On Channel Aware Routing Policies in Shallow Water Acoustic Networks

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***Abstract*—In this paper we consider shallow-water acoustic networks, and propose a routing policy that exploits qualitative information about the behavior of the channel, given some key parameters such as the position and depth of the source, the location of the receiver and the sea bottom profile. Our policy is based on a set of several synthetic channel realizations obtained using the Bellhop ray tracing software, where the channel variability is obtained via random perturbations of the sound speed profile and of the sea surface shape. The channel realizations are translated into Signal-to-Noise Ratio (SNR) statistics: the relay sought must comply with the constraint that the SNR exceeds a threshold with a given probability. We show that these SNR statistics allow the routing policies to identify geographic areas where a high SNR is more likely to occur.**

Our policy is compared to shortest-path routing (obtained via a centralized algorithm and oblivious of channel statistics), and to an optimal, genie-aided policy that always picks the best relay which complies to the SNR constraint. Results show that channel-aware policies consistently outperform the shortest path policy, and that our heuristic policy performs very close to the optimal one in several scenarios.

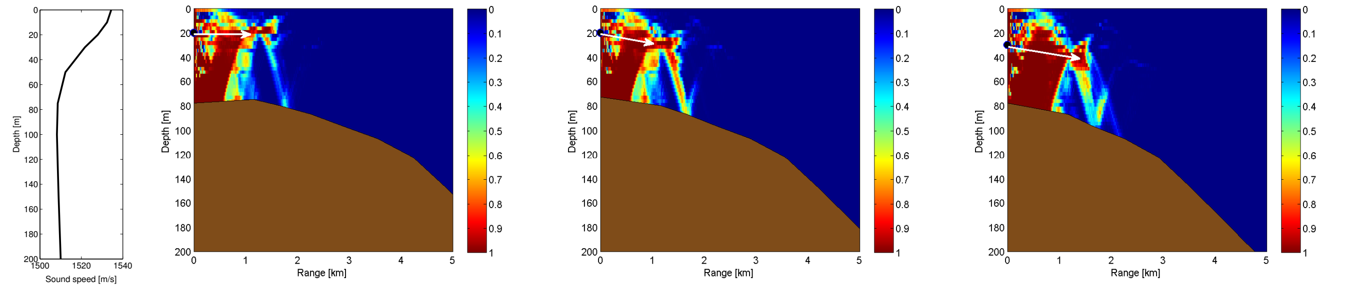
I. Introduction and Motivation

As demonstrated by several recent studies, underwater communications are subject to highly varying environmental conditions [1]–[3], which are compensated for either by designing modulation schemes resilient against adverse channel effects, or by increasing the complexity of signal processing algorithms at the receiver [4]. In addition, networking protocols should also be designed in accordance to the peculiar features of underwater propagation [5]. Such features have a significant impact on the performance of all levels of the protocol stack.

While many channel access and link control protocols designed for acoustic networks deal with (or exploit) the effects of the underwater channel, comparatively less attention has been devoted to the design of routing protocols. In particular, among the first routing protocols proposed for underwater networks, those in [6], [7], e.g., exploit some typical topological features of these networks, and account for attenuation using a simple link budget model [8]. Building on the considerations in [9], Focused Beam Routing (FBR) [10] implements an algorithm for finding relays that provide a good trade-off between energy consumption and hop length. Such relay nodes are sought at increasing distance from the transmitter, since it was shown in [9] that, given a certain optimal hop length, a path with more (hence shorter) hops is less suboptimal than a path with fewer (longer) hops in terms of energy and delay. The authors in [11] look at the issue of underwater routing from a delay viewpoint, and study policies for delay-tolerant and delay-sensitive underwater networks. Another protocol exploiting the underwater channel, and in particular the typically better sound propagation over vertical channels, is Depth-Based Routing (DBR) [12]. DBR assumes all nodes to be equipped with a pressure gauge from which the current depth can be estimated: routing is then performed by looking for relays at progressively lower depth, so as to advance the packet towards the sea surface. A similar concept, along with a recovery technique to cope with the absence of suitable neighboring relays at lower depth than the current packet holder, is discussed in [13].

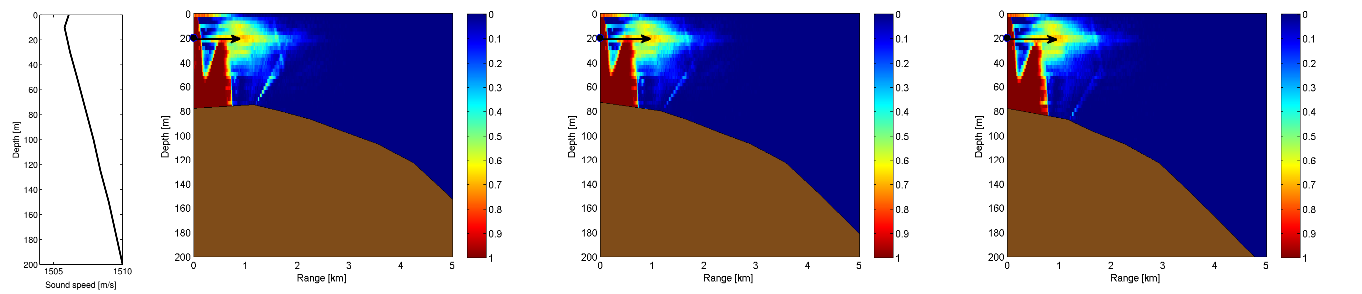
In this paper, we focus on the design of a channel-aware, local routing policy for acoustic networks. Our study stems from the idea that the different sound refraction effects observed in different seasons require specific routing approaches. Consider a shallow water scenario in summer. Typical temperature gradients due to warmer surface layers tend to increase the speed of sound near the surface, causing sound waves to be refracted downward. Conversely, in winter the speed of sound is more uniform, albeit typically lower close to the surface, and higher near the sea bottom: this causes sound waves to be slightly bent upward, and therefore to insonify the upper water layers more than the bottom ones. Routing policies should take such effects into account: for example, next hops located near the surface beyond a given maximum distance should not be considered when transmitting in summer and from a deeper location: in fact, the sound would be confined towards the sea bottom because of refraction. Hence, the probability that a sufficiently high signal power is able to reach the relay would be very low.

As an example, Figs. 1 and 2 depict the probability that a signal is received with a Signal-to-Noise Ratio (SNR) of at least $20\,\mathrm{dB}$ as a function of the position of the receiver, when the transmission takes place from the position indicated by the black dot on the left of each picture. The figures refer to a summer and a winter scenario, respectively. The location of the simulation is near the Pianosa island, Italy. The received signal power is obtained via the Bellhop [14] ray tracing software and is computed as the power of the complex sum of all rays reaching the receiver. This approximates, e.g., an



(a) (b) (c) (d)

Figure 1. Example of next hop choices in a shallow water scenario in summer. (a) sound speed profile; (b)–(d) 1st to 3rd hop. Red hues correspond to a higher probability that the received SNR exceeds a threshold of $20\,\mathrm{dB}$.



(a) (b) (c) (d)

Figure 2. Example of next hop choices in a shallow water scenario in winter. (a) sound speed profile; (b)–(d) 1st to 3rd hop. Red hues correspond to a higher probability that the received SNR exceeds a threshold of $20\,\mathrm{dB}$.

incoherent receiver which observes the superposition of several arrivals of the same acoustic signal and does not perform any equalization or similar signal processing techniques.[1] The probability that the SNR exceeds the wanted threshold of $20\,\mathrm{dB}$ at any point is computed as an average over 100 realizations of the propagation process, where each realization is obtained by applying a small random displacement to the sound speed profile (SSP) and by generating a different sea surface shape.

Assume that a packet is to be routed towards the right of the scenario, starting from the point on the left in each figure. In order to ensure correct packet reception, the transmitter may seek a relay in an area where the SNR matches the constraints described above, in addition to advancing the packet as much as possible towards the destination. In the figures, an arrow indicates a preferable location where to find a relay that jointly addresses these two objectives. In more detail, assume that the transmitter wants to allow a probability of at least 0.75 that the SNR is greater than $20\,\mathrm{dB}$ while traveling hops at least $1\,\mathrm{km}$ long. Considering Fig. 1, as observed before, in summer the sound tends to be refracted towards the bottom. This is apparent, e.g., from Fig 1(c), where we observe several zones where the SNR is unlikely to be above $20\,\mathrm{dB}$. We also note that some of these zones are even quite close to the source. In addition, observe that the down-bent sound waves tend to bounce off the bottom and to be refracted downward, never to reach the surface again with sufficient power. In such a scenario, the preferred relay position is consistently located closer to the bottom than the source over the last two hops. The first hop shows a different behavior, in that the next relay is located at roughly the same depth as the source: this is due to the slightly increasing depth of the sea bottom up to a distance of $1\,\mathrm{km}$ from the source.

Overall, these observations suggest that a good heuristic policy, when transmitting over multiple hops in summer, would be to look for deeper relays within a distance of $500\,\mathrm{m}$ to $1\,\mathrm{km}$, depending on the source depth (the deeper the source, the longer the range). If the transmitter can allow a lower probability that the received signal exceeds the desired SNR, the downward refraction of the bottom bounces creates a second zone even farther from and deeper than the receiver, where a relay can also be sought. We note that, in a typical network, it is reasonable to assume that the nodes can retrieve depth information from embedded pressure sensors, and that they have at least a rough estimate of their distance (e.g., due to handshaking procedures, or due to previous time-stamped message exchanges): therefore, simple policies such as the one described above are quite easy to implement in practice.

In winter (Fig. 2), a mild upward refraction effect allows a more even sound distribution throughout the watercolumn.

[1] Other receiver behaviors can also be modeled by properly processing the received ray patterns output by Bellhop. For example, defining the received signal power as the sum of the powers of all rays (or a fraction thereof) would make a better model for coherent receivers. In this paper we present results for both cases.

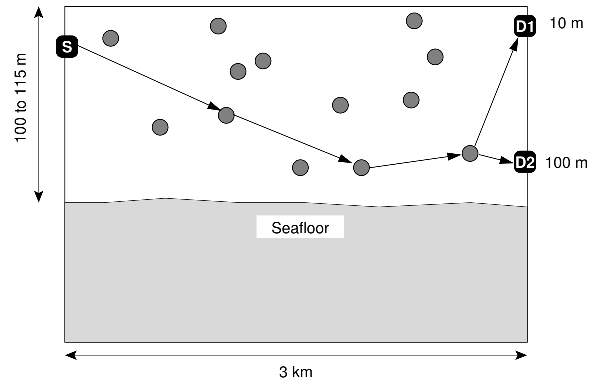


Figure 3. Example of a scenario considered in our evaluation. The source is placed on the left, whereas two separate destinations are placed at $3\,\mathrm{km}$ from the source at a depth of $10\,\mathrm{m}$ and $100\,\mathrm{m}$. A typical summer routing path is also shown: the links connect nodes at increasingly greater depth until the packet reaches the proximity of the receivers, where direct delivery (possibly via a more convenient vertical channel) is performed.

Therefore, it is more convenient to look for relays located at the same depth as the source, within a distance of around $1\,\mathrm{km}$. In this case, we also note that transmitting to a relay located at a lower depth would also yield a good probability of having an SNR greater than $20\,\mathrm{dB}$, but even a relay at the same depth as the source would meet the SNR constraint, while on the other hand providing a longer hop distance.

II. Scenario and protocol description

In order to better explain the type of scenarios considered in this paper we refer to Fig. 3. We assume that one source and several destinations are placed at a distance of $3\,\mathrm{km}$ in a shallow water environment. The presence of more destination nodes is suitable to highlight the different behavior of routing policies as they forward packets toward the sea bottom or the surface. The overall network (including the source and the destinations) is composed of 10 to 30 nodes, randomly deployed within the network area. This makes it possible to model several network densities. In order to have a connected network, all network realizations are such that any node has at least one neighbor within a radius of $1500\,\mathrm{m}$. We consider two different sea bottom shapes, namely, a flat and a decreasing bathymetry. As the propagation of sound is quite different in summer and winter, we will consider both seasons.

We recall from Sect. I that the behavior of the channel is statistically modeled starting from a collection of several channel realizations. Each realization is made different by adding a random displacement of $\pm 1\,\mathrm{m/s}$ to each sample of the seasonal average values of the SSP extracted from the World Ocean Database [15]. In addition, a random surface wave profile is generated each time according to a Bretschneider 2-parameter spectrum [16] with characteristic wave height $\bar{H}_{\mathrm{char}} = 1.5\,\mathrm{m}$ and average wave period $\bar{T} = 3\,\mathrm{s}$. For each realization of the environment, we compute the propagation in the network area every $50\,\mathrm{m}$ of distance and every $10\,\mathrm{m}$ of depth, and repeat the computation for several source depths, from 10 to $100\,\mathrm{m}$, in steps of $10\,\mathrm{m}$. This sampling is fine enough to allow a good evaluation of the channel behavior for nodes placed at any point in the network area. However, the quite high burden related to the computation of channel statistics requires to subsample the possible distances at which a relay is typically found, and from which the channel behavior should be simulated again in order to model the performance of the relay transmission. In the following study, we reduce this by setting the carrier frequency of the acoustic signals (which is also employed to perform ray tracing) to $25\,\mathrm{kHz}$ and the transmit power per unit frequency to 120 dB re $\mu\mathrm{Pa/Hz}$. These choices result in forwarders being found at a distance of about $1\,\mathrm{km}$ from the current relay. Therefore, we simulate the channel at distances that are multiples of $1\,\mathrm{km}$ and, at every forwarding step, we pick the set of results corresponding to the location closest to the current relay.

Our evaluation will involve three different protocols. The first one is a pure shortest path approach, which builds routes with the least number of hops. We note that the shortest path algorithm is completely oblivious of the channel performance. Therefore, in such scenarios as the one in Fig. 1(b), a relay may as well be found in the area around $1.5\,\mathrm{km}$, between 30 and $80\,\mathrm{m}$ of depth, where the specific propagation pattern makes it very unlikely that the received signal has a sufficiently high SNR (recall that the blue area corresponds to a very low probability that the SNR exceeds $20\,\mathrm{dB}$). In turn, this would require many retransmissions to compensate errors over such a link or, in the absence of retransmissions, it would lead to a very low probability of success.

The second policy we consider for comparison implements a genie-aided approach which pursues the optimization of packet delivery ratio (PDR) at each forwarding step. The PDR is defined as the probability that the SNR exceeds a desirable threshold θ_D, where $\theta_D = 20\,\mathrm{dB}$ in Fig. 1(b). This policy assumes that the transmitter has complete knowledge of the channel and always chooses the path that ensures the maximum packet delivery ratio for a given scenario. We recall that we consider a shallow water scenario, hence the choice of a purely vertical channel spanning the typical relay distance of about $1\,\mathrm{km}$ is not possible, which ensures that data packets are in fact advanced towards the destination.

The last approach is our heuristic routing policy, and is based on the qualitative description of the watercolumn sections where it is likely to find a relay that experiences a desirable SNR statistics. For example, refer again to Fig. 1(b). To ensure that the SNR exceeds a threshold $\theta_D = 20\,\mathrm{dB}$ with a certain probability, say at least 0.75, a relay must be located at the same depth of the source within a distance of about $1.5\,\mathrm{km}$, or otherwise below the source, at a depth-dependent distance (e.g., $900\,\mathrm{m}$ for a depth of around $30\,\mathrm{m}$ or $750\,\mathrm{m}$ for a depth of $50\,\mathrm{m}$). Similar considerations, albeit with slightly different numbers, apply to the other scenarios in Fig. 1. Following this rationale, based on the heuristic policy, the nodes pick the next relay node based on their distance (the greater the better) and on the depth (the deeper the better during summer, whereas depth is not relevant during winter). We note that these policies require only some degree of knowledge about the position of the nodes in terms of distance and depth, and are quite easy to implement in practice: depth sensors are commonly available equipment in typical underwater node packages [12], while the selection of a relay node (possibly out of several) typically involves some form of handshaking from which the distance of the relay can be inferred, as also observed in [10].

As a final remark, note that channel conditions change as a function of the time of day. Hence, for our policy to work correctly, the nodes in the network should be periodically informed about the areas where the relays should be looked for. In other words, the channel state information at the transmitter should be periodically updated. In this work, we assume that some networked entity with good computational power (e.g., a ship at sea, or a lab ashore connected to a network node) can perform the required processing and deliver the information about convenient relay search areas to the nodes. While this may seem a burdensome operation, we observe that, on one hand, our policy requires only a rough specification of search areas in terms of depth and distance, and on the other hand it is not necessary to perform very frequent updates, as also discussed in [17].

A. Routing metrics

In the following, we will perform a comparison between the routing protocols mentioned above in terms of typical routing metrics such as the delivery delay and the probability of success over a link as well as that of a complete route. For computing the delay, we will consider both a non-reliable and a fully-reliable transmission scheme over each link, where in the first case only one attempt to transmit a data packet is made, whereas in the second case, nodes keep trying until the packet has been correctly received, as confirmed via an acknowledgment (ACK) packet. Call L_D and L_A the length of a data and an ACK packet, respectively. Let R be the transmit bit rate, so that the packet transmission times for data and ACKs are $T_D = L_D/R$ and $T_A = L_A/R$, respectively. Call h the number of hops to be traveled towards the destination, and τ_i the propagation delay over link $(i, i+1)$. In accordance with the arguments in the previous subsection, we model correct packet reception using a threshold model. Namely, let γ_i be the SNR over link $(i, i+1)$, and call $p_i = \mathbb{P}[\gamma_i > \theta_D]$, where θ_D is the Signal-to-Noise Ratio (SNR) threshold that ensures the correct reception of a data packet.[2] In the absence of retransmissions to recover erroneous packets, the transmission delay D_i over link $(i, i+1)$ can be computed as $D_i = T_D + \tau_i$, whereas in case of a fully reliable retransmission policy over each link, we have $D_i = (T_D + T_A + 2\tau_i)/p_i$, where we assumed the use of Stop-and-Wait ARQ for simplicity. In other words, in the latter case the data packet is retransmitted until it is correctly received by the next hop. In either case, the overall path delay is found as the sum of the delay over each link of the path, $D = \sum_{i=0}^{h-1} D_i$. Along the same line, the PDR in the unreliable case is $\prod_{i=1}^{h}(1 - p_i)$, whereas it is trivially equal to 1 for the fully reliable transmission policy.

[2]We assume that the data packet is encoded using a powerful channel code, so that the threshold model for the PDR is sufficiently accurate.

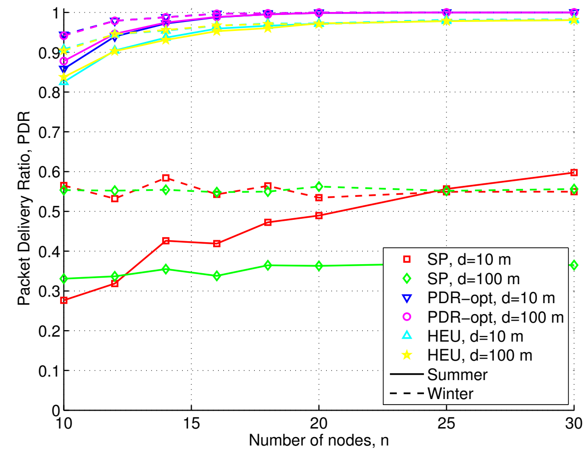


Figure 4. Packet delivery ratio (PDR) for different routing policies with no retransmissions in a flat sea bottom scenario. The received signal power at any point is computed as the sum of the powers of all rays reaching that location.

III. Simulation results

In the following we present a performance comparison for the routing policies described above in different settings. We will consider the overall route packet delivery ratio, the number of hops and the packet delivery delay. We will distinguish between two different destinations, one situated at a depth of $d = 10\,\mathrm{m}$ and a second one at a depth of $d = 100\,\mathrm{m}$. To fix ideas, we set the data and ACK packet lengths to 1000 and 100 bits, respectively, so that $T_D \approx 0.21\,\mathrm{s}$ at a bit rate of $4800\,\mathrm{bps}$, and $T_A = 0.1T_D$. For the moment, the received signal power at any given point is computed as the sum of the powers of all rays arriving at that location. All other parameters are as described at the beginning of Sect. II: we recall here that the network consists of a given number of nodes n ranging from 10 to 30, randomly placed within the watercolumn. All simulation results are averaged over 1000 network realizations, which guarantees the required statistical confidence.

We start from Fig. 4, which depicts the route packet delivery ratio (PDR), defined as the product of the probabilities of transmission success across all route links, see also Sect. II-A. The curves are plotted as a function of the number of nodes, n. In this figure, as well as in the following ones, we draw two sets of lines: solid ones refer to a summer environment, whereas dashed lines refer to winter. In either season, we compare our heuristic policy (HEU) against a shortest path (SP) algorithm and a centralized channel-aware policy performing the optimization of the packet delivery ratio throughout the route (PDR-opt). For each policy, we plot two separate curves: one refers to the route toward the destination at $10\,\mathrm{m}$ of depth, the other to the $100\,\mathrm{m}$ deep destination node. The first observation regarding Fig. 4 is that the SP policy performs poorly both in summer and in winter: in fact, SP operates in a way that is completely oblivious of the acoustic channel, and therefore may end up selecting relays characterized by a low probability that the SNR is above the required threshold.

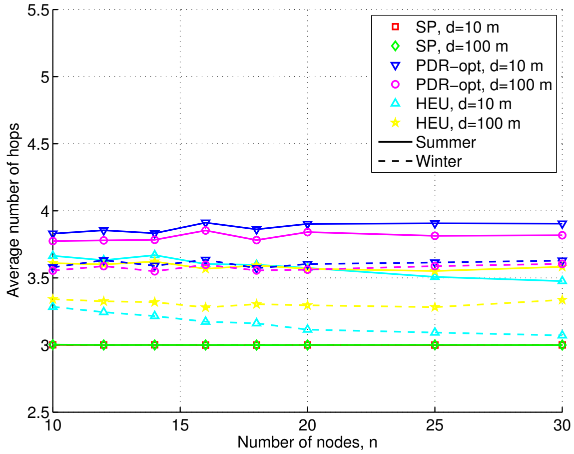


Figure 5. Average number of hops for different routing policies with no retransmissions in a flat sea bottom scenario (unreliable case). The received signal power at any point is computed as the sum of the powers of all rays reaching that location.

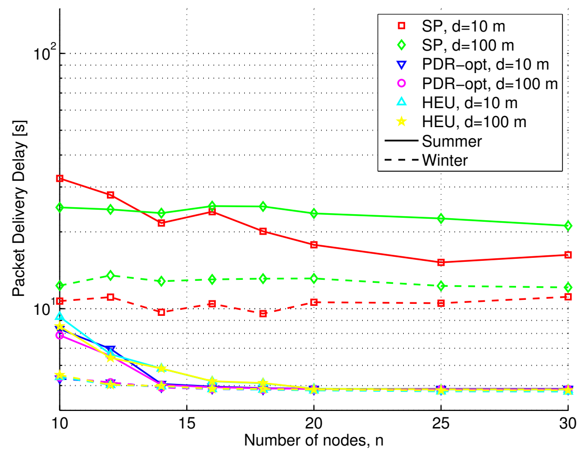


Figure 6. Average delivery delay for different routing policies with S&W ARQ in a flat sea bottom scenario. The received signal power at any point is computed as the sum of the powers of all rays reaching that location.

The slightly higher performance achieved in winter is due to the better distribution of the acoustic power throughout the watercolumn, which in turn increases the probability that a relay is actually reached by a signal with a sufficiently high SNR. While the PDR-opt policy outperforms all other policies in both seasons and all scenarios, the heuristic (HEU) policy has a very similar performance for a sufficiently dense networks, whereas it slightly suffers when the network is sparse: in fact, in the latter case there is a lower chance to find a relay located at a convenient position in terms of SNR. Observe that there is little difference between the curves for the destinations at 10 and $100\,\mathrm{m}$: this is due to the fact that the established routes are very similar until the packet is in the proximity of the destinations, from where direct delivery is performed. For example, both the PDR-opt and HEU policies try to find relays with good channels, which leads to the choice of nodes closer to the sea bottom in summer (as also exemplified in Fig. 3).

We recall that the route packet delivery ratio inherently assumes that link-level communications are performed in an unreliable way, i.e., without performing any retransmissions. In this case, the delivery delay, for those packets that correctly reach their destination, is low and equal to the propagation delay of the acoustic signal plus one data packet transmission time for each route hop. Since the latter is the only relevant information, we plot the average number of hops in Fig. 5. We observe that the SP policy consistently employs the minimum number of hops (i.e., 3) to reach either destination, whereas the PDR-opt and HEU policies require on average more hops to reach the destination. This is because these policies look for nodes towards which the transmission is reliable rather than simply finding the farthest possible node towards the destination at any hop. We also note that in summer these channel-aware policies require a slightly higher number of hops, because the insonification of the watercolumn in this season is less homogeneous, and yields a lower probability to find nodes at longer hop distances.

We now switch to the reliable case, where we assume that a Stop-and-Wait (S&W) ARQ scheme is used at the link layer to ensure correct data transmission at each hop. In this case, the delivery delay obeys the equations in Sect. II-A, and is depicted in Fig. 6. The behavior of the curves reflects that of the PDR in Fig. 4, as the SP policy requires a much longer time before a packet can correctly reach its destination. On the contrary, the channel-aware policies perform better, and in particular HEU achieves a delivery delay as low as that of PDR-opt whenever the number of nodes is sufficiently high.

In Fig. 7, we still focus on the packet delivery delay, but consider a decreasing sea bottom profile. As opposed to the previous figures, the deepest destination here is placed at a depth of $75\,\mathrm{m}$ as the sea bottom is shallower than $100\,\mathrm{m}$ at a distance of $3\,\mathrm{km}$ from the source. We observe that the trend of the curves is qualitatively similar to that of the flat scenario. However, the delivery delay achieved by the SP policy for the deepest destination in summer is much higher: this is due to the fact that, again, the best insonification is located close to the bottom, in contrast to most of the relay choices performed by SP, which are oblivious to channel conditions. On the contrary, channel-aware policies take these aspects into consideration, and thus their delay performance is similar to the flat bottom case.

We conclude our evaluation by considering the delivery delay of the routing policies with S&W ARQ using a different receiver model: namely, we compute the received signal power at any point of the watercolumn as the power of the coherent sum of all rays traced to that point. The sea bottom profile is flat in this case. The results are reported in Fig. 8, which shows slightly worse results than in Fig. 6. In fact, in this case the superposition of different rays may give rise to destructive interference, and to such patterns as those in Fig. 1 and 2. As the distribution of sound power is not uniform, when the number of nodes is low the routing policies typically have

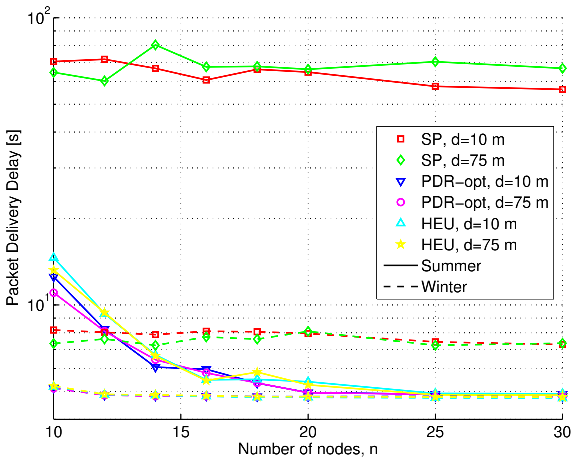


Figure 7. Average delivery delay for different routing policies with S&W ARQ in a decreasing sea bottom scenario. The received signal power at any point is computed as the sum of the powers of all rays reaching that location.

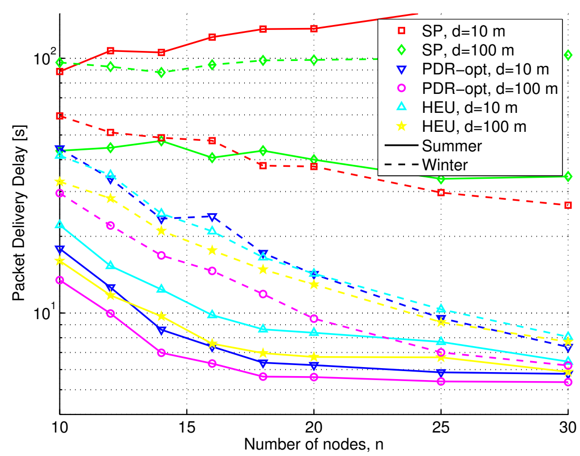


Figure 8. Average delivery delay for different routing policies with S&W ARQ in a flat sea bottom scenario. Unlike in the other figures the received signal power at any point is computed as the power of the coherent sum of all rays reaching that location.

to use less reliable links, which turns into a higher delivery delay due to the greater number of retransmissions to be performed. Notably, the HEU policy performs very close to the PDR-opt policy, as HEU is designed around the features of the acoustic propagation both in summer and in winter. This channel awareness makes HEU improve significantly over SP, even if the propagation patterns in this last case are less favorable, due to the different way of computing the received acoustic power.

IV. Conclusions

In this paper, we have discussed channel-aware routing policies for underwater acoustic networks operating in shallow waters. Starting from the observation that the areas of strong sound propagation can be predicted and easily characterized in terms of distance and depth of suitable relays, we designed a heuristic routing policy that selects relay nodes according to such a description of the channel behavior. Our comparison shows that this policy works well in different scenarios and seasons: it consistently outperforms channel-oblivious shortest-path policies, and yields similar results with respect to a genie-aided, centralized policy which is perfectly aware of the channel and always picks the relays providing the best packet delivery ratio.

Future work on this topic includes the design of a full-fledged routing protocol tailored around the behavior of the heuristic policy, and the integration and evaluation of techniques that automatically describe the areas where the channel yields the best performance.

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