# Energy efficient interference-aware routing and scheduling in Underwater Sensor Networks

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***Abstract*—Underwater Wireless Sensor Networks (UWSNs) are emerging as a key enabling technology for a wide range of applications in the marine environment. Although there are significant efforts to find viable alternatives, acoustics are still the main technology in use for underwater communications. The use of acoustic transmissions in water, however, introduces several challenges such as variable and long propagation delays, low data rate, significant fluctuations in terms of link reliability over time and long interference range. Furthermore, sensor nodes are usually powered by batteries whose replacement can introduce high cost and complexity. The objective of this paper is to design a cross-layer heuristic solution for an efficient use of the scarce resources of Underwater Acoustic Sensor Networks (UASNs), such as bandwidth and energy. We propose a class of scheduling and routing policies, supporting the use of power control, to achieve reliable, low power, interference aware communications.**

***Index Terms*—Underwater wireless sensor networks, scheduling, routing, cross-layer design, optimization problem.**

## I. Introduction

Underwater Wireless Sensor Networks (UWSNs) are emerging as a key solution for a wide range of potential applications, such as monitoring of the environment and critical infrastructures, coastline protection, and prediction of underwater seismic and volcanic events [1], [2]. However, we are still far from having reliable and efficient underwater solutions which can be actually deployed in field. More robust and reliable technologies and communication solutions are needed.

These solutions need to adapt to the underwater channel dynamics while trying to reduce the energy consumption of the nodes in order to prolong the network lifetime. The replacement of node batteries in offshore deployments can in fact introduce high cost and complexity.

In this paper we propose a cross-layer heuristic for an efficient use of the scarce resources of Underwater Acoustic Sensor Networks (UASNs), such as bandwidth and energy. Based on the observation that the traffic load for several classes of underwater application is typically periodic, we develop a class of scheduling and routing policies that optimize the use of the underwater acoustic network resources, supporting also the use of power control. These policies assign to each node the best transmission time, forwarding link and transmission power level to achieve reliable, low power, interference aware communications.

More specifically, we provide the following contributions:

- We propose a class of scheduling policies that consider delay in packet delivery, nodes buffer size, distance to the sink (which represents the destination node for all the generated packets), and channel usage when selecting the node and time for the next transmission. Node transmissions are therefore scheduled following different policies: 1) Priority is given to nodes that are ready to transmit earlier than the others, thus reducing the delay in packet transmissions (**FIFO**); 2) priority is given to nodes which have more packets in their buffers, thus avoiding problems of buffer overflow in the network (**LOAD**); 3) priority is given to nodes which are far away from the sink, thus increasing the probability for packets that have to traverse long routes to be delivered to the sink (**LWS**); 4) priority is given to nodes that have performed a lower number of transmissions with respect to the others, thus balancing the possibility to transmit data for all the nodes in the network (**FAIR**).
- We propose a class of routing policies to optimize relevant end-to-end performance metrics, while at the same time increasing the probability to forward data to the sink. When selecting the next hop relay the objective is to: 1) Reduce the gap between the time when a packet is ready for transmission and its effective transmission in water (**FAN**); 2) reduce the maximal buffer size of relay nodes (**LIGHT**); 3) limit the length (in number of hops) of the path towards the sink (**SP**); 4) reduce the overall traffic load in the network (**LIN**). A set of different transmission power levels is considered, selecting each time the lowest one which permits to find a reliable relay node on the route towards the sink.
- Several combinations of the proposed scheduling and routing policies are evaluated by means of simulations. We refer to a scenario typical of a pipeline monitoring and control application, where each node transmission can traverse several hops before being delivered to the sink. To produce more realistic results, we consider the use of the Bellhop Gaussian Ray tracer [3], with real environmental data, to more accurately model signal attenuation and propagation of the underwater acoustic channel.

The reminder of the paper is organized as follows. Section II outlines related results in the literature. A detailed description of the propose system model is presented in Section III. Section IV describes the different strategies considered for link scheduling and routing with the use of power control. Section V presents the experimental results. Finally, concluding remarks are given in Section VI.

## II. Related works

Several solutions have been proposed in the past investigating novel MAC, scheduling and routing solutions for UASNs [4]–[19]. Most of these solutions address these problems separately. The majority of the efforts on MAC solutions in UASNs have considered random access protocols and carrier sensing with collision avoidance (CSMA/CA). In [4], the authors perform an analytical study on random access and handshaking protocols. The performance evaluation shows that while random access performs well in sparse networks with low data traffic, RTS/CTS protocols are more suitable for dense networks with high data traffic. Variants of the Aloha protocols are proposed in [5]. The resulting schemes achieve low throughput and, due to packet collisions, suffer from a high energy consumption. In [6] RTS/CTS handshaking is improved with carrier sensing, while in [7] uncertainties are resolved by adding a centralized controller. A TDMA-based approach is introduced in [8], where a period is divided in an experimental portion reserved for control packets exchange and an established portion for data transmissions. In [9] the authors investigate the possibility to split the available bandwidth to create two separate channels, one for control and one for data packets. Although this solution allows to avoid possible collisions and interference between control and data packets, it is effective only when a large bandwidth is available. When a low bandwidth is considered, channel multiplexing affects performance negatively, increasing source-to-sink packet latency and decreasing throughput.

Several solutions have investigated the problem of scheduling transmissions in UASNs assuming a predefined routing [14]–[17]. More specifically, in [14] an optimal traffic schedule, named ST-MAC, is computed for single-hop networks with a known network propagation delay. In [15] the link scheduling problem for single-hop networks is reduce to a standard traveling salesman problem. A link scheduling algorithm which avoid pairwise interference between transmissions is proposed in [16]. A fixed routing is assumed. All these solutions consider only pairwise interference. In [17], an analytical framework for routing and scheduling is proposed which considers a more accurate interference model. This new model accounts not only for pairwise interference but also for interference caused by multiple transmissions overlapping destructively during a packet reception. This approach does not support power control.

Several routing protocols have been proposed by the networking community for UASNs in the past years [13], which, however, ignore problems related to medium access control and scheduling. Most of these solutions focus on finding the optimal routes to deliver packets to the final destination while at the same time reducing the energy consumption in the network. In [10], a virtual pipe towards the sink is constructed, by considering as next hop relays only nodes closer to it. In [11], [12] nodes are equipped with special hardware for pressure sensing. Next hop relay selection is then based on depth information, hop count and control data exchanged between nodes.

Cross-layering schemes have been proposed in [18], [19]. A combination of a hybrid CDMA/ALOHA MAC with geographical routing is proposed in [18]. In [19] a cross-layer routing protocol is proposed which combines link quality and topology information to select the best next hop relay on the path towards the sink. The resulting scheme, CARP, is shown to lead to significant performance improvements over benchmarks selected among representatives of the classes of solutions proposed in the literature.

In this paper we follow a cross layering design and provide a class of scheduling, power control and routing policies that result into low power, interference aware effective solutions for underwater sensor networks. We assume an accurate description of the underwater acoustic channel considering a complete interference model, and modeling acoustic signal attenuation and propagation through the Bellhop ray trace software [3], instantiated with historical environmental data of the selected area.

## III. System model

The network is modeled via a directed graph $G(V, E)$, where $V$ is the set of sensor nodes and $E$ is the set of links available in the network. We assume that each node can choose among a fixed number of transmission power levels (denoted by $\Phi = \{P_{min}, \cdots, P_{max}\}$) when transmitting a data packet in water. There is a link $e_{ij} \in E$, from node $i$ to node $j$, if there exists a transmission power level $P \in \Phi$ such that a reliable transmission can occur, i.e., the *Signal-to-Noise Ratio* (SNR) of $i$'s transmission at $j$ is higher than a given threshold $SNR_{th}$. For each node $i$, we denote with $E_i^O$ the set of outgoing links from $i$, and with $E_i^I$ the set of links entering $i$.

We consider a periodic traffic generation schema where the whole lifetime of the network is divided into multiple fundamental periods, called frames. All the frames have the same length denoted by $T$. Source nodes generate data at the beginning of frames. Frames are divided into multiple slots, each of a fixed length. We assume that a packet transmission can start only at time slots boundaries. The duration of each slot is set equal to the time needed to transmit a data packet, assumed equal for all nodes.

We denote by $load_i^t$ the number of packets inside the buffer of node $i$ ready for transmission at time slot $t$. Packets that cannot be transmitted directly to the sink are relayed through intermediate nodes. With $d_{ij}$ we denote the propagation delay between nodes $i$ and $j$, expressed in number of slots. It is obtained dividing the link length by the product of sound speed and the duration of the time slot in seconds.

To model possible conflicts and interference in the network, we consider the approach followed in [17]. We account not only for pairwise conflicts/interference, but also for the combination of multiple transmissions that can impair correct receptions if overlapping at some receiver. We assume a half-duplex model, which is typical in underwater acoustic networks. A node cannot simultaneously transmit on more than one link and cannot receive from more than one link at the same time. Moreover, a node cannot receive if it has not completed an ongoing packet transmission.

The results of our system is a set of tuples $\ddot{S} = \{< e_{ij}, t, P >\}$, each identifying a transmission. Tuple $< e_{ij}, t, P >$ refers to a packet transmitted on the link $e_{ij}$, from node $i$ to node $j$, during the time slot $t$ using the transmission power level $P$.

Table I shows a summary of the notation used for the model formulation.

Table I
NOTATION SUMMARY

| | |
|---|---|
| $i, j$ | Nodes of the network |
| $e_{ij}$ | Link between node $i$ and $j$ in network |
| $E_i^O$, $E_i^I$ | Sets of outgoing/incoming links for node $i$ |
| $d_{ij}$ | Propagation delay expressed in number of slots between nodes $i$ and $j$ |
| $load_i^t$ | Number of packets inside the buffer of node $i$ at time slot $t$ |
| $T$ | Frame length |
| $\Phi = \{P_{min}, .., P_{max}\}$ | The set of available transmission power levels |
| $SNR_{th}$ and $SIR_{th}$ | Signal-to-Noise Ratio (SNR) and Signal-to-Interference Ratio (SIR) thresholds |
| $\ddot{S} = \{< e_{ij}, t, P >\}$ | System output. It is defined as a set of tuples, each identifying the link selected for the transmission ($e_{ij}$), the slot to be used for the transmission ($t$) and the power level to use ($P$) |
| $A_i^t$ | Set of available slots in the interval $[t, T-1]$ for which node $i$ can send a packet, without any conflict or interference with already scheduled transmissions. |
| $\pi$ | Packet transmitted in water |
| $N_\pi$ | Set of nodes previously visited by packet $\pi$ |
| $R_i^\pi$ | The set of nodes providing a positive advancement towards the sink for node $i$ when transmitting packet $\pi$ |
| $d_{iSink}^H$ | The number of hops on the shortest path separating node $i$ from the sink |

## IV. Scheduling and Routing policies

In this section we investigate the problem of link scheduling and routing with the use of power control. The final goal is to derive a class of scheduling and routing policies which assign to each node the best transmission time, next-hop relay and transmission power level in order to optimize the network performance in terms of throughput and energy consumption.

### A. Main procedure

Scheduling and routing are constructed in a greedy fashion (Algorithm 1), where at each step:

- The next transmission to be scheduled is selected, according to the *scheduler_policy*. A tuple $< i^*, t^*, \pi >$ is computed which represents the node selected for transmission ($i^*$); the first time slot where the transmission can takes place ($t^*$) and the packet to transmit ($\pi$).
- The best link, time slot and transmission power level, $< e_{ij}^*, t^{**}, P^* >$ are selected, based on a *routing_policy* and on the computed scheduling information (tuple $< i^*, t^*, \pi >$). The link $e_{ij}^*$ will be used as part of the route towards the sink. Node $i$ will transmit its packet to node $j$ at time slot $t^{**}$, using as transmission power level $P^*$.
- The buffer size of source $i$ and destination node $j$ are updated, according to scheduling and routing decisions.

**Algorithm 1:** Schedule and Routing

```
input  : Node loads at slot t, load_i^t, i ∈ V, t ∈ [0, T−1], Available
         transmission power levels Φ
output : Link Schedule S̈
begin
    while ∃ < i, t >: load_i^t > 0 and i ∈ V\{sink} do
        < i*, t*, π > ⟵ scheduler_policy();
        < e*_ij, t**, P* > ⟵ routing_policy(< i*, t*, π >);
        S̈ ⟵ S̈ ∪ < e*_ij, t**, P* >;
        load_{i*}^{t**} ⟵ load_{i*}^{t**} − 1;
        arrival_time ⟵ MOD(t** + d_ij, T);
        load_{j*}^{arrival_time} ⟵ load_{j*}^{arrival_time} + 1;
    end
    return S̈;
end
```

The process is performed until there are still packets to be forwarded to the sink. At each step, new transmissions are scheduled avoiding conflicts and interference with already scheduled ones[1]. The effectiveness of the proposed approach depends on the strategies used to schedule and route packet transmissions, with the support for power control. We detail the different policies as optimization problems below. The solutions space is, however, limited and these can be solved in an iterative way.

### B. Scheduling policies

The class of scheduling policies selects the next transmitting node considering different objectives: Delay in packet delivery; maximal node buffer size; distance to the sink (in terms of number of hops); and channel usage.

- **FIFO**: This policy aims at minimize the gap between the time when a packet is available for transmission and its effective transmission in water. Nodes first scheduled for transmission are those which are ready to transmit earlier than the others.

[1] If there are ties when selecting the transmitting node (scheduling) and next hop relay (routing), priority is given to the node with the lowest ID.

$$\begin{aligned} &\textbf{FIFO} && \textbf{scheduler\_policy} \\ &\textbf{Given}: && load_i^t \ \forall \{i : i \in V \setminus \{Sink\}\},\ t \in [0, T-1] \\ &\textbf{Find}: && < i^*, t^* > \\ &\textbf{Objective}: && \text{Minimize } t \\ &\textbf{Subject to}: && load_i^t > 0 \end{aligned}$$

- **LOAD**: To increase the probability of having all packets forwarded to the sink, the scheduler gives priority to nodes that have more packets ready for transmission inside their buffers. This allows to reduce/avoid possible buffer overflow problems in the network.

$$\begin{aligned} &\textbf{LOAD} && \textbf{scheduler\_policy} \\ &\textbf{Given}: && load_i^t \ \forall \{i : i \in V \setminus \{Sink\}\},\ t \in [0, T-1] \\ &\textbf{Find}: && < i^*, t^* > \\ &\textbf{Objective}: && \text{Maximize } load_i^t \\ &\textbf{Subject to}: && load_i^t > 0 \end{aligned}$$

- **LWS**: Priority for transmission is given to nodes which are far away from the sink in terms of number of hops. The packets generated by these nodes will have to traverse more hops and will be therefore more prone to possible collision and interference. Defining by $d_{iSink}^H$ the estimated distance (in numbers of hops) between the sink and node $i$, the scheduling policy works as follows:

$$\begin{aligned} &\textbf{LWS} && \textbf{scheduler\_policy} \\ &\textbf{Given}: && d_{iSink}^H, load_i^t \ \forall \{i : i \in V \setminus \{Sink\}\},\ t \in [0, T-1] \\ &\textbf{Find}: && < i^*, t^* > \\ &\textbf{Objective}: && \text{Maximize } d_{iSink}^H \\ &\textbf{Subject to}: && load_i^t > 0 \end{aligned}$$

- **FAIR**: To assure a fair usage of the underwater acoustic channel, nodes that have performed a lower number of transmissions, with respect to the others, are preferred. We use the terminology *good* or *bad* for time slots that are predicted to be clear of or affected by conflicts/interference. Since packet transmissions are scheduled in a greedy manner, at each step previously scheduled transmissions and computed routes are already known. Based on this *semi-defined* solution, we can compute interference that can affect future transmissions. For this purpose, we denote as $A_i^t$ the set of *good* available slots in the interval $[t, T-1]$. During these slots, node $i$ can send a packet without any conflict or interference with already planned transmissions. The FAIR policy gives priority to nodes with reduced possibilities to transmit their data (smaller $A_i^t$).

$$\begin{aligned} &\textbf{FAIR} && \textbf{scheduler\_policy} \\ &\textbf{Given}: && \ddot{S} \text{ semi-defined solution} \\ & && load_i^t \ \forall \{i : i \in V \setminus \{Sink\}\},\ t \in [0, T-1] \\ &\textbf{Find}: && < i^*, t^* > \\ &\textbf{Objective}: && \text{Minimize } \left|A_i^t\right| \\ &\textbf{Subject to}: && load_i^t > 0; \quad (1) \\ & && \forall t' \in A_i^t : \\ & && t' \in [t, T-1] \quad \wedge \quad (2) \\ & && \forall e_{ik} \in E_i^O, \forall P \in \Phi,\ < e_{ik}, t', P > \notin \ddot{S} \wedge \quad (3) \\ & && \exists e_{ij} \in E_i^O: \\ & && \{\nexists < e_{jk}, t_j, P > \in \ddot{S}: \\ & && t' + d_{ij} \le t_j \le t' + d_{ij} + 1\} \wedge \quad (4) \\ & && \{\nexists < e_{kj}, t_k, P > \in \ddot{S}: \\ & && t_k + d_{kj} - 1 \le t' + d_{ij} \le t_k + d_{kj} + 1\} \quad (5) \\ & && \{\ \exists P \in \Phi: SIR_{ij}(t', P) > SIR_{th}\} \quad (6) \end{aligned}$$

Constraint (1), imposes that nodes selected for transmission are those which have packets to forward to the sink. Constraint (2) assures that node $i$ can transmit only in the time interval $[t, T-1]$. Constraint (3) avoids that slots considered in $A_i^t$ are already scheduled for transmission, while constraints (4), (5) and (6), guarantee that for each $t' \in A_i^t$, there exist a link $e_{ij} \in E_i^O$, such that:

- The destination node $j$ is not scheduled for transmission during the reception interval $[t' + d_{ij}, t' + d_{ij} + 1]$. As we assume that transmission starts at the beginning of a slot, this translates into checking that there are no scheduled transmissions for node $j$ in that interval (4).
- There are no possible overlapping receptions for the destination node $j$. This consists in checking that, if there are scheduled transmissions on the links entering node $j$ ($< e_{kj}, t_k, P > \in \ddot{S}$), the two packet reception time intervals $[t_k + d_{kj}, t_k + d_{kj} + 1]$ and $[t' + d_{ij}, t' + d_{ij} + 1]$ are disjoint (5).
- The SIR measured at the destination node during the reception time interval $[t' + d_{ij}, t' + d_{ij} + 1]$ has to be above a certain threshold $SIR_{th}$. As it was discussed in section III, for a more realistic interference characterization we need to consider the more general case, where a set of multiple transmissions may produce a non negligible interference at some receiver (6).

### C. Routing policies and power control

When designing routing strategies we focused on optimizing relevant end-to-end performance metrics, while at the same time increasing the probability to forward data to the sink. We have therefore defined multiple strategies with the objective to reduce: The time packets spend in the buffer before being transmitted; the maximal buffer size of relay nodes; the length of the routes toward the sink in terms of number of hops; the traffic load in the network. For a better usage of available energy resources we have combined routing with power control. A set of different transmission power levels has been considered, selecting each time the lowest power level which permits to find a reliable relay node.

In order to compute optimal routes towards the sink, we have to avoid possible loops on the selected paths. Usually this is done by selecting as next hop relays the nodes with a positive advancement towards the sink. The positive advancement is generally defined in terms of distance to the sink. This assumption works correctly when the acoustic propagation and transmission loss models make use of empirical formulas, such as the ones presented in [20], where, fixed the working frequency and bandwidth, the acoustic signal attenuation depends only on the distance between the nodes. These empirical formulas, however, do not consider possible channel dynamics related to environmental factors and result in an oversimplified and not accurate acoustic channel model [21].

When considering a more realistic model for the underwater acoustic channel, such as the Bellhop Gaussian ray tracer [3] with historical data from databases available online [22], [23], it is possible that considering only the nodes with a positive advancement towards the sink no reliable routes can be found due to variable quality asymmetric links. To solve this issue, we have defined a $ILP$ model which, given a source node $i^*$ and a data packet $\pi$, checks if starting from node $i^*$ there exists a path for packet $\pi$ towards the sink that is loop free.

**Variable**:

$B_i$, is an integer variable that counts the number of packets inside the buffer of node $i$.

$X(e_{ij})$, is a binary variable equal to 1, if link $e_{ij} \in E$ is active in the feasible path.

**Objective**: Find a feasible solution, where $B(Sink) > 0$.

$$\mathbf{NLOOP\_ROOTE(i^*, \pi)}: \ B_{Sink} > 0$$

$$s.t:$$

$$\sum_{e_{ij} \in E_i^I} X(e_{ij}) - \sum_{e_{ij} \in E_i^O} X(e_{ij}) = B_i, \qquad \forall i \in V \qquad (7)$$

$$B_i - X(e_{ij}) \geq 0, \quad \forall i \in V, e_{ij} \in E_i^O \qquad (8)$$

$$X(e_{ij}) = 0, \quad \forall i \in N_\pi, e_{ij} \in E_i^O \qquad (9)$$

$$B_{i^*} = 1 \qquad (10)$$

$$B_i = 0, \qquad \forall i \in V \backslash \{i^*\} \qquad (11)$$

Constraint (7) assures flow conservation. Constraint (8) imposes that a link $e_{ij}$ is active if and only if, the source node $i$ has packets inside the buffer. Denoting by $N_\pi$ the set of nodes previously visited by packet $\pi$, constraint (9) assures that none of the outgoing links from previously visited nodes is active. Constraints (10) and (11) are used to guarantee that the only available data packet is the one inside the buffer of node $i^*$.

In Figure 1, we show a visual representation of model $NLOOP\_ROUTE$ $(i, \pi)$. The rectangular squares in the Figure represent the buffer of the nodes in the network which are modeled through variables $B$. Each square has outgoing and entering links, modeled using variables $X$. The problem is feasible, when there is a path towards the sink such that a packet $\pi$ moves from $i$-th buffer to sink buffer (i.e. $B(Sink) = 1$), without entering the nodes already visited by packet $\pi$ (such as the one marked with the cross).

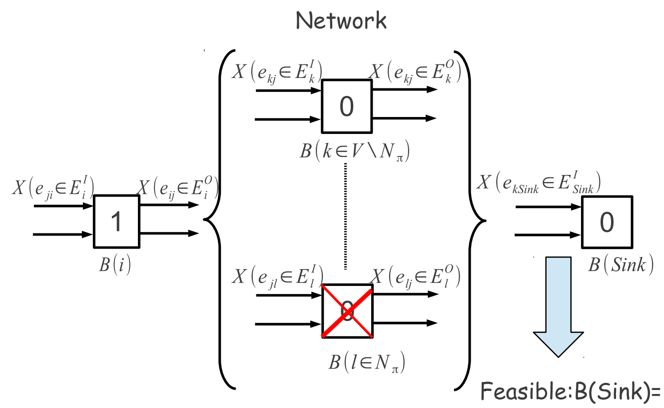


Figure 1. Find a path from node $i$ to the sink for packet $\pi$ without traversing nodes already visited (according to $N_\pi$)

We define by $R_i^\pi$ the set of neighbors of node $i$ offering a suitable loop free advancement towards the sink when transmitting packet $\pi$:

$$R_i^\pi = \{j \in V : \exists e_{ij} \in E \wedge NLOOP\_ROUTE(j, \pi) \text{ feasible}\} \qquad (12)$$

$R_i^\pi$ therefore represents the set of neighbor nodes that can be selected as next hop relays by node $i$ when transmitting packet $\pi$. Using this definition, in what follows we detail the considered routing policies:

- **FAN**: This strategy selects as next hop relay the neighbor node that can receive the transmitted packet earliest than any other potential relay, according to already scheduled transmissions.

  **FAN routing_policy**
  **Given**: $< i^*, t^*, \pi >$
  **Find**: $< e_{ij}^*, t^{**}, P^* >$
  **Objective**: Minimize $t^{**}$
  **Subject to**: $e_{ij} \in E_{i^*}^O$
  $j \in R_{i^*}^\pi$
  $P^* := min_{P \in \Phi}\{SNR_{ij}(P) > SNR_{th}$ and $SIR_{ij}(t^{**} + d_{ij}, P) > SIR_{th}\}$

  $SNR_{ij}(P)$, and $SIR_{ij}^*(t^{**} + d_{ij}, P)$ represent the Signal-to-Noise Ratio (SNR) and Signal-to-Interference Ratio (SIR) measured at receiver $j$ for a signal emitted by node $i$ with transmission power level $P$.

- **LIGHT**: This strategies aims at assuring load balancing between relay nodes, minimizing the maximal buffer size of the possible relays.

$$\begin{aligned}
&\textbf{LIGHT} \;\; \textbf{routing_policy}\\
&\textbf{Given}: \; < i^*, t^*, \pi > ;\, load_j^t,\, \forall j \in V,\, t \in [t^*, T]\\
&\textbf{Find}: \; < e_{ij}^*, t^{**}, P^* >\\
&\textbf{Objective}: \text{ Minimize } load_j^{t^{**}+\lceil d_{ij}\rceil+1}\\
&\textbf{Subject to}: \; e_{ij} \in E_{i^*}^O\\
&\qquad j \in R_{i^*}^{\pi}\\
&\qquad P^* := min_{P\in\Phi}\{SNR_{ij}(P) > SNR_{th} \text{ and}\\
&\qquad\qquad SIR_{ij}(t^{**}+d_{ij}, P) > SIR_{th}\}
\end{aligned}$$

- **SP**: This policy chooses the next hop relay among neighbor nodes that are part of a shortest paths toward the sink. The next hop relay is selected between neighbors $j \in E_i^O$, which have the estimated shortest path distance $d_{jSink}^H$, lower than source node $i$.

$$\begin{aligned}
&\textbf{SP} \;\; \textbf{routing_policy}\\
&\textbf{Given}: \; < i^*, t^*, \pi > ;\, d_{jSink}^H,\, \forall j \in V\\
&\textbf{Find}: \; < e_{ij}^*, t^{**}, P^* >\\
&\textbf{Objective}: \text{ Minimize } P\\
&\textbf{Subject to}: \; e_{ij} \in E_{i^*}^O\\
&\qquad d_{jSink}^H < d_{iSink}^H\\
&\qquad P^* := min_{P\in\Phi}\{SNR_{ij}(P) > SNR_{th} \text{ and}\\
&\qquad\qquad SIR_{ij}(t^{**}+d_{ij}, P) > SIR_{th}\}
\end{aligned}$$

- **LIN**: This routing policy selects as next hop relay the neighbor node which has a higher probability to reserve the channel, being less affected by other transmissions interference. We therefore define the *load-to-time* metric, which represents the ratio between number of packets that a node has to transmit and the number of *good* available slots for transmission.

$$load - to - time(i,t) = \frac{load_i^t}{|A_i^t|}$$

Sending data to neighbors which have more available slots for the current load, i.e. lower *load-to-time*, increases the probability of a correct forwarding of the data to the sink.

$$\begin{aligned}
&\textbf{LIN} \;\; \textbf{routing_policy}\\
&\textbf{Given}: \; < i^*, t^*, \pi > ;\, \forall j \in V,\, t \in [t^*, T-1]\text{: } load_j^t,\, A_{i^*}^t\\
&\textbf{Find}: \; < e_{ij}^*, t^{**}, P^* >\\
&\textbf{Objective}: \text{ Minimize } \frac{load_j^{t^{**}+\lceil d_{ij}\rceil+1}}{\left|A_j^{t^{**}+\lceil d_{ij}\rceil+1}\right|}\\
&\textbf{Subject to}: \; e_{ij} \in E_{i^*}^O\\
&\qquad j \in R_{i^*}^{\pi}\\
&\qquad P^* := min_{P\in\Phi}\{SNR_{ij}(P) > SNR_{th} \text{ and}\\
&\qquad\qquad SIR_{ij}(t^{**}+d_{ij}, P) > SIR_{th}\}
\end{aligned}$$

For all the investigated policies, relay nodes and transmission slots are selected in order to avoid conflicts and interference with previously scheduled transmissions.

## V. Performance evaluation

We have conducted a thorough set of experiments to evaluate the performance of several combinations of the proposed scheduling and routing policies. Section V-A describes the considered simulation scenarios and parameters. Results are presented in section V-B.

### A. Simulation scenarios and parameters

We refer to the scenario of an oil well and pipeline monitoring and control application, detailed as part of the FP7 CLAM (Collaborative embedded networks for submarine surveillance) project [24]. The sink is located at the surface on a offshore platform, with the transducers placed at 10m depth. We consider rectangular shape network areas, $1\,\text{km} \times 6\,\text{km}$ and $1\,\text{km} \times 4\,\text{km}$, where $40$ and $60$ nodes are deployed, respectively. Packets are routed through multiple hops. The sink is assumed to be placed 500 m north and 500 m west of the bottom right corner of the network area. To produce more accurate results, we have modeled the signal attenuation and propagation through the Bellhop Gaussian ray tracer [3]. We have use real historical environmental data for our computation as input for Bellhop. Environmental data such as sound speed profile and bathymetry profile have been obtained from real measurements. The environmental data we have considered refer to a location in the North of Europe.[2] Environmental noise is modeled using the empirical power spectral density equations reported in [25]. As parameters to those equations, we chose a moderate shipping factor of 0.5 and a wind speed of 7 m/s. The latter corresponds to level 4 of the Beaufort scale, which is typical of the considered region. The set of transmission power levels available is set to $\Phi = \{178, 176, 174\}$ dB re $\mu$Pa. To process the results computed by Bellhop and to give these in input to our optimization routing model, the SUNSET framework has been considered [26].

Table II shows the network topologies set-up and the parameters considered to model the acoustic modem, which are in line with current commercial devices. We have performed experiments considering different network traffic loads where $25\%$ and $100\%$ of the nodes in the network generate data, with the exception of the sink.

Table II
Simulation parameters

| | |
|---|---|
| Carrier frequency | 25.6 kHz |
| Bandwidth | 4 kHz |
| Source Power Levels (SPL) at 1 m | $\{174, 176, 178\}$ dB re $\mu$Pa |
| Modulation | BPSK |
| Acquisition threshold | 1 dB |
| Slot_duration ($\tau$) | 0.2 s |
| Bit rate | 1000 bps |
| Sound speed | 1500 m/s |
| Area sizes | $1 \times 4\,\text{km}$, $1 \times 6\,\text{km}$ |
| Number of nodes | 40, 60 |

### B. Results

We have investigated the combination of several routing and scheduling policies to evaluate the performance of the

[2] Additional details are omitted as covered by a non disclosure agreement.

proposed cross layering approach. Table III shows the average power consumption obtained for the two different traffic generation rates, respectively, for both 40 nodes and 60 nodes topologies. We observe that when less packets are generated in the network fair routing policies, like LIGHT and LIN, obtain a lower energy consumption for all the considered scheduling policies. When the number of nodes increases, LIN policy starts performing better since it tries to reduce the overall traffic load, preferring nodes with better chance to forward data towards the sink. When the number of packets generated in the network increase, the combination of the FAIR scheduling with the LIN routing results in a reduction of energy consumption of about $23\%$ with respect to the average energy consumption achieved by the other combinations in the case of 40 nodes topology, and about $25\%$ when considering 60 nodes topology. Similarly to what described above, the LIN routing policy performs better when more packets are pushed in the network (more nodes or higher traffic). In this case the FAIR scheduling strategy has to be preferred, since it keeps track of nodes with less chance to reserve the channel and try to obtain better performance at a network level rather than at the node level.

Table III
AVERAGE ENERGY CONSUMPTION(J) - P={178, 176, 174} dB re $\mu$Pa.

25% traffic rate

| S/R policies | FAN | | LIGHT | | SP | | LIN | |
|---|---|---|---|---|---|---|---|---|
| Topologies | 40 | 60 | 40 | 60 | 40 | 60 | 40 | 60 |
| FIFO | 7.5 | 29.1 | 6.02 | 22.4 | 7.43 | 22.11 | 6.8 | 16 |
| LOAD | 7.5 | 25.6 | 4.9 | 19.8 | 7.5 | 21.5 | 4.34 | 20.5 |
| LWS | 7.5 | 20.5 | 6.03 | 19.8 | 7.5 | 22.11 | 6.7 | 16 |
| FAIR | 6.03 | 25.9 | 6.03 | 19.5 | 6.03 | 16.6 | 5.43 | 16 |

100% traffic rate

| S/R policies | FAN | | LIGHT | | SP | | LIN | |
|---|---|---|---|---|---|---|---|---|
| Topologies | 40 | 60 | 40 | 60 | 40 | 60 | 40 | 60 |
| FIFO | 123.4 | 422.3 | 130.8 | 266.6 | 103.9 | 276.6 | 99.8 | 241.1 |
| LOAD | 116.8 | 362.9 | 104.7 | 240.8 | 115.7 | 262.3 | 80.13 | 221 |
| LWS | 103.2 | 405.2 | 104.9 | 257.5 | 97.6 | 286.5 | 89.93 | 232.9 |
| FAIR | 88.19 | 405.5 | 110 | 238.5 | 92.5 | 279.1 | 80.1 | 217.5 |

Looking at the power control data, we have seen that on average $21.5\%$ ($18.2\%$) of the transmissions are scheduled with the highest transmission power, $22.4\%$ ($26.1\%$) with the medium one and $56.1\%$ ($55.7\%$) with the lowest one, for a network of 60 (40) nodes.

Table IV shows the same scenarios as in Table III where only the highest transmission power level is used. We can see that using power control we have a reduction in terms of energy consumption of about $26.5\%$ and $17.5\%$ in the case of low traffic considering 40 nodes and 60 nodes topologies, respectively. When traffic load increases the improvement in the energy consumption performance, increases as well ($35\%$ and $27.6\%$ for 40 nodes and 60 nodes topologies, respectively). When a larger number of transmissions and receptions occur in the network, the use of an adaptive routing and transmission power scheme becomes more important. We have also considered the case where only the lowest transmission power level can be used. We have an average increase in the energy consumption, with respect to the case with power control, of about $45.7\%$. Using always the lowest transmission power level, only shortest links can be selected, thus increasing the number of hops that need to be traversed to reach the sink. This results in a higher number of packet transmissions and receptions and an overall higher energy consumption.

Table IV
AVERAGE ENERGY CONSUMPTION(J) - P={178} dB re $\mu$Pa.

25% traffic rate

| S/R policies | FAN | | LIGHT | | SP | | LIN | |
|---|---|---|---|---|---|---|---|---|
| Topologies | 40 | 60 | 40 | 60 | 40 | 60 | 40 | 60 |
| FIFO | 8.9 | 32.15 | 7.2 | 25.13 | 8.84 | 24.98 | 8.7 | 19.4 |
| LOAD | 8.6 | 27.9 | 7.8 | 22.5 | 8.15 | 24.9 | 7.2 | 24.11 |
| LWS | 9.8 | 38.14 | 8.6 | 25.13 | 11.9 | 24.97 | 9.05 | 21.62 |
| FAIR | 8.6 | 33.7 | 8.6 | 23.8 | 8.6 | 20 | 7.3 | 19.5 |

100% traffic rate

| S/R policies | FAN | | LIGHT | | SP | | LIN | |
|---|---|---|---|---|---|---|---|---|
| Topologies | 40 | 60 | 40 | 60 | 40 | 60 | 40 | 60 |
| FIFO | 178.8 | 523.7 | 176.7 | 386.6 | 164.9 | 351.3 | 158.4 | 380.9 |
| LOAD | 171.8 | 473.9 | 153.9 | 252.8 | 186.7 | 346.2 | 123.3 | 341.5 |
| LWS | 137.6 | 506.5 | 149.8 | 375.9 | 154.9 | 366.7 | 142.7 | 376.6 |
| FAIR | 176.3 | 498 | 169.2 | 441.5 | 142.3 | 443.8 | 123.3 | 349.9 |

While reducing the energy consumption, the proposed cross layer design aims also at increasing the network throughput. Reducing the number of seconds necessary to complete all the transmissions to the sink (frame length) we increase the channel utilization and the throughput in the network. Table V shows the minimum frame lengths obtained for the different scheduling/routing combinations. We observe that again the combination of FAIR scheduling and LIN policy is the one achieving the best performance, resulting in lower frame length and higher throughput. Giving the priority to transmit to nodes that have less chances to reserve the channel and, at the same time, reducing the overall traffic load results in more accurate selections at the network level to increase the network throughput.

Table V
MINIMUM FRAME LENGTH (S) - P={178, 176, 174} dB re $\mu$Pa.

25% traffic rate

| S/R policies | FAN | | LIGHT | | SP | | LIN | |
|---|---|---|---|---|---|---|---|---|
| Topologies | 40 | 60 | 40 | 60 | 40 | 60 | 40 | 60 |
| FIFO | 3.2 | 6.8 | 2.8 | 6 | 3.2 | 5.6 | 3.2 | 5.2 |
| LOAD | 3.2 | 6.4 | 2.8 | 5.6 | 3.2 | 5.6 | 2.4 | 6 |
| LWS | 2.8 | 5.6 | 3.6 | 5.6 | 3.2 | 5.6 | 3.2 | 5.2 |
| FAIR | 2.8 | 6.4 | 2.8 | 5.6 | 2.8 | 5.2 | 2.4 | 5.2 |

100% traffic rate

| S/R policies | FAN | | LIGHT | | SP | | LIN | |
|---|---|---|---|---|---|---|---|---|
| Topologies | 40 | 60 | 40 | 60 | 40 | 60 | 40 | 60 |
| FIFO | 12.4 | 20.2 | 12.8 | 15.4 | 12 | 15 | 12 | 15.4 |
| LOAD | 11.6 | 19.8 | 12 | 14.2 | 12 | 15.4 | 11.2 | 14.2 |
| LWS | 12.4 | 23.4 | 12.4 | 17 | 12 | 15.4 | 12 | 15 |
| FAIR | 11.2 | 18.6 | 12.8 | 15 | 11.6 | 14.6 | 11.2 | 14.2 |

Considering only the highest transmission power level (Table VI) in smaller scale scenarios there is a throughput improvement of about $8.3\%$ and $4.7\%$, when part or the entire network is generating data, respectively. Considering a network with 60 nodes, the throughput improvement increase to about $10\%$ and $6\%$. Using a higher transmission power level allows to reach the sink with a lower number of hops thus reducing the frame length. On the other hand, a much higher energy consumption is required (as presented above). Similarly, when using only the lowest transmission power level each packet has to be delivered through longer routes, thus requiring more time to reach the sink. In this case the reduction in the network throughput, with respect to the case when power control is used, is about 41%.

Table VI
**MINIMUM FRAME LENGTH (S) - P={178} dB re $\mu$Pa.**

25% traffic rate

| S/R policies | FAN | | LIGHT | | SP | | LIN | |
|---|---|---|---|---|---|---|---|---|
| Topologies | 40 | 60 | 40 | 60 | 40 | 60 | 40 | 60 |
| FIFO | 2.8 | 5.2 | 2.8 | 5.2 | 3.2 | 5.2 | 2.8 | 5.2 |
| LOAD | 2.8 | 4.8 | 2.4 | 4.9 | 2.8 | 4.8 | 2.4 | 4.8 |
| LWS | 2.4 | 5.6 | 2.4 | 5.6 | 3.2 | 5.2 | 2.8 | 4.8 |
| FAIR | 2.8 | 5.2 | 2.4 | 5.6 | 2.8 | 4.8 | 2.8 | 4.8 |

100% traffic rate

| S/R policies | FAN | | LIGHT | | SP | | LIN | |
|---|---|---|---|---|---|---|---|---|
| Topologies | 40 | 60 | 40 | 60 | 40 | 60 | 40 | 60 |
| FIFO | 12 | 16.8 | 11.2 | 15.6 | 11.2 | 14.6 | 11.2 | 14.4 |
| LOAD | 11.6 | 15.6 | 11.6 | 15 | 12 | 15.4 | 11.2 | 14.2 |
| LWS | 11.2 | 19.6 | 11.2 | 15.6 | 11.2 | 15.4 | 11.6 | 14.4 |
| FAIR | 11.2 | 15.6 | 11.6 | 14.8 | 11.2 | 14.2 | 11.2 | 14.2 |

## VI. CONCLUSION

In this paper we have proposed a centralized cross layer heuristic that aims at finding a reliable interference aware scheduling, routing and power assignment schema for UASNs. We developed a class of scheduling and routing policies supporting the use of power control, which assign to each node the best transmission time, forward link and transmission power level to achieve reliable, low power, interference aware communications. Results show that a fair scheduling strategy combined with a routing solution which tries to reduce the overall network load should be preferred. These strategies lead to a solution that optimizes the overall network performance rather that the single node's ones and allows to achieve the best performance in terms of energy consumption and throughput in the network. The conducted analysis also show that the use of power control mechanism can significantly improves the network energy consumption and can also increase the overall throughput of the network.

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