Energy Efficiency Analysis of Effective Hydrocast for Underwater Communication

J. V. Anand and S. Titus

M.A.M College of Engineering, Trichy, Tamilnadu, India.

(Received 17 October 2014; accepted: 30 September 2015)

Underwater acoustic communication is difficult due to a low propagation speed, limited bandwidth, and energy consumption. There is a communication void primarily due to oceanic currents, which cause node mobility. Hence, protocol recovery has been focused on two means: Eulerian and Lagrangian. This work provides an analysis using the Eulerian approach with internetworking between sensors, wherein an effective hydrocast is proposed with the concept of triangulation to avoid long detour paths for recovery. The protocol Effective Hydrocast uses normalized advance where the cost is calculated with energy consumption, throughput, packet delivery ratio and propagation delay. Simulations with the ns2 simulator using an aquasim patch with the development of an effective hydrocast protocol are done for throughput with two values of bandwidth minimal 3 kHz and maximal 1000 kHz. The results of throughput are compared with depth based routing, energy efficient depth based routing, energy efficient fitness based routing, hydrocast and void aware pressure routing (VAPR) of which effective hydrocast is better. Then, values obtained for energy consumption between an effective hydrocast and VAPR obtained using ns2 simulation is subjected to a time series analysis using a statistical package for social science. An autoregressive integrated moving average is developed and the best fitting model is estimated with the Bayesian information criterion, where an effective hydrocast is found to be better than VAPR.

1. INTRODUCTION

Acoustics in the underwater environment with sensor technology plays a vital role, as it distorts less than the electromagnetic and optical signals and spans for a longer distance.¹ The propagation loss in an underwater environment is mainly characterized by geometrical spreading (K) and attenuation. Geometrical spreading associates to the spreading of sound energy caused by the expansion of the wave fronts. The energy decomposition rate for spreading is characterized by transmission range (R) from a source and it decomposes at a rate of R^{-2} for spherical spreading and R^{-1} for cylindrical spreading.¹ The value of geometrical spreading is taken as $K = 2$ (spherical spreading) for deep water and $K = 1$ (cylindrical spreading) for shallow water, and $K = 1.5$ for practical purposes, which was standardized.²

To overcome the communication void due to mobility and to find a proper recovery with minimal detour path, effective hydrocast was proposed. To forecast the protocol performance with future prediction in an uncertain underwater environment where data was obtained with simulation could be done using auto regressive integrated moving average. Hence, primary simulations were done in the ns2 simulator with an aquasim patch³ using the meandering current mobility model with the random waypoint model with various protocols, such as the depth based routing,⁴ energy efficient depth based routing,⁵ energy efficient fitness based routing,⁶ hydrocast⁷ and void aware pressure routing (VAPR)⁸ for throughput with minimal bandwidth of 3 kHz and maximal bandwidth value of 1000 kHz with the proposed effective hydrocast. Then, comparisons were made for energy consumption between VAPR and the effective hydrocast.

2. NETWORK MODELS AND DEFINITIONS

2.1. Architectural Overview

Two-dimensional architecture uses a group of sensor nodes to measure the ocean bottom, while the three-dimensional architecture was used to measure the ocean column at a preset

depth. This paves the way for sensing coverage and communication coverage in a wireless scenario.^{2,9}

2.2. Underwater Protocols Based On Localization

The taxonomy of routing protocols based on localisation in underwater acoustic sensor networks, which are classified as location-based and/or location-free.¹⁰ Location-based (geographical) routing in the location-based category assumes that each node knows some geographical information about itself and sinks to geographically identify the suitable progress area towards the sink.¹⁰ Location-free (non-geographical) routing protocols do not use full geographical information for routing. This can be classified as pressure-based routing (with a preset depth) and beacon-based routing.¹⁰ In the case of pressure-based routing protocols, every node is equipped with a depth sensor, which is made to float at a preset depth.¹⁰ The beacon-based approach uses ranging based on time of flight, angle of arrival, and round trip time. The beacon-approach can be stated as a periodic approach wherein beacon carries the necessary information. In a beacon-approach, network-wide synchronization is achieved with all sensor and anchor nodes, and a packet from the anchor determines its position. The number of anchors needed is three for the two dimensional geometry and four for the three dimensional geometry.¹¹

2.3. Disruption Tolerant Networks

Connectivity and its void in connectivity due to node movement can be understood by using disruption tolerant networks (DTN). The underwater DTN uses two mechanisms for routing, namely scheduled contact and unscheduled contact mechanisms.¹² A scheduled contact mechanism uses a base station, where concurrence must be obtained by two communicating sensor nodes with indirect links.¹² Due to time varying channel conditions, this approach fails. An unscheduled contact mechanism does not use a base station and is suitable for time varying channels that exhibit irregularity.¹² It can be divided

Figure 1. The work flow analysis. The designs in our simulations are depicted by broader arrows.

into opportunistic contact and predicated contact. An opportunistic contact, where a relay based scheme is in a node over-hearing mode, can convey information by forwarding it to the destination. A predicted contact, on the other hand, is based on a simple mode where previous observations are taken into consideration, where no relay entities are used and where a direct mode of communication is deployed.¹²

2.4. Geographic Routing

Geographic routing or position-based routing uses location information for packet delivery in multi-hop wireless networks. It can be classified into per-contact routing and per-hop routing.¹³ In per-contact routing, a node receiving data to be forwarded will exchange control packets and then select a suitable neighbouring node to forward the data to it, i.e., a neighbouring node with the minimal distance to the sink. The disadvantage of this protocol is high control overhead in per-contact routing.¹³ In per-hop routing, the relaying nodes are determined by themselves. The source node or relaying nodes broadcast the data. The neighbouring node receiving the data will determine whether it is suitable to relay the data. The qualified nodes will be the relay nodes, and they will continue forwarding the data. The advantages of per-hop routing are its low control overhead and its fast forwarding, because no control packet exchange is incurred.¹³ Initially, the effective hydrocast uses per-contact routing and when there is a void the node uses per-hop routing for forwarding.

3. SURVEY OF NETWORK PROTOCOLS WITH ITS SCHEMATIC ANALYSIS

3.1. Protocols for Void Avoidance with Recovery Using the Partially Lagrangian Approach

Improved Adaptive mobility of courier nodes in Threshold Optimized DBR protocol (iAMCTD) is based on depth,

residual energy, the signal-to-noise-ratio, and the sojourn time of courier nodes. The selection of optimal forwarders is decided on the basis of the prioritization of signal quality index (a value based on local signal-to-noise-ratio), an energy cost function (based on enduring energy), and a depth dependent function (based on both local signal-to-noise-ratio and enduring energy).¹⁴ The void recovery paradigm with mechanical devices such as a floating buoy, autonomous underwater vehicles as in QUO VADIS,¹⁵ and Depth Controlled routing¹⁶ are not preferred due to the extra energy cost incurred by it.

3.2. Protocols for Analyses without Void Avoidance using the Eulerian Approach

In depth based routing (DBR),⁴ the sender forwards the packet to a set node at a lower depth than itself. Before it forwards the packet, it checks its packet history buffer to avoid frequent retransmission. If the packet is already in its packet history buffer, it checks its hop count. If it is less than the previous hop count, then it forwards the packet by adding in the priority queue. Otherwise, it discards the packet. It also has a timer that expires if it cannot find any neighbours within its transmission range.⁴ The problem with DBR is its increased number of packet transmissions and voids due to node mobility, where the sensor nodes are out of the transmission range. The depth-based multi-hop routing protocol¹⁷ for an underwater sensor network forwards packets using the depth and sleep wake algorithm. The sender forwards the packet to the place where only one node is selected as the next hop neighbour. Other nodes are in a sleep state. Only when they have a wake up control packet that makes them wake up and receive data. Otherwise, they continue in their sleep state.¹⁷ Energy-efficient localization-free routing (EEDBR)⁵ forwards packets with depth and residual energy. It is similar to DBR, but it is sender based because the nodes on the record are sorted based on their remaining energy, which shows their precedence of forwarding. To prevent redundant data packet forwarding, each contender node judges a holding time according to its remaining energy and precedence, in which a smaller holding time is assigned to a node with more remaining energy and it receives the packet.⁵ The energy-efficient fitness (EEF)⁶ protocol which uses depth, residual energy, and fitness, which is calculated based on the distance between the sending node, forwarding node, and sink.⁶ Channel aware pressure routing (CARP)¹⁸ is a stateful approach, which depends on number of hops, link quality, and energy consumption. Its methodology was based on contention based approach with handshaking methodology and used as PING PONG messages, where a shorter hop is preferred for the highest throughput, whereas longer hops are present for better link quality.¹⁸

3.3. Protocols for Void Avoidance with Recovery and Message Based Transmission

The message-based wireless protocol with geographic routing mostly uses normalized advance¹⁹ and considers the criteria of advance, which prefers a node that is closer to the sink and the furthest within its transmission range. Hydrocast, which uses a permissible delay and normalized advance where the cost is calculated by the packet delivery, does not provide energy efficiency and incurs long detour paths with void avoidance.⁷ Vector-based void avoidance uses concave and convex routing to overcome voids due to unequal load distribution among sensor nodes. However, this context depends upon the voids due to collisions.²⁰

3.4. Void Aware Pressure Routing

Methodology of VAPR is as follows:⁸

- 1) Every sonobuoy on surface sends a beacon message.
- 2) Sensor that receives the beacon message updates its depth only if the beacon sequence is greater than the previous beacon sequence.
- 3) If the beacon sequence is equal to the previous beacon sequence, then it checks for its hop count.
- 4) If steps 2 and 3 are true, then it updates its next hop data forwarding direction (N_DF_Dir) and data forwarding direction (DF_Dir).
- 5) The direction for data flow is set 'up' when the beacon is received from shallower depth node otherwise it is set as 'down.'
- 6) Route Initialization is used to initialize each node's internal states:
 - i. Initially, each node in the network begins as an isolated local maximum with a hop count equal to infinity, except the sonobuoy.
 - ii. Then, it will have a connected component to one of the sonobuoy whose state will be changed to non-local maxima.
 - iii. If current sensor node is a source node, then set the data forwarding direction, hop count and sequence number as zero.
If the sensor node is a forwarding node, then set the data forwarding direction, next hop data forwarding direction, sequence number and the number of hops as infinity.
- 7) Data Forwarding: Nodes forward data solely based on the data forwarding direction (DF_Dir) and next hop data forwarding direction (N_DF_Dir).
- 8) Initialize all nodes in the connected set:
If the neighbour node depth is lesser than or equal to the present node depth then the data forwarding direction is equal to next hop data forwarding direction. This indicates the packets are transferred towards the sonobuoy which is indicated as downwards.
If the neighbour node depth is greater than the present node depth then the data forwarding direction is equal to next hop data forwarding direction. This indicates the packets are not transferred towards the sonobuoy. It should then transmit in the direction which is indicated as upwards.
- 9) Clustering:
 - i. Form all nodes in the forwarding set (F) and select the best one.
 - ii. Get one hop neighbour from the best node and form cluster.
 - iii. Remove the best node from its one hop neighbour and from forwarding set.
 - iv. If F is not empty, repeat steps i–iii, else Stop.

The purpose of the VAPR protocol discussed in detail is compared with the effective hydrocast. The problem with VAPR is that it is fully based on control messages, which increase the delay and overhead.

The protocols discussed in the literature either focus on greedy routing with energy consumption or greedy routing with a recovery mode. To the best of our knowledge, no protocol focuses on greedy routing with energy consumption, minimal overhead, and a minimal detour path so much so this work focuses on these constraints. The prior work of effective hydrocast²¹ is based on geographic routing with normalized advance, which is an advance divide by cost, wherein the cost was calculated with throughput, packet delivery ratio, energy consumption, and propagation delay was estimated for offered load (data packet generated by source node with energy consumption and throughput) with analytical analysis using regression. However, regression was found without lags and hence it fails to consider for the relationship through time and overestimates the relationship between the dependent and independent variables. So this work focuses on data obtained for time interval and comparisons with ARIMA model for forecasting.

4. ALGORITHM DEVELOPMENT

4.1. Methodology

All nodes initialize its surface ID and depth as infinity. Other than sonobuoy, all sensor nodes send and receive 'hello' messages periodically and update their neighbour information of their expected neighbour list. The source node then checks for the nodes within its upper hemispherical transmission range and computes the angle between neighbours using:

$$\text{Hemisphere Transmission Range} = \frac{2 \times \pi^2}{(\text{Angle})^2}. \quad (1)$$

Then, the verification is done to check whether the node reaches a local maxima point. If the nodes do not reach points of local maxima, then they can form a dominating triangle. The sender sends a message for triangle formulation along with the depth. Receiving nodes include that information in the triangle table maintained by each node with x, y, z positions. Every node maintains its position, which is checked every 1 second. Table is formed with the three nodes information $X1, X2, X3$ and $X0$ which is the geographical centre of the triangle. Nodes then attach its depth, Data Forwarding direction, NADV (Normalized advance) Status

$$\text{Normalized Advance} = \frac{\text{Advance}}{\text{Cost}}. \quad (2)$$

Advance is the same criteria used in geographic routing and the cost is estimated using throughput with varying bandwidth, packet delivery ratio, energy consumption, and propagation delay. The formulas for estimating cost are:

$$\text{Throughput} = \frac{\text{Received Packets} \times \text{Maximum Packet Size} \times 8}{\text{Current Time} \times \text{Bandwidth}}; \quad (3)$$

$$\text{Packet Delivery Ratio} = \frac{\text{Received Packets}}{\text{Send Packets}} \times 100; \quad (4)$$

$$\text{Energy Consumption} = \text{Initial Energy} - \text{Nodes Current Energy}; \quad (5)$$

$$\text{Propagation Delay} = \frac{(T_2 - T_1) + (T_4 - T_3)}{2}; \quad (6)$$

Figure 2. The flowchart for data analysis used in ARIMA model identification.

T_1 is the time stamp at sender and T_2 is the time stamp at receiver, T_3 is the time stamp of retransmission time at receiver and T_4 is the time stamp of reception time at the sender. So when a node comes under a communication void, then it knows the recovery nodes in its dominating triangle formulations thus avoiding long detour paths for recovery. In addition, if the node recovers from a void, then it switches back to the greedy mode. Otherwise, it tries to route towards a node within its communication capabilities, even in its lower hemispherical transmission range.

5. DATA ANALYSIS

5.1. Time Series Model

There are two methods to analyse the time series either in frequency domain (used for periodic and cyclical observations) or in time domain (estimates relationship using data collected over time).²² This work focuses on univariate autoregressive integrated moving average (ARIMA) model for data obtained in time domain for two protocols: the effective hydrocast and the void aware pressure routing.

5.2. Autoregressive (AR) (Regression on Self)

The value of the variable in one period is related to the value of the variable in the previous period.²³ $AR(p)$ is an autoregressive model with

$$y_t = a + \sum_{i=1}^p \psi_i \psi_{(t-i)} + \epsilon_t; \quad (7)$$

where a is a constant, ψ_i is the coefficient of the model, $\psi_{(t-i)}$ is the lagged variable in time, and ϵ_t is the error (assumed to be normally distributed as well as independent error). The summation is taken till an order of polynomial p .

When regression is done there are errors (residuals) which have a time series structure. Adjusting the estimated regression coefficients and the errors are possible when it has time series structure and is called regression on self or auto-regressive function.

5.3. Moving Average (MA)

This model states for the option of a relationship between a variable and the residuals from previous model.²³ $MA(q)$

Figure 3. This energy consumption analysis was done to report the interval at two milliseconds, each till 200 milliseconds for 100 values for the effective hydrocast and void aware pressure routing, of which the effective hydrocast was found better than the VAPR protocol.

model with q lags is:

$$y_t = a + \epsilon_t + \sum_{i=1}^q \theta_i \epsilon_{(t-i)}; \quad (8)$$

where θ_i is the coefficient of the lagged error term in time $t - i$. The parameters of errors are not known and the optimal values have to be chosen by iterations until sum of squares of errors is minimized and average error is zero.

5.4. Autoregressive Moving Average (ARMA)

It combines p -th order autoregressive and q -th order moving average models, so it is called auto regressive moving average (ARMA(p, q)).^{22,24}

$$y_t = a + \sum_{i=1}^p \psi_i \psi_{(t-i)} + \epsilon_t + \sum_{i=1}^q \theta_i \epsilon_{(t-i)}. \quad (9)$$

5.5. Stationary (Standing in Time)

Modelling an ARMA(p, q) process requires stationarity. The sequence of process, which is said to be random not only in time, but also in space, is called as a stationary process, if it has a mean and variance that do not change over time. If it is not stationary, the model is subjected to differencing and integrating the variables to develop an autoregressive integrated moving average (ARIMA). ARIMA(p, d, q) denotes a ARMA model with p autoregressive lags and q moving average lags supplemented with d differencing operations.²⁴ Differencing here computes the difference among a pair of data at some time interval.

5.6. Autocorrelation Function

Autocorrelation function (ACF) is the proportion of the autocovariance of y_t and y_{t-k} to the variance of y_t :

$$ACF(k) = \frac{\text{COVARIANCE}(y_t, y_{t-k})}{\text{VARIANCE}(y_t)}. \quad (10)$$

ACF gives the cross correlation between y_t and y_{t-k} .^{24,25}

5.7. Partial Autocorrelation Function

Partial autocorrelation function (PACF) is the simple correlation between y_t and $y_{(t-k)}$, where $y_{(t-k)}$ denotes the part explained by the intervening lags.²⁵ PACF gives the amount of correlation between the variable and its lower order lags.

Figure 4. The autocorrelation function and partial autocorrelation function plot for graphing the residual of 24 lags for an effective hydrocast.

5.8. Goodness of Fit Bayesian Information Criterion (BIC)

In statistics, the Bayesian information criterion (BIC)^{24,26} or Schwarz criterion (also SBC, SBIC) is a principle for model selection among a finite set of models. It is based upon the likelihood function and it is closely related to the Akaike information criterion (AIC).^{24,26} They measure the trade-off between the model fit and complexity of the model:

$$AIC = -2 \ln(L) + 2K; \quad (11)$$

$$BIC = -2 \ln(L) + \ln(N)K; \quad (12)$$

where L is the parameter for the likelihood functions assessed as parameter estimates, N is the number of observations, and K is the number of estimated parameters.

5.9. Normalized Bayesian Information Criterion (Normalized BIC)

Normalized BIC is a calculation of the overall fit of a model that attempts to report for model complexity. It is a score based upon the mean square error and includes a penalty for the number of parameters in the model and the length of the series. This consequence takes away the advantage of models with more parameters, making the statistic easy to compare across diverse models of the same series.²⁶

6. RESULTS AND DISCUSSION

The simulation in our scenario are based on ns2 with aquasim patch³ which incorporates the metrics of underwater using uw-common, uw-mac, uw-routing, and uw-tcl.³ The energy consumption on all the nodes was calculated by two means: first by calculating the residual energy of each node using Eq. (5) and secondly by calculating the overall energy consumption with the number of nodes:

$$\text{Average Energy Consumption} = \frac{\text{Total Consumed Energy}}{\text{Number of nodes}}. \quad (13)$$

Then, the series was analysed with the ARIMA model with the energy consumption as a dependent variable. For the void aware pressure routing the sequence of values was found to be stationary with ARIMA values of (1,0,0). Then the effective hydrocast was found to be non stationary with ARIMA values (0,1,1) after differentiation and integration.

Figure 5. The autocorrelation function and partial autocorrelation function plot graphing of residual for 24 lags for void aware pressure routing.

7. CONCLUSIONS

In this paper, an effective hydrocast was proposed with a normalized advance where the criteria advance prefers the node that is closer to the sink and cost was estimated using packet delivery ratio, propagation delay, energy consumption, and throughput with minimal detour paths using triangulation. Then comparisons were made with depth-based routing, energy efficient depth based routing, energy efficient fitness based routing, hydrocast, and VAPR for throughput with minimal bandwidth of 3 kHz and maximal bandwidth value of 1000 kHz. Comparisons of the effective hydrocast for energy consumption had been made with void aware pressure routing — a fully stateful approach for void avoidance, which uses beacon messages along with depth, direction, sequence number, and hop count mentored by a sonobuoy. It was analysed through simulations by using ns2 based simulator with aquasim patch. The effective hydrocast with partially stateful approach was better with reduced control packet transmissions. Then, an autoregressive integrated moving average analysis had been developed for all the data obtained for energy consumption and the best model had been selected with minimal value of root mean square error and normalized Bayesian information criterion by using statistical package for social science. This analysis showed that the effective hydrocast was better than VAPR. Future work will deal with empirical characteristics of attenuation analysis in underwater with recovery from void using scalene triangle formulation.

REFERENCES

- Preisig, J. Acoustic propagation considerations for underwater acoustic communications network development, *ACM SIGMOBILE Mobile Computing and Communications Review*, **11** (4), 2–10, (2007). <http://dx.doi.org/10.1145/1347364.1347370>
- Akyildiz, I. F., Pompili, D., and Melodia, T. Underwater acoustic sensor networks: research challenges, *Ad Hoc Networks*, **3** (3), 257–279, (2005). <http://dx.doi.org/10.1016/j.adhoc.2005.01.004>
- Xie, P., Zhou, Z., Peng, Z., Yan, H., Hu, T., Cui, J.-H., Shi, Z., Fei, Y., and Zhou, S. Aqua-Sim: An NS-2 based simulator for underwater sensor networks, *Proceedings of*

Table 1. The values used for simulation parameters in our scenario.

	Protocol Used					
	Depth Based Routing	Energy Efficient Depth Based Routing	Energy Efficient Fitness	Hydrocast	Void Aware Pressure Routing	Effective Hydrocast
Sonobuoy	4					
Number of nodes	200					
Node Speed	1–3					
Attenuation Model	Thorps					
Transmission Power	1 Watt					
Receiving Power	0.01 Watt					
Idle Power	0.05 Watt					
Mobility Model	Random waypoint					
Area	1000×1000					
Simulation Duration	200 milliseconds					

Table 2. The values used for estimating throughput in our scenario with a minimal of 3 kHz used and maximum of 1000 kHz within the acoustic range of which an effective hydrocast was better than all the other protocols.

Bandwidth	Depth Based Routing	Energy Efficient Depth Based Routing	Energy Efficient Fitness	Hydrocast	Void Aware Pressure Routing	Effective Hydrocast
3 kHz	0.0000128	0.0000256	0.0000256	0.0018432	0.0024576	0.0015360
1000 kHz	0.0007168	0.0001536	0.0001536	0.1958400	0.1974270	0.0851456

OCEANS 2009, MTS/IEEE Biloxi-Marine Technology for Our Future: Global and Local Challenges, 1–7, (2009).

- ⁴ Yan, H., Shi, Z. J., and Cui, J.-H. DBR: depth-based routing for underwater sensor networks, *Proceedings of NETWORKING 2008 Ad Hoc and Sensor Networks, Wireless Networks, Next Generation Internet*, 72–86, Springer, Berlin, Heidelberg, (2008). http://dx.doi.org/10.1007/978-3-540-79549-0_7
- ⁵ Wahid, A. and Kim, D. An energy efficient localization-free routing protocol for underwater wireless sensor networks, *International Journal of Distributed Sensor Networks*, **8** (4), (2012). <http://dx.doi.org/10.1155/2012/307246>
- ⁶ Ashrafuddin, Md., Manowarul Islam, Md., and Mamun-or-Rashid, Md. Energy efficient fitness based routing protocol for underwater sensor network, *International Journal of Intelligent Systems and Applications (IJISA)*, **5** (6), 61–69, (2013). <http://dx.doi.org/10.5815/ijisa.2013.06.08>
- ⁷ Lee, U., Wang, P., Noh, Y., Vieira, L. F. M., Gerla, M., and Cui, J.-H. Pressure routing for underwater sensor networks, *Proceedings of IEEE INFOCOM 2010*, 1–9, (2010). <http://dx.doi.org/10.1109/INFCOM.2010.5461986>
- ⁸ Noh, Y., Lee, U., Wang, P., Choi, B. S. C., and Gerla, M. VAPR: void-aware pressure routing for underwater sensor networks, *IEEE Transactions on Mobile Computing*, **12** (5), 895–908, (2013). <http://dx.doi.org/10.1109/TMC.2012.53>
- ⁹ Akyildiz, I. F., Pompili, D., and Melodia, T. State-of-the-art in protocol research for underwater acoustic sensor networks, *Proceedings of the 1st ACM International Workshop on Underwater Networks*, 7–16, (2006). <http://dx.doi.org/10.1145/1161039.1161043>
- ¹⁰ Kheirabadi, M. T. and Mohamad, M. M. Greedy routing in underwater acoustic sensor networks: a survey, *International Journal of Distributed Sensor Networks*, **9** (7), (2013). <http://dx.doi.org/10.1155/2013/701834>
- ¹¹ Ramezani, H. and Leus, G. Ranging in an underwater medium with multiple isogradient sound speed profile layers, *Sensors*, **12** (3), 2996–3017, (2012). <http://dx.doi.org/10.3390/s120302996>
- ¹² Cho, H.-H., Chen, C.-Y., Shih, T. K., and Chao, H.-C. Survey on underwater delay/disruption tolerant wireless sensor network routing, *IET Wireless Sensor Systems*, **4** (3), 112–121, (2014). <http://dx.doi.org/10.1049/iet-wss.2013.0118>
- ¹³ Chen, Y.-D., Lien, C.-Y., Wang, C.-H., and Shih, K.-P. DARP: A depth adaptive routing protocol for large-scale underwater acoustic sensor networks, *Proceedings of OCEANS 2012 — Yeosu*, 1–6, (2012). <http://dx.doi.org/10.1109/OCEANS-Yeosu.2012.6263505>
- ¹⁴ Javaid, N., Jafri, M. R., Khan, Z. A., Qasim, U., Alghamdi, T. A., and Ali, M. IAMCTD: Improved adaptive mobility of courier nodes in threshold-optimized dbr protocol for underwater wireless sensor networks, *International Journal of Distributed Sensor Networks*, **10** (11), (2014). <http://dx.doi.org/10.1155/2014/213012>
- ¹⁵ Chen, B. and Pompili, D. QUO VADIS: QoS-aware underwater optimization framework for inter-vehicle communication using acoustic directional transducers, *Proceedings of the 8th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON)*, 341–349, (2011). <http://dx.doi.org/10.1109/SAHCN.2011.5984916>
- ¹⁶ Coutinho, R. W. L., Vieira, L. F. M., and Loureiro, A. DCR: Depth-Controlled routing protocol for underwater sensor networks, *Proceedings of the IEEE Symposium on Computers and Communications (ISCC)*, 000453–000458, (2013). <http://dx.doi.org/10.1109/ISCC.2013.6754988>
- ¹⁷ Guangzhong, L. and Zhibin, L. Depth-based multi-hop routing protocol for underwater sensor network, *Proceedings of the 2nd International Conference on Industrial Mechatronics and Automation (ICIMA)*, **2**, 268–270, (2010). <http://dx.doi.org/10.1109/ICINDMA.2010.5538317>
- ¹⁸ Basagni, S., Petrioli, C., Petrocchia, R., and Spaccini, D. Channel-aware routing for underwater wireless networks, *Proceedings of OCEANS 2012 — Yeosu*, 1–9, (2012). <http://dx.doi.org/10.1109/OCEANS-Yeosu.2012.6263538>
- ¹⁹ Lee, S., Bhattacharjee, B., and Banerjee, S. Efficient geographic routing in multihop wireless networks, *Proceedings of the 6th ACM International Symposium On Mobile Ad Hoc Networking And Computing*, 230–241, (2005). <http://dx.doi.org/10.1145/1062689.1062720>

Table 3. The energy consumption obtained for a duration of 200 milliseconds.

Report Interval (Milliseconds)	Effective Hydrocast (Watts)	Void Aware Pressure Routing (Watts)
2	14.8041	14.3095
4	12.8916	13.9857
6	12.0827	12.3933
8	11.6686	10.8739
10	11.4532	12.2012
12	11.2997	10.7577
14	11.1975	11.6511
16	11.0979	10.7143
18	11.0533	10.7006
20	10.9957	11.0213
22	10.9416	11.3662
24	10.9471	11.1653
26	10.8915	11.3429
28	10.8900	11.0994
30	10.8502	11.2544
32	10.8416	11.2920
34	10.8168	10.8549
36	10.7922	11.0019
38	10.7930	10.9884
40	10.8080	10.9595
42	10.7810	10.9096
44	10.7426	10.9479
46	10.7415	10.8599
48	10.7406	10.7733
50	10.7485	10.5962
52	10.7287	10.6059
54	10.7529	11.0722
56	10.7338	10.8041
58	10.7378	10.6838
60	10.7018	10.7465
62	10.7013	11.1037
64	10.6970	10.8962
66	10.6791	10.7597
68	10.6902	10.9215
70	10.6707	10.7448
72	10.6850	11.1603
74	10.6964	10.9839
76	10.6764	10.5660
78	10.6903	10.5900
80	10.6710	10.9032
82	10.6609	10.9323
84	10.6832	11.0493
86	10.6691	10.7379
88	10.6455	10.5825
90	10.6446	10.8489
92	10.6420	10.8529
94	10.6407	11.0639
96	10.6408	10.8591
98	10.5880	10.7734
100	10.6433	10.8221

Report Interval (Milliseconds)	Effective Hydrocast (Watts)	Void Aware Pressure Routing (Watts)
102	10.6534	10.7115
104	10.5951	10.8126
106	10.6193	10.8245
108	10.6156	10.5935
110	10.6433	10.8262
112	10.6312	10.5813
114	10.6406	10.6502
116	10.6036	10.8506
118	10.6276	10.8639
120	10.6214	10.7786
122	10.6115	10.8173
124	10.5950	10.9254
126	10.6392	10.5818
128	10.6306	11.0392
130	10.6197	10.8570
132	10.6214	10.8192
134	10.6027	10.8405
136	10.6182	10.7526
138	10.5925	10.8264
140	10.6147	10.7069
142	10.6199	10.7122
144	10.6229	10.7628
146	10.6105	10.9044
148	10.6119	10.7348
150	10.6104	10.8190
152	10.6151	10.8143
154	10.5986	10.8228
156	10.6013	10.8744
158	10.6016	10.8334
160	10.6035	10.8473
162	10.6182	11.0584
164	10.6151	10.9880
166	10.6031	10.9155
168	10.6172	10.8224
170	10.6062	10.7149
172	10.6018	10.9599
174	10.6148	10.8326
176	10.5976	10.7311
178	10.5941	10.7808
180	10.5951	11.0003
182	10.5956	10.6626
184	10.5959	10.8218
186	10.5968	10.5945
188	10.5944	10.5937
190	10.5943	10.8174
192	10.5947	10.7732
194	10.5960	10.8359
196	10.5958	10.7695
198	10.5651	10.7361
200	10.6119	10.6040

Table 4. The values used for estimating the model using normalized Bayesian information criterion of which effective hydrocast was found to be better than VAPR.

MODEL	MODEL FIT STATISTIC			Ljung box Q		
	Stationary R Square	RMSE	Normalized BIC	Statistics	DF	Sig
EFFECTIVE HYDROCAST	0.015	0.211	-3.063	28.385	17	0.041
VOID AWARE PRESSURE ROUTING	0.245	0.468	-1.427	26.524	17	0.065

- ²⁰ Xie, P., Zhou, Z., Peng, Z., Cui, J.-H., and Shi, Z. Void avoidance in three-dimensional mobile underwater sensor networks, *Wireless Algorithms, Systems, and Applications*, 305–314, Springer Berlin Heidelberg, (2009). http://dx.doi.org/10.1007/978-3-642-03417-6_30
- ²¹ Anand, J. V. and Titus., S. Regression based analysis of effective hydrocast in underwater environment, *Proceedings of the IEEE Region 10 Conference TENCON 2014*, 1–6, (2014). <http://dx.doi.org/10.1109/TENCON.2014.7022394>
- ²² Brockwell, P. J. and Davis, R. A. *Time Series: Theory and Methods*, Springer Science & Business Media, 1–266, (2013).
- ²³ Melard, G. Algorithm AS 197: A fast algorithm for the exact likelihood of autoregressive-moving average models, *Applied Statistics*, **33** (1), 104–114, (1984). <http://dx.doi.org/10.2307/2347672>
- ²⁴ Choi, B. S. *ARMA Model Identification*, Springer Science & Business Media, 29–75, (2012).
- ²⁵ Bartlett, M. S. On the theoretical specification and sampling properties of autocorrelated time-series, *Supplement to the Journal of the Royal Statistical Society*, **8** (1), 27–41, (1946). <http://dx.doi.org/10.2307/2983611>
- ²⁶ Schwarz, G. Estimating the dimension of a model, *The Annals of Statistics*, **6** (2), 461–464, (1978). <http://dx.doi.org/10.1214/aos/1176344136>