-world data from a S2S WiFi link operating at 2.4 GHz over an intertidal zone.

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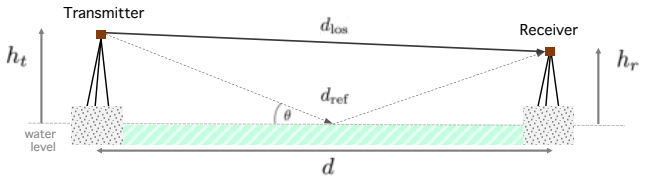

Fig. 1: The two-ray model showing the direct line-of-sight path (d_{los}) and the path reflected on the water surface (d_{ref}).

II. Two-Ray Propagation Model

Fig. 1 illustrates a S2S overwater link composed of two signal paths: i) *line-of-sight path* and ii) *reflected path* with a path length of d_{los} and d_{ref}, respectively. The angle of incidence of the reflected ray is θ. As in [3] the terms θ, d_{los} and d_{ref} are computed from simple geometry. The difference in path lengths introduces a phase shift, $\Delta_\phi = 2\pi(d_{\text{ref}} - d_{\text{los}})/\lambda$, where λ is the wavelength.

Full two-ray model [7]. Formally, the received power (P_r) is determined for vertical antenna polarization using:

$$P_r = P_t G_t G_r \left[\frac{\lambda}{4\pi}\right]^2 \left| \frac{1}{d_{los}} + \Gamma \, \frac{\mathrm{e}^{-j\Delta_\phi}}{d_{ref}} \right|^2 \qquad (1)$$

where P_t is the transmit power, and G_t and G_r are the transmitter (TX) and receiver (RX) antenna gains, respectively.

The Fresnel reflection coefficient Γ is given by $\Gamma = (\sin(\theta) - Z) \,/\, (\sin(\theta) + Z)$ where the impedance Z is defined as $Z = \sqrt{\varepsilon_r - \cos^2\theta}/\varepsilon_r$ for vertical polarization and ε_r is the relative permittivity of the reflective medium. As in [3] we

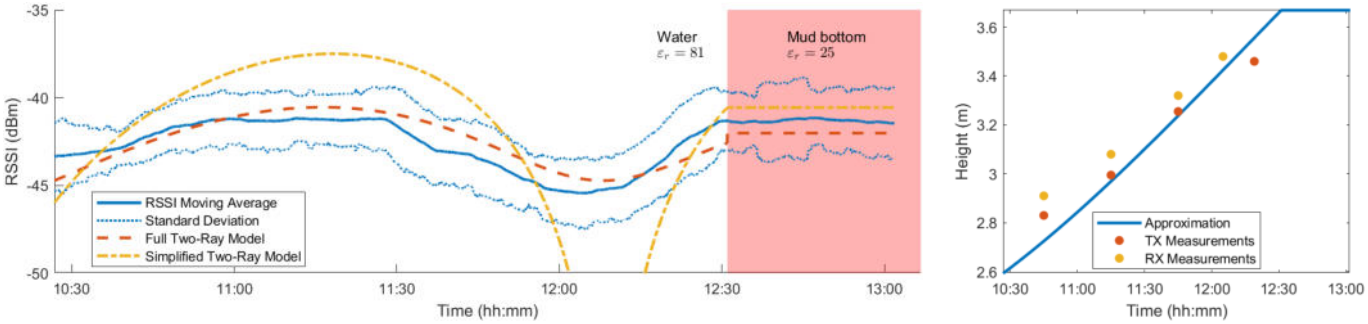

Fig. 2: (Left) RSSI moving average over bins of 4000 consecutive measurements and corresponding standard deviation over the retret of the waterline (ebb period). The results show the temporal impact of water level on RSSI compared to the full and simplified two-ray models. (Right) Empirical measurements for TX and RX antenna heights and the height approximation based on tidal modelling as in [3].

Environment	Full Two-Ray Model		Simplified Two-Ray Model	
	RMSE (dB)	MAE (dB)	RMSE (dB)	MAE (dB)
Over Water	0.84	0.73	5.71	3.63
Over Mud	0.68	0.68	0.79	0.78

TABLE I: RMSE and MAE for both the two-ray models.

account for the impact of the reflection point (RP) on the relative permittivity and terrain variability[1].

Simplified two-ray model [8]. The simplified version of the two-ray model assumes that the magnitude of the reflection coefficient Γ is equal to -1 under a set of conditions. Then, the received power (P_r) simplifies to:

$$P_r = P_t G_t G_r \left[\frac{\lambda}{4\pi}\right]^2 \left[2\sin\left(\frac{2\pi h_t\, h_r}{\lambda d}\right)\right]^2 \qquad (2)$$

where h_t, h_r are the Tx and Rx antenna heights, respectively, and d is the (horizontal) link distance.

III. Results

Setup. The S2S experimental campaign described in [5] used WiFi commercial devices with vertically positioned omnidirectional antennas (5 dBi gain) configured using i) channel 6 at 2437 MHz, ii) 20 MHz bandwidth, and iii) transmission power of 30 dBm. The radios transmitted standard-compliant beacons every 102.4 ms in IEEE 802.11b mode, with a data rate of 1 Mbps and a payload of 94 B. The links operated over an intertidal zone, where the reflective surface transitioned from water to mud (highlighted in red in Fig. 1 (Left)). Measurements were taken during the ebb period, lasting about 2.5 hours. The TX-RX separation was approximately 95.8 m. Further details on this campaign can be found in [5].

Results. Fig. 1 (Left) depicts the moving average of the RSSI measurements and the corresponding standard deviation. The dataset entries were averaged in bins of 10 consecutive RSSI measurements and compared to the full and simplified two-ray model estimates when using antenna heights in Fig. 1 (Right). Table I summarizes the Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) on over-water and over-mud environments. The results show that the full two-ray model accurately predicts the effects of constructive and destructive interference, achieving a RMSE and a MAE below 1 dB. In contrast, the simplified model shows RMSE and MAE larger than 5 dB and 3 dB, respectively. Similar results are obtained for both models when considering the over-mud environment.

[1]We assume $\varepsilon_r = 81$ when the RP is on water and $\varepsilon_r = 25$ when the RP is on mud (good ground [8]) while assuming the relative height to the surface is fixed when the RP touches the mud.

IV. Conclusion

This research offers a novel validation of the two-ray model as an accurate mathematical tool for predicting tidal fading in short-range S2S overwater WiFi links. We demonstrate the i) need for adopting the full two-ray model version instead of the widespread simplified one that exhibits almost 5 dB higher error values and the ii) role of permittivity and antenna polarization on the accuracy of overwater WiFi modeling, while emphasizing its relationship with the reflection point. This further validates the two-ray-based methodology in [3] specifically proposed for estuarine intertidal zones.

Prospectively, we will explore the impact of both vertical and horizontal antenna polarization to further study the full two-ray model version parameters.

References

[1] D. Taplin, "Tidal fading on short oversea paths elliptical, vertical and horizontal polarisation compared," *NASA STI/Recon Technical Report N*, vol. 76, p. 15328, 1975.

[2] A. Macmillan, M. K. Marina, and J. T. Triana, "Slow frequency hopping for mitigating tidal fading on rural long distance over-water wireless links," in *IEEE Conference on Computer Communications (INFOCOM) Workshops*. IEEE, 2010, pp. 1–5.

[3] M. G. Gaitán, P. M. d'Orey, J. Cecílio, M. Rodrigues, P. M. Santos, L. Pinto, A. Oliveira, A. Casimiro, and L. Almeida, "Modeling LoRa communications in estuaries for IoT environmental monitoring systems," *IEEE Sensors Journal*, vol. 22, no. 21, pp. 21 312–21 325, 2022.

[4] M. G. Gaitán, P. M. Santos, L. R. Pinto, and L. Almeida, "Experimental evaluation of the two-ray model for near-shore WiFi-based network systems design," in *IEEE Vehicular Technology Conference (VTC-Spring)*. IEEE, 2020, pp. 1–3.

[5] P. M. d'Orey, M. G. Gaitán, P. M. Santos, M. Ribeiro, J. B. de Sousa, and L. Almeida, "Assessing Short-range Shore-to-Shore (S2S) and Shore-to-Vessel (S2V) WiFi Communications," *Computer Networks*, vol. 249, p. 110505, 2024.

[6] M. G. Gaitán, P. M. d'Orey, P. M. Santos, M. Ribeiro, L. Pinto, L. Almeida, and J. B. De Sousa, "Wireless radio link design to improve near-shore communication with surface nodes on tidal waters," in *OCEANS 2021: San Diego–Porto*. IEEE, 2021, pp. 1–8.

[7] A. Goldsmith, *Wireless Communications*. USA: Camb. Univ. Press, 2005.

[8] T. Rappaport, *Wireless Communications: Principles and Practice*, 2nd ed. USA: Prentice Hall PTR, 2001.