Buoy-to-ship experimental measurements over sea at 5.8 GHz near urban environments

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***Abstract*—Current marine wireless communication systems used for monitoring applications based on buoys suffer from lots of weakness. Many research works concern the design and development of new technological applications to improve marine communications. Particularly, a wireless communication system based on WiMAX standard at the 5.8 GHz band (license-exempt band) could be a good candidate. As an initial task, a propagation channel measurement campaign in maritime environments was carried out to investigate the impact of the wireless channel in different situations. This work provides large scale path loss measurements over sea around urban environments. In particular, a radio link between a buoy and a ship at 5.8 GHz is studied. NLOS (Non-Line-Of-Sight) paths are investigated in depth and they are compared to LOS (Line-Of-Sight) paths. The designed measurement system is described and the experimental measurements are shown. An empirical model is obtained using these experimental data and the key wireless channel parameters are analyzed. In addition, the empirical model is compared to the free space and two-ray theoretical models. This investigation is useful, among others, for planning Worldwide Interoperability for Microwave Access (WiMAX) networks offshore around these challenge environments.**

Propagation channel measurements; Sea; WiMAX; urban environments;

I. INTRODUCTION

Recently, many studies have identified an emerging demand for telecommunication services in several applications over sea. Some of them are getting great interest for the scientific community, e.g., those related to real-time monitoring through sensing multiple physical parameters from the sea. Although the number and kind of parameters depend on the specific application, monitoring systems are quite similar. Basically, these systems are based on a set of buoys and each one is equipped with two main subsystems. Firstly, a subsystem including a lot of sensor devices that measure locally the data. Secondly, a radio system which is in charge of transmitting them to a central base station for processing and monitoring purposes. The base station could be installed on shore or aboard a ship. This last case is particularly interesting for some applications, e.g., those related to oceanography campaigns.

Current wireless technologies used in this kind of applications are mainly based on VHF, cellular mobile telecommunication systems (GSM, UMTS, etc.) and satellite communications systems (INMARSAT, VSAT, etc.). However, these systems suffer from lots of weakness [1], like low bandwidth or capacity (GSM, Satellite and VHF systems), short range (cellular mobile telecommunication systems), high cost for certain applications (satellite and cellular mobile telecommunication systems) and the large size and weight of antennas and hardware transceivers (VHF systems). These limitations have motivated a new research activity in this field. The general goal is to design and develop a novel broadband wireless communication system to perform applications like the one mentioned above.

A wireless system based on WiMAX standard ([2], [3]) could be a good candidate to accomplish this task. WiMAX is an evolving technology that is optimized for operating on land environments where its good performance has been extensively demonstrated. Several frequency bands can be used for deploying this system. The license-exempt 5 GHz band is of interest to WiMAX because this is generally available worldwide and it is free for anyone to use, i.e., it could enable deployments in underserved markets, like the maritime one. In particular it is the upper 5.725 GHz-5.850 GHz band that is most attractive due to the fact that many countries allow higher power output compared to other bands. This facilitates less costly deployments. Regarding range and peak data rates, field tests on land have shown tens of kilometers and Mbps, respectively. All these potential characteristics overcome the weakness described above. However, the performance of WiMAX networks in marine environments is not optimum due to the different radio propagation conditions. Hence, the main goal is to optimize the WiMAX standard for maritime applications.

An initial and crucial task for the optimization of this standard over sea is to study the radio propagation channel in these scenarios in the 5 GHz band. Particularly, in this work, buoy-to-ship propagation measurements were performed over sea near urban environments.

Propagation models and measurements for land, both large-scale path loss and small scale multipath, have been discussed extensively [4]. Further works in this field have been done in urban and suburban environments [5], [6]. Besides, although [7], [8] and [9] present experimental measurements of propagation characteristics for maritime radio links, they do not

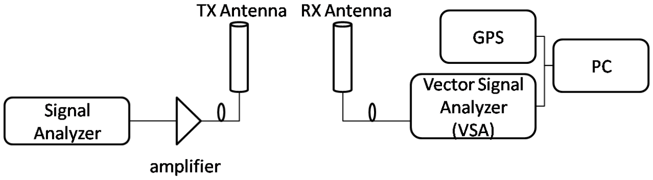

Figure 1. Block diagram of the measurement system.

apply to conditions covered by our study. To the best of the authors' knowledge, buoy-to-ship path loss characteristics over sea at 5.8 GHz near urban environments have not been investigated. In this work, we focus on large scale characteristics in NLOS (Non-Line-Of-Sight) and LOS (Line-Of-Sight) paths. We discuss them analyzing path loss measurements performed in a real marine scenario. Based on the measured data, a simple path loss model is developed. Two important parameters, the path loss exponent and the standard deviation of the shadowing random process, are characterized. This work is helpful, among others, to deploy WiMAX systems in these challenges scenarios.

II. Measurement System

Measurements were carried out by transmitting a 30 dBm Continuous Wave (CW) from an antenna installed on a buoy and receiving this signal in a receiver installed aboard a ship. This measurement system is fully described in Fig. 1. A 0 dBm CW signal at 5.8 GHz was transmitted from a signal generator. This output CW signal was further amplified 33 dB by a broadband amplifier up to 1 W (transmitter cable loss was 3 dB). This signal was the input of the antenna installed on the buoy. The used antenna had the following main characteristics: 9dBi gain, vertical polarization, omnidirectional radiation pattern in the horizontal plane and 7º beam-width in the vertical plane. This transmitter antenna was mounted 1.7 m from the sea surface. The receiver antenna was the same as the transmitter one and it was mounted 9.8 m from the sea surface. The received signal by the antenna was the input to a vector signal analyzer which was in charge of measuring it. A computer was connected to the analyzer in order to record the received signal to further processing. In addition, a GPS (Global Position System) device was also connected to the computer to time-stamp the received signal. Moreover, the GPS signal acquired by the computer was useful to calculate the separation distance between the ship and the buoy.

The instantaneous received signal from a CW transmission is measured. Therefore, shadowing and multipath effects are present in the measurements. We need to separate both variations in order to perform an independent study. The separation is performed by means of a temporal window that is slid through the data and calculates the local mean power. Due to buoy natural movements on the sea and the radio wavelength, the mean operation was made over a distance of several wavelengths.

III. Experimental Environment and Measurements Routes

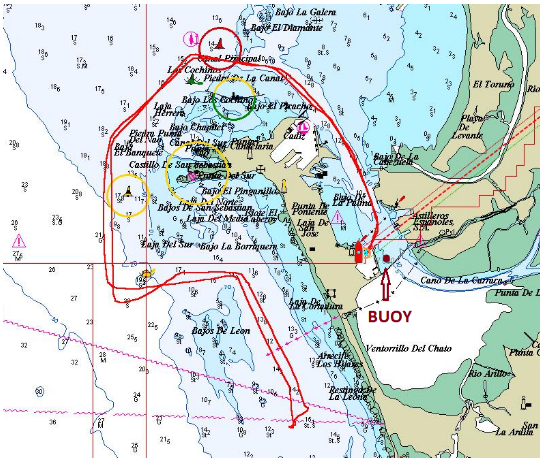

Figure 2. Route followed by the ship (red) and fixed location of the buoy in a nautical chart.

Cadiz bay (Spain) was selected to represent a maritime challenge scenario where it is possible to take into account lots of environments characteristics. This zone has a heterogeneous topography with dense populated urban areas including large infrastructures and buildings. Moreover, some nautical clubs and an important commercial port are along the shore. Therefore, large and small ships are anchored around and the fairways are very dynamics.

The measurements were carried out during a shiny day. The temperature ranged between 9 and 10 ºC. The humidity was around 95 %. The sea condition was calm and there was no large wave. The atmospheric pressure was 759 mm. The wind strength reached 5 and 6 force level.

In order to investigate the impact of these kinds of environments on the transmitted signal, a measurement campaign was planned over certain paths along the route showed in Fig. 2. Particularly, this work shows results from measurements carried out over the route showed in Fig. 3,

Figure 3. Fixed location of the transmitter buoy (red) and route followed by the receiver ship (blue) in the measurement campaign. Measurements carried out over green and yellow waypoints are considered LOS and NLOS, respectively.

which represents several intermediate waypoints along the route. In this figure, measurements carried over green and yellow waypoints are considered as LOS and NLOS measurements, respectively.

IV. RESULTS

A. Theoretical Results from Reference Models

A simple model being able to apply to propagation in maritime environment, under some assumptions, is the two-ray model. It takes into account two rays between transmitter and the receiver: a direct ray and a reflected one by the sea surface. Other model often used as complementary reference is the free space model. It assumes that both antennas are in the vacuum. These both models are considered in this work as theoretical references [10].

For the free space model, it is possible to calculate the path loss at a given point, according to (1): the distance range, i.e., the distance between the transmitter and the receiver (*d*), and the radio wavelength (λ). Therefore, in (1), l_{fs} is the predicted propagation path loss in free space when isotropic antennas are assumed. It should be noted especially the square law dependence on the distance (20 dB per decade on a logarithmic scale).

$$l_{fs} = \left(\frac{4\pi d}{\lambda}\right)^2 \tag{1}$$

For the two-ray model, it is possible to calculate the path loss at a given point, according to (2): the magnitude and phase of the reflection coefficient on the sea ($|R|$ and β, which also depend on the wave polarization, the incidence angle of the reflected ray on the sea, and the conductivity and permittivity of the sea), the phase difference (Δ) due to the different path lengths between the direct ray and the reflected one (it also depends on the relative heights of the transmitter and the receiver from the sea), and *d* and λ that were defined in (1). Therefore, l_{2r} is the propagation path loss that predicts the two-ray model which is frequently used to calculate the propagation path loss over sea surface when isotropic antennas are assumed.

$$l_{2r} = \frac{\left(\frac{4\pi d}{\lambda}\right)^2}{1+|R|^2+2|R|\,cos\ (\Delta+\beta)} \tag{2}$$

Equation (2) comes from the fact that it is possible to estimate the total received electric field (E_r) from (3), where E_{direct} is the received field from the direct ray and $E_{reflected}$ is the received field from the reflected ray. Both of them are complex magnitudes. Besides, *R* and Δ have the same meaning as in (2).

$$E_r = E_{direct} + E_{reflected} = E_{direct}(1+\mathrm{R}\,e^{j\Delta}) \tag{3}$$

Then, since the power is proportional to the amplitude of the electric field squared and the direct path is itself subject to free space loss, l_{2r} can be obtained from (4) using (3), where p_t and p_r are the transmitted power and the total received power, respectively, and the rest of parameters were defined above.

$$l_{2r} = \frac{p_t}{p_r} = \frac{|E_{direct}|^2\left(\frac{4\pi d}{\lambda}\right)^2}{|E_r|^2} = \frac{\left(\frac{4\pi d}{\lambda}\right)^2}{\left|1+\mathrm{R}\,e^{j\Delta}\right|^2} \tag{4}$$

If we assume in (2) that the antenna heights are small compared with the total path length (*d*), then Δ can be approximated as:

$$\Delta \approx \frac{2\pi}{\lambda}\left(\frac{2h_t h_r}{d}\right) \tag{5}$$

Besides, if the angle of incidence with the sea is close to grazing, the magnitude and the phase of the reflection coefficient will be close to one and 180°, respectively. With these two assumptions, the propagation path loss for large distances predicted by the two-ray model is simplified as indicated in (6), where h_t and h_r are the transmitter height and the receiver height, respectively. It should be noted that the distance dependence is d^4 (40 dB per decade on a logarithmic scale), implying that energy loss is more severe with distance in this more real scenario.

$$l_{2r} \approx \frac{d^4}{h_t^2 h_r^2} \tag{6}$$

B. Experimental Results

In order to accurately describe real propagation scenarios, empirical models are often developed using experimental data. One of the simplest and most common is the following empirical path loss formula [4]:

$$pl = \frac{p_t}{p_r} = k\left(\frac{d}{d_0}\right)^{\alpha}\chi \quad for\ d > d_0, \tag{7}$$

which groups all various effects into two parameters: the path loss exponent α and the zero-mean Gaussian random variation χ that represents the shadow fading effect. In this model, *k* is the path loss at a reference distance d_0 and it should be determined from measurements; however, it is well approximated, within several dB, as the free space path loss at d_0, where d_0 is often chosen around 100 m or 1000 m in outdoors environments. Since it is more common to work in decibel units, (8) will be used:

$$PL = K + 10\alpha\log_{10}\left(\frac{d}{d_0}\right) + \mathrm{X} \quad for\ d > d_0, \tag{8}$$

where *K* and *X* are *k* and χ, in decibel units, respectively.

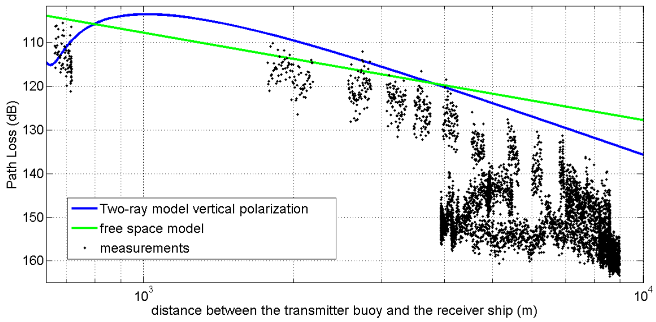

Figure 4. All path loss measurements carried out in the maritime environmet. The two-ray model for vertical polarization transmission and the free space model are represented as theoretical references.

The shadowing value X is typically modeled as a normal random variable, i.e.:

$$X \sim N(0,\sigma^2)\ , \tag{9}$$

where $N(0,\sigma^2)$ is a Gaussian (normal) distribution with mean 0 and standard deviation σ, in decibel units.

Path loss models, as the represented by (8), attempt to account for the distance-dependent relationship between transmitted and receiver power as well as for large-scale variations in signal strength due to macroscopic objects within the propagation environment that creates shadow zones. For instance, in sea environments, large ships, buoys, coast relief, buildings near harbor, islands situated between transmitter and receiver, etc., can create high variations in the received signal and this phenomena is not distance-dependent. Hence, the received power and the propagation path loss are modeled as a random process.

In Fig. 4 all the path loss measurements carried out as explained in Section II over the route plotted in Fig. 3 are shown. The measured path loss was estimated from the received power as indicated in (10). In Fig. 4 the results expected from the two theoretical models described above as references are also shown, where the 20 dB per decade and 40 dB per decade trends can be observed as discussed. The differences between the measurements results and the results expected by the theoretical models are clear. The level differences are partly due to antenna movement effects and characteristics; this should be taken into account to compare with theoretical models which assume isotropic antennas. Moreover, it should be noted that there are some locations where more measurements are available (see Fig. 3).

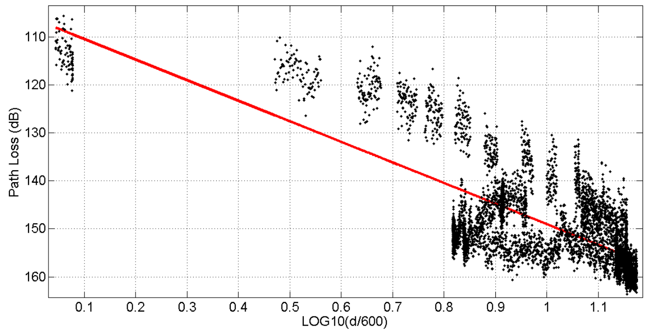

Figure 5. All path loss measurements carried out in the maritime environmet and linear regression analysis.

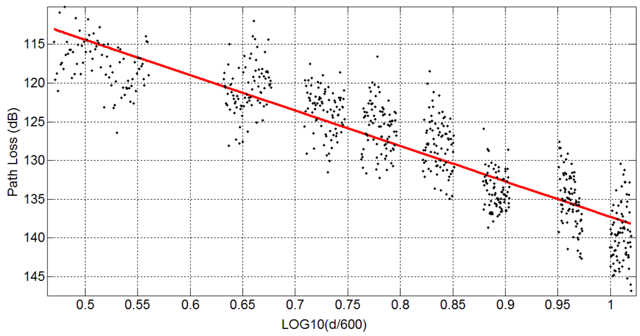

Figure 6. LOS path loss measurements carried out in the maritime environmet and linear regression analysis.

$$l_{measured} = \frac{p_t g_{tx} g_{rx}}{p_r l_c} \tag{10}$$

Based on (8), linear regression analysis with minimum mean square error (MMSE) can be applied to find the path loss exponent α and the standard deviation σ. These both parameters characterize the large-scale effects in our experimental scenario. In data processing, d_0 was chosen to be 600 m. The scatter plot is shown in Fig. 5.

In order to characterize these key wireless channel parameters in LOS and NLOS conditions, the same analysis were performed separately as illustrated in Fig. 3. Note that NLOS condition criterion is chosen here whether buildings and large infrastructures are situated between transmitter and receiver. Strictly speaking, it is difficult to maintain the LOS condition in real marine scenarios due to temporal LOS blocking by ships and sea waves. Besides, the curvature of the earth blocks the signal gradually with the distance. In Fig. 6 and Fig. 7 the scatter plots are shown. In Table I, all results are summarized, where the path loss exponent and the standard deviation can be compared for LOS and NLOS conditions. Although a path loss exponent between 2 and 4 is expected by the two-ray model for the locations that LOS measurements were performed, a measured path loss exponent of 4.5768 was found for these measurements, indicating higher rate signal attenuation in a real scenario. On other hand, for NLOS measurements a path loss exponent close to that of the predicted by the free space model was found; however, the received signal suffers high additional losses in respect of which predicted by the theoretical models.

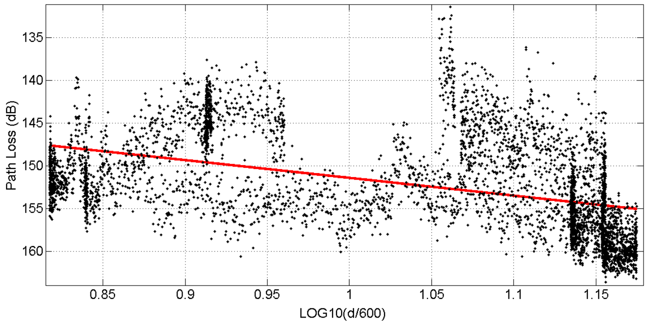

Figure 7. NLOS path loss measurements carried out in the maritime environmet and linear regression analysis.

TABLE I. RESULTS OF THE MMSE LINEAR REGRESSION FOR PATH LOSS MEASUREMENTS IN CADIZ BAY IN DIFERENTS CONDITIONS

Condition	**Key Wireless Channel Parameters**		
	α	***σ(dB)***	***K(dB)***
LOS	4.5768	3.4890	91.5129
NLOS	2.0790	5.1224	130.6247
LOS and NLOS	4.2923	7.1520	106.1019

V. CONCLUSIONS

This work presented experimental researches on new wireless technologies applied to marine environments for emerging applications. The characterization of the wireless propagation channel is necessary to understand accurately de behavior of radio waves in these kinds of scenarios.

It should be noticed that two-ray model fits measured large scale path loss reasonably well when LOS condition remains [11]. At short distances the radio signal attenuates at a rate close to that of the predicted by two-ray model. However, when the distance is very large, the received signal is found to attenuate at a higher rate. This limits the coverage zone of WiMAX. Other important aspect to be considered before deploying these systems over sea is the presence of nulls as predicted by two-ray model at short distances.

Regarding the impact of buildings and large infrastructures that block the LOS signal (see Fig. 4), it is found that although the signal attenuates at a rate close to that of the predicted by the free space model, the received signal suffers high additional losses. Furthermore, higher values of the standard deviation were found in NLOS conditions. This is likely due to severe absorption, diffraction and scattering mechanisms. Therefore, careful networking planning is needed in order to ensure broadband connectivity everywhere over sea.

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REFERENCES

[1] F. Bekkadal, and Kun Yang, “Novel Maritime Communications Technologies,” Microwave Symposium, MMS 2010, 25-27 Aug. 2010, (pp. 338-341).

[2] IEEE standard 802.16d-2004.

[3] IEEE standard 802.16e-2005.

[4] T.S. Rappaport, Wireless Communications Principles and Practice, Second Edition. Pretince Hall PTR, Upper Saddle River (2002).

[5] V. Ercerg, et al., “Channel Models for Fixed Wireless Applicatios”, IEEE 802.16a-03/01R.

[6] V. Erceg, et al., “An Empirically Based Path Loss Model for Wireless Channels in Suburban Environments”. IEEE Journal on Selected Areas in Communications, vol 17, No 7, July 1999, (pp. 1205-1211).

[7] J. Joe, S.K. Harza, S.H. Toh, M.W. Tan, J. Shankar, V.D. Hoang, M. Fujise. “Path Loss Measurements in Sea port for WiMAX”, Wireless Communications and Networking Conference, IEEE WCNC, 11-15 March 2007, (pp. 1871-1876).

[8] Rosario G. Garroppo, Stefano Giordano, Davide lacono, Alessandro Cignoni, Matteo Falzarano. “WiMAX Testbed For Intenrconnection Of Mobile Navy Units In Operational Scenarios”, Military Communications Conference, IEEE MILCOM, 16-19 Nov. 2008, (pp. 1-7).

[9] Le Roux Y.M., Menard J., Toquin C., Jolivet J.P., Nicolas F., “Experimental measurements of propagation characteristics for maritime radio links”, 9th International Conference on Intelligent Transport Systems Telecommunications (ITST), 20-22 Oct. 2009, (pp. 364-369).

[10] J.M. Hernando Rábanos, Transmisión por radio, Sexta edición. Editorial Universitaria Ramón Areces, Madrid (2008).

[11] J.C. Reyes-Guerrero, Luis A. Mariscal, M. Bruno and A. Medouri. “WiMAX Technology application in maritime environments” EuroMediterranean Scientific Congress on Engineering, EMSCE2011, 19-20 May. 2011, (pp. 956-962).