A Multi-band Noise-aware MAC Protocol for Underwater Acoustic Sensor Networks

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***Abstract*—We present a MAC protocol for underwater acoustic sensor networks (UASN) able to overcome the shortcomings induced by the temporary presence of noise sources within, or close-by, the region covered by the UASN. Our solution, named NAMAC for Noise-aware MAC protocol, exploits the ability of nodes equipped with multi-band modems to rapidly switch the frequency band used for communications upon detecting an increase of the in-band noise. Neighboring nodes may collectively decide to migrate to a different band and, as soon as the noise source is no longer impairing communications, to switch back to the default one. NAMAC also ensures connectivity across regions operating on different frequency bands induced by a different impact of noise at different locations. Additionally, if nodes are equipped with acoustic sensors able to monitor low frequencies, i.e., in the range from 0 to 5 kHz, NAMAC can exploit this capability to detect the approaching of a noisy vessel in advance, since noise at low frequencies is audible at larger distances. In this way, nodes can be pre-alerted for a band switch.**

We perform an extensive comparative performance evaluation of NAMAC based on ns-2 MIRACLE simulations. The noise frequency spectrum used in our simulations reproduces that of existing powerboats. Our performance evaluation shows that NAMAC is able to significantly outperform existing noise unaware MAC protocols that use a single band, increasing the network reliability in the presence of temporary noise sources like passing-by noisy vessels.

***Index Terms*—Underwater Acoustic Sensor Network, Non-stationary noise sources, Medium Access Control.**

I. Introduction

Underwater Acoustic Sensor Networks (UASNs) are an emerging and rapidly growing field of research which aims at extending the communication capabilities of sensors and autonomous underwater vehicles (AUVs). Such a growth is fostered by the increasing demand for pervasive underwater monitoring systems in different industries, e.g., environmental monitoring, seismology, ocean exploration, monitoring of off-shore drilling plants, monitoring of gas and oil pipes, surveillance of critical sites. Acoustic communications allow an easy deployment or redeployment of fixed nodes for UASNs, and increase the capability to interoperate with AUVs to an extent which is not possible with alternative means like cable-based, radio, or optical communications. However, underwater acoustic channels pose difficult challenges to communication protocol designers, because of the following aspects:

(i) Relatively low power attenuation as a function of distance: especially at low-medium frequencies (less then 10-15 kHz) acoustic power can propagate up to hundreds of kilometers. This entails that each transmission can interfere on nodes at a very large distance.

(ii) Relatively slow propagation speed of the acoustic signal: Propagation delays may be much larger than the typical symbol of any digital communication system, which poses challenges at the PHY and MAC layers. At the PHY layer, one option could be that of resorting to multi-carrier techniques [1]. At the MAC layer, collision avoidance [2]–[7] or scheduling mechanisms [8], [9], tailored for the underwater acoustic environment need to be devised.

(iii) High time and frequency variability of the channel transfer function, which makes it hard to identify, estimate, and track relevant channel parameters for transmission optimization [10].

(iv) Characteristics of the background noise: in the underwater acoustic environment background noise is neither a white random process (as it is, typically, for wireless radio communications) nor a stationary one, since it may include components coming from noise sources that appear and disappear from the scene, like motorboats or ships. Indeed, the presence of such close-by noise sources may temporarily get the network operating frequency band out of service, thus inducing an UASN loss of connectivity.

The first three aspects in the above list have been the subject of intense research efforts for several years. However, the noise caused by close-by sources has unique characterstics that have not received much attention in the past. In particular (i) the order of magnitude of the time interval in which the presence of a ship may cause an SNR degradation and (ii) the fact that such an impairment may not involve the overall network, but only limited regions, makes it possible to devise adaptive communication and networking protocols at the network level, minimizing the impact of noise on communications.

In this paper, we elaborate on this idea by designing and evaluating a novel MAC protocol that exploits knowledge on the current noise power spectral density (psd) to select the communication band of the UASN among a set of available ones. The proposed protocol, called NAMAC (Noise-aware MAC), can be combined with existing contention-based protocols [2]–[7], where nodes share a common spectral resource, endowing them with the required robustness to non-stationary noise. For simplicity, we present NAMAC in combination with the MACA protocol [11], selecting its basic implementation (i.e., without NAMAC) as a benchmark. However, NAMAC is general and can run in combination with more sophisticated contention-based protocol, enhancing its performance in terms of reliability and network connectivity.

We assume that nodes are equipped with transceivers able to transmit using a bandwidth of 5-10 kHz, as typical of many existing commercial or research-oriented acoustic modems [12]. NAMAC nodes typically operate on a default acoustic spectral band, but are able to switch among a set of different bands. As the noise in the default band increases above a given threshold, the nodes belonging to the portion of the UASN affected by noise will migrate to a new frequency band, where they can find a better signal to noise ratio (SNR). Indeed the effect of close-by noise sources may impact on the network connectivity in different ways on different areas of the UASN operating region: a noise source might significantly impair communications of nodes close to it, but have a negligible impact on the rest of the nodes. NAMAC is a simple distributed solution that enables only the portion of the UASN impaired by noise to migrate to an alternative band, while ensuring reliable packet forwarding across regions operating on different bands.

Optionally, underwater sensor nodes may be equipped with a low frequency noise monitoring system: since acoustic waves at low frequencies attenuate much less than medium-high frequencies, nodes would be able to detect the presence of noise sources, e.g. ships, that are approaching the UASN area from afar, before they actually impair the quality of communications in the band in use. In this way, the network has more time to adapt to the potentially changing conditions, and get prepared to the foreseen risk that the current communication bandwidth may go out of service in a short time. In the following, for space reasons[1], we describe the basic variant of the protocol, although we have implemented and tested both versions.

Summarizing, our contributions are the following:

- We design a mechanism through which nodes can cooperatively decide, at the local level, when to migrate to a new frequency band and which band to select.
- We propose a procedure to preserve network connectivity across the border of network areas that are operating on different frequency bands.
- We evaluate the performance of the proposed protocol, benchmarking it to the MACA protocol and showing that NAMAC is able to significantly improve the network connectivity and reliability.

The rest of the paper is organized as follows: Section II provides technical details motivating our work and explain the basic ideas behind the NAMAC protocol. Section III describes the protocol in detail. Section IV discusses the results of our comparative performance evaluation. Finally, in Section V we conclude the paper.

II. Motivation and basic idea

Acoustic signal power attenuates as a function of the distance l and frequency f according to the path loss formula

$$A(l,f) = A_0 l^{\eta} a(f)^l, \quad (1)$$

where η is the path loss exponent, $a(f)$ is the (frequency dependent) absorption coefficient, and A_0 is a unit-normalizing constant[2]. The absorption coefficients in (1) increases with frequency according to the empirical formula[3] [14]

$$10 \log a(f) = 0.11 \frac{f^2}{1+f^2} + 44 \frac{f^2}{4100+f} + 2.75 \cdot 10^{-4} f^2 + 0.003 \ . \quad (2)$$

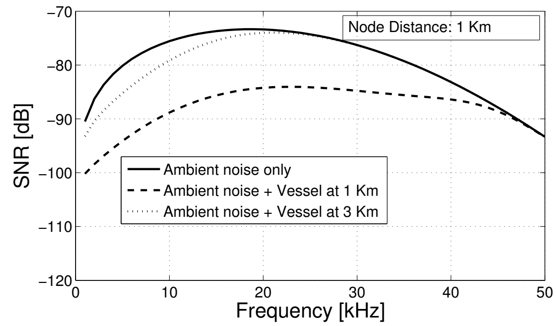


Figure 1: Signal to Noise Ratio of an acoustic link with a noise source placed nearby.

The underwater acoustic environment is characterized by an *ambient noise* coming from different sources: turbulence, shipping, waves, and thermal noise [15]–[20]. Each type of noise has a specific psd and may be present or not depending on the specific scenario: ocean, lake, rivers, and so on. The overall contribution for each kind of noise can be modeled as a stationary process with continuous psd. Empirical formulae for the psd, measured in dB re μPa per Hz, of the four noise components in the ocean have been provided as [15]:

$$\begin{aligned}
\text{Turbulence: } & 10\log N_t(f) = 17 - 30\log(f) \\
\text{Ship activity: } & 10\log N_s(f) = 40 + 20(s-0.5) + 26\log f - 60\log(f+0.03) \\
\text{Waves: } & 10\log N_w(f) = 50 + 7.5\sqrt{w} + 20\log f - 40\log(f+0.4) \\
\text{Thermal noise: } & 10\log N_{th}(f) = -15 + 20\log f,
\end{aligned}$$

where f is the frequency measured in kHz and the subscripts *t, s, w, th,* indicate the four different sources of noise. The overall psd of the ambient noise is just $N(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f)$.

Fig. 1 shows the signal to noise ratio at the receiving end of a 1 Km acoustic link. The different curves represent the SNR obtained using a transmit power of 180 dB re 1μPa, in the presence of ambient noise alone (solid line), and with a motorboat placed at a distance of 3 Km (dotted line) and 1 Km (dash-dot) from the middle point of the acoustic link. For this example, we used the acoustic emission spectrum of a Twin Inboard Diesel found in [21].

Assume that nodes communicate using an acoustic modem tuned on a 10 kHz bandwidth centered around 15 kHz. It can be seen that, in the presence of the close-by noise source, a

[1]Besides additional hardware requirements, the version of NAMAC that exploits low-frequency monitoring also employs more sophisticated rules for deciding a band migration.

[2]Besides the attenuation due to path loss and absorption, underwater acoustic links undergo multi-path fading effects resulting in high frequency and time selectivity [13]. For simplicity, we do not consider such effects in this paper, assuming (1) as the only attenuation effect, although our approach keeps its validity even when multi-path fading is taken into account.

[3]Expression (2) is valid for frequencies above a few hundred Hertz, a similar formula is provided in [14] for lower frequencies.

better choice would be that of switching to a band centered at a higher frequency, e.g., 25 kHz. In fact, while for large distances the only noise components that survive attenuation and absorption are those at low frequencies [17], [22], at short distances, the high frequency content of noise emissions, like that studied in [21], [23], [24], can have a considerable impact. Notice that Fig. 1 shows the effect on a single powerboat, whereas the typical situations of superimposed noise sources would produce an SNR degradation in the default band even worse than that showed in this example. If one or several of such noise sources are, even temporarily, close enough to the network, their effect can be that of perturbating the average SNR profile of the UASN nodes. This kind of noise is inherently non-stationary (at least on time scales on the order of several minutes and above) because ships and boats may approach or leave the network area, possibly changing their engine power and speed, giving rise to different effects due to [19], [25]: (i) Propulsion and auxiliary engines, (ii) Propeller radiated pressure and bearing forces (cavitation), (iii) Slamming phenomena. Such a characterization advocates for an adaptive protocol design.

The selection of the band on which an UASN operates depends on the inter-node distance required by the application. In fact, the noise power density decays with frequency, thus limiting the useful acoustic bandwidth from below, and does not depend on the distance between the communicating nodes; power attenuation depends on the distance and low frequencies attenuate less then high ones. Such counteracting effects result in the existence of an optimal bandwidth for each distance. Most of the existing UASN protocols assume a common band, selected considering a "typical" inter-node distance for the specific scenario[4]. The described way for band selection does not take into account the possible presence of close-by sources of noise, such as motorboats or ships which, due to the nature of their specific noise emission, may alter the SNR shape as a function of frequency. With NAMAC, the same approach is taken, but rather then having a rigid band allocation, the proper choice is done adaptively to changing conditions.

III. Protocol description

Sensors periodically monitor the noise level in the default band. If the noise level at a node raises above a predetermined threshold, the node activates a procedure which will eventually lead a portion of the network to migrate to a new frequency band. Maintaining the possibility to communicate across different bands has an overhead cost. For this reason, it is advisable not to have single nodes migrate to a new band, but rather perform the migration if the SNR degradation affects at least a small set of neighboring nodes. Therefore, we assume that the decision to migrate is taken collectively by a set of one-hop neighbors: only if the SNR experienced in the band in use by at least a set of one-hop neighbors is, or is going to be, not sufficient to guarantee the desired network performance, the set of nodes in that region will migrate to a new band.

[4]More sophisticated schemes may confine short-range communications to higher frequencies than long-range ones.

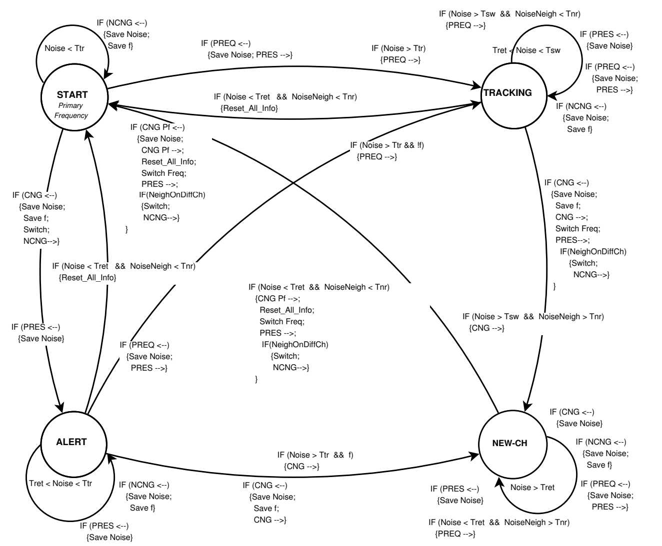


Figure 2: State diagram for the NAMAC protocol.

Nodes can find themselves in one of the following states:

- START: In which nodes use the default band.
- ALERT: In which a node becomes aware that the noise level has increased so that it might be worth migrating to a new frequency band in the near future.
- TRACKING: In which nodes exchanges information with their neighbors, through PREQ and PRES packets, to update/get updates on the measured noise level.
- NEW-CHANNEL: The node has changed its operating band and now transmits over a new channel.

The operations of the nodes across different states are represented in the state diagram of Fig. 2. To implement the required procedures, in addition to the conventional RTS, CTS, DATA, and ACK packets, NAMAC uses the following packets:

- PREQ: Packet used for noise-level requests; it contains node ID and own noise level.
- PRES: Packet used to reply to noise level requests; it contains node ID and own noise level.
- CNG: Packet used to ask neighbors nodes to change channel; it contains node ID, own noise level, and the ID of the new band.
- NCNG: Packet used to inform neighbors that a node is not willing to change band; it contains node ID, own noise level and the ID of the band currently in use.

A. *Formation of a set of nodes in the TRACKING state*

Consider a noisy vessel approaching the UASN, and in particular one of its nodes. The noise level perceived by the sensor in the default band will start increasing. We denote with $n_i(t)$ the noise level measured at node i at time t. A threshold T_{tr} is set so that if the node detects a noise level $n_i(t) > T_{tr}$ it starts the following procedure:

1) Node i asks its one-hop neighbors to exchange their noise level values. This is achieved by broadcasting a PREQ packet.
2) Its neighbors reply with a PRES packet containing their own measured noise level. A backoff-based mechanism

is implemented to avoid collisions among PRES packets sent by different nodes. Details and optimal tuning of the backoff mechanism are given in [26].

3) The originating node and the nodes that receive the PREQ transit to the TRACKING state.
4) Nodes receiving only the PRES packet transit to an ALERT state.

Each time a node receives a PRES packet, it stores the information contained in it. In this way, after the maximum backoff time interval plus the maximum propagation delay between any two neighboring nodes, all the nodes in the TRACKING state will also be aware of the noise levels of their neighbors in the TRACKING state. A set of neighboring nodes in the TRACKING state has hence been formed.

B. Band switch of the set of nodes in the TRACKING state

The first node in the set whose noise level reaches a second threshold of T_{sw} and has an average of neighbors' noise levels exceeding a threshold T_{nr}, broadcasts to its neighbors a CNG packet telling them to switch to a different band. If the average of the stored neighbors' noise levels is less than T_{nr}, the node sends a new PREQ, prompting its neighbors to provide an updated noise level. The neighbors will reply with a PRES. Upon receiving all the replies, if the new neighbors' average is larger than T_{nr}, the node takes a new sample measurement of its noise-level and, if it is still above T_{sw} it sends the CNG packet to trigger the band switching.

In particular conditions, it may happen that a node finds itself in a situation in which its noise level is above T_{sw} while the average of its neighbors' levels stays below T_{nr}. Eventually, if the noise source gets closer, also the neighbors' noise level will exceed the threshold. If the noise source disappears, the node will stop sending PRES packets, and will fall back to the START state. Finally the noise level is such that it only exceeds a single node's threshold, the node will keep sending PRES packets.

Each node, after sending the CNG packet, transits to the NEW-CHANNEL state, changing the frequency band for its operation, and sends a PRES to announce its presence in the new band. If the node is aware of neighbors using a band different from the one to which it has recently switched to and from the previous one, it sends a NCNG packet *on the bands they are using* to inform them of its recent change of receiving band. The actions taken by nodes receiving a CNG packet depend on the state they are in: nodes in the TRACKING state (relatively to a tracking procedure started following a PREQ sent by a neighbor) or in the ALERT state that receive the CNG, immediately switch to the new frequency band, and forward the CNG packet; nodes in the START state switch to the ALERT state but do not switch to the new frequency band, sending a NCNG packet to inform their neighbors that they will stay in the current band. In case of loss of control packets due to the raising noise, one or more nodes may become temporarily isolated. In this case, nodes can recover connectivity with their neighbors using the procedure described in Subsection III-F. It is also worth pointing out that with the NAMAC version that includes noise monitoring at the low frequencies, which we briefly described in Section I, the probability to loose control packets is considerably reduced.

C. Expansion of the set of nodes using an alternative band

A node in the ALERT state measuring a noise level above T_{tr} and that has not previously received any CNG packet, sends a PREQ and transits to the TRACKING state. Nodes in the ALERT state that receive a PREQ packet transit to the TRACKING state and send a PRES packet back.

Furthermore, a node in the ALERT state may be aware of some of its neighbors in the NEW-CHANNEL state because of a CNG packet received when it was in the START state. For such a node, if the noise level in the default band increases above T_{sw}, it immediately migrates to its neighbors' band and transits to the NEW-CHANNEL state.

D. Switch back to the default band

Once the ship (or ships) moves away from the network, the noise level in the default band will decrease to the typical level. Thanks to the periodic noise level measurements that nodes keep taking on the default band, they became aware of this new situation. As this happens, nodes may want to go back to the default band since, in nominal operating conditions, it is supposed to be the best band to operate in.

For this purpose, a threshold T_{ret} is set such that the first node in the NEW-CHANNEL state whose noise level in the default band falls below T_{ret}, triggers the following events:

a) If the average of its stored neighbors' noise levels is lower than T_{nr}, the node sends a CNG packet containing the default band identifier in broadcast, and switches back to the default band and goes in the START state. Each node in the NEW-CHANNEL state that receives the CNG packet, forwards it in broadcast, switches back to default band and goes in the START state. After switching, each node announces its presence by sending a PRES packet.

b) If the average of its stored neighbors' noise levels is larger than T_{nr}, it asks its neighbors to exchange their noise levels through a PREQ packet. The neighbors reply with a PRES containing their noise levels, then: (i) If the new average is less than T_{nr}, the node sends a CNG packet containing the default band identifier in broadcast, and switches back to the default band and goes in the START state. Each node in the NEW-CHANNEL state that receives the CNG packet, forwards it in broadcast, switches back to default band and to the START state. After switching, each node announces its presence by sending a PRES packet, (ii) If the new average is still larger than T_{nr}, similarly to the case described for the migration *from* the default band, it waits for an exponential backoff and, if the noise level is still below T_{ret}, it sends another PREQ.

Nodes in the TRACKING or in the ALERT state that have not switched to the new band, staying in the default one, keep taking noise measurements. If they detect a noise-level in the default band below a threshold T_{ret} and have an average of neighbors noise levels smaller than T_{nr}, they return to the START state.

Summarizing, the following thresholds are used to determine transitions between different states and bands.

- *Tracking Threshold (T_{tr})*: If exceeded by the noise level at a node, leads the node in the TRACKING state.
- *Neighbors Threshold (T_{nr})*: Threshold that must be reached by the average of a node's neighbors' noise levels to allow a migration to a new band.
- *Switching Threshold (T_{sw})*: Threshold that must be exceeded by a node to initiate the band switch procedure.
- *Return Threshold (T_{ret})*: If a node in the NEW-CHANNEL state measures a noise level below this threshold, it starts a procedure to migrate to the default band.

The following relations hold among the above described thresholds:

$$T_{ret} < T_{nr} \lesseqgtr T_{tr} < T_{sw} \ .$$

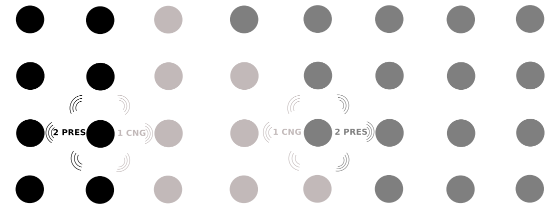
Notice that, having T_{ret} lower than T_{sw} induces an hysteresis in the system, which is beneficial since it avoids starting migration procedures too frequently.

E. Edge Nodes

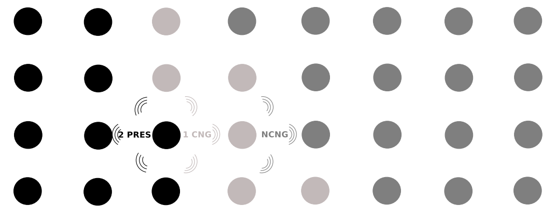
Edge Nodes are nodes with some neighbors operating on bands different from their own; these nodes play an important role to avoid that the network becomes disconnected. Two neighboring nodes belonging to sets that are using different bands, to communicate among them, use the band of the receiving node to transmit while keep on receiving in their current band. However, to preserve the functionality of the RTS/CTS mechanism, i.e., to keep all neighbors *in both* bands informed about ongoing transmissions, RTS and CTS packets are replicated, sequentially, in both the bands. Suppose that a node A, who is using band 1 to receive packets, wishes to transmit to a node B who A knows is listening on band 2. With NAMAC, instead of transmitting a simple RTS, node A transmits an RTS on band 1, immediately followed by a copy of the same packet on band 2, in this way, node B and all its neighbors on band 2, as well as node A's neighbors on band 1 receive the RTS. Similarly, upon receiving the RTS, node B sends the CTS, first on band 2 (to inform its neighbors) and then on band 1, where node A and its neighbors receive it. In this way, neighboring nodes on both bands are notified of the ongoing transmission, and will thus refrain from transmitting. There is no need to duplicate DATA and ACK packets on both bands, and they are only sent on the listening band of their destination node.

F. Neighbors on unknown Channel

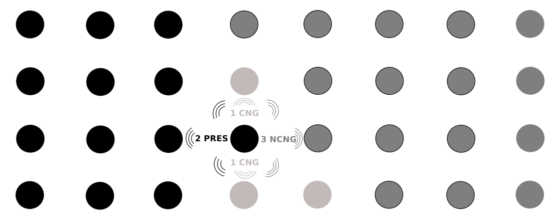
A node that fails to establish a communication with a neighbor on the channel used by the latter for a predetermined number of times, before discarding a data packet, performs a neighbor search on all channels: it tries to establish a handshake with the node for a maximum number of times on each channel starting from the default one. If the procedure terminates without finding the neighbor, the data packet is discarded. To avoid collisions, the same RTS/CTSs duplication mechanism described in Subsection III-E is used.



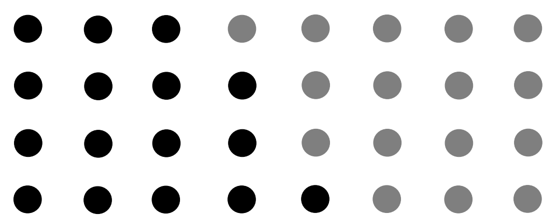
(a) Two ships approach from opposite sides of network, generating three sets of nodes operating on different bands.



(b) Two sets of nodes using two different bands, corresponding to the approach of two ships from opposite directions, expand. Accordingly, the set of nodes using the default band shrinks. A node refuses to join a group and receives a second CNG by the other set of nodes.



(c) The node chooses the best set and joins it by sending CNG, PRES and NCNG to the other set of nodes.



(d) The network uses two bands different from the default band.

Figure 3: Cross-border communication; expansion and contraction of network areas operating in different bands.

G. Multiple vessels close to the network

A particular case is that in which multiple vessels transit close to the network. In such a situations, the protocol may react in different ways: If multiple noisy vessels approach the network coming from the same direction, the protocol is not able to distinguish among them and it will see them as a single big noisy vessel. This does not create problems for the normal execution of the protocol.

If multiple vessels are located in different network areas they may produce multiple sets of nodes using bands different from the default one. This is not a problem as long as the various sets do not grow up to have common boundary nodes. If the sets use the same band, they simply merge together to create a single set. If they use different bands, as can be seen from Figures 3a-3d, border nodes join the set from which they received a CNG containing the band used more frequently by their neighbors. These nodes perform the usual operations of channel changing by sending a CNG packet before switching and a PRES packet after switching. Finally, the nodes inform all their neighbors that are on different bands transmitting a NCNG packet. For data packets, the RTS/CTS mechanism described above can be extended to include multiple replicas on different bands.

H. Carrier-Sense, Collision Avoidance, and Handshake

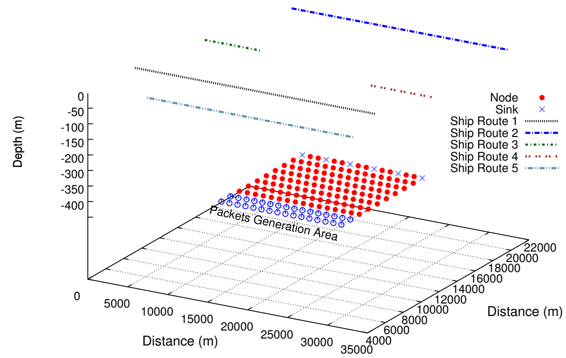
NAMAC can work with most contention-based protocols. In our implementation, we used an handshake procedure with a MACA scheme [11] and Carrier Sense. Further details are given in [26].

IV. SIMULATION RESULTS

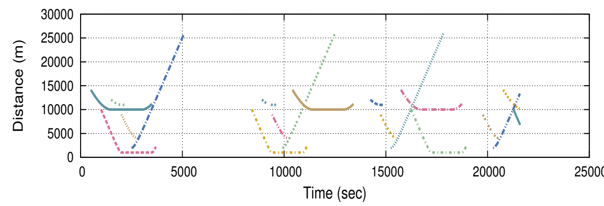
We evaluate the effectiveness of NAMAC comparing the performance of a modified version of the MACA [11] protocol that incorporates NAMAC to operate on multiple bands with its standard, single-band, implementation, which is used as a benchmark. We conducted experiments using a controlled simulation environment based on the MIRACLE [27] extension of the ns-2 simulator [28]. To compute the channel attenuation on each band for each link <noise-source, node> pair, we used the Bellhop ray tracing program [29] exploiting the WOSS interface [30]. Additionally, we extended the simulator to include a multi-channel PHY layer, which was required to implement NAMAC. We discretized the trajectories of each vessel in points 300m apart, and computed the attenuation between each point and each network node. We used real environmental data from an area located in the Mediterranean sea off the coast of the Giglio Island (Tuscan archipelago), with coordinate $(0,0,0)$ corresponding to $41°, 58', 32.98''N$ and $10°, 33', 37.36''E$. Sound speed profiles (SSP), bathymetry profiles and information on the type of bottom sediments of the selected area are obtained from the World Ocean Database [31], from the General Bathymetric Chart of the Oceans (GEBCO) [32] and from the National Geophysical Data Center's Deck41 Database [33], respectively. The SSP is retrieved by WOSS from the World Ocean Database.

We tested NAMAC in a network with 160 nodes deployed on a grid over plane of 15×9 Km^2 located at a depth of 400 m as showed in Fig. 4a. Data packets of 180 bytes were generated according to a Poisson process by nodes on a side of the network area and were forwarded in multi-hop, using a static routing, to sinks that were located on the opposite side. We ran simulations with 19 vessels navigating close to the deployment area, repeating the same route for the entire simulation time of 6 hours on five possible routes, as showed in Fig. 4a. Fig. 4b shows the distance between the vessels and the closest network node of the region from which packets are generated, as function of time. Fig. 4c shows the distance of the vessels from the area where the sinks are located.

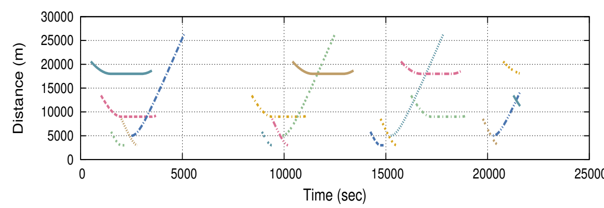
The overall system band was comprised between 15kHz and 40kHz, and divided into five sub-bands with bandwidth of 5 kHz each. Transmit power was equal to 180 dB re 1 μPa@1m. We used the following values for the power of noise emitted by close-by ships in the different bands, which we computed



(a) 3-D representation of nodes deployment and the vessels' routes.



(b) Vessels distance from the packet generation area.



(c) Vessels distance from the sinks area.

Figure 4: Network deployment and vessels' routes.

from the psd of a boat with two inboard diesel engines, which we picked from [21]:

- Band 1 ($\sim$15-20kHz) - 168 dB re:1 μPa @1m,
- Band 2 ($\sim$20-25kHz) - 164 dB re:1 μPa @1m,
- Band 3 ($\sim$25-30kHz) - 151 dB re:1 μPa @1m,
- Band 4 ($\sim$30-35kHz) - 148 dB re:1 μPa @1m,
- Band 5 ($\sim$35-40kHz) - 145 dB re:1 μPa @1m.

To evaluate the protocol's performance we used the following metrics: *Packet Delivery Ratio* (PDR), *Throughput, Average Power Consumption* (APC), and *End-to-End Delay* (E2E) for each packet to reach the sink. Performance are presented in the following figures in terms of the selected metrics' moving average (MA), computed over time-windows of 80 seconds, except for the E2E Delay, which is reported as a function of the packet ID. The figures refer to a single simulation. However, we observed a similar behavior in all the simulation we ran. The interested reader can check additional simulation results in [26]. The running MA is reported with a granularity of 20 seconds and represents the average of the selected metric over the last 80 seconds. The PDR stands for the ratio between the number of packets *generated* in the time-window and those *delivered* to the sinks, *not necessarily in the same window*. Throughput is the ratio between the amount of correctly delivered bits during a time-window and the time-window duration. APC is, for each instant, the total amount of energy

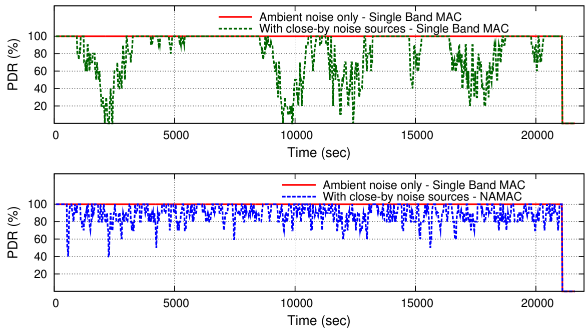


Figure 5: PDR in absence or presence of vessels with and without band switching.

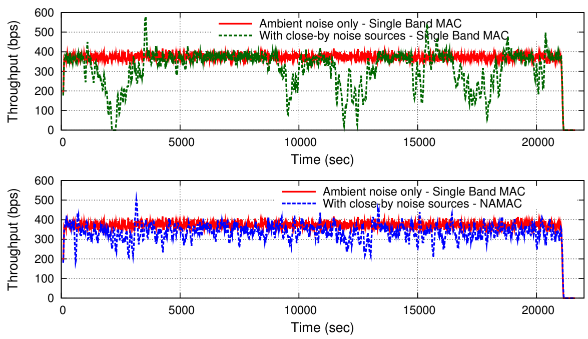


Figure 6: Throughput in absence or presence of vessels with and without band switching.

Table I: Modem Average Power Consumption used for simulations.

State	**Power Consumption** (Watts)
IDLE	0.158
RX	0.158
TX	7
SWITCH	1

consumed by the network in the preceding time-window of 80 seconds, divided by its duration. The APC is hence measured in Watts. The energy consumed by each node takes into account the power consumption of the four modem's states: IDLE, TX, RX and Frequency SWITCH. Table I shows the energy consumption values used for simulations. We choose these value taking [34] as a reference. The E2E Delay is the time between the generation of a packet and its delivery to its destination sink.

The presented simulation results refer to three different configurations: using the benchmark MACA protocol in the absence of noisy vessels, using the benchmark MACA protocol with vessels passing by the network, and using NAMAC in the presence of vessels passing by the network. In the latter two cases, vessels' activity was also stopped for a time interval, to evaluate the network settle-down times. In Figures 5-8, results in terms of PDR, Throughput, EC and E2E Delay are presented in all three cases considered.

Without any ship activity: In this case, the PDR is equal to 100%, indicating that all generated packets are delivered to sinks. Throughput keeps good values without ever suffering sharp falls: no packets are dropped and they are all delivered to the sink. The global average power fluctuates around 4 Watts,

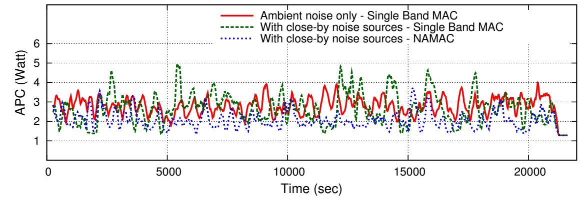


Figure 7: Network Average Power Consumption in absence or presence of vessels with and without band switching.

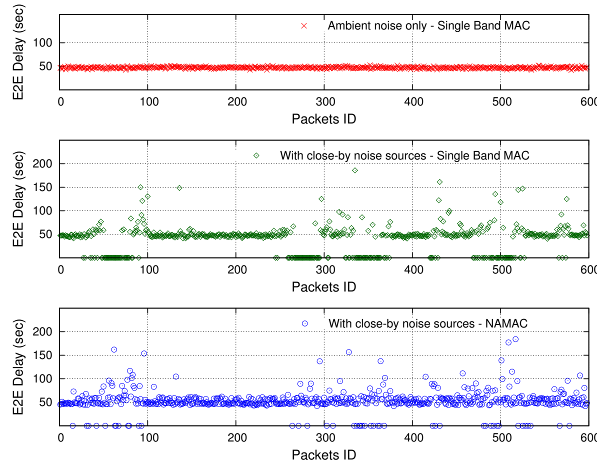


Figure 8: End-to-End Delay in absence or presence of vessels with and without band switching.

with minimum and maximum peaks at 1,6 and 4 Watts. The E2E Delay is approximately 50 seconds except in some cases where it is larger. In these cases the long delay is caused by the exponential backoff. In this configuration all the 600 generated packets wer delivered in all our simulations.

With the presence of ships but without band switching (MACA): In this case, it can be seen from Fig. 5 and 6 that both PDR and Throughput undergo a dramatic degradation until they reach a null value corresponding to the time intervals during which the vessels are closer to network, either to the packet generation area or to the sinks (cfr. Fig. 4b and 4c).

The first drop of the PDR and Throughput to null values occurs between seconds 1500 and 3000 of the simulation. In this interval, five vessels are passing by the network. Similar situations occur around time 10.000, 13.000, 15.000 and 20.000 seconds, when there are vessels close to the network. In such cases, both the PDR and Throughput performance degradation is milder than in the first case because fewer vessels are passing by. Between seconds 3.000 and 10.000 both PDR and Throughput don't suffer performance degradation because in such interval there is no ship activity. The APC decreases rapidly when vessels are close to network and then increases as vessels leave, see Figs. 4b and 4c. This is because when vessels are close to network, the network gets disconnected, as it is unable to forward packets. The same packets will be forwarded when the vessels move away (and the network recovers connectivity). The protocol delivered about 480 packets out of 600 (lost packets are showed in the bottom line of the figure, as if they had delay zero). Packets are lost when vessels are closer to the packets generation area. Packets incur larger delays (approximately 150 seconds) while vessels are approaching or leaving the network. A graphic representation of delays and packet drops, represented by circles lying on the lower axis, is given in Fig. 8.

With ships and using NAMAC: As shown in Figures 5 and 6, with NAMAC both PDR and Throughput suffers drop in the same intervals during which the vessels are close to the network: either to the packets generation area (Fig. 4b) or to the sinks (Fig. 4c). However, differently from the case without band switching, both PDR and Throughput degradation are much milder: PDR (Fig. 5) never falls below 40%, and it is most of the time above 80%, whereas Throughput (Fig. 6) never falls below 200 bps, and it stays most of the time above 300 bps; this shows that migrating to a different band helps communications when vessel are close-by. Fig. 7 shows that the APC decreases slightly when vessels are close to network, but the curve does not exhibit the peaks of the curve corresponding to the benchmark MACA protocol. This shows that the network gets never disconnected. With NAMAC, the network delivered about 565 packets out of the generated 600, keeping latency below 150 seconds for 98% of the delivered packets, see Fig. 8.

V. Conclusion

NAMAC has been proved to be a practical means to mitigate the disruptive effect that the noise emitted by close-by noise sources like motorboats or large ships may have on the connectivity and operation of UASNs. We showed an UASN running NAMAC outperforms one running a conventional single band MACA protocol. Good results are obtained in terms of Packet Delivery Ratio, Throughput, End-to-End Delay, and energy consumption. In particular, the risk of having the network disconnected is drastically reduced by NAMAC.

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