On the Impact of the Environment on MAC and Routing in Shallow Water Scenarios

Saiful Azad*, Paolo Casari*, Chiara Petrioli‡, Roberto Petroccia‡, Michele Zorzi*

*Department of Information Engineering, University of Padova, via Gradenigo 6/B, 35131 Padova, Italy

‡Department of Computer Science, University of Rome "La Sapienza," via Salaria 133, 00198 Rome, Italy

E-mails: {azad,casarip,zorzi}@dei.unipd.it , {petrioli,petroccia}@di.uniroma1.it

***Abstract*—In this paper, we investigate the impact of environmental changes on Medium Access Control (MAC) and routing protocols for underwater acoustic networks. We carry out the evaluation using the ns2-Miracle network simulator and the WOSS extensions, which interface the simulator to the Bellhop ray tracing software. We further extend the simulator to take into account the change of environmental parameters during the day, and to be able to generate random realizations of surface waves.**

We start by discussing how the acoustic propagation pattern changes due to changing temperature conditions, and show the impact of such variability on the performance of two random access protocols, namely CSMA-ALOHA and DACAP. As CSMA-ALOHA proves best in our simulation, we consider this protocol in a converge-casting scenario, where all nodes have to deliver their data to a centrally placed sink. In this scenario, we show that keeping the routes fixed is not the best strategy because of time-varying propagation effects, and that even infrequent route updates (once every 3 hours) achieve much better results in terms of throughput, delivery delay, and average route length than static routes.

***Index Terms*—Underwater acoustic networks, MAC, routing, time-varying environmental conditions, simulation, ns2-Miracle, WOSS, adaptive routes.**

I. Introduction

The recent advances in underwater acoustic modem technology have fostered the interest for undersea exploration using autonomous fixed and mobile objects, and motivate the investigation of new protocols and applications for underwater networking. In particular, considerable attention is being given to the feasibility of underwater wireless sensor networks (UWSNs).

The CoLlAborative eMbedded networks for submarine surveillance (CLAM) project, funded by the European Commission under the 7th Framework Programme, has the objective to reduce the complexity and cost of pervasive and fine-grained underwater surveillance. This problem, inherently a formidable task due to the harshness of the environment and to the limited technology we can count on today, will be tackled via remotely controlled and cooperating underwater sensor nodes. These nodes will be networked via acoustic communications over multi-hop topologies. Information flows are foreseen to be bi-directional: from a control center to the nodes (to change configuration parameters, perform task allocation, control node operation) and from the nodes to the control center (to provide reports on the sensed data). For this purpose new protocol solution will be proposed with particular attention to Medium Access Control (MAC) and routing protocols.

Recently, many solutions for underwater MAC and Routing have been proposed, mostly based on variants of typical terrestrial radio approaches.These methods rely on simple modifications of the ALOHA scheme [1], of Carrier-Sense Multiple Access (CSMA) without [2], [3] and with [4] collision avoidance, of TDMA [5], [6], and CDMA [7]. Hybrid schemes have also been proposed [8], [9]. The performance of some of these schemes have also been compared by means of simulations [10]. Similarly, several routing solutions have been proposed, for both fixed and mobile networks (see, e.g., [11] for an overview).

For both routing and MAC protocols, most of the study and evaluation phases have been carried out via simulations. However, every network simulation software needs to approximate the behavior of sound propagation in the water: therefore, the reproduction of actual channel variability will also be approximated (see, e.g., the discussion related to the Bellhop ray tracing package in [12]). In turn the behavior of the protocols simulated on top of approximated channel behaviors may be different than what would happen in practice. Other than the error related to our knowledge of the environmental data and to the way we exploit it to model sound propagation, simulation packages may also be subject to other systematic errors, if they do not typically reflect the dynamics of the environment. In fact, e.g., the sound speed profile changes over time, the profile of surface waves evolves, and these changes can affect the accuracy of the simulation results. This is especially true for shallow water scenarios, where the channel dynamics strongly affect the quality of network links over time.

Because typical scenarios in the CLAM project entail shallow water monitoring, the first contribution of this paper is to improve the network simulation tool of choice in what follows, namely ns2-Miracle [13] connected to the Bellhop propagation simulator [14] via the WOSS extensions [2], to make it capable to track environmental changes over time. This helps mitigate the problem introduced above, and makes the results of the simulations more realistic, provided that actual data retrieved *in situ* is available, e.g., in the form of SSP samples taken at fixed time intervals during one or more days. In particular, this feature is key to run evaluations that cover large spans of simulated time. In addition, we also consider the reproduction of surface wave patterns according to standard surface wave spectrum functions: this also makes the computation of propagation patterns more realistic. Ultimately, this whole effort improves the convenience of simulation as a tool to experiment what would be too difficult to test in real life.

It is worth noting that some works considered the behavior of networking protocols in the presence of different environmental data. Among these, [15] focuses on the simulation of MAC protocols using WOSS [2], using environmental data from both the summer and the winter seasons. However, the authors do not consider changes over a shorter time scale and their effects on protocols, as we do instead in the present paper.

The second contribution of our paper is a study of how the time-varying behavior of the underwater acoustic channel (as accounted for in simulations) impacts the performance of network protocols over time. We perform this evaluation over scenarios of practical interest for the CLAM system. We study the effects of different environmental conditions on the performance of network protocols, with focus on MAC and routing. We also show that it is convenient to let the network adapt to changing environmental conditions, e.g., by recalculating the routes packets should follow on the way towards the sink over time. Our results show that this is actually beneficial not only in terms of typical metrics such as throughput and packet delivery ratio (which improve by about 10 to 20%), but also in terms of transmission efficiency, as the shorter routes devised by allowing adaptation to the environment help avoid useless data replication over multiple hops.

II. Considered Protocols

For the forthcoming comparison, we consider two different MAC protocols (CSMA-ALOHA and DACAP), that have been implemented in our framework.

CSMA–ALOHA is a form of ALOHA with a very short channel sensing phase before a packet is actually transmitted. Given that the typical balance between the packet transmission time and the propagation delay in underwater networks makes CSMA inefficient, the short sensing introduced here serves the only purpose to avoid a trivial collision scenario (i.e., where the current node starts its own transmission while a different signal is propagating in the same area where the node is located, resulting in likely collision at the intended receiver of such signal). The sensing time is randomized to avoid the synchronization of channel access attempts and repeated collisions. In case the channel is found busy, the transmitter employs a standard binary exponential backoff scheme. This protocols is a mixed form of both ALOHA and CSMA, hence the name.

The **Distance Aware Collision Avoidance Protocol** (DACAP) [4] uses an extended version of a Request-To-Send/Clear-To-Send (RTS/CTS) handshake for reserving the channel before packet transmission. More specifically, when a node has a packet to send, it senses the channel: if the channel is idle, the node transmits an RTS. Upon receiving the RTS, the destination replies with a CTS and then waits for the data packet. With respect to the usual CSMA/CA scheme, DACAP adapts to the underwater channel characteristics by using the following mechanism. If, while waiting for a data packet, a destination node overhears a control packet for some other node, it sends a short warning packet to its transmitter. In addition, every sender defers the data packet transmission for a prescribed amount of time, after receiving a CTS. If it overhears another control packet or receives a warning packet from the destination during this period, the sender aborts the current transmission attempt. The length of the defer time depends on the distance between the source and its destination, which the sender can estimate using the RTS/CTS round-trip time. When the receiver overhears an RTS and sends a warning, it does not know whether the warning will reach the sender on time to make it abort the transmission. Since a data packet can still arrive, the receiver must continue listening to the channel even after a warning has been sent. For this reason, the defer time is defined as the minimum waiting period between receiving the CTS and sending the data that guarantees the absence of harmful collisions.

III. Extensions to WOSS and Scenario Description

The World Ocean Simulation System (WOSS) [2] employs oceanographic databases for environmental parameters in order to bring realistic acoustic propagation patterns into ns2-Miracle using the Bellhop ray tracing software [14]. In particular, WOSS has been interfaced with public databases such as the World Ocean Database for SSPs [16], the General Bathymetric Chart of the Oceans [17] for bathymetry and the National Geographic Data Center's Deck41 Database [18] for bottom sediments. Furthermore, it also supports data retrieval from user-custom datasets.

We extended the capabilities of WOSS to support the processing of time-varying environmental conditions. For example, this allows to implement SSP changes over the duration of a day. However, we note that SSP measurements are typically available only at certain time epochs throughout a day, whereas the simulator should model the transition between the current and the next SSP samples as well. This would include a much more detailed representation of the environment (e.g., considering all phenomena that cause sudden temperature changes such as currents and internal waves). In order not to put too much complexity in the simulator, we model the transition from one SSP sample to the following one via a simple convex combination as follows:

$$\mathrm{SSP}(t) = \mathrm{SSP}(t_i)\frac{t_{i+1}-t}{t_{i+1}-t_i} + \mathrm{SSP}(t_{i+1})\frac{t-t_i}{t_{i+1}-t_i} \qquad (1)$$

where t_i and t_{i+1} are the time epochs when the ith and $(i+1)$th samples of the SSP have been measured, respectively, and t is the current time epoch, $t_i \le t < t_{i+1}$. The user is allowed to specify as many SSPs as needed, possibly spanning more days. In addition, we implemented a random generation

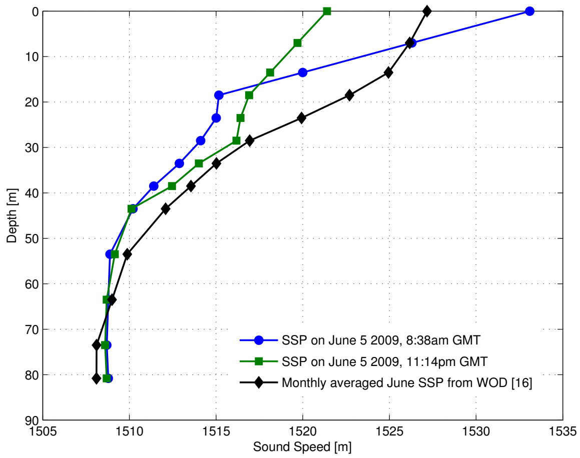


Figure 1. Sound speed profile realizations taken during the SubNet'09 campaign off the island of Pianosa, Italy, between June 5 and 6, 2009. A monthly average of the SSP across the month of June, taken from the WOD 2009 database [16], has been included for comparison.

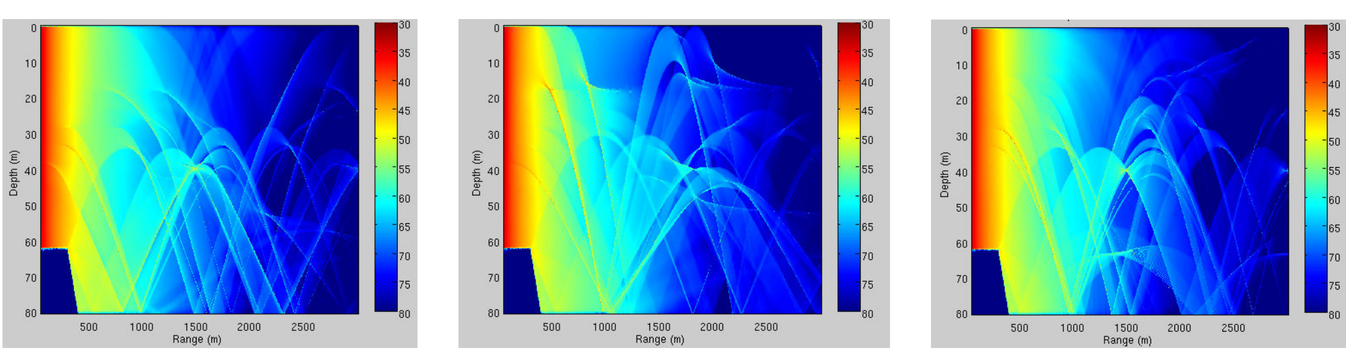
of surface wave profiles, which have been set to obey a Bretschneider 2-parameter spectrum [19].[1]

The SSP samples we use in this paper have been collected during the SubNet'09 sea trials, which took place off the eastern shore of the Pianosa Island, Italy ($42.585°$N, $10.1°$E) [12]. This location has therefore been chosen as the simulation area. From the SubNet'09 dataset, we pick 8 distinct SSP samples spanning the duration of one day on June 5th, 2009. Some SSP realizations used in the simulation are shown in Fig. 1: note that the database samples do not include sound speed measurements at very shallow depths: therefore, we have linearly extrapolated the SSP starting from the last two known speed samples (located at a depth of 18 and $13\,\text{m}$, respectively). For comparison, we also depict in Fig. 1 the monthly average of the SSPs realizations in the WOD 2009 database, i.e., the realization which WOSS would automatically retrieve if not supplied with external data. We observe that the measurements and the monthly average are in fact similar, with the exception that the latter yields slightly higher sound speed values at low depth. This difference is amplified by the fact that the SubNet'09 SSPs we used have been taken on the 5th of June, whereas the monthly SSP average contains a significant contribution from later June days, when surface waters are typically warmer, yielding higher sound speed.

These variations can substantially affect the way sounds travels through water. In fact, the change of sound speed across the water column causes the trajectory of sound waves to bend, and can thus change the level of the sound pressure in time at any point in the network area. To exemplify this phenomenon, two channel realizations obtained via Bellhop[2] are shown in Figs. 2(a) and 2(b), using a nighttime and a daytime SSP, respectively. For comparison, a realization generated using the June SSP from WOD 2009 has been shown in Fig. 2(c). From these patterns we observe that the attenuation of a signal at a given point in space can vary significantly due to the varying refraction effects caused by different temperature gradients throughout the day. For example, acoustic rays bent downward relatively sharply in daytime, whereas during nighttime this refraction effect is less pronounced, which makes the insonification more uniform and able to reach slightly larger distances. For example, consider the attenuation in Figs. 2(a) and 2(b) at a depth of 0 to $15\,\text{m}$ from a distance of about $2000\,\text{m}$ from the source (located on the left in the pictures at a depth of $40\,\text{m}$): during daytime, the attenuation is very high and almost no sound reaches the area due to strong downward refraction; conversely, the attenuation is estimated to about $70\,\text{dB}$ during nighttime, thanks to a more uniform SSP and to bottom bounces which reach the top of the watercolumn thanks to milder downward refraction. For comparison, the WOD 2009 SSP in Fig. 2 shows an even larger shadow zone with little sound propagation extending deeper than in Fig 2(b), whereas the insonification level before a distance of $2000\,\text{m}$ is comparable to that in Figs. 2(a) and 2(b). Such changes may

[1]The characteristic height has been set to $\bar{H}_{char} = 1.5\,\text{m}$ and the average wave period to $\bar{T} = 3\,\text{s}$. This yields surface wave realizations matching a windy day.

[2]We consider here the "incoherent" propagation profile calculation option.



(a) Nighttime SSP

(b) Daytime SSP

(c) June SSP from WOD 2009

Figure 2. Attenuation profiles obtained with Bellhop using (a) a nighttime SSP (b) a daytime SSP and (c) the monthly averaged June SSP automatically retrieved by WOSS from the World Ocean Database 2009 [16]. In the bottom-left corner of the pictures we observe the bathymetry profile as extracted by WOSS from General Bathymetric Chart of the Oceans [17].

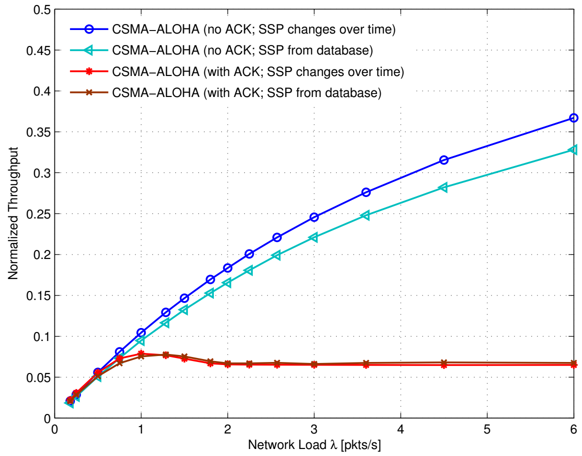


Figure 3. Normalized throughput as a function of the traffic generation rate in the network using CSMA-ALOHA.

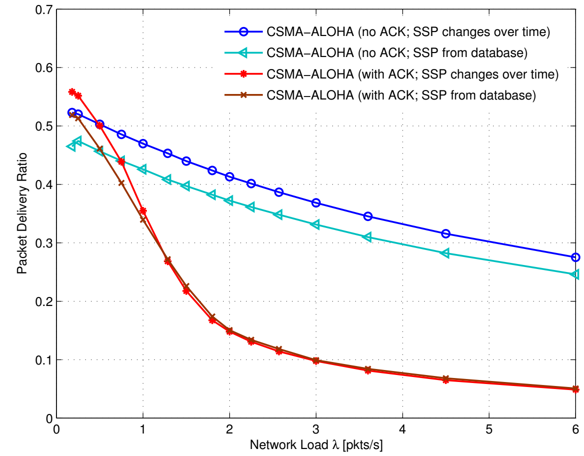


Figure 4. Packet delivery ratio as a function of the traffic generation rate in the network using CSMA-ALOHA.

have a significant impact on the performance of networking protocols, as will be discussed in Subsections IV-A and IV-B.

In the following evaluation, we assume that all nodes transmit using a Binary Phase Shift Keying (BPSK) modulation technique at a bit rate of $4800\,\mathrm{bps}$ at a central frequency of $25\,\mathrm{kHz}$, similar to one of the possible configurations of the WHOI micromodem [20]. The length of data and ACK packets is fixed at $L_D = 125\,\mathrm{Bytes}$ and $L_A = 10\,\mathrm{Bytes}$, respectively. The traffic is generated randomly according to a Poisson process of fixed rate λ packets per second in the whole network. We recall that the network area chosen for the simulations is off the eastern coast of the Pianosa Island, in Italy, at about $42.585°$N, $10.1°$E. All nodes are randomly placed within the network area except the sink, which is centrally placed. The channel is periodically re-computed according to the new propagation conditions dictated by the SSP changes as per Eq. (1).

We will now consider two different sets of network results: the first focuses on MAC performance, whereas the second one focuses on routing performance. In the MAC test scenario, we consider a network of 19 nodes plus one sink, centrally placed at a depth of $3\,\mathrm{m}$. The network is put under stress by considering a relatively small area of $3\,\mathrm{km} \times 1.5\,\mathrm{km} \times 80\,\mathrm{m}$, where however the nodes located farthest from the sink still have a fair probability of delivering a packet correctly (albeit this probability may decrease according to SSP changes). In the routing test scenario, we consider a larger network area of $5\,\mathrm{km} \times 5\,\mathrm{km} \times 80\,\mathrm{m}$, in order to increase the average distance among the nodes, their neighbors, and the sink. In this case, the farthest nodes are not guaranteed any consistently good-quality link towards the sink, and must therefore resort to routing in order to have their own packets delivered. All simulation results are averaged over 25 different rounds for MAC experiments and 45 different runs for routing experiments.

IV. Simulation Results

A. MAC results

We start our comparison by considering the MAC-level performance of static topologies. We consider first the CSMA-ALOHA MAC protocol described in Sec. II. Figs. 3 and 4 depict the normalized throughput (i.e., the average number of packets delivered to their intended destination per packet transmission time) and the packet delivery ratio (i.e., the ratio of the correctly received packets over all sent packets) for a network of 19 nodes and one sink. Each figure contains four curves, corresponding to two different versions of the protocol, with and without Stop-and-Wait Automatic-Repeat reQuest, S&W ARQ: in the latter case, the transmitter sends a packet and waits for the confirmation of correct reception from the sender in the form of an acknowledgment message (ACK). The two versions have been evaluated both under changing SSP conditions and under the same (fixed) SSP that WOSS would retrieve from the WOD database.

By comparing the curves for fixed and varying SSP in Figs. 3 and 4, we indeed observe different performance, mainly due to the stronger downward refraction caused by the averaged SSP in the WOD 2009 database, which deviates most of the sound pressure towards the bottom and does not favor long-range transmissions, and in turn causes packet reception errors. This effect is similar to that observed, e.g., in Fig. 2(b). Notice that, while negligible in terms of absolute values, the difference between the two no-ACK CSMA curves is about 10% and increasing for higher traffic, meaning that as the network approaches the point of maximum throughput, the value obtained using WOD's SSP is quite lower than what would be obtained in a real scenario, and makes the usage of more frequent environmental data samples worth whenever possible. However, when a more detailed data set is not available, the curves of the protocols under the monthly averaged SSP show the same trend as those obtained with a varying SSP. Hence,

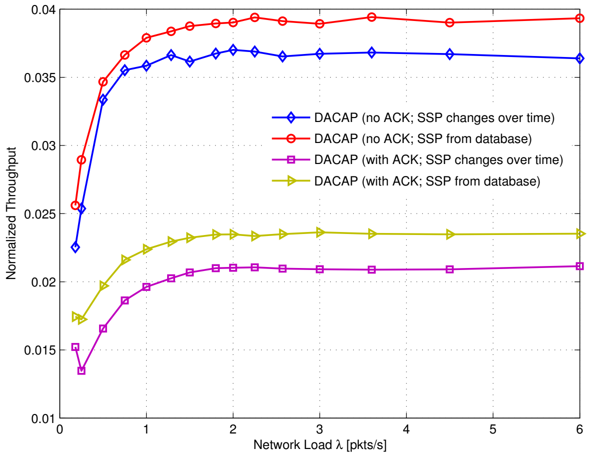


Figure 5. Throughput as a function of the traffic generation rate in the network using DACAP.

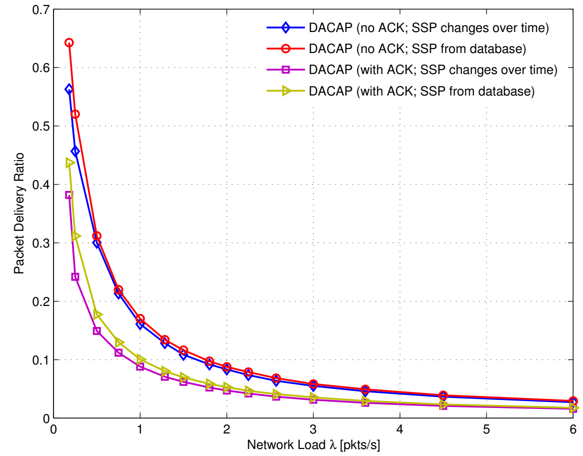


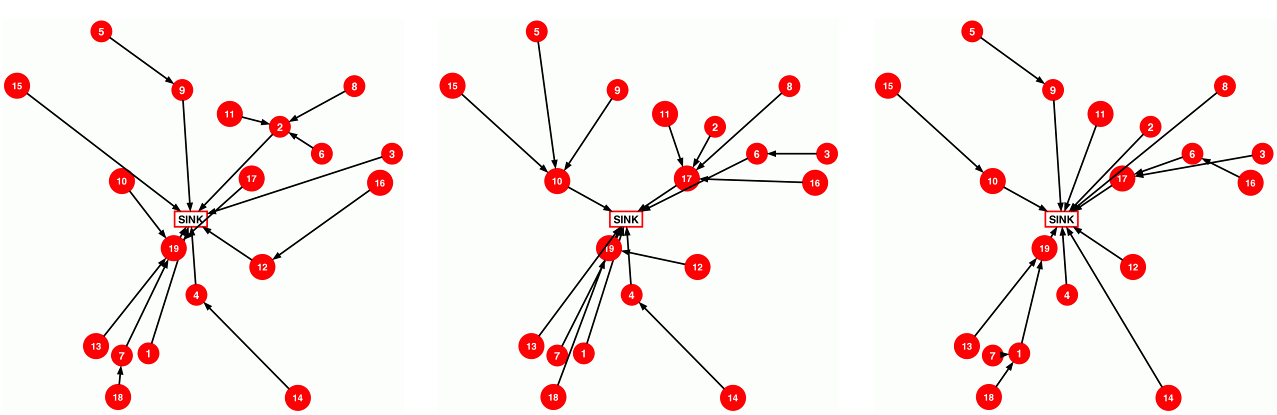
Figure 6. Packet delivery ratio as a function of the traffic generation rate in the network using DACAP.

higher-level performance indications, such as the network load for which the maximum throughput is reached, are similar. For example this is the case for the throughput and packet delivery ratio of CSMA-ALOHA with S&W ARQ in Figs. 3 and 4, respectively. In fact, the throughput curves show a very similar trend, and their difference is further mitigated by the inherently higher waiting times caused by S&W, which translate into lower throughput in both the fixed and the varying SSP cases. On the other hand, the slight difference between the two maxima of the throughput curves in Fig. 3 can be explained via the higher delivery ratio obtained in the varying SSP case (Fig. 4).

Similar observations apply to Figs. 5 and 6, which present normalized throughput and delivery ratio results for DACAP. In this case the throughput is comparatively lower than CSMA-ALOHA's, due to the requirement to perform 3-way and 4-way handshakes in the no-ACK and ACK cases, respectively. In addition, hidden terminal effects and collisions between control and data packets [10] adversely affect the capability to set up links, and decrease the throughput of the DACAP protocol.

B. Routing results

As the variation of the sound propagation pattern over time has an impact on the performance of MAC protocols, likewise such change affects the capability of a network to route data. In this section, we present some results to show this phenomenon. We consider static topologies where 19 nodes are deployed in the same network area described above, with a sink centrally placed at a depth of $3\,\mathrm{m}$. In this evaluation, the network must convey (or converge-cast) the data generated by all nodes to the sink. Given the better performance of CSMA-ALOHA in the previous evaluation, we employ it as the medium access control technique in what follows. For simplicity, the network maintains static routes. This means that each node knows exactly what the following neighbor is on the path toward the sink. The objective of the study is to



(a) After 3:20 hours (b) After 10:00 hours (c) After 20:00 hours

Figure 7. Example of how optimal routes evolve as the SSP changes at different times during a day. The deployment is actually three-dimensional, but is seen from above and therefore depicted as two-dimensional for convenience.

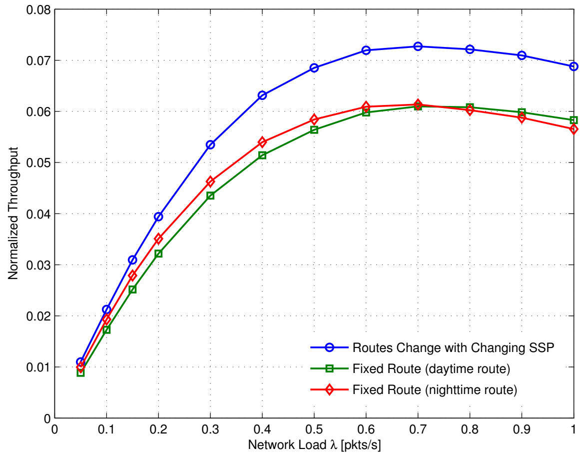


Figure 8. Normalized throughput as a function of the traffic generation rate in the network using fixed and adaptive routes.

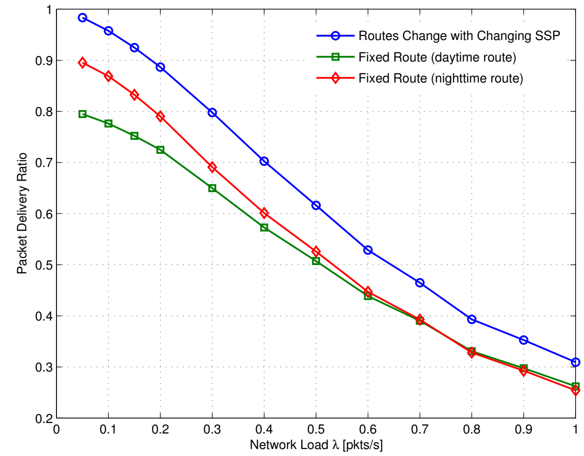


Figure 9. Packet delivery ratio as a function of the traffic generation rate in the network using fixed and adaptive routes.

show that recalculating such routes once every so often yields performance improvements both in terms of the maximum data throughput and in terms of the length of the routes: these tend to be shorter, which avoids useless replication of transmitted packets over multiple hops.

In more detail, we take 8 SSP samples from the SubNet'09 data set, which span the duration of one day between June 5th and June 6th, 2009. For each of these samples, we run Bellhop to get a measure of the attenuation over the link between all pairs of nodes. We then calculate shortest paths to the sink via a simple Dijkstra algorithm, with the constraint that the link between nearest neighbors should span the longest distance and guarantee a Signal-to-Noise Ratio (SNR) of at least $15\,\mathrm{dB}$.[3] Network simulations are then performed by letting the SSP change over time according to the discussion in Sec. III. However, at each time epoch corresponding to one of the 8 SSP measurements taken from the SubNet'09 dataset, we recalculate all the routes to match the new propagation conditions. Figures 7(a)–(c) give an example of how such routes change over time at different epochs throughout the simulation. Note that we do not explicitly implement a route dissemination protocol: the study of a suitable approach for this is left as a future extension.

Figs. 8 and 9 show the throughput and packet delivery ratio as a function of the traffic generation rate in the network. This time, throughput is defined as the number of packets correctly delivered to the sink per packet transmission time. For each traffic rate, simulations are run for about 24 hours of simulated time, spanning all considered SSP samples. Along with the adaptive route case we will also evaluate a scenario

[3]An even more realistic approach would require to perform multiple Bellhop runs for each link, each featuring a small randomization of the environmental parameters. The links to form the routes could then be constrained to have an *average* SNR (over all realizations) exceeding some threshold. However, this would substantially increase the computational burden. We therefore decided to perform only one realization per link, and compensated for small-scale changes by imposing a quite high threshold of $15\,\mathrm{dB}$.

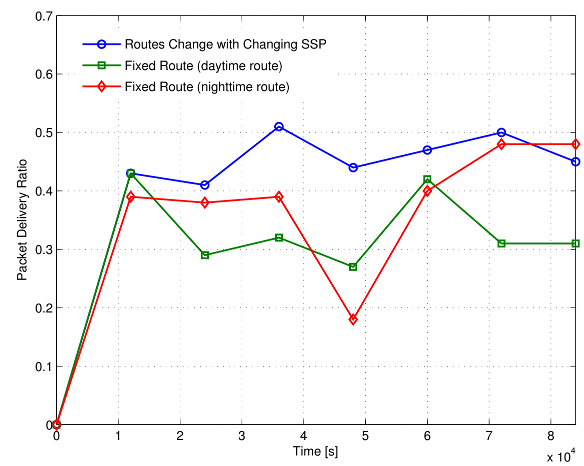


Figure 10. Packet delivery ratio experienced over time by a specific node, using adaptive and fixed routes.

with two different fixed routes, one computed using a daytime SSP, and a second one using a nighttime SSP. From Fig. 8, we observe that route changes cause a throughput increase of roughly 20% over fixed routes. This improvement is mainly due to the better packet delivery ratio (Fig. 9), consistently 10% better than both fixed route cases.

In spite of the relatively limited difference between the adaptive and fixed route cases, single nodes can suffer from worse performance and affect the network as a consequence. For example, consider Fig. 10, which depicts the packet delivery ratio experienced by a specific node as a function of time, as it forwards its packets to the next hop towards the sink. Each point corresponds to the packet delivery ratio measured over the preceding 3 hours. As environmental conditions change with the time of day, the link between the two nodes can become quite unreliable. The usage of adaptive routes allows to choose next hops according to how much the link

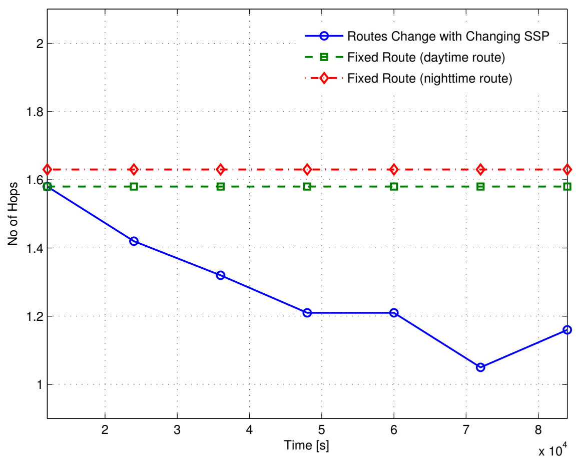


Figure 11. Average route length in the network over time using adaptive and fixed routes.

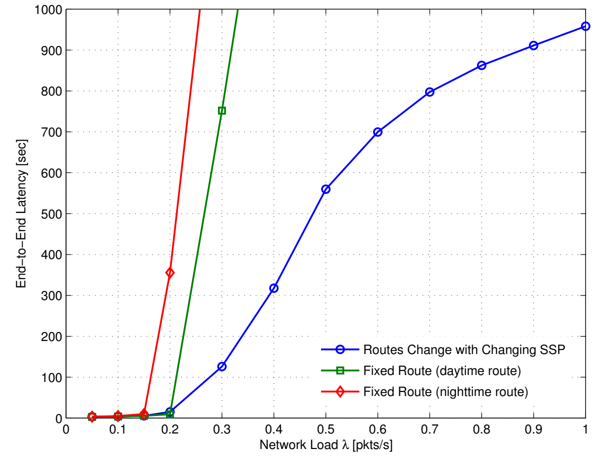


Figure 12. Delivery delay as a function of the traffic generation rate in the network using fixed and adaptive routes.

towards them is reliable, and therefore leads to a better and more stable performance. In addition, adapting routes allows to keep them short, avoiding useless packet replication through multiple nodes. This effect can be seen in Fig. 11, where we observe that the average route length decreases significantly with adaptive routes: this makes the network almost single-hop towards the end of the simulation. These results explain the quite sharp advantage gained by adaptive routes in terms of average delivery delay, defined as the time elapsed between the generation of a packet and its delivery to the sink. Fig. 12 details the comparison among the delivery delays as a function of traffic for the adaptive routes and the fixed daytime and nighttime routes. The curves show that both fixed routes lead to very long delays at low traffic; on the contrary, adaptive routes keep the delay within more acceptable levels, and help reduce the rate at which delay increases with traffic.

V. Conclusions

In this paper, we have evaluated the effects of changing environmental conditions on the performance of MAC and routing protocols in underwater acoustic networks. To this end, we employ a modified version of the WOSS simulator where the sound speed profile over the watercolumn is allowed to change in time. Our results show that MAC protocols are in fact impacted by the SSP employed to simulate, even though the performance achieved using measured environmental data and that measured using the sound speed retrieved from the free World Ocean Database 2009 are relatively similar, and in any event show the same trend.

We then showed that it is not convenient to set up static routes in a multihop network, as SSP changes would make such routes suboptimal over time. We argued that even a route update as rare as once every three hours achieves much better performance, especially in terms of delivery delay and of the average length of the routes.

Future work on this topic includes a more detailed study of the optimal route update frequency and the implementation of a route dissemination and update protocol.

Acknowledgments

This work has been supported in part by the European Commission under the 7th Framework Programme (grant agreement no. 258359 – CLAM).

The authors gratefully acknowledge the Nato Undersea Research Centre, La Spezia, Italy, for providing the samples of the sound speed profile from the SubNet'09 dataset.

References

[1] N. Chirdchoo, W.-S. Soh, and K. C. Chua, "ALOHA-based MAC protocols with collision avoidance for underwater acoustic networks," in *Proc. of IEEE INFOCOM*, Anchorage, AK, May 2007.

[2] F. Guerra, P. Casari, and M. Zorzi, "World Ocean Simulation System (WOSS): a simulation tool for underwater networks with realistic propagation modeling," in *Proc. of ACM WUWNet 2009*, Berkeley, CA, Nov. 2009.

[3] S. Basagni, C. Petrioli, R. Petroccia, and M. Stojanovic, "Choosing the packet size in multi-hop underwater networks," in *Proceedings of IEEE OCEANS*, Sydney, Australia, May 2010.

[4] B. Peleato and M. Stojanovic, "Distance aware collision avoidance protocol for ad hoc underwater acoustic sensor networks," *IEEE Commun. Lett.*, vol. 11, no. 12, pp. 1025–1027, Dec. 2007.

[5] A. Syed, W. Ye, and J. Heidemann, "Understanding spatio-temporal uncertainty in medium access with ALOHA protocols," in *Proc. of ACM WUWNet*, Montréal, Canada, Sep. 2007.

[6] J. Yackoski and C. Shen, "UW-FLASHR: Achieving high channel utilization in a time-based acoustic MAC protocol," in *Proc. of ACM WUWNet*, San Francisco, CA, Sep. 2008.

[7] D. Pompili, T. Melodia, and I. Akyildiz, "A CDMA-based medium access control for underwater acoustic sensor networks," *IEEE Trans. Wireless Commun.*, vol. 8, no. 4, pp. 1899–1909, Apr. 2009.

[8] K. B. Kredo II and P. Mohapatra, "A hybrid medium access control protocol for underwater wireless networks," in *Proc. of ACM WUWNet*, Montréal, Canada, Sep. 2007.

[9] R. Diamant and L. Lampe, "A hybrid spatial reuse MAC protocol for ad-hoc underwater acoustic communication networks," in *Proc. of IEEE ICC*, Cape Town, South Africa, May 2010.

[10] C. Petrioli, R. Petroccia, and M. Stojanovic, “A comparative performance evaluation of MAC protocols for underwater sensor networks.” in *Proc. of MTS/IEEE OCEANS*, Québec City, Canada, Sep. 2008.

[11] D. Pompili and I. Akyildiz, “Overview of networking protocols for underwater wireless communications,” *IEEE Commun. Mag.*, vol. 47, no. 1, pp. 97–102, Jan. 2009.

[12] B. Tomasi, G. Zappa, K. McCoy, P. Casari, and M. Zorzi, “Experimental study of the space-time properties of acoustic channels for underwater communications,” in *Proc. IEEE/OES Oceans*, Sydney, Australia, May 2010.

[13] N. Baldo, M. Miozzo, F. Guerra, M. Rossi, and M. Zorzi, “MIRACLE: The Multi-Interface Cross-Layer Extension of ns2,” *EURASIP Journal on Wireless Communications and Networking*, Jan. 2010. [Online]. Available: http://www.hindawi.com/journals/wcn/2010/761792/cta/

[14] M. Porter *et al.*, “Bellhop code.” [Online]. Available: http://oalib.hlsresearch.com/Rays/index.html

[15] F. Guerra, P. Casari, and M. Zorzi, “A performance comparison of MAC protocols for underwater networks using a realistic channel simulator,” in *Proc. of MTS/IEEE Oceans*, Biloxi, MS, Oct. 2009.

[16] “World ocean database.” [Online]. Available: http://www.nodc.noaa.gov/OC5/WOD09/pr_wod09.html

[17] “General bathymetric chart of the oceans.” [Online]. Available: www.gebco.net

[18] “National geophysical data center, seafloor surficial sediment descriptions.” [Online]. Available: http://www.ngdc.noaa.gov/mgg/geology/deck41.html

[19] C. L. Bretschneider, “A one dimensional gravity wave spectrum,” in *Proc. of the Conference on Ocean Wave Spectra*. Prentice Hall, 1963.

[20] L. Freitag, M. Grund, S. Singh, J. Partan, P. Koski, and K. Ball, “The WHOI micro-modem: An acoustic communications and navigation system for multiple platforms,” http://acomms.whoi.edu/umodem/, 2005.