Adaptive Space Time - Time Division Multiple Access (AST-TDMA) Protocol for an Underwater Swarm of AUV's

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***Abstract*—This paper presents a new MAC protocol: Adaptive Space Time – TDMA (AST-TDMA) for Autonomous Underwater Vehicles (AUV) operating as a swarm in the open ocean. The aim of the protocol is to allow the dissemination of navigational information amongst the vehicles as quickly as possible such that they may operate as a group in a swarm like fashion.**

The proposed new protocol incorporates a method to handle the unique channel characteristics experienced underwater, in particular low bandwidths and long propagation delays and is designed to operate in a single channel broadcast acoustic environment. The protocol is based on a TDMA approach where vehicles are allocated a slot in a cycle. In AST-TDMA however, the slot size is not fixed but will adaptively change, from slot-to-slot and cycle-to-cycle, due to the changes in range and therefore propagation delay resulting from vehicles position in the swarm and the swarm movement. As slot size varies, so will the cycle time for the exchange of each vehicles' information.

AST-TDMA has significant advantages over other time-based protocols as it avoids both the need for guard times and time synchronization, which are both major drawbacks in time based protocols. It also works with the spatial-temporal diversity created in long propagation delay environments to allow 'non exclusive channel access' in a single channel, while maintaining the collision avoidance benefit of contention free protocols. This is demonstrated through simulation.

A new metric, NCCP, was developed to test the new MAC protocol for swarm operational effectiveness. It has been shown through simulations that the AST-TDMA protocol outperforms TDMA for swarm operations in its ability to disseminate information in a timely manner and with higher channel utilization. Using AST-TDMA also allows a much higher density of vehicles to operate in a swarm like network.

Keywords—medium access control protocol, TDMA; underwater acoustic communication; swarm networks

I. Introduction

Mobile swarms of autonomous underwater vehicles (AUVs) have exciting potential for extending the current operational sensor network applications underwater and to add new opportunities to the working environment of the oceans. Applications include areas such as mapping and surveying [1, 2], military tasks such as to replace workers for dangerous tasks in ocean war zones [3], 3D plume identification and analysis [4] and other more general scientific and commercial studies of dynamic oceanographic phenomena such as phytoplankton growth or fish migration [5,6,7]. Current solutions have been built around static sensor networks and single ROV's (remotely operated vehicles) and single AUV's. The benefits, however, of several vehicles working together over any single vehicle include greater speed and range of operation, increased system reliability and higher quality measurements [1,3]. To achieve these multi-vehicle system benefits, data communication between vehicles is essential.

Typically, a swarm of AUV's can be considered as being composed of many simple, homogeneous and autonomous agents, deployed in a decentralized mobile topology with interaction on a local level for a combined purpose. The communication protocol for a swarm needs to facilitate 'awareness' of other vehicles in a neighborhood and needs each vehicle to be able to work autonomously. Swarm control algorithms require at a minimum, to exchange location information from all vehicles to all vehicles in a neighborhood in a continuous fashion, so that the network can operate in a swarm-like behavior. Thus the MAC protocol needs to operate in a distributed manner, that is without any central controller, and needs to minimise the end-to-end packet delay to each vehicle whilst being able to exchange navigational information around all vehicles within the swarm in a timely fashion.

In this paper, a new MAC layer protocol is proposed, the Adaptive Space Time – Time Division Multiple Access (AST-TDMA) protocol, which is designed to effectively use a single channel broadcast acoustic environment while incorporating a method to handle the unique characteristics of long propagation delay and low bandwidths underwater. It has been designed to work independently of time synchronization, require no guard times and no prior knowledge of propagation delays. Section II of this paper provides a review of research into acoustic swarm communication and the spatial-temporal phenomena experienced underwater. In Section III, the new protocol is described, and Section IV provides a description of

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the swarm topology used. The simulation analysis and results are presented in Sections V and VI respectively.

II. Recent Work

A. Medium Access Protocols for Underwater Swarms

There is a growing interest in the research community around the coordination and formation control algorithms for underwater multi-vehicle mobile networks [2,3,4,7,8], however the focus has been on more sparsely deployed networks that only require periodic updates due to the distances between vehicles and therefore more sporadic communication is acceptable.

Paley [8] and Chen [7] based their work on the co-ordination of sparsely deployed gliders, while Petillo [4] and Yoon [2] investigated multi-vehicle deployment using AUV's. The designs proposed by both Petillo and Paley included vehicles surfacing periodically. Petillo [4] suggested that until better swarm communications is possible then 'Periodic Surface Communication' would work best where AUV's need to surface with enough frequency to obtain information that could re-direct them to more optimal sampling positions. Paley [8] also used periodic surfacing to access the RF network and to access GPS co-ordinates. The option of surfacing however takes away the ability of maintaining a practical real-time swarm operation, which limits the application and operational functionality and efficiency of the network.

A number of solutions have been proposed for the design of communication protocols for mobile multi-vehicle underwater networks [3,5,6,9]. Of these only Daladier [6] and Schill [5] have focused on swarm like structures, where intelligent, multi-vehicle AUV's are operating at close ranges and in quite dense deployments and thus with the need for short range communication with continuous interchange of information.

Daladier [6] investigated the use of an OFDMA (Orthogonal Frequency-Division Multiple Access) physical layer and determined that only 3 sub-channels were possible because of the small bandwidths available under water and combined this with a MACAW (Multiple Access with Collision Avoidance for Wireless) MAC layer protocol. Only low throughputs were shown because contention based approaches such as this require handshaking and re-transmission strategies that can both reduce channel utilization and increase packet delay. This contention-based approach did not take advantage of the knowledge of continuous data traffic required by the swarm.

Schill [5] used a TDMA protocol that incorporates a request slot within each timeslot to allow vehicles to identify that they will need a future slot to send a packet. Schill's protocol requires time synchronization, which can be problematic under water and it also requires the use of node scheduling that is really superfluous when continuous traffic conditions between all vehicles is expected.

Using a time-based protocol however has many advantages for swarm communications. Due to the density of vehicles, the broadcast nature and continuous traffic required in swarm communication and the spatial-temporal diversity (because of the propagation delays that are unique to underwater environments [10, 11, 12]), the probability of packet collisions occurring at the receiver is very high if a random access based protocol is used. Thus, a scheduling protocol can avoid collisions and therefore avoid re-transmissions as well as avoiding the issues of hidden and exposed nodes.

Time synchronization, however, is a significant disadvantage when working with time-based protocols and this is particularly problematic underwater where GPS is not available. To do time synchronisation between vehicles underwater has been approached in two ways: through signal processing or protocol design. Syed [10] demonstrated a software based time synchronisation algorithm in a high latency acoustic network which effectively synchronises clock offset and skew in two phases; suggesting reasonable accurate synchronisation is possible underwater if the propagation delay is predictable and static for short periods of time. In swarm operations this may not be possible. Alternatively, RIPT (Receiver-Initiated Reservation-Based Protocol) [15] is a protocol for peer-to-peer decentralized ad-hoc acoustic networks using receiver reservation to build a transmission schedule that avoids time synchronization, however with the need for handshaking higher end-to-end delays occur.

TDMA is the most common timing-based protocol which divides the channel access into time-slots, which are often incorporated into repeating frames or cycles. It is the variations in time-slot allocation or scheduling and time-slot length that determines the nuances of different TDMA protocols. Time slot length are determined by the transmission time of packets and a large guard time which is incorporated due to the variable and large propagation delays possible underwater and the potential synchronisation error times. Ahn [12] analysed the use of guard times underwater using the ALOHA protocol and showed that guard times were more influential when transmission time (t_t) > propagation delay (τ) and that fixed guard times lead to suboptimal throughtput, which are both problematic for short-range underwater acoustic systems. Yackoski [11] has designed a protocol so that guard times are not needed each slot but each cycle which has reduced the overall packet delay and increases channel utilisation, however, the protocol is limited by the 'experimental portion' which provides the scheduling that is required within the protocol.

A TDMA approach, in addition, has the advantage of simplicity, from a hardware and computational perspectives and energy efficiency viewpoint [11], which are practical features important to consider in any underwater system.

An Adaptive Token Polling MAC [13] and a Token-Based MAC [14] have both been suggested which have a similar approach to this work, however, they both require a leader node with a single point of control. The AST- TDMA protocol has been developed to operate in a distributed manner without any central controller or leader in an ad-hoc reconfigurable network. The aim is to minimise the information exchange period while maximising channel utilisation, by taking advantage of the unique spatial-temporal channel available underwater. Design considerations also included the need to work with time synchronisation and guard times while avoiding packet collisions.

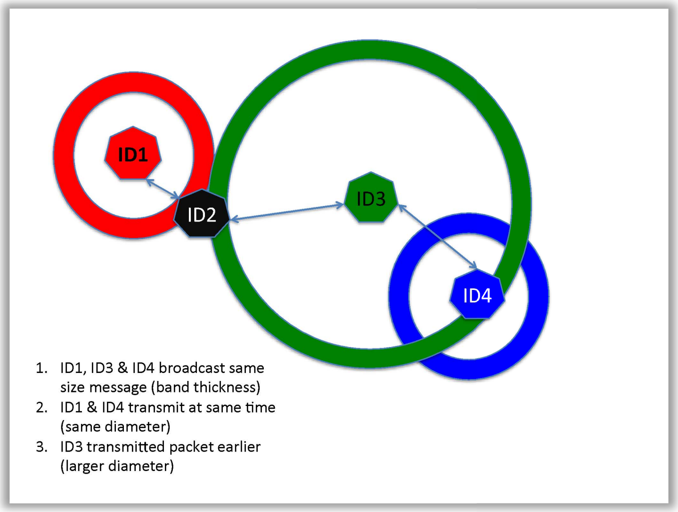

Fig. 1. Spatial-Temporal Diversity

B. *Understanding Spatial-Temporal Diversity Underwater*

The shorter range between vehicles in a swarm topology, considered in this paper, means that propagation delays will be smaller than for the more typical longer-range underwater applications. However, the delays are still significant when compared to transmissions in RF, where propagation delay is considered negligible. In fact, the transmission time for packets underwater in short range scenarios will be in the same order of magnitude as the propagation delay, which creates a unique spatial-temporal environment for underwater communication, and is far different from what is experienced in a terrestrial RF setting. Syed [10] & Yackoski [11] have illustrated this by showing that both the times of transmission and range to receiver need to be considered in underwater environments to avoid packet collisions, when comparison to traditional analysis where only the time of transmission is considered. That is, in RF, the propagation delay is considered negligible, which means that packets which start transmissions at the same time will collide at the receiver and thus protocols are designed for 'exclusive' channel access to avoid collisions.

Fig. 1 illustrates some of the spatial-temporal situations that can occur underwater when using a four-vehicle system, ID1 to ID4. The diagram shows one moment in time, where the ID3 packet was transmitted earlier than the ID1 and ID4 packets. Despite ID1 & ID3 starting their transmission at different times, their packets will collide at ID2, while the concurrent transmissions of the ID1 and ID4 packets will not collide at ID3 or ID2. Exclusive channel access based on transmission time of data becomes an ineffective way to avoid collisions, unless large guard times are incorporated to take into account propagation delays between all possible vehicles in the network. Therefore, non-exclusive access can occur due to the space diversity, which allows more than one transmission-reception activity in the channel at the same time, see Fig 2 and further discussion in Section III.

III. The AST-TDMA Protocol

The proposed new protocol is based on a TDMA approach where vehicles are allocated a slot in a cycle. Instead of the fixed slot size used in TDMA protocol, which is established from the transmission time and guard time (determined by the maximum propagation delay), AST-TDMA has an adaptively changing slot size. As slot size varies, so will the slot timing, and therefore the cycle time to disseminate information around the swarm which is one of the critical QoS requirements for short-range swarm communication.

The new protocol adaptively modifies the slot size based on the propagation delay between the transmitting vehicle and the vehicle next in the slot sequential. That is, the arrival of the packet at the vehicle which is next in the sequence, triggers that vehicle to send its packet immediately. Therefore, it is only the transmission time and propagation delay between these two vehicles that determines each slot size. Omni-directional antennas are used to broadcast (one-to-many) the packet, which will allow all neighborhood vehicles within hearing range to receive the transmitted packet. This protocol therefore can take advantage of the spatial-temporal diversity experienced underwater, by allowing concurrent transmissions in the channel, thus permiting 'non exclusive channel access'. Fig. 2 demonstrates this where vehicles are able to receive previous transmissions from other vehicles while the vehicle with the allocated transmission slot is transmitting. Transmitters are allocated a slot in a cycle, and even though these slots will vary in length and as a consequence the cycle times will vary, they are designed so that packet collisions are avoided. In addition, AST-TDMA has significant advantages over other time-based protocols as it avoids both the need for guard times and time synchronization, which are both major drawbacks in time based protocols.

Thus, AST-TDMA operates in a similar fashion to a token ring, in the context that, when a packet arrives at the vehicle, which is to send out the next packet, it acts like a token or trigger to give permission to that vehicle and no others to transmit. Thus the lowest ID vehicle, say vehicle ID1, begins the sequence by sending its data packet. When vehicle ID2 completes the reception of ID1's packet, it schedules and begins the transmission of its data packet. This can occur while ID1's packet is still propagating and being received by other vehicles in the neighborhood. Fig. 2 demonstrates the basic

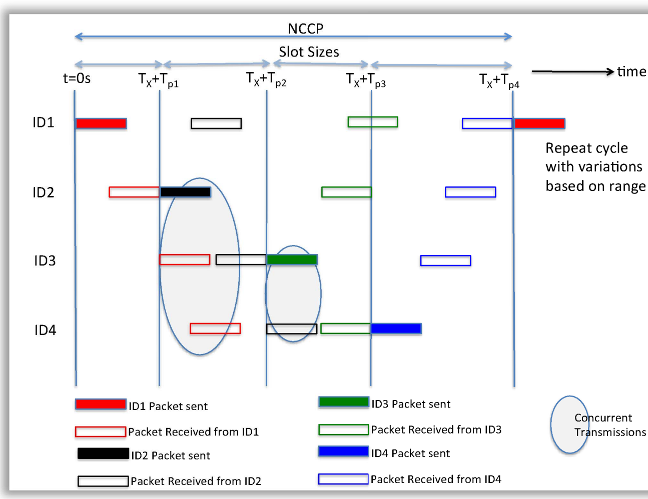

Fig. 2. AST-TDMA: One cycle of slot times based on configuration of Fig.1

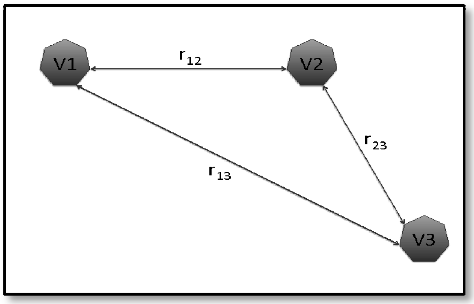

Fig. 3. Determining validity of AST-TDMA

principles of AST-TDMA using the topology of Fig 1. The protocol therefore effectively changes the slot size and timing of an information exchange cycle, which when vehicles are moving will mean that the slot size will vary cycle to cycle as well.

The most critical timing in this protocol and the essence to its success is to ensure the avoidance of packet collisions at a third vehicle such as V3 in Fig. 3. That is, V1's packet must have finished its reception at vehicle V3 by the time vehicle V2's packet arrives. This can be confirmed if the transmission time of the packet that goes directly to V3 is less than the transmission time via V2.

Using the triangle inequality, the range r13 ≤ r12 + r23 needs to be statisfied if this protocol is to work, refer to Fig. 3.

Let the propagation delay between vehicle V1 and V2 be pd_{12} and the transmission time of the packet sent from V1 is t_{t1}. Then let V1 be broadcasting a package to V2 and V3, with V2 next in line to broadcast its packet. To avoid a collision at the receiver of V3, the time for V1's packet to end reception at V2 and for V2's packet to start its arrival at V3, which is equal to $pd_{12} + t_{t1} + pd_{23}$, needs to be greater than or equal to the time for V1's packet to end reception at V3, which is $pd_{13} + t_{t1}$. Thus, $pd_{13} + t_{t1} \leq pd_{12} + t_{t1} + pd_{23}$ or,

$$pd_{13} \leq pd_{12} + pd_{23} \tag{1}$$

The propagation delay between vehicles i & j equals the range between them divided by the speed of sound underwater (1500m/s), i.e. $pd_{ij} = r_{ij}/1500$. Substituting, this in (1) gives $r_{13} \leq r_{12} + r_{23}$ which by the triangle inequality is true. If $r_{13} = r_{12} + r_{23}$ then the vehicles are in a straight line and the reception of the packet from V1 via r_{13} is completed at the time instance that the packet from V2 via r_{23} arrives. Thus without considering processing time, this would not cause collision. Slot size is thus determined and will vary from slot-to-slot and cycle-to-cycle based upon the distance between consecutive transmitters. However, it will always be less than or equal to a TDMA slot size which is determined by the maximum distance between any two transmitters in the network.

For the AST-TDMA protocol vehicles will need to know only the vehicle ID that it follows in sequence as this is the trigger for it to transmit and it will not need to have the complete sequence. The vehicle at the beginning of the sequence, will need to have prior knowledge of the number of vehicles within the neighborhood or swarm to define the end of the sequence so that the sequence can start again. In this paper, the vehicle's ID determines its sequence position, however alternative sequencing approaches are being developed for both increasing and decreasing the number of vehicles within the neighborhood as well as their position within the swarm.

Allowance also needs to be made in the protocol for two possible events that would disrupt the sequence. Firstly, if a packet did not arrive at the vehicle that is next in sequence to transmit its data, the cycle would be broken, as it would not be triggered to send the next packet. In this event the protocol uses a pre-determined back-off to trigger a transmission.

The second event that would break the cycle is if the vehicle that is to send the next data packet does not have a packet ready to send. Without it sending a packet, the following vehicle in sequence would not receive a packet to trigger it to continue the cycle. In this event a small 80 bit null token is used which will be the trigger for the next vehicle however it does force another cycle or part cycle for other vehicles as they have to wait until this vehicle sends an updated package. An alternative approach instead of using a null token is to trigger a short back-off which allows for processing time to generate a the new packet, which is then sent to continue the cycle.

The timing of the collection and processing of this sensor and navigational data is critical to the reliability of this protocol. The current design of the protocol, uses a constant inter-arrival time for the generation of vehicle information packets which are then ready to send and the rate of generation is set so that there is always a packet in the queue to send. If there is more than one packet in the queue, the queue will be flushed of the oldest packets and only the lastest packet will be sent. This however means that the packet will be created before the arrival of the last vehicle(s) information which means that previous cycles information is used. An alternative approach is being investigated that will only use the latest updated information, and therefore will require some processing time prior to transmission, which will be discussed further in Section V.

IV. Swarm Topology and Traffic

A swarm of AUV's is defined as a collection of V vehicles randomly distributed with ranges between consecutively transmitting vehicles being similar (except the range between the end vehicles in the String Topology to be defined later). It is assumed that each vehicle is identical, meaning that all vehicles in the network have the same capability. The only communication mechanism between vehicles is through a wireless acoustic medium using a single frequency band for transmission. Each node is capable of sending and receiving data at a channel data rate of 4800 bps. The transceiver will operate in half-duplex mode, that is, it will be either transmitting or receiving but not both at the same time and a single omni-directional antenna is mounted on each small vehicle. The operation of the antennas is in broadcast (one-to-many) mode, which is beneficial for three main reasons:

- vehicle orientation to horizontal is not always guaranteed and therefore there is potential for vehicles to be hovering off horizontal,

- transmission and reception needs to occur in at least two directions unless the vehicle is located on the outer edges of the neighborhood, and
- to avoid vehicle collisions, to be able to inform vehicles that venture too close to another vehicle not registered in its neighborhood

The traffic within a swarm needs to be continuous, as the location data of each vehicle needs to be distributed around the swarm on a frequent and regular basis for each vehicle to do its trajectory calculations. Based on the SeaVision AUV [16] the size of a packet to contain information about its relative position, direction, velocity and/or other sensor data as well as location of another close neighbour could be packaged into 40 bytes, with another 20 bytes of overheads, resulting in a 480 bit packet.

A simple topology will be analyzed as a stable structure; that is, all vehicles are moving in the same direction at the same speed and that all vehicles will maintain the same range between each other during the simulation. Vehicles will calculate their own next trajectory based on a swarming algorithm that requires the location data from all other vehicles in its neighborhood. The topologies of Fig. 4, a String Topology and Fig. 5 a Cluster Topology are used to demonstrate the advantages of AST-TDMA protocol. The first 5 vehicles Veh_1 to Veh_5 are placed identically. Vehicles Veh_6 to Veh_10 are wrapped around as a second line to create the Cluster Topology. Both topologies shown have

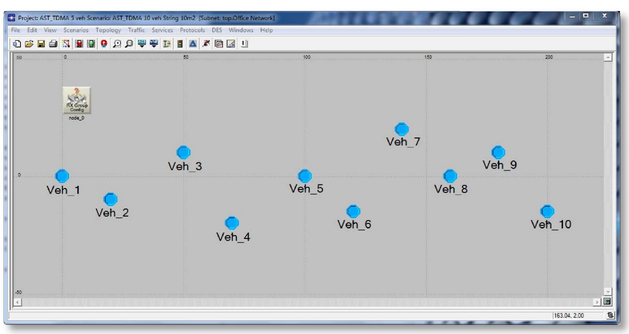

Fig. 4. String Topology

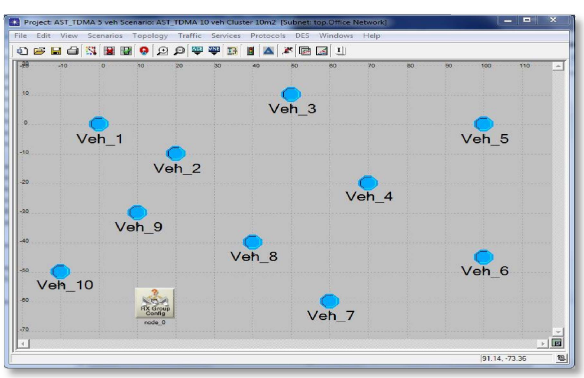

Fig. 5. Cluster Topology

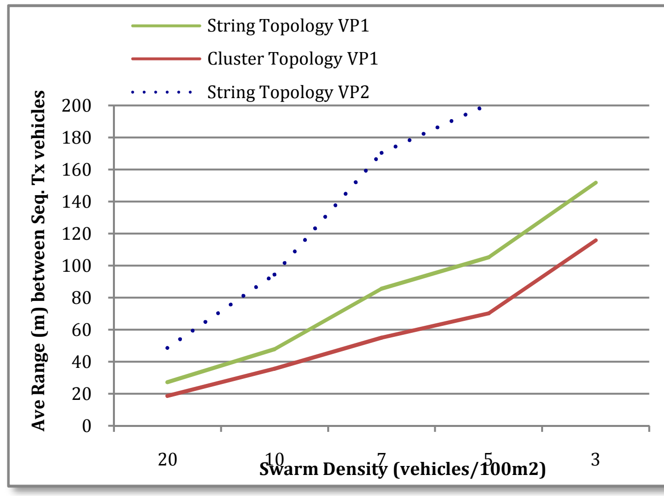

Fig. 6. Average Range between vehicles vs Swarm Density based on a 10 vehicle swarm

approximately the same density of vehicles being the ratio of number of vehicles to the 2-dimensional area (m^2) which is ~ 10 vehicles per 100 m^2. The maximum and average ranges for the String Topology is 200 m/48.3 m and for the Cluster Topology is 120 m/35.7 m. Four other densities of vehicles will be used, 20, 7, 5 & 3 veh/100m^2 each using 10 vehicle swarms. Fig. 6 shows the average range between the consecutively transmitting vehicles vs Swarm Density. This range can change when vehicles are placed in different locations in the swarm which may occur during mobile swarm operations. This is referred to as vehicle placement (VP) with VP1 as shown in Fig. 4 and 5 and VP2 having vehicles (Veh_2 & Veh_6) and (Veh_5 & Veh_8) swopped. A more gradual change in position would occur in real operations, however, VP2 is used to demonstrate the variations that will arise when vehicle sequencing is altered.

V. Simulation and Metrics

The performance of AST-TDMA was tested using OpNet (Optimized Network Engineering Tool) Modeler, which is an advanced network simulation tool. OpNet, however, does not have an acoustic underwater channel model and therefore modifications to the physical layer or pipeline stages were made to match the characteristics of a short-range acoustic channel. These characteristics include the transmission loss that is both range and frequency dependent and the SNR qualities, specifically related to the acoustic signal and unique noise features underwater.

Table I summaries the channel and transmission parameters used in the simulations unless otherwise stated. Also, results presented are those of Veh_1 unless otherwise stated. Variations in results between vehicles are generally small but do occur when using AST-TDMA due to the vehicles position and sequence within the cycle. Simulations were terminated when Veh_1 has successfully received 10,000 packets. An ideal channel (i.e.100% packet success rate) has been used in this paper to test the AST-TDMA protocol, which is compared against a simple TDMA protocol where the slot size is constant

TABLE I. MAIN PARAMETERS AND TRANSMISSION CHARACTERISTICS

Channel		Transmission	
Acoustic Signal	1500 m/s	Transmission Rate	4800 bps
Centre Frequency	35 kHz	Modulation	BPSK
Bandwidth	5 kHz	Data Packet Size	480 bits
Attenuation Model	Thorp [17]	Information packet generation rate	1 pkt/s
Vehicle Density	10 veh/100m^2	Transmission time	100 ms

TABLE II. NCCP$_{MIN}$ (S) FOR TWO DIFFERENT STATIONARY PLACEMENTS

		AST- TDMA		TDMA	
Vehicle Placement (VP)	*Swarm Density (veh/ 100m^2)*	*String Topology (s)*	*Cluster Topology (s)*	*String Topology (s)*	*Cluster Topology (s)*
1	10	1.32	1.23	2.3	1.8
2	10	1.63	1.44	2.3	1.8
1	7	1.57	1.36	3.4	2.3

and determined using the maximum propagation delay (τ_{max}) of the network plus the transmission time t_t.

The remainder of this section will discuss the key metrics used in testing the protocols and analysing its performance, with the results being presented in Section VI.

A. Neighbourhood Communication Cycle Period (NCCP)

An information exchange period, as described in Section III, and referred to as a Neighborhood Communication Cycle Period (NCCP), is defined as the time period where each vehicle has sent its information and each vehicle has received the equivalent information from all other vehicles in its neighborhood. The optimization of NCCP is critical to support up-to-date and continuous data communication so as to facilitate the required distribution of navigational and sensor data throughout the swarm to allow control of the swarm to be informed by this data.

The creation time of the vehicles information packet being sent is significant, as the older the navigational information received by neighborhood vehicles the less accurate their new trajectory calculations will be. Thus, NCCP is determined by the sum of the propagation delays between vehicles i and j (τ_{ij}), the transmission time (t_t) of each packet sent from each vehicle, and the time that the packet which was generated first in that cycle spent in the transmitter queue (t_{queue}).

$$\text{NCCP} = \sum_{i=0}^{V-1}\left(\tau_{ij} + t_t\right) + t_{queue} \quad (2)$$

where j = i+1 mod V

A simple TDMA protocol is used for comparison purposes. The NCCP for a TDMA protocol is:

$$NCCP_{TDMA} = \sum_{i=0}^{V-1} SS + t_{queue} \quad (3)$$

where SS is slot size = $\tau_{max} + t_t$

For the analysis, three other NCCP related values are important. NCCP$_{min}$, which is the theortical minimum NCCP time for one cycle that includes only the time for propagation and transmission of a packet from each vehicle. The other two NCCP times, NCCP$_{soft}$ and NCCP$_{hard}$ are working boundaries determined by the requirements of information exchange for safe and successful swarm operations. Each of these will now defined.

NCCP$_{min}$ assumes that transmitted data is generated in the vehicle at the time it is sent, therefore does not include t_{queue} and only includes one cycle. This is theoretically calculated to compare the two topologies of Fig. 4 & 5 and the two protocols, see Table II. Take the 10 veh/100m^2, 10 vehicle String Topology for example, NCCP$_{min}$ for TDMA = 10 * (0.1 + 0.13) = 2.3 s where packet length is 0.1 s and τ_{max} is 0.13 s ($\frac{200\,m}{1500\,m/s}$). For AST-TDMA, the cumulative propagation time, τ_{total}, between each vehicle in sequence is 0.32 s and transmission time for the 10 vehicles is 1 s (10*0.1 s) which means NCCP$_{min}$ for AST-TDMA = 1 + 0.32 = 1.32 s which is almost a 50% time saving.

Table II also shows the value of NCCP$_{min}$ for VP2 which will not change for the TDMA protocol based on the same swarm density and provided that the maximum range has not changed, but it will change for the AST-TDMA protocol. This does highlight the benefits of minimising the distance between vehicles that are next in slot sequence in the ADT-TDMA protocol which is not necessary for TDMA. A comparison is also made using VP1 with a more sparsely deployed swarm of 7 veh/100m^2, which shows that placement can be more important than the size of the area the swarm is operating in for minimising NCCP.

The soft bound, NCCP$_{soft}$, represents the preferred upper time interval required between re-calculation of each vehicles new trajectory to provide smooth swarm operations. A quicker cycle would be even better however there is a trade-off between a quicker cycle time producing a smoother operation, and the subsequent increase in energy consumption costs with more transmissions. In the first instance a suggested update of vehicle trajectory should occur at the range to maneuver out of danger and this will depend on such things as the maneuverability of the vehicle, the speed that the vehicles are travelling at and water currents. Based on knowledge of the SeaVision vehicle the following maneuverability ranges (M) were used: 3 m if vehicles are travelling at 1 m/s (i.e. 3 s) and 6 m at 2 m/s (i.e. 3 s). Water currents were ignored on the assumption that all vehicles will be affected equally.

Note that based on the NCCP$_{min}$ values shown in Table II, the TDMA String Topology of 7 veh/100m^2 has its minimum above 3 s, indicating that at this swarm density there is potential for vehicle collisions. Which means that either the number of vehicles or the area per vehicle needs to be reduced. Thus setting a limit to the size of the swarm and the swarm density.

The hard bound, NCCP$_{hard}$, is defined by ensuring that there are no vehicle collisions based on their range and speed. That is, using the worst-case scenario where two vehicles are

TABLE III. HARD AND SOFT TIME BOUNDARIES OF NCCP

		Vehicle Speed: 1m/s (2 knots)			Vehicle Speed: 2m/s (4 knots)		
Swarm Density veh/ 100m²	*Ave Rge (m)*	*Remain -ing Range (m)*	*NCCP hard (s)*	*NCCP soft (s)*	*Remain -ing Range (m)*	*NCCP hard (s)*	*NCCP soft (s)*
20	20	7	7	3	4	2	3
10	30	12	12	3	9	4.5	3
7	50	22	22	3	19	9.5	3

* This case the $NCCP_{hard}$ bound is the maximum NCCP cycle time allowable

moving towards each other at the pre-determined vehicle speed of operation (S), then they will each have to cover half their range (r) before they collide. To avoid a collision, each vehicle will need enough time to obtain information from its neighbors and re-calculate its trajectory with enough range to maneuver out of danger. It is possible that more than 2 vehicles are in contention and thus these boundaries are irrespective of the number of vehicles. Thus, the maximum NCCP allowed ($NCCP_{hard}$) for information dissemination around all vehicles within a neighborhood is: $NCCP_{hard} = \frac{(\frac{r}{2} - M)}{S}$.

Table III provides some examples of the hard and soft time boundaries of NCCP for various ranges and at different speeds of operation. Calculations are shown only for up to average range of 50 m as the hard bound becomes irrelevant compared to the soft bound beyond this range. Alternatively, at very short ranges the $NCCP_{hard}$ bound becomes the maximum allowable time interval for a NCCP cycle, and thus overrides the $NCCP_{soft}$ bound value.

B. ETE Delay

NCCP provides a network wide value of the cycle time that incorporates the queuing delay and the propagation delays, but does not give the actual age of each packet when it arrives at its destination for use in the trajectory calculations. To understand the age of each packets information in each cycle, the end-to-end delay (ETE_{delay}) is defined as the time that has passed from when a packet was generated to when that packet was used by the destination vehicle averaged over a cycle. This time takes into account the propagation delay, transmission time, queuing time and the time it waits in the destination node to be used in the swarm algorithm calculations. This metric provides a picture of the validity of the sensor information at the receiver.

C. Channel Utilisation

In underwater environments, bandwidth utilization is very important to consider due to its extremely limited availability. Channel Utilisation (U) takes a network wide view on the effectiveness of the protocol which includes the comparison between an exclusive access protocol, TDMA, and a non-exclusive access protocol, AST-TDMA. It establishes how much wasted channel time there is based on the half-duplex, single channel operations. In particular, we are comparing the amount of time used in transmission and reception of packets (t_{tx}, t_{rx}) including overheads in one vehicle to the total simulation time (T) that includes all the unused channel time: $U = \frac{\sum(t_{tx}+t_{rx})}{T} * 100$

VI. RESULTS

Visualisation of the packet transmission and reception times is done by examing a 5-vehicle String Topology, Veh_1 to Veh_5 of Fig. 4. is shown in Fig. 7 where the simulation has been stopped after Veh_1 has received its 20th packet. Each packet is 100 ms long and the 'spaces' represent the time when the vehicle is idle, that is, not transmitting or receiving a packet. The red bar in the bottom graph of Fig.7 illustrates the first packet transmission from Veh_1. That packet is then received by Veh_2 to Veh_5 (blue bars) at increasing delays, as the first activity in each of these vehicles. When Veh_2 receives the packet, it gets the trigger to transmit, which it does immediately. Veh_2's packet is then received by Veh_1, 3,4 & 5, with Veh_3 being the next to transmit. Fig. 8 shows the comparison of the timing between the two different protocols, looking only at Veh_5. The top graph of Fig. 8 is the same as the top graph of Fig. 7 using AST-TDMA protocol while the bottom graph of Fig. 8 demonstrates the use of the TDMA protocol.

As a broadcast medium, all the vehicles in range will receive the sent message which may be received at times based on propagation delays. For the TDMA protocol, the slot time is based on the time it takes for the last vehicle to complete

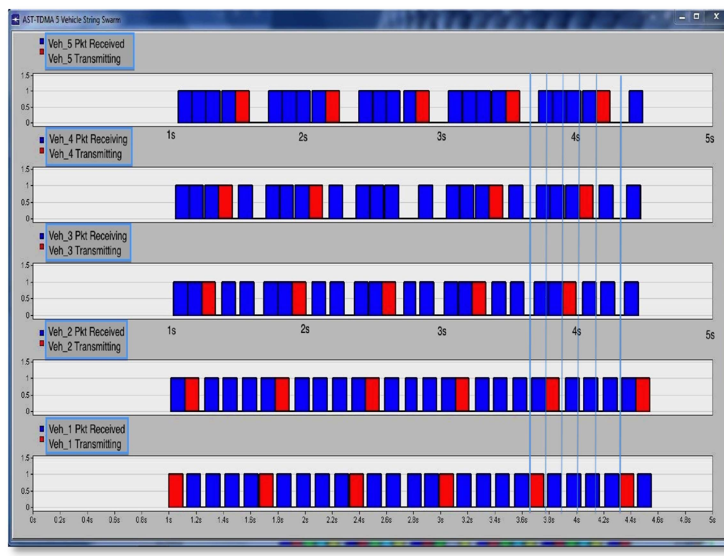

Fig. 7. AST-TDMA Protocol, 5 Vehicle String Swarm, Packet Tx & Rx

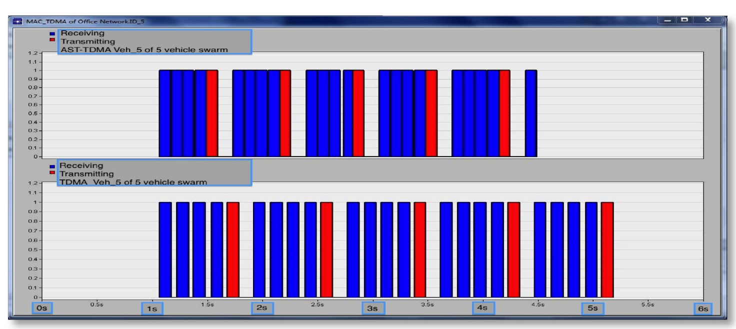

Fig. 8. Comparison of Timing between AST-TDMA & TDMA, Veh_5 of 5

reception, and therefore all receptions will occur within a slot used to send out the packet, thus maintaining exclusive access in each slot period. Fig. 7, however, shows that the AST-TDMA protocol can allow non-exclusive access by allowing vehicles next in sequence to start transmitting before all vehicles have received the previous packet without causing collisions. The vertical lines from around 3.5 s in Fig. 7 show one NCCP cycle and demonstrate this overlap. At the start of the cycle, Veh_1 transmits and the other vehicles begin to receive Veh_1's packet as it propagates towards Veh_5. The second vertical line shows the start of Veh_2's transmission which crosses Veh_1's packet still being received by Veh_3, 4 & 5. This shows that the AST-TDMA protocol utilisies non-exclusive access of the channel while avoiding collisions which is how it can improve its channel utilisation.

Refering to Fig. 8, the reduction in NCCP time when using AST-TDMA can be seen. Five full cycles are completed using AST-TDMA protocol before the fourth cycle is completed using the TDMA protocol. These time differences will be presented in more detail in Fig. 9.

Note the large idle time in Veh_5 following the transmission of it's packet, top graph in Fig. 8. This is because Veh_5 has to wait while its packet propagates to Veh_1 and then for Veh_1's packet to return, which means 2 x τ_{max} time. This time is exactly the same as for Veh_5 in the TDMA protocol, see bottom graph in Fig. 8, as the TDMA slot size is based on τ_{max}. In reality, the TDMA slot-time should also include an additional guard time to take into account mobility and the potential changes in range, thus, the timings shown for the TDMA results are best case. In any case, it does illustrate that the AST-TDMA protocol can have one slot size approaching that of TDMA for a String Topology but this should not happen in the Cluster Topology case.

Also, notice in Fig. 7 that Veh_4 does not have a packet to send in the third round. It instead sends a token (not shown) that allows the cycle to continue. This will mean that the other vehicles will need to wait until the second cycle to receive an updated packet from Veh_4 and therefore increasing the NCCP. Thus, it is important to ensure that there is a packet ready to send, however also to ensure that the packet is not generate to early so that it is sitting in the queue too long as the age of the data may make it less acurate and increase ETE_{delay}. The results of not having a packet to send increases the NCCP, as just discussed, as more than one cycle is needed to complete the exchange of information, but this will not be investigated further here.

To investigate the performance of the protocol in a error free channel, the 10 vehicle swarms of Fig's. 4 and 5 will now be used with the results of Veh_1 provided. Using a constant 1 s information packet generation inter-arrival time ($1/\lambda$) for each of the vehicles in the swarm, which is less than the $NCCP_{min}$, will mean that there is always a packet in the queue ready to send for each cycle. The variations in the information exchange cycle time, NCCP, between the two protocols, topologies and vehicle placements and the theortical limit, $NCCP_{min}$ (values shown in Table II), are compared in Fig. 9. In this figure, the substantial time savings for an NCCP cycle when using AST-TDMA protocol compared to the TDMA protocol can be easily seen. The Cluster Topology also shows lower NCCP than the String Topology as expected, due to the lower average range between consecutive transmitting vehicles.

The difference between the theortical minimum $NCCP_{min}$ and NCCP is due to the queueing time of the oldest generated packet in the cycle. The value of NCCP is the critical metric to consider for successful swarming as it is this value that determines if the requirements of the $NCCP_{soft}$ boundary are met. Thus minimising or eliminating the queueing delay would further improve the NCCP.This would require scheduling the generation of each packet in the vehicle to the $NCCP_{min}$, that is, generating the information packet just prior to when it is that vehicles' turn to transmit. This will not be straight forward when there is vehicle movements, as $NCCP_{min}$ will vary on a cycle-to-cycle basis and therefore a predictive algorithm will be required. Alternatively, when it is a vehicles turn to send a packet it could use this as the trigger to do the trajectory calculations which would allow the information from the last packet received to be incorporated which would decrease the ETE_{delay}, but a processing time would need to be incorporated. This is being investigated in future work.

Fig. 9 also illustrates the variations that occur when vehicle positions within the swarm change relative to each other. The values of $NCCP_{min}$ and NCCP for TDMA do not vary between VP1 and VP2 as the slot times are fixed due to the overall maximum range not changing and therefore the required guard time within the slot length did not change. For the AST-TDMA protocol, there will be changes due to the ranges between each of the vehicles in sequence changing, meaning that the $NCCP_{min}$ will change and as a consequence also the time a packet might spend in the queue. With the potential for changes in the relative positions of the vehicles in the swarm as vehicles maintain a swarm pattern, there will be benefits to monitoring the range between each consecutive vehicle pair in sequence and be able to change a vehicles sequence slot allocation in subsequent cycles. This is fundamentally the Traveling Salesman Problem which will need to be implemented in real-time and has not been shown in this paper.

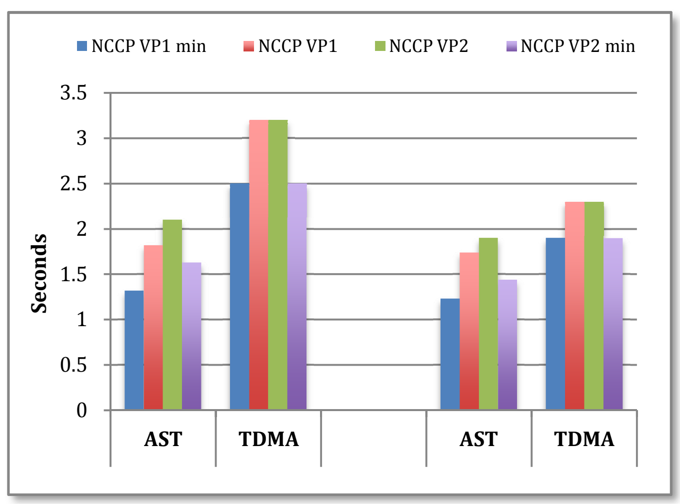

Fig. 9. Comparing NCCP for Veh_1, 10 veh/100m^2 with $1/\lambda$ = 1s

The potential density of a swarm is limited by the ability of a protocol to disseminate each vehicles information in a timely fashion based on the $NCCP_{soft}$ and $NCCP_{hard}$ bounds analysed in Table III. Fig. 10 compares the AST-TDMA protocol with the TDMA protocol against increasing Swarm Density for the two different topologies and protocols proposed. As expected, NCCP increases for increasing swarm densities in both protocols, with the TDMA protocol beginning at a higher NCCP and increasing at a faster rate. It is not possible to operate a swarm using the TDMA protocol at 20 veh/100m^2 as the NCCP is higher than the $NCCP_{hard}$ bound where vehicle collisions will occur. As the swarm densities becomes lower and vehicles are more spread out at above 7 veh/100m^2, the NCCP is above 3 s using the TDMA protocol, which means it is above the 'preferred' $NCCP_{soft}$ bound although still below the $NCCP_{hard}$ bound meaning vehicle collisions are unlikely, but that the swarm algorithm will get slower update rates. The AST-TDMA protocol can be seen to have spare time capacity (below 3 s) each cycle compared to the $NCCP_{soft}$ and $NCCP_{hard}$ bounds (Table III) for all the swarm densities shown, and therefore is able to provide communication amongst the vehicles working as a swarm.

The average ETE packet delay per cycle, shown in Fig. 11, shows a slow increase as swam density's decline, reflecting the NCCP time as is expected. The time difference reflects that the age of most packets used in the trajectory calculations will be less than the NCCP. The AST-TDMA protocol's ETE_{delay} shows the influence of the packet generation rate ($1/\lambda = 1$ s) within the vehicle and the timing of the flushing of the queue, which is seen in the kick up at 20 veh/100m^2 and kick down at 3 veh/100m^2. The TDMA String Topology, in particular, shows a growing ETE_{delay} as swarm densities decline, which is also influenced by the generation rate of packets in a vehicle. The black bars show the maximum and minimum average packet delay before use in calculations per cycle, illustrating that most cycles remain around average, however due to one missed vehicle update in a cycle, an addition complete cycle is required, meaning that the age of one or two packets used in the calculations have to be more than one cycle old.

As can be seen in Fig. 8 and Fig. 12, Channel Utilisation is excellent using the AST-TDMA protocol particularly when vehicles are closer to each other and therefore propagation delays are lower. The big difference between the protocols is due to there being no requirement for guard times in the AST-TDMA protocol and taking advantage of the spatial-temporal diversity which means the channel does not sit idle during these times.

VII. Conclusions

This paper introduces a new MAC layer protocol, Adaptive Space Time (AST) - TDMA, designed to allow communication between a distributed mobile group of AUV's that are to operate in a swarm like fashion. The aim was to develop a communication approach that is flexible, yet robust enough to allow each vehicle to operate autonomously in a swarm of identical vehicles and within the physical and environmental constraints experienced underwater.

An OpNet model of the physical layer channel for short-

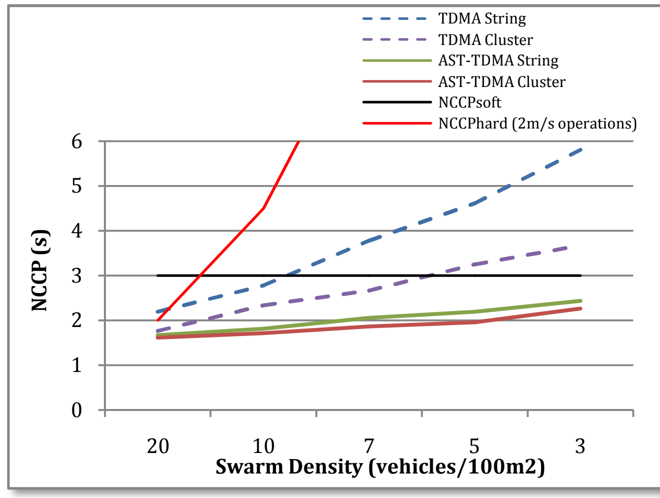

Fig. 10. NCCP vs Swarm Density based on a 10 vehicle swarm

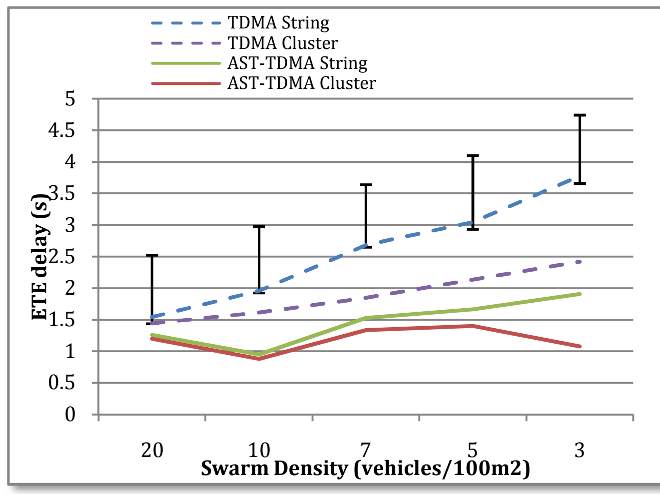

Fig. 11. Average ETE packet delay per cycle

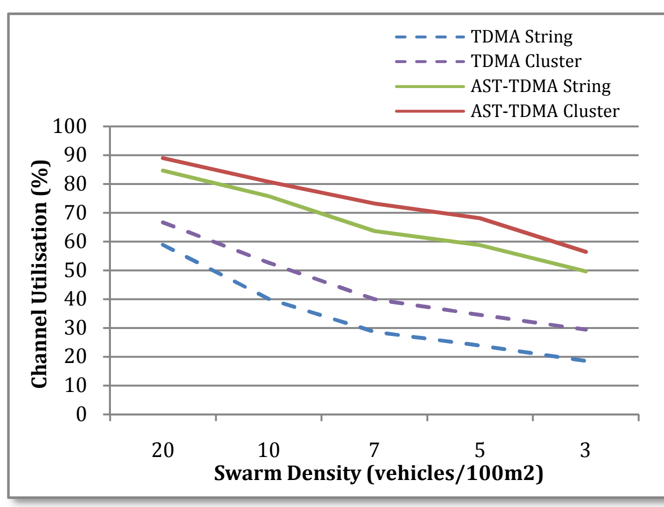

Fig. 12. Channel Utilisation vs Swarm Density

range communication was developed and used to test the AST-TDMA protocol against a standard TDMA protocol. A new metric, NCCP, was developed to test the protocols operational effectiveness. The average end-to-end packet delay used in the swarm algorithm calculations per NCCP cycle and Channel Utilisation were also analysed.

It has been shown through simulations that the AST-TDMA protocol outperforms TDMA in it's ability to handle a larger number of vehicles within a network and at a much higher density.

Future developments which have already been mentioned in this paper, that are showing further improvements to the AST-TDMA protocol are to use the received packet as a trigger to do the calculations for that vehicles next position and therefore also its next packet to send instead of using the received packet as a token and therefore the need for null tokens in some cycles. In addition, the development of algorithms for updating the sequencing of the vehicles within the swarm to maintain minimum NCCP could also provide flexibility for vehicles to enter and exit a neigbhourhood which would also provide scalability to a swarm.

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