DRDC-RDDC-2014-P143

Location-free Link State Routing for Underwater Acoustic Sensor Networks

Michel Barbeau, Stephane Blouin, Gimer Cervera, Joaquin Garcia-Alfaro and Evangelos Kranakis

***Abstract*— We propose a location-free link state routing protocol for Underwater Acoustic Sensor Networks (UASNs). Additionally, we present the mathematical background for the theoretical capacity and transmission power metrics of an underwater acoustic channel. UASNs are formed by devices enabled with acoustic communication capabilities that are deployed underwater to perform collaborative monitoring tasks. Information is collected by a sink at the surface also equipped with a radio. The underwater communication channel is characterized by a limited bandwidth and high propagation delay. The network topology constantly changes due to mobility of the nodes. In our routing protocol, every node ranks the quality of the path that it offers toward the sink. Packet forwarding is performed hop-by-hop considering one or several routing metrics, e.g., hop count or pressure. To avoid communication void problems, every node selects a one-hop neighbor within an area that guarantees progress toward a sink. Our strategy is loop-free. It includes a recovery mode handling network topology changes. Our routing protocol was implemented in *ns*-3 to conduct experiments.**

I. INTRODUCTION

Underwater Acoustic Sensor Networks (UASNs) consist of devices enabled with acoustic communication capabilities that are deployed underwater at different depths to perform collaborative monitoring tasks [1]. Underwater nodes gather and send information to a sink that is also equipped with a radio to communicate with other network components located on the surface. We present a location-free routing protocol designed for UASNs. Research in UASNs focuses on both physical and link layers [2], [3], whereas research on the network layer is still in an early stage. The design of an efficient routing mechanism should consider the limitations of the medium. The underwater acoustic channel is characterized by a high bit error rate, low data rate and large propagation delay. Underwater routing protocols must be energy-aware since the deployment and maintenance of underwater devices are particularly difficult. UASNs are formed by nodes in constant motion that leads to continuous changes in the network topology.

Electromagnetic and optical waves do not work well underwater due to the nature of the medium, especially in the case of seawater. Acoustic waves are used for underwater communication due to the relatively low attenuation (i.e., signal reduction) of sound in water, specially in thermally stable, deep water settings. In shallow water, acoustic waves are severely affected by temperature, site specific noise and multipath propagation due to reflection and refraction. The speed of sound in water varies according to the depth and is affected by temperature, salinity and pressure. The speed of acoustic waves is about 1500 m/s [4] close to the ocean surface, which is more than four times faster the speed of sound in air, but five orders of magnitude smaller than the speed of light [5]. Compared with electromagnetic and optical waves in terrestrial networks, the speed of acoustic waves is significantly lower. As a consequence, underwater channel communication is also affected by a severe Doppler effect.

The characteristics of the underwater acoustic communication channel require new efficient and reliable data communication protocols. Underwater communication is characterized by a path loss (i.e., path attenuation) that depends not only on the distance between the transmitter and receiver, but also on the signal frequency [2]. Low frequency waves (e.g., below 10 kHz) are effective for long-range communication [5]. Bandwidth for underwater communication is typically in the order of kHz. Routing protocols for ad hoc networks are not suitable for underwater communication. Proactive routing protocols require a constant exchange of control information to keep the routing information up to date. In reactive approaches, the route discovery process is affected by an increased delay.

Several routing protocols in UASNs are based on a greedy hop-by-hop method for packet delivery [6]. Unlike the end-to-end routing, greedy hop-by-hop routing approaches select as next hop those one-hop neighbors that have positive progress toward the sink. Greedy routing protocols do not guarantee to find a path toward the sink, e.g., data packets reach a node with no positive progress. This problem is known as *communication void*. Routing protocols for UASsN can be classified as *location-based* or *location-free*. Location-based approaches assume that nodes know both their geographical position and the sink position. As a main drawback, finding the location information of nodes is a main challenge due to the inapplicability of GPS under the water. Location-free approaches can be divided in the pressure-based and beacon-based categories. In pressure-based routing protocols, the depth information

M. Barbeau and E. Kranakis are with School of Computer Science, Carleton University, Ottawa, ON, Canada K1S 5B6, {barbeau,kranakis}@scs.carleton.ca
S. Blouin is with Defence R&D, Canada-Atlantic, Dartmouth, NS, Canada, B2Y 3Z7, Stephane.Blouin@drdc-rddc.gc.ca
G. Cervera is with Universidad Tecnológica Metropolitana, Merida, Yuc., Mexico, 97279, gimer.cervera@utmetropolitana.edu.mx
J. Garcia-Alfaro is with Telecom SudParis, CNRS Samovar, Evry, France, UMR 5157, joaquin.garcia-alfaro@acm.org

(i.e., pressure) is used to identify the positive forwarding area. Beacon-based approaches implement beacon messages with information to reach the sink, e.g., distance in hops. Greedy routing protocols in UASNs do not consider the quality of the links. In our location-free link state routing approach, every node ranks the quality of the path that it offers toward a sink. Packet forwarding is performed hop-by-hop. Every node selects a one-hop neighbor with the lowest hop count toward a sink. If there is a tie, then the one-hop neighbor with the best quality path toward a sink is selected. If the tie persists, then the neighbor with lowest pressure is selected. Our strategy is loop-free. It includes a recovery mode handling network topology changes. Our location-free routing protocol was implemented in *ns*-3. The UAN model developed by L. Tracy was adapted to interact with our routing protocol.

Organization of the paper — Section II describes the related work. Section III describes an example of the routing metric calculation in UASNs. Our location-free routing protocol is presented in Section IV. Section V presents our experiments and results. Section VI concludes the paper.

II. RELATED WORK

In this section we present greedy routing protocols designed for UASNs. We divide this section into location-based and location-free routing protocols.

A. Location-based routing in UASNs

In the location-based category it is assumed that nodes know their geographical position. Nodes also know the location of the sink. Using this information, a data packet sender establishes the conditions to reach the forwarders with positive progress toward the sink. The sender computes an area, i.e., a cone [7], pipeline [8] or a zone, to select the forwarders. Receivers within this area retransmit the data packet until it reaches the sink. The size of the forwarding area has a direct impact on the performance of the network. If the size is too big, then more nodes retransmit the packets increasing the network overhead and the overall energy consumption. If the size is too small, then the probability of having a communication void problem increases.

The Vector-Based Forwarding (VBF) [8] proposed by Xie et al., is a greedy location-based routing protocol designed for UASNs. Every node knows its own location and the sink location. Originators of packets create an imaginary vector to the sink with a predefined radius, e.g. node A. Information about the vector is included in the packets. Receivers use the radius information as a threshold. If their distance to the vector is less than the radius, then they are allowed to retransmit the packet. The protocol was designed to address the constant movement of nodes and energy consumption. VBF does not consider the communication void problem. The Hop-by-Hop VBF (HH-VBF) routing protocol is an enhanced version of VBF proposed by Nicolaou et al. in [9]. The protocol attempts to reduce the probability of communication void problem in sparse networks. In HH-VBF every forwarder computes its own pipeline toward the sink. This increases the chances of finding nodes with positive progress to the sink. The Focused Beam Routing (FBR), protocol is a location-based routing protocol proposed by Stojanovich et al. in [7]. The protocol considers nodes with different power levels in order to compute the forwarding area. FBR is considered a cross-layer routing protocol. FBR uses a finite number of predefined power levels, i.e., $P_1, P_2, \ldots, P_n$, where P_n is the highest power level. A sender of a data packet computes a cone with angle θ toward the sink. The radius size of the cone is determined by the power level, i.e., P_i. A request to send (RTS) message is generated by the sender. Receivers within the cone replay with a clear to send (CTS) message including its ID and location. The sender selects the closest node to the sink as a forwarder. Every node repeats the same procedure until the packet reaches the sink. If the sender does not receive any CTS message using a power level P_i, then it increases the power level, i.e., P_{i+1}, until a neighbor node is found or the power level is P_n. If there is no neighbor node inside the cone computed with power level P_n, then the cone can be rotated until finding a neighbor node. The performance of FBR relies on the selected angle θ. The angle should be wide enough in sparse networks in order to avoid a communication void. In dense networks, the angle θ should be small enough to reduce overhead and energy consumption.

B. Location-free routing in UASNs

In the location-free category, nodes are not fully aware of their geographical position. Instead, they use other information such as depth or hop-count to route a data packet to the sink. This category can be divided in two subcategories: *beacon-based* and *pressure-based*. In the beacon-based subcategory, every node periodically broadcasts beacon messages in order to provide dynamic information for identifying positive progress toward the sink. In the pressure-based subcategory, only depth information measured locally by pressure sensors is used to identify a positive progress area toward the sink.

Depth-based routing (DBR) [10] is the first location-free greedy hop-by-hop routing protocol designed for UASNs. DBR assumes multiple sinks and nodes equipped with a pressure sensor to calculate their depth. The routing approach is as follows. Every sender broadcasts a data packet including a packet sequence number and its depth information. One-hop neighbors with lower depth value are candidates to forward the packet toward the sink. Receivers compute a *holding time* based on its depth before retransmitting. In order to reduce overhead caused by redundant packet transmission, every forwarder computes a different holding time. The closest node to the surface retransmits the packet first. Receivers reject a data packet either if it arrives from a node with lower depth or if it has been processed. DBR handles the constant movements of nodes but does not tackle the communication void problem.

III. CAPACITY AND POWER METRICS IN UASNs

We developed the mathematical background for the theoretical capacity and transmission power metrics of an underwater acoustic channel. Both capacity and power depend on attenuation and noise.

A. Attenuation and Noise

For an underwater acoustic channel, attenuation and noise are frequency dependent. For attenuation, we use the model of Thorp [11]. An underwater acoustic signal is attenuated during propagation. There are two main causes: conversion of acoustic energy into heat and geometrical spreading loss. Conversion of acoustic energy into heat is proportional to the frequency of the signal. Geometrical spreading component captures the fact that as sound wave travels away, the distance from the source increases. The surface covered covered by the waves expands. The sound energy intensity drops. These factors are represented in the Thorp model [2]:

$$A(d,f)_{dB} = k \cdot 10 \log d + d \cdot a(f) \tag{1}$$

where d is the transmitter-receiver separation distance (in km), k is a geometrical spreading loss exponent (with values in the interval $[1,2]$), f is frequency (in kilo Hertz), and $a(f)$ is a frequency-dependent absorption coefficient (in dB/km). The geometrical spreading loss exponent depends on the geometry of propagation, which can be cylindrical (1), spherical (2) or *practical* (1.5). For a frequency f above a few hundred Hertz, the absorption coefficient can be determined using the equation:

$$a(f)_{dB/km} = \frac{0.11 \cdot f^2}{1+f^2} + \frac{44 \cdot f^2}{4100+f^2} + 2.75 \cdot 10^{-4} \cdot f^2 + 0.003 \tag{2}$$

otherwise the following equation can be used:

$$a(f)_{dB/km} = 0.002 + \frac{0.11 \cdot f^2}{1+f^2} + 0.011 \cdot f^2 \tag{3}$$

There are two main kinds of noise affecting underwater acoustic communications: site-specific noise and ambient noise. Sources of site-specific noise are geographically dependent. They include noise made by breaking ice and sea creatures. Four sources of ambient noise have been identified: turbulence, shipping, waves and thermal. Ambient noise is approximated using the following equation [12]:[1]

$$N(f)_{\text{dB re } \mu \text{ Pa per Hz}} = 50 - 18 \cdot \log f \tag{4}$$

Alternatively, equations do exist modeling turbulence, shipping, waves and thermal noise, individually [12]. The resulting ambient noise is the sum of the evaluation of all of them. The three-dimensional surface of Fig. 1 shows the attenuation-noise (AN) product (in dB form) as a function of frequency, measured in k Hertz, and distance, in km. For each distance, there is a frequency where the attenuation-noise product reaches a minimum. This is the frequency where communication conditions are optimal for that distance.

[1]The term *re μ Pa* stands for *reference pressure 1 micropascal*. The *pascal* is a unit of force per unit area, i.e., pressure. It is equal to one newton per square meter.

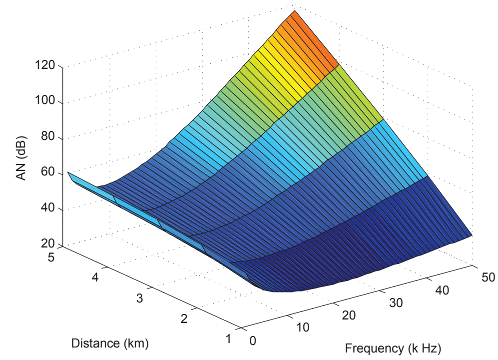


Fig. 1: Attenuation-noise (AN) product, in dB re μ Pa, versus frequency, in Hertz, and distance, in km.

B. Capacity and Power Calculation

There are two methods for estimating the bandwidth of an underwater acoustic channel [2]. The first is called *3 dB bandwidth*. Among the available bandwidth, it finds the optimal frequency, i.e., with minimum attenuation-noise product. The Signal-to-Noise-Ratio (SNR) is determined for that frequency. The lower and upper sidebands are included, while the SNR stays below two times the minimum attenuation-noise product. This method has been implemented by Harris and Zorzi for NS2 [13]. The *3 dB bandwidth* method does not guarantee optimality. Stojanovic describes a second method called *optimal* [2]. This method calculates the bandwidth according to a required SNR_0, e.g., 20 dB. As a function of frequency, the transmission power is distributed and adapted to the estimated attenuation and noise in the channel. Let $A(d,f)$ denote the attenuation, in linear form, as a function of distance d, in km, and frequency f, in kilo Hertz. Let $N(f)$ denote the noise, in μ Pa per Hertz, as a function of frequency. Let $P(f)$ denote the transmission power, in μ Pa per Hertz, as a function of frequency. According to the *water-filling principle* [14], at distance d, channel capacity is maximized (with respect to bandwidth) when the following equality holds:

$$P(f) = K - A(d,f)N(f) \tag{5}$$

In the sequel, K is called the *water-filling constant*. The *optimal* method determines the actual value of this constant. The *optimal algorithm* is as follows. Within the total channel bandwidth, the optimal frequency is identified. The optimal frequency f_{opt} is where the attenuation-noise product $A(d,f)N(f)$ is minimal. The value of the *water-filling constant* K is initialized at a value slightly above the attenuation-noise product at the optimal frequency, i.e., K is set to the product $1.01 \cdot A(d,f_{opt})N(f_{opt})$. The following procedure is executed repeatedly. Within the total available bandwidth, the sub-band, around frequency f_{opt} where the product $A(d,f)N(f)$ is lower than or equal to K is determined. Let us assume that this sub-band extends from f_{min} to f_{max}, with $f_{min} \leq f_{opt} \leq f_{max}$. Assuming that the power is distributed according to Equation 5, we have that

$$SNR = \frac{\int_{f_{min}}^{f_{max}} P(f)A(d,f)^{-1}df}{\int_{f_{min}}^{f_{max}} N(f)df}. \tag{6}$$

Substituting $K - A(d,f)N(f)$ for $P(f)$ (Equation 5), we get

$$SNR = K \cdot \frac{\int_{f_{min}}^{f_{max}} A(d,f)^{-1}df}{\int_{f_{min}}^{f_{max}} N(f)df} - 1. \tag{7}$$

If the SNR is lower than SNR_0, then the *water-filling constant* K is augmented using a multiplicative factor, e.g., the *new* K is $1.01 \cdot K$. When the SNR is greater than or equal to SNR_0, the procedure stops.

The channel capacity is

$$C_{\text{bps}} = \int_{f_{min}}^{f_{max}} \log_2\left(\frac{K}{A(d,f)N(f)}\right) df. \tag{8}$$

The transmission power is

$$P_{\mu \text{ Pa}} = \int_{f_{min}}^{f_{max}} P(f)df. \tag{9}$$

Substituting $K - A(d,f)N(f)$ for $P(f)$ (Equation 5), we get

$$P_{\mu \text{ Pa}} = K\cdot(f_{max}-f_{min}) - \int_{f_{min}}^{f_{max}} A(d,f)N(f)df. \tag{10}$$

IV. LOCATION-FREE ROUTING FOR UASNs

We present a new location-free UASN routing protocol. For the purposes of packet forwarding in the direction of the sink, every node selects a next hop according to link-state metrics. Figure 2 depicts an example. To prevent communication voids, the next hop is selected such that progress toward a sink, S in Figure 2, is guaranteed. It is assumed that nodes are equipped with pressure measurement sensors and have the same transmission range. Every node ranks the quality of the path that it offers toward the sink. Path quality is a metric that evaluates redundancy of routes. Every node generates beacon messages that include hop count, path quality toward a sink and pressure. Sinks generate beacon messages with path quality equal to one and hop count and pressure equal to zero. For an underwater node, the initial path quality is equal to zero. The steps to send a beacon message are illustrated in function SendBeacon. Upon receiving a beacon message, the receiver updates its path quality and hop count state. Function ReceiveBeacon illustrates the steps to process a beacon message. In Figure 2, arcs are labeled with beacon messages, parameterized with hop count (hc), path quality (pq) and pressure (pr). Beacon messages are tagged in the order they were generated. For instance, S starts generating beacon messages with hop count equal to zero, path quality equal to one and its pressure value, i.e., [0, 1, pr_S]$^{(1)}$. After receiving the beacon message from sink S, underwater nodes v_a and v_b generate a new beacon message with path quality and hop count equal to one. The one-hop neighbor with lowest hop count value is selected as next hop for packet forwarding. In case of a tie, the greatest path quality neighbor is selected. If the tie persists, then the lowest pressure neighbor is selected. Function SelectNextHop illustrates the steps to select the next hop. Initially, nodes v_a and v_b generate beacons with zero path quality and *null* hop count. After receiving the message from S, both update their state. Node v_a generates beacon message [1, 1, pr_a]$^{(2)}$. Node v_b produces [1, 1, pr_b]$^{(3)}$. Node v_d receives beacon messages from both v_a and v_b. The path quality of v_d becomes two, i.e., the sum of the path quality of neighbors v_a and v_b. Assuming that it has the lowest pressure, node v_d selects v_a for packet forwarding. It is the neighbor closest to the surface. To reach the sink, v_g has two equal hop count options: v_d and v_e. Node v_d is selected because it has the highest path quality. The routing protocol is loop-free and comprises a recovery mode handling network topology changes, e.g., when links are broken.

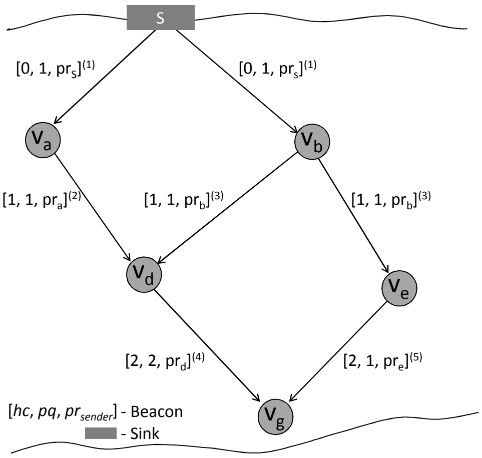


Fig. 2: Beacon messages include: *hop count (hc), path quality (pq)* and *pressure (pr)*.

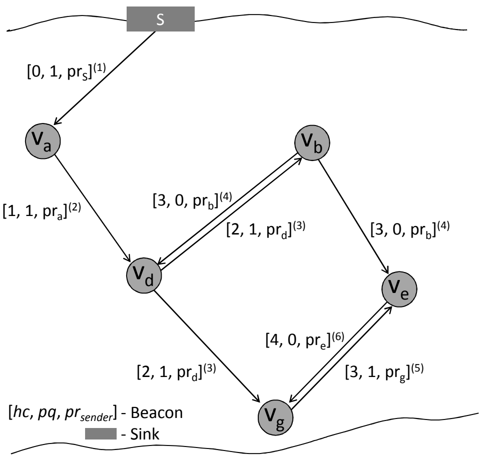


Fig. 3: Recovery Mode.

Function SendBeacon(v)

Compute pressure, i.e., $pr_v \leftarrow Pressure(v)$;
if *(v is a sink)* **then**
  Hop count is equal to zero, $hc \leftarrow 0$;
  Path quality is equal to one, $pq \leftarrow 1$;
else
  Select next hop, $NextHop \leftarrow SelectNextHop(v)$;
  Get its hop count, $hc \leftarrow HopCount(NextHop)$;
  if *(Hop count is equal to null)* **then**
    Path quality is equal to zero, $pq \leftarrow 0$;
  else
    Get path quality of v, $pq \leftarrow PathQuality(v)$;
    Increase hop count by one, $hc \leftarrow hc + 1$;
v generates a new beacon message, $[hc, pq, pr_v]$;

Function SelectNextHop(v) $\rightarrow$ $NextNode$

Initialize the set $nNodes$ as empty set, $nNodes \leftarrow \emptyset$;
Select among the one-hop neighbors of v, $N_1(v)$, the lowest hop count neighbor, $nNodes \leftarrow lowestHopCount(N_1(v))$;
if *(there is a tie, $|nNodes| > 1$)* **then**
  Select the highest path quality neighbor, $nNodes \leftarrow highestPathQuality(nNodes)$;
  if *(the tie persists, $|nNodes| > 1$)* **then**
    Select the lowest pressure neighbor, $nNodes \leftarrow lowestPressure(nNodes)$;
$NextNode \leftarrow GetFirst(nNodes)$;
return $NextNode$;

A. Communication void and Recovery Mode

In UASNs the network topology changes very frequently. As a consequence, some paths might become broken. For instance, suppose that in Figure 3, the link (v_b,S) is broken. Nodes generate beacon messages according to the network topology changes. The first goal is to avoid communication void problems. Nodes must be aware that v_b has lost communication with the sink. Therefore, v_b generates beacon messages with a path quality value equal to zero and hop count equal to infinity. v_b accepts beacon messages from v_d because it has the lowest hop count value. v_b updates its hop count toward the sink and generates beacon messages with a path quality value equal to zero. Receivers update their local information about the network topology and select as next hop, nodes in an area without communication voids. For instance, v_g and v_b select v_d as the next hop to reach the sink. The second goal is to provide a mechanism to find new routes to reach a sink when the network topology changes, i.e., a recovery mode. For instance, v_e has two one-hop neighbors with the same hop count toward the sink, i.e., v_b and v_g. v_e selects v_g as next hop because it has the highest positive degree value.

Function ReceiveBeacon(v, $[hc, pq, pr_s]$)

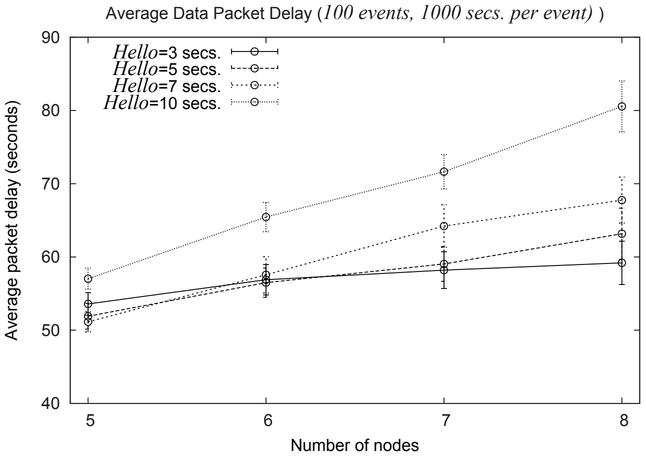
v receives a beacon message from sender s and updates its one-hop neighbor table,
$N_1(v) \leftarrow Update(N_1(v), [hc, pq, pr_s])$;
SendBeacon(v);

TABLE I: Parameter settings.

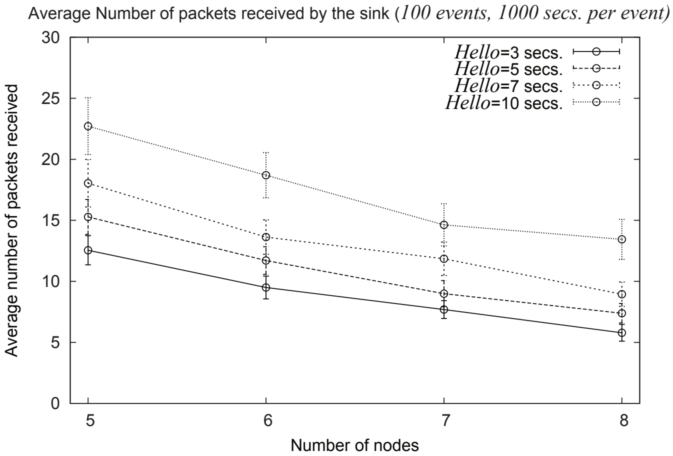
Parameter	Value
Simulation Time	1000 seconds
Number of events	100
Number of nodes	5-8
Data rate	80bps
Transmit power	160 dB re μ Pa
Minimum SINR	80dB
Neighbor holding time	100seconds
Transmission range	50m
Volume	$100m^3$

V. EXPERIMENTS AND RESULTS

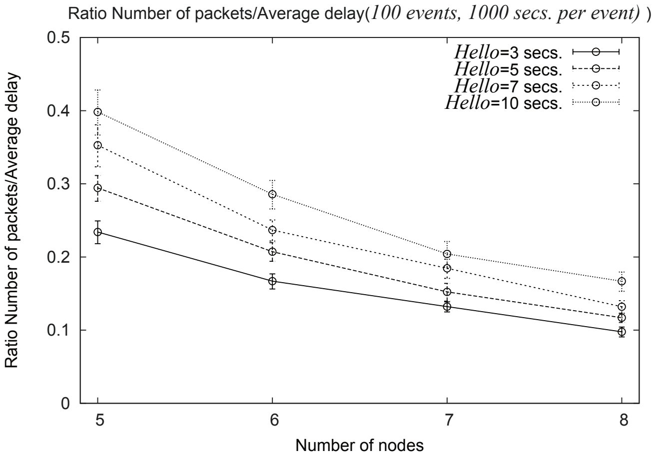
We conducted our experiments using the *ns*-3 simulator [15], version 3.21 and the UAN model developed by L. Tracy. The UAN model was adapted to interact with our routing protocol. Table I describes the parameter we used in our simulations. In every experiment, nodes are randomly distributed in a tree-dimensional space of $100m^3$. We simulate scenarios with five to eight nodes plus the sink. Every node has a transmission power of 160 dB re μ Pa and a minimum signal-to-interference-plus-noise-ratio (SINR) equal to $80dB$. The maximum transmission range is 50 meters and the data rate is 80bps. We simulate every scenario during one thousand seconds (i.e. an event), after this time, we update the position of every node. The sink is static. We execute one hundred events per experiment. We use the end-to-end delay and number of data packets received by the sink as metrics to evaluate the performance of our routing protocol. Nodes generate data packets addressed to the sink every five seconds. Figure 4 shows our results with 95% confidence intervals. Figure 4a plots the average data packet delay. The hello messages interval varies from three to ten seconds. Figure 4b shows the amount of data packets received by the sink. Figure 4c presents the ratio between the average data packet delay and the amount of information received at the sink. According to our results, the data packet delay is lower when nodes generate hello messages every three seconds. Nevertheless, the number of data packets received at the sink is the lowest due to the increased amount of control traffic in the network, as shown in Figure 4b. If the nodes increase the hello message interval, then links with neighbor nodes are more likely to be lost. Figure 4c shows that if we tune the hello messages interval equal to ten seconds, then we obtain the best trade-off between control traffic and number of packets received at the sink.



(a) Average data packet delay.



(b) Average amount of data packets received by the sink.



(c) Ratio between the amount of data packets received at the sink and the data packet delay

Fig. 4: Experiments and results.

VI. Conclusions

We presented a location-free link state routing protocol for UASN. Our approach considers the characteristics of the communication channel to avoid communication void problems. Every node ranks the quality of the path that it offers toward the sink and generates beacon messages that include hop count, path quality toward a sink and pressure. Every node selects as next hop, a one-hop neighbor with the lowest hop count value as next hop for packet forwarding. In case of a tie, the greatest path quality node is selected. If the tie persists, then the lowest pressure node is selected. Our strategy is loop-free and comprises a recovery mode that kicks in when network topology changes. We implemented our routing protocol in *ns*-3 to conduct experiments.

VII. Acknowledgments

The authors graciously acknowledge the financial support received from the following organizations: PWGSC contract # W7707–145688, Natural Sciences and Engineering Research Council of Canada (NSERC), Spanish Ministry of Science (project TIN2011-27076-C03-02 CO-PRIVACY) and Ministry of Education of Mexico (SEP–PRODEP).

References

[1] D. Pompili, T. Melodia, and I. Akyildiz, "Distributed routing algorithms for underwater acoustic sensor networks.," *IEEE Transactions on Wireless Communications*, vol. 9, pp. 2934–2944, September 2010.

[2] M. Stojanovic, "On the relationship between capacity and distance in an underwater acoustic communication channel," *SIGMOBILE Mob. Comput. Commun. Rev.*, vol. 11, pp. 34–43, Oct. 2007.

[3] D. Pompili and I. Akyildiz, "A multimedia cross-layer protocol for underwater acoustic sensor networks," *Wireless Communications, IEEE Transactions on*, vol. 9, pp. 2924–2933, September 2010.

[4] M. Stojanovic and J. Preisig, "Underwater acoustic communication channels: Propagation models and statistical characterization," *Communications Magazine, IEEE*, vol. 47, pp. 84–89, January 2009.

[5] L. Lanbo, Z. Shengli, and C. Jun-Hong, "Prospects and problems of wireless communication for underwater sensor networks," *Wirel. Commun. Mob. Comput.*, vol. 8, pp. 977–994, Oct. 2008.

[6] M. T. Kheirabadi and M. M. Mohamad, "Greedy routing in underwater acoustic sensor networks: A survey," *International Journal of Distributed Sensor Networks, vol. 2013*, vol. 2013, p. 21, June 2013.

[7] J.-M. Jornet, M. Stojanovic, and M. Zorzi, "Focused beam routing protocol for underwater acoustic networks," in *Proc. of Third ACM International Workshop on Underwater Networks (WUWNeT'08), pages 75–82, MobiCom 2008*, 2008.

[8] P. Xie, J.-H. Cui, and L. Lao, "VBF: Vector-based forwarding protocol for underwater sensor networks," in *Proc. of IFIP Networking*, pp. 1216–1221, 2005.

[9] N. Nicolaou, A. See, P. Xie, J.-H. Cui, and D. Maggiorini, "Improving the robustness of location-based routing for underwater sensor networks," in *OCEANS 2007 - Europe*, pp. 1–6, June 2007.

[10] H. Yan, Z.-J. Shi, and J.-H. Cui, "DBR: Depth-based routing for underwater sensor networks," in *Proceedings of the 7th International IFIP-TC6 Networking Conference on AdHoc and Sensor Networks, Wireless Networks, Next Generation Internet*, NETWORKING'08, (Berlin, Heidelberg), pp. 72–86, Springer-Verlag, 2008.

[11] W. Thorp, "Analytic description of the low frequency attenuation coefficient," *The Journal of the Acoustical Society of America*, vol. 42, pp. 270–271, 1967.

[12] R.Coates, *Underwater Acoustic Systems*. New-York: Wiley, 1989.

[13] A. F. Harris and M. Zorzi, "Modeling the underwater acoustic channel in NS2," in *Proceedings of the 2nd International Conference on Performance Evaluation Methodologies and Tools*, ValueTools '07, pp. 18:1–18:8, 2007.

[14] J. G. Proakis and M. Salehi, *Digital Communications*. New York, NY, U.S.A.: McGraw-Hill, fifth ed., 2008.

[15] T. H. et. al., "The NS-3 network simulator." Software package retrieved from http://www.nsnam.org/, 2014.