Energy-Efficient Routing Schemes for Underwater Acoustic Networks

Michele Zorzi, *Fellow, IEEE*, Paolo Casari, *Member, IEEE*, Nicola Baldo, *Student Member, IEEE*, and Albert F. Harris III

***Abstract*—Interest in underwater acoustic networks has grown rapidly with the desire to monitor the large portion of the world covered by oceans. Fundamental differences between underwater acoustic propagation and terrestrial radio propagation may call for new criteria for the design of networking protocols. In this paper, we focus on some of these fundamental differences, including attenuation and noise, propagation delays, and the dependence of usable bandwidth and transmit power on distance (which has not been extensively considered before in protocol design studies). Furthermore, the relationship between the energy consumptions of acoustic modems in various modes (*i.e.*, transmit, receive, and idle) is different than that of their terrestrial radio counterparts, which also impacts the design of energy-efficient protocols. The main contribution of this work is an in-depth analysis of the impacts of these unique relationships. We present insights that are useful in guiding both protocol design and network deployment. We design a class of energy-efficient routing protocols for underwater sensor networks based on the insights gained in our analysis. These protocols are tested in a number of relevant network scenarios, and shown to significantly outperform other commonly used routing strategies and to provide near optimal total path energy consumption. Finally, we implement in ns2 a detailed model of the underwater acoustic channel, and study the performance of routing choices when used with a simple MAC protocol and a realistic PHY model, with special regard to such issues as interference and medium access.**

***Index Terms*—Underwater acoustic networks, routing schemes, performance analysis, characteristic distance, energy-efficient protocol design.**

I. Introduction

THE GROWING interest in the design of underwater ad hoc networks is driven by the desire to provide autonomous support for many activities, such as monitoring of equipment (*e.g.*, underwater oil mining rigs) and natural events (*e.g.*, underwater seismic activity). Radio technology is unsuitable for underwater environments due to its poor propagation through water. As a result, acoustic modems are the current technology of choice for these scenarios [1]–[3].

Underwater protocol design has drawn the attention of the networking research community only very recently, and as a result little work exists in this area. While considerable work has been done at the physical layer [4]–[6] and in building devices [7], work at higher layers of the protocol stack is just beginning [1]–[3]. There have been a few proposals for MAC-layer schemes to handle increased delay while still providing reliability or energy efficiency [8]–[14]. This work has shown that the differences in propagation properties for underwater acoustic signals may greatly affect the optimal choices for MAC-layer protocols, and that there is still much room for innovation. Early work on routing and transport layer protocols has focused on dealing with the long delays present for acoustic signals while providing energy-efficient reliability [15]–[18], but has not included important propagation factors such as the bandwidth-distance and power-distance relationships, which affect energy consumption through both power and rate, nor specific modem energy consumption characteristics.

Energy-efficient routing in terrestrial networks has been well studied and a large number of algorithms have been proposed [19]–[25]. Some of these algorithms deal with increasing the hop-count, thereby decreasing hop-distance, which may result in lower total energy consumption. Other works deal with selecting paths that allow the maximum number of nodes to transition into a low-power sleep state. The relationship between the total energy consumption along a straight route and the number of hops has been explored in [26], where it is also shown that in this case the minimum energy path consists of equally spaced relays, where the optimal hop distance (called *characteristic distance* in the paper) can be analytically computed from the propagation characteristics and a first-order energy model. The implications this result has on the design of routing schemes, not explored in [26], have been considered in [27], where forwarding techniques are designed in the context of energy and traffic balancing. The paper that comes closest to our approach is [28], where a routing protocol is designed in which a relay is chosen as the node closest to the optimal relay position determined in [26].

A critical component for the development of routing protocols is the understanding of the impacts of channel properties, such as path loss and bandwidth, on key metrics used for routing, such as energy consumption and delay. While work on capacity and bandwidth for terrestrial radio networks is well known [29], no equivalent work is available for underwater acoustic networks. Preliminary link capacity results were presented in a very recent paper [30], that defines the impact of the bandwidth-distance relationship on link bit rate and power but does not directly extend to a multihop or multi-flow viewpoint.

Manuscript received March 1, 2008; revised August 31, 2008. This work has been partially supported by the NATO Undersea Research Center under contract no. 40480700 (ref. NURC-010-08). Part of this work was presented at the IEEE SECON 2007 conference.

M. Zorzi, P. Casari and N. Baldo are with the Department of Information Engineering, University of Padova (e-mail: {zorzi,casarip,baldo}@dei.unipd.it).

A. Harris is with the Center for Remote Sensing of Ice Sheets, University of Kansas (e-mail: afh@cresis.ku.edu).

Digital Object Identifier 10.1109/JSAC.2008.081214.

In the present paper, we develop algorithms to minimize the total path energy consumption in an underwater acoustic network by leveraging observations made through a study of the impacts of the propagation characteristics of acoustic signals. To our knowledge, this is the first attempt to perform such a study for underwater acoustic networks. Taking these effects explicitly into account provides a much more realistic study, and leads to different design criteria, whereas traditional approaches lead to inefficient solutions. When considering a different scenario (underwater vs. terrestrial), where the rules of acoustic propagation are significantly different from those for radio, it remains to be determined whether the design criteria and the results reported for terrestrial networks still apply. For example, in underwater acoustics, where the relationship between the relay displacement compared to the optimal position and the energy consumption is significantly asymmetric (i.e., choosing longer- rather than shorter-than-optimal hops leads to significantly different degrees of energy suboptimality), the symmetric approach of [28] does not necessarily lead to good solutions. In addition, the analyses reported in [26]–[28] tend to consider rather simplified network deployments, or do not study in detail the suboptimality effects related to the random node deployments.

The main contribution of this work is the first in-depth analysis of the effects of all the main characteristics of underwater acoustic signal propagation and of the acoustic modem energy consumption profiles on energy-efficient routing design. To this end, we first present in Section II the characteristics of underwater acoustic channels (highlighting especially the bandwidth-distance relationship), the energy consumption profile of current acoustic modems, and the relevant computations of delay and energy consumption over an acoustic link, which provide the basis for the analysis of multihop schemes in an underwater scenario and the design of proper protocols. To provide protocol design guidelines, we analyze the routing performance based on hop-distance, delay, and energy consumption. We first develop in Section III a simple analysis to test the effect of hop length and node density on the statistics of the path energy consumption. Based on the key observation that an optimal hop distance exists, in Section IV we develop routing algorithms where relays are chosen so as to provide a hop length close to the optimum, and compare them with standard routing approaches such as shortest path and greedy minimum energy, as well as the centrally computed minimum-energy benchmark. By means of simple simulations, we show that the overall path energy consumption for the routes found by the proposed algorithms is always close to the optimum and significantly better than those obtained with the other schemes. For a more realistic evaluation, we also implement a complete protocol suite (PHY, MAC, routing and application) together with the underwater channel model in ns2, and use this model to test the impact of some issues expected in real systems, such as interference and congestion, on the performance of our routing protocol. The numerical results again show that our approach outperforms other strategies, achieving better trade-offs between energy, throughput and delay. Finally, Section V outlines some conclusions and future directions.

II. Basic Features of Underwater Propagation

This section characterizes the unique bandwidth-distance relationship, signal-to-noise ratio (SNR), and propagation delay in an underwater acoustic channel. For a more complete description of underwater channel characteristics see Urick [31] and Stojanovic [30]. The energy consumption characteristics of a typical acoustic modem, as well as the relevant link budget equations to be used in the computation of path energy consumption, are also described.

We stress that all these features of acoustic propagation and devices significantly affect the performance of a protocol. Unlike past efforts, in which only a subset of these effects were considered, the protocol design proposed in this paper is the first to explicitly include all of them.

A. Attenuation and propagation delay

The attenuation factor $A(\ell, f)$ of an underwater acoustic channel for a distance ℓ and a frequency f can be empirically modeled in terms of the spreading loss, the absorption loss, and the spreading coefficient k, as follows [31]:

$$10 \log A(\ell, f) = k \cdot 10 \log \ell + \ell \cdot 10 \log a(f), \qquad (1)$$

where the first term is the spreading loss and the second term is the absorption loss. The spreading coefficient defines the geometry of the propagation (*i.e.*, $k = 1$ is cylindrical, $k = 2$ is spherical, and $k = 1.5$ is practical spreading [31]).

Thorp's formula (also empirically derived) can be used to express the absorption coefficient $a(f)$ for frequencies above a few hundred Hz as follows [32]:

$$10 \log a(f) = \frac{0.11 f^2}{1+f^2} + \frac{44 f^2}{4100+f^2} + \frac{2.75 f^2}{10^4} + 0.003, \qquad (2)$$

where $a(f)$ is given in dB/km and f is in kHz. The absorption coefficient is the major factor that limits the maximum usable bandwidth at a given distance, as it increases very rapidly with frequency. This model describes the attenuation on a single, unobstructed propagation path. If a tone of frequency f and power P is transmitted over a distance ℓ, the received signal power will be $P/A(\ell, f)$.

The underwater acoustic propagation speed c in m/s has been shown to depend on a number of factors, including the water depth and its temperature and salinity [31]. For the purposes of this paper, also in view of the rather weak dependence of c on these factors, we assume $c = 1500$ m/s, which is a commonly considered average value. The use of more sophisticated models, e.g., to relate the depth of an underwater link to the corresponding propagation delay, is left for future study, although we do not expect them to provide any significant additional insight on routing, compared to what is discussed in the present paper.

B. Transmission Distance and Bandwidth

For typical terrestrial radio environments, shorter transmission distances lead to either the ability to use lower power (due to less signal attenuation), or the ability to use higher bit rates (due to a higher signal-to-noise ratio), but the bandwidth available remains constant. For the underwater acoustic environment, however, not only do these two effects

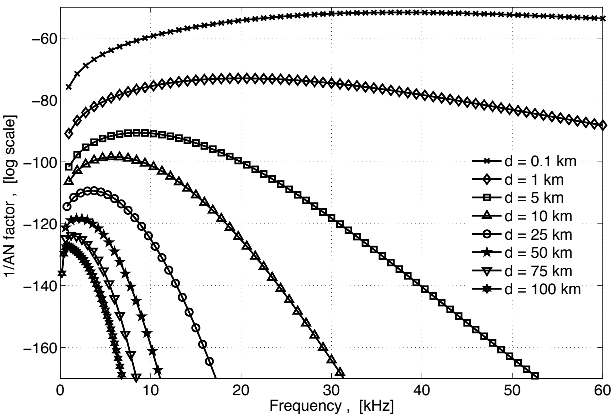

Fig. 1. 1/AN factor vs. frequency, for various link distances

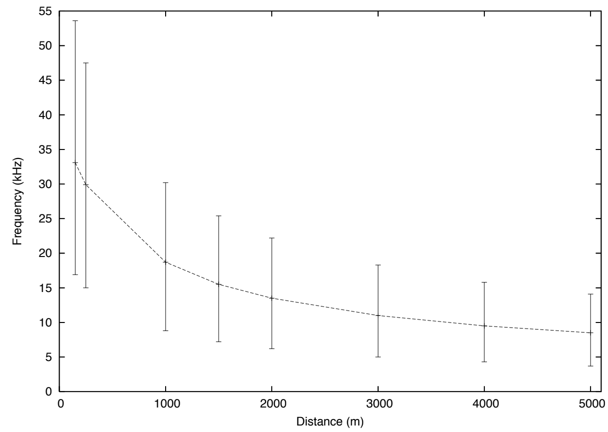

Fig. 2. Optimal frequency vs. distance, and 3-dB bandwidth (bars)

exist but the bandwidth available increases as the distance decreases, a fundamental difference between acoustic channels and radio channels. This is due to the fact that both signal propagation and noise in underwater environments show a significant dependence on frequency [31], unlike in wireless radio where the noise at the receiver is well approximated as white, and frequency selectivity, though present, is usually less pronounced [33]. The combination of these two effects, represented by the attenuation $A(\ell, f)$ and the noise power spectral density $N(f)$, characterizes the communications behavior in the frequency domain.

The complex distance–bandwidth relationship is best explicated by considering the $1/AN$ factor (which is proportional to the SNR at the receiver) across frequencies for different distances (Figure 1). For a given value of the distance ℓ, there exists a frequency that corresponds to the best attenuation/noise combination for the channel, and the bandwidth can then be defined using some criterion. In [30], two examples were given, i.e., a heuristic 3 dB bandwidth definition and an optimal capacity-based bandwidth definition. In both cases, as distances decrease, not only do the maxima in the curves change (different attenuation), but also the widths of the curves change (different bandwidth). This corresponds to a broader bandwidth spectrum available to the shorter links, allowing a larger link capacity. Figure 2 shows the best frequency as a function of the link distance ℓ, with the bars representing the available bandwidth.

Following the theoretical analysis in [30], for a given performance objective (target SNR) the usable bandwidth $B(\ell)$ and the required transmit power $P_t(\ell)$ can be calculated as a function of the transmitter-receiver distance, ℓ. Such relationships can also be approximated by empirical formulas of the form

$$B(\ell) = b\ell^{-\beta}, \qquad P_t(\ell) = p\ell^{\pi} \tag{3}$$

where the positive parameters b, β, p, π depend on the target SNR. More details can be found in [30].

Note that the theoretical behavior illustrated in (3), where the transmit power and the transmission bandwidth can be adjusted to any value, is not available in current devices, and may present significant difficulties even in next generation modems. The analysis that we present, however, has significant theoretical value both as a bound to what can be achieved and as a motivation for more capable devices, e.g., based on software-programmable waveform design.

C. Energy consumption of acoustic modems

For each specific acoustic modem interface, the receive energy is fixed (as an example, we consider here the WHOI micro-modem [7] that has a few Watts of receive power). The transmit energy of the WHOI micro-modem has a maximum transmit power of 50 W that can achieve over 190 dB re μPa of acoustic pressure (acoustic pressure is the equivalent of RF power for underwater environments) at distances up to 4 km. It has a 10 W minimum transmit power level, potentially providing a 40 W dynamic range for power control.[1] Because this range represents 80% of the maximum energy consumption in transmit mode, transmit power control has the potential to have a large impact on energy consumption. By way of contrast, the dynamic range for power control in current radio modems is on the order of 90 mW and only represents a small percentage of the maximum energy consumption in transmit mode [34]. Additionally, the difference in energy consumption between receive and idle modes for acoustic modems can be an order of magnitude or more [2], [7], whereas for radio modems they are nearly identical [34], an aspect that can be exploited in the design of energy-efficient topology control schemes [35].

D. Computation of the hop delay and energy consumption

The attenuation equations of Section II-A and [30] provide a means to compute the received acoustic power (and consequently the SNR) for an underwater link of a given length. In order to properly relate these computations with the energy consumption associated to one hop (which includes both the transmit and the receive energy at the two ends of the link), we must take into account modem specifications such as those discussed in Section II-C, as well as the proper conversion between the level of radiated acoustic power (expressed in dB re μPa) and the corresponding electrical power consumption in the device (in Watts). In addition, the bandwidth calculations

[1] Note that power control is not currently implemented in the WHOI micro-modem, but is expected to be considered for future versions [7].

of Section II-B make it possible to compute the transmission time, which affects both the energy consumption and the delay.

More precisely, in the presence of power control the transmit energy consumption depends on the distance to be covered, as longer links require more power in general.[2] Based on the attenuation equations, and following the analysis of [30], the acoustic power that needs to be radiated in order to meet some quality threshold at the receiver depends on distance.

Assuming the use of BPSK,[3] and the transmission of packets of length L, the transmit power level required to achieve a target packet error rate (PER) Π_{tgt} can be found by inverting the BPSK error equations. For example, under the assumption of independent channel errors, PER can be found as

$$\Pi_{pkt} = 1 - \left(1 - \frac{1}{2}\mathrm{erfc}\sqrt{\xi \mathrm{SNR}}\right)^L , \quad (4)$$

where SNR is the signal-to-noise ratio at the receiver, and ξ is a penalty factor that accounts for signal processing inefficiencies at the receiver. In order for (4) to be equal to Π_{tgt}, the following condition on the transmit power must hold:

$$P_t(\ell) = \frac{\chi}{\xi} B(\ell) N(f_0(\ell)) A(\ell, f_0(\ell))\, \mathrm{SNR}_{tgt} , \quad (5)$$

where $f_0(\ell)$ is the optimal transmit frequency at a given distance ℓ [30] (see also Figure 2), $B(\ell)$ is found according to (3), an analogous approximation is used for $f_0(\ell)$, and SNR_{tgt} is given by

$$\mathrm{SNR}_{tgt} = \left(\mathrm{erfc}^{-1}(2 - 2(1 - \Pi_{tgt})^{1/L})\right)^2 . \quad (6)$$

Note that in (5) both noise and attenuation are calculated at $f_0(\ell)$ and approximated as constant over the whole bandwidth. Also, (5) includes a margin, χ, so that the average SNR at the receiver is larger than the minimum required by (4), in order to protect the system from random fluctuations. In order to translate acoustic power into electrical power the following empirical relation is applied [31]:

$$P_t^{el}(\ell) = P_t(\ell) \cdot 10^{-17.2}/\eta , \quad (7)$$

where $10^{-17.2}$ is the conversion factor from acoustic power in dB re μPa to electrical power in Watt, and η is the overall efficiency of the electronic circuitry (power amplifier and transducer).

Unlike the transmit power, the receive power P_r is independent of distance, and rather depends on the complexity of the receive operations (e.g., whether coherent detection and/or equalization are performed). Other fixed costs (such as the electrical power required to keep systems active) are neglected here, as they cause minimal variations of the overall energy consumption.

[2]In order to evaluate the greatest possible gain, in this paper we assume continuous transmit power control, whose performance provides an upper bound to what may be achievable by practical devices where there is typically only a discrete set of possible power levels for transmission.

[3]BPSK is one of the transmission modes available in the WHOI micro-modem [7], along with FH-FSK. The methodology explained here can be extended to any modulation scheme in a straightforward manner, by just replacing (4) with the appropriate error rate expression.

Therefore, for a given SNR requirement, the total energy consumption associated to a single hop of length ℓ can be computed as the total (transmit plus receive) power, equal to $P_r + P_t^{el}(\ell)$, times the duration of time the modems need to be operated, which is equal to the transmission time of the packet, i.e., $\frac{L}{\alpha B(\ell)}$, where L is the packet size in bits, $B(\ell)$ is the bandwidth available (which depends on the link distance), and α is the bandwidth efficiency of the modulation in bps/Hz.

Finally, the hop delay and energy consumption can be expressed as[4]

$$\Delta_{hop}(\ell) = \frac{L}{\alpha B(\ell)} + \frac{\ell}{c}, \quad E_{hop}(\ell) = \frac{(P_r + P_t^{el}(\ell))L}{\alpha B(\ell)} \quad (8)$$

The delay and energy consumption associated to a complete multi-hop path are computed by adding the delays and energy consumptions of the individual hops. In the following, we will assume $L = 256$ bytes, $\Pi_{tgt} = 0.01$, $\xi = -10$ dB, $\chi = 10$ dB, $\eta = 0.25$ and $P_r = 2$ W, unless differently stated.

III. Analysis of Path Delay and Energy Consumption

To evaluate the impact that the characteristics of acoustic propagation and devices described in the previous section have on routing algorithm design, we first study the effects of node density and hop length on end-to-end delay and energy consumption in simple networks. To calculate the bit rate and power for a given distance, we use the models summarized in Section II. The goal of our evaluation is to gain insights that can be used to design a routing algorithm to minimize energy consumption for underwater networks.

A. Linear topologies

As a first step, we consider the simplest scenario of a linear topology, where all nodes are placed on a straight line, and study how the overall path delay and energy consumption depend on the number of nodes between source and destination.

More specifically, consider a one-dimensional axis with coordinate x. The source and final destination are placed in positions $x_0 = 0$ and $x_n = D$, respectively, with $n-1$ intermediate nodes at $x_i, i = 1, \dots, n-1$, with $x_i < x_{i+1}, i = 0, \dots, n-1$. The resulting n-hop path has total delay and energy consumption

$$\Delta_{path}(n) = \sum_{i=1}^{n} \Delta_{hop}(\ell_i), \quad E_{path}(n) = \sum_{i=1}^{n} E_{hop}(\ell_i) \quad (9)$$

where $\ell_i = x_i - x_{i-1}$ is the distance covered by the i-th hop.

If the hops are all of the same length, we have $\ell_i = D/n$ and

$$\begin{aligned} \Delta_{path}(n) &= \frac{nL}{\alpha B\left(\frac{D}{n}\right)} + \frac{D}{c}, \\ E_{path}(n) &= \frac{n(P_r + P_t^{el}\left(\frac{D}{n}\right))L}{\alpha B\left(\frac{D}{n}\right)} \end{aligned} \quad (10)$$

[4]Note that it may be appropriate to add to the delay term a component which accounts for processing delay at each hop. This would be a constant term which does not essentially affect the behavior of the delay curves, and is ignored here for simplicity.

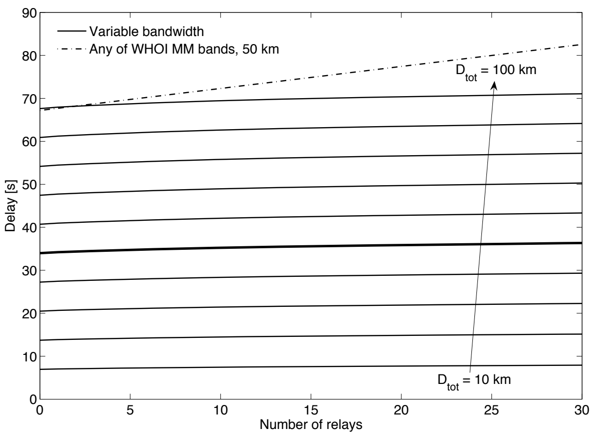

Fig. 3. Linear network: Delay vs. number of relays. The thicker line highlights an overall path length $D_{tot} = 50$ km

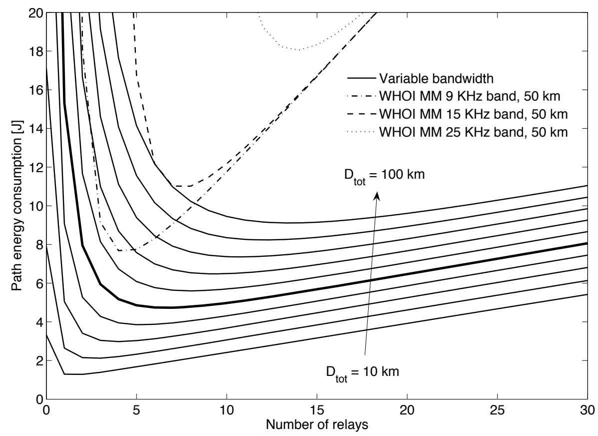

Fig. 4. Linear network: Total path energy vs. number of relays. The thicker line highlights an overall path length $D_{tot} = 50$ km

Adding evenly spaced nodes into a network results in a smooth decrease in per-hop distance as the number of nodes in the network increases. We refer to the extra nodes between the sender and the receiver as *relay nodes*, and each graph in the following plots various metrics against the number of relay nodes. While the overall propagation time of the data for a given transmission distance does not depend on the number of relays, it obviously increases as the total path length increases. On the other hand, the total transmission time for the path depends on the number of relay nodes. (The transmission and propagation delay components correspond to the first and second terms in the $\Delta_{path}(n)$ expression in (10).) In RF multihop communications, the transmission time would be linearly dependent on the number of hops, since the same message needs to be sent multiple times at the same rate.[5]

The path delay is plotted vs. the number of hops in Figure 3, which shows that for acoustic multihop transmission this dependence is sub-linear, since as the number of hops increases, the reduced distance makes it possible to send data faster on each hop. Figure 3 also shows that the most important factor is the propagation delay (all curves are nearly constant)[6]. For comparison, the dash-dotted curve in the figure shows the delay performance obtained with any of the WHOI micro-modem (MM) pre-defined operating bands [7] for a total path length of 50 km. Recall that the MM features 3 operating bands, all 4 KHz wide and centered at around 9, 15, or 25 KHz. In this case, since any band is fixed to 4 KHz, the delay increases linearly with distance, as the fixed MM bandwidth does not allow to exploit the higher transmission rate allowed for shorter hops. For comparison, the corresponding delay in case the optimal bandwidth is used (the thicker line in the graph) is much lower.

The dependence of the total path energy consumption on the number of relays in a linear topology is shown in Figure 4. The path energy is highest for direct transmission (no relays), except for short distances, but rapidly decreases as the number of relays moves from one to 10 nodes. As the number of relays

[5]However, it should be noted that, for data fragmented into multiple packets, the pipeline effect might mitigate this linear relationship to some extent.

[6]This behavior of course depends on the parameters used in the computation, which on the other hand are representative of realistic scenarios.

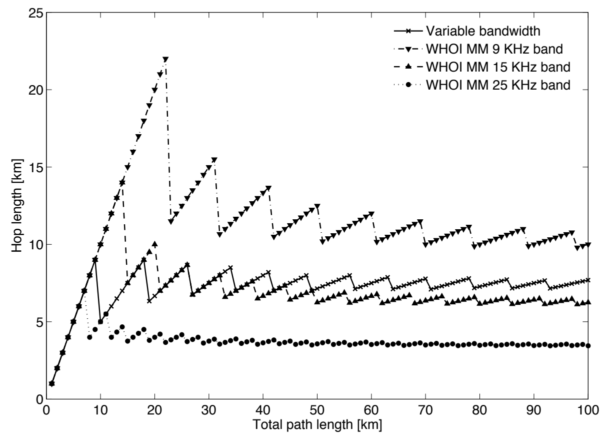

Fig. 5. Linear network: Optimal per-hop distance vs. total network distance

increases, the total transmit energy decreases, and the overall path energy consumption improves, until the receive power (2 W in our setting) becomes the dominating factor, so that little further savings are possible. In this regime, the energy consumption is dominated by the fixed costs, and therefore increases with the number of relays, as shown in Figure 4. As in Figure 3, we have compared the best achievable performance (corresponding to the use of the optimal bandwidth) to the use of any of the WHOI MM pre-defined bands, at a total path length of 50 km (in both cases, perfect power control is assumed). Again, the fixed MM bandwidth does not allow to exploit the greater capacity of shorter hops, and thus forces longer transmission times, which in turn consume more energy. Moreover, choosing a high-frequency band has the only effect to increase the cost of longer hops which explains the behavior of the MM curves for a low number of relays.

As can be seen in Figure 4, the optimal number of relays varies over a rather wide range. However, the hop length that corresponds to the optimal node placements is roughly constant for a total path length greater than 40 km and undergoes limited variations for shorter path lengths (see Figure 5). This observation applies to micro-modem-related curves as well, though with a somewhat larger variance in the high-frequency bands. Hence, a rule of thumb for energy-efficient routing algorithms could be to attempt to choose hops that cover the optimal distance seen in Figure 5 (between 7 and 8 km for the variable bandwidth case). Also, we observe from Figure 4 that, while the performance is generally not very sensitive to the exact hop lengths, having too few relay nodes, and so distances longer than optimal, can yield a worse effect than having a few extra nodes, or shorter than optimal distances. [7] Therefore, a routing algorithm should approach the optimal distance from below (*i.e.*, using distances that are shorter than optimal). If no relay is found within the optimal distance, then the nearest relay should be used.

In practical topologies, it may not be easy to have all relays equally spaced, either because of random fluctuations that perturb the actual positions of the nodes, or because the node deployment itself is random. In order to study the effect of such non-ideal positioning, we have simulated the behavior in the presence of randomized node positions, and have found similar results, which have been omitted here for brevity.

B. Two- & Three-Dimensional Topologies

The main outcome of the previous subsection is that, for a linear topology, the best choice is to deploy equally spaced relays, with an optimized hop length that can be computed as a function of the propagation characteristics. This is qualitatively similar to the result obtained in the terrestrial sensor network context by Bhardwaj et al. [26], although in that case the propagation laws considered were different (radio vs. acoustics), and no dependence of bandwidth on distance was considered.

Unfortunately, linear topologies are not often found in practical underwater network scenarios, whereas two- and three-dimensional deployments are more common. A two-dimensional topology may be a good model for a seafloor-mounted sensor network or for a shallow water network deployment, whereas a three-dimensional network is representative of a deep water deployment. In this subsection, we discuss whether the insight gained from the results of the previous subsection also holds for these more realistic scenarios. Unlike in a linear topology, in the present case it is not completely obvious how to define routes and compute the optimal hop distance.

We first observe that, given a source and a destination, and in the presence of a very high density, regardless of the two- or three-dimensional character of the network, the best possible path would be a straight line with equally spaced relays at optimal distance as computed in the previous subsection. However, unlike in terrestrial sensor networks, the assumption of high node density is not always very realistic in underwater scenarios, and therefore this asymptotic result, while providing some guidance, cannot be directly applied.

Intuitively, if the density of nodes is rather low, it is not easy to find a straight path of equally spaced relays (which would be optimal), and therefore we expect some energy suboptimality as well as some variance in the hop lengths. As the node density grows, these effects have a lesser impact, and more regular paths will be found, until at some point the overall behavior will degrade again, since increasing the node density leads to choosing paths with too many hops.

In order to illustrate these behaviors more precisely, and to analyze the dependence of the energy consumption on the node density in the network, we used a technique similar to the one for the linear topology. We considered a network where the width and depth were held at 2 km and 400 m, respectively, whereas the length of the network was varied.[8] Given a specific network deployment, i.e., the number of nodes and their locations, we apply a path search algorithm which tries to use as many short hops as possible according to the number of nodes in the network. This is done by picking at any hop the node which is closest to the transmitter, while providing a positive advancement towards the final destination[9]. With this technique, we can find the total path energy cost and the statistics of the hop length, averaged over the random node locations. Observing the behavior of these quantities as a function of the number of nodes in the network, we can then draw some conclusions about the relationship between various metrics, in particular between overall path energy consumption and average hop length.

Figure 6 plots the overall average path energy consumption as a function of the number of nodes in the network. What is immediately apparent is that the general trends are the same as for the linear topology, and for each network size there exists a value of the number of nodes that minimizes the path energy. The corresponding optimal number of relays per unit volume turns out to be roughly constant across different network sizes, as shown in Figure 7 where the optimal hop distance is plotted as a function of the path length. For the case considered here, this optimal distance was found to be slightly more than 4 km, which can be used to design deployments that allow energy-efficient routing. This result is also confirmed by Figure 8, which depicts the average number of hops on a multihop path against energy consumption. Curves are spanned counter-clockwise by increasing the number of nodes in the network from 1 to 80 as before. Figure 8 shows that by linearly increasing the total path length, both the optimal number of hops and the minimum path energy also scale almost linearly, which means that we perform proportionally more hops of the same length.

C. Discussion

The goal of this analysis was to derive some useful guidelines for use in the construction of energy-efficient routing algorithms. In particular, we wanted to gain some understanding on the relationship between the density of relay nodes (and correspondingly the average hop length) and the total path energy consumption. The main fact that was consistently observed across the entire analysis is that the optimal hop length for different total path lengths remains nearly constant for a given set of modem parameters (*e.g.*, target SNR value and transmit power levels) and a given scenario. For example, for the parameter values provided in section II-D, which are

[7]When designing a real network the number of nodes also affects the total deployment cost, which is not the focus of the present work.

[8]Since the results for two- and three-dimensional networks exhibit entirely similar behaviors, only 3D results are shown here for brevity.

[9]This heuristic corresponds to the scheme called *greedy minimum energy*, that will be studied in more detail in Section IV.

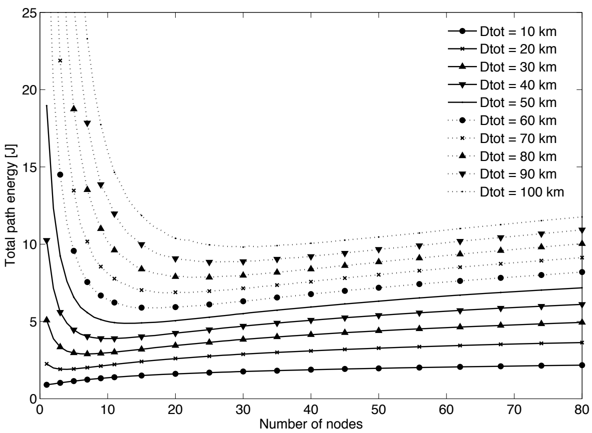

Fig. 6. 3D network: Total path energy vs. number of nodes in the network

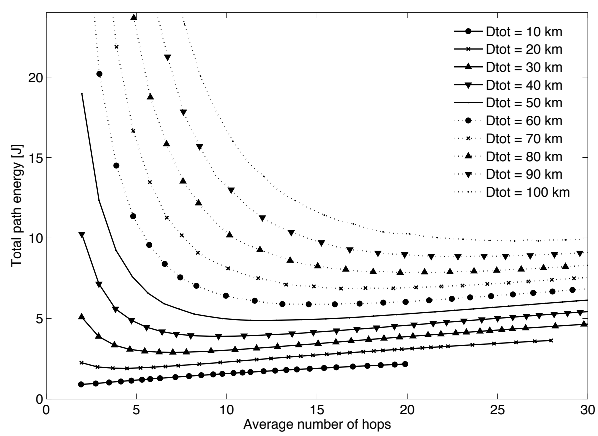

Fig. 8. 3D network: Number of hops vs. total path energy

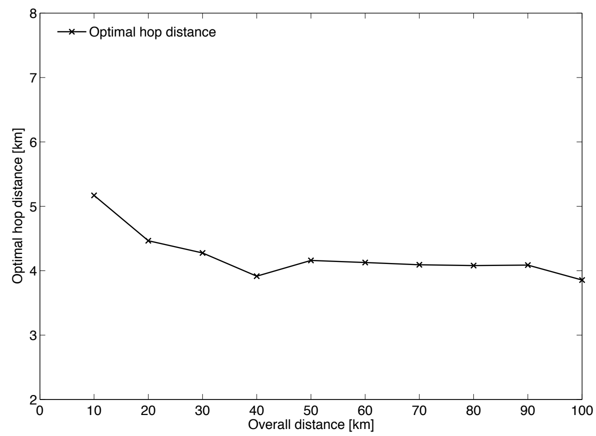

Fig. 7. 3D network: Optimal per-hop distance vs. total network distance

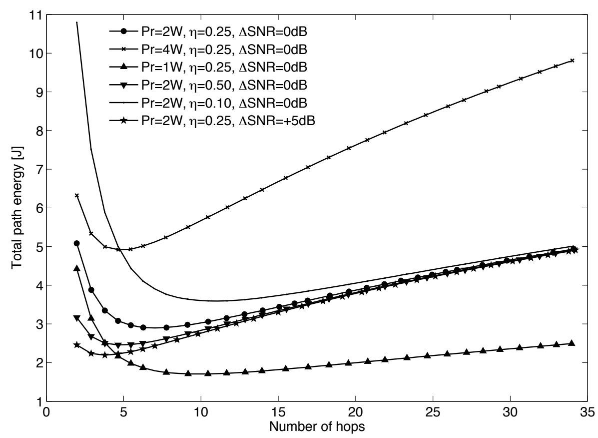

Fig. 9. 3D network: effect of modem parameters on energy consumption

in line with those of the WHOI micromodem, the optimal per-hop distance is approximately $4\ \mathrm{km}$ (as shown in Figure 7) and is weakly dependent on the overall network size, which makes the resulting scheme very general and robust. We highlight that the optimal hop distance is affected by modem parameters, especially the receive power P_r and the overall efficiency of the amplifier and transducer η. To show the role each of these parameters plays, we provide in Figure 9 a comparison of the total path energy as a function of the number of hops, for different combinations of P_r and η. The network size is $30\ \mathrm{km} \times 2\ \mathrm{km} \times 0.4\ \mathrm{km}$ here. With respect to the values reported in Section II-D, increasing P_r worsens the fixed per-hop energy costs, so that the optimum number of hops decreases from 7 to 5. Conversely, a smaller P_r improves the effectiveness of multihop routing, making the optimum number of hops increase to 10. Similar observations hold for the effects of the efficiency η. Additionally, Figure 9 shows that more effective receiver-side signal processing (modeled as an increase equal to ΔSNR in the effective received SNR) would also make longer hops more convenient.

Regardless of variations to modem-related parameters, the observation that there is an optimal distance at which relays should be chosen holds in general, and thus leads to the definition of energy-efficient rules for network deployment and routing protocol design. In particular, we argue that a reasonable heuristic to find energy-efficient paths is to look for relays that, besides bringing the packet towards the final destination (i.e., not going backwards), try to cover a hop distance close to the one that characterizes the optimal path. Algorithms designed following this approach are introduced in the next section.

IV. Energy-Efficient Underwater Routing Protocols

In this section, we use the results obtained above to design energy-efficient routing protocols for underwater acoustic networks. We assume that the network topology, while not necessarily static, is at most slowly moving, so that it does not significantly change during a round trip time, which is a reasonable assumption for underwater sensor networks. A natural choice in this case is an algorithm that tries to choose per-hop distances that are close to the optimal found according to the analysis of Section III. To this end, our routing scheme uses a geographic forwarding approach to choose the next hop toward the destination, which allows a distributed implementation that only requires local positioning information.[10] The optimal per-hop distance (an essential input

[10]How this information is gained is out of the scope of this paper. However, there has been recent work on localization for underwater nodes (*e.g.*, [36]–[38]).

to the algorithms) can be computed off-line based on the expected features of the application scenario, and communicated to all nodes at network setup. In dynamic scenarios, one or more specific nodes may be in charge of periodically computing this information and broadcasting it to all nodes in the network, or alternatively a distributed scheme based on locally measured quantities can be envisioned. The tradeoffs related to these design choices are left for future study.

A. Algorithms for energy-efficient paths

Let s and d be the sender node and the final destination, respectively, D_{tot} the total path length, and D_{max} the desired per-hop distance (computed according to the analysis of the previous section). Let X be the space within an angle Θ of the line connecting s to d,[11] and let X_{in} and X_{out} be the portions of X containing the nodes whose distance from s is $\leq D_{max}$ or $\geq D_{max}$, respectively. We have considered and compared the following algorithms.

Algorithm 1 (Bounded Distance from above): At any hop, if d is in X_{in} then transmit to d directly, otherwise pick as the next relay the node in X_{out} that is closest to s.[12]

Algorithm 2 (Bounded Distance from below): At any hop, if d is in X_{in} then transmit to d directly, otherwise pick as the next relay the node in X_{in} that is farthest from s. If no such node exists, apply Algorithm 1.

Algorithm 3 (Modified GeRaF [19]): At any hop, pick as the next relay the node that is closest to the destination, among those within a circle with center in s and radius D_{max}. If no such node exists, apply Algorithm 1.

Algorithm 4 (Modified EEGR [28]): At any hop, consider the line from the current relay to the destination, pick the point on this line at a distance D_{max} from the current relay, and a circle of radius D_{max} centered at that point. If d is in the circle, then transmit to d directly, otherwise choose as the next hop the node within the circle which is closest to its center. If no nodes are found within the circle, progressively increase the circle radius by a factor $\sqrt{2}$ until the destination or a relay is found within the circle. In any case, do not consider nodes that provide no advancement.

Greedy minimum energy: At any hop, pick as the next relay the node in X that is closest to s.

Shortest path: Follow the path with the minimum number of hops. If there is no bound to the transmit power, this will be a single direct transmission, whereas if the transmit power is limited and the sender-destination distance is sufficiently large, this may involved multiple hops.

Centralized optimum: Follow the globally minimum-energy path.

The first five algorithms are distributed and heuristic and can be easily implemented in practice, as they only need local information (i.e., each node only needs to know its own position, that of the final destination, and that of all its own neighbors, which can be obtained by proper handshaking messages and positioning techniques). The last two are used here as benchmarks, and use Dijkstra's algorithm with hop count and energy metrics, respectively, where full knowledge of the topology is assumed.

Note that the Bounded Distance algorithms try to approximate the optimal hop length from above (Algorithm 1) or from below (Algorithm 2), choosing the relay that corresponds to the hop length closest to D_{max} while being farther or nearer to the source than the optimal distance, respectively. Algorithm 4 instead is an adaptation of the EEGR algorithm proposed in [28], which only considers the closeness of a relay to the optimal position, with no consideration of whether it is farther or nearer to the source. Given the behavior of the path energy consumption as a function of the hop distance, which shows a greater sensitivity towards distances longer than optimal, we expect Algorithm 2 to give better performance.

The modified GeRaF algorithm [19] always guarantees the maximum advancement towards the destination within a coverage range of D_{max}. In all cases, there is a backup choice provided by Algorithm 1, which guarantees that the progress towards the destination cannot stop. More in general, one would have to provide some rules that avoid connectivity issues related to network separation or dead ends. This can be done in a number of ways, e.g., see [39], [40], but is not included in this preliminary evaluation and is left as future work. The greedy minimum energy algorithm selects at each step the cheapest possible hop, among those leading towards the destination, which is the one corresponding to the shortest distance.[13] The relay search scope Θ is assumed equal to $45°$ in the sequel.

In terms of path energy performance, we expect the shortest path algorithm to perform poorly, as it chooses hops that are too long and therefore very expensive in energy terms. The greedy minimum energy algorithm will also perform poorly, as choosing the cheapest hop totally ignores the advancement towards the destination and therefore does not consider the overall number of hops needed, which leads to excessive energy consumption for high densities, due to the dominance of the distance-independent energy cost per hop. On the other hand, based on the discussion in the previous section, we expect that the first three algorithms (which we are proposing in this paper) and Algorithm 4 (which is our adaptation of a scheme proposed for terrestrial scenarios) should perform close to the centralized optimum, thanks to their ability to select paths whose characteristics mimic those of energy-optimal routes.

B. Matlab Simulator for path energy evaluation

In order to test the performance of the routing algorithms described above, we developed a simulator using Matlab. This simulator implements the physical layer (that includes attenuation, delays, bandwidth, and power and energy requirements) using the models presented in Section II. The simulator allows various routing metrics to be used to choose paths through a one-, two-, and three-dimensional network, including geographic-based and energy metrics, according to the various algorithms specified in Section IV-A. This Matlab

[11] This space is a circular sector of angle 2Θ in two dimensions, and the rotation of such a sector around the sender-destination axis in three dimensions.

[12] Note that if there is no upper bound on the transmit power this algorithm will never fail, as if no relay is found, the final destination can be reached via a direct transmission.

[13] A similar approach is also followed in [41].

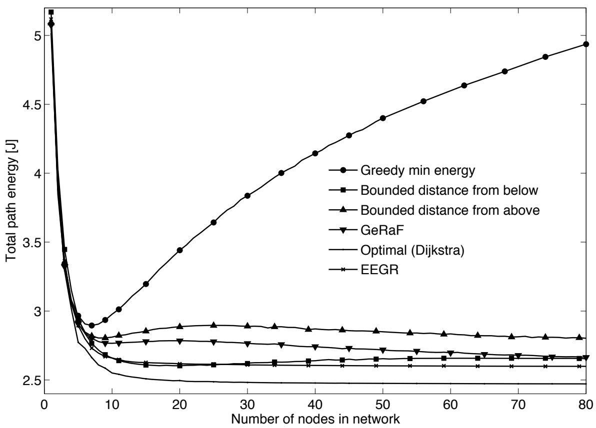

Fig. 10. 30 km network length: Total path energy vs. number of nodes in the network

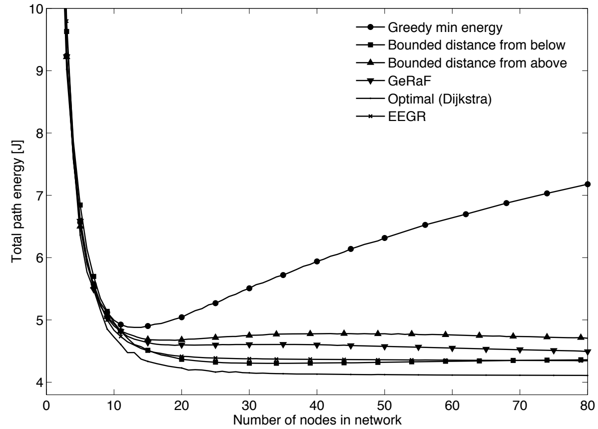

Fig. 11. 50 km network length: Total path energy vs. number of nodes in the network

simulator focuses on energy-efficient routes, and only finds paths according to the algorithms compared and calculates the cost to send data through these links, ignoring collisions and other costs related to multiple traffic flow interactions. In contrast, the ns2 simulations in Section IV-C take into account all these costs and effects, including interference, collisions, and the presence of cross-traffic flows.

1) Simulation Setup: The three-dimensional network used in the simulations has a constant depth and width (of size 400 m and 2 km, respectively) and a length of either 30 or 50 km, which may model a network of sensors traversing a long distance (e.g., monitoring a pipeline). Varying the dimension has the effect of varying the node density, which directly affects the possible per-hop lengths. For each simulation run, we vary the number of relay nodes placed randomly in the network from 1 to 150. The sender is fixed at point $(0,0,0)$ and the receiver is placed at the opposite corner of the network. The compared algorithms are those described in section IV-A.

2) Results: We present results for network lengths of 30 km and 50 km in Figures 10 and 11. We also tested other network lengths from hundreds of meters to hundreds of kilometers, but omit those results here due to similarity. The shortest path algorithm is not presented in the figures, in order to focus on the most interesting curves. Suffice it to say that its energy consumption is constant with the number of nodes and equal to around 8.3 J and 37 J for 30 km and 50 km, respectively, which is significantly worse than all other schemes shown.

The greedy minimum energy protocol, for all network lengths, performs near optimally until the number of nodes in the network causes the average hop length to exceed the optimal length. At this point, the greedy minimum energy curve begins to diverge from the optimal because it chooses hops that are individually cheapest, while not considering total path cost, and therefore its overall energy consumption increases linearly with the number of nodes. Our "bounded distance from above" protocol performs very close to the optimum for all distances. Essentially, when the node density is not sufficient to provide hops of the optimal distance, the bounded distance protocol performs similarly to the greedy minimum energy protocol. However, once the node density is such that hops that are significantly shorter than optimal start to appear, the greedy algorithm chooses paths with too many hops, whereas the bounded distance protocol maintains its proximity to optimal. For larger networks, the number of nodes required to cause the greedy protocol to diverge significantly from our bounded distance protocol may be quite large; however, for smaller networks, a substantial difference in energy consumption can be observed even with few relays in the network. It is worth noting that the EEGR protocol [28] eventually reaches the minimum energy performance achieved by the "bounded distance from above" protocol, but for a larger number of nodes. In fact, EEGR searches nodes in a circle centered on the optimal relay position, and on average half of the times will select a relay which is farther from the destination than the optimal relay position, thus partially exhibiting the drawbacks of the "bounded distance from below" scheme. Therefore, while the two protocols achieve almost the same optimal performance, "bounded distance from above" yields the further advantage that it can operate at lower densities, which are typical for a host of underwater applications [1].

These results show that even with the unique behavior of acoustic propagation, the concept of characteristic hop distance (that minimizes the energy consumption over a path) already found in radio networks still applies. However, while accounting for the effects of path length, transmission distance, and attenuation, these results ignore competition for channel access and MAC issues. Any decisions on scheduling and transmit power levels, as well as the existence of multiple traffic flows in the network, affect how nodes interfere with each other, which may lead to severe performance degradation. In the next subsection, we provide results that explicitly take these effects into account, and show that our conclusions still hold in more realistic scenarios.

C. ns2 Simulator

In order to understand the impact of channel contention and the interaction of multiple flows in the network, we implemented a complete underwater acoustic communication system in NS-Miracle [42], which is an extension of the widely used ns2 simulation platform [43] and provides enhanced support for channel models as well as PHY, MAC and Routing layer implementations [44]. Both NS-Miracle and the specific modules and simulation scripts used to obtain the results presented in this section are available for download [45].

1) Simulation Setup: The three-dimensional network used in these simulations is 30 km by 30 km, with a depth of 0.4 km and a number of 80 nodes randomly placed in this volume. Each particular topology is simulated twice, with a number of communication flows of 5 and 20, respectively. For every flow, a transmitter and a receiver are randomly selected within the set of nodes. The sender node generates 256-byte messages according to a Poisson process with an average rate of one packet per minute; this particular choice of the sender rate was made to have a congestion-free network in the presence of a single flow, which gets progressively more congested as the number of flows increases. The set of experiments just described is repeated with most of the routing algorithms described in Section IV for different values of the parameter D_{max}. The results presented here have been obtained by averaging the performance over 50 random topologies, which was found to provide sufficient statistical confidence.

For the channel model, we implemented all the aspects described in Section II. For the PHY layer, we implemented a BPSK system in which the center frequency and the bandwidth (and therefore the rate) are adapted according to the model in Section II; reception errors were determined using the model for coherent BPSK of (4), where interference was included in the noise term. A sensing threshold of 10 dB was used to squelch too weak signals. Power Control was performed by determining the minimum power required to achieve a packet error probability of 0.01 at the receiver, by using the error model just described. We used a SNR penalty of $\xi = -10$ dB in (4), and a transmission power margin of $\chi = 10$ dB in (5). As a result, the power chosen for transmission over a given distance matches with the one used for the Matlab simulations described in the previous section.

For the MAC layer, it is to be noted that the majority of MAC protocols which have been proposed for underwater communications [8]–[13] have poor performance for large network sizes, and therefore would not work well when combined with those routing protocols selecting longer hops.[14] For this reason, in order to consider a MAC protocol which would perform as evenly as possible with respect to different routing protocols, while still being able to evaluate the effect of congestion and interference, we adopted a simple ALOHA protocol. A joint optimization of MAC and routing is out of the scope of this paper, and is left as a future research direction.

2) Results: Figure 12 shows the average energy consumption for the end-to-end delivery of a packet, computed as the total amount of energy consumed by all nodes divided by the total number of packets that reach their final destination. From the figure, it can be seen that for the distance-parametric algorithms, i.e., the two bounded distance schemes and EEGR, there exists an optimal value of the D_{max} parameter which provides the minimum energy consumption. For the bounded distance algorithms, the optimal distance is similar to the one found in section IV-B, which confirms the results obtained from the simpler analysis. The optimal distance for 20 flows can be seen to be shorter than that for 5 flows, which is probably due to the fact that under heavy interference conditions it is better to reduce the coverage range to limit the overall interference in the system. It is also to be noted that the lowest energy consumption achieved by the distance-parametric algorithms is very close to the one obtained by the optimal centralized minimum energy algorithm. Finally we observe that, for values of the distance parameter which tend to zero and infinity, the performance of the bounded distance algorithms converges to that of the greedy minimum energy and shortest path algorithms, respectively, as was to be expected.

Figures 13 and 14 report, for the same scenarios and routing algorithms, the end-to-end throughput and delay performance averaged among different flows. For every flow, the throughput is computed by taking the total amount of data (in bits) received at the destination and dividing it by the simulation time, while the delay is the time from when a packet is generated to when it is finally delivered, averaged over all packets reaching their destination. It is to be noted that the shortest path algorithm almost always achieves the best performance with respect to both throughput and delay, whereas the optimal and the greedy minimum energy algorithms reach a significantly lower performance. Since the shortest path algorithm was also reported to achieve the highest energy consumption, there exists a clear trade-off between energy and delay/throughput performance. In this view, the distance-parametric routing schemes are interesting in that they allow to achieve different trade-offs by varying the value of D_{max}. Both versions of the bounded distance algorithm achieve very good trade-off points: under the energy-optimal choice of D_{max}, the delay and throughput performances are very close to the best ones, provided by the shortest path algorithm; similarly, there are values of D_{max} which provide optimal throughput and delay while also giving a close to optimal energy consumption.

To better illustrate this behavior, we plot the normalized energy consumption and the throughput against each other in Figure 15 (a similar figure, not shown here, can be obtained for the delay-energy tradeoff), where each curve is traveled by changing the value of the D_{max} parameter (with the upper right point of each curve corresponding to a large value of D_{max}, i.e., shortest path, and the other end to greedy minimum energy). It is interesting to see that the curves for the bounded distance protocols point towards the upper left corner of the graph (i.e., the most favorable region), which means that these schemes are able to simultaneously achieve good throughput and energy performance. The EEGR scheme is not able to achieve as good trade-offs as the bounded distance algorithms, as shown by the fact that the corresponding curves point slightly towards the lower left corner of the graph: for the energy-optimal value of D_{max}, the throughput performance is rather far from optimal, and the energy performance degrades very quickly as D_{max} moves away from the energy-optimal value. Finally, the shortest path and greedy minimum energy schemes correspond to the two ends of each curve, and are therefore very far from the desirable behavior, whereas

[14]As an example, using the model described in this section, at a distance of 30 km the transmission of a packet has a duration of roughly 2 s, while the propagation delay is on the order of 20 s. Both TDMA-based and handshake-based MAC schemes would be extremely inefficient under these conditions.

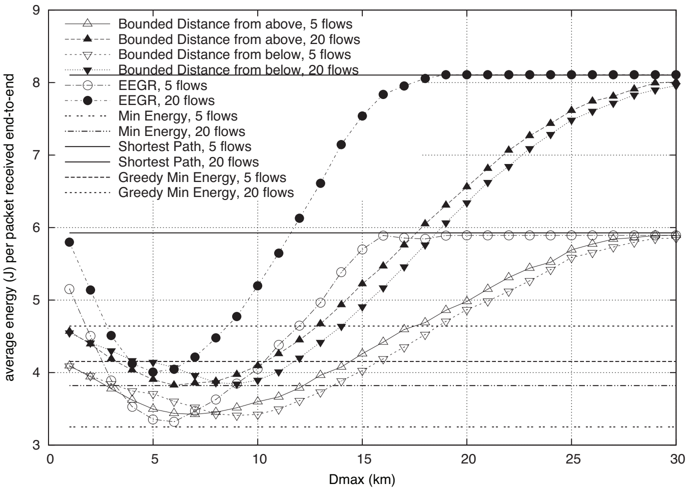

Fig. 12. ns2 simulation: average energy consumption for the end-to-end delivery of a packet for different routing schemes

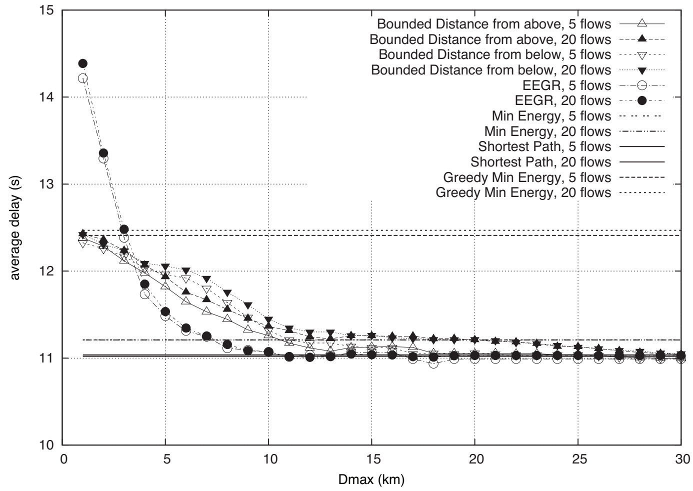

Fig. 14. ns2 simulation: average end-to-end delay for different routing schemes

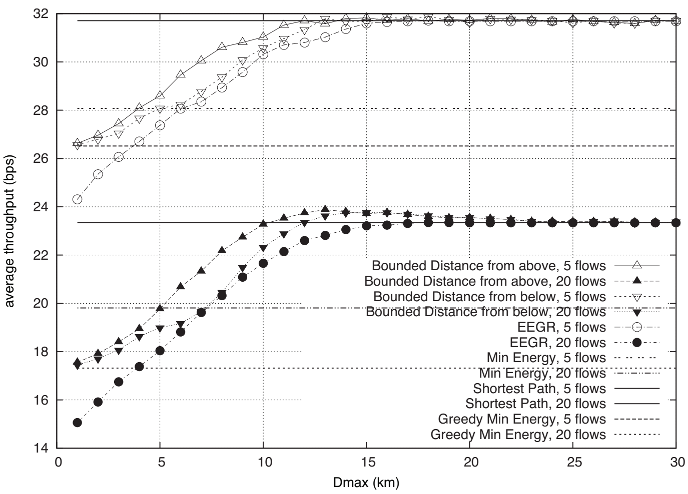

Fig. 13. ns2 simulation: average end-to-end throughput for different routing schemes

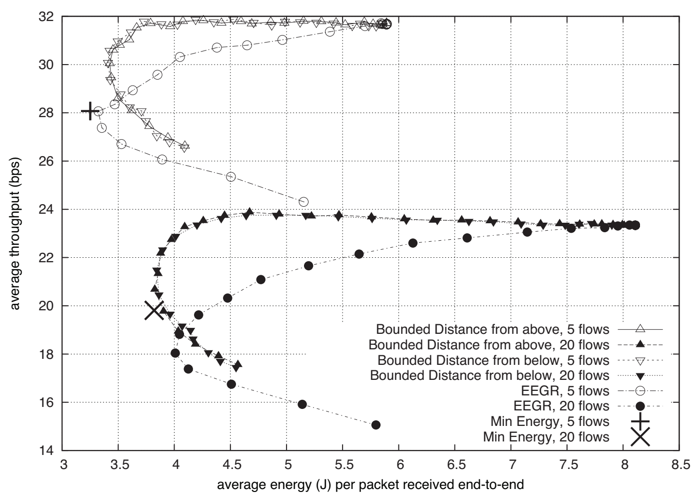

Fig. 15. ns2 simulation: energy-throughput tradeoff for different routing schemes

in the minimum energy scheme the small gain in terms of energy consumption does not seem to justify the rather large throughput loss. These results show that the proposed bounded distance protocols are the ones that are best able to trade off the different performance metrics, and are therefore to be preferred to the other schemes considered.

We ran several simulations in other scenarios with different parameters, in particular for different network sizes and different numbers of flows: the results confirm the qualitative behavior just described, and are therefore omitted due to space considerations.

V. Conclusion and Future Directions

Underwater acoustic networks are a new area of networking research. In many applications, underwater nodes are energy constrained, and therefore energy-efficient protocol design is a very important issue. However, the dramatically different propagation characteristics of underwater acoustic signals may make energy-efficient protocols designed for terrestrial radio networks sub-optimal in this scenario.

In this paper, we proposed a class of routing schemes designed taking into account all major effects that characterize underwater communications, i.e., attenuation and absorption, propagation delay, bandwidth-distance and power-distance relationships, and modem energy consumption profiles. We studied the effects of the channel characteristics on energy consumption and delay for varying path distances and hop lengths. We showed that, given the characteristics of a particular modem, the concept of characteristic hop distance known in radio networks still applies (choosing hops that cover the characteristic distance minimizes energy consumption over a path). This corresponds to an optimal number of relays per unit distance, area or volume that should be used in network deployment. We also provided a methodology to find such optimal distance in a three-dimensional topology and applied it to a typical set of parameters (which mimic those of the WHOI's micro-modem). This insight was then used to design and test a class of simple underwater routing protocols that exhibit large energy savings compared to other routing algorithms, and achieve quasi-optimal energy consumption.

Finally, to validate our results for realistic network scenarios, we designed routing protocols based on the analysis and showed that our solution outperforms strategies that are commonly considered in terrestrial wireless sensor networks. Performance evaluation was carried out first in Matlab using a detailed model of the underwater acoustic channel, and subsequently in ns2 to be able to characterize, in addition to the channel, important aspects of the PHY and MAC components of an underwater communication system. Both evaluation methods confirmed that the proposed routing strategy achieves a higher energy efficiency compared to other schemes, and is actually close to the optimal energy performance, while at the same time achieving a very good trade-off with respect to throughput and delay.

Future research includes further optimizations and parameter tuning of the protocol, integrating this work with idle-time power management, and consideration of other MAC layer protocols. Also, extending the link capacity analysis to a network capacity analysis (by explicitly including the interference) could lead to further observations that would impact the design of protocols at all layers of the network stack.

REFERENCES

[1] I. Akyildiz, D. Pompili, and T. Melodia, "Underwater acoustic sensor networks: Research challenges," *Elsevier Ad Hoc Networks*, vol. 3, no. 3, pp. 257–279, 2005.

[2] J. Heidemann, W. Ye, J. Willis, A. Syed, and Y. Li, "Research challenges and applications for underwater sensor networking," in *Proc. IEEE Wireless Communications of Networking Conference (WCNC)*, Las Vegas, USA, Apr 2006.

[3] E. M. Sozer, M. Stojanovic, and J. G. Proakis, "Underwater acoustic networks," *IEEE J. Oceanic Eng.*, vol. 25, no. 1, pp. 72–83, Jan. 2000.

[4] H. Song, W. Hodgkiss, and W. Kuperman, "MIMO Time Reversal Communications," in *Proc. International Workshop on UnderWater Networks (WUWNet)*, Montréal, Canada, Sep 2007.

[5] S. Hwang and P. Schniter, "Efficient multicarrier communication for highly spread underwater acoustic channels," *IEEE J. Select. Areas Commun., this issue*, 2008.

[6] D. Lucani, M. Medard, and M. Stojanovic, "Network coding schemes for underwater networks: The benefits of implicit acknowledgement," in *Proc. International Workshop on UnderWater Networks (WUWNet)*, Montréal, Canada, Sep 2007.

[7] L. Freitag, M. Grund, S. Singh, J. Partan, and P. K. K. Ball, "The WHOI micro-modem: an acoustic communications and navigation system for multiple platforms," in *Proc. MTS/IEEE Conference and Exhibition for Ocean Engineering, Science and Technology (OCEANS)*, Washington, DC, USA, Sep 2005.

[8] M. Molins and M. Stojanovic, "Slotted FAMA: a MAC protocol for underwater acoustic networks," in *Proc. MTS/IEEE Conference and Exhibition for Ocean Engineering, Science and Technology (OCEANS)*, Raffles City, Singapore, May 2006.

[9] B. Peleato and M. Stojanovic, "A MAC protocol for ad hoc underwater acoustic sensor networks," in *Proc. International Workshop on UnderWater Networks (WUWNet)*, Los Angeles, CA, USA, Sep 2006.

[10] V. Rodoplu and M. Park, "An energy-efficient MAC protocol for underwater wireless acoustic networks," in *Proc. MTS/IEEE Conference and Exhibition for Ocean Engineering, Science and Technology (OCEANS)*, Brest, France, Jun 2005.

[11] A. Syed, W. Ye, and J. Heidemann, "Comparison and Analysis of T-Lohi MAC for Underwater Acoustic Sensor Networks," *IEEE J. Select. Areas Commun., this issue*, 2008.

[12] A. Syed, W. Ye, B. Krishnamachari, and J. Heidemann, "Understanding spatio-temporal uncertainty in medium access with aloha protocols," in *Proc. International Workshop on UnderWater Networks (WUWNet)*, Montréal, Canada, Sep 2007.

[13] K. B. Kredo and P. Mohapatra, "A hybrid medium access control protocol for underwater wireless networks," in *Proc. International Workshop on UnderWater Networks (WUWNet)*, Montréal, Canada, Sep 2007.

[14] D. Pompili, T. Melodia, and I. F. Akyildiz, "A distributed CDMA medium access control for underwater acoustic sensor networks," in *Proc. IFIP Annual Mediterranean Ad Hoc Networking Workshop (Med-Hoc-Net)*, Corfu, Greece, Jun. 2007.

[15] E. Sozer, M. Stojanovic, and J. Proakis, "Initialization and routing optimization for ad hoc underwater acoustic networks," in *Proc. OP-NETWORK*, Washington, DC, Sep. 2000.

[16] R. Nitzel, C. Benton, S. G. Chappell, and D. R. Blidberg, "Exploiting dynamic source routing to enable undersea networking over an ad-hoc topology," in *Proc. International Symposium on Underwater Technology*, Tokyo, Japan, Apr. 2002.

[17] D. Pompili, T. Melodia, and I. Akyildiz, "Routing algorithms for delay-insensitive and delay-sensitive applications in underwater sensor networks," in *Proc. Annual International Conference on Mobile Computing and Networking (MobiCom)*, Los Angeles, CA, USA, Sep 2006.

[18] ——, "A resilient routing algorithm for long-term applications in underwater sensor networks," in *Proc. IFIP Annual Mediterranean Ad Hoc Networking Workshop (Med-Hoc-Net)*, 2006.

[19] M. Zorzi and R. R. Rao, "Geographic Random Forwarding (GeRaF) for Ad Hoc and Sensor Networks: Energy and Latency Performance," *IEEE Trans. Mobile Comput.*, vol. 2, no. 4, pp. 349–365, 2003.

[20] K. Kar, M. Kodialam, T. V. Lakshman, and L. Tassiulas, "Routing for network capacity maximization in energy-constrained ad-hoc networks," in *Proc. of the IEEE Conference on Computer Communications (INFOCOM)*, San Francisco, CA, USA, Apr 2003.

[21] J.-H. Chang and L. Tassiulas, "Energy conserving routing in wireless ad-hoc networks," in *Proc. IEEE Conference on Computer Communications (INFOCOM)*, Tel-Aviv, Israel, Mar 2000.

[22] S. Banerjee and A. Misra, "Minimum energy paths for reliable communication in multi-hop wireless networks," in *Proc. ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc)*, Lausanne, Switzerland, Jun 2002.

[23] Y. Xu, J. Heidemann, and D. Estrin, "Geography-informed energy conservation for ad hoc routing," in *Proc. Annual International Conference on Mobile Computing and Networking (MobiCom)*, Rome, Italy, Jul 2001.

[24] R. C. Shah and J. M. Rabaey, "Energy aware routing for low energy ad hoc sensor networks," in *Proc. IEEE Wireless Communications of Networking Conference (WCNC)*, Orlando, FL, USA, Mar 2002.

[25] C. Sengul and R. Kravets, "Conserving energy with on-demand topology management," in *Proc. IEEE International Conference on Mobile Ad Hoc and Sensor Systems (MASS)*, Washington, DC, USA, Nov 2005.

[26] M. Bhardwaj, T. Garnett, and A. P. Chandrakasan, "Upper bounds on the lifetime of sensor networks," in *Proc. IEEE International Conference on Communications (ICC)*, Helsinki, Finland, Jun 2001.

[27] J. Wang and I. Howitt, "Optimal traffic distribution in minimum energy wireless sensor networks," in *Proc. IEEE Global Communications Conference (GLOBECOM)*, St. Louis, MO, USA, Nov-Dec 2005.

[28] H. Zhang and H. Shen, "EEGR: energy-efficient geographic routing in wireless sensor networks," in *Proc. of the IEEE International Conference On Parallel Processing (ICPP)*, Xian, China, Sep 2007.

[29] P. Gupta and P. R. Kumar, "The capacity of wireless networks," *IEEE Trans. Inform. Theory*, vol. 46, no. 2, pp. 388–404, Mar 2000.

[30] M. Stojanovic, "On the relationship between capacity and distance in an underwater acoustic communication channel," in *Proc. of the International Workshop on UnderWater Networks (WUWNet)*, Los Angeles, CA, USA, Sep 2006.

[31] R. Urick, *Principles of Underwater Sound*. McGraw-Hill, 1983.

[32] L. Berkhovskikh and Y. Lysanov, *Fundamentals of Ocean Acoustics*. Springer, 1982.

[33] A. Goldsmith, *Wireless Communications*. Cambridge University Press, 2005.

[34] Aironet, "PC4800 user guide," 1998, http://www.aironet.com/.

[35] A. F. Harris III, M. Stojanovic and M. Zorzi, "When underwater acoustic nodes should sleep with one eye open: idle–time power management in underwater sensor networks," in *Proc. International Workshop on UnderWater Networks (WUWNet)*, Los Angeles, CA, Sep. 2006, pp. 105–108.

[36] D. Mirza and C. Schurgers, "Energy-efficient localization in networks of underwater drifters," in *Proc. International Workshop on UnderWater Networks (WUWNet)*, Montréal, Canada, Sep 2007.

[37] M. Erol, L. Vieira, and M. Gerla, "Localization with Dive'N'Rise (DNR) Beacons for Underwater Acoustic Sensor Networks," in *Proc. of the International Workshop on UnderWater Networks (WUWNet)*, Montréal, Canada, Sep 2007.

[38] D. Mirza and C. Schurgers, "Energy-efficient ranging for post-facto self-localization in mobile underwater networks," *IEEE J. Select. Areas Commun., this issue*, 2008.

[39] P. Casari, M. Nati, C. Petrioli, and M. Zorzi, "Efficient non–planar routing around dead ends in sparse topologies using random forwarding," in *Proc. IEEE International Conference on Communications (ICC)*, Glasgow, Scotland, Jun 2007.

[40] B. Karp and H. T. Kung, "GPSR: greedy perimeter stateless routing for wireless sensor networks," *Proc. Annual International Conference on Mobile Computing and Networking (MobiCom)*, Aug 2000.

[41] J. M. J. Montana, M. Stojanovic, and M. Zorzi, "Focused beam routing protocol for underwater acoustic networks," in *Proc. International Workshop on UnderWater Networks (WUWNet)*, San Francisco, CA, Sep. 2008.

[42] N. Baldo, F. Maguolo, M. Miozzo, M. Rossi, and M. Zorzi, "NS2-MIRACLE: a Modular Framework for Multi-Technology and Cross-Layer Support in Network Simulator 2," in *Proc. ACM International Workshop on Network Simulation Tools (NSTOOLS)*, Nantes, France, Oct 2007.

[43] ns2 Network Simulator, http://www.isi.edu/nsnam/ns/.

[44] N. Baldo, F. Maguolo, and M. Miozzo, "A new approach to simulating PHY, MAC and Routing," in *Proc. ACM International Workshop on NS-2*, Athens, Greece, Oct 2008.

[45] "Model for underwater channel in ns2," 2008. [Online]. Available: http://telecom.dei.unipd.it/download/

Michele Zorzi (S'89, M'95, SM'98, F'07) was born in Venice, Italy, in 1966. He received the Laurea degree and the Ph.D. degree in Electrical Engineering from the University of Padova, Italy, in 1990 and 1994, respectively. During the Academic Year 1992/93, he was on leave at the University of California, San Diego (UCSD), attending graduate courses and doing research on multiple access in mobile radio networks. In 1993, he joined the faculty of the Dipartimento di Elettronica e Informazione, Politecnico di Milano, Italy. After spending three years with the Center for Wireless Communications at UCSD, in 1998 he joined the School of Engineering of the University of Ferrara, Italy, and in 2003 joined the Department of Information Engineering of the University of Padova, Italy, where he is currently a Professor. His present research interests include performance evaluation in mobile communications systems, random access in mobile radio networks, ad hoc and sensor networks, and energy constrained communications protocols.

Dr. Zorzi was the Editor-In-Chief of the IEEE WIRELESS COMMUNICATIONS MAGAZINE from 2003 to 2005, is currently the Editor-In-Chief of the IEEE TRANSACTIONS ON COMMUNICATIONS, and serves on the Steering Committee of the IEEE TRANSACTIONS ON MOBILE COMPUTING, and on the Editorial Boards of the IEEE TRANSACTIONS ON COMMUNICATIONS, the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, the WILEY JOURNAL OF WIRELESS COMMUNICATIONS AND MOBILE COMPUTING and the ACM/URSI/KLUWER JOURNAL OF WIRELESS NETWORKS. He was also guest editor for special issues in the IEEE PERSONAL COMMUNICATIONS MAGAZINE (Energy Management in Personal Communications Systems) and the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS (Multi-media Network Radios).

Paolo Casari (S'05-M'08) was born in Ferrara, Italy, on August 20th, 1980. He received the Laurea degree (BE) in Electronics and Telecommunications Engineering (2002) and the Laurea Specialistica degree (ME) in Telecommunications Engineering (2004) summa cum laude, both from the University of Ferrara, and the Ph.D. degree in Information Engineering (2008) from the University of Padova. In 2007 he was on leave at the Massachusetts Institute of Technology, Cambridge, MA, working on energyefficient protocol design for underwater acoustic sensor networks. He currently holds a post doctorate research position at the University of Padova. His main research interest is crosslayer protocol design for wireless networks through PHY/MAC/routing interactions, with a particular focus on MIMO ad hoc networks, wireless sensor networks, and underwater acoustic networks.

Nicola Baldo (S'07) was born in Rovigo, Italy, in 1981. He received his Laurea (BE) and Laurea Specialistica (ME) degree in Telecommunications Engineering in 2003 and 2005, respectively, from the University of Ferrara, Italy. In summer 2003 he was an internship student at the Ericsson Eurolab Deutschland, Aachen, Germany, working on Wireless Multimedia Communications. In 2005 he was on leave at the STMicroelectronics Advanced System Technology group, Agrate Brianza (MI), Italy, working on Cross-layer Optimization for VoIP over Wireless LAN. Since 2006 he is a Ph.D. student at the University of Padova, Italy, under supervision by Prof. Michele Zorzi. In 2008 he was on leave at the Calit2 department, University of California, San Diego, working on Cognitive Networks and Software Defined Radio. His research interests include Cognitive Radio and Networks, Cross-layer Optimization, Underwater Communications and Network Simulation Tools.

Albert F. Harris III is a research assistant professor at the University of Kansas in the Center for Remote Sensing of Ice Sheets (CReSIS). He earned his Ph.D. in computer science from the University of Illinois at Urbana-Champaign, specializing in wireless network protocol and mobile systems design. Following his time at UIUC, he completed a one year post doctorate position at the University of Padova, Italy. His current interests are underwater acoustic networks, delay tolerant networks, and network support for assisted living and disaster recovery environments.