On-Demand Data Collection in Sparse Underwater Acoustic Sensor Networks Using Mobile Elements

Jalaja M.J. and Lillykutty Jacob
Department of Electronics and Communication Engineering
National Institute of Technology, Calicut, India
Emails: {jalaja@rit.ac.in, lilly@nitc.ac.in}

***Abstract*—Underwater Wireless Sensor Networks (UWSNs) is a group of sensors and underwater vehicles, networked via acoustic links, that perform collaborative tasks and enable a wide range of aquatic applications. Due to hostile environment, resource constraints and peculiarities of the underlying physical layer technology, providing energy-efficient data collection in a sparse UWSN is a challenging problem. We consider mobility-assisted routing technique for enabling connectivity and improving the energy efficiency of sparse UWSN, considering it as a Delay/Disruption Tolerant Network (DTN) or Intermittently Connected Network (ICN). We use analytical models to investigate the performance of the data collection scheme. Based on the result that the DTN scheme improves energy efficiency and Packet Delivery Ratio (PDR) at the cost of increased message latency, we investigate techniques to improve the delay performance. The effects of using multiple mobile elements for data collection and priority-polling based on traffic class and data generation rate are investigated. The analytical results are validated through extensive simulations. The results show that our model for data collection in sparse UWSNs can effectively capture the underwater acoustic network conditions. Also, the improved DTN framework shows superior performance in terms of energy efficiency and network connectivity over ad hoc multihop network, and in terms of message latency and fairness over simple polling-based DTN framework.**

Keywords-Underwater Sensor Networks; Delay Tolerant Network; Mobile Sink; Priority Polling; Energy Efficiency; Fairness.

I. INTRODUCTION

Underwater Wireless Sensor Networks (UWSNs) have emerged as powerful systems for providing autonomous support for several activities like oceanographic data collection, marine surveillance, disaster prediction, assisted navigation etc. Acoustic communication, with its associated pros and cons, is the underlying physical layer technology used in UWSNs. Features like high latency, low bandwidth, high error probability and 3-dimensional deployment make the UWSNs significantly different from terrestrial WSNs [1]. The energy saving/efficiency is a critical issue for UWSN because of the high cost of deploying and/or re-deploying underwater equipment. Underwater sensors are expensive, partially because of their more complex transceivers and the ocean area that needs to be sensed is quite large. Hence, UWSN deployment can be much sparser compared with terrestrial WSNs. Due to sparse deployment, harsh environment, node mobility and resource limitations, the network can be easily partitioned and a contemporaneous path may not exist between any two nodes. This results in sparse UWSNs that need to be treated as Intermittently Connected Networks (ICN) or Delay / Disruption Tolerant Networks (DTN) [2]. DTNs are characterised by frequent partitions and potentially long message delivery delays. Such networks may never have an end-to-end contemporaneous path and traditional routing protocols are not practical since packets will be dropped when no routes are available.

The primary objective of DTN routing is to provide eventual delivery of data, rather than optimizing some routing metric, say message latency. In energy-constrained underwater sensors, for certain delay-tolerant applications like environmental sensing or continuous monitoring, enhanced network lifetime will be more important than message delay. Enabling reliable and energy-efficient data collection in resource-constrained sparse UWSNs is a challenging problem that requires specialized routing approaches and QoS metrics. Conventional DTN approaches like multipath routing are resource-hungry and hence not suitable for resource-constrained underwater applications.

The three main approaches used for data collection in wireless sensor networks, in general, are [3]: (i) Base Station (BS) approach which uses direct communication between the source and the sink; (ii) Ad hoc network which uses a multi-hop path from the source to the sink; and (iii) Mobility assisted routing which makes use of a mobile sink or mobile relays for data collection. The first approach provides fast delivery, but suffers from reduced life time of sensors due to the increased requirement of communication energy. The ad hoc network provides medium delay and medium power requirement, but suffers from the ‘hot spot’ problem and the necessity for an end-to-end contemporaneous path. Mobility assisted routing approach supports the DTN concept, reduces transmit power consumption, and eliminates the relaying overhead. However, due to the limited travel speed of the mobile elements, data collection latency will be large, but such large latency may be acceptable in certain environmental sensing applications which are not time-critical. Typical example of such an application is the continuous monitoring and recording of the behaviour of underwater plates in tectonics, for later scientific analysis. Providing support for delay-sensitive applications like pollution monitoring and earthquake prediction, and ensuring fairness among different traffic classes using energy-efficient mobility-assisted routing in sparse UWSNs is the focus of this paper.

We start with a basic DTN framework for energy efficient data collection in sparse underwater sensor networks using a mobile sink; and then augment it with techniques to improve its data collection performance by introducing priority and employing multiple data collectors. Analytical results for energy efficiency, packet delivery ratio, message latency, and sensor buffer occupancy are presented. The analytical results are validated using our own simulation model developed in Aqua-Sim [4], an NS-2 [5] based network simulator, developed by the University of Connecticut. A brief review of the related work is given in Section II. The system model is presented in Section III. The expressions used for analytical results are developed in Section IV. Section V discusses the analytical and simulation results. The paper is concluded in Section VI.

II. RELATED WORK

Several routing protocols have been developed for underwater sensor networks, most of them suitable only for connected networks. Vector Based Forwarding (VBF) is a typical geographical routing protocol and Hop-by-hop Vector-based forwarding (HH-VBF) [6] is its more energy-efficient version, better suited for sparse networks. Both VBF and HH-VBF do not support mobility-assisted data collection and they require the network to be connected. Recently, considerable effort has been devoted to developing architectures and routing algorithms for DTNs and routing in DTNs is investigated by Jain et al. [7]. Guo et al. have proposed an adaptive routing protocol for UWSNs, considering it as a DTN [8]. Shah et al. [3] have presented a three-tier architecture based on mobility to address the problem of energy efficient data collection in a terrestrial sensor network. The same architecture with an enhanced analytical model has been presented by Jain et al. [9]. Energy analysis of routing protocols for UWSNs is presented by Domingo [10] and by Zorzi et al. [11]. An M/G/1 queueing model is used by He et al. [12] for mobility-assisted routing, proposed for reducing and balancing the energy consumption of sensor nodes. The use of controlled mobility for low energy embedded networks has been discussed by Arun et al. [13]. AUV-aided routing for UWSNs is discussed by Yoon et al. [14] and Hollinger et al. [15]. Polling-based scheduling in body sensor networks has been discussed by Motoyama [16] and the usage of message ferries in ad hoc networks is considered by Kavitha et al. [17].

The development of routing protocols for dense UWSNs and the adaptation of DTN approaches for terrestrial sensor networks have already been addressed, but the energy-efficient data collection in resource-constrained sparse/disconnected UWSNs has not been adequately investigated. Also, an analytical framework and the simulation environment for evaluating the performance metrics of data collection in UWSNs will be useful for designing application-oriented networks. In this paper, we propose a mobility-assisted DTN scheme for data collection in sparse UWSNs and propose techniques for providing support for delay-sensitive applications, by employing multiple data collectors and introducing priority.

III. SYSTEM MODEL

We consider large and sparse underwater sensor networks with possibly disconnected components and with mobile elements used for data collection. The static sensors monitor the underwater surroundings, generate data and store it in the sensor buffer. They have limited non-rechargeable battery power and they can communicate using acoustic links. Sensors' bulk data communications are limited to transferring data to a nearby mobile collector (MC), so as to reduce energy consumption. Mobile Collectors are mobile entities with large processing and storage capacity, renewable power, and the ability to communicate with static sensors, BS and other MCs (if any). As an MC moves in close proximity to (i.e., within transmission range of) a static sensor, the sensor's data is transferred to the MC and buffered there for further processing. The mobility of the MC can be either random or controlled.

The static sensors can request the service of the MC by sending service request messages to the base station (BS) using direct or ad hoc multi-hop communication. The service request packet is assumed to be very short compared to data packets and the former will contain location information of the node, priority of application, and any other relevant information like data rate or the delay-sensitivity of request. The BS will collect the requests and based on the system load and the delay requirements, it can decide the number of MCs needed and the sequence of visiting the nodes by each MC. Accordingly, BS will create one or more visit tables specifying the order of visiting the nodes and schedule the required number of MCs with a unique visit table assigned to each one of it. Each MC will visit the sensor, collect the data generated and buffered so far, and proceed towards the next node in the table and this process is repeated. After one cycle is completed, it may visit the BS and collect the updated visit table if it has been modified by the BS during that cycle. The data is assumed to have been successfully delivered once it has been collected by the MC.

Underwater Channel: If a tone of frequency f and power P is transmitted over a distance l, the received signal power will be $P/A(l, f)$, where the attenuation factor $A(l, f)$ is the sum of absorption loss and spreading loss. At shorter ranges, spreading loss plays a proportionally larger role compared with absorption loss. Spreading loss is frequency-independent, but depends on the geometry. The SNR of an emitted underwater signal at the receiver is expressed by the passive sonar equation [18] and the transmission loss or the attenuation factor $A(l, f)$ of an underwater acoustic channel for a distance l and frequency f is given by Eqn. 1 as [18]:

$$10 \log A(l, f) = k\ 10 \log l + l\ 10 \log a(f) \tag{1}$$

where the first term is the spreading loss and the second term is the absorption loss. The spreading coefficient k = 1 for cylindrical spreading (shallow water scenario) and k = 2 for spherical case (deep water scenario). The absorption coefficient can be expressed empirically, using the Thorps formula which gives a(f) in dB/km for f in kHz as Thorp's formula [18] is used to express the absorption coefficient as :

$$10\ log\ a(f) = \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100+f^2} + \frac{2.75f^2}{10^4} + 0.003 \quad (2)$$

The absorption coefficient increases rapidly with frequency (typical values being 50 dB/km at 200 kHz and 320 dB/km at 1 MHz, thus imposing a limit on the maximal usable frequency for an acoustic link of a given distance l (which may typically vary from a few metres to a few kilometres).

IV. ANALYTICAL STUDY

In this section, we develop the necessary analytical expressions, the numerical results of which are compared with the simulation results in Section V.

A. Energy Efficiency

One important motivation for employing a mobile sink is that it increases the lifetime of the network by balancing the energy consumption of the sensor nodes. The energy consumption of the static nodes alone is considered, since the mobile node is assumed to be rechargeable or having much higher initial energy compared to the static sensors. The energy consumed by the static sensor nodes for sensing and processing are negligible compared with that for underwater acoustic data transmission, and hence we consider the energy consumption for data transmission only. For a given target signal-to-noise ratio SNR_{tgt} at receiver, available bandwidth $B(l)$, and noise power spectral density $N(f)$, the required transmit power $P_t(l)$ can be expressed as a function of the transmitter-receiver distance l [11]. If P_r is the receive power, L is the packet size in bits, M is the number of packets transferred from the source node to the destination and α is the bandwidth efficiency of modulation, the energy consumption for the single hop data transfer becomes

$$E_{hop}(l) = \frac{M(P_r + P_t^{el}(l))L}{\alpha B(l)} \quad (3)$$

where $P_t^{el}(l)$ is the electrical power (in watts) corresponding to $P_t(l)$ in dB re μPa. Compared to P_r, P_t^{el} is very large and hence its contribution to the energy consumption of sensor nodes is significant.

In order to assess the energy efficiency of the MC-based DTN model, let us compare the energy overhead associated with transferring one packet from the sensor to the BS using the ad hoc multi-hop approach and the *store-carry-and-forward* DTN approach.

Assuming N static sensor nodes randomly and uniformly deployed over a circular area A of radius R as in [13], we can calculate the minimum energy requirement of each node for transferring one packet generated by each node to the sink at the centre of the circular area, in the ad hoc multi-hop network.

If every static node with a transmission range r and located in the kth annulus of the circular area generates one packet, then the minimum number of transmissions due to packets originated from the kth annulus is $MinTx(k) = N\frac{A(k)}{A}k$, where $A(k)$ is the area of the k^{th} annulus and k = 1 for the innermost annulus. In the mobility-assisted data collection, irrespective of the position of the nodes, each static node transmits only the packets generated by it. Instead, in the case of multi-hop architecture, if every node generates 1 packet each, for a large value of N, on an average, the number of receptions and transmissions to be undertaken by a node in annulus k will be, respectively, $NodeRx(k) = \frac{A(k+1)}{A(k)}NodeTx(k+1)$ and $NodeTx(k) = 1 + \frac{A(k+1)}{A(k)}NodeTx(k+1)$, except for the outermost annulus $\left(k = \lceil \frac{R}{r} \rceil\right)$ where the corresponding values are 0 and 1.

The above analysis shows the increased relaying overhead of a sensor node with its proximity to the sink. If we define the *Energy Overhead Factor* (EOF) of a node as the ratio of the total number of transmissions from the node to the number of transmissions corresponding to the packets originated at that node, it is seen that all the sensor nodes have the same EOF (equal to 1 with an error-free channel) in MC-based scheme, while it is approximately equal to $NodeTx(k)$ in multihop network. High *Energy Overhead Factor* implies low energy efficiency.

B. Data Collection Latency

A polling model is used to investigate the delay performance of MC-based data collection. In the basic polling model, a single server visits (or polls) the queues in a cyclic order and after completing a visit to queue i, the server incurs a switch over period or *walk time* [19]. The period during which the server continuously serves queue i is called a *service period* of queue i and the preceding period is called the *switch over* period of queue i. Different service policies can be employed, out of which the *Exhaustive* service scheme is the optimal. Mobile Collector and the static sensor buffers in our model correspond to the single server and queues of the polling model, respectively. Travel time of the MC to move from one location to the next is modelled as the *walk time* and the time spent at each location to transfer data from the near by sensor's buffer to the MC is modelled as the *service time*.

Assuming Poisson arrival of packets at rate λ at each sensor buffer, the offered load is given by $\rho = N\lambda\overline{X}$, where $\overline{X}$ is the mean message service time. For system stability, ρ should be less than 1. If the mean of the total walk time is denoted by R, the mean cycle time of the MC is given by

$$E[C] = \frac{R}{1-\rho} \quad (4)$$

Let $\overline{X^2}$ denote the second moment of the packet transfer time and the MC travel time between two consecutive locations be a random variable with mean and variance $\overline{W}$ and $\overline{W^2}$, respectively. Under the assumption of symmetric queues and *exhaustive* service, the mean waiting time of the packet in the sensor buffer before the MC approaches it for data transfer can be obtained as:

$$W_q = \frac{\overline{W^2}}{2\overline{W}} + \frac{N\lambda\overline{X^2} + \overline{W}(N-\rho)}{2(1-\rho)} \tag{5}$$

Assuming that the static nodes are uniformly distributed in the network, their locations can be treated as random points in the square sensing field. The probability density function of the distance between two arbitrary points in a unit square is given by [12] $f_D(d) =$

$$\begin{cases} 2d(\pi - 4d + d^2) & 0 \le d \le 1 \\ 2d[2sin^{-1}(\frac{1}{d}) - 2sin^{-1}\sqrt{1-\frac{1}{d^2}} & \\ \quad + 4\sqrt{d^2-1} - d^2 - 2] & 1 \le d \le \sqrt{2} \\ 0 & \text{otherwise} \end{cases} \tag{6}$$

From this, if the MC moves at a constant velocity V, the mean and the variance of the MC travel time between two arbitrary points in a unit square area can be obtained as $0.4555/V$ and $3.95/V^2$, respectively.

The expected response time of a message, buffer size, and number of messages in the system (in queue and in service) are $\overline{X} + W_q$, $W_q\lambda$, and $(\overline{X} + W_q)\lambda$, respectively. Using the parameters of data generation, data transfer, and MC mobility, the delay performance of our system model is evaluated. The controlled mobility of the MC gives better performance compared to random mobility and hence the former is recommended if the deployment permits.

The delay performance of the MC-based DTN scheme with a single mobile element is not at all comparable with that of ad hoc multihop network (of the order of several minutes for the former, while a few seconds for the latter). Correspondingly, the buffer requirement of static sensors is negligible in an ad hoc network, while it is considerably high in the MC-based scheme.

C. Packet Delivery Ratio (PDR)

In the *exhaustive* service policy of polling scheme, all the data generated at one sensor in one *cycle time* is transferred in one visit of the MC. The mean number of packets generated in 1 cycle time = $\lambda E[C]$. Assuming sufficiently large buffer space to avoid buffer overflow, ideal channel, and no MC failures, the PDR will be 1. But practically, there exists a probability that a node is not detected (or a *contact* does not occur) within a reasonable time period. In such situations, the significance of the data may be lost if the application is delay-sensitive, or the data itself may be lost due to buffer overflow.

D. Performance Enhancement

To improve the delay and delivery performance of the basic DTN scheme with a single MC, two techniques can be employed: i) use of multiple mobile sinks or mobile collectors, and ii) priority polling. In the first technique, more than one mobile sink or mobile collectors are used, thus increasing the effective service rate, thereby reducing the message waiting time. In the second one, different priority is assigned to different nodes (based on data generation rate, traffic class etc) and the order and/or frequency of polling or visiting the static sensor nodes is modified to account for the service requirement. In both cases, the scheduling of MC(s) should take into account the service demand, in terms of varying network load, meeting deadline, or ensuring fairness.

1) Multiple Mobile Collectors: In our basic polling model, there is only a single server, servicing a number of queues in a cyclic manner, with a non-zero switch-over time. When the number of mobile data collectors is increased, the model is converted to a Multi Server Multi Queue (MSMQ) system or *multi server polling model*, the exact analysis of which is not available. Assuming independent mobile collectors, symmetric Poisson-distributed data arrivals, independent and identically distributed *service times* and *walk times* and no server clustering, an approximate expression for the mean waiting time can be derived following the approach used in [20]. If S is the number of MCs, to get the mean message waiting time in the multiple MC case, the expression for mean waiting time in single MC case as given by Eqn. 5 can be modified by substituting $\overline{X}/S$, $\overline{X^2}/S^2$, $\overline{W}/[S-(S-1)\rho]$, and $\overline{W^2}/[S-(S-1)\rho]^2$ in place of, respectively, $\overline{X}$, $\overline{X^2}$, $\overline{W}$, and $\overline{W^2}$. Thus the mean waiting time in the multiple MC situation becomes

$$W_q = \frac{\overline{W^2}}{2\overline{W}[S-(S-1)\rho]} + \frac{N\left[\frac{\lambda\overline{X^2}}{S} + \frac{\overline{W}(S-\lambda\overline{X})}{S-(S-1)\rho}\right]}{2(S-N\lambda\overline{X})} \tag{7}$$

Compared to the basic single MC network, here the expected waiting time and the sensor buffer occupancy decrease with the number of servers S. Thus, the delay and delivery performance is improved by the use of multiple data collectors, while energy consumption and network lifetime are not affected, since the number of transmissions and the range of transmission are not changed by the use of more number of MCs.

2) Priority Polling: In practical situations, all the nodes may not be generating data at the same rate and hence the earlier assumption of symmetric queues may not be valid. When the data generation rates among the static sensor nodes vary considerably, it will be better to visit the nodes with higher arrival rates more frequently, rather than following the cyclic order. In cyclic polling, the server polls the queues in the order $Q_1, Q_2, ..., Q_N, Q_1, Q_2, ..., Q_N, ...$ In *Periodic* polling, the server visits the queues in a fixed order specified by a *polling table* in which each queue occurs at least once [21].

Consider the single server polling model with the difference that the arrival rates at the queues are not equal, instead the packet arrival intensity at sensor i is λ_i, i 1,...*N*. The offered load at sensor i is $\rho_i = \lambda_i\overline{X_i}$, where $\overline{X_i}$ is the mean service time at sensor i. The total offered load in the network $\rho = \sum_{i=1}^{N}\rho_i$. The MC visits the sensors according to a periodic - not necessarily cyclic - polling scheme. The approach followed in [21] can be used to minimize the workload in the system and to ensure *fairness* among the sensors by using optimum visit frequencies. For *exhaustive* service, assuming W_i to be the switch-over time from queue $i-1$ to queue i, the visit frequency at node i becomes

$$f_i^{exh} = \frac{\sqrt{\rho_i(1-\rho_i)/W_i}}{\sum_{j=1}^{N}\sqrt{\rho_j(1-\rho_j)/W_j}} \tag{8}$$

Now, all the nodes are not visited equally in a cycle, instead the nodes having more buffered data waiting for transmission (due to higher arrival rate) will be visited more often than those with less buffered data. Assume that sensor i is visited n_i times in a cycle of the MC and these visits are spread as evenly as possible. Considering the interval between two successive MC visits to a node i as a sub cycle, the mean residual time of a sub cycle of i will be

$$ERSC_i \propto \frac{E[C]}{n_i} \tag{9}$$

where $E[C]$ is the mean time for one complete visit cycle of the MC according to the polling table. Now the mean waiting time at node i will be [21]:

$$(W_q)_i \propto (1-\rho_i)\frac{E[C]}{n_i} \tag{10}$$

which shows that the sensor nodes with high data generation rates (having high values of ρ_i and n_i) get better treatment and majority of the generated packets get good treatment, in terms of waiting time and buffer requirement.

V. ANALYTICAL AND SIMULATION RESULTS

Extensive simulations have been done to validate our analytical results using the NS-2 based network simulator for underwater applications, Aqua-Sim. It is an event-driven, object-oriented simulator written in C++ with an OTCL (Object-oriented Tool Command Language) interpreter as the front-end. We have incorporated in it, the DTN concepts of beaconing, *contact* discovery and *store-carry-and-forward* and the polling based (*exhaustive* service) data collection.

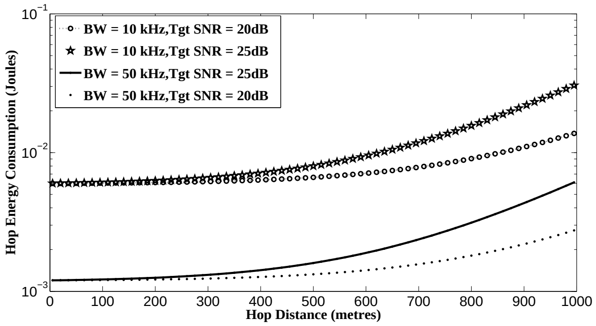

Figure 1. Hop Energy Consumption for varying hop length and bandwidth

Assuming tunable transmit power P_t, receive power P_r fixed at 0.075 W, and packet length L fixed to 400 bits [4], the effect of hop length, target SNR, and channel bandwidth on per-hop energy consumption as expressed by Eqn. 3 is plotted in Fig. 1 for shallow water environment. Decreasing the source to sink distance reduces the transmission loss and increasing the bandwidth reduces the time required for transmission. Both situations lead to reduced transmit energy consumption, thus validating the suitability of short range communication in energy-constrained environments.

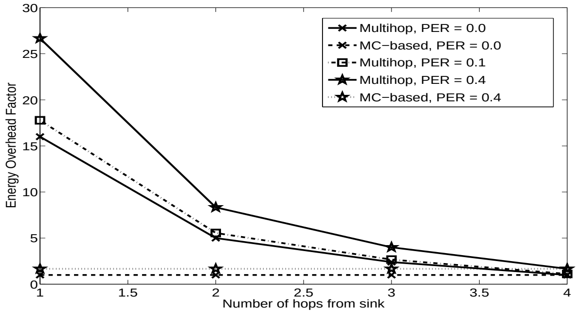

Figure 2. Transmit Energy Overhead of static sensor nodes with multi-hop and MC-based schemes for different PERs

Assuming static sensor nodes having transmission range 250m uniformly distributed in the area of radius 1000m, the variation of the *Energy Overhead Factor* (defined in Section IV A) with proximity to the sink, in multi-hop routing is illustrated in Fig. 2. Due to the increased relaying overhead, the nodes nearer to the sink will deplete their battery power soon. The impact of packet error rate (PER) due to non ideal channel is also shown in this figure. If we define the lifetime of a network as the timespan till the first node dies due to energy depletion, it is evident that the use of mobile elements for data collection leads to enhanced lifetime of the network due to reduced and balanced energy consumption among the sensor nodes.

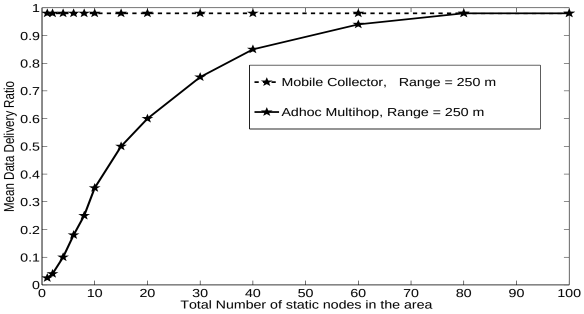

Figure 3. PDR with multi-hop and MC-based data collection

The variation of packet delivery ratio with node density is shown in Fig. 3. Assuming infinite buffer size and no communication errors, ideally the packet delivery ratio should be 1 for the DTN data collection scheme irrespective of the number of nodes in the network. For ad hoc multi-hop network, delivery ratio is very small for low node density due to end-to-end connectivity issues. As the node density is increased, PDR increases initially and finally reaches a maximum value. It then remains almost constant if only one node is transmitting, but starts reducing due to packet collisions if multiple nodes are transmitting. For the DTN scheme, delivery ratio is independent of node density. Hence, it is the ideal one for sparse networks and heavy traffic environments, provided the network lifetime and successful data delivery are of prime concern and the application is not time-critical. If the sensors are not equipped with sufficient buffer space to avoid buffer overflow at high loads, packets are dropped and PDR is reduced.

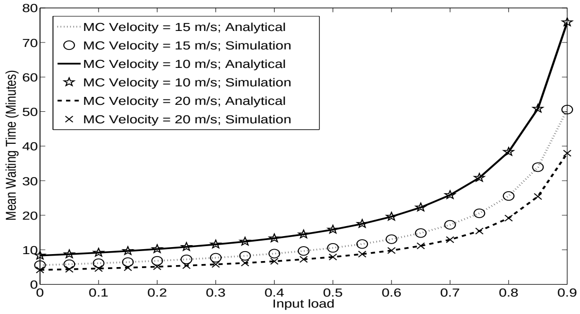

Figure 4. Variation of Mean Waiting Time

The mean waiting time for different values of data generation rate and different speeds of the single MC is plotted in Fig. 4, considering the controlled motion of the mobile sink in a square area of size 1000m × 1000m with 10 nodes randomly and uniformly distributed in this area. The sensors are equipped with sufficient buffer space so that packets are not lost due to buffer overflow. The mean waiting time increases with the packet arrival rate and decreases with the speed of the MC. Analytical and simulation results show close agreement, validating the suitability of our model. Fig. 5 shows the variation of the mean buffer occupancy with varying load and MS speeds for the same scenario. The buffer space requirement also increases with the input load and decreases with MC speed.

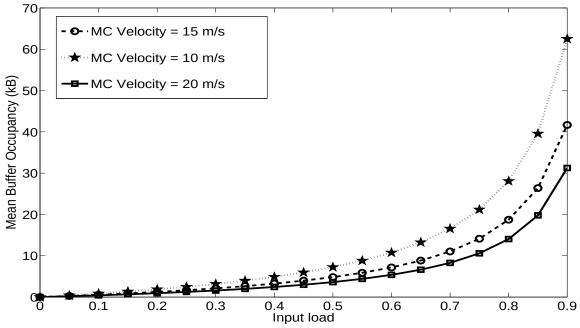

Figure 5. Variation of Mean Buffer Occupancy

Fixing the packet size to be 50 Bytes, and data rate 10 Kbps, the impact of the speed and number of MCs on the delay performance is also studied and plotted in Fig. 6. Since it not practical to have MC speeds above 20 m/s, use of multiple MCs is to be adopted for heavy traffic environments, delay-sensitive applications, and very limited sensor buffer situations. Also, the performance gain obtained by using 3 MCs over 2 MCs is much less compared to that obtained by using 2 MCs over a single one.

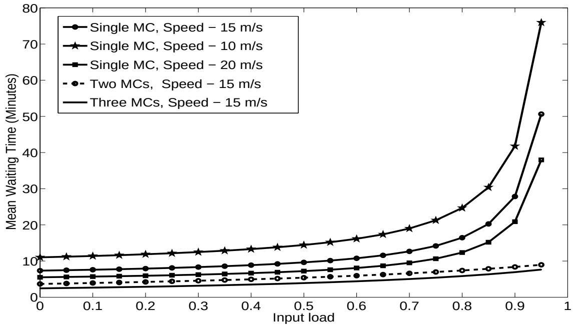

Figure 6. Mean Waiting Time with Multiple MCs

With priority polling, assuming 10 sensor nodes randomly and uniformly distributed in an area of size $1000m \times 1000m$, generating packets (of size 50 bytes) at four different rates, a single MC moving at 15 m/s, and having a data rate 10 kbps, Table I gives the visit frequency and the mean waiting time for different packet arrival rates. Based on the simulation for a fixed finite amount of time, the percentage of packets missed due to the MC not arriving in time is also noted. As the packet generation rate λ_i at node i increases, the input load ρ_i, the number of sub-cycles n_i, and the visit frequency f_i increase, while the mean waiting time $(W_q)_i$ decreases. Due to the unequal visit frequency at different nodes, the percentage of packets collected by the MC within a finite simulation time is also not equal (more at high data rate nodes and less at low data rate nodes). Thus by reducing the unnecessary travels to the low data rate nodes, the overall system utilization is improved and majority of packets will be serviced within a reasonable waiting time.

TABLE I. MEAN MESSAGE WAITING TIME AT DIFFERENT NODES

Arrival Rate (Pkts/min)	Visit Freq. (Percentage)	Waiting Time (Minutes)	Miss Ratio (Percentage)
0.01	1.53	22.37	71.25
0.1	5.10	17	57.42
1.0	16.58	12.43	13.10
2.0	23.7	11.47	1.01

VI. CONCLUSION

The suitability of a mobility-assisted framework for energy-efficient data collection in sparse underwater acoustic sensor networks has been investigated in this paper. The mobility-assisted data collection improves energy efficiency and delivery ratio at the cost of increased latency and hence it is more suited for sparse or disconnected networks and in situations where network lifetime is more important than message delay. For applications which are delay sensitive but not critical, techniques like multiple mobile collectors and priority polling have been found to improve the delay performance. The basic DTN framework having a single mobile sink and cyclic polling and the enhanced one having multiple mobile collectors and priority polling have been implemented in the NS-2 based network simulator, thus enhancing the scope for further research in this area. The enhanced model has been found to support delay-sensitive applications and optimize the delay and delivery performance.

REFERENCES

[1] I. F. Akyildiz, D. Pompili, and T. Melodia, “Underwater acoustic sensor networks: research challenges,” Ad hoc networks, vol. 3, no. 3, 2005, pp. 257–279.

[2] K. Fall, “A delay-tolerant network architecture for challenged internets,” in Proceedings of the 2003 conference on Applications, technologies, architectures, and protocols for computer communications. ACM, 2003, pp. 27–34.

[3] R. C. Shah, S. Roy, S. Jain, and W. Brunette, “Data mules: Modeling and analysis of a three-tier architecture for sparse sensor networks,” Ad Hoc Networks, vol. 1, no. 2, 2003, pp. 215–233.

[4] P. Xie, Z. Zhou, Z. Peng, H. Yan, T. Hu, J.-H. Cui, Z. Shi, Y. Fei, and S. Zhou, “Aqua-sim: an ns-2 based simulator for underwater sensor networks,” in OCEANS 2009, MTS/IEEE Biloxi-Marine Technology for Our Future: Global and Local Challenges. IEEE, 2009, pp. 1–7.

[5] ns-2 network simulator. [Online]. Available: http://www.isi.edu/nsnam/ns, [last accessed : April 2014]

[6] X. Peng, Z. Zhong, N. Nicolas, C. Jun-Hong, and S. Zhijie, “Efficient vector-based forwarding for underwater sensor networks,” EURASIP Journal on Wireless Communications and Networking, vol. 2010, 2010, pp. 1–13.

[7] S. Jain, K. Fall, and R. Patra, Routing in a delay tolerant network. ACM, 2004, vol. 34, no. 4.

[8] Z. Guo, G. Colombo, B. Wang, J.-H. Cui, D. Maggiorini, and G. P. Rossi, “Adaptive routing in underwater delay/disruption tolerant sensor networks,” in Wireless on Demand Network Systems and Services, 2008. WONS 2008. Fifth Annual Conference on. IEEE, 2008, pp. 31–39.

[9] S. Jain, R. C. Shah, W. Brunette, G. Borriello, and S. Roy, “Exploiting mobility for energy efficient data collection in wireless sensor networks,” Mobile Networks and Applications, vol. 11, no. 3, 2006, pp. 327–339.

[10] M. C. Domingo and R. Prior, “Energy analysis of routing protocols for underwater wireless sensor networks,” Computer Communications, vol. 31, no. 6, 2008, pp. 1227–1238.

[11] M. Zorzi, P. Casari, N. Baldo, and A. F. Harris, “Energy-efficient routing schemes for underwater acoustic networks,” Selected Areas in Communications, IEEE Journal on, vol. 26, no. 9, 2008, pp. 1754–1766.

[12] L. He, Y. Zhuang, J. Pan, and J. Xu, “Evaluating on-demand data collection with mobile elements in wireless sensor networks,” in Vehicular technology conference Fall (VTC 2010-Fall), 2010 IEEE 72nd. IEEE, 2010, pp. 1–5.

[13] A. A. Somasundara, A. Kansal, D. D. Jea, D. Estrin, and M. B. Srivastava, “Controllably mobile infrastructure for low energy embedded networks,” Mobile Computing, IEEE Transactions on, vol. 5, no. 8, 2006, pp. 958–973.

[14] S. Yoon, A. K. Azad, H. Oh, and S. Kim, “Aurp: An auv-aided underwater routing protocol for underwater acoustic sensor networks,” Sensors, vol. 12, no. 2, 2012, pp. 1827–1845.

[15] G. A. Hollinger et al., “Underwater data collection using robotic sensor networks,” Selected Areas in Communications, IEEE Journal on, vol. 30, no. 5, 2012, pp. 899–911.

[16] S. Motoyama, “Flexible polling-based scheduling with qos capability for wireless body sensor network,” in Local Computer Networks Workshops (LCN Workshops), 2012 IEEE 37th Conference on. IEEE, 2012, pp. 745–752.

[17] V. Kavitha and E. Altman, “Queuing in space: Design of message ferry routes in static ad hoc networks,” in Teletraffic Congress, 2009. ITC 21 2009. 21st International. IEEE, 2009, pp. 1–8.

[18] R. J. Urick, “Principles of underwater sound,” McGraw-HiII, New York, London, 1983.

[19] H. Takagi, Stochastic analysis of computer and communication systems. Elsevier Science Inc., 1990.

[20] M. Ajmone Marsan, L. De Moraes, S. Donatelli, and F. Neri, “Cycles and waiting times in symmetric exhaustive and gated multiserver multiqueue systems,” in INFOCOM’92. Eleventh Annual Joint Conference of the IEEE Computer and Communications Societies, IEEE. IEEE, 1992, pp. 2315–2324.

[21] O. J. Boxma, Analysis and optimization of polling systems. Centre for Mathematics and Computer Science, 1991.