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Over the Ocean RF Propagation Modeling and Characterization

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ABSTRACT
This paper presents results and analysis of a series of propagation measurements conducted in Florida's coastal waters. The measurements were conducted in the 2.4GHz ISM band with the transmitter placed on the shore and the receiver placed on a boat. The analysis show that the path loss may be modeled using the log-distance path loss model. The parameters of the models are determined from the measured data.
Keywords-RF path loss characterization, propagation in coastal waters, drive test studies, log-distance path loss model

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I. INTRODUCTION

At the beginning of the 21st century, wireless communication technologies are an important part of our everyday life. Today, one relies on wireless communication when using a cell phone, browsing the Internet through WiFi, or listening to the satellite radio. Most of the wireless communication technologies are terrestrial. That is, they exist over the landmass, where the appropriate access infrastructure may be deployed and easily connected to communication backbones. For example, cellular systems require the deployment of thousands of base stations. These base stations provide radio signal connectivity to cellphones on one side and backhaul connectivity to terrestrial voice and data communication networks on the other side.

Oceans cover Two-thirds of the world surface. Today, if one tries to connect and communicate from the ocean's surface, the only choice that he/she has is the satellite-based connectivity. Satellite communication systems are large and expensive, and usually with data rates that are significantly lower than what is found in terrestrial counterparts. However, as they represent the only option, satellite systems are used extensively by marine vessels worldwide. This is true on the open ocean, but also in the waters close to the coast.

This paper proposes wireless terrestrial access that extends its radio coverage some distance from the shore. By extending its coverage, such as system may provide connectivity to boats that are within coastal waters. It is proposed that the infrastructure be deployed using 2.4GHz ISM frequency band. There is plenty of communication equipment that already works within this band, and the hope is that some of them may be modified and adapted for coastal communication use. The design and deployment of a terrestrial alternative to satellite connectivity require a thorough understanding of the ocean's RF signal propagation in the areas next to the coast. This aspect is addressed in the paper.

The outline of the paper is as follows. Section II reviews relevant prior work in this area, Section III describes data collection, and Section IV provides some analysis of the data. A summary and conclusion are presented in Section V

II. LITERATURE REVIEW

In the past decade, the propagation of radio signals in coastal waters has received considerable attention. Much of the research is dedicated to the characterization of path loss at different frequencies. For example, in [1], one finds an analysis of fix 5.2 GHz microwave links within a harbor environment. The path loss in the ocean environment at frequencies around 1900 MHz is analyzed in [2-4]. In [5, 6], the authors analyze the applicability of the two-ray path loss model. They have discovered that a two-ray path loss model fails to represent the measured data in some instances accurately. As a result, they have introduced the three-ray model [7]. According to [8], both two-ray and three-ray model at frequencies 2.4GHz and 5.8GHz fail to account for ducting and extremely rough conditions of the sea. That led to the introduction of various correction factors.

This paper provides additional measurements of the radio signal propagation in 2.4 GHz band. The measurements are performed within coastal waters of Florida, USA. The goal is to understand impact of common sea conditions on the propagation path loss.

III. DATA COLLECTION

A measurement campaign is set up to evaluate path loss over the frequency range of interest (2.4 GHz ISM band) and the geographical area of interest (coastal waters). The propagation study area is the area of the half-circle that is centered at the location of the transmitter and extends over the ocean to the radius of the radio horizon. The site of the measurements is presented in Fig. 1. The red marker is the location of the transmitter. The black dashed line is the radio horizon. The distance to the radio horizon is a function of the transmitter height above the sea level. The approximate relationship for the radio horizon distance is given by [11,14,15]

$$R = 3.57\sqrt{h_{TX}} \qquad (1)$$

Where
R - distance to the radio horizon given in km
h_{TX} - height of the transmitter given in m

Since the study is aimed at evaluating the propagation over water, the study area is located to the east of the transmitter – i.e. it consists of the part of the radio-horizon circle that is over the ocean.

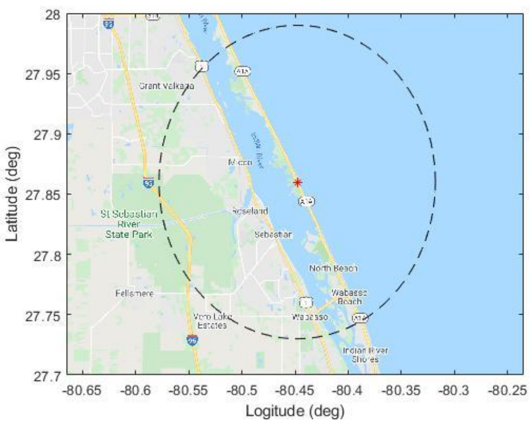

FIGURE 1. Study area for propagation evaluation

The transmission frequency is set to 2.401GHz. This frequency is in the portion of the ISM band that is clear from the WiFi use. The signal is a narrowband sinusoidal Continuous Wave (CW). Total EiRP is 36 dBm, as permitted by the rules of the 2.4 GHz ISM band. The transmitter is placed at approximately 10 m (33 ft) above the sea level. The transmit antenna is omnidirectional, with the gain of 11 dBi. According to (1), the radio horizon is about 13 km (8 miles). The receiver is placed in a 7 m (23ft) boat. According to the manufacturer specifications, the receiver's antenna has a 2 dBi gain, and it is placed at the height of 2 m (7 ft) above thesea surface. Measurements of the Received Signal Level (RSL) are recorded while the boat travels *east* (i.e. away) from the transmitter. Once the boat reaches the radio horizon, it is turned back, and the measurements are collected while the boat is traveling *West* (i.e. towards the transmitter). The same experiment is repeated several times in different ocean conditions.

Measurements are collected following Lee criterion [12]. The RSL is space averaged over the distances of 40λ, which at 2.4 GHz amounts to 5 m. It is ensured that the receiver collects as least 50 samples over the averaging distance. The data collection is performed in the area extending from a few hundred meters away from the transmitter to the radio horizon limits. Date, time, GPS location, and received signal level are recorded. The recording is done in an automated manner and the measurements are stored as a set of text files.

The transmitter equipment used in the experiment is shown in Fig. 2. It is a commercial transmitter manufactured by BVS – Lizard [12]. The transmitter is ruggedized and capable transmitting the signal with output power 0-30 dBm with resolution of 0.1 dB and accuracy of 0.5 dB. Given the maximum allowed transmit EiRP of 36dBm, cable and connector losses of 3dB and antenna gain of 11 dBi, the transmitter's conductive power was set to 28dBm.

FIGURE 2. *Transmitter equipment used for the study*

The receiver equipment was mounted on the boat as shown in Fig. 3. The receiver is a commercial receiver manufactured by BVS –

Gazelle [11]. The receiver has a noise figure of 7dB, and IF bandwidth of 12 kHz. The measurements' accuracy is better than 1 dB for Received Signal Level (RSL) in the range -105 dBm to -30 dBm and better than 1.5 dB in the range -120dBm to -106 dBm.

The receiver antenna is placed on a ladder at a height of 2 m above the water surface (c.f. Fig. 3). This way, the effects of the surroundings (i.e. boat and boat equipment) are minimized.

IV. RESULTS

4.1. Ocean Conditions

Three tests are performed. The ocean condition for the tests is summarized in Table 1. The conditions are characterized by five fundamental parameters: wind direction, wind speed, the height of the waves and dominant period between the waves, and Douglas scale values [13].

Figure 1. *Receiver side setup*

TABLE 1

Ocean conditions For Three Tests

Test	Wind direction	Wind speed (knot)	Wave height (m)	Dominant period (s)	Douglas scale values
1	East	5-10	0.3-0.6	6	2, 2
2	West	5-10	0.6-0.9	10	3, 3
3	West	5-10	0.3-0.6	9	2, 1

1 knot = 1.15 mph = 1.85 kmph

The Douglas scale values are used to represent the state of the sea. The scale has two main components. The first component describes the sea surface (c.f. Table 2). The second component describes the sea swell in meters (c.f. Table 3).

TABLE 2

Douglas Scale -State Of The Sea (Wind)

Douglas - sea state (wind)	Condition	Average wave height (m)
0	Calm (glassy)	0
1	Rippled	0.00-0.10
2	Smooth	0.10-0.50
3	Slight	0.50-1.25
4	Moderate	1.25-2.50
5	Rough	2.50-4.00
6	Very rough	4.00-6.00
7	High	6.00-9.00
8	Very high	9.00-14.00
9	Phenomenal	> 14.00

TABLE 3

Douglas Scale State Of The Swell

Douglas - swell	Condition	Wavelength (m)	Wave height (m)
0	No swell	-	-
1	Very low	Short	Low
2	Low	Long	Low
3	Light	Short	Moderate
4	Moderate	Average	Moderate
5	Moderate rough	Long	High
6	Rough	Short	High
7	High	Average	High
8	Very high	Long	High
9	Confused	Undefinable	Undefinable

The wavelength and wave height classification in Table 3 are provided in Table 4.

TABLE 4

Wavelength and Wave Height Classification

Wavelength (m)		Wave height (m)	
Short	< 100	Low	< 2
Average	100-200	Moderate	2-4
Long	> 200	Heigh	> 4

The sea conditions during tests (c.f. Table 1) correspond to shaded rows of Douglas scale tables 2 and 3. One notices that all the tests in this study were performed during relatively calm seas.

4.2 Measurements

The trajectory followed during the three tests is shown in Fig. 4. The boat traveled north-east in the straight line from the transmitter. Once the boat reached the vicinity of the radio horizon, it turned around and traveled back towards the transmitter. Therefore, each test consisted of two paths. The first path is labeled as *east* as the boat traveled mostly in the eastern direction, and the second path is labeled *West* as the boat traveled West. In data processing, two paths are analyzed independently to determine if the boat orientation impacts any of the modeling parameters.

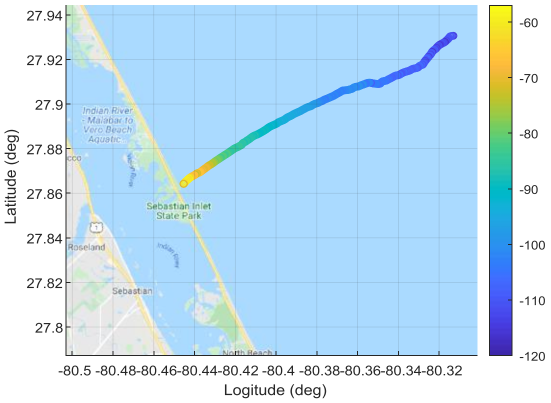

FIGURE 4.Trajectory of the boat during tests

The Color of the measurement points in Fig. 4 indicates the recorded Received Signal Level (RSL) in dBm. As expected, the RSL becomes lower as the distance between the transmitter and the boat increases. The dependence between distance and RSL for the measurements recorded for the eastern path of Test 1 is shown in Fig. 5. The measurements in Fig. 5 are "curve fitted" by a 2-ray path loss model [9] (green line) and long-distance path loss model [9] (red line). The 2-ray model seems to overpredict the path loss, so the log-distance path loss model is selected for further propagation modeling.

The accuracy of the log-distance path loss model is accessed through the difference between measurements and predictions. This difference is usually regarded as a random variable with a Probability Density Function (PDF) that may be approximated as normal in log (i.e. dB) domain. The histogram of the difference between measurements and predictions obtained in Test 1 – East (c.f. Table 1) is shown in Fig. 6. As seen, the error distribution shows a log-normal character with a mean of zero and a standard deviation of 2.27 dB.

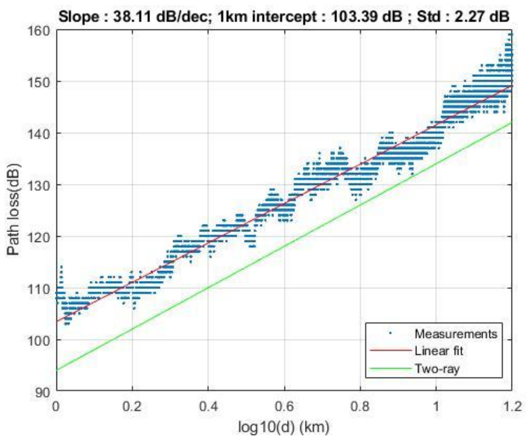

FIGURE 5 Pathloss as a function of distance in km

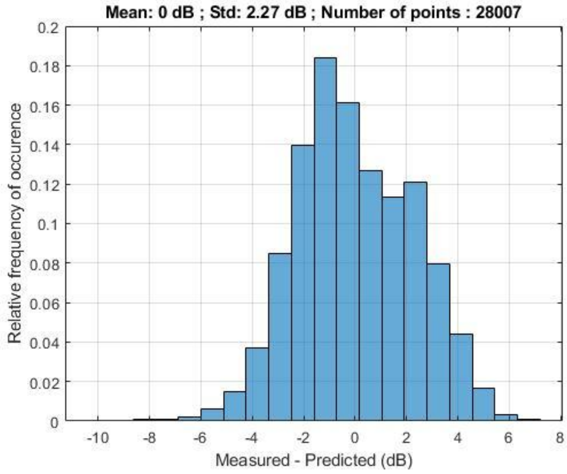

FIGURE 6. Normalized histogram between measurements and predictions

*4.3*MODELING

The path loss equation for the log-distance path loss model is given as:

$$PL = PL_{do} + m\log\left(\frac{d}{d0}\right) + \chi_\sigma \qquad (2)$$

where $PL$is the median path loss, PL_{do} is the median path loss to the reference distance, $m$is the slope, d is the distance between the transmitter and the receiver andd_0 is the reference distance. The reference distance in this study is taken as 1 km. The last term in (2), χ_σ, is a random variable that models variations between the model predictions and the actual measurements of path loss. In practice, PL_{do} and m are obtained from measured data. They represent the parameters of the log-distance model. The values for 1 km intercept and slope obtained from all the tests are summarized in Table 5.

TABLE 5

Log-Distance Model Parameters for Three Tests

Test	**Slope (dBm/dec)**	**1 km intercept (dB)**	**Std. (dB)**	**# points**
1-East	38.1	103.4	2.27	28,007
1-West	35.4	103.2	2.02	17,114
2-East	42.4	102.2	1.95	12,660
2-West	43.3	100.4	1.52	11,081
3-East	42.5	99.5	2.07	19,268
3-West	40.9	100.8	1.36	19,522
Weighted average	**40.0**	**101.7**	**1.90**	

From Table 5, the following observations may be made:

- The values obtained for the model parameters in all tests are very similar. The slope values range from 35 to 43 dB/dec. The 1km intercept values are between 99 and 103dB. One may notice some impact of the sea roughness on the slope. The slope appears to increase as the sea becomes rougher slightly. However, the effect is not well pronounced and if one is to draw more definite conclusions, further studies are needed.

- The standard deviation of the difference between measurements and predictions is relatively small. It ranges between 1.36 and 2.27 dB for all the sea conditions in this study. This is significantly smaller than what is found in terrestrial environments where the log-distance model typically has standard deviations of prediction error over 6 dB.
- Data in Table 5 are used to estimate average slope, intercept, and standard deviation across all measurements. In the estimate, model parameters from individual tests are weighted with the number of measurement points. The results of the averaging are reported in the last row of Table 5. These values could be used for nominal coverage planning when Douglas scale numbers are between 0 and 3.

The log-distance models obtained for individual tests and the model obtained through averaging are compared in Fig. 7. One sees that the average model is never more than 3-4 dB away from each individual model.

V. SUMMARY AND CONCLUSIONS

This paper documented the results of a radio propagation study. The study examined propagation path loss at 2.4 GHz and within Florida's coastal environment. The measurements were taken in relatively calm seas, where Douglas scales for both wind and swell are below 3. It is shown that the log-distance model may be used for path loss prediction. The slope's nominal value is 40 dB/dec and the nominal value of the 1 km intercept is 101.7 dB. Prediction error has a log-normal character with a zero mean and a standard deviation of about 2dB.

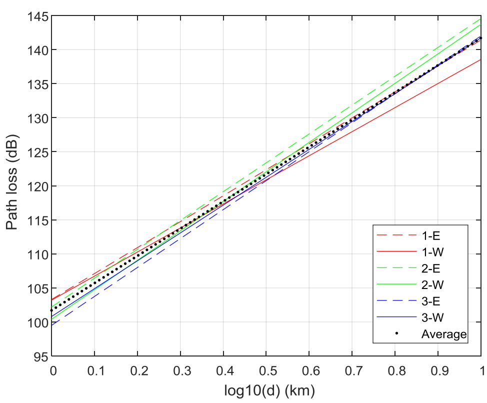

FIGURE 7. Comparison between log-distance models obtained in various tests

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