Optimal antenna-height design for improved capacity on over-water radio links affected by tides

Miguel Gutiérrez Gaitán*

Pedro Miguel Santos*

Luis Pinto

Luís Almeida*

*CISTER Research Centre

CISTER-TR-200802

2020/10/05

Optimal antenna-height design for improved capacity on over-water radio links affected by tides

Miguel Gutiérrez Gaitán*, Pedro Miguel Santos*, Luis Pinto, Luís Almeida*

*CISTER Research Centre

Rua Dr. António Bernardino de Almeida, 431

4200-072 Porto

Portugal

Tel.: +351.22.8340509, Fax: +351.22.8321159

E-mail: mjggt@isep.ipp.pt, pss@isep.ipp.pt, pin@isep.ipp.pt, lda@fe.up.pt

https://www.cister-labs.pt

Abstract

Modern observation systems can be composed by heterogeneous entities (e.g., buoys, USVs, UAVs, on-shore sensors, etc.) that rely on dependable communications for coordination and data collection, often provided by over-water radio-frequency (RF) links. In tide-affected water bodies, RF links at a fixed height from the shore can experience the so-called tidal fading, a cyclic time-varying tide-induced interference. To mitigate it, the classical space-diversity reception technique (i.e., the use of two or more receiver antennas positioned at different heights) is often applied, commonly combined with the consideration of having one of the antennas at the largest possible height. Yet, this approach does not always ensure the best performance. In this work, we focus on static over-water links of short-to-medium-range distances that use antennas installed at a few meters above surface. We leverage the geometrical basis of the two-ray propagation model to investigate the optimal single-antenna height design that minimizes overall average path losses over a given tidal range. We then extend this analysis to incorporate a second receiver antenna and identify its optimal antenna height. Analytical results show that our method considerably outperforms the more classical approach, thus enabling superior (average) link capacities.

Optimal antenna-height design for improved capacity on over-water radio links affected by tides

Miguel Gutiérrez Gaitán*†‡, Pedro M. Santos†‡, Luis R. Pinto§ and Luis Almeida†
*Facultad de Ingeniería, Universidad Andres Bello, 8370146 Santiago, Chile – miguel.gutierrez@unab.cl
†CISTER Research Centre, FEUP, University of Porto, Portugal – {mgg, pmsantos, lda}@fe.up.pt
‡CISTER Research Centre, ISEP, Polytechnic of Porto, Portugal – {mjggt, pss}@isep.ipp.pt
§IFPN, Instituto Superior Técnico, Lisboa, Portugal – lpinto@ipfn.tecnico.ulisboa.pt

***Abstract*—Modern observation systems can be composed by heterogeneous entities (e.g., buoys, USVs, UAVs, on-shore sensors, etc.) that rely on dependable communications for coordination and data collection, often provided by over-water radio-frequency (RF) links. In tide-affected water bodies, RF links at a fixed height from the shore can experience the so-called tidal fading, a cyclic time-varying tide-induced interference. To mitigate it, the classical space-diversity reception technique (i.e., the use of two or more receiver antennas positioned at different heights) is often applied, commonly combined with the consideration of having one of the antennas at the largest possible height. Yet, this approach does not always ensure the best performance. In this work, we focus on static over-water links of short-to-medium-range distances that use antennas installed at a few meters above surface. We leverage the geometrical basis of the two-ray propagation model to investigate the optimal single-antenna height design that minimizes overall average path losses over a given tidal range. We then extend this analysis to incorporate a second receiver antenna and identify its optimal antenna height. Analytical results show that our method considerably outperforms the more classical approach, thus enabling superior (average) link capacities.**

***Index Terms*—marine communication, maritime networks, over-sea paths, space-diversity, tidal fading, tides, two-ray.**

I. INTRODUCTION

Maritime and underwater observatories are growing in complexity and can be often perceived as sophisticated distributed systems requiring dependable communication solutions. As buoys, ships, unmanned surface (and aerial) vehicles and nodes onshore must articulate tightly towards a common goal, technologies ensuring reliable and timely transfers of data and control information are critical [1]–[3]. Likewise, the growing adoption of high data-rate capable devices (e.g., cameras or sonars) supporting emerging marine surveillance/monitoring systems, stress the need for more reliable broadband support.

Dependable connectivity in maritime conditions is being addressed e.g. in the AQUAMON[1] project, a Portuguese initiative dedicated to develop a continuous (on-line) monitoring platform for applications in aquatic environments using wireless-sensor-networks (WSNs) [2]. Wireless radio-frequency (RF) links are indeed the natural option to support much of the over-water component of communication on such a kind of systems [3], but they are still subject to a multiplicity of factors that can affect signal propagation [4]–[7]. The flat and conductive properties of the water medium make RF signal reflections stronger and this can lead to extremely severe destructive interference (often referred to as deep fading). The natural water movements (e.g., tides, waves) add extra propagation effects (both path loss and fading), thus increasing design complexity [6]–[8].

In particular, the impact of tides on the link quality becomes noticeably aggravated when at least one of the communication terminals does not keep a fixed height to the water level. Due to the varying geometry of the ray reflected on the water surface over the tidal cycle, the quality of the received signal can be greatly degraded because of severe destructive interference with the line-of-sight (LoS) ray during periods of the cycle; a phenomenon also known as tidal fading [9]. To counteract such an issue, the classical space-diversity reception technique, i.e., the use of two (or more) receiver antennas conveniently positioned at different heights, is often applied [10], commonly combined with placing one of the antennas at the highest possible position. The method, although effective since early works reported in the literature [11] and until more recent years [12], has been focused almost exclusively in long-range distances. The case of over-water links of short-to-medium-range distance that use antennas close to the surface (and within the magnitude order of the tidal range) is a barely explored but borderline scenario [13] [14] which challenges the applicability of the classical technique; thus deserving further research.

This paper addresses the case of static over-water links affected by tides operating over relatively short distances (e.g, few hundred meters) with antennas fixed at a few meters above surface. We investigate the optimal single-antenna height design that minimizes large-scale fading (path loss) over a given tidal range. We then extend the analysis to a second receiver antenna and identify its optimal height. Analytical results suggest that our approach considerably outperforms the classical technique, thus enabling superior (long-term) broadband link support.

The rest of the paper is organized as follows. Section II presents the related work and outlines the main contributions. Section III describes the two-ray propagation model in the presence of tides and revisits prior experimental evidence as motivation. Section IV formulates the antenna-height optimization problem and presents both the classical and proposed technique. Section V evaluates both approaches and presents comparative results. Finally, Section VI draws the conclusions.

---

[1] https://aquamon.di.fc.ul.pt/

II. Related Work & Contribution

In recent literature, mitigation techniques used to counteract the effects of tidal fading have received very little attention; especially, if compared with the considerable amount of (recent) work studying over-water radio propagation [4], [5], [15]–[18]. Moreover, the case of links of short-to-medium-range distances (∼100-500m) with antennas installed at a few meters above surface (∼1-5m) is still a borderline scenario [19] with very few efforts fully dedicated to study the impact of tides on wireless links [13], [14]. The conventional methods and guidelines for link design (e.g., [20], [21]), as well as other recent approaches (e.g., [8], [22], [23]), are often optimized for kilometric link distances and/or for much larger antenna heights, and thus, do not show straightforward applicability on this particular setting. In addition, the fact that near-surface antenna heights are within the magnitude order of the tidal range, makes these overall circumstances fairly unique; thus reducing the amount of related/comparable work.

We aim to contribute to the state-of-the-art, first, by showing that the classical space-diversity reception technique, deemed as the *de facto* solution to counteract tidal fading, does not always show the best performance. Second, and more importantly, we propose a novel optimization method leveraging the two-ray propagation model to design links with (optimal) antenna-heights that offer minimal (average) path losses when evaluated over (all the possible values of) a given tidal range. We show, in Section V, that both the proposed single and two-antenna height design outperforms the corresponding largest possible antenna height and the classical (two-antenna) space-diversity.

III. Background & Motivation

The impact of tides and surface reflections on the receive signal strength of over-water links can be well-described by the geometry of the two-ray model [8], [13], [14]. This model takes the resulting signal strength on the receiver side as the vectorial sum of two copies of the same transmitted signal arriving at the receiver from two different paths: (1) a direct line-of-sight (LoS) path between the transmitter and the receiver, and (2) an indirect path reflected from the surface. The reflected path is longer, and thus a length difference between both paths exist, leading to a phase difference between the two signal copies. By considering the case of static over-water links design, the tide-induced water level oscillation can be incorporated in the model as a small variation (Δ_k) that influences both relative antenna-to-surface heights, thus always changing the second path length, but keeping the LoS path unaffected (see Fig. 1).

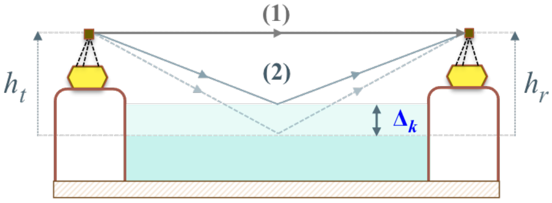


Fig. 1. The two-ray model showing: (1) the direct LoS ray, and (2) the indirect ray reflected from the surface when experiencing a water level variation of Δ_k.

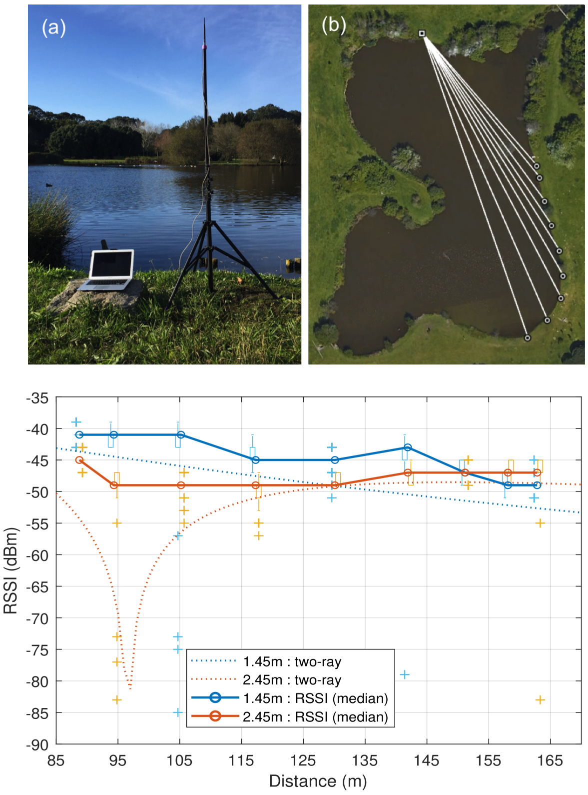


Fig. 2. Experimental evaluation showing: **top(a)**, testbed setup with node deployment, and **top(b)**, set of links and node positions at the actual location; **bottom**, two-ray model prediction (dotted) vs. RSSI measurements at different links and antenna heights (boxplot); with median points connected (solid line).

A. *Two-ray model: a proof-of-concept*

In prior work [14], we empirically evaluated the applicability of the two-ray model on an equivalent rather simplistic tidal-fading situation for links of short-to-medium range distances. We assessed the received signal strength [indicator] (RSSI) on a set of 9 static over-water radio links, with distances from ∼ 88m to ∼ 164m, at two different antenna-to-surface heights (1.45m and 2.45m) so as to mimic two different water-level instants within an arbitrary tidal cycle. The results, although preliminary, showed a considerable consistency between both the average packet-based measurements of RSSI (using Wi-Fi COTS) and the theoretical model predictions. Fig. 2 summarizes this campaign, firstly presented in [14], [24].

The experimental work served us as motivational evidence to conclude that, for our particular distance-height region of interest, (i) the two-ray model can be used to represent major path loss trends experienced by radio signal propagation in tide-affected over-water links, and (ii) that antenna-height adjustment (even when lowering the antenna height) can be an effective design approach to mitigate the detrimental effect of surface reflections, and thus to (noticeably) improve the signal quality of over-water links. Along this line, here we make use of these prior results as a proof-of-concept enabling the proposed (optimal) antenna-height design method in Section IV.

IV. Problem Formulation

Consider an over-water (shore-to-shore) link as the one presented in Figure 1, where both transmitter and receiver antennas are installed at the same height w.r.t. an average water level, i.e., h=h_t=h_r, and separated by a distance d. Then, consider a tidal pattern causing a water level variation which influences the nominal antenna-to-surface heights in Δ_k. By assuming the large-scale fading of such link is well-described by the classical two-ray (ground-reflection) model [25], the attenuation of the link (in dB) when incorporating the effect of tides can be formally expressed as follows:

$$L_{2ray} = -10\log_{10}\left(\frac{\lambda^2}{(4\pi d)^2}\left[2\sin\left(\frac{2\pi(h+\Delta_k)^2}{\lambda d}\right)\right]^2\right) \quad (1)$$

where λ is the signal wavelength.

A. Optimal antenna-height design

Leveraging Eq. 1, the problem of finding the optimal (single) antenna height h that minimizes the (average) path losses experienced over all possible $\pm\Delta_k$ values of a given tidal pattern can be formally expressed as:

$$\begin{aligned} \underset{h}{\text{minimize}} \quad & \frac{1}{N}\sum_{k=1}^{N} L_{2ray}(\Delta_k) \\ \text{subject to} \quad & \Delta_k \in [\Delta_L, \Delta_H],\ \forall k \in [1, N], \\ & h \in [h_{min}, h_{max}] \end{aligned} \quad (2)$$

where $N \in \mathbb{N}$ is the number of (steps) values of the discretized tidal pattern where the optimization expression is evaluated; Δ_k is the (signed) value of the k^{th} step, valid within the respective lower (Δ_L) and higher (Δ_H) maximum deviations of the tidal pattern (w.r.t. h); and $[h_{min}, h_{max}]$ is the h feasibility region.

B. Two (or more) optimal antenna-height design

The previous method can be extended to incorporate a second receiver antenna assuming the first one is already positioned at the optimal antenna height (hereinafter, h_1). We extend the method assuming the second antenna height (h_2) is chosen as the one providing the largest improvement w.r.t. to the overall path loss attenuation obtained using only h_1. To this purpose, we assume the system is able to select the receiver antenna (between the two) with the best signal quality (or lower attenuation). This reasoning implies the original objective function in (2) can now be modified to select the receiver antenna (height) experiencing the minimum path loss attenuation at each Δ_k. We formally present this extended method as follows:

$$\begin{aligned} \underset{h_2}{\text{minimize}} \quad & \frac{1}{N}\sum_{k=1}^{N} \min[L_{2ray}^{h_1}(\Delta_k), L_{2ray}^{h_2}(\Delta_k)] \\ \text{subject to} \quad & \Delta_k \in [\Delta_L, \Delta_H],\ \forall k \in [1, N], \\ & h_2 \in [h_{min}, h_{max}] \end{aligned} \quad (3)$$

where $L_{2ray}^{h_1}(\Delta_k)$ and $L_{2ray}^{h_2}(\Delta_k)$ denote the corresponding link attenuation (in dB) for h_1 and h_2, at each Δ_k.

The general expression that incorporates n diversity antennas can be defined in a similar rather straightforward fashion. To this purpose, we can assume a number of $(n-1) \in \mathbb{N}$ receiver antennas have already been placed at their optimal antenna heights, namely $h_1, \cdots h_{n-1}$. Thus, the loss attenuation at each Δ_k denoted as $L_{2ray}^{h_1}(\Delta_k) \cdots L_{2ray}^{h_{(n-1)}}(\Delta_k)$ can be computed beforehand using Eq. 1. Then, to determine the n^{th} optimal antenna height, h_n, the formal expression for the method in (3) can be re-written as follows:

$$\begin{aligned} \underset{h_n}{\text{minimize}} \quad & \frac{1}{N}\sum_{k=1}^{N} \min[L_{2ray}^{h_1}(\Delta_k), \cdots, L_{2ray}^{h_n}(\Delta_k)] \\ \text{subject to} \quad & \Delta_k \in [\Delta_L, \Delta_H],\ \forall k \in [1, N], \\ & h_n \in [h_{min}, h_{max}] \end{aligned}$$

Note that for the prior case, $n = 2$, the general method is reduced to the expression in (3), where the associated input h_1 can be directly obtained by using (2). The case of $n \geq 3$ although useful for the overall system reliability (e.g., under more unpredictable circumstances), might not be of (significant) further help when mitigating tidal fading, thus this case is not being explored in this paper.

C. Classical (two-antenna) space-diversity reception

For reference, we revisit here the classical space-diversity reception technique. A key design concept for the classical space-diversity reception technique is the so-called *diversity separation* distance (d_{sep}). It refers to the recommended (and typically vertical) antenna separation used to conveniently counteract the occurrence of nulls (or deep fades) affecting two receiver antennas at the same time. In practical two-antenna systems, this design criterion is often combined with the consideration of having one of the antennas at the largest feasible height (i.e., $h_1 = h_{max}$). Thus, the second antenna is placed (at least) at d_{sep} meters apart from the first antenna, hence taken the recommended (minimal) separation for diversity.

We present here the simplified expression of the diversity separation criterion borrowed from [10]:

$$d_{sep} \simeq \alpha\frac{\lambda \cdot d}{h_1} \quad (4)$$

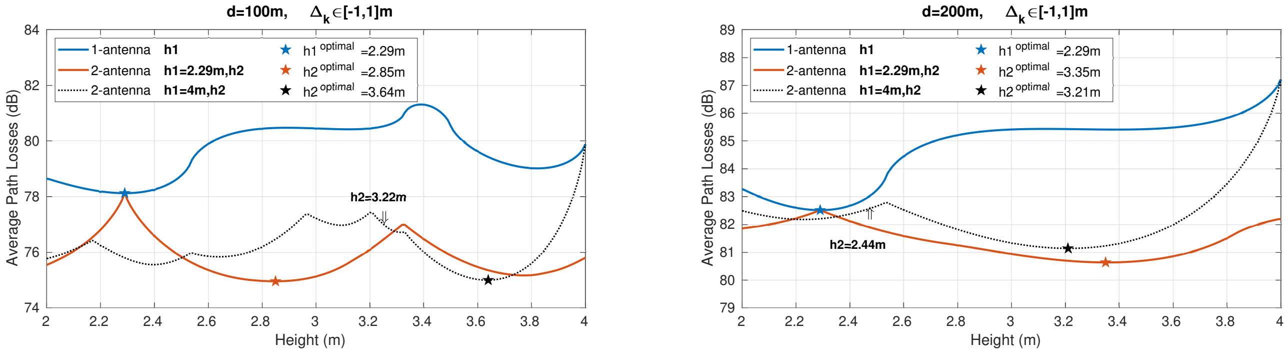
where α is a constant $\simeq 0.25$ and λ, d and h_1 are expressed in the same unit (e.g., meters).

By assuming h_1 is the (given) largest available height of the system, the height of the second antenna can be estimated as:

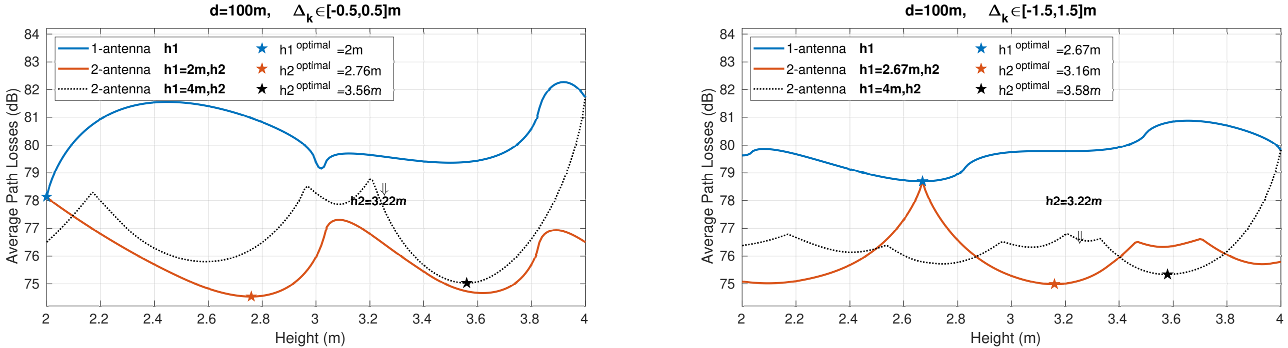
$$h_2 = h_1 - d_{sep}$$

Note that the classical space-diversity reception technique with more than two antennas is a useful but rather exceptional approach, used e.g. in cases where more than one source of deep fading can degrade the link quality of both antennas simultaneously. In over-water links, such a situation can occur, e.g., due to the combined presence of *evaporation duct* [26] and surface reflections; yet this is not within our present scope.

IMPACT OF LINK DISTANCE



IMPACT OF TIDAL RANGE



IMPACT OF ANTENNA-HEIGHT FEASIBILITY RANGE

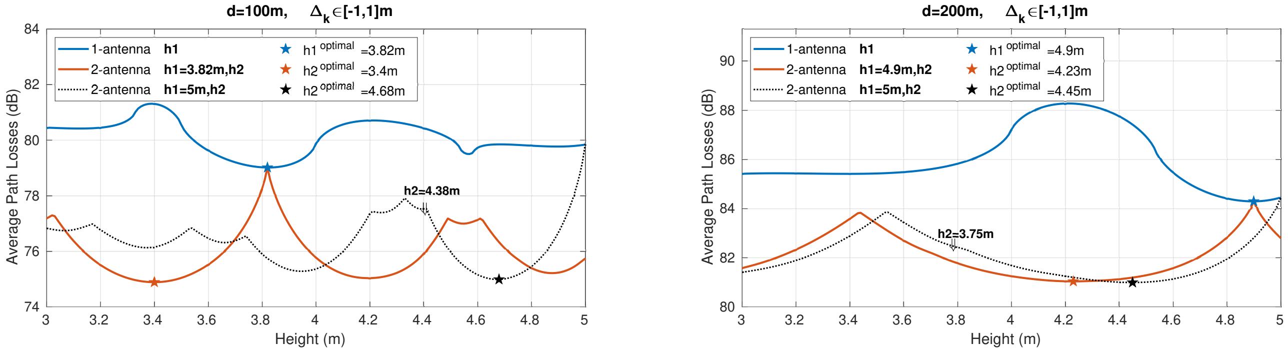


Fig. 3. Link average path losses over a given tidal range as a function of the antenna height when using: **(blue)** 1 ANTENNA; **(orange)** 2 ANTENNAS, one of them at the optimal single-case height; and **(black-dotted)** 2 ANTENNAS, one of them placed at the top. The star symbols mark the antenna heights at which reception experiences minimal average attenuation. The arrow symbol indicates the second antenna height (and overall path loss) for the classical space-diversity approach when using the first antenna at the top, and the second at the given height according to the space-diversity criterion in [10].

V. EVALUATION

In this section, we assess the performance of both the proposed optimal single-antenna and two-antennas height design versus the classical techniques. As for the single-antenna case, we contrast our method against the largest available height. The proposed two-antennas method is compared to the classical space-diversity reception technique, in this case, using one antenna at the largest possible height and the other one lowered by the recommended diversity separation according to [10].

A. *Simulation Setup*

We consider the case of static over-water links of fixed distance d, operating at a carrier frequency of $f = 2.4$ GHz (where $\lambda = c/f$, with c being the speed of light), that use both transmitter and receiver antennas at the same (nominal) height, $h_t = h_r = h$ (in meters). We assume the links are affected by a given tidal pattern which symmetrically deviate the nominal antenna-to-surface height h within $[\Delta_L, \Delta_H]$, i.e., $|\Delta_L| = |\Delta_H| = \Delta$. We also assume this is a step-wise (discretized) tidal pattern behavior with step size (resolution) of Δ_k, where Δ_k is sufficiently small for the purpose at hand.

Note that the premise of symmetric water-level variations implies the reference for the antenna height h is the same than for the tidal pattern, i.e., the midpoint between Δ_L and Δ_H. This leads to a tidal range of 2Δ, a parameter which indicates the maximum (absolute) difference between the lowest (Δ_L) and highest (Δ_H) water level deviations w.r.t. the reference. Accordingly, we suppose h is tall enough to avoid water level values to reach the antenna, thus defining a minimum height constraint, h_{min}. As for cost/deployment constraints, we assume h to be constrained to a maximum antenna height, h_{max}.

Given this setting, we search the solution space of the two optimization problems defined in (2) and (3). First, for the single-antenna case, we inspect the average path losses over the full gamut of values that h can take, and then find the height which provides minimum attenuation. Then, this output is chosen as the input for the first antenna height (h_1) of the two-antennas optimization method. We then investigate h_2 in a similar fashion, and derive the height providing the largest improvement with respect to the average path losses obtained using only h_1. We recall these results correspond to the overall average of the (mean) path loss experienced by the link, when evaluated over all the possible values within the tidal pattern.

The blue and orange curves in Fig. 3 present the average path losses as a function of the antenna height for the first and second optimization methods, respectively. The black-dotted curve is presented as benchmark, and shows the two-antennas case when one of the antennas is at the top, and the other is placed according to our method. We contrast these results versus the classical largest feasible height approach (1-antenna), as well as against the classical space-diversity techniques (2-antenna) according to [10], using one antenna at the top. We discuss these results in detail in the next subsection.

B. Simulation Results

For the given setup, we evaluate the impact of the following parameters: (1) the link distance, (2) the tidal range, and (3) the antenna-height feasibility range.

(1) **Impact of link distance.** Fig. 3 (top) presents the results of the (overall) average path losses experienced by an overwater link when evaluated over a given tidal pattern $\in [-1, +1]$m as a function of the antenna height, and when using link distances of $d = 100$m (top-left) and $d = 200$m (top-right). We consider these results are constrained to have heights within $[2, 4]$m; a common value, e.g., in ship-to-ship/land communications [18].

By observing Fig. 3 (top), we see that our method outperforms the classical techniques on both the single-antenna and the two-antennas systems, for the two link distances analyzed. On the single-antenna case, our method achieves lower overall attenuation (or equivalently, better signal strength) using a considerably lower antenna height, i.e., $h_1 = 2.29$m ($\ll 4m$) on both link distances. In particular, this (optimal) much lower antenna-height solution showed an average path loss improvement of $\sim$ 2dB and $\sim$ 5dB, for the first and second link distances, respectively. In a similar fashion, our dual antenna system outperforms the classical space-diversity technique, both in terms of antenna height and path loss.

The sub-optimal antenna-height configuration in which one antenna is at the top, and the other is placed according to our method, is shown by the black-dotted curve. This approach, although sub-optimal (but simpler), also outperformed the classical technique regarding average path loss, albeit at the cost a superior height for the second antenna (3.64m vs. 3.22m).

We observed, through further exploratory experiments, that for the same configuration but longer distances (i.e., $\gg$ 300m), our method shows observable gains of antenna height and path loss with respect to the classical techniques, with more expression in the single antenna-height case.

(2) **Impact of tidal range.** Fig. 3 (middle) presents results akin to the previous case with link distance $d = 100$m (top-left), but when reducing the tidal variation from $[-1, +1]$m to $[-0.5, +0.5]$m (middle-left), and when increasing it to $[-1.5, +1.5]$m (middle-right).

The case with smaller tidal range (typically deemed as a better scenario) shows that for the single-antenna height optimization, the minimum achievable attenuation is obtained at $h_1 = 2$m, instead of the previous $h_1 = 2.29$m; thus, representing a better result in terms of antenna-height, although with comparable overall attenuation. Interestingly, this outcome also reveals that by keeping the previous optimal antenna-height, i.e., $h = 2.29$m for the tidal behavior $[-0.5, +0.5]$m, we obtained a worse path loss performance (in about $\sim$ 5dB); thus clearly not representing a better (tidal) scenario.

In the case with greater tidal range $[-1.5, +1.5]$m (bottom-right), i.e., with larger antenna height deviations, we observe that, at the scales of distance and height considered, greater tidal ranges benefit from increasing antenna heights for both the single- and two-antenna cases, as can be drawn by inspecting the results for $[-0.5, +0.5]$m, $[-1, +1]$m and $[-1.5, +1.5]$m in sequence. Bear in mind, however, that this behaviour may not hold for other ranges of distances and heights since different evolution patterns for the phase shifts between the two received signal copies may emerge.

Then, when evaluating the classical space-diversity technique, our two-antennas optimization method shows lower overall attenuation (in $\sim$ 2-3dB), and lower antenna heights on both tidal ranges; thus, demonstrating its dominance.

A key aspect when comparing our approach against the classic technique is given by the fact that the diversity criterion (in Eq. 4) does not incorporate the tidal range as a parameter, thus making h_2 (classical) independent of this input. This observation can be corroborated, e.g., on the sub-figures top-left, middle-left, and middle-right, in Fig. 3, where the same h_2 is valid for three different tidal-range scenarios.

(3) **Impact of antenna-height feasibility range.** As stated previously, the classical space-diversity criterion does not use the tidal range as a parameter, but it depends on the link distance (d) and the maximum achievable height (h_{max}), thus being influenced by the antenna-height feasibility region. In Fig. 3 (bottom) we show the corresponding results with a configuration akin to the one presented in Fig. 3 (top), but now considering the antenna-height results to be constrained within $[3, 5]$m. This variation has a direct impact on all the methods.

As shown in Fig. 3 (bottom-left), both optimization methods (single and two-antenna) are still noticeably superior, both in terms of height and path loss, for the case of link distance $d = 100$m, but showing marginal improvement on the longer link ($d = 200m$) (see bottom-right). In addition, when comparing these results with the prior case (feasibility region within $[2, 4]$m) (see top left-and-right), both the new second diversity antennas (h_2) of the classical technique shows to be larger. This is a consistent behavior because of the simple fact that h_{max} is higher, and thus d_{sep} becomes smaller. Note that being a geometrical problem, the particular combination of distances and heights is what makes this problem relevant.

C. Discussion

Taking into account: (i) the premise that the two-ray path loss model offers a reasonably accurate description of over-water propagation; (ii) considering its application to model RF transmission over tide-affected bodies of water; and (iii) encompassing the sensible and straightforward design option of leveraging two antennas at the receptor; we observe that the behaviour of path loss can change dramatically within fairly limited ranges of distances and antenna heights.

We highlight the following noteworthy insights. The benefits of performing antenna height selection through our methods become more apparent at the shorter link distances (i.e., 100m) from the ranges considered in this work. As the ranges of tidal variation increase, the range of path loss decreases and the margin for more meaningful gains from the second antenna decreases. This can be stated by comparing the top-left, middle-left and middle-right graphs of Fig. 3. Finally, even if applying our optimization method, we conclude that placing the antenna at larger heights does not necessarily bring any considerable improvement (compare bottom-left and top-left of Fig. 3). This observation further supports our intuition that the classical approach – placing the antenna at the highest feasible height – does not lead to performance gains in this range of distances and antenna heights. The traditional approach to place the second antenna also shows its limited capability to decrease path loss, as it is not informed by the tidal range.

We finally argue that through the use of our antenna-placement methods, overall path loss decreases considerably leading to a better signal-to-noise ratio (SNR), which in turns increases the overall capacity of the link, evaluated over the full span of values of a given tidal pattern.

VI. CONCLUSION & NEXT STEPS

This work proposes a novel method for antenna-height design on short-to-medium range over-water links affected by tides. The method allows finding the height at which the minimum average path loss is experienced over (all the possibles values of) a given tidal range. Simulation results suggest that our method outperforms both (i) the common rule of using the largest possible antenna height for the single-antenna case, as well as (ii) the classical space-diversity approach when using two receiver antennas, being one of them at the top. We showed this dominance is visible on varying link configurations.

In future work, we aim at refining the general optimization method using stochastic distributions for the water level variations (e.g., over a month or year-period), as well as to evaluate the impact of its benefits on the average link capacities of over-water Wi-Fi network systems.

ACKNOWLEDGMENT

This work was partially supported by National Funds through FCT/MCTES (Portuguese Foundation for Science and Technology), within the CISTER Research Unit (UIDB/04234/2020) and within the AQUAMON project (PTDC/CCI-COM/30142/2017).

REFERENCES

[1] A. Zolich, D. Palma, K. Kansanen, K. Fjørtoft, J. Sousa, K. H. Johansson, Y. Jiang, H. Dong, and T. A. Johansen, "Survey on communication and networks for autonomous marine systems," Journal of Intelligent & Robotic Systems, vol. 95, no. 3-4, pp. 789–813, 2019.

[2] A. Casimiro, J. Cecílio, P. Ferreira, A. Oliveira, P. Freire, M. Rodrigues, and L. Almeida, "AQUAMON–a dependable monitoring platform based on wireless sensor networks for water environments," in Proceedings of the 38th International Conference on Computer Safety, Reliability and Security, 2019.

[3] G. Xu, Y. Shi, X. Sun, and W. Shen, "Internet of things in marine environment monitoring: A review," Sensors, vol. 19, no. 7, p. 1711, 2019.

[4] J. Wang, H. Zhou, Y. Li, Q. Sun, Y. Wu, S. Jin, T. Q. Quek, and C. Xu, "Wireless channel models for maritime communications," IEEE Access, vol. 6, pp. 68070–68088, 2018.

[5] A. Habib and S. Moh, "Wireless channel models for over-the-sea communication: A comparative study," Applied Sciences, vol. 9, no. 3, p. 443, 2019.

[6] M. Pereira, "Spread spectrum techniques in wireless communication part 2: Transmission issues in free space," IEEE Instrumentation & Measurement Magazine, vol. 13, no. 1, pp. 8–14, 2010.

[7] C.-W. Ang and S. Wen, "Signal strength sensitivity and its effects on routing in maritime wireless networks," in 2008 33rd IEEE Conference on Local Computer Networks (LCN), pp. 192–199, IEEE, 2008.

[8] 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 2010 IEEE Conference on Computer Communications (INFOCOM) Workshops, pp. 1–5, IEEE, 2010.

[9] D. Taplin, "Tidal fading on short oversea paths elliptical, vertical and horizontal polarisation compared," STIN, vol. 76, p. 15328, 1975.

[10] C. Haslett, Essentials of Radio Wave Propagation. USA: Cambridge University Press, 1st ed., 2008.

[11] A. Henk, "Optimum diversity separation for over-sea line-of-sight radio links," Radio and Electronic Engineer, vol. 51, no. 11, pp. 561–570, 1981.

[12] N. Fuke, K. Sugiyama, and H. Shinonaga, "Long-range oversea wireless network using 2.4 GHz wireless LAN installation and performance," in Proc. of the 12th Int'l Conf. on Computer Communications and Networks, pp. 351–356, IEEE, 2003.

[13] M. G. Gaitán, L. Pinto, P. M. Santos, and L. Almeida, "On the two-ray model analysis for overwater links with tidal variations," in 2019 11th National Symposium on Informatics (INFORUM), 2019.

[14] M. G. Gaitán, P. M. Santos, L. Pinto, and L. Almeida, "Experimental evaluation of the two-ray model for near-shore WiFi-based network systems design," in 91st Vehicular Technology Conference (VTC), IEEE, 2020.

[15] W. Wang, R. Raulefs, and T. Jost, "Fading characteristics of ship-to-land propagation channel at 5.2 GHz," in OCEANS 2016-Shanghai, pp. 1–7, IEEE, 2016.

[16] J.-H. Lee, J. Choi, W.-H. Lee, J.-W. Choi, and S.-C. Kim, "Measurement and analysis on land-to-ship offshore wireless channel in 2.4 GHz," IEEE Wireless Communications Letters, vol. 6, no. 2, pp. 222–225, 2017.

[17] K. Yang, A. F. Molisch, T. Ekman, T. Røste, and M. Berbineau, "A round earth loss model and small-scale channel properties for open-sea radio propagation," IEEE Transactions on Vehicular Technology, vol. 68, no. 9, pp. 8449–8460, 2019.

[18] J.-H. Lee, J.-S. Choi, J.-Y. Lee, and S.-C. Kim, "Experimental results of a land-to-ship propagation channel using a wideband channel sounding system at 2.4 GHz," in 2018 International Conference on Computing, Networking and Communications (ICNC), pp. 243–248, IEEE, 2018.

[19] B. Yamamoto, A. Wong, P. J. Agcanas, K. Jones, D. Gaspar, R. Andrade, and A. Z. Trimble, "Received signal strength indication (RSSI) of 2.4 GHz and 5 GHz wireless local area network systems projected over land and sea for near-shore maritime robot operations," Journal of Marine Science and Engineering, vol. 7, no. 9, p. 290, 2019.

[20] ITU, "P.530-17: Propagation data and prediction methods required for the design of terrestrial line-of-sight systems," Recommendation P.530-17, International Telecommunication Union, 2017.

[21] J. Joe, S. Hazra, S. Toh, W. Tan, J. Shankar, V. D. Hoang, and M. Fujise, "Path loss measurements in sea port for WiMAX," in 2007 IEEE Wireless Communications and Networking Conference, pp. 1871–1876, IEEE, 2007.

[22] F. B. Teixeira, R. Campos, and M. Ricardo, "Height optimization in aerial networks for enhanced broadband communications at sea," IEEE Access, vol. 8, pp. 28311–28323, 2020.

[23] A. Abdelmoaty, G. Dahman, A. A. Bousselmi, G. Poitau, and F. Gagnon, "Using vertically separated MIMO in ship-to-ship communications," IEEE Access, vol. 8, pp. 103601–103609, 2020.

[24] M. G. Gaitán, P. M. Santos, L. Pinto, and L. Almeida, "Wi-Fi-based network systems design over freshwater: Experimental evaluation using COTS devices," in 15th Doctoral Symposium in Informatics Engineering (DSIE), 2020.

[25] T. Rappaport, Wireless Communications: Principles and Practice. USA: Prentice Hall PTR, 2nd ed., 2002.

[26] L. Yee Hui, F. Dong, and Y. S. Meng, "Near sea-surface mobile radiowave propagation at 5 GHz: measurements and modeling," Radioengineering, vol. 23, no. 3, pp. 824–830, 2014.