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# Opportunistic Constant-Time Underwater Acoustic Network Discovery

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**Abstract**—Network discovery (ND) is a crucial task of underwater acoustic networks (UANs). When the UAN nodes are initially deployed, how can they discover the network topology and establish multi-hop routes to the surface gateway without any *a priori* information? To this end, we propose an opportunistic protocol, called OCTAVE, which has a fixed runtime specified at the start of ND that cannot be exceeded, regardless of the network size, density or channel conditions. It does not require clock synchronisation among the network nodes; instead, the gateway specifies the duration of the three stages of OCTAVE ND as part of its probe transmissions. Simulations show that OCTAVE provides a significantly higher probability of discovering all nodes of a network in the presence of random link fading, compared with a sequential collision-free ND protocol. OCTAVE was implemented in hardware and a 6-node UAN was deployed in a lake on 9 May 2024. This lake trial demonstrated successful node discovery and fixed time operation in challenging channel conditions and highly time-variable node connectivity.

**Index Terms**—network protocol, network discovery, underwater acoustic network

## I. INTRODUCTION

Underwater acoustic networks (UANs) have a wide range of applications: water quality monitoring [1], seismic monitoring [2], marine animal tracking [3], off-shore asset monitoring [4], coastal defense [5], etc. UAN protocol design is a challenging task due to several characteristics of the underwater acoustic (UWA) communication medium, such as slow propagation, low bandwidth and highly variable bit error and frame error rates often encountered at sea.

There is relatively little research on ND protocols for UANs. Typically, UAN protocols require a separate ND phase, where the nodes broadcast packets to discover their neighbours and adapt to topology changes [6]–[9]. For example, DQA-MAC [9] requires a dedicated network setup stage involving the measurement of propagation delays and the assignment of a new packet schedule. Similarly, in the DIVE protocol [8] if a "Hello" packet is received from a new node, the other nodes

restart the ND process to update the topology. DIVE features two procedures: 1) new node discovery and ID assignment; 2) duplicate node ID detection and recovery. A first contact protocol that extends the JANUS standard [10] was proposed in [11]. It aims to establish unique short nicknames for nodes within a 2-hop neighborhood. The GUWMANET network protocol [12] can then use these local nicknames in conjunction with regular node addresses to route packets across a network. In this paper, we do not consider the problem of ID assignment as part of ND; we assume that the nodes already have a unique address before deployment; however, these addresses do not need to be known *a priori*.

In our previous work [13], we developed a collision-free ND protocol as part of a UAN data gathering protocol stack, and deployed it in the North Sea from 11 Oct to 26 Nov 2021. The key disadvantage of this ND protocol was the uncertainty in the duration required to discover the nodes. It was significantly affected by the number of lost packets, timeouts and retransmissions involved in the process, which varied widely depending on the channel conditions and network density.

The aim of this paper is to propose a new, opportunistic, constant-time UAN ND protocol (OCTAVE) the key feature of which is a fixed runtime, where the GW can set the duration of the ND phase that cannot be exceeded regardless of the network size, density or channel conditions. Having a fixed, appropriately dimensioned duration of ND phases is crucial for reliably supporting the operation of UANs, e.g. data gathering in sensor networks.

The rest of the paper is organised as follows: Section II describes the OCTAVE protocol; Sections III and IV present the results of the simulation study and lake trials, respectively; finally, Section V concludes the paper.

## II. THE OCTAVE NETWORK DISCOVERY PROTOCOL

The OCTAVE protocol was developed with the following practical assumptions: the network nodes are quasi-static (e.g. moored sensor nodes), they are not synchronised, no collision-free channel access mechanism is in place during network discovery, no *a priori* knowledge of the network topology is required, including the number of nodes or their addresses. The aim of this protocol is to enable all nodes, including the

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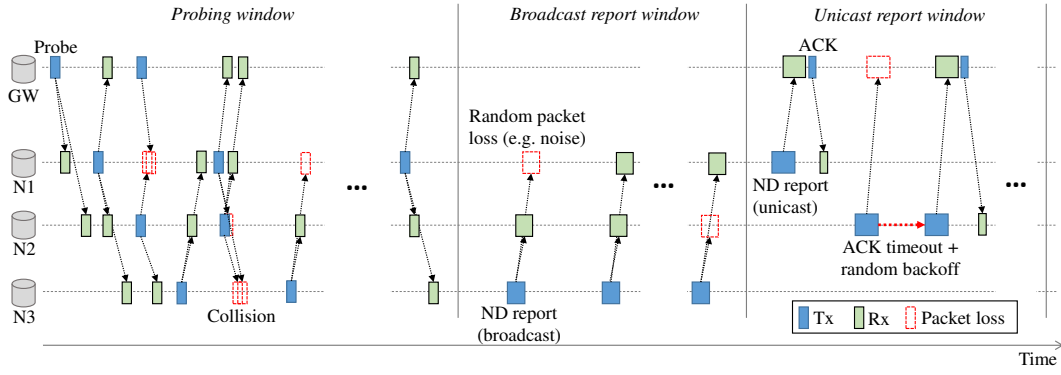


Fig. 1. Example packet flow of the OCTAVE protocol; the durations of the three windows is fixed *a priori* by the gateway.

GW, to discover their 2-hop neighbourhood and estimate the link qualities within it. It can be extended to propagate the topology information beyond the two hops as described below.

Fig. 1 shows an example packet flow that describes the protocol's operation. It comprises three fixed duration stages:

- *Probing window* – time window during which all nodes opportunistically transmit broadcast probe packets;
- *Broadcast report window* – time window for those nodes that have not heard directly from the GW to broadcast their “ND report” packets;
- *Unicast report window* – time window for the GW's single-hop neighbours to send their ND reports (including the ND data received from their neighbours in the previous window) to the gateway via unicast transmissions with acknowledgements (ACKs) and random backoff.

During the probing window, all nodes (including the GW) transmit a predetermined number of broadcast probe packets, e.g. 5, at uniformly distributed random times. The probe packets have the following structure: {SRC, ND\_ID, TT\_EOPW, BRW\_DUR}, containing the packet source, ID of this ND phase, time till the end of the probing window and broadcast report window duration, respectively. The latter two fields allow the ND phase to be coarsely synchronised among the nodes without the need for synchronised clocks. Note that the propagation delays among the nodes are unknown, which introduces small differences in the timing of these windows at different nodes. To address this, a predetermined guard period (e.g. 5 sec) is added at the end of each window. The duration of the necessary guard period is small compared with the probing window size, and can be slightly shortened or lengthened depending on the size of the network's coverage area.

After the end of the probing window, any nodes that did not hear from the GW directly, broadcast several copies (e.g. 3) of their “ND report” packet at uniformly distributed random times within this time window. The ND report packet has the following structure: {SRC, ND\_ID, ADDR1, NRXP1, ADDR2, NRXP2, ...}, where the ADDR<sub>n</sub>, NRXP<sub>n</sub> pair states how many probes were received from the node address ADDR<sub>n</sub>. Note that the broadcast report window is optional for dual-hop networks; it is also possible to run the probing window

followed directly by the unicast report window; however, this will deliver a reduced level of information on 2-hop links to the GW. In contrast, in order to propagate the network topology information beyond two hops, multiple successive broadcast report windows can be used; e.g. for an  $n$ -hop network,  $n - 1$  windows are needed.

Lastly, after the broadcast report window elapses, the GW's single-hop neighbours attempt to deliver their ND reports directly to the GW using unicast transmissions with ACKs and uniform random backoff (e.g. between 0 and 5 sec). These nodes also include the ND data they received from their neighbours in the previous window. The duration of this unicast report window  $\tau_{urw}$  is determined as follows:

$$\tau_{urw} = N_{\text{attempts}}^{\max} (\tau_{\text{ndr}} + T_{\text{timeout}} + T_{\text{backoff}}^{\max}) + T_{\text{guard}} \quad (1)$$

where  $N_{\text{attempts}}^{\max}$  is the maximum number of transmission attempts,  $\tau_{\text{ndr}}$  is the duration of an ND report packet,  $T_{\text{timeout}}$  is the ACK timeout duration,  $T_{\text{backoff}}^{\max}$  is the maximum backoff period, and  $T_{\text{guard}}$  is the guard period to account for the propagation delay uncertainty.

The duration of these time windows must be appropriately dimensioned for a given network size, packet duration and number of probe and NDR packets broadcast by every node. The results in Section III give an example of this.

At the end of these three fixed length time windows, the ND procedure is complete, and all nodes, including the GW, have information about their two-hop neighbourhood.

### III. SIMULATION STUDY

In this section we evaluate the OCTAVE protocol using the MATLAB network simulator developed in [14]. It uses a BELLHOP-based UWA channel model described in [15], that uses beam tracing data for 50 network topologies (for every network size), with every topology simulated using 50 random seeds. A Signal-to-Interference-plus-Noise (SINR) threshold of 3 dB is used to determine whether a given packet is successfully received and decoded.

The simulated network topologies comprise 10–100 UWA sensor nodes spread randomly in a  $6 \times 6$  km<sup>2</sup> area near the sea bed at 470–490 m depth, and a surface GW in the middle of this area with its modem at 10 m depth. The UWA

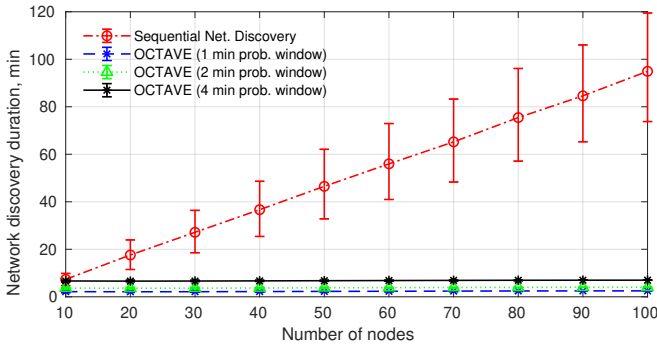


Fig. 2. Network discovery phase duration.

modem specifications are: 24 kHz centre frequency, 7.2 kHz bandwidth, 6000 bit/s bitrate (uncoded), 1/3 coding rate [16].

We evaluate the network performance under unreliable link conditions, i.e. when a proportion of transmissions fail due to random environmental factors, e.g. noise, multipath fading, Doppler, etc. This was modelled using a classical two-state Markov process [17], on top of the BELLHOP-based propagation model, to approximate large-scale UWA link fading. Both the duration of random link outage and the duration of normal link operation are exponentially distributed [18], with the mean link outage duration set to 10 s.

**Results.** Fig. 2 plots the average ND phase duration against network size, with the error bars showing the 10th – 90th percentile range. By design, OCTAVE runs in fixed time regardless of the network size, which is crucial for scalability to large UANs. However, the probability of probe collision (Fig. 3) increases with the network size due to an increased contention for the channel. The time required to complete a ND phase using the sequential collision-free protocol from [13] increases approximately linearly with the network size, which makes it impractical for large UANs.

Fig. 3 shows how the probability of probe packet loss is affected by the duration of the probing window. In these simulations, the probability of random link outage (due to environmental factors) was set to 0.1, while any additional packet loss incurred by OCTAVE was due to probe collisions. As expected, shorter probing windows lead to an increase in probe collisions. For example, in 80 node networks, reducing the probing window from 4 to 2 minutes increased the probability of probe packet loss from 0.2 to 0.3. The probing window size must be appropriately dimensioned to provide the desired trade-off between the reliability and speed of ND. A theoretical framework for determining the protocol parameters for this will be developed in further work.

Fig. 4 examines the robustness of ND in different channel conditions: ranging from 0 to 0.4 probability of random link outage. It shows the probability of node discovery – calculated as the ratio between the number of nodes that were discovered by the GW and the maximum possible number of nodes that could be discovered. These results are for 30-node networks. The plot shows that OCTAVE is able to discover nodes significantly more robustly in poor channel conditions,

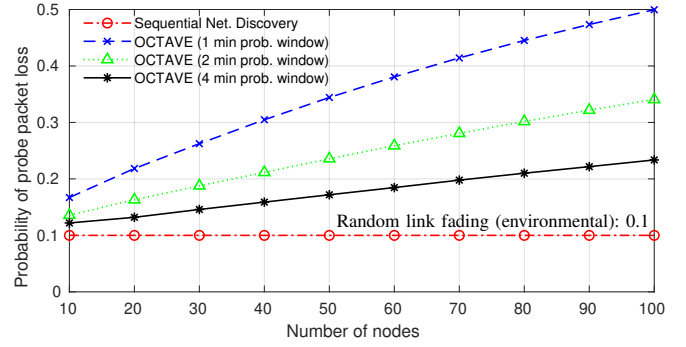


Fig. 3. Probability of probe packet loss during network discovery.

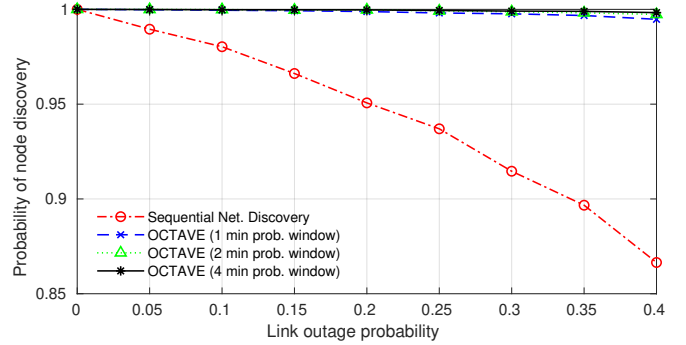


Fig. 4. Probability of node discovery in different channel conditions.

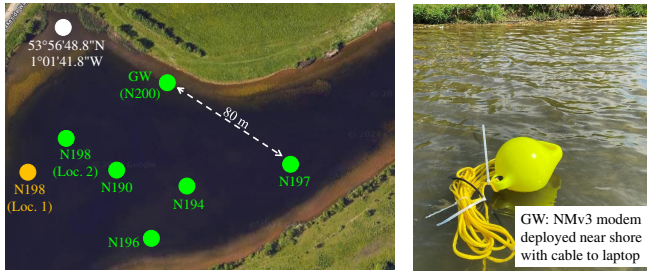
because the network links are being discovered and tested in a distributed way, instead of sequentially.

#### IV. LAKE TRIALS

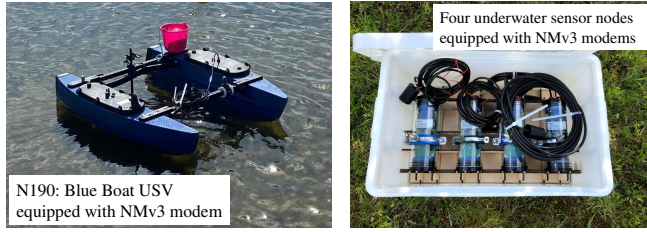
In this section we report the outcomes of deploying a “proof-of-concept” UAN running the OCTAVE ND protocol in lake trials on the Heslington East lake at the University of York campus on 9 May 2024. The simple version of the OCTAVE protocol was implemented, where the probing window was followed by the unicast report window, i.e. without the broadcast report window in the middle. The full OCTAVE protocol will be implemented in hardware and tested using a larger network in our further work.

Fig. 5 summarises the experimental setup. A six node network was used: the gateway modem was deployed near the shore in shallow water (approx. 40 cm depth), four underwater sensor nodes and a Blue Boat USV were deployed in approx. 1–2 m deep water, at the locations shown in Fig. 5a. All nodes were equipped with the NMv3 acoustic modems, operating at 640 bit/s and 168 dB re 1  $\mu$ Pa @ 1m source level [19]. More details of this hardware setup are given in [13]. Note that there was no connectivity observed with Node 198 for 32 consecutive ND phases; therefore, it was moved from its initial deployment location as shown in Fig. 5a.

The lake trial consisted of 83 OCTAVE ND phases (from 11:42 to 14:33 on 9 May 2024), with the probing window duration varied between 20 and 60 sec. The main goal of the trial was to validate the protocol design and demonstrate its constant time operation. Fig. 6 shows that this was achieved successfully; the time it took for the gateway to discover the



(a) Node locations (N198 was moved) (b) Gateway node (N200)



(c) BlueBoat node (N190) (d) Four underwater sensor nodes

Fig. 5. Lake trial setup.

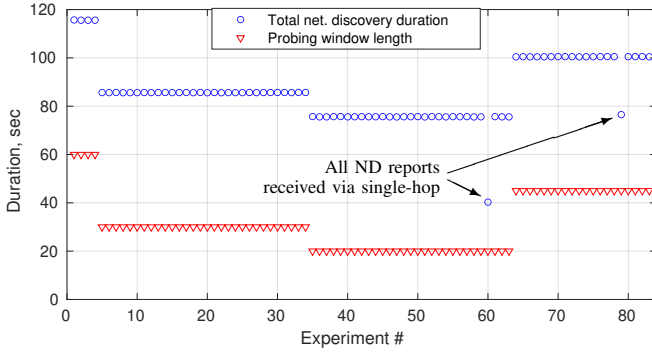
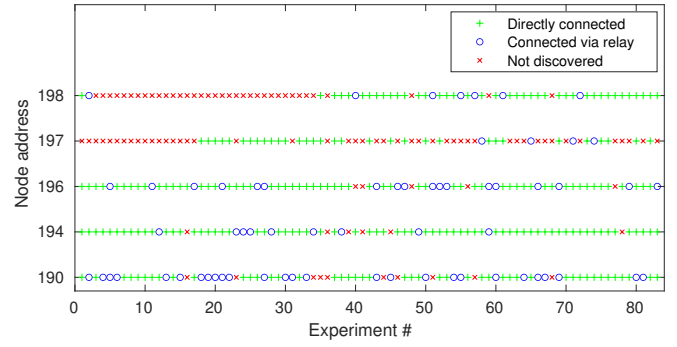


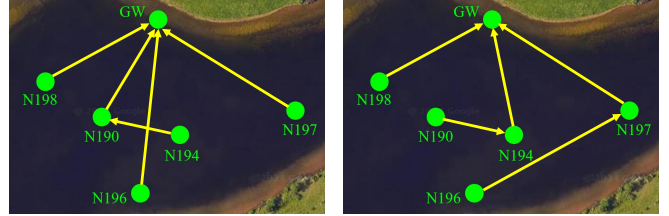
Fig. 6. Network discovery duration in the lake trial.

network and establish the routes had a fixed maximum value which comprised: 1) the probing window (20 – 60 sec); 2) the unicast report window. The latter window was 50 sec in all experiments to allow for a maximum number of 5 attempts, each with a 5 sec ACK timeout and the maximum backoff time of 5 seconds (see Equation (1)). Note that in this short range deployment the ACK timeout could have been much shorter (e.g. 1 second), which would have shortened the unicast report window to 30 sec. Furthermore, as soon as the GW receives a report from every sensor node in the network, the ND procedure is finished. In this trial, it happened only in two experiments (60 and 79), as shown in Fig. 6, where all nodes delivered their ND reports directly to the GW via single-hop. In further work, the addition of the broadcast report window to the real-time protocol implementation will lead to a higher likelihood of such early completions of the ND.

Fig. 7a shows the variability in the node connectivity observed in the lake trial. It shows whether the given node was connected via a single-hop or dual-hop link, or not discovered at all in that phase. Two of the nodes (197 and 198) experienced particularly poor connectivity, failing to be discovered



(a) Node connectivity timeline



(b) Topology established in Exp #38 (c) Topology established in Exp #60

Fig. 7. Network connectivity observed in the lake trial.

in many phases. However, after N198 was moved to a closer location (Exp #36), its connectivity significantly improved. Similarly poor acoustic performance due to extremely shallow depth and a large amount of vegetation was also observed in our previous trials on this lake [13]. Fig. 7b and 7c show two examples of topologies discovered in the trial. The routes were chosen by maximising the end-to-end total link quality. In many of the experiments, the single-hop links provided the highest end-to-end link quality, but in some cases the dual-hop routes (e.g. those shown Fig. 7b and 7c) were found to provide stronger links than direct connections to the gateway.

## V. CONCLUSIONS AND FURTHER WORK

The OCTAVE protocol based on opportunistic broadcast probing provides a solution for ND that runs in constant time regardless of the network size, density or channel conditions. It does not require clock synchronisation among the network nodes; instead, the gateway node specifies the duration of the three stages of OCTAVE ND as part of its probe transmissions. There is a trade-off between minimising the duration of the ND phase and minimising the probability of probe packet loss. Nevertheless, simulations showed that the OCTAVE protocol provides a significantly more robust ND solution in the presence of random link fading, even with relatively short probing windows and high probe packet loss, compared with a sequential collision-free ND approach. The protocol was implemented in hardware and tested in the Heslington East campus lake on 9 May 2024. This lake trial demonstrated successful performance of the protocol with a fixed maximum runtime in challenging acoustic channel conditions and highly time-variable node connectivity. Future work includes further implementation and refinement of the hardware prototype and larger scale lake and sea trials.

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