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Unsynchronized Dual-Hop Scheduling for Practical Data Gathering in Underwater Sensor Networks

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***Abstract*—In this paper, we propose a centralized dual-hop scheduling approach for efficient and practical data gathering in underwater acoustic sensor networks - Sequential Dual-Hop Transmit Delay Allocation MAC (SDH-TDA-MAC). The practical advantages of this approach include scalability to large networks, little control overhead, no requirement for clock synchronization and low energy consumption and computational complexity. BELLHOP-based simulations reveal that our proposed protocol can achieve full network connectivity with 15 dB lower transmit power, compared with standard single-hop TDA-MAC, while still achieving network throughput in excess of 50% of the theoretical maximum. Furthermore, a comparison with sequential polling show that our proposed protocol can facilitate multiple times faster data gathering by utilizing TDA-MAC for all many-to-one connections at the surface gateway and relay nodes.**

***Index Terms*—Medium Access Control, TDA-MAC, Underwater Acoustic Network, Wireless Sensing**

I. INTRODUCTION

The use of wireless sensor networks (WSNs) for remote monitoring of the ocean environment is becoming an increasingly popular research subject, owing to the modern developments in underwater acoustic modem technologies [1] [2]. It is investigated as a solution to a range of environmental monitoring tasks, such as water pollution measurements [3], fish tracking [4], seismic monitoring [5], etc. The WSN approach to ocean monitoring provides significant advantages over the traditional deployment of data logging sensor nodes from dedicated ships, because WSNs allow flexible long term deployments and eliminate the need to retrieve the sensor nodes from the sea bed in order to collect the data.

In contrast with terrestrial wireless communication systems, underwater radio propagation is severely limited in range due to high absorption of electromagnetic (EM) waves in seawater, while optical communications suffer from both high absorption and optical scattering [6]. Acoustic waves are the preferred practical medium of communication in the underwater environment; they exhibit significantly better propagation characteristics compared with EM waves. However, acoustic communications are fundamentally limited by the low sound propagation speed, approximately 1500 m/s in water, and by low bandwidth with carrier frequencies typically limited to tens of kHz, or lower for long range transmissions [2] [6].

The long propagation delays of acoustic signals present a significant challenge in Medium Access Control (MAC), i.e. coordinating transmissions of multiple acoustic communication nodes potentially spaced kilometres apart from one another. Much of the well-established research on MAC in underwater acoustic networks (UANs) focuses on schedule-based TDMA protocols. There, the nodes are scheduled to transmit their data packets in particular time slots such that the packets arrive at the intended receivers without collisions, e.g. [7] [8] [9]. Schedule-based MAC schemes do not involve contention for communication resources, thus removing the need for control signalling, e.g. Request-to-Send (RTS), Clear-to-Send (CTS), acknowledgements etc., in order to establish collision-free links. Therefore, they are capable of achieving high throughput by efficiently scheduling transmissions in a way that results in a stream of data packets separated by guard intervals at the intended receivers. The drawback of such coordinated scheduling protocols is their need for clock synchronization across different nodes, which is a challenging task in UANs due to long propagation delays, noisy time-varying multipath channels, and the signaling overhead that is not negligible compared with terrestrial radio systems [2] [10]. The use of chip-scale atomic clocks is an alternative way of providing an accurate synchronized time reference to the network nodes for long periods of time, but they are not feasible in many scenarios, in particular due to their excessive cost, higher power consumption and ageing [11] [12].

In this paper we consider the problem of scheduled data gathering in large networks of low cost, low specification sensor nodes that are currently being investigated in the EPSRC "Smart dust for large scale underwater wireless sensing (USMART)" project [13]. In particular, we focus on designing a practical MAC protocol with the following key properties:

- scalability to large networks (up to hundreds of nodes),
- no requirement for clock synchronization,
- little control signalling overhead,
- low energy consumption,
- low computation requirements.

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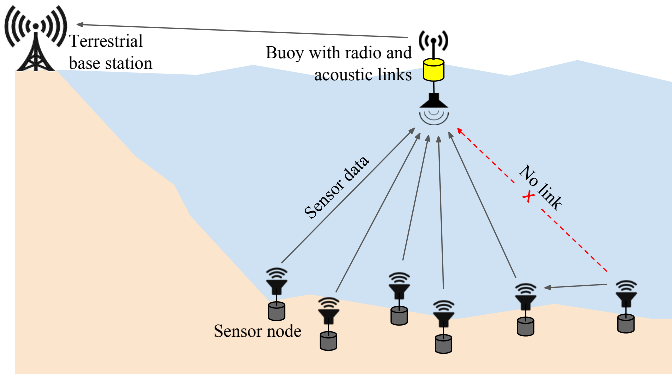


Fig. 1. Underwater wireless sensor network deployment with sensor nodes on the sea bed and a surface buoy used as the gateway node.

To this end we propose the Sequential Dual-Hop Transmit Delay Allocation MAC (SDH-TDA-MAC) approach to data gathering in UANs, improving on our previous work on the single-hop TDA-MAC protocol [14] that was designed with the same practical considerations as above. The key feature that separates SDH-TDA-MAC from TDA-MAC is that the former can operate in dual-hop topologies, thus dramatically reducing node outage due to acoustic shadows and surface node's limited coverage, and improving energy efficiency by using shorter links at lower transmit power.

The rest of the paper is organized as follows: Section II introduces the TDA-MAC protocol and its application to data gathering in UANs; Section III extends this protocol to a dual-hop setting and gives details of the SDH-TDA-MAC protocol proposed in this paper; Section IV evaluates the performance of the proposed protocol using a detailed simulation model; finally, Section V concludes the paper.

II. Data Gathering in UANs Using TDA-MAC

Fig. 1 shows a typical underwater WSN deployment scenario that is considered in this study. There, a buoy is used as the surface gateway node to gather the readings from sensor nodes deployed on the sea bed via acoustic communications, and to relay these sensor readings to an on-shore base station via a wireless radio link.

In [14] we proposed the TDA-MAC protocol for centralized scheduling of data transmissions from sensor nodes connected to the same gateway node, such as in the scenario depicted in Fig. 1. Its main advantage over other MAC protocols found in the literature is that it can achieve network throughputs close to the maximum channel capacity, while not requiring clock synchronization or any other advanced functionality at the sensor nodes. Therefore, it shows great potential as a practical solution for efficient data gathering in UANs. Fig. 2 gives a simple example that shows the packet flow in TDA-MAC. There, the gateway node transmits a broadcast data request (REQ) packet that is received by every sensor node at a different time (due to long propagation delays of acoustic links). Each sensor node then waits for a specific (individually

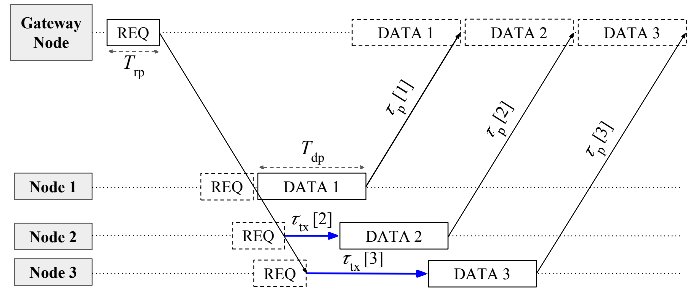


Fig. 2. TDA-MAC packet flow example, where a single gateway node gathers data from 3 sensor nodes [14].

assigned) amount of time before transmitting their data packet back to the gateway node.

The gateway node assigns a transmit delay to every individual sensor node using the following iterative equation:

$$\tau_{\text{tx}}[n] = \tau_{\text{tx}}[n\text{-}1] + T_{\text{dp}}[n\text{-}1] + T_{\text{g}}[n\text{-}1] - 2(\tau_{\text{p}}[n] - \tau_{\text{p}}[n\text{-}1]), \quad (1)$$

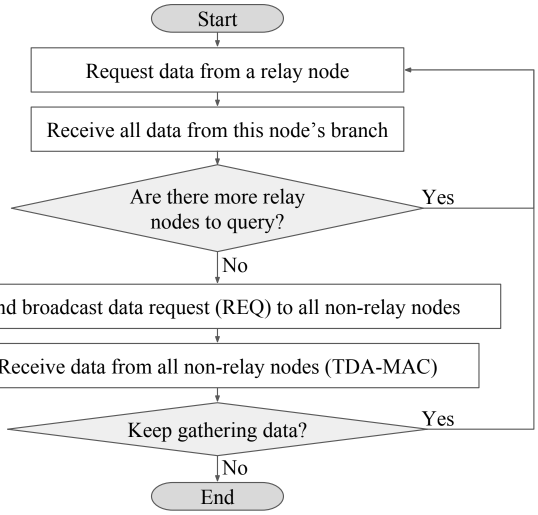
where $\tau_{\text{p}}[n]$ is the estimated propagation delay from the gateway node to the n^{th} sensor node, $\tau_{\text{tx}}[n]$ is the transmit delay assigned to the n^{th} sensor node, $\tau_{\text{tx}}[1] = 0$, i.e. the first node starts transmitting its data packet as soon as it receives the REQ packet from the gateway node, $T_{\text{dp}}[n]$ is the duration of the n^{th} node's data packet and $T_{\text{g}}[n]$ is the guard interval after the n^{th} node's data packet reception at the gateway node. The nodes in the $\boldsymbol{\tau}_{\text{tx}} = (\tau_{\text{tx}}[1], \tau_{\text{tx}}[2], ..., \tau_{\text{tx}}[N])$ and $\boldsymbol{\tau}_{\text{p}} = (\tau_{\text{p}}[1], \tau_{\text{p}}[2], ..., \tau_{\text{p}}[N])$ vectors are sorted from the shortest to the longest propagation delay from the gateway node. In some cases, transmit delays calculated using (1) may be negative. Then they are set to zero before continuing to iterate over the rest of the nodes in $\boldsymbol{\tau}_{\text{tx}}$.

The guard interval $T_{\text{g}}[n]$ is an important design parameter that is used to avoid packet collisions due to inaccuracies in propagation delay estimates, slow variations in node positions and the multipath spread. For example, in this paper we use a 100 ms guard interval which can tolerate approximately up to 150 m changes in relative node positions before the transmit delays have to be adjusted to compensate for the drift.

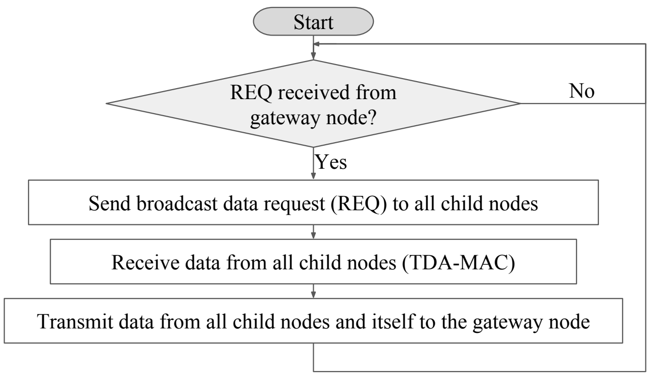
The only prerequisite for implementing TDA-MAC is the knowledge of propagation delays between the gateway node and every sensor node, which can be measured using a sequence of ping signals during the initial network deployment. Afterwards, during the normal operation of the network, the gateway node can continuously monitor the accuracy of the estimated propagation delays by measuring the error in the timing of the received data packets. For full details of the initialization process and operation of TDA-MAC, see [14].

III. Sequential Dual-Hop TDA-MAC

The main disadvantage of TDA-MAC is that it requires a centralized single-hop topology, which cannot accommodate nodes outside of coverage of the gateway node, e.g. due to acoustic shadows or if a sensor node is out of range of the gateway node. In this section we propose Sequential Dual-Hop



(a) Implementation at the gateway node



(b) Implementation at the relay nodes

Fig. 3. The Sequential Dual-Hop TDA-MAC protocol. The gateway node first gathers data from all relay nodes (including their child nodes), and then uses TDA-MAC for the remaining directly connected nodes. Relay nodes employ TDA-MAC to gather data from their child nodes.

TDA-MAC (SDH-TDA-MAC), an extension of TDA-MAC, that can operate in a dual-hop setting, i.e. those nodes that do not have a direct link with the gateway node can be connected via another sensor node that acts as a relay. Therefore, in addition to scheduling, SDH-TDA-MAC also incorporates the routing process, i.e. managing the hops between sensor nodes to deliver the packets to the gateway node.

The advantage of our proposed dual-hop approach, compared with more generic distributed multi-hop MAC protocols, is that limiting the number of hops to two and controlling the entire network operation at a single gateway node reduces the amount of uncertainty about the channel availability and, thus, reduces the amount of control signalling and idle listening time required, e.g. RTS/CTS and ACKs. This in turn enables the network to achieve high throughputs atypical for multi-hop UANs, as shown in the results in Section IV.

First, the links between the gateway node and all in-range sensor nodes, and the links between the relay nodes and out-of-coverage sensor nodes, need to be established via the network discovery and localization processes, including the propagation delay estimation for every link. The details of our implementation of these functions are out of the scope of this paper. However, there are a number of algorithms proposed in the literature that can achieve this goal, e.g. [15] [16].

After all the links and their propagation delays are established, the network employs the SDH-TDA-MAC protocol explained in Fig. 3. The gateway node gathers data from every relay node's branch of the network sequentially (see Fig. 3a). This avoids packet interference between different relay branches due to the space-time uncertainty, at the cost of a reduction in channel utilization efficiency, which is examined in the simulation results in Section IV. However, all other transmissions from sensor nodes to their gateway (Fig. 3a) or relay node (Fig. 3b) are performed using TDA-MAC described in Section II, which significantly speeds up the data gathering process compared with individually polling every sensor node.

IV. Simulation Results

A. Simulation Setup

Table I describes the parameters of the MATLAB model used for the simulation experiments in this paper. They correspond to a UAN data gathering scenario with 100 low cost, low specification sensor nodes deployed across a 6×6 km area on the sea bed at 470-490 m depth.

TABLE I
Simulation parameters

Parameter	Value
Sensor node coverage area	6×6 km
Number of nodes	100 (uniform random positions)
Sea depth	500 m
Surface node depth	10 m
Sensor node depth	Uniform random, 470-490 m
Frequency channel	24-28 kHz
Transmit power	140-170 dB re μPa @ 1 m
Channel bitrate	140 b/s [17]
Packet size	Data: 128 bits, REQ: 32 bits
SNR threshold for reception	-12 dB [17]
Noise power	Ambient noise model [18], 10 m/s wind speed, 0.5 shipping activity factor
Channel model	BELLHOP with multipath fading [19]
Sound speed profile	Based on average summer data at (56.5^{o}N, 11.5^{o}W) [20]

The channel between every pair of nodes was modelled using the BELLHOP ray tracing program [19], a well-established platform for simulating underwater acoustic wave propagation. For every source-receiver pair, the output of BELLHOP includes N echoes, each with a spreading loss $A_{\text{spr}}(n)$, propagation delay τ_n and phase shift θ_n. We then calculate the linear channel gain as follows:

$$G = \int_{f_{\text{min}}}^{f_{\text{max}}} \left| \sum_{n=1}^{N} A_{\text{spr}}(n)\ A_{\text{abs}}(n,f)\ e^{j(-2\pi f(\tau_n - \tau_0)+\theta_n)} \right|^2 df, \tag{2}$$

where f_{min} and f_{max} are the minimum and maximum frequency in the simulated channel, $A_{\text{abs}}(n,f)$ is the absorption loss of the n^{th} echo at frequency f calculated using Thorp's formula [18], and τ_0 is the propagation delay of the first received echo.

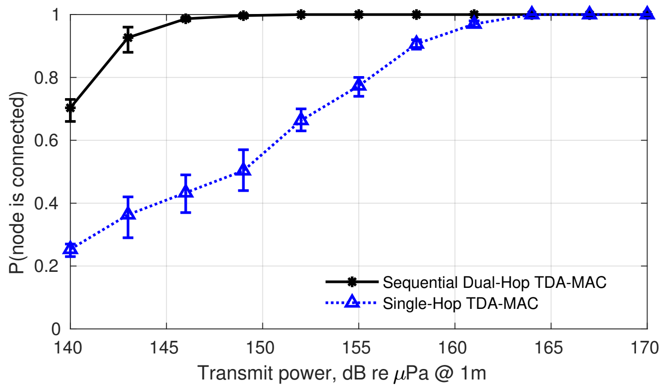


Fig. 4. Extending TDA-MAC from single-hop to dual-hop dramatically improves the probability of a node being connected and reduces the transmit power required to achieve full connectivity.

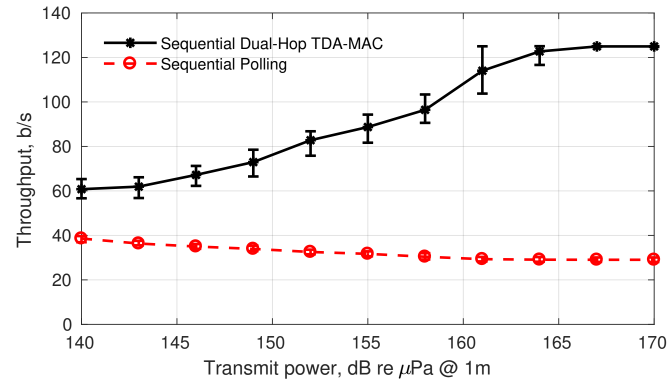


Fig. 5. Sequential Dual-Hop TDA-MAC achieves signficantly higher data gathering throughput compared with multi-hop sequential polling.

B. Network Connectivity

Fig. 4 shows the improvement in network connectivity achieved by SDH-TDA-MAC, compared with single-hop TDA-MAC. A connection between any pair of nodes is assumed to be present if the Signal-to-Noise Ratio (SNR) at the receiver is above the minimum threshold of -12 dB [17]. All datapoints show an average of 50 simulations with different random seeds and node locations, with the error bars representing the 5th and 95th percentiles. The plot shows that the sensor nodes can afford to reduce their transmit power by approximately 15 dB to maintain full network connectivity via the dual-hop protocol, which can dramatically extend the battery life and reduce the cost of the sensor nodes. Fig. 4 also shows that even in scenarios where roughly 50% of the sensor nodes are out of the gateway node's communication range (149 dB re μPa @ 1 m transmit power), those nodes can establish dual-hop links to achieve full connectivity, thus greatly improving network coverage.

C. Network Throughput

Fig. 5 shows how the aggregate throughput from all single-hop and dual-hop connected nodes changes with transmit power, i.e. ranging from only ≈25% of the nodes with a single-hop connection to the gateway node to a 100% single-hop topology. The results at 167-170 dB re μPa @ 1 m show that in a single-hop topology TDA-MAC performs highly efficiently and achieves 125 b/s throughput, 89% of the total 140 b/s channel capacity, with most of this throughput loss being due to a purposely designed 100 ms guard interval between the data packet slots. As the transmission range decreases, the SDH-TDA-MAC protocol is still able to achieve high network throughput. For example, at 149 dB re μPa @ 1 m transmit power, when on average 50% of the nodes are connected via dual-hop links, the network throughput is 73 b/s which is still more than 50% of total channel capacity.

Fig. 5 also compares the network throughput achieved by the SDH-TDA-MAC protocol with that provided by sequential polling, similar to UW-Polling [21] but optimized for our static scenario. It works similarly to the flowchart shown in Fig. 3, but instead of employing TDA-MAC, the gateway and relay nodes gather the data by sequentially polling their child nodes. The plot shows that using TDA-MAC for all direct many-to-one communication links controlled by the gateway and relay nodes improves network throughput by a factor of 2-4 in full network connectivity scenarios, i.e. with transmit power ≥149 dB re μPa @ 1 m. For example, at 149 dB re μPa @ 1 m, SDH-TDA-MAC is able to collect data from all 100 nodes in just under 3 minutes, whereas it takes sequential polling over 6 minutes to achieve the same task. At 164 dB re μPa @ 1 m transmit power, when most of the nodes have a direct link with the gateway node, SDH-TDA-MAC can gather data every 1 min 45 sec, while the fastest data gathering achievable via sequential polling is every 7 min 20 sec. This allows the underwater sensor network to monitor the environment considerably closer to real-time.

V. Conclusions and Further Work

The SDH-TDA-MAC protocol proposed in this paper facilitates efficient data gathering in UANs via centralized dual-hop scheduling, but without the need for clock synchronization among the sensor nodes. BELLHOP-based simulations revealed that SDH-TDA-MAC can achieve full network connectivity with 15 dB lower transmit power, compared with its single-hop counterpart, while still achieving throughputs in excess of 50% of the theoretical maximum. This is because of the spectral efficiency of TDA-MAC employed for all many-to-one connections at the gateway and relay nodes. A comparison with sequential polling showed that our proposed protocol can improve the data gathering speed by a factor of 2-4, depending on the number of sensor nodes that are out of the surface gateway node's coverage.

In conclusion, the high throughput, low transmit power and no requirement for clock synchronization make SDH-TDA-MAC an efficient and practical data gathering approach.

Further work includes utilizing more detailed localization information to allow for spatial reuse of the channel at separate relay nodes, and extending this MAC approach beyond dual-hop to an arbitrary number of hops, which will also require more sophisticated routing strategies.

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