On the Two-Ray Model Analysis for Overwater Links with Tidal Variations

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Abstract. This work explores the impact of antenna heights and polarization on overwater links during the cycle of tidal variations. We focus our attention on links of short-to-medium-range distances with antenna heights near-to-the-water-surface. The typical use-case for such a scenario is an overwater, water quality monitoring wireless sensor network. The radio propagation is simulated using a featured two-ray model that considers the relative permittivity of the water surface and the antenna polarization. The results show that the performance of overwater links may be better with lower antennas than higher antennas as well as with one polarization or the other, intuitively, during part of the tidal cycle.

Keywords: Wireless communications · WSN · communications over water · maritime communications · tidal fading · two-ray model· RSSI.

1 Introduction

Wireless Sensor Networks (WSNs), networks of devices that collaborate to measure environmental metrics in the physical surroundings, have shown their usefulness in a variety of settings and applications, e.g., building monitoring, forest fire tracking, or water quality monitoring. Concerning the latter, a particular scenario is that of WSNs deployed in or at the margin of large bodies of water that experience tidal variations, and that are installed at a few meters from the surface and at a fixed height with respect to the bedrock. Here, overwater links are used to support wireless communications for large-scale water monitoring applications such as water quality assessment or early warning and flood forecasting systems [1]. The communication challenges under this particular setting are different than the ones experienced over land, especially from the perspective of radio signal propagation [9]. The water medium is considered a flat and conductive surface that significantly reflects electromagnetic signals (such as radio and visible light). This condition may lead to strong constructive or destructive interference that affects the performance of the overwater links. A situation that is well predicted by the two-ray propagation model [8].

The two-ray model as represented in Figure 1 is a geometrical model deemed as a good predictor of the propagation of radio signals over the water surface [9]. This model considers that the signal power at the receiver node is the result of mainly two rays of the transmitted signal. The first ray is the direct ray that follows the line-of-sight (LoS) path between the transmitter and the receiver, and the second indirect ray follows a non-line-of-sight (NLoS) path reflected off the surface. The reflected path is longer, and thus a length difference between both paths exist. This difference yields to a phase shift on the second ray with respect to the first one, and that in turn to constructive or destructive interference as a result of the superposition of the two signals.

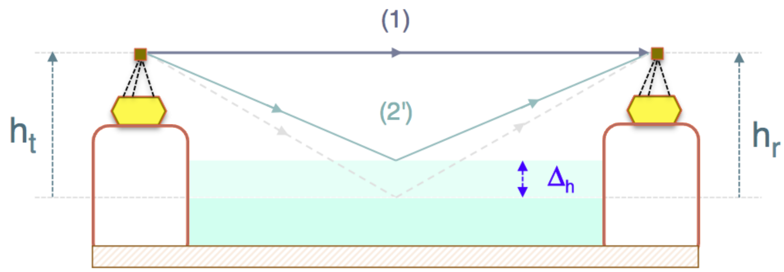

Fig. 1. The two-ray model showing: (1) the direct LoS ray, and (2') the indirect ray reflected from the water surface when experiencing a tide level variation of Δ_h.

The Fresnel reflection coefficient Γ complements this geometrical model by incorporating the effects of the material properties of the reflected surface (in particular, the relative permittivity of the medium ε_r) and the antenna polarization. Equations 1 presents the expressions to compute Γ for both vertical and horizontal polarization, Γ_V and Γ_H respectively.

$$\Gamma_V(\theta) = \frac{-\varepsilon_r \sin\theta + \sqrt{\varepsilon_r - cos^2\theta}}{\varepsilon_r \sin\theta + \sqrt{\varepsilon_r - cos^2\theta}} \qquad \Gamma_H(\theta) = \frac{\sin\theta - \sqrt{\varepsilon_r - cos^2\theta}}{\sin\theta + \sqrt{\varepsilon_r - cos^2\theta}} \tag{1}$$

where θ is the incidence angle of the reflected ray relative to a horizontal surface. The amplitude A of the signal resulting from the vectorial summation of the two rays when considering the effects of Γ is presented as follows:

$$A(\theta) = \sqrt{(1 + \Gamma\cos\theta)^2 + (\Gamma\sin\theta)^2} \tag{2}$$

The two-ray model, as presented in Equation 3, shows the average power received P_r as the result of incorporating the Friis free-space loss [8] predictions into the geometrical analysis.

$$P_r(d,\theta) = A^2 \frac{\lambda^2}{(4\pi d)^2} P_t G_t G_r \tag{3}$$

where λ is the carrier wavelength, d is the link distance, P_t is the transmitted power, G_t is the transmitter antenna gain, and G_r is the receiver antenna gain. Figure 2 shows the solutions for such equation for a given range of link distances when using vertically polarized antennas, a carrier frequency of 2.4GHz and a flat surface with permittivity $\varepsilon_r = 81$. The picture highlights the difference obtained when two different antenna heights h_0 relative to the reflective surface are used.

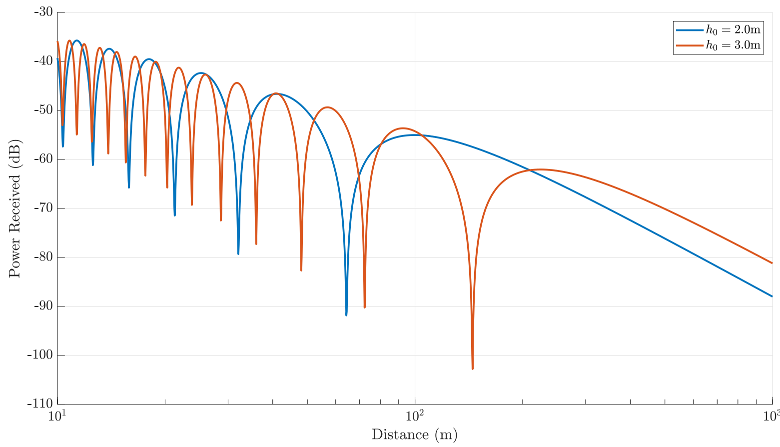

Fig. 2. Two-ray model showing that received power is affected by both the link distance and the antenna height (h_0) relative to the reflective surface.

The results of Equation 3 allow us to observe the actual position of the nulls (i.e., significant dips in the received power) that occur at specific combinations of link distances and antenna heights. This issue, also known as deep fading [8], is often avoided during the design process by simply adjusting the height of the antennas or other available parameters such as tilt, inclination or polarization [3].

Tidal variations add a temporal dimension to the analysis of the two-ray propagation model. The tidal cycle continuously modifies the relative height of the antennas to the water surface as it progresses over time. A water-level variation experienced at two different time instants of an arbitrary tidal cycle (as represented in Figure 1) is shown to be equivalent to the effect of a change in the antenna heights relative to the water surface (as represented in Figure 2). The tidal cycle has an impact only on the reflected path, thus modifying the received signal strength due to the dynamic interaction between the two rays. This phenomenon, known as tidal fading [5] is a significant and barely explored problem deemed as one of the most detrimental issues affecting overwater links [7].

2 Related Works & Contribution

The mitigation techniques for the tidal fading problem have received very little attention when compared with the considerable amount of work studying the propagation of radio signals over-the-water-surface [9]. Early works, such as the one in [4], have already reported a clear dependence of received signal strength and water level cycles, but the analysis of such a situation has been brought again to the forefront only recently. The work in [5] has proposed a novel mitigation technique that exploits the frequency dependence of the two-ray model in the form of a channel-hopping approach. This work, when compared with other hardware-redundant strategies, is shown as a cost-effective alternative to overcome the impact of tides on long-range overwater links. Similarly, the work in [6] exploits the two-ray model principles but from the perspective of the space-diversity concept, i.e., with the use of two receiver antennas at a specific vertical separation to counteract the impact of time-varying surface reflections [2]. This work, although novel, since applied on the emerging context of overwater-WSNs for offshore wind-farm monitoring, rely on the basic principles of space-diversity; which is the most popular and robust approach used by practitioners [2]. Other applicable works in the literature exploit this and other variants of diversity reception or transmission using different parameters (such as angle, frequency, path, polarization) but with an increase in the cost or complexity of the system, which often brings only a little gain when compared to the widely adopted space-diversity approach. The ITU-R P.530 [3] recommendation is a good source of detail regarding diversity and non-diversity strategies to counteract surface reflections, but its applicability is usually restricted to the case of kilometric distances with antenna heights in the range of tens of meters.

In this work, we aim to analyze the impact of antenna heights and polarization on the performance of overwater links during a complete tidal cycle. We analyze the average power received as a metric closely related to the two-ray model. We focus our attention on links of short-to-medium-range distances with antenna heights near-to-the-water-surface that experience tidal variations. This scenario poses two significant challenges: first, the short-to-medium-range distances are substantially more affected by the occurrence of nulls when compared to the long-range case; and second, the tide level variations (e.g., 1m to 2m) are in the range of the antenna heights (e.g., 2m to 5m), which is particularly restrictive with respect to the course of actions to take.

3 Analytical Characterization

We used MATLAB simulations to reproduce a representative overwater link in the presence of tidal variations. We based the analysis on the two-ray featured model presented in Equation 3 that take into account the precise values of the Fresnel reflection coefficient when considering the antenna polarization and the relative permittivity of the reflective medium.

We assumed both vertically and horizontally polarized antennas for a link operating at 2.4GHz over a reflective medium with relative permittivity set to $\varepsilon_r = 81$ (a typical value for sea/fresh water) [8]). The link distance is set to $d = 100$m and the antenna height for both transmitter and the receiver is fixed at 2m and 3m with respect to the average water level. We refer to these heights as $h_0 = 2$m and $h_0 = 3$m, respectively.

Tide levels fluctuate 1.25m above and below the average water level, following a cosine function along a full tide cycle. As a result, the relative antennas heights to the water surface are represented mathematically as follows:

$$h(t) = h_0 + 1.25 \cos(2\pi t/100), \forall t \in [0, 100] \quad (4)$$

Figure 3 shows the results for the power received in dB for both vertical (top) and horizontal (middle) polarization when using antenna heights fixed to

$h_0 = 2$m (blue) and $h_0 = 3$m (red). The picture also shows the amplitude of the relative antenna heights (bottom) with respect to the water surface as a function of the progress on the tidal cycle.

The case of vertical polarization (top) reveals significant deep fades for both antenna configurations as the result of tide level variations. The number of the nulls (and thus the percentage of the time the nulls degrade the received power) is higher for the case of antennas being placed higher. Only two nulls for the case of $h_0 = 2$m and four nulls for the case of $h_0 = 3$m. Moreover, on both cases, there is a long and continuous time-span of at least 20% of the tidal cycle with good power reception levels.

In the horizontal polarization case (middle), the signal reception is quite similar and stable during the full cycle for both antenna configurations. There are no deep fades since the reflection coefficient never approaches one. Also, the power received is generally higher than the observed for the vertical scenario.

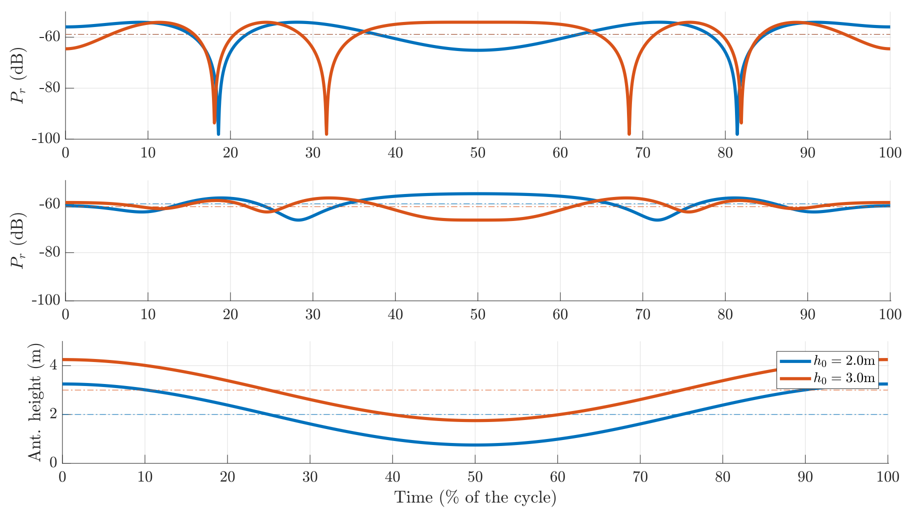

Fig. 3. Power received at $d = 100m$ for vertical (top) and horizontal (middle) polarization, and relative antenna height to the surface $h(t)$ (bottom) along a tidal cycle.

Although the results presented in Figure 3 suggest a less susceptibility on signal degradation when using horizontally polarized antennas, it is important to notice that in practice, horizontal polarization is typically achieved by placing dipole antennas horizontally. This puts an extra consideration on the directionality required for the antenna alignment under such configuration. A factor that may put a considerable drawback for the design of large-scale WSN deployments.

4 Conclusion

WSNs are commonly used to monitor wide areas but their use on overwater environments requires a careful analysis of the overwater communication channel.

We target WSN deployments to monitor overwater areas with noticeable tidal variations using links of short-to-medium range distances that are installed at a height close to the water surface. We analyzed the impact of antenna heights and polarization on the average power received over a full tidal cycle. We used the two-ray propagation model with the actual Fresnel reflection coefficient of the water ($\varepsilon_r = 81$) to analyze both vertical and horizontal polarization.

Our simulation results showed that for a given link distance, the antenna heights and polarization have an important influence on the received signal strength. We observed different behaviours for the signal reception when using one polarization or the other, with the vertical polarization being more susceptible to signal degradation. The vertical polarization exhibited significant deep fades for the two different antenna heights, a situation that was not observed on the horizontal case. The higher antenna configuration revealed a higher number of nulls, and thus a longer period with a poor signal reception; which is often a counter-intuitive observation. The overall analysis suggests that typical approaches using higher antenna heights and vertical polarization may present a lower performance when evaluated over a full tidal cycle.

In future works, we aim to understand which antenna configuration provides better link quality for a longer interval of the tidal cycle. We argue that the particular overwater scenario analyzed in this work is an important and barely explored problem demanding for further studies.

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