ASUNA: A Topology Dataset for Underwater Network Emulation

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Abstract

We report the details of ASUNA, a freely shared dataset for underwater network emulation (ASUNA). ASUNA tackles the time-consuming and costly logistics of multiple underwater networking sea trials by providing a benchmark database of time-varying network topologies recorded across multiple sea experiments, thus facilitating *experiment replay* and *network emulation*. The ASUNA database currently includes 20 diverse, time-varying topology structures, multimodal communication technologies, and different link quality measurements. With the aim of becoming a standard benchmark, ASUNA is open to extensions as new data becomes available from the underwater communications community. We provide the details of ASUNA structure, the list of recorded topologies, as well as examples of how to use the database as an emulation system to test the performance of two scheduling protocols. We freely share the database and the emulation code both through a web server and via the Code Ocean repository.

Index Terms

Underwater acoustic communication networks; emulation system; underwater acoustic network benchmark; sea experiments; experiment replay; network performance validation.

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I. Introduction and motivation for this work

Underwater communication devices have been steadily improving over time in terms of both reliability and bit rate [1], and can be arranged into underwater acoustic communication networks (UWANs) to support a broad variety of applications [2]. A multitude of protocols have been designed for UWANs to date, providing different functionalities at different layers of the ISO/OSI protocol stack [3]–[5].

Sea trials are considered a good option to test the performance of UWAN protocols. However, organizing and performing a sea experiment is usually time-consuming, effort-intensive, and implies high costs in terms of materials, rental of ship time, purchase, transport and deployment of underwater transceivers, etc. Moreover, sea experiment results are related to a local set of environment and channel conditions, which makes it difficult to extrapolate the results to different environments. Finally, a single experiment does not allow a fully fair comparison between algorithms.

As a result, simulations are often preferred when evaluating the performance of newly designed protocols against competing approaches in the literature. Simulations make it possible to approximately evaluate communication protocols and schemes by abstracting from specific hardware issues, However, on the one hand there are no statistical models of the underwater acoustic channel that are broadly agreed upon, so that a realistic simulation often has to rely on complex numerical propagation modeling (e.g., [6]); on the other hand a full-fledged evaluation necessarily needs to take into account the many practical issues that occur in actual underwater scenarios. This includes the time-dependency of the acoustic channel, the conditions of actual underwater environments, and possibly the behavior of hardware devices.

Hardware-in-the-loop systems are one of the means to improve the agreement between simulated protocol performance and actual performance at sea, at least in terms of the peculiarities of underwater transceivers. Examples of frameworks offering hardware-in-the-loop capabilities include DESERT Underwater [7], SUNSET [8], UNetStack [9], Aqua-Net-Mate [10], NET-SIM [11], as well as the software-defined cognitive communications architecture presented in [12]. These capabilities are made possible by interchanging the procedures that simulate underwater propagation and compute link budgets with software drivers for specific underwater modems. However, even the hardware-in-the-loop concept can reproduce actual underwater propagation and the variation thereof over time only to a limited extent.

The above discussion leads to the conclusion that, in the absence of both a fully detailed simulation model of an underwater acoustic communication system and of the resources to organize a sea experiment, a reliable performance evaluation method should preferably involve recordings from a real sea environment.

For the design and test of point-to-point underwater communication systems in realistic conditions, the community often resorts to publicly shared communication datasets in order to reproduce the broadest possible span of underwater channels (e.g., long or short delay spread, heavier or milder Doppler spread, single or multiple receivers, etc.). Examples include the measurements presented in [13], the SPACE08 and KAM11 datasets, employed among others in [14]–[17]). More recently, the release of the Watermark benchmark [18] makes it possible to reproduce the distortion of acoustic waveforms transmitted through underwater channels that are either measured or stochastically replayed.

In this paper, we propose a similar solution for the testing of underwater network protocols, named *ASUNA*, for "A shared underwater network emulation dataset." ASUNA is a collection of measurements from multiple sea experiments, and aims to be the first freely shared database that enables the replay of underwater acoustic networking trials, often referred to as *emulation*. To the best of our knowledge, this is the first attempt to assemble a dataset for the direct evaluation of the performance of network protocols. ASUNA provides a collection of time series of link quality indicators, collected over time during several sea experiments at different locations around Europe, Israel and West Africa. These experiments are representative of a broad set of conditions: different numbers of nodes, different deployments resulting in multiple network topologies, different transceivers, and multimodal setups (where communications are realized through a set of orthogonal technologies, not necessarily acoustic). Once this data has been loaded into a network emulator, the link quality time series can be used to reproduce the same realistic performance that could be experienced at the same location and time each experiment had been carried out. As a result, the user can evaluate networking solutions with a degree of accuracy that stands in between a simulation and a full-fledged sea experiment, in a fully reproducible setting, without having to actually go to sea.

In total, ASUNA includes 22 network topologies from 7 different sea experiments, for a total of more than 10 hours of underwater data packet transmissions. We make the data available in an Octave/Matlab format, so that it can be easily manipulated, converted to other formats, as well as integrated into existing Octave/Matlab code. For each dataset, we document the experiment it is extracted from, so that the user knows the experiment's location and time; the location of the nodes; the conditions of the water body at that time; and the types of link quality measurements available for that experiment. The metrics provided by the dataset so far include received signal strength, bit error ratios, and "0/1" indicators conveying whether a given packet would be received correctly or not if transmitted at a given time. Different metrics may be embedded in the future as additional datasets are added to the collection.

We hope that the community will find ASUNA useful and will contribute additional datasets to the collection. Along with the database, we provide a network emulation code as an example of how to use ASUNA. The emulator runs a simple time-division-multiple-access (TDMA) protocol over the recorded topologies. Yet, by no means is the usage of ASUNA confined to such a solution.

While there is some novelty in our approach and it has been recently endorsed that reproducible and interactive research results bear significant value for the underwater community [19], the focus of this technical communication is on the tool per se, rather than on novel results obtained through it. The remainder of this paper is organized as follows: Section II provides an account of related work; Section III describes the ASUNA dataset; Section IV discusses the emulator provided with the dataset and some results obtained with it; Section V concludes the paper.

II. Related Methods

In terrestrial radio networks, it is customary to evaluate the performance of wireless networking protocols by means of simulations, supported by different types of channel models [20]–[22]. Initial studies on channel modeling for underwater networks followed the same approach. For example, [23] modeled packet errors from the SubNet09 campaign using Markov and hidden

Markov models. Typical statistical distributions of large-scale underwater channel gain [24]–[26] have been observed to be valid across a number of channel measurements.

Besides simulation, network performance can be evaluated through emulation or trace-based simulation. Emulation refers to the use of realistic networking hardware, or to the execution of actual applications on top of hardware components that reproduce the behavior of wireless networking equipment. For example, this implies running complex channel models in real-time in some dedicated hardware. Trace-based simulation [27]–[29], also described as channel replay-based, relies on the recording of the time series (or "traces") of link quality metrics [30]. This makes it possible to exactly reproduce the same wireless channel conditions repeatedly, and to test different protocols in fully comparable scenarios. For tests that do not require to learn the channel evolution over time, the evaluation can be extended by suitably scrambling the measurements so that channel properties remain statistically coherent [31], [32].

In the underwater community, several works have tackled the reliable and validated reproduction of the communications performance measured during experimental campaigns. These studies mainly focused on the physical layer. For example, [13] proposed to collect underwater channel recordings in order to reproduce the impact of the acoustic channel on underwater modulation schemes. The collected dataset includes channel estimates from several sea experiments. More recently, Watermark [18] has been released as a benchmark for underwater modulation schemes. Watermark is based on the validated MIME tool, which enables both direct and stochastic underwater channel replay [16], [33]. In some cases, channel estimates can be directly obtained through deployed infrastructure that is shared with the community at large, typically for limited periods of time and under some form of collaboration agreement. This includes the NATO CMRE LOON [34], the equipment of Ocean Networks Canada [35], the SUNRISE testbed federation [36], as well as permanently online infrastructure such as the THEMO observatory [37].

Besides direct and stochastic channel replay, other methods have been considered to enable model-based channel reproduction. For example, in [38] the authors propose to evaluate the reliability of underwater communications through the multipath structure of previously measured underwater channels, which can be evaluated using numerical models rather than sea experiments.

Realistic channel simulations obtained through the Bellhop ray tracing software [6] have been incorporated in the World Ocean Simulation System (WOSS) [7], a framework that automatically retrieves the environmental information required by Bellhop in order to compute attenuation figures and channel impulse responses. A similar integration of models based on parabolic equations in network simulations is discussed in [39]. Like many other channel simulators, both Bellhop and a parabolic equation solver present the issue that their output is deterministic for fixed boundary conditions. This was addressed, e.g., in [25], which provides time-varying channel realizations as would result from the movement of the transmitter and receiver around their nominal locations. When numerical models or stochastic replay are not sufficient, hardware-in-the-loop systems offer one additional degree of realism by allowing network protocol code (typically written for simulations) to run on actual underwater transceivers. Examples of this approach include DESERT Underwater [40], SUNSET [8], UNetStack [9], Aqua-Net-Mate [10] and NETSIM [11].

Replicating a real underwater communication experiment in network simulations is often challenging and necessarily leads to approximations. Typical approaches include: placing nodes at random in an area and using acoustic models to predict the success of packet transmissions [41]–[45]; simulating node motion, especially in the presence of autonomous underwater vehicles (AUVs) or other types of mobile nodes [46]–[49]; letting nodes drift, e.g., by using water current models [50]–[52]; and injecting the acoustic noise generated by ships and AUVs navigating near the network deployment [53].

While the above methods approximate realistic scenarios to some degree, only in sea experiments can all the details of actual underwater communications be taken into account. Experiments with a large number of nodes were demonstrated by large organizations or collaborations. Relevant examples include the joint TNO/FFI tests on the NILUS node [1] (7 nodes); the collaborative experiments promoted by the NATO STO CMRE, such as CommsNet13 [54] (up to 9 nodes); the MISSION 2013 campaign [9] (10 nodes); the final sea trial of the RACUN project [55] (15 nodes); as well as the Jaffe lab sub-mesoscale ocean sampling experiment, featuring 5 static pingers and 13 passive drifters [56].

Besides their complex logistics and cost, underwater networking experiments still capture only the local conditions of the underwater channel at a single location and time: such conditions are not easily extrapolated to different times and scenarios. Through ASUNA, we provide a number of experiment traces. each conveying recorded time series of link quality metrics for all links of several networking experiments. Our objective is to grow ASUNA into a rich and significant benchmark tool through contributions from the community: however, the experiments initially provided already represent a number of different conditions. ASUNA enables “network replay” in a form similar to [57] and [45], which employed previously recorded packet receptions or signal-to-noise ratio (SNR) traces in order to test the performance of underwater routing and scheduling protocols, respectively. There are also similarities with the physical layer replay capabilities of the architecture in [12]. However, while the focus of the above approaches is on the performance evaluation of specific protocols or communication architectures, our objective here is to provide a growing collection of network communication traces. In doing so, we aim at making available a tool that remains positioned between pure simulation and pure experimentation, and that joins the repeatability of trace-based simulation with the rich representation of environments and contexts provided by a sea trial database.

III. Description of the Dataset

A. Overview and link reliability measurements

The ASUNA database is available for download at https://sites.google.com/marsci.haifa.ac.il/asuna/. ASUNA’s databases are basically constructed as time series of link reliability metrics opportunistically collected from UWAN experiments at sea. In each experiment, one or more network topologies were tested.

Link reliability signifies the integrity of the communications between adjacent nodes. It enables hard decisions about the existence of a link (e.g., by setting a threshold on the metric) or, alternatively, soft decisions (e.g., tying the bit error ratio to the probability of packet error). The link reliability is typically a time-varying property. This is especially true for underwater acoustic communications, where the channel impulse response and the ambient noise tend to change rapidly. While emulating physical layer reliability requires a fine time resolution (at least matching the symbol rate) the resolution constraint can be relaxed for the evaluation of underwater networks, where the most important aspect is typically the average (rather than instantaneous) link performance throughout the duration of a packet. In our experiments, we either (*i*) collected data on a per-packet rather than per-symbol basis, or (*ii*) relied on link metrics returned by the modems. The latter are derived either from a packet's preamble, or by observing whether packets are successfully received. We remark that such phenomena as flickering (a condition by which a link appears and disappears at a fast rate in the network's topology) are still present in our topologies at packet transmission time scales, and still enable the evaluation of adaptive protocols that specifically react to such phenomena.

We employ both physical layer and network layer metrics to characterize the link's reliability. Depending on the experiment, we provide: bit error ratio (BER) values computed as the ratio of correctly received bits over the total number of bits in a received packet; received signal strength indicator (RSSI) values related to voltage readings at the receiver upon packet reception, or 0/1 flags that convey whether a link is available or not at a given time epoch. While these metrics can serve for experiment re-play, future contributors of ASUNA are welcome to also record quality indices that are more specific to the setup of their experiment including, e.g., the packet error ratio (PER) or the link throughput.[1] We remark that the datasets of ASUNA are opportunistically extracted from experiments originally designed to test specific communication protocol and schemes. As a consequence, the availability of link metrics depends on the logs collected from the experiment, and may vary across different sea trials. Moreover, the experiments were not necessarily focused on collision modeling. We leave the collection of collision-specific datasets to future extensions of ASUNA. In the meantime, it is still possible for ASUNA users to model collisions approximately by assuming that concurrently transmitted packets are always lost or that they are recovered with a given probability (e.g., as in the case of frequency-hopping schemes, where the recovery probability can be determined based on the hopping pattern).

[1]Providing fine-grained information about the packet transmission and reception times as well as about multipath propagation would be very convenient and would convey additional details about acoustic propagation at the time of the experiment. Unfortunately such accurate information is not available for the current version of ASUNA. We still plan to include it for any future datasets we will integrate, provided that these datasets can demonstrate sufficiently accurate time reckoning and multipath measurements.

B. Topology matrix information (TMI) structure

For each experiment, our database includes a description of the experiment's setup, an Octave/Matlab `.mat` file grouping link quality time series into a matrix for (called topology matrix information in the following, or TMI for short), and a reference to the publication(s) that provide the broader context of each experiment. The basic building block of each TMI is an instantaneous snapshot of the quality of all links. This can be seen as an $N \times N$ matrix, whose entry (i, j) reflects the link quality between nodes i and j as measured from the experiment, and where N is the number of nodes in the network.[2]

The time variation of the TMI is captured by adding a time dimension to each topology matrix. The time samples depends on the context of the experiment and on the configuration of the communication protocols. For example, for an experiment based on a time-division-multiple-access (TDMA) schedule, the topology information is obtained for each time frame. Conversely, in experiments focusing on the physical layer, we update the topology information once for every transmitted packet. Still, the sampling time is sufficiently frequent to enable the interpretation of the topology information as a continuous process.[3] During replay processes it is then possible to, e.g., check the quality of a link at the time of each transmission in order to determine which data packets are correctly received, and how many useful application bits they carried, so as to compute the goodput (defined as the rate of reception of useful information bits over time); alternatively, it is possible to provide the communicating nodes with a noisy version of the TMI to emulate some form of topology instability.

In some experiments, the time variation of the TMI was achieved through the dynamic relocation of one or more nodes in the same area. In this case, we provide link data for each topology separately in the same `.mat` file, with the understanding that the duration of the experiments may be different for each topology. The ASUNA dataset is generally obtained from static deployments. Some of these deployments include drifting nodes (e.g., the REP and

[2]Note that the TMI may be asymmetric. This is the case when the SNR is location- or depth-dependent, and in scenarios involving near-far conditions, where interference blocks one end of the communication link.

[3]We remark that the link sampling time is a feature of the data provided in the dataset, and depends on the structure of the experiment from which we derived the link quality measurements. For this reason, it is not possible to configure this parameter.

Haifa Harbor datasets), which leads to limited mobility. To improve the possibilities for the user to simulate some form of mobility, as well as to emulate underwater networking scenarios where abrupt link quality changes occur, we also provide a global time series that covers a whole experiment across all tested topologies. This is obtained by concatenating the link measurements of each TMI. In fact, between subsequent topologies in a given dataset, some links typically disappear, some new links appear, and those that persist experience significant quality changes. Additionally, we remark that mobility can be approximately emulated by rotating the position of the nodes throughout the locations indicated in each dataset.

In case several communication technologies are involved in an experiment, as is the case for multimodal network setups, a further dimension is added to the TMI. In this case, the time-varying TMI is provided per-technology. This makes it possible to have simultaneous or very close samples of the link quality perceived by different communication technologies. We remark that different technologies often have different transmission capabilities. For example, this is the case for the SC2R high-frequency (80-120 kHz) EvoLogics modem, which has a much higher nominal bit rate than the EvoLogics modem working in the 7-17 kHz band. Such different bit rates cause asynchronous channel sampling at unequal rates. Details about the sampling time are provided in the companion document of each dataset in ASUNA.

C. Analysis of TMIs

The resulting TMIs that create the heart of the database can be analyzed in different ways. For example, by setting a threshold over the link measurements, one may create an emulation system that avoids a physical layer and only uses realistic binary topologies to form time-varying communication links. This may become relevant when testing scheduling and routing protocols. The user can also treat the soft link quality measures to form a time-varying statistical model that generates links based on measured link reliability information. While some of our reported TMIs are small in terms of the number of nodes or short in terms of the testing time, the network size can be virtually increased by duplicating parts of it, and the time duration can be extended cyclically. In this manner, larger networks and longer deployment scenarios can be tested more

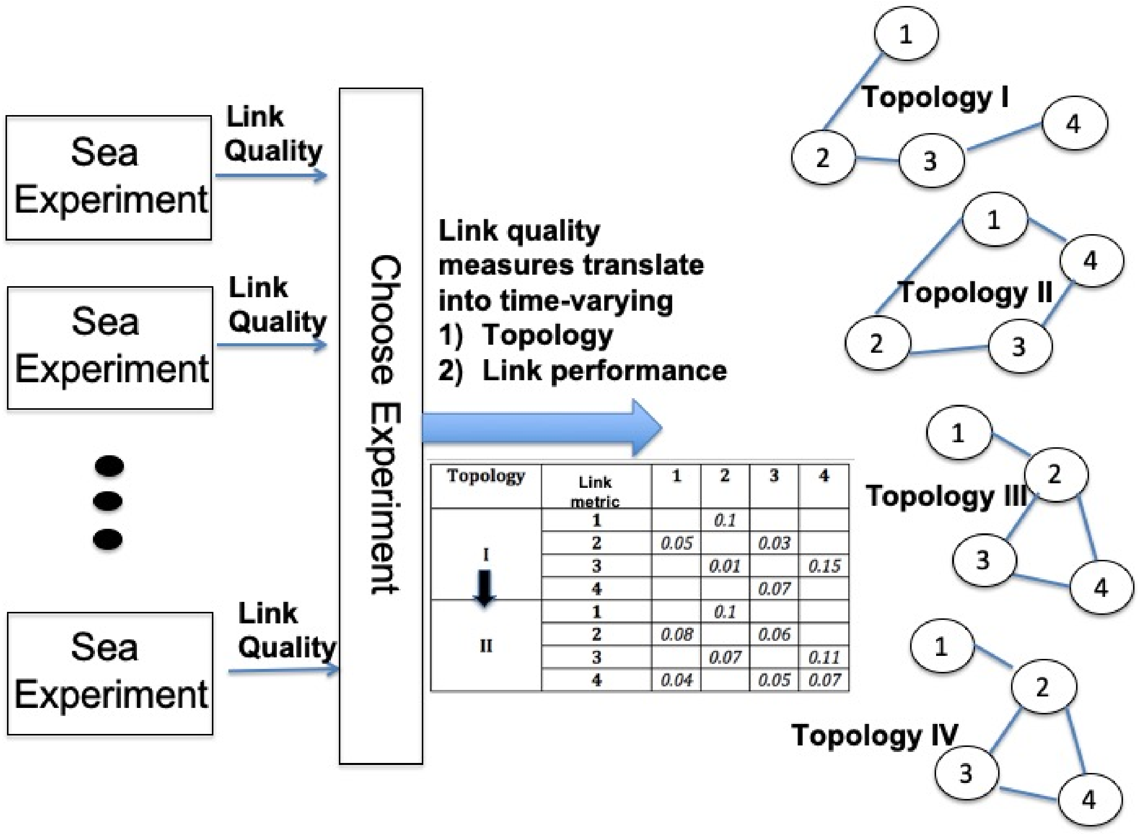


Fig. 1. Illustration of the network emulation process.

reliably than using models, although such an extension to the network cannot be considered as a replay.

An illustration of the emulation process is given in Fig. 1. The process begins with link quality data collection during a single sea experiment to form a matrix of time-varying TMIs. The experiment may include several arrangements of the network nodes into different topologies. The link quality data is used for *network replay*, where the time-varying link quality information determines the success of each data transmission. Similar to channel realizations used for channel replay [33], [58], the result is a reliable representation of the network performance in the sea conditions that occurred during the recorded network topology.

D. Structure and variety of the shared datasets

In this section, we describe the structure of the network TMIs currently available in ASUNA. When downloading ASUNA from the web site, TMIs come organized in separate folders. For a given TMI, call N the number of nodes, P the number of (physical layer) transmission technologies available to each node, and $T|$ the total number of link quality sampling epochs. Normally, these epochs are separated by an interval $\Delta t = 1$ second, unless otherwise stated in the experiment description. The `.mat` files of the TMIs have the same structure, and contain the following data:

- a `TopMat` matrix of size $T \times N \times N \times P$, where each entry `TopMat(t,i,j,p)` (using Octave/Matlab notation) conveys the link quality for the link between nodes `i` and `j` through physical layer technology `p` at time `t`;
- a `LocMat` matrix of size $T \times N \times 3$, where the three entries `LocMat(t,i,1:3)` represent the two UTM coordinates and the depth of node `i`, respectively;
- a `TechMat` matrix of size $T \times N \times P$, where each of the $k = 1, \ldots, P$ entries `TechMat(t,i,1:P)` is 1 if node `i` has technology k at epoch `t`, and 0 otherwise;
- an `AdjMat` matrix of size $T \times N \times N$, where each entry `AdjMat(t,i,j)` is 1 if nodes `i` and `j` are linked by any technology, at time `t`, and 0 otherwise.

A single experiment may contain measurements either for a single or for multiple TMIs. In the latter case, we provide the above matrices for each TMI separately, and name them, e.g., `TopMat1`, `TopMat2`, etc. We also provide four matrices resulting from the concatenation of all matrices over the time dimension. The latter are called, `FullTopMat`, `FullLocMat`, `FullTechMat` and `FullAdjMat`, respectively. This enables the emulation of abrupt link connectivity changes, as is often the case in UWANs. In particular, such changes may serve to emulate the performance of adaptive protocols.

A complete summary of the shared dataset is provided in Table I. The experiments from which the dataset has been retrieved were performed for a number of different purposes and applications, including the design of scheduling protocols, physical layer tests, and underwater communications security. As a result, each experiment has peculiarities which make it different than others in our database, and contributes to increasing the coverage of a variety of scenarios. This is reflected in the list, which shows broad differences among the tests: from relatively large networks of 10 modems, to small link tests with 3 modems; from experiments of long duration (up to a few hours) to short experiments of a few tens of minutes; from tests including one type of modems to multimodal tests including multiple acoustic communication transceivers operating in orthogonal bands; and from tests involving commercial modems to tests that include custom modems and offline processing.

In Table I, we describe only the main points for each experiment. The full description is given in the document distributed with each dataset, as well as in related publications cited in each description and in the table. As the database is open to the community, we also welcome external datasets provided by other institutions, with the only constraints that the datasets should be adapted to match the format described above.

IV. Example of results

We now present the results of a network emulator built upon the ASUNA database. We remark that these are just meant to serve as an example, and that the applications are by no means limited by the scope of our results. In Section IV-A we describe the structure of the emulator, whereas in Section IV-B we provide its results.

TABLE I: SUMMARY OF THE SHARED DATASETS AND RELATED EXPERIMENTS (L_P IS THE PACKET SIZE IN BYTES)

Location, time and coordinates	Topologies	Equipment	Means of measurement	Measurement rate	Total time	Protocol details	Original trial purpose	Interference-free?	References
Haifa harbor, Israel May 2009	6	Custom modems (ITC and Brüel&Kjær transducers, offline processing)	BER from raw acoustic samples	Once every 5 s	6 hours	Spatial reuse TDMA L_P: 100 Bytes	Scheduling and PHY design	Yes	[45]
Garda lake, Italy December 2015	4	5 EvoLogics SC2R 18-34 modems; network stack on laptops	RSSI from modem logs	Less than once every 5 s	2 hours	TDMA, CSMA/CA L_P: 60 Bytes	Scheduling and handshake design	No	[59], [60]
Werbellin lake, Germany June 2016	5	5 EvoLogics SC2R 18-34, 3 SC2R 48-78, 2 SC2R 80-120 modems; network stack on laptops	Transmission success from modem logs	Less than once every 5 s	~1 hour	OMR, flooding L_P: 25 Bytes	Multimodal routing design	Yes	[61]
ALOMEX15, Spain, Morocco, West Sahara July 2015	1	3 EvoLogics SC2R 18-34, network stack on laptops	RSSI from modem logs	Less than once every 5 s	22 minutes	TDMA and continuous transmission L_P: 23 Bytes	Topology discovery	No	[62]
Hadera, Israel May 2017	1	3 software-defined EvoLogics 7-17 modems; 2 Cetacean RUDAR mk2 recorders; offline processing	RSSI from raw acoustic samples	Once every 20 s	10 minutes	TDMA L_P: 30 Bytes	Physical layer security	Yes	[63]
Hadera, Israel May 2017	2	4 software-defined EvoLogics 7-17 modems	RSSI from modem logs	Once every 5 s	45 minutes	TDMA L_P: 25 Bytes	Multimodal scheduling	Yes	[64]
REP16-A Sesimbra, Portugal July 2016	3	4 EvoLogics S2CR 18/34, laptops	Transmission success from modems logs	Every second	1 hour	Custom protocol L_P: 32 Bytes	Topology estimation	No	[65]

A. Structure of a network emulator

Our example of emulator is a discrete-event system written in an Octave/Matlab-compatible code, and comes with all datasets currently shared. These datasets are already placed in the right subdirectory structure to make it possible to load them correctly in the simulator. In this way, the user can open the main file, `TDMAsim.m`, and run it upfront to obtain some first results. The emulation code is freely provided along with the dataset on the ASUNA web site, and the users may employ, extend or modify it to suit their purposes. The code has also been uploaded to the Code Ocean platform [66], from where the results provided below can be reproduced.

The baseline emulator implements an interference-free TDMA scheduling protocol, where each node is assigned an exclusive time slot to transmit a unicast packet to any of its neighbors. The parameters of the protocol can be tuned via a configuration script named `setGlobals.m`. In the main file `TDMAsim.m`, a marked section instructs the user how to choose their desired dataset by commenting/uncommenting specific lines. After importing the data from the corresponding `.mat` files into the structures of the simulator, the emulation sets up the TDMA schedule and arranges a periodic computation of network metrics.

The TDMA schedule is computed based on the distances among the nodes as derived from the `LocMat` matrix. For a given sound propagation speed (system parameter), the emulator computes the time slot length as the sum of the packet duration (also a system parameter) and of a guard interval as long as the maximum propagation delay in the network. For each TDMA transmission, the emulator uses the instantaneous TMI in order to infer the one-hop neighbors of the transmitter (through the `AdjMat` matrix). The unique destination is then chosen at random out of this list. In case a multi-modal communication dataset is chosen, the emulator also checks which communication technologies are in use both by the transmitter and by its receiver (through the `TechMat` matrix) and chooses one of them at random. The transmission outcome is finally determined by comparing the link quality from matrix `TopMat` to a threshold (system parameter). In the provided code, such threshold is pre-set in order to make it easier for the user to immediately operate with the data, but can be changed in order to obtain different results.

(a) Experiment map. (b) Tested network topologies.

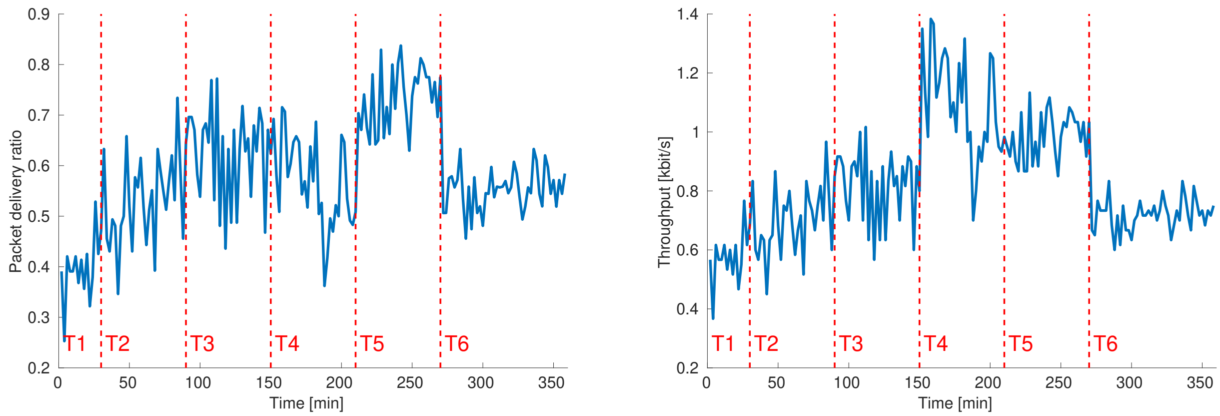
Fig. 2. Information about the "Haifa Harbor" experiment. (From [45]). The letters indicate subsequent locations at which the nodes were moved to form the six deployments in Fig. 2b. For example, node 1 was moved from location 1A to 1B, 1C, and finally 1D.

At tunable intervals, the emulator collects relevant metrics for post-processing. This includes a count of the transmitted and correctly received packets, as well as the network throughput. The metrics are plotted at the end of the emulation, and the resulting figures are saved as images. Next, we show results obtained from our TDMA emulation.

B. Results

1) Haifa Harbor: We first discuss results obtained for the "Haifa Harbor" dataset. The experiment was carried out in Israel, and included four boats carrying custom modems. The boats moved to different positions in the harbor at designated times. Due to the structure of the harbor, no communication between docks was possible in the absence of line of sight. Hence, the change in the boat's position created a time-varying network topology. A map of the experiment location is shown in Fig. 2a, and the formed topologies are illustrated in Fig. 2b. The recorded dataset includes the per-link time-varying BER measurements arranged in a single TMI and in per-topology TMIs. The experiment included roughly six hours of data collection.

In order to obtain the longest possible emulation, we resort to the `FullTopMat` matrix, which contains the concatenation of the datasets corresponding to each TMI. In our emulation,



(a) Packet delivery ratio.

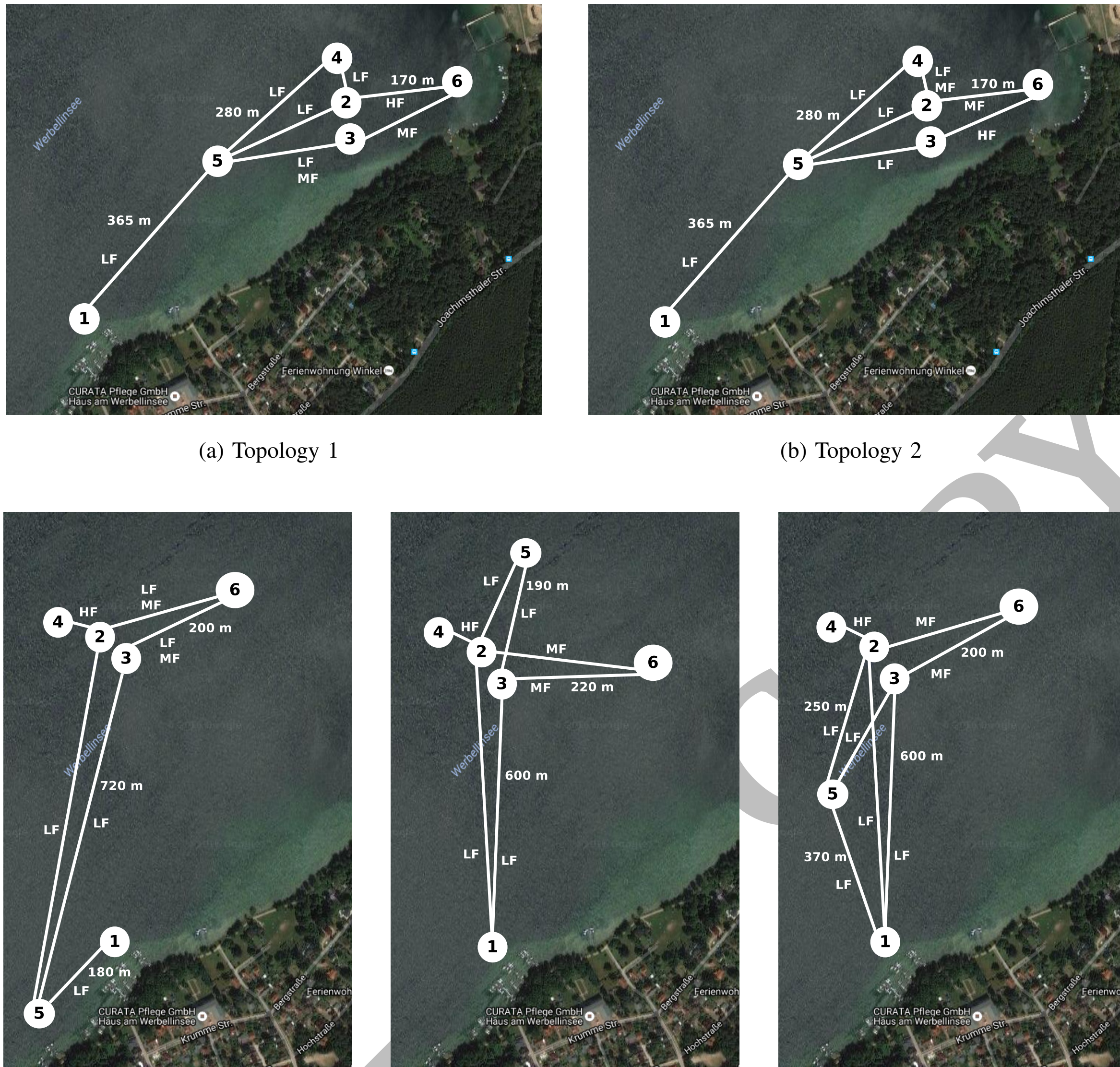
(b) Throughput.

Fig. 3. Results for the full "Haifa Harbor" dataset. All topology data has been concatenated: dashed red lines indicate the transition between subsequent TMIs.

we consider a successful packet delivery only if the instantaneous BER value is less than 10^{-2}. Considering this threshold,[4] the packet delivery ratio (PDR) and the per-link throughput are shown in Fig. 3. Metrics are collected every 120 seconds and plotted against the collection epoch. Vertical dashed lines mark the instant where the switch between different subsequent topologies occurs, and the TMI enumeration fits the number of topologies in Fig. 2b.

We observe that the PDR changes over time, and its change depends on both the topology configuration and the link quality measurements. The former is mostly observed when there is a transition between TMIs, while the consequences of the latter are observed when the TMI remains stable. We also remark that the node deployment affects the throughput, as the maximum propagation delay in the network determines the TDMA slot length, and therefore the packet transmission rate. In all topologies, the maximum propagation delay is about 1 s (corresponding to a maximum distance of about 1500 m), except in topologies 1 and 4, where the maximum

[4]This value has been chosen for demonstration purposes. However, we note that this BER regime may be easily related to PER regimes depending on the employed modulation and coding scheme. For example, a BER of 10^{-2} yields a PER of about 0.5 for 64-bit, uncoded packets transmitted using BPSK. In the same conditions, applying a convolutional code of rate $1/3$ and soft Viterbi decoding would yield a BER of 10^{-5}, which enables the transmission of 1024-bit packets with a PER of 0.01 [67, Section 8.2.8].



(a) Topology 1

(b) Topology 2

(c) Topology 3

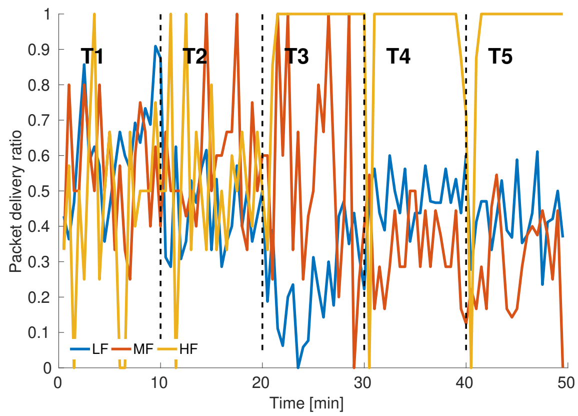
(d) Topology 4

(e) Topology 5

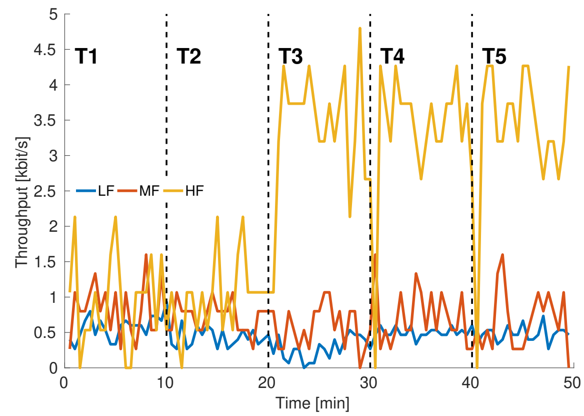
Fig. 4. Setup and tested topologies for the "Berlin Multimodal" dataset. (From [61].)

propagation delay is 0.88 s and 0.55 s, respectively. For example, in topology T4, this means that the TDMA frame has a significantly shorter duration, which accommodates about 45% more transmissions than in topologies 2, 3, 5, and 6. For this reason, the throughput is larger for topology T4, despite a similar or lower PDR than in topology T3.

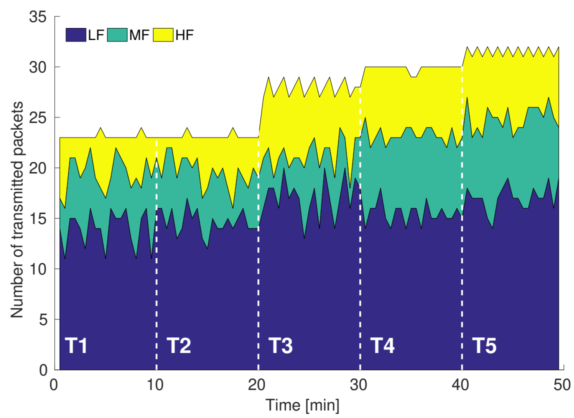
2) Berlin Multimodal: We now discuss network emulation results based on the "Berlin Multimodal" dataset, which provides a set of simultaneous measurements from three different



(a) Packet delivery ratio.



(b) Throughput.



(c) Number of transmitted packets.

Fig. 5. Results for the full "Berlin Multimodal" dataset. All topology data has been concatenated: dashed lines indicate the transition between subsequent TMIs.

acoustic communication technologies. As reported in Table I, the communication technologies used in the experiment are the EvoLogics SC2R 18-34 kHz (5×), 48-78 kHz (3×) and the 80-120 kHz (2×) modems, respectively named LF, MF, and HF in the following, as a shorthand for low-frequency, medium-frequency, and high-frequency. The TDMA emulator assumes that the transmission rates of each modem are 4 kbit/s, 16 kbit/s, and 32 kbit/s, respectively. The setup of the experiment and the tested topologies are shown in Fig. 4.

The results are given in Fig. 5. Each point along the curves corresponds to average values taken over windows of 30 s. The most marked difference between the TMIs is the performance of the HF modem, which requires a low-noise, short-distance link, in order to operate at its maximum efficiency. Since the distance between the only two nodes with an HF modem was smaller in topologies T3, T4, and T5 than in topologies T1 and T2, the HF throughput is much higher and stable for T3, T4, and T5. We also observe that the success ratio for the LF and MF TMIs is similar, and slightly lower for MF in topologies T4 and T5. Since the deployment includes a total of 3 MF and 5 LF modems, this explains the similar throughput achieved by LF and MF in Fig. 5b.

The area plot in Fig. 5c shows that the number of packets sent is about the same in each measurement window. The absolute values tend to remain stable over each window and depend on the connectivity of the sub-networks formed by each technology. For example, in topology T3, the nodes transmit fewer MF packets than in all other TMIs. The reason is that, in topology T3, all nodes with MF also have LF. More specifically, we recall that in our tested TDMA scheduling protocol, a neighbor is chosen at random, and only then the transmission technology is determined. Since there are more LF modems, a node with both LF and MF is likely to have additional neighbors, and thus it is less likely to transmit using MF in T3 than in any other topology.

Finally, we demonstrate the flexibility of ASUNA by testing the optimal multimodal scheduling (OMS) scheme in [64]. OMS is an adaptive TDMA-based algorithm that exploits multimodal links in order to schedule transmissions that obey a number of constraints. These include network topology structure, bounds to interference, and measures to favor multihop routing. OMS was already tested at sea via a dedicated experiment [64] (also part of ASUNA, see the second-to-last line of Table I), hence here we rather test OMS using the "Berlin Multimodal" dataset. This also enables a direct comparison against the baseline TDMA protocol considered above.

As before, we concatenate all topologies of the dataset, in order to obtain longer link quality time series, exhibiting significant connectivity changes across subsequent topologies. Figure 6 shows the average throughput per technology. We observe that the OMS protocol adapts well to the characteristics of the topology by allowing simultaneous transmissions over different technologies and by balancing channel access throughout the network. By setting a slot length of 2.5 s, it adapts the packet length to fill this slot length minus the maximum propagation delay. This results in a slightly smaller number of transmissions being made, constantly equal

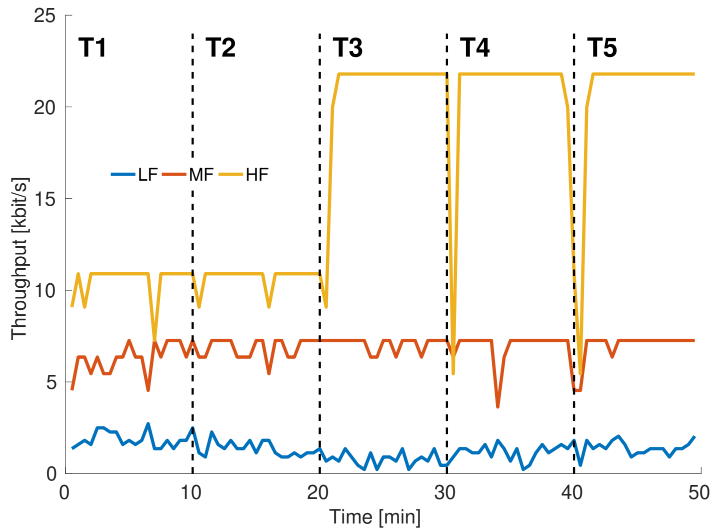


Fig. 6. Throughput for the OMS protocol tested over the "Berlin Multimodal" dataset. All topology data has been concatenated: dashed lines indicate the transition between subsequent TMIs.

to 12 packets per measurement interval of 30 seconds. However, OMS enables transmissions through multiple technologies at the same time, and additionally the above settings yield longer packets than for the baseline TDMA case of Fig. 5. As a result, the throughput achieved by all technologies is higher (see also Fig. 5c).

V. Conclusions

We presented ASUNA, a shared database containing recorded time-varying link quality measurements from various sea experiments. ASUNA serves as a tool to test underwater acoustic communication network algorithms through emulations or experiment replay. The ASUNA database includes an ensemble of time-varying link quality measures arranged as topology information matrices. The datasets cover different network configurations measured through a variety of acoustic communication devices, and using different network protocols. To demonstrate the use of ASUNA, we described the details and results of an emulation system built to test a time-division multiple-access scheduling protocol over all collected topology matrices. For a multimodal communications dataset, we also test the optimal multimodal scheduling approach in [64]. We freely share ASUNA as well as the emulation code with the underwater communications community, with the hope that ASUNA will constitute a benchmark to test underwater acoustic networking solutions including, but not limited to, scheduling, routing, and automatic repeat query schemes. ASUNA is open to future contributions. With the expansion of the database that would result, we believe that this benchmark has the potential to greatly contribute to establishing and standardizing UWAN research.

ACKNOWLEDGMENT

The authors express their gratitude to the institutions that collaborated to the organization and logistics of the sea trials, and gave their consent that the respective datasets be included in ASUNA. In particular, we thank the NATO STO Centre for Maritime Research and Experimentation (La Spezia, Italy) for the "ALOMEX15" and "REP16" datasets, Rafael Ltd. (Israel) for the "Haifa Harbor" dataset, the Israeli Electrical company for the "Hadera" datasets, and EvoLogics GmbH (Berlin, Germany) for the "Berlin Multimodal" dataset.

This work was sponsored in part by the European Commissions's Horizon 2020 research and innovation programme under grant agreement no. 773753 (SYMBIOSIS), by the Israeli Ministry of Science and Technology (grant no. 3-12473), and by Germany's Federal Ministry of Education and Research (BMBF) (grant no. 3-15249).

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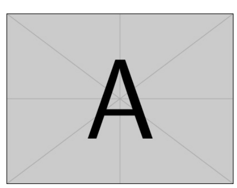

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