Data Upload from a Static Underwater Network to an AUV: Polling or Random Access?

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***Abstract*—In this paper, we consider data uploading from a network of fixed sensors to a mobile Autonomous Underwater Vehicle (AUV). We approach the problem using both random and controlled access: in particular, we propose UW-Polling, a data retrieval protocol based on controlled access, and evaluate it against channel access protocols based on random access. We compare the performance of these protocols in terms of throughput, Packet Delivery Ratio and energy consumption, discussing the impact of the source power level on these metrics.**

Our results show that our polling-based protocol outperforms the other protocols in several cases, and thereby confirm that polling is an effective approach to enable AUVs to retrieve data from a network of fixed sensors.

***Index Terms*—Underwater acoustic networks, AUV, MAC, random access, controlled access, polling.**

I. Introduction and Related Work

One of the main applications of underwater acoustic networks is remote telemetry and data retrieval [1]. There are several ways to organize the deployment of a network in order to accomplish this task. One common line of action is to set up the network topology so that the nodes form a connected network, where end-to-end communications are made possible by multihop routing [2]. However, there are several practical cases where this type of deployment is impossible or inconvenient [3]. For example, area coverage issues may require to sparsely deploy the nodes over a given region: this may create disconnects in the network, as even nearest neighbors may be out of each other's communications range. Moreover, even in denser deployments, the continuous change of the properties of the environment may alter the propagation of underwater sound waves; in turn, this may temporarily break existing links and abridge networks that would be connected otherwise.

In both scenarios above, the presence of mobile nodes may greatly help the data retrieval process. An Autonomous Underwater Vehicle (AUV) may be dispatched in the network area to bridge the portions of the network in case environment-induced partitioning occurs; it may also act as a mobile sink and retrieve sensed data from the fixed sensors, thereby eliminating the need for multihop routing.

In this paper, we concentrate on the second case, and in particular on devising an efficient mechanism for allowing a set of fixed sensors (e.g., deployed on the seafloor in a given area) to upload data packets to an AUV. We focus specifically on underwater sensor deployments that are sufficiently sparse to make multihop routing infeasible or unreliable in the long term, and yet where a patrolling AUV can typically have multiple nodes within its communication range at any given time. (We refer the reader to Section IV for more details on the network scenario.) An important issue to be dealt with in this case is the contention for channel access among the nodes located within the coverage area of the AUV. In fact, as the channel to the AUV becomes available, the transmissions of the sensors may start closely, and be quite concentrated in space and time; hence both contention and interference may occur. While it is the role of Medium Access Control (MAC) protocols to administer channel access in order to mitigate contention, it is not clear what is the best way to do so. Most underwater channel access protocols are based on some form of deterministic or random access [4], which however may make inefficient or untimely use of the opportunity to transmit to the AUV.

For this reason, in this paper we propose UW-Polling, a controlled access protocol based on a polling mechanism and a preliminary neighbor discovery procedure via beacon transmissions. UW-Polling mitigates interference by circulating the permission to transmit among the nodes that are discovered by the AUV. Collisions can still occur during the neighbor discovery phase, and during the setup of the polling phase: in any event, their impact is much lower than the impact of collisions affecting data packets in the presence of random access. In addition, UW-Polling incorporates a scheme to choose which nodes should transmit (and what they should transmit) based on a priority metric whose value depends on the contents of their buffer. For example, the highest priority may be given to the most recently generated data packets: other than providing the AUV with recent data, this mechanism helps distribute transmission turns evenly among the nodes: those that transmitted most recently are unlikely to have further up-to-date packets, and will thus be given lower priority in subsequent transmission phases.

We compare the performance of UW-Polling by means of simulations against two protocols based on random access, namely the Distance-Aware Collision Avoidance Protocol (DACAP) [5] and Carrier-Sense Multiple Access-Aloha (CSMA-Aloha) [6]. The former implements a form of collision avoidance scheme based on Request-to-Send/Clear-To-Send (RTS/CTS) handshakes, whereas the latter employs Aloha-like channel access, with preliminary short channel sensing periods to avoid some collision events. However, CSMA-Aloha is oblivious to the presence of the AUV (unlike DACAP, where the nodes do not transmit data packets if they receive no CTS from the AUV). Therefore, in this paper we consider a modified version of CSMA-Aloha called CSMA-Aloha-Trig, where the AUV notifies nodes of its presence by sending a special TRIGGER packet: this packet enables the nodes to transmit for a certain time, hence saving useless transmissions in case the AUV is not in range.

The rest of this paper is organized as follows. Section II describes some works related to the topics of this paper; Section III describes in more detail the protocols considered in this paper; Section IV presents the scenario of the simulations; Section V concludes the paper.

II. Related Work

A first evaluation of the performance of random access protocols for the upload of data to an AUV was performed in [7], where the authors compared random access and handshake-based communications in the data retrieval scenario described above.

In [8] the authors compare optical and acoustic communications in a scenario with one mobile node and a field of sensors. In particular, the authors observe that the optical channel can be exploited for high-rate low-range communications whenever possible, whereas the acoustic channel can be used in order to transmit brief control signals over longer ranges. No discussion on networking protocols is given in the paper, as a very simple MAC protocol is employed. In [9] the authors use the acoustic channel to perform neighbor discovery. In particular, the AUV locates static nodes using the vision capabilities enabled by a downward-oriented camera, and then hovers above the static nodes. In addition, the AUV can change trajectory based on the information retrieved from the nodes. While the full autonomy of the AUV (which is initially unaware of the position of the nodes) is a remarkable contribution in the paper, there is still no focus on networking protocols.

In [10], the authors show (using wireless sensors and a robot) that having an AUV patrol the network and retrieve data from the sensors significantly increases the network lifetime, as sensor nodes can save energy they would employ for long-range communications otherwise.

Finally, in [11] the authors also consider the retrieval of data from a network of fixed nodes using an AUV, and devise a scheduling approach based on Time-Division-Multiple-Access with Acknowledgements (TDMA-ACK) to administer communications. This approach is interesting and achieves good data retrieval performance. However, it requires node synchronization: this can be difficult to realize in practice, and would anyways require some signaling to maintain the common time reference. With the protocol proposed in this paper, we aim at achieving good data transfer performance with no requirements for synchronization or for knowledge of the node positions.

III. Protocols Description

A. UW-Polling

We now proceed by describing the data retrieval protocol proposed in this paper, UW-Polling. The protocol works in three subsequent phases:

- neighbor discovery;
- retrieval of a summary of available data from the discovered nodes;
- sorting according to a given priority criterion and sequential polling of the nodes.

The AUV starts the neighbor discovery by broadcasting a very short TRIGGER packet. The transmission of the trigger is repeated periodically until an answer is received. Every node that hears the TRIGGER and has data to transmit picks a backoff time, chosen uniformly at random in an interval whose boundaries are communicated by the AUV using the TRIGGER packet. Note that this option allows the AUV to adapt to the local density of the network deployment: if only a few nodes reply, the AUV can shorten the backoff interval and thereby reduce the duration of the UW-Polling handshake; otherwise, if many nodes reply, or any collision is detected, the AUV can increase the duration of the backoff interval, hence making collisions less likely.

At the end of the random backoff time, each discovered node sends a PROBE packet, containing the value of the chosen backoff time (which is required to estimate the round-trip time between the node and the AUV), as well as an indication of priority of the data in its own buffer. In this paper, we assume that most recently generated data packets have the highest priority: in accordance with this criterion, the node writes the timestamp of the most recent packet in the PROBE, along with the number of packets in its buffer. This information is required so that the AUV can sort the polling sequence according to the node priority, and assign a transmission period to each node.

The AUV waits for PROBEs only for a given time, chosen to enforce the maximum distance between itself and the discovered nodes to be lower than a maximum value. At the end of this listening period, the AUV assigns a priority to the nodes and starts the polling phase, using a POLL message directed to the first neighbor in the list. The POLL contains the whole polling list, along with the time before the turn of each node. This option allows the nodes to "sleep" while waiting for their turn, if their hardware so allows.

Upon receiving a POLL, the node at the top of the polling list starts sending the number of packets until the time assigned to it is over. At the end of this phase, the AUV removes the first elements of the polling list and re-transmits the POLL. This sequence of operations goes on until the last node in the list has completed its transmission. At this point, the AUV starts a fresh neighbor discovery phase by transmitting another TRIGGER packet.

For reference, Figs. 1 and 2 show the finite state machines of the protocol for the AUV and the nodes, respectively. From the figures we note that several timeouts are used to take care

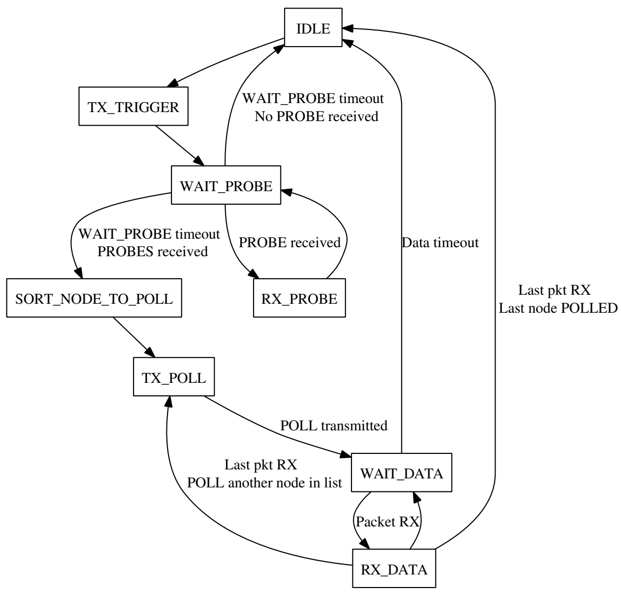


Figure 1. UW-Polling: AUV state machine.

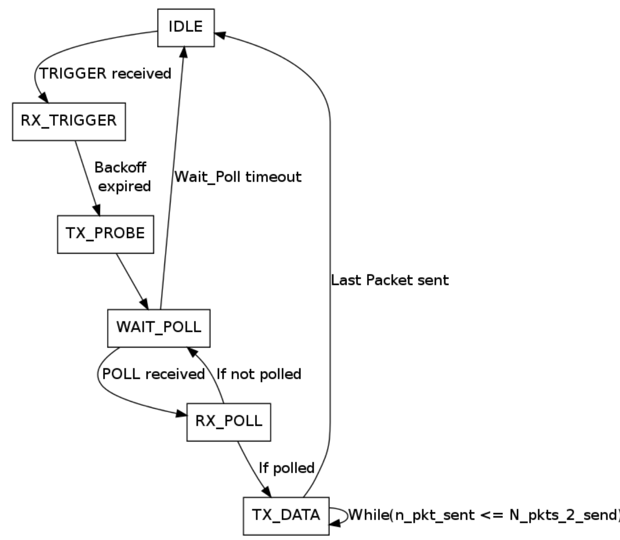


Figure 2. UW-Polling: node state machine.

of exceptions that may arise in practical cases. For example, one such timeout avoids that the AUV waits indefinitely for the transmissions of a node that ended up out of range as the AUV moved.

B. Other protocols considered in this paper

In the next section, we will compare the performance of UW-Polling with that of two protocols based on random access: a "triggered" version of CSMA-Aloha [6] and the Distance-Aware Collision Avoidance Protocol (DACAP) [5]. We briefly present these protocols in this subsection.

CSMA-Aloha [6] is an Aloha enhancement whereby short random channel sensing periods precede packet transmissions. Namely, before sending a packet, a node checks if the channel is free for a random amount of time, much shorter than the typical packet transmission and signal propagation time. If the channel is sensed busy, a subsequent channel sensing phase is scheduled (again of random duration), until the channel remains free for a whole sensing period. At this point the node can transmit the packet. This policy makes it possible to avoid most of the collisions induced by the lack of coordination in Aloha, while keeping channel access latencies low, and is hence a good representative of the class of uncoordinated random access protocols.

However, we stress that CSMA-Aloha is oblivious to the presence of the AUV within the transmission range of the nodes, and may hence lead to conspicuous packet losses if packets are transmitted while the AUV cannot hear them. For this reason, in this paper we will consider a modified version of CSMA-Aloha, named **CSMA-Aloha-Trig**, where the nodes are enabled to transmit only upon the reception of a `TRIGGER` packet from the AUV (akin to UW-Polling) and only for a given amount of time after that.

DACAP [5] is based on the exchange of Request-To-Send (`RTS`) and Clear-To-Send (`CTS`) packets to coordinate packet transmissions and thereby avoid that interference is originated within a certain distance from the transmitter and the receiver. In addition, before the actual transmission of a data packet, a further defer time is allowed, in order to overhear nearby signaling traffic, and detect likely collision events. In case potentially interfering traffic is taking place in the proximity of the receiver, there is an option to warn the transmitter through a specific packet. The length of the defer time is tunable: in principle, the collisions with signals from progressively lower-power interferers can be avoided by prolonging the defer time accordingly. We stress that DACAP does not allow the nodes to transmit in the absence of a `CTS` from the sink, but the `RTS` transmission is subject to no restriction: if a node has data in the queue, it will transmit an `RTS`, wait for a `CTS`, and back off for a random amount of time in case no `CTS` is heard in response. This procedure is repeated continuously until a `CTS` is finally received.

IV. SIMULATION PARAMETERS AND RESULTS

We set up a simulation scenario with 25 nodes arranged in a 5×5 square grid topology, with nearest neighbors $2\,\mathrm{km}$ apart. The network is deployed on the seafloor at a depth of about $1000\,\mathrm{m}$ in the Adriatic sea ($41.90°$N, $17.51°$E). The average January sound speed profile taken from WOD 2009 [12] and the corresponding channel power attenuation computed using Bellhop's coherent mode are reported in Fig. 4.

The AUV patrols the network at a depth of $600\,\mathrm{m}$, following the trajectory depicted in Fig. 3 at a speed of $4\,\mathrm{knots}$. The transmissions both of the nodes and of the AUV are performed at a carrier frequency of $25\,\mathrm{kHz}$. The data packet size is $125\,\mathrm{bytes}$. Every node can store up to 20 packets. Unless otherwise stated, the source power level is set to $150\ \mathrm{dB\ re}\ \mu\mathrm{Pa}$.

The duration of each simulation run is $214000\,\mathrm{s}$, which translates into 14 complete laps of the AUV along the trajec-

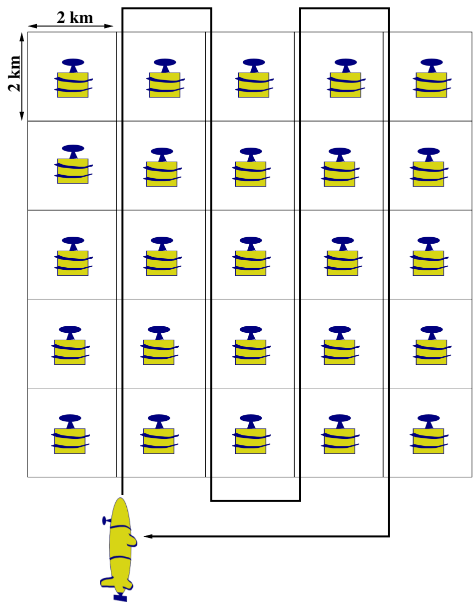
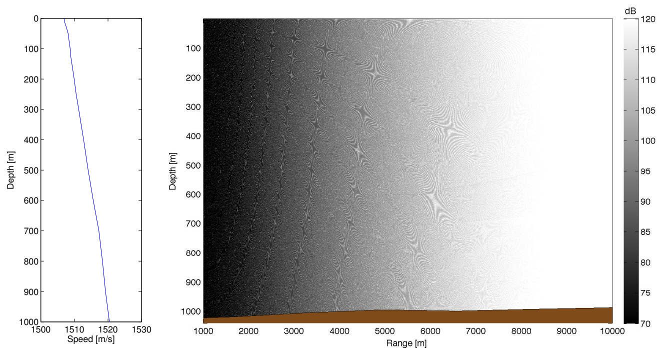


Figure 3. Topology of the network and trajectory of the AUV.



(a) (b)

Figure 4. Simulation scenario at (41.90°N, 17.51°E): (a) Monthly averaged January SSP from [12]; (b) channel power attenuation obtained using Bellhop (coherent mode) at a frequency of 25 kHz. The mild increase of the SSP for increasing depth translates into a relatively uniform propagation pattern.

tory in Fig. 3. The results are averaged over 10 simulation runs. The simulations are performed using the nsMiracle software [13]. The acoustic propagation is modeled using the empirical channel power attenuation equations in [14], [15], with a path-loss exponent $k = 1.8$. This value has been obtained by performing a number of Bellhop runs to compute the power attenuation as a function of distance for several positions of the AUV (hence several realizations of the surrounding environment), and by choosing the value of the path-loss exponent for which the empirical attenuation fits the attenuation found with Bellhop. The value of k is in line with the observations in [11].

In Figs. 5 and 6 we plot the throughput (defined as the number of data bytes that correctly reach the sink per minute) and the packet delivery ratio (PDR) of the three protocols considered in this paper. DACAP and UW-Polling exhibit almost the same throughput, wherease CSMA-Aloha-Trig shows

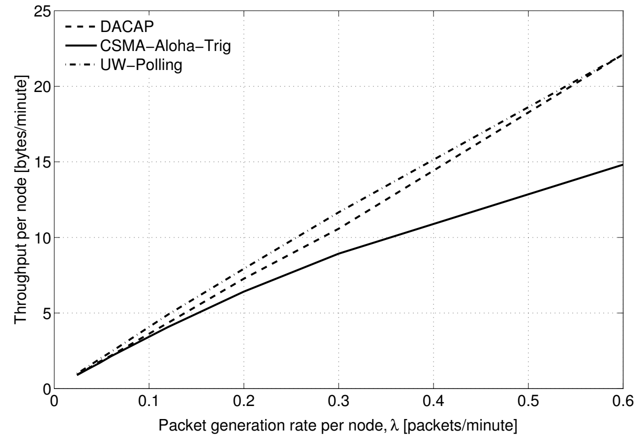


Figure 5. Throughput as a function of the packet generation rate, λ in packets per minute per node. The source power level is 150 dB re μPa.

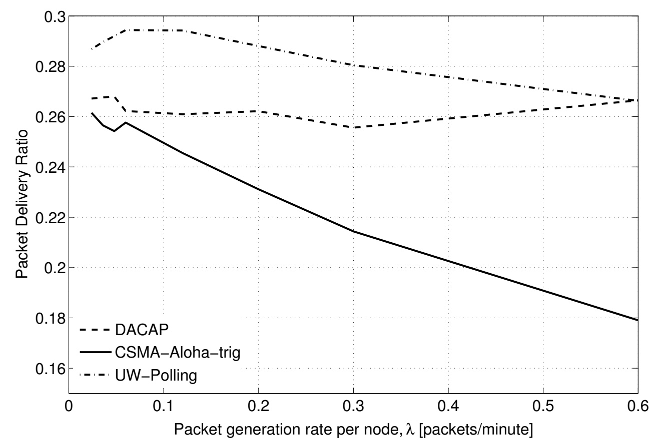


Figure 6. Packet delivery ratio as a function of the packet generation rate, λ in packets per minute per node. The source power level is 150 dB re μPa.

worse performance. The main reason for this behavior is that the `TRIGGER` sent by the AUV to enable transmissions gives rise to contention for channel access among all nodes that have packets to transmit. This observation is supported by Fig. 6, where we observe that the PDR of CSMA-Aloha-Trig decreases for increasing traffic. On the contrary, UW-Polling takes advantage of the interference-free data packet transmissions enabled by the controlled access procedure. DACAP also sets up interference-free links, as only the AUV can send `CTS`s. However, the handshake procedure itself has to be repeated for all packet transmissions. In turn fewer packets are transmitted while the AUV is available, increasing the chance that some of them are dropped due to full queues.

From Fig. 6 we also observe that the PDR of UW-Polling and DACAP is almost constant for increasing traffic. Since the throughput increases linearly with increasing traffic in Fig. 5, we infer that packet losses are due to full queues rather than transmission errors. This is expected because the AUV takes time to complete its trajectory, and spends only a limited time

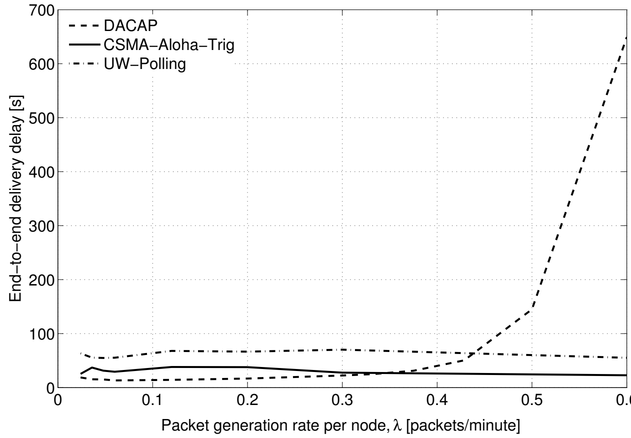


Figure 7. End-to-end delivery delay as a function of the packet generation rate per node, λ in packets per minute per node. The source power level is 150 dB re μPa.

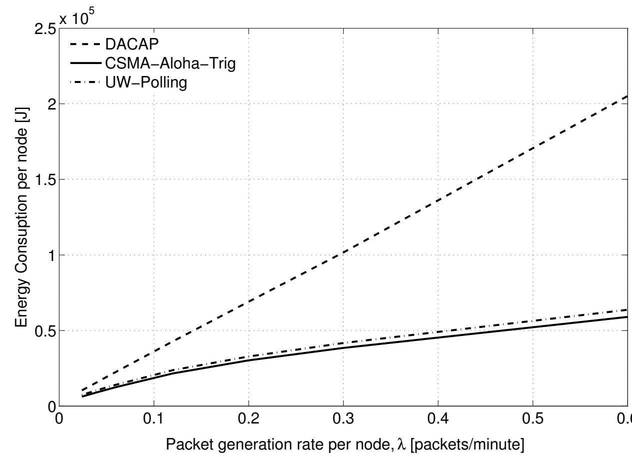


Figure 8. Energy consumption per node as a function of the packet generation rate, λ in packets per minute per node. The source power level is 150 dB re μPa.

within the communications range of each node.

Fig. 7 shows the end-to-end delivery delay per packet received by the sink, in seconds. We observe that CSMA-Aloha-Trig achieves the lowest delay: this is both because of its simple transmission policy and because the delay is measured only among correctly received packets. On the contrary, UW-Polling's network discovery phase takes more time, which in turn makes the nodes wait longer before one of their packets can be delivered. A different outcome is observed for DACAP, for which the delay increases much more than for UW-Polling and CSMA-Aloha-Trig. The contention among the nodes during the RTS/CTS handshake plays a major role in this case: for high traffic, it is more likely that the handshake fails, causing repeated backoff events.

Fig. 8 shows the average energy consumption per node, assuming a power consumption of $100\,\mathrm{W}$ for transmissions, $0.8\,\mathrm{W}$ for receptions, and $0.008\,\mathrm{W}$ for idling. (These parameters have been chosen to be equivalent to those of the EvoLogics modem [4].) We observe that UW-Polling and CSMA-Aloha-Trig achieve almost the same amount of energy consumption. For UW-Polling, the consumption is slightly higher due to the transmission of signaling messages during the neighbor discovery and polling phases. In any event, the limited energy consumption is mainly due to the occurrence of transmissions only when the AUV is actually in range to hear them. DACAP's RTS transmissions, instead, are oblivious to the presence of the AUV: therefore, they lead to larger energy consumption, which increases linearly with the traffic generation rate.

As a final comparison, we perform the same set of simulations with a higher source level of 190 dB re μPa. With this value, the transmission range of both the nodes and the AUV is higher, hence the data packet transmissions are very unlikely corrupted by noise. On the other hand, the number of neighbors discovered by UW-Polling or triggered by CSMA-Aloha-Trig will be higher. Figs. 9 and 10 show the throughput per node and the packet delivery ratio for the new source level. The first noticeable effect is that the higher number of nodes that are in range of the AUV, on average, allows the latter to retrieve more packets, reducing the probability that some packets are dropped because of full queues. This improves the throughput and the packet delivery delay for all protocols. The improvement is even more remarkable for CSMA-Aloha-Trig at low traffic, thanks to its lightweight channel access scheme. As the traffic generation rate increases, however, the probability that packets are dropped becomes considerable; in addition, the more frequent access attempts will lead to a higher number of collisions between data packets. As a consequence, CSMA-Aloha-Trig's traffic decreases as already observed in Fig. 5. With respect to CSMA-Aloha-Trig, UW-Polling exhibits a lower throughput for low packet generation rates, but the value of the throughput itself is more stable thanks to interference free data packet transmissions. DACAP, instead, shows poor throughput and Packet Delivery Ratio in this case, due to the harsher interference generated by the increased source power level.

The results above demonstrate that controlled channel access via the UW-Polling protocol is a suitable choice for data retrieval using AUVs, especially if the affordable transmit power level is low. In any event, the setup of interference-free transmissions (although at the cost of initial signaling traffic for neighbor discovery) makes the packet delivery ratio and throughput performance stable with increasing traffic.

V. Conclusions

In this paper, we presented UW-Polling, a protocol to enable an Autonomous Underwater Vehicle (AUV) to retrieve data from a network of fixed sensors using controlled access. UW-Polling performs significantly better than random access protocols if the available source power level is low; in the presence of high source power level, it still performs better than random access for high values of the packet generation

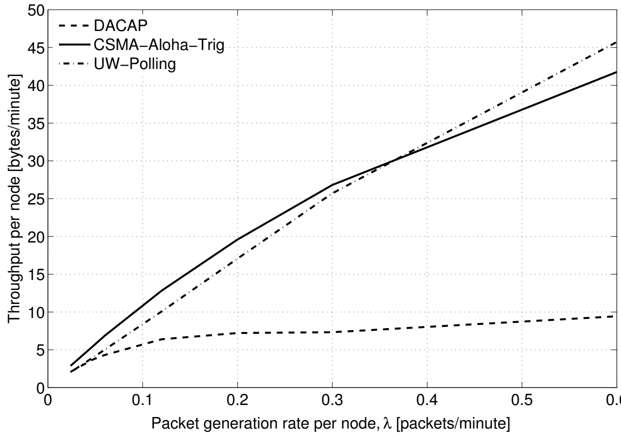


Figure 9. Throughput as a function of the packet generation rate, λ in packets per minute per node. The source power level is 190 dB re μPa.

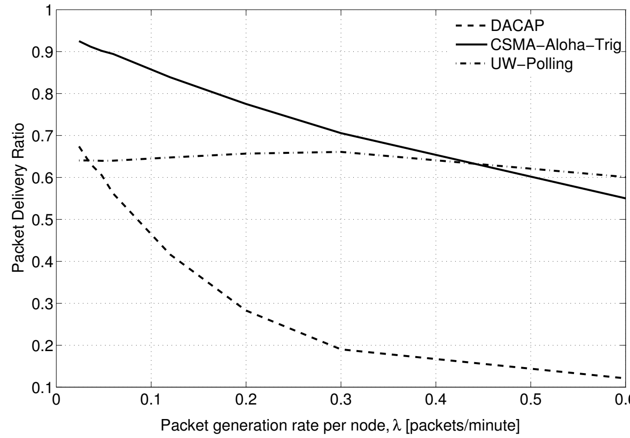


Figure 10. Packet delivery ratio as a function of the packet generation rate, λ in packets per minute per node. The source power level is 190 dB re μPa.

rate per node Due to its neighbor discovery phase, UW-Polling's end-to-end delivery delay is slightly higher than the delay experienced by random access protocols; however, it remains stable for all values of traffic considered in our evaluation. The energy consumption of UW-Polling is also negligibly higher than the consumption of CSMA-Aloha-Trig, the best of the two random access protocol considered in this paper.

These considerations make UW-Polling a valid alternative to random access protocols for automatic data retrieval using AUVs.

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REFERENCES

[1] D. B. Kilfoyle and A. B. Baggeroer, "The state of the art in underwater acoustic telemetry," *IEEE J. Ocean. Eng.*, vol. 25, no. 1, pp. 4–27, Jan. 2000.

[2] I. Akyildiz, D. Pompili, and T. Melodia, "Underwater acoustic sensor networks: research challenges," *Elsevier's Ad Hoc Networks*, vol. 3, no. 3, 2005.

[3] J. Partan, J. Kurose, and B. Levine, "A survey of practical issues in underwater networks," in *Proc. of ACM WUWNet*, Los Angeles, CA, Sep. 2006.

[4] P. Casari and M. Zorzi, "Protocol design issues in underwater acoustic networks," *Elsevier Computer Communications*, vol. 34, pp. 2013–2025, 2011.

[5] B. Peleato and M. Stojanovic, "Distance aware collision avoidance protocol for ad hoc underwater acoustic sensor networks," *IEEE Commun. Lett.*, vol. 11, no. 12, pp. 1025–1027, Dec. 2007.

[6] F. Guerra, P. Casari, and M. Zorzi, "World Ocean Simulation System (WOSS): a simulation tool for underwater networks with realistic propagation modeling," in *Proc. of ACM WUWNet 2009*, Berkeley, CA, 2009.

[7] F. Guerra, P. Casari, A. Berni, J. Potter, and M. Zorzi, "Performance evaluation of random and handshake-based channel access in collaborative mobile underwater networks," in *Proc. of MTS/IEEE Oceans*, Seattle, WA, Sep. 2010.

[8] I. Vasilescu, K. Kotay, D. Rus, M. Dunbabin, and P. Corke, "Data collection, storage, and retrieval with an underwater sensor network," in *Proceedings of the 3rd international conference on Embedded networked sensor systems, SenSys '05*. New York, NY, USA: ACM, 2005, pp. 154–165. [Online]. Available: http://doi.acm.org/10.1145/1098918.1098936

[9] M. Dunbabin, P. Corke, I. Vasilescu, and D. Rus, "Data muling over underwater wireless sensor networks using an autonomous underwater vehicle," in *IEEE International Conference on Robotics and Automation, ICRA 2006*, May 2006, pp. 2091 –2098.

[10] O. Tekdas, V. Isler, J. Lim, and A. Terzis, "Using mobile robots to harvest data from sensor fields," *IEEE Wireless Communications*, vol. 16, no. 1, pp. 22 –28, February 2009.

[11] G. A. Hollinger, S. Choudhary, P. Qarabaqi, C. Murphy, U. Mitra, G. S. Sukhatme, M. Stojanovic, H. Singh, and F. Hover, "Communication protocols for underwater data collection using a robotic sensor network," in *IEEE GLOBECOM Workshops, 2011*, Dec. 2011, pp. 1308 –1313.

[12] "World ocean atlas." [Online]. Available: www.nodc.noaa.gov/OC5/WOA05/pr_woa05.html

[13] N. Baldo, F. Maguolo, M. Miozzo, M. Rossi, and M. Zorzi, "NS2-MIRACLE: a modular framework for multi-technology and cross-layer support in network simulator 2," in *Proc. of ACM NSTools*, Nantes, France, Oct. 2007.

[14] R. Urick, *Principles of Underwater Sound*. New York: McGraw-Hill, 1983.

[15] M. Stojanovic, "On the relationship between capacity and distance in an underwater acoustic communication channel," *ACM Mobile Comput. and Commun. Review*, vol. 11, no. 4, pp. 34–43, Oct. 2007.