On the Path Loss Model for 5-GHz Microwave-Based Pinless Subsea Connectors

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Abstract—In this work, a simple propagation channel model for microwave-based pinless subsea connectors in the 5 GHz band is presented. Both high electromagnetic attenuation in seawater due to absorption and the near-field working conditions typically present for underwater connectors are taken into consideration. Therefore, a simplified path loss model based on linear regression is identified. The study shows that high-speed pinless subsea connectors are a reality over several cm of seawater gap when appropriate microwave receiver technology is selected with sensitivities of about -100 dBm. Experimental results show that both half-duplex gigabits-per-second and full-duplex 100-Mbps technologies have a strong potential to be developed in the 5 GHz band.

1. INTRODUCTION

Nowadays more and more technologies are being deployed in subsea environments for a variety of applications. Within the communication technologies, underwater pinless connectors have recently received great attention to overcome shortcomings of pin-to-pin connectors, being rapidly developed based on acoustics [1, 2], optical [3, 4] and electromagnetic (EM) signalling [5–7]. However, the subsea industry is calling for higher data rates over 100 Mbps for seawater gaps of several cm. In addition, reducing antennas misalignment issues, especially when large angles exist between the main faces of underwater connectors, is of paramount importance. Therefore, EM signalling is suggested as the best candidate.

In fact, systems based on EM signalling are not susceptible to turbidity, particles, pressure gradients, acoustic noise, and small changes on antennas' alignments [8]. There are several developments of underwater EM systems in the MHz range and below [8–11]. At higher frequencies, in the GHz band, communication distances are not expected to be large because of the high signal attenuation in seawater. Nevertheless, this attenuation feature could be beneficial for short-range subsea applications, because it ensures non-interference with other EM signals. Recently, some developments have shown that the 2.4 GHz band is of tremendous interest for several configurations [12–14]. Previous studies have demonstrated the potential of this band in terms of signal propagation under several conditions [15, 16].

Furthermore, the 5 GHz band is attractive since it offers higher bandwidths, enabling new performance limits. Novel innovative solutions like full-duplex 100-Mbps pinless connections may be applied to the subsea market at the 5 GHz band. Subsea oil & gas production networks demand full-duplex fibre-optic connectors. Such contactless connectors intend to remove the faults inherent with mechanical wet-mate connectors while providing the same data throughput performance. It would

allow the link of both communicating sides of a typical Ethernet connection by two streams running in parallel, avoiding any undesired bottleneck.

The main challenge for full-duplex 100-Mbps wireless connections in the context of pinless subsea connectors is the implementation of two independent broadband channels with sufficient electromagnetic isolation between each other when installed in compact small-size metal-based connectors equipped with an antenna. One critical issue is to keep both wireless channels working at similar levels. In order to accomplish this task, a minimum received power level must be available at the receiver antenna port for both channels. 4.7 GHz and 5.7 GHz are selected as reference frequency carriers for the system design. Signal attenuation is expected to be even higher than 2.4 GHz propagation in seawater. Experimental research works have been performed in freshwater [17, 18]. However, to the best of the authors' knowledge the behaviour in seawater has not been explored in typical subsea working conditions until now. This work fills this gap, aiming to investigate propagation limits in typical subsea working conditions for such systems.

This study shows that the deployment of optimized antennas in terms of both matching and directivity, taking into consideration the surrounding environment, in addition to the presence of available power budget margin, is capable to implement high-speed wireless underwater connections in typical subsea environments at the 5 GHz band for short range communication of several centimetres for Line of Sight scenarios.

This paper is organized as follows. Related work is discussed in Section 2. Theoretical radio channel model is presented in Section 3. The proposed measurement setup is exposed in Section 4. Section 5 shows measurement results, data fitting models, and includes the discussion. Finally, the conclusions and future works are exposed in Section 6.

2. RELATED WORK

Propagation of EM waves underwater is a promising research area [19–21]. In [22] several experiments investigate the behavior of EM waves underwater for several frequency bands. Horizontal and vertical polarizations, launching of radio waves with coated and uncoated antennas are studied and taken into consideration. Experiments show that EM signal attenuates rapidly up to 10 m, and afterwards the attenuation decreases. A simple frequency based attenuation model is also derived. In [23], authors demonstrated that underwater transmission at MHz frequencies are feasible, and coverage range reaches up to 100 m. In [24], path loss in seawater is calculated taking into account several parameters such as temperature, salinity and frequency. In [25] a communication model for Underwater Sensor Network is presented. A distance dependent attenuation coefficient to explain the near and far field behavior of EM waves in the sea is introduced. Elrashidi et al. [26] presented a three path model for path loss at 2.4 GHz which includes reflections from the water surface. Hattab et al. [27] presented a path loss analysis for under water communication systems. Two types of losses are studied. The first is attenuation loss, and the second is reflection loss. The authors in [28] presented underwater channel characterization parameters at 2.4 GHz such as propagation velocity, total path loss, wavelength and frequency with different values of distance and conductivity.

Moreover, there are many papers discussing the propagation scenarios for acoustic waves in underwater communication and applications [29–31]. In fact, the challenge is to work on high frequency bands (in the range of GHz) for underwater communication and applications, which is an open area.

Table 1. Comparison of underwater communication carriers.

Carrier	Transmission distance	Bandwidth	Mode of Communication	Achievable data rates	Propagation speed
Radio	< 1 m	1 MHz	Line Of Sight/ Non Line Of Sight	High	High
Accoustics	1000 km	< 1 kHz	Line Of Sight/ Non Line Of Sight	Very Low	Very Slow
Optical	< 10 m	1 GHz	Line Of Sight	Very High	Very High

Many researchers have researched the medium characteristics and illustrated the comparative study over the various frequencies used for underwater wireless communication such as acoustic, radio, and optical signals. Table 1 compares three types of underwater communication systems. These systems are differentiated based on the carrier frequency, bandwidth, transmission distance, mode of communication, and achievable data rates in underwater. There is a trade-off between the transmission distance and bandwidth depending on the selected application. An optimal carrier has to be chosen accordingly [32].

3. RADIO CHANNEL MODEL

A simple power budget that provides a general view of the received power (P_r) calculation is presented in Eq. (1), where P_t is the transmitted power, G_t the gain of the transmitter antenna, L the propagation channel losses, and G_r the gain of the receiver antenna [33]. A simplified block diagram presenting the measurement experimental setup is shown in Fig. 1. The received power is measured by a Vector Network Analyzer (VNA) using specific coaxial cables and designed antennas in a water tank.

$$P_{r\,(\text{dBm})} = P_{t\,(\text{dBm})} + G_{t\,(\text{dBi})} - L_{(\text{dB})} + G_{r\,(\text{dBi})} \tag{1}$$

In Eq. (1), P_t is usually set to the maximum level available at the transmitter. 20 dBm is considered as a typical maximum value for low-power 5 GHz transmitters. L is set by the particular subsea environment and operating frequency. G_t and G_r are actually the key parameters in the system design. Water conductivity is taken into account since it affects the propagation signal. Losses due to the coaxial lines and adapters are assumed to be zero. The design goal is to optimize the antenna gain for system working conditions. Particularly, underwater connections focus on achieving maximum gap (distance between transmitter and receiver), while offering operational flexibility under different rotations, cross-axial, and angular misalignments. All of these factors help, among others, system installation and connection robustness. This study focuses on the modelling of L in the 5 GHz band for pinless subsea microwave-based connectors.
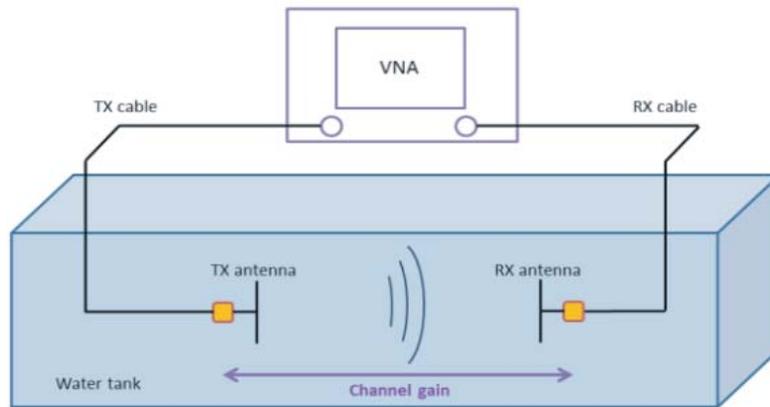

Figure 1. Block diagram of the measurement setup.

3.1. The Free Space Loss: Friis Contribution

L in Eq. (1) can be further analyzed by two main physical mechanisms: free space loss and seawater absorption loss. Electromagnetic signals will spread along the free space with a certain pattern mainly governed by the fabricated radiator performance and its surrounding environment. The propagation loss is traditionally modelled by the well-known Friis formula valid in far-field conditions, indicated in Eq. (2), where PLF is the Polarization Loss Factor between antennas, λ the wavelength of the electromagnetic signal in the medium, and R the separation distance between antennas. K is a modelling constant that integrates all the factors that do not depend on the seawater gap [33].

$$L_{\text{friis\,(dB)}} = \text{PLF}_{(\text{dB})} + 20\log_{10}(\lambda/4\pi R) = K - 20\log_{10}(R) \tag{2}$$

It is important to remark that Eq. (2) is not valid in the near-field region. Thus, due to the particular configuration in underwater connections, this issue needs to be analyzed in the modelling process.

3.2. Seawater Absorption Loss

In addition to signal spreading, signal absorption is a key mechanism taking place when an electromagnetic signal propagates in seawater. High conductivity in seawater leads to high signal attenuation. It can be estimated by using Eq. (3), where exp is the exponential function with base e, and α is a key channel parameter, which is the signal specific attenuation [33].

$$L_{\text{abs (dB)}} = 10 \log_{10}(\exp(-2\alpha R)) = -20 \log_{10}(e^{\alpha R}) \tag{3}$$

3.3. Modelling of the Received Power: The Complete Model

Combining Eqs. (1), (2), and (3), it is straightforward to estimate the received power level as indicated in Eq. (4), where C integrates the contribution from P_t, G_t, G_r, and K as defined in Eq. (3) [33].

$$P_{r \text{ (dB)}} = C - 20 \log_{10}(R) + 20 \log_{10}(e^{\alpha R}) \tag{4}$$

4. MEASUREMENT METHOD

Channel measurements at both 4.7 GHz and 5.7 GHz were carried out in a seawater tank. A simplified block diagram of the test bench is shown in Fig. 1. An overview of the lab setup is included in Fig. 2. Fig. 2(a) shows the aluminium housings with test antennas installed behind, and Fig. 2(b) shows a general view of the working conditions in the water tank. The testing tank is made of glass with a width of 25 cm, height of 30 cm, and length of 50 cm. Seawater for experimentation was selected from the Bergen fjord with measured salinity and conductivity values of 33 ppt and 5.8 S/m, respectively. The water temperature was set to 20°C.


(a)   (b)

Figure 2. Lab setup: aluminum connectors where antennas were installed in (a), and overview of the measurement system (b).

A seawater-optimized antenna was designed and manufactured to test the 5 GHz propagation channel. The antennas were connected to a Vector Network Analyzer (VNA) with low-loss coaxial cables (Fig. 1). The VNA computes the S_{21} parameter which gives experimental data on the channel gain including antenna effects. The main effects included in the measurements are considered in Eq. (4).

5. MEASUREMENTS RESULTS, MODELING AND DISCUSSION

Channel measurements are presented in Fig. 3 for both 4.7 GHz and 5.7 GHz. In particular, the received power is calculated in dBm along the distance assuming that the transmitted power is 0 dBm.

In Fig. 3, two fitting models can also be observed. Firstly, we have implemented a fitting function based on the complete model described in Eq. (4). The fitting method is based on nonlinear least square, by using robust LAR with Lvenberg-Marquardt algorithm. However, the matching is not satisfactory in the whole distance range. Therefore, we have decided to look for the simplest model that fits the measurement data. We finally find a linear model that fits the experimental data accurately, whereas
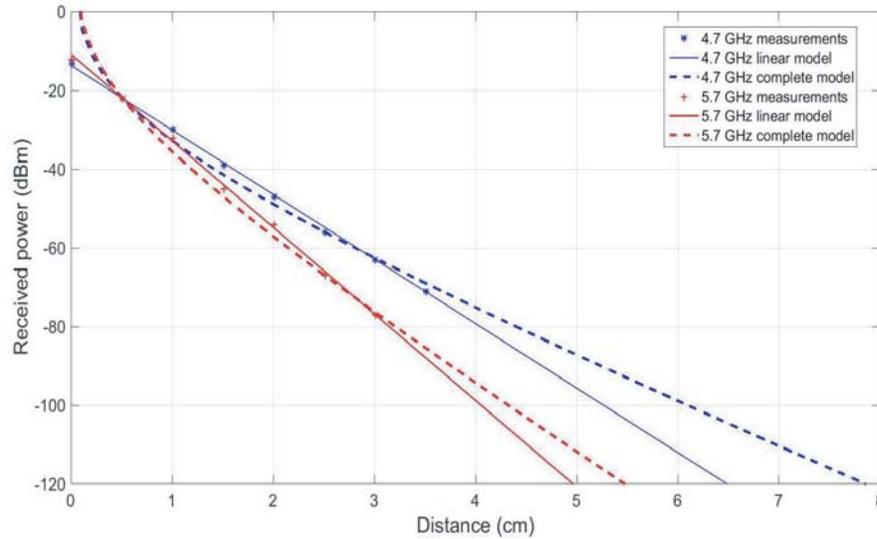
Figure 3. Channel measurements and models fit at 4.7 GHz and 5.7 GHz.

it provides a global overview of the specific attenuation. Table 2 provides the estimation of the key channel parameters for both models. Specifically, the complete model is based on Eq. (4), in which main parameters are indicated as α and C. Moreover, the linear model is described as $Y = M \times R + S$, where Y is a straight line, M the slope of the line, R the distance along which the values are calculated, and S is constant. The data fitting is based on standard linear least square regression [33].

In addition, an estimation of the "goodness" of the fit is included in Table 2 as well. It was computed by the standard R-square method. As we can observe, the linear model is more accurate for our working conditions, and the global specific attenuation is 16.40 dB/cm and 22 dB/cm for 4.7 GHz and 5.7 GHz, respectively.

Table 2. Key channel parameters and goodness of the fit.

	4.7 GHz		5.7 GHz	
	Parameters	R-square fit	Parameters	R-square fit
Complete model	$\alpha = -1.165$ $C = -22.61$	$R = 0.9251$	$\alpha = -1.794$ $C = -19.90$	$R = 0.9290$
Linear model	$M = -16.40$ $S = -13.64$	$R = 0.9910$	$M = -22.00$ $S = -10.78$	$R = 0.9985$

Figure 3 shows that the complete model based on Eq. (4) is not accurate in the near-field region. However, the linear model describes the signal attenuation along the measured range. If we consider that this model is usable at larger distances, current receiver technology with typical sensitivities around -100 dB would operate at high speeds for seawater of up to 4 cm (5.7 GHz channels) and 5.2 cm (4.7 GHz channels). Taking into account this difference, it is possible to design a symmetrical full-duplex system using two different and distant broadband channels within this band.

6. CONCLUSION AND FUTURE WORK

This work has presented experimental results confirming that underwater connectors based on microwave technology can operate at the 5 GHz band under measurement conditions that have not been explored until now. We have shown that received power levels are over typical receiver sensitivities for seawater gaps up to 4 cm (5.7 GHz) and 5.2 cm (4.7 GHz) when optimized antennas are used during the measurement campaign. It allows tremendous system flexibility in terms of gap for pinless subsea

connections.

The main contribution of this paper is a very useful channel model that can be easily adjusted in the 5 GHz band for subsea environments. Specifically, we have used it to design a symmetrical 100-Mbps full-duplex pinless subsea connector which is under development.

ACKNOWLEDGMENT

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