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A PAIR OF DISTRIBUTED GEOGRAPHICAL ROUTING ALGORITHMS FOR UNDERWATER ACOUSTIC SENSOR NETWORKS

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Abstract

As a support for broad range of applications, sensor devices capable of processing, data acquisition, communication are arranged under water. Because of the high attenuation and scattering affecting radio and optical waves, respectively they enable communication technology for distances over one hundred meters is wireless acoustic networking. The present work, by considering the interactions between the routing functions and the characteristics of the underwater acoustic channel, investigates the problem of data gathering. We propose two distributed geographical routing algorithms for delay-insensitive and delay-sensitive applications and through simulation experiments it is shown that the application requirements are met.

Index Terms: *Routing Algorithms, Sensor networks*

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1. INTRODUCTION

As a support for broad range of applications, sensor devices capable of processing, data acquisition, communication are arranged under water. [1], [2]. These, so as to support applications for oceanographic data collection, ocean sampling, pollution and environmental monitoring, offshore exploration, disaster prevention, assisted navigation, distributed tactical surveillance, and mine reconnaissance, are envisioned.

There is a need to enable efficient communication protocols among underwater devices, to make underwater applications viable. Because of the high attenuation and scattering affecting radio and optical waves, respectively, these devices are based on acoustic wireless technology for distances over one hundred meters.

In our current work, Two bandwidth- and energy efficient distributed geographical routing algorithms are being proposed. These algorithms are designed to meet the requirements of delay-insensitive and delay-sensitive static underwater sensor network applications. The routing solutions proposed are tailored for the characteristics of the 3D underwater environment. When adopted communication protocols not specifically designed for this environment, these characteristics lead to a very low utilization of the underwater acoustic channel.

The rest of this paper is organized as follows. The suitability of existing ad hoc and sensor routing solutions for the underwater environment, and motivate the use of

Geographical routing are discussed in section II. The 3D communication architecture considered is focused in section III, and in Section IV, finally the two algorithms to solve the acoustic underwater channel misuse are proposed. And this is followed by the conclusion.

2. BACKGROUND WORK

An intensive study in routing protocols for terrestrial wireless ad hoc [9] and sensor networks [10] has been done in the last few years. The unique characteristics of the propagation of acoustic waves in the underwater environment have caused several drawbacks with respect to the suitability of existing terrestrial routing solutions for underwater networks. There are three categories of routing protocols, namely proactive, reactive, and geographical routing protocols. Network-layer protocols specifically designed for underwater acoustic networks are proposed in some recent work.

In [19], three versions of a reliable unicast protocol are proposed, which integrate Medium Access Control (MAC) and routing functionalities and exploit different levels of neighbor knowledge: no neighbor knowledge,) one-hop neighbor knowledge, and two-hop neighbor knowledge. The protocols, which rely on controlled broadcasting with no power control, have been compared in static as well as mobile scenarios in terms of different end-to-end networking metrics leading to the following conclusions: The three versions of the protocol outperform solutions that do not fully exploit neighbor knowledge in the design phase; In a static environment, no version is optimal for all the metrics considered; The higher the mobility, the lower the amount of information needed for making good routing decisions.

In [14], the problem of data gathering for three-dimensional underwater sensor networks tailored for long-term monitoring missions is investigated, with a particular emphasis to resiliency; while the provided routing solution is optimal, little reconfiguration is allowed in case of node mobility or channel state changes.

In [13], the authors have proposed a routing protocol that autonomously establishes the underwater network topology, controls network resources, and establishes network flows, which relies on a centralized network manager running on a surface station. The proposed mechanisms performance has not been thoroughly studied, although the idea is promising.

In [15], a vector-based forwarding routing is developed, which does not require state information on the sensors and only involves a small fraction of the nodes. The algorithm, however, does not consider applications with different requirements.

In [16], the authors investigate the delay-reliability trade-off for multihop underwater acoustic networks, and compare multi-hop versus single-hop routing strategies while considering the overall throughput. The analysis shows that increasing the number of hops improves both the achievable information rate and reliability.

In [17], the authors provide a simple design example of a shallow water network where routes are established by a central manager based on neighborhood information gathered from all nodes by means of poll packets. However, the authors do not describe routing issues in detail, nor do they discuss the criteria used to select data paths. Moreover, sensors are only deployed linearly along a stretch, and the characteristics of the 3D underwater environment are not investigated.

In [18], a long-term monitoring platform for underwater sensor networks consisting of static and mobile nodes is proposed, and hardware and software architectures are described. The nodes communicate point-to-point using a high-speed optical communication system and broadcast using an acoustic protocol. The mobile nodes, called mules, can locate and hover above the static nodes for data muling, and can perform useful network maintenance functions such as deployment, relocation, and recovery. However, due to the limitations of optical transmissions, communication is enabled only when the sensors and the mobile mules are in close proximity.

3. NETWORK MODELS AN ARCHETECTURE

This section, a communication architecture for three-dimensional underwater sensor networks is considered. We also conceder the network and propagation models to be used in the formulation of our routing algorithms. Three-dimensional networks can perform cooperative sampling of the 3D ocean environment, and are used to detect and observe phenomena that cannot be adequately observed by means of ocean bottom sensor nodes.

As a matter of fact, in three-dimensional underwater networks, underwater sensor nodes float at different depths to observe a given phenomenon. While the study of deployment strategies for 3D UW-ASNs are out of the scope of our work,

We represent this network as a directional graph $(\mathcal{V}, \mathcal{E})$, where $\mathcal{V} = \{v1, .., vN\}$ is a set of nodes in a 3D volume, with $N = |\mathcal{V}|$, and $\mathcal{E}$ is the set of directional links among nodes; $eij \in \mathcal{E}$ equals 1 if node vj is in the neighborhood of node vi, i.e., if vj can successfully decode packets transmitted by vi. Note that, eij and eji may not have the same value as underwater links may be asymmetric. Node vN (also N for simplicity) represents the sink, i.e., the surface station. Each link eij is associated with its distance dij [m], expected propagation delay $T\ q\ ij = dij/qij$ [s], where qij [m/s] is the acoustic propagation speed of link (i, j), and with the standard deviation of the propagation delay, $\sigma q\ ij$ [s]. In [21], the underwater acoustic propagation speed (z, s, t) [m/s] is modeled as,

$$\begin{aligned} q(z,s,t) = 1449.05 + 45.7 \cdot t - 5.21 \cdot t^2 + 0.23 \cdot t^3 + \\ +(1.333 - 0.126 \cdot t + 0.009 \cdot t^2) \cdot (s - 35) + \\ +16.3 \cdot z + 0.18 \cdot z^2, \end{aligned} \quad (1$$

4. PROPOSED WORK

In this section, a distributed geographical routing solution for delay-insensitive underwater applications is introduced. The Proposed routing solution aims to efficiently exploit the underwater acoustic channel and to minimize the energy consumption

$\mathbf{P}^{\text{dist}}_{\text{insen}}$: **Delay-insensitive Distributed Routing at Node** i

Given (offline): $L^*_P, L^H_P, E^b_{elec}, r, P^{TX}_{i,max}$

Computed (online): $\mathcal{S}_i, \mathcal{P}^N_i, \hat{\Lambda}_{0j}$

Find: $j^* \in \mathcal{S}_i \cap \mathcal{P}^N_i,\ P^{TX}_{ij^*}{}^* \in [0, P^{TX}_{i,max}],\ L^{F*}_{Pij^*}$

Minimize:
$$E^{(j)}_i = E^b_{ij} \cdot \frac{L^*_P}{L^*_P - L^H_P - L^F_{Pij}} \cdot \hat{N}^{TX}_{ij} \cdot \hat{N}^{Hop}_{ij} \quad (5)$$

Subject to:

(Relationships)

$$E^b_{ij} = 2 \cdot E^b_{elec} + \frac{P^{TX}_{ij}}{r}; \quad (6)$$

$$L^F_{Pij} = \Psi^{\mathcal{F}^{-1}}\left(L^*_P, PER_{ij}, \Phi^{\mathcal{M}}\left(\frac{P^{TX}_{ij}}{\hat{\Lambda}_{0j} \cdot r \cdot TL_{ij}}\right)\right); \quad (7)$$

$$\hat{N}^{TX}_{ij} = \frac{1}{1 - PER_{ij}};\ \hat{N}^{Hop}_{ij} = \max\left(\frac{d_{iN}}{< d_{ij} >_{iN}}, 1\right). \quad (8)$$

The proposed routing solution – as a summarize - allows node i to select as next hop that node $j*$ among its neighbors that satisfies the following two requirements: it is closer to the surface station than i, and it minimizes the link metric $(j)*$. While this heuristic approach does not guarantee global optimality as a sender does not have a global view of the network, it achieves the 'best' possible performance given the limited information at the sender.

As of the same with the delay-insensitive algorithm, is being proposed to select in a distributed manner, and this has two constraints. The end-to-end packet error rate should be lower than an application-dependent threshold; The probability that the end-to-end packet delay be over a delay bound $Bmax$, should be lower than an application-dependent parameter γ.

$\mathbf{P}^{\text{dist}}_{\text{sen}}$: **Delay-sensitive Distributed Routing at Node** i

Given (offline): $L^*_P, L^H_P, M = \lfloor \frac{L^*_T - L^H_T}{L^*_P} \rfloor, E^b_{elec}, r, P^{TX}_{i,max}$

Computed (online): $\mathcal{S}_i, \mathcal{P}^N_i, \hat{\Lambda}_{0j}, \Delta B^{(m)}_i, \hat{Q}_{ij}$

Find: $j^* \in \mathcal{S}_i \cap \mathcal{P}^N_i,\ P^{TX}_{ij^*}{}^* \in [0, P^{TX}_{i,max}],\ L^{F*}_{Pij^*}$

Minimize:
$$E^{(j)}_i = E^b_{ij} \cdot \frac{L^*_P}{L^*_P - L^H_P - L^F_{Pij}} \cdot \hat{N}^{Hop}_{ij} \quad (10)$$

Subject to:

(Relationships)

$$E^b_{ij} = 2 \cdot E^b_{elec} + \frac{P^{TX}_{ij}}{r}; \quad (11)$$

$$L^F_{Pij} = \Psi^{\mathcal{F}^{-1}}\left(L^*_P, PER_{ij}, \Phi^{\mathcal{M}}\left(\frac{P^{TX}_{ij}}{\hat{\Lambda}_{0j} \cdot r \cdot TL_{ij}}\right)\right); \quad (12)$$

$$\hat{N}^{Hop}_{ij} = \max\left(\frac{d_{iN}}{< d_{ij} >_{iN}}, 1\right); \quad (13)$$

(Constraints)

$$1 - \left(1 - PER_{ij}\right)^{\lceil \hat{N}^{Hop}_{ij} \rceil} \leq PER^{e2e}_{max}; \quad (14)$$

$$\frac{\bar{d}_{ij}}{\bar{q}_{ij}} + \delta(\gamma) \cdot \sigma^q_{ij} \leq \min_{m=1,\ldots,M}\left(\frac{\Delta B^{(m)}_i}{\hat{N}^{Hop}_{ij}}\right) - \hat{Q}_{ij} - \frac{L^*_P}{r}. \quad (15)$$

The new notations used in the delay-sensitive problem formulation are described as below:

$M = \lfloor (L^*_T - L^H_T)/L^*_P \rfloor$

is the fixed number of packets transmitted in a train on each link,

PER^{e2e}_{max} :

are the application-dependent end-to-end packet error rate and delay bounds

$\Delta B^{(m)}_i = B_{max} - [t^{(m)}_{i,now} - t^{(m)}_0]$ [s]

is the time-to live of packet m arriving at node i,

$T_{ij} = L^*_P/r + T^q_{ij}$ [s]

accounts for the packet transmission and propagation delay associated with link (i, j), as described in Sect. III; according to easurements on underwater channels reporting a symmetric delay distribution of multipath rays [5], we consider a Gaussian distribution

By substituting (17) into (16), and by assuming a Gaussian distribution for T, (16) can be rewritten as

$$\Pr\left\{T_{ij} \geq \frac{\Delta B^{(m)}_i}{\hat{N}^{Hop}_{ij}} - \hat{Q}_{ij}\right\} =$$
$$= \frac{1}{2}\left[1 - erf\left(\frac{\frac{\Delta B^{(m)}_i}{\hat{N}^{Hop}_{ij}} - \hat{Q}_{ij} - \overline{T_{ij}}}{\sqrt{2} \cdot \sigma^q_{ij}}\right)\right] \leq \gamma, \quad (19)$$

where the $erf()$ function is defined as $erf(\Gamma) = \frac{2}{\sqrt{\pi}} \cdot \int_0^\Gamma e^{-t^2} dt$. Because $\overline{T_{ij}} = L^*_P/r + \overline{T^q_{ij}}$, and $\overline{T^q_{ij}} = \bar{d}_{ij}/\overline{q_{ij}}$, (19) simplifies to

$$\frac{\bar{d}_{ij}}{\overline{q_{ij}}} + \delta(\gamma) \cdot \sigma^q_{ij} \leq \frac{\Delta B^{(m)}_i}{\hat{N}^{Hop}_{ij}} - \hat{Q}_{ij} - \frac{L^*_P}{r}, \quad (20)$$

5. SIMULATION AND RESULTS

The simulation performance of the proposed routing solutions for delay-insensitive and delay-sensitive UWASN applications is presented here.

TABLE I
SIMULATION PARAMETERS FOR SCENARIOS 1,2, AND 3

	Scen. 1	Scen. 2	Scen. 3
App. Type [Delay-]	insensitive	insensitive	sensitive
Traffic Type	background	event	event
No. of Sources	100	15	15
Volume [Km^3]	.1x.1x.1	.5x.5x.05	.5x.5x.05
Packet Size [KByte]	.5	.5	.1
Source Rate [Kbps]	.01	.15, .3, .6	.15, .3, .6
Max. TX Power [W]	.5	5	5

The wireless package of the J-Sim simulator [25] is extended, which implements the whole protocol stack of a sensor node, to simulate the characteristics of the 3D underwater environment. We modeled the underwater transmission loss, the transmission and propagation delays of vertical and horizontal links, and the physical layer characteristics of underwater receivers.

And then, we tuned all the parameters of IEEE 802.11 according to the physical layer characteristics. For example, the value of the slot time in the 802.11 back off mechanism has to account for the propagation delay at the physical layer[26].

Three sets of experiments to analyze the performance of the proposed routing solutions are performed. In table I, we summarized the main parameters differentiating the three experimental scenarios, while the common parameters are reported hereafter: 100 sensors are randomly deployed in a 3D volume, the initial node energy is set to 1000 J, and the available bandwidth is 50 kHz.

In Table II, we present the average number of hops and the standard deviation of the number of hops (computed among all the nodes in the network) when the different link metrics are used. In the table, we also provide the 95% confidence intervals associated with both measurements; these intervals are computed across multiple simulation runs for statistical purpose.

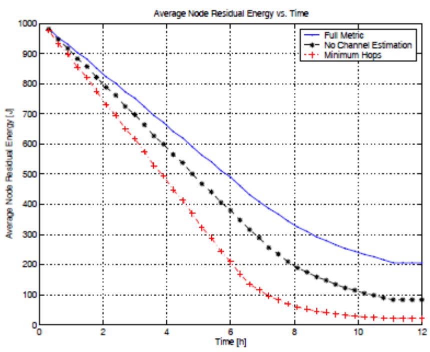


Fig. 2. **Scenario 1: Delay-insensitive routing.** Average node residual energy vs. time, for different link metrics.

TABLE II
SCENARIO 1- DELAY-INSENSITIVE ROUTING: AVERAGE AND STANDARD DEVIATION OF NO. OF HOPS (WITH CONFIDENCE INTERVALS)

	Full Metric	No Channel	Min. Hops
Average	2.3 ± 1.1	1.2 ± 0.3	1.2 ± 0.3
Std	1.3 ± 0.2	0.4 ± 0.2	0.2 ± 0.1

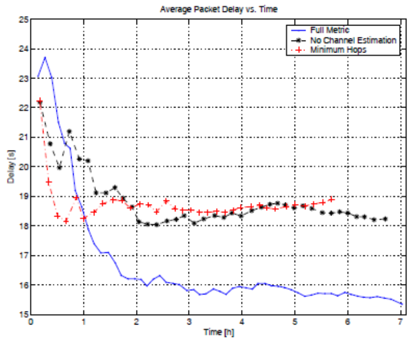
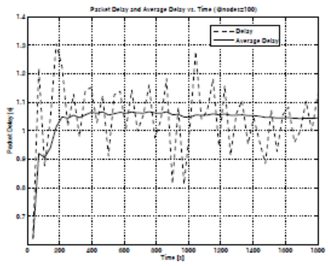


Fig. 3. **Scenario 1: Delay-insensitive routing.** Average packet delay vs. time, for different link metrics.

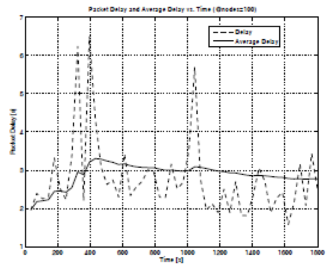
A lower number of packet transmissions is to be expected as the full metric takes the state of the underwater channel into account. Hence, next hops associated with better channels are selected. This, in turn, reduces the average queuing delays as packets are less likely to be retransmitted. By comparing the path lengths and the average end-to-end packet delay results, we can conclude that when our full link metric is adopted (i.e., the Full Metric), packet delays are smaller than with the other metrics, although the data paths chosen are longer.

6. CONCLUSION

We have investigated, the problem of data gathering in a 3D underwater acoustic sensor network by considering the interactions between the routing functions and the signal propagation characteristics in the underwater environment.



(a)



(b)

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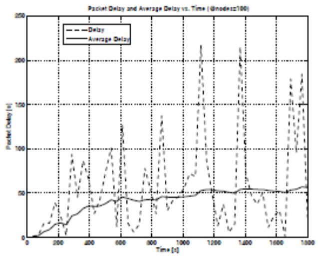


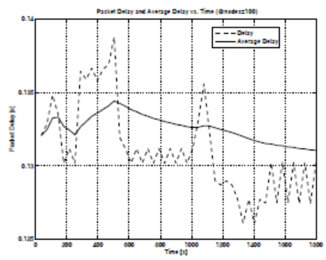
(c)

Fig 4: Scenario 2: Delay-insensitive routing. Packet delay and average delay vs. time for three source rates. (a): Source rate equal to 150 bps; (b): Source rate equal to 300 bps; (c): Source rate equal to 600 bps.

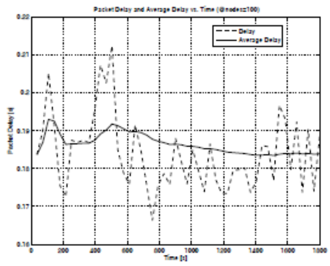
We then proposed 2 distributed geographical routing algorithms for delay-insensitive and delay-sensitive applications were introduced and evaluated through simulations; their objective is to minimize the energy consumption.

TABLE III
SCENARIOS 2 AND 3: SURFACE STATION AND NODE AVERAGE ENERGY EXPENDITURE PER BIT [μJ/bit] (WITH CONFIDENCE INTERVALS)

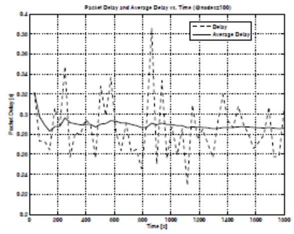
Source Rate [bps]	150	300	600
Scen. 2. Surface Station	8 ± 1.4	6.5 ± 0.9	7.5 ± 1.2
Scen. 2. Node Average	7 ± 1.0	4 ± 0.6	5.5 ± 0.8
Scen. 3. Surface Station	21 ± 3.1	17 ± 2.7	18 ± 2.9
Scen. 3. Node Average	9 ± 1.4	6 ± 0.8	5 ± 0.6



(a)



(b)



(c)

Fig. 5. **Scenario 3: Delay-sensitive routing.** Packet delay and verage delay vs. time for three source rates. (a): Source rate equal o 150 bps; (b): Source rate equal to 300 bps; (c): Source rate equal to 600 bps.

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