A Mobility Based Architecture for Underwater Acoustic Sensor Networks

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***Abstract*— Underwater acoustic sensor networks face unique challenges in the design and development of communication and network protocols, because of the inherently different characteristics of water as a medium for signal propagation. In the mobile sink architecture, a mobile sink that traverses the network to transfer non delay-sensitive data from the sensors directly and avoid multi-hop transmissions. An area partitioning algorithm is proposed in this paper to divide the network in regions to minimize the traveling distance of the sink and the formation of clusters that maximize the throughput. A transmission mechanism based on superposition coding is developed to increase the throughput of downlink control messages to the sensors. Finally, a MAC protocol is developed to facilitate the transmissions.**

I. INTRODUCTION

Underwater Acoustic Sensor Networks (UW-ASNs) are envisioned to perform collaborative monitoring tasks in ocean settings because of their relative ease of deployment and the absence of cables. UW-ASNs have attracted considerable interests in a number of military scenarios, environmental monitoring, assisted navigation and disaster prevention [1].

While extensive literature exists on wireless sensors networks, a number of factors specific to underwater environments requires the development of separate technology for UW-ASNs. First, the transmission medium of UW-ASNs have different propagation characteristics due to the unique properties of underwater acoustic channels [2]. Underwater channels are typically severely impaired. Second, the high rate of absorption of electromagnetic and optical signals in water makes acoustic signaling the primary form of communications in underwater environments [4]. The propagation delay of acoustic sensor nodes is much higher than terrestrial sensor nodes. Finally, the available bandwidth is severely limited in acoustic sensor networks [1]. The low bandwidth, sparse deployment and poor channel conditions lead to a larger power consumption on transmissions in UW-ASNs and thus multi-hop transmissions are not always attractive. Additionally, avoiding collisions during channel access is important but incurs overhead due to the large propagation delays.

The architecture based on the use of a mobile sink that may traverse the entire network, and collecting information directly from the sensors thereby avoiding multi-hop communications are attracted great interests. Area partitioning and path planing are proposed to divide a given network into appropriate regions with the objective of minimizing the travel time of the sink and form clusters that maximize the rate at which messages may be delivered to the sensors. In order to reduce the transmission time of control messages or other cooperation data from the sink to the sensors, a transmission mechanism based on the use of superposition coding is proposed. A medium access control (MAC) protocol to facilitate the sink-to-sensor as well as the sensor-to-sink communications is also proposed.

The rest of the paper is organized as follows. Section II describes the related work. Section III describes the system architecture, superposition coding performance and MAC protocol of the UW-ASN system. Validating simulation results are presented in Section IV. Section V concludes our paper.

II. RELATED WORK

UW-ASNs represent a powerful technology with the potential for enabling many aquatic applications and has attracted great attention from the networking research community in the recent past. At the physical layer, existing work has shown that both electromagnetic and optical signals experience a high rate of absorption and optical signals have the added disadvantage of scattering by suspended particles and high ambient light at shallow depths [4]. The channel characteristics and capacity of acoustic signals have been investigated.

The MAC protocols in UW-ASN are still remained a largely open problem. The slotted floor acquisition multiple access (FAMA) [5] uses carrier sensing and a handshaking mechanism for channel access. However, the synchronization difficulties degrade the performance of slotted FAMA and the handshake process incurs a large overhead due to the large propagation delay. A delay tolerant MAC protocol that avoids collisions by appropriately scheduling the activity of sensors is proposed [6]. However, the protocol does not provide a flexible solution for applications with heterogeneous requirements. The MAC protocol proposed in [7] uses transmit, listen and sleep cycles to improve energy efficiency and can be used for delay tolerant applications. However, the protocol has low throughput and the collision probability increases dramatically when the number of nodes increases. In the R-MAC protocol [8], the transmissions of control and data packets need to be scheduled to avoid collision.

III. SYSTEM ARCHITECTURE

In this section, we assume underwater sensors with limited battery capacity are deployed for long-term monitoring of a region and are equipped with a single acoustic communication device. Also, we assume a 3D architecture [1] with sensors capable of adjusting their depth or position. In this architecture, the sink traverses on the surface of the sensed area in order to exchange data and control information directly with the sensors by using single-hop transmissions. The surface sink may act as the control station or may relay the data to an on-shore station. The movement of the sink is exploited to achieve two objectives: (1) increase the throughput by facilitating transmissions by using superposition coding from the optimal position and (2) reduce the energy consumption of the sensors by eliminating the need for packet forwarding. It is assumed that the sink is aware of the position of the sensors using acoustic positioning techniques such as those in [9].

The system consists of two components: (1) area partitioning and motion planning component that divide the network in a way that minimizes the travel time of the sink as well as the time required for transferring the data from each region; (2) a MAC protocol that schedules collision free data transmissions from the sensors and uses a superposition coding based downlink to minimize the transmission times.

A. Superposition Coding and Rate Allocation

In UW-ASNs, reduction in the transmission times of even small packets can lead to a significant improvement in the throughput. With a mobile sink whose movement is not restricted by energy constraints, we propose the use of superposition coding for downlink transmission of command and control packets to improve the system performance.

Superposition coding involves the simultaneous transmission of messages over the same bandwidth to multiple receivers with different channel conditions, using two or more modulation and coding schemes [10]. Consider a scenario with one sender and two receivers with the closer receiver (i.e. with the better channel condition) designated the secondary receiver. With superposition coding, in addition to sending a message to a primary receiver, the transmitter superimposes an additional message destined to a secondary receiver on top of the message destined for the primary receiver. The available transmission power is split between these two transmissions. The transmitter then modulates and encodes the two packets separately at the desired rates and the modulated symbols are scaled according to the desired power split. The primary receiver decodes its packet while treating the superimposed signal as interference. The secondary receiver first decodes the primary packet, then re-encodes the packet, and then subtracts it from the original received signal. It then decodes the remaining signal to obtain the secondary transmission.

In the proposed scheme, the sink uses superposition coded transmissions to simultaneously transmit the control messages to the sensors. In order to maximize the throughput, the sink positions itself so that the rate assignments to the transmissions to different sensors are made appropriately. Consider a scenario where the sink wants to transmit messages to n sensors. The length of the message for sensor i is denoted by L_i and the length may be different for different sensors. Since the total transmission time is decided by the last node finishing reception, the minimum time to complete the transmission of messages of length $L_1, L_2, \cdots, L_n$ to n sensors is achieved when the allocated downlink rates are proportional to the message lengths, and results the same amount of transmission time at each node.

A fundamental requirement for the feasibility of superposition coding is that the channel gain to each receiver should be different. If the ambient noise, multipath and scattering effects are assumed to follow the same statistical distribution at each sensor, the difference in the channel gain is primarily due to the difference in the distance between the sink and the sensors. If the distance from the sink to sensor i is denoted by d_i, and the distances are assumed to satisfy $d_1 > d_2 > \cdots > d_n$, the maximum rate that can be achieved at sensor i with arbitrarily low error rates is given by [11]

$$r_i = W \log_2 \left(1 + \frac{P_i h(d_i)}{\sum_{j=i+1}^{n} P_j h(d_j) + N_0} \right) \tag{1}$$

where W is the available bandwidth, P_i is the power allocated the transmission to sensor i, $h(d_i)$ is the channel gain as a function of the distance d_i and N_0 is the expected ambient noise. The sink superimposes $n-1$ additional messages on a basic message destined for sensor n. Sensor 1 decodes its packet treating the superimposed additional layers as interference. Sensor 2 first decodes the basic layer, re-encodes it, and subtracts it from the original signal, then decodes remaining signal treating the other superimposed $n-2$ additional layers as interference. Similarly, sensor n first decodes the basic layer and $n-1$ additional layers, re-encodes them, and subtracts them from the original signal. It then decodes the remaining signal. The sink splits the available transmission power P among all the sensors. The power constraint condition is then given by $P \geq P^* = P_1 + P_2 + ... + P_n$. The channel gains $h(d_i)$ are dependent on the attenuation and absorption characteristics of the signal as a function of the carrier frequency f and the spreading factor k. The attenuation coefficient $a(f)$ in dB/km [3] is given by

$$a(f) = \frac{0.11 f^2}{1+f^2} + \frac{44 f^2}{4100 + f^2} + 2.75 \times 10^{-4} f^2 + 0.03 \tag{2}$$

with f in kHz ($f = 25kHz$ in practical systems). The channel gain of path i is

$$h(d_i) = \frac{1}{{d_i}^k a^{d_i}} \tag{3}$$

$k = 1.5$ in typical practical systems. Once the sink determines the lengths of the messages that it needs to send to a given set of sensors, it needs to find the optimal position from where to transmit and allocate proportional rates. For any point on the water surface $(x^*, y^*, 0)$ and sensor node i, the channel gain function is given by $h_i(x^*, y^*)$. Without loss of generality, let the distance of sensor i from the sink, $d_i(x^*, y^*)$, satisfy $d_n(x^*, y^*) < d_{n-1}(x^*, y^*) < \cdots < d_1(x^*, y^*)$. Since the channel gain is a monotonically decreasing function of the distance, we have $h_n(x^*, y^*) > h_{n-1}(x^*, y^*) > \cdots > h_1(x^*, y^*)$ Select an arbitrary set of transmission rates that are proportional to the message lengths

$$K_r^* = \frac{r_1}{L_1} = \frac{r_2}{L_2} = ... = \frac{r_n}{L_n} \tag{4}$$

From Eqns. (1) and (4), the transmission rates to the sensor i can be written as

$$r_i = W \log_2 \left(1 + \frac{P_i h_i(x^*, y^*)}{\sum_{j=i+1}^{n} P_j h_i(x^*, y^*) + N_0} \right) = L_i K_r^* \tag{5}$$

Eqn. (5) can now be solved recursively to obtain the P_i in terms of x^*, y^* and K_r^*, starting with P_n. This solution is

$$\begin{aligned} P_i(x^*, y^*, K_r^*) &= (2^{L_i K_r^*} - 1) \times \\ &\frac{(N_0 + \sum_{j=i+1}^{n} P_j(x^*, y^*, K_r^*) h_i(x^*, y^*))}{h_i(x^*, y^*)} \end{aligned} \tag{6}$$

There may be multiple points on the water surface where the sink can achieve proportional rates. To maximize the transmission rate, the sink should select the location that minimizes the transmission time. Equivalently, it should select the position that maximizes the ratio K_r subject to the power constraint. To find its optimal position, the sink needs to evaluate the maximum K_r possible over the entire region and then select the location with the highest K_r. We use a exhaustive search mechanism to evaluate every position and find out the optimal one. Since the real-time results are not required, the optimal position can be calculated off-line.

B. Path Planing

Given the location of the sensors, the total time spent in the exchange of messages can be minimized by planning the path that the sink follows. The path planning is also influenced by the partitioning of the network that may be done to facilitate the downlink transmissions using superposition coding since it is sufficient for the sink to visit a point in each partition. This section describes the network partitioning algorithm to minimum the traveling distance or maximum the throughput. Once the network has been partitioned, the sink has to traverse through each partition to exchange messages with all sensors. The problem of determining the shortest path is equivalent to the well known traveling salesman problem.

In large networks, the time spent by the sink on traversing the network may dominate the time spent on the exchange of messages. In these scenarios, the network partitioning should focus on reducing the distance the sink has to travel. In large networks or in the scenario that the achievable data rates are very low, an algorithm that partitions the network so as to maximize the throughput is desirable. This section describes two algorithms specific to the two scenarios described above. We consider a network with N sensors and the location of sensor i is denoted by η_i.

Minimum Travel Distance Partitioning: The algorithm to partition the network in order to minimize the sink's travel distance is shown in Algorithm 1. The algorithm partitions the network into k regions, if feasible, under the constraint that in each partition, the distance from the sink's data collection position to the underwater sensor nodes should be less than the communication range r_{max}. As described later, this algorithm is used in conjunction with the path planning algorithm to determine the partition size k, $1 \leq k \leq N$, that results in the shortest travel distance for the sink.

The algorithm initially randomly selects k points on the water surface. These points represent possible positions of the sink in each partition. Each sensor is assigned to the partition that has the closest sink position. Once all sensors have been assigned, the sink's position in each partition is recalculated so that it is closest to centroid while being confined to the water surface. The assignment and recalculation of the sink positioning steps are repeated until there is no further change in the sink's position. If a sensor exists for which the distance to all sink positions is greater than r_{max}, the partitioning is declared infeasible. Once the partitioning is done, the algorithm then finds the optimal position inside each partition that maximizes the downlink throughput.

Algorithm 1 Minimum Travel Distance Partitioning

```
STATE: $k$ Data Collection Position Generation
Randomly generate $k$ points, $C_j$, $1 \leq j \leq k$, on the water surface.
while $C_j \neq \hat{C}_j$ do
    $\hat{C}_j = C_j$
    STATE: Associations
    Associate each sensor to each closest collection point.
    $D_{i,j} = \| \eta_i^j - C_j \|, \forall \eta_i^j \in C_j$.
    if $D_{i,j} \leq r_{max}$ then
        Partition found; break.
    end if
    STATE: Re-calculate Data Collection Points and Re-assign Sensors
    Find $C_j$ that minimizes $\max_{\eta_i^j \in C_j} \| \eta_i^j - C_j \|$.
    if $C_j = \hat{C}_j \ \forall j$, and $D_{i,j} > r_{max}$ for any $i$ then
        No partition found; break.
    end if
end while
STATE: Position Adjustment
Solve the Eqn. (6) for each partition to obtain the optimal position to achieve the max $K_r$ for the sink in each partition.
```

Maximum Throughput Partitioning: The algorithm to partition the network so as to maximize the downlink throughput is shown in Algorithm 2. First, a distance matrix D_{ij} corresponding to the distance between each pair of nodes is generated. The throughput of each sensor i, Γ_i, is then calculated assuming the sink is vertically above the sensor. Initially, all sensors are assigned to the same partition. Next, the sensor pair with the minimum distance d_{ij} is picked. The throughput with superposition coding to these nodes is then calculated and compared against the overall throughput when nodes are transmitted to sequentially. If the superposition throughput is lower, the node with the higher individual throughput is assigned to its own partition and its entries are removed from the distance matrix. If the superposition throughput is higher, the two nodes are put in the same partition. The sensor closest to these two is then picked and the superposition throughput of the new group is compared to their sequential throughput. The process of adding new nodes continues while the throughput is higher. Once a new addition fails to improve the throughput, the entries in the distance matrix corresponding to the previous sensors are removed and the whole process is repeated, starting with the next pair with the shortest distance. In each partition, the distance from the data collection point to the sensors should be less than the communication range r_{max}.

C. MAC Protocol

As the sink moves to each partition, a centralized MAC protocol is used to schedule the transmissions from the sensors in that partition. The centralized approach eliminates collisions and also reduces the synchronization requirements among the sensors. In each partition, the sink first moves to the optimal position that maximizes the downlink throughput. While the sum of the downlink and uplink throughputs may be maximized if the sink moved over each sensor individually, the

Algorithm 2 Maximum Throughput Partitioning

```
Initialize: number of partitions $N_c = 1$; iteration size $n = N$; set $partition(i) = 1, \forall i$
Generate $n \times n$ distance matrix $M_D$ and calculate $\Gamma_i$.
while $n > 0$ do
  Find the minimum distance value $d_{ij}$ in the matrix.
  $\Gamma_{NEW} = \Gamma_{OLD} = \max(\Gamma_i, \Gamma_j)$.
  $k = \arg\max(\Gamma_i, \Gamma_j)$; $partition(k) = N_c$
  while $\Gamma_{NEW} \geq \Gamma_{OLD}$ and $d_{ij} < d_{max}$ and $\exists$ point $p \in (x, y, 0)$ such that $d_{ip}, d_{jp} \leq r_{max}$ do
    Calculate: $\Gamma_{OLD}$ as the sequential throughput of $i$ and $j$ and $\Gamma_{new}$ as the maximum superposition throughput
    if $\Gamma_{NEW} > \Gamma_{OLD}$ then
      $partition(j) = N_c$; $n = n - 1$
      Delete entries in $M_D$ corresponding to sensor $j$.
      Find $\min_{l \in (1,n)} d_{k,l}$; $j = \arg\min_{l \in (1,n)} d_{k,l}$
    end if
  end while
  Delete entries in $M_D$ corresponding to sensor $i$.
  $N_c = N_c + 1$; $n = n - 1$
end while
STATE: Position Adjustment
Solve the Eqn. (6) for each partition to obtain the optimal position to achieve the max $K_r$ for the sink in each partition.
```

increase in the travel distance would negate the benefits of the improvement in the throughput. An example of the proposed MAC protocol with two sensors is shown in Figure 1. After the sink moves to the data collection position, it polls each sensor sequentially. A sensor with data to transmit does so immediately after it is polled and in the absence of data, sends a small packet to just acknowledge the receipt of the poll. Then the sink estimates the propagation delay for each sensor based on the measurement of the round trip time. A sensor may be re-polled immediately if its data is not received correctly. Also, if no response is obtained in response to a poll, the sink may repeat polls subject to limit number of retransmissions.

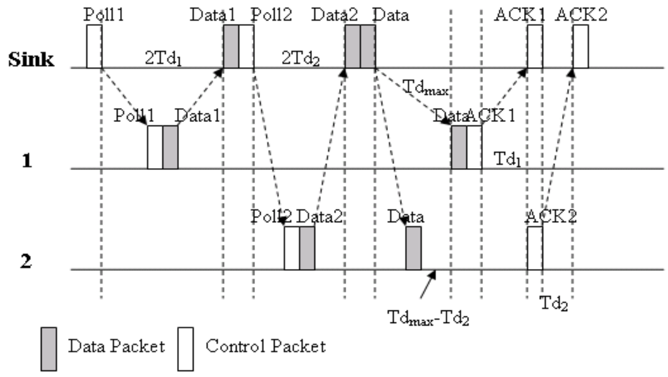

Fig. 1. Example operation of the proposed MAC protocol

After the uplink transmissions, the sink transmits the control messages to the sensors. These transmissions are done simultaneously, using superposition coding. The messages sent by the sink also contain the schedule according to which the sensors send back their ACK packets. The schedule is calculated as follows. The propagation delay to all sensor i, Td_i, is first arranged in an increasing order with ties broken randomly. Without loss of generality, let the delays be such that $Td_1 > Td_2 > \cdots > Td_n$. Thus $Td_{max} = Td_1$ and $Td_{min} = Td_n$. The sensor i is assigned to transmit the ACK according to the sequence $Td_{max} - Td_i$ seconds after it receives the message to ensure non-interference at the sensor with the longest delay. Each subsequent sensor is assigned to transmit its ACK T_{ACK} seconds after the end of the ACK transmission from the previous sensor where T_{ACK} is the time taken to transmit an ACK. In order to avoid collision at the sink, the sensor with the minimum transmission delay replies first, and the sensor with the maximum delay replies the last. For example, in Figure 1, sensor 2 has shorter delay, then after polling from the sink, the ACK reply schedule is sensor 2 first, then sensor 1 replies ACK. The sensor 2 waits $Td_{max} - Td_2$, then replies ACK; The sensor 1 waits T_{ACK} of sensor 2 according to the schedule, then replies its own ACK. In this figure, we have shown the time between the sensor receives previous packet and sends out new packet, however the time is quite small compared to the transmission delay, and we can assume it as 0.

We assume that the transmission time of each poll is T_{POL} seconds and that of the data from sensor i is T_{L_i} seconds. Since proportional rates are assigned to all sensors, the time spent on sending the control messages, T_{CTR}, is the same for all sensors. Each sensor sends its ACK only after the previous transmission is completed. Thus the total transmission time is

$$\begin{aligned} T_{delay} &= 2\sum_{i=1}^{n} Td_i + nT_{POL} + \sum_{i=1}^{n} T_{L_i} + T_{CRT} \\ &\quad + nT_{ACK} + 2\max_{1 \leq i \leq n}\{Td_i\} \end{aligned} \tag{7}$$

The total energy spent by the sink on the transmissions consists of the energy spent on the polls and the energy spent on the downlink transmissions. Denoting the length of the control message for sensor i by L_i, the energy consumption is

$$E_{sc} = \sum_{i=1}^{n} PT_{POL} + \sum_{i=1}^{n} P_i \frac{L_i}{r_i} = nP_rT_{POL} + \sum_{i=1}^{n} \frac{P_i}{K_r} \tag{8}$$

Note that sleep-wake cycles can also be easily incorporated into the MAC protocol.

IV. SIMULATION RESULTS

In this section, we present simulation results to evaluate the performance of the proposed system and compare it with other schemes. The simulations were conducted using Matlab and the device parameters used correspond to the acoustic devices manufactured by LinkQuest [12]. The maximum transmission range is 2km with rate 9600bits/sec, and the bandwidth is 2kHz. The maximum transmitting power is 2 Watts.

To compare the performance of the two partitioning mechanisms, we consider a 20km×20km ×2km region with varying number of nodes. Figures 2 and 3 show the total distance traveled by the sink and its average throughput in each partition as a function of the number of nodes. The minimum distance partitioning leads to a lower travel distance while the maximum throughput algorithm leads to higher throughputs. The partitioning algorithm may be selected based on the speed of the sink, the amount of data generated by the sensors as well as the maximum transmission power of the devices.

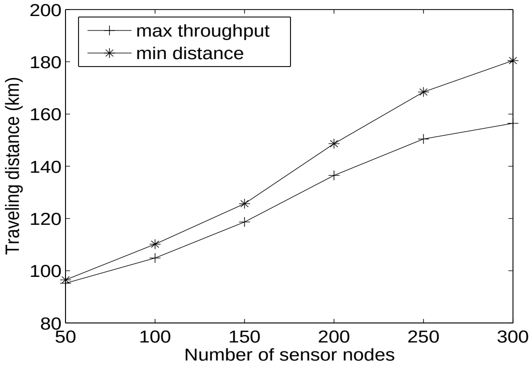

Fig. 2. Total distance traveled by the sink.

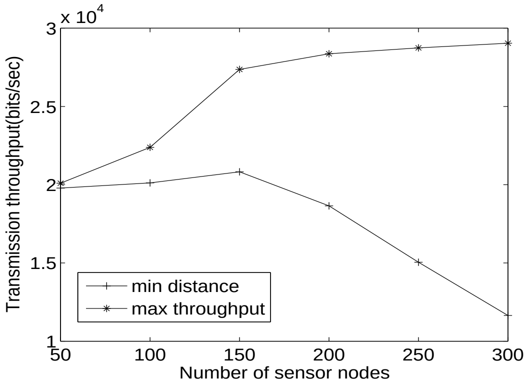

Fig. 3. Average sink throughput in each partition.

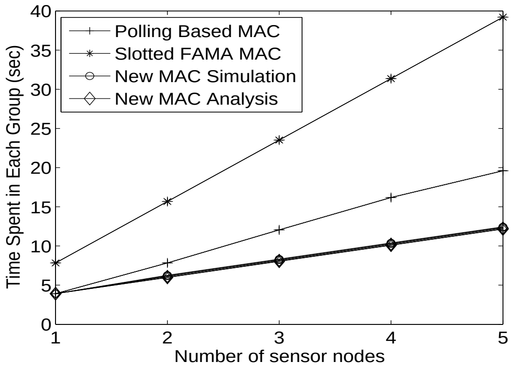

Fig. 4. Total transmission time per partition with different MAC protocols.

The transmission time for the exchange of messages between the sensors and the sink in a partition for various MAC protocols is shown in Figure 4. The analysis and simulation results for the proposed MAC protocol are compared with the slotted FAMA and polling based MAC protocols. The delay for slotted FAMA delay increases more rapidly with the number of sensors in the partition because of collisions. The improvement in the performance with the proposed scheme as compared to traditional polling based schemes is due to the use of superposition coding and reduction in the number of steps necessary to complete each transmission. Also, even with the 1024 bytes long data packets used in the simulations, the propagation delays dominate over the transmission time.

Figure 5 compares the energy consumed by the sink as a function of the number of sensors, and the transmission power is 2 Watts. As the number of sensors in the partition increases, for a given available transmission power, the power available at the sink per node decreases. Consequently, the per node achievable rates with superposition coding decrease. This decreases the transmission rates and thereby increasing the transmission time and the total energy consumed.

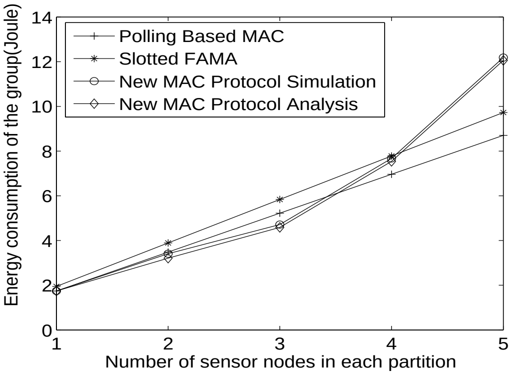

Fig. 5. Per partition energy consumption for different MAC protocols

V. CONCLUSIONS

This paper proposed a path planing and MAC protocol for mobile sink architecture in UW-ASN. The architecture is based on exploiting a sink that facilitates superposition coding based downlink transmissions to improve the throughput. Two network partitioning algorithms are proposed to partition the network for planning the sink's path and can be used to either minimize the travel distance or maximize the throughput. To facilitate the superposition coding based transmissions, a centralized polling based MAC protocol is proposed.

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