Undersea wireless sensor network for ocean pollution prevention

A novel paradigm for truly ubiquitous underwater systems

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Abstract—**The ability to effectively communicate underwater has numerous applications, such as oceanographic data collection, pollution monitoring, disaster prevention, assisted navigation, tactical surveillance applications, and exploration of natural underwater sea resources. In this paper, we have developed a completely decentralized ad-hoc wireless sensor network for the ocean pollution detection. We mainly emphasize on the deployment of sensors, protocol stack, the synchronization algorithm and the routing algorithm in order to maximize the lifetime of the network and also to improve its Quality of Service (QoS).**

Keywords – ***Network Architecture; Protocol Layers and Planes; Synchronization Protocol; Routing Protocol; Network Lifetime; QoS***

I. INTRODUCTION

The application of wireless sensor networks to the underwater domain has huge potential for monitoring the health of river and marine environments. The ocean alone cover 70% of our planet and along with rivers and lakes are critical to our well-being. The search for oil reserves offshore is moving into deeper and deeper waters, and crude oil and oil products are being transported across the globe in increasingly larger tankers. As a result, oil spills pose a serious threat to the ecology of the World's oceans. The amount of oil spilled annually worldwide has been estimated at more than 4.5 million tons. The biggest contributor to oil pollution in the World's oceans (some 45%) is operational discharges from tankers (i.e. oil dumped during cleaning operations). Approximately 2 million tons of oil is introduced annually by such operations, equivalent to one full-tanker disaster every week [1]. Only 7% of the oil in the sea can be directly attributed to accidents. Land-based sources such as urban waste and industrial discharges, which reach the ocean via rivers, are also a major contributory factor (Figure 1).

Monitoring marine environment is difficult and costly for humans: divers are regulated in the hours and depths at which they can work and require a boat on the surface that is costly to operate and subject to weather. In recent papers [2] [3], some Underwater wireless network models have been proposed where Autonomous Underwater Vehicles (AUV), Unmanned Undersea Vehicles (UUVs) and Buoys are utilized to accept data from the sensors periodically and send them to the base station. We argue that, in most cases, this is not the right choice. They are costly, very much energy consuming and for time-critical applications [4] like ocean pollution monitoring they cannot be utilized efficiently.

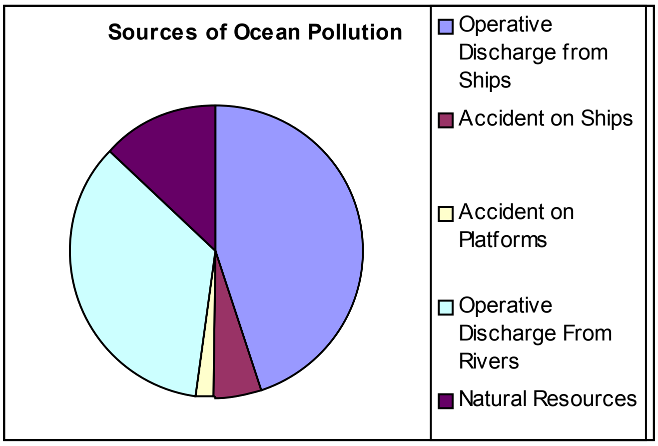

Figure 1. *Sources of Ocean Pollution*

The main contributions of our work when compared to the existing literature are the following: (1) we have suggested a completely decentralized ad-hoc wireless sensor network model where the nodes communicate through neighbors (ad hoc network paradigm). (2) We prefer short-range acoustic communication (50 – 500 m) to long range communications (1 – 90 Km) that are currently in use. (3) We have developed a novel node synchronization protocol for almost uniform battery wastage by the deployed sensors. (4) Due to different nature of the underwater environment and applications from its terrestrial counterpart, the Underwater Wireless Sensor Network (UWSN) has some major challenges [2] [5]: (i) acoustic communication instead of radio; (ii) expensive compared to terrestrial sensor nodes, hence sparse deployment of sensors; (iii) limited Bandwidth; (iv) higher & variable propagation delay; (v) cannot be recharged by solar power under the sea; (vi) prone to failures because of fouling and corrosion; (vii) underwater channel is severely impaired, especially due to multi-path and fading; so, high bit error rate & temporary losses of connectivity; (viii) requires self-configurable topology; (ix) GPS system does not work under water properly. We have developed a novel protocol stack for the UWSN to counter all these problems and improve the output.

II. THE PROPOSED UWSN ARCHITECTURE

We assume that the topology is decentralized ad hoc. $V = \{ v_1, v_2, \ldots\ldots\ldots v_N \}$ is the set of nodes; where v_N is the sink node at the surface and its position is fixed. The range of each sensor node is r and each node is omni directional. So an edge e_{ij} between two sensors v_i and v_j will exist if and only if $| e_{ij} | <= r$. Hence, the overall network will be a 3-D disk graph of coverage radius r for each node. Next we shall consider the minimum no. of nodes required to cover the entire volume in 3-D. In 1-D, it must be (a / r) to get total length coverage and to ensure the connectivity of the graph; where a is the monitored length and r the range of each sensor (Figure 2).

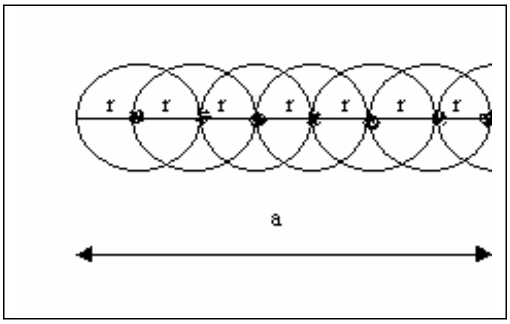

Figure 2. *1-D deployment of Sensors*

Figure 3 suggests that for 2-D, we require minimum $(a / r)^2$ no of sensors to get total area coverage and to maintain connectivity among nodes. Another advantage of these types of deployment is that for any position of source and sink, the locally selected best next-hop will be the globally best next-hop. Since memory less random routing is preferred to global routing in sensor networks, these types of deployments will improve the percentage of successful message delivery using memory less random routing scheme to a great extent.

By similar argument, we can say that the minimum no of sensors required to be active in 3-D is $(a / r)^3$. Nodes can be air-dropped with uniform distribution from certain height above the sea level. . Sensor nodes are equipped with a low-cost floating device that can control their depth from the sea surface. However, since the nodes are air-dropped, to guarantee total volume coverage and connectivity, we actually need to deploy total $m \times (a / r)^3$ no of sensors; where m is a positive integer.

The nodes do not have any mobility property. But because of the drift of water, they may move at the speed of 1.0 – 1.5 m/sec in a typical underwater condition. Some synchronization protocols are used to keep most of the nodes in sleep mode so that the active nodes at any time are sparsely distributed (as required for the UWSN). Now-a-days, underwater sensors are available for collecting accurately several water quality parameters such as; temperature, chemical substances, water density etc.

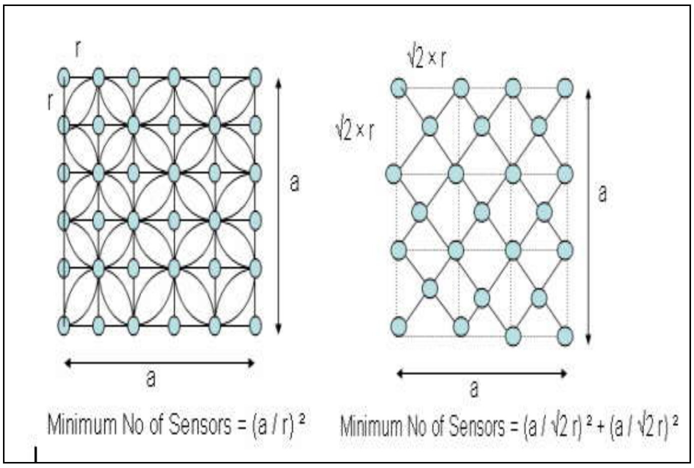

Figure 3. *2-D deployment of Sensors*

A. *Selection of r and m*

We prefer short-range communication (50 – 500 m) to the conventional long-range acoustic (1 – 90 Km) communication underwater. The objective is to make the acoustic modem inexpensive, so that it costs as much as the CPU and packaging, around $30 – 100. Relatively lower costs of sensors allow dense deployment underwater, with m varying from 8 to 10. Now long-range communication can be achieved by multi-hop routing over many sensors. Also focusing on short-range communication can eliminate some challenges of long-range underwater communication, e.g. acoustic ducting, multi-path effects etc. and thus, it will greatly simplify the modem design. Moreover, available acoustic channel bandwidth increases with decreasing the communication range [6] as shown in the following table. In our model, we choose the range of each sensor r = 500 m.

TABLE I. AVAILABLE BANDWIDTH FOR DIFFERENT RANGES IN UW-A CHANNEL

	Communication Range	Available Acoustic Bandwidth
Very Long	1000 Km	< 1 KHz
Long	10 – 100 Km	2 – 5 KHz
Medium	1 – 10 Km	10 KHz
Short	0.1 – 1 Km	20 – 50 KHz
Very Short	< 0.1 Km	> 100 KHz

III. UWSN PROTOCOL STACK

A protocol Stack [7] for UWSN should combine power awareness and management, and promote cooperation among the sensor nodes (Figure 4). It should consist of physical layer, data link layer, network layer, transport layer, and application layer functionalities. The protocol stack should also include power management plane, a coordination plane, and a localization plane.

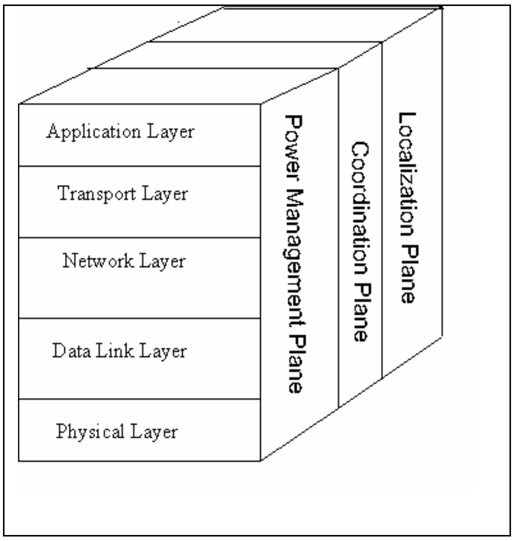

Figure 4. *UWSN Protocol Stack*

A. *Power Management Plane*

The power management plane is responsible for using proper synchronization protocol to enhance the network lifetime. Since the coverage radius of each node is r, it is unnecessary that total $m \times (a / r)^3$ no of nodes will remain active throughout the entire lifetime of the network. Nodes will be in active mode and sleep mode periodically with a time-period of T sec. We have designed our synchronization protocol for the UWAN regarding the Dominant-Pruning Algorithm [7], developed by Dai and Wu, as the base. But we cannot utilize the Dominant-Pruning Algorithm in its original form because of three major difficulties: (1) Dominant-Pruning algorithm has been designed especially for Static Nodes. But UWSN nodes are mobile. (2) In this algorithm, connected dominating set of sensors monitor the other nodes within their neighborhood. But, instead of full node coverage, we require total volume coverage. (3) Also the algorithm defines node priority only by node identifiers. But the synchronization protocol required for our UWAN must be energy-efficient too.

Synchronization Protocol: First, there will be a small t sec time interval during which nodes exchange information (position and priority, which is a number proportional to the node's remaining battery life) with the neighbors. In this t sec time period, all nodes in the network will be in low-power listening and transmitting mode and they will not do any sensing or data routing. Then the nodes will apply the following algorithm to determine their future mode.

Input: A node's position and priority at t sec time-interval, its neighbors' positions and priorities at t sec time-interval.

Output: Detect whether the node will be in active mode or sleep mode for next T sec time period.

Algorithm:

```
for each node v in the network do
  begin
    if (a subset S of its neighbors is fully connected) and (all
       nodes in that subset S have higher or equal priority
       compared to that of v) and (the nodes in S fully cover
       the volume that is covered by v) then
          v will be in sleep mode
    else
          v will be in active mode
    endif
  endfor.
```

For the next T sec (T > t) time period, only the active nodes will do sensing and routing. If any of the sleeping nodes has some data previously in its buffer that is yet to reach the sink, it will transmit the data to the locally selected best neighbor just before it is going to sleep. The value of t is fixed for a particular network. The optimal values of T and r1 are discussed in the Mathematical Modeling section.

The algorithm ensures total volume coverage, connectivity of the sub graph formed by active nodes (Lemma 1) and also minimum and almost uniform energy wastage by all the nodes in the network (Figure 5).

Lemma 1*(Proof of total area coverage)*

Let G be the volume-dominating sets that our synchronization algorithm generates, and let F be the dominating set of G that the dominant-pruning protocol generates. If the monitoring volume of a node u is covered by a connected subset of its neighbors with more battery life, the set of neighbors of u is fully covered by the same subset. In other words, if a node does not belong to G, it also does not belong to F. Hence, the volume-dominating set G includes the constructed dominating set (of neighbors) F. Since F is proven to be connected [8], it follows that G is also connected.

Proof of Almost Uniform Power Wastage: We shall consider the case in 2-D as shown in Figure 5. The node priorities are in the following order: $w1<w2<w3<w4<w5<w6$. Now, the application of our node synchronization algorithm shows that the nodes with higher priority remain in active mode, whereas the nodes with lower priority are mostly in sleep mode. This will ensure almost uniform battery power wastage by all the nodes in the network.

B. *Coordination Plane*

Coordination Plane is responsible for time synchronization among all the sensors. The synchronization is done during each t sec time interval. Since synchronization is performed

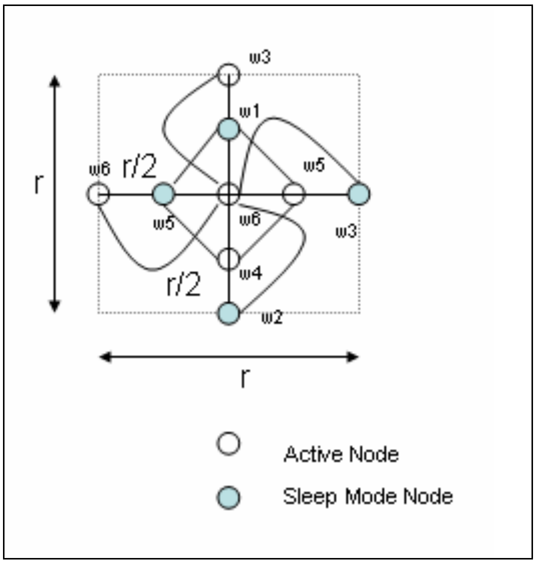

Figure 5. Application of Synchronization Protocol

after every T sec time period, the nodes do not require to be accurately synchronized with respect to the real time; rather synchronization with respect to each other can serve our purpose. Here we employ the technique of receiver-to-receiver synchronization [9] rather than sender-to-receiver synchronization. This approach exploits the property of the physical broadcast medium that if any two receivers receive the same message in a single-hop transmission, they receive it approximately at the same time. Instead of communicating with the sender, the receivers interact with each other and compute their offsets based on the difference in reception times. The obvious advantages are the reduction of message overhead and also the decrease in message delay variance. Also instead of correcting the clock time of each sensor, we can opt for building a table of parameters that relate the local clock of each node to the local clock of every other node in the network. Local timestamps are then compared using the table. In this way, a global timescale is maintained while letting the clocks run undisturbed. A considerable amount of energy can be saved in this way.

C. Localization Plane

Localization plane is responsible for informing each node about its neighbors and it also helps a node to select its best neighbor in order to send a data packet to the sink. So the function of this plane is associated with that of network layer and discussed in the Network Layer sub-section.

D. Physical Layer

As the electromagnetic waves cannot propagate over long distances in seawater, acoustic provides the most obvious choice of channel to enable underwater communication. In this realm, the carrier frequency is relatively low, i.e. <20 KHz, with long bit intervals. As whales and sonar systems can attest, these signals may propagate for long distance underwater. It also supports broadcasting in a shared medium. Since the sound speed in seawater is much lower, the effect of Doppler Shift creeps in. In communication schemes where the synchronization signal is sent over communication channel, the Doppler shift may automatically be corrected if synchronization signal Doppler shift automatically compensates for the data signal Doppler Shift. Extended Kalman Filter (EKF) [10] [11] can be used for tracking the Doppler shift of a peer modem in real-time for cases where the two modems are in more or less constant communication.

E. Data Link Layer

Time varying multi-path propagation and non-Gaussian noise are two of the major factors that limit acoustic communications in shallow water. Time-varying multi-path propagation increases the inter-symbol interference (ISI) and causes frequency dependent fading, thus limiting the communication data rates. We propose that the Direct Sequence Spread Spectrum (DSSS) Communication with Chaotic Synchronization techniques can be adopted to improve underwater acoustic communications. The advantages are: 1) Low power spectral density, 2) Interference limited operation, 3) Privacy due to unknown random codes & Good anti-jam performance, 4) robustness against various imperfection of the channel, e.g. multi beam spreading or muffling, 5) Random access possibilities, 6) the spreading of frequency spectrum of a data-signal using a code uncorrelated with that signal results much higher bandwidth occupancy than required, which is suitable for the limited bandwidth acoustic communication of UWSN.

One of the problems with long PN codes is that the codes generated by digital signal processor tend to be periodic due to the digital nature of the processor. So synchronized chaos generator may be used to provide PN codes for DSSS communication.

Since acknowledgement scheme may not be suitable with the limited bandwidth acoustic communication of UWSN, we choose Reed-Solomon forward error correction code. These large block codes are easy to generate and provide excellent burst-error detection and correcting ability.

F. Network Layer

Our routing protocol works in two stages.

Localization: During each t sec time-period, the sink broadcasts an interest. The interest entry includes a gradient field. A gradient is a reply link to a neighbor from which the interest was received. By utilizing interests and gradients several path could be established. Also in this way, each node becomes aware about its neighbors.

Routing: When a node u has a data packet to send, it will select its next neighbor v using the following random memory less algorithm:

$$\mathrm{v} = \min \{Euv \mid v \in N(u) \cap S(u)\} \tag{1}$$

$$\mathrm{E_{uv}} = \mathrm{E_{buv}} \times \mathrm{N_{uv}} \times \mathrm{N_{u-hop}} \tag{2}$$

$$\mathrm{N_{u-hop}} = \max\left\{\mathrm{distance}\left(\mathrm{u, sink}\right) / \mathrm{distance}\ \left(\mathrm{u, v}\right)\ ;\ 1\right\}. \tag{3}$$

Where $N(u)$ is the set of nodes that are neighbors to u; $S(u)$ is the set of nodes that are closer to the sink than node u; and E_{uv} is the estimated energy cost metric associated with the edge e_{uv}. E_{buv} is the energy required to transmit one bit from node u to node v; N_{uv} is the total number of bits is the current data packet; and N_{u-hop} is the estimated number of hops from node u to the sink.

All these values are calculated using the data available at the end of earlier t sec time interval. If the topology does not change much in the T sec time period (i.e. the best neighbor calculated above does not go beyond the sender's transmission range); the above routing scheme will guarantee successful message delivery for connected networks as well as minimum energy utilization.

Routing is done during the T sec time periods. If one T sec time period ends before a data packet reaches to the sink, the current node will hold the data packet for the next t sec time interval and restarts routing with new co-ordinates at the end of this t sec interval.

IV. MATHEMATICAL MODELING

Suppose we are monitoring a volume V_1 = (l × d × h) underwater. According to our topology, number of sensor nodes required $= m \times \frac{V_1}{r^3}$; r being the range of each sensor node. Initial energy of each sensor node E. Data transmission Rate is D_{tran} over a distance r at a transmit power P_{tran}; and Data Receiving Rate D_{recv} over the distance r at a reception power P_{recv}. Data Packet size is S_D and Control Packet size S_c. Power wastage by each node in low power listening mode $= P_l$. Energy required for running the synchronization algorithm $= P_S$. From empirical observation, underwater objects may move at the speed of v = 1.0 – 1.5 m / sec in a typical underwater condition. We assumed a Poissonian Model with node failure rate μ. All deployed sensors have sensing capability and can act as source, with data-packet inter arrival time to active sensors $= Td$. Speed of sound underwater V = 1500 m/sec.

Since each node has m neighbors in the network, each node will get m control packets from its neighbors. Now, network set-up time t is given by:

t = (m × maximum Propagation Time for one control packet)+ (m × maximum Transmission Time for one control packet) + (Time required for applying the Synchronization algorithm)

$$= \frac{\text{m} \times \text{maximum distance}}{\text{speed of sound underwater}} + \frac{\text{m} \times \text{maximum distance} \times \text{control packet size}}{\text{Range of sensor} \times \text{Transmission Rate}} + T_S$$

$$= m \times \sqrt{(l^2 + d^2 + h^2)} \times \left(\frac{1}{V_s} + \frac{S_c}{r \times D_T}\right) + T_S \,. \tag{4}$$

Now the value of T should be such that the energy spent by the active nodes in T sec time period is considerably higher than the energy spent by the nodes in t sec time interval. This demands a higher value of T. It will increase the lifetime of the network. On the contrary, if T has a large value, the possibility that the network topology will change to a great extent in that time period is very high. This will actually decrease the performance of the network, since the active nodes has no way to know the new positions of their neighbors within that T sec period. To counter this effect of node drifting and node failure, we can slightly modify our node synchronization protocol. The algorithm, as it is stated earlier, ensures that at the beginning of each T sec time period, active nodes will be separated at most by a distance r. At this point, we propose to temporarily change the definition of neighbor that two nodes will be neighbors only if there separation is r_1 ($r_1 < r$). Now again, if we apply the same algorithm, it will guarantee that at the starting of each T sec time-period, the maximum separation between two active nodes can be r_1. By properly selecting the value of r_1 and T, we can ensure that even though the nodes drift, the neighbors (according to our new definition) of a node will be within its actual range r during that T sec time period.

However, the most important thing is that the choice of T and r1 are not independent. If we want to increase the value of T, we need to decrease r_1; and vice versa. So we have first selected the value of T, so that E_t, the energy spent by the nodes in t sec time interval is negligible compared to E_T, the energy spent by active nodes during T sec time period. Then we have selected an optimal value of r_1 so that there is a trade-off between the network lifetime and network performance.

By similar analysis, maximum time required to transmit one data packet by one hop is given by:

$$T_{one\_hop} = r \times \left(\frac{1}{V_s} + \frac{S_D}{r \times D_T}\right) . \tag{5}$$

S_D being data packet size.

Also, the maximum time required to transmit one data packet from one end to another end of the network is given by:

$$T_{\max} = \sqrt{(l^2 + d^2 + h^2)} \times \left(\frac{1}{V_s} + \frac{S_D}{r \times D_T}\right) . \tag{6}$$

We choose T = n × $T_{\max}$. (7)

Now, the number of data packets received by one active node is T sec time period is given by d = $\frac{T}{Td}$.

Hence,

$$E_T = (d \times \mathrm{P_{tran}} \times T_{one\_hop}) + (d \times \mathrm{P_{recv}} \times T_{one\_hop}) \tag{8}$$

$$E_t = (t \times P_l) + Ps \tag{9}$$

The value of n should be chosen such that $E_t << E_T$.

Suppose, L_r be the lifetime of the network when the active nodes are separated by a distance r. Now, if the active nodes are separated at most by a distance r1 instead of r (r1 < r), the minimum no of sensors required to be active in one T sec time period will be $\frac{V_1}{r_1^3}$ instead of $\frac{V_1}{r^3}$. Since $E_T >> E_t$, assuming uniform distribution of battery power wastage, the lifetime will be decreased to: $L_{r1} = L_r \times \frac{r_1^3}{r^3}$ (10)

On the other hand, the maximum drift of a node during T sec time period is given by: $a = v \times T$ .They can move in horizontal two-dimensional space, i.e., in the X-Y plane (which is the most common mobility pattern in underwater applications) [12]. So the distance will increase by

$$b = \sqrt{(a\cos\alpha - a\cos\beta)^2 + (a\sin\alpha - a\sin\beta)^2}$$

$$\approx a|\alpha - \beta|\,;\ 0 \le \alpha \le \pi\,,\ 0 \le \beta \le \pi \qquad (11)$$

So the probability that the distance between two nodes with initial separation r_1 will be greater than r is given by:

$$P_d = \Pr obability\{|\alpha - \beta| > \frac{r - r_1}{a}\} = \frac{\{\pi - \frac{r - r_1}{a}\}^2}{2\pi^2}. \qquad (12)$$

Also, the probability that at least one node will fail in T sec time period can be determined as: $P_f = 1 - \left[e^{-(\mu \times T)}\right]$.

So the maximum probability of a data-packet failure in T sec: $M_F = P_d + P_f$.

For optimization, we have defined a metric Utilization U as:

$$U = L_{r1} \times (1 - M_F)$$

$$= \left(\frac{r_1}{r}\right)^3 \left(e^{-\mu T} - \frac{\left(\pi - \frac{r - r_1}{a}\right)^2}{2\pi^2} \right) L_r \qquad (13)$$

We have to determine the optimum value of r_1 for which U is maximum. We can easily determine it since the other parameters are known for a particular system.

V. CASE STUDY AND SIMULATION

We have performed the case study for a monitoring volume of (*5Km ×5Km×5Km)* underwater. The parameters are set using the standard values as follows:

TABLE II. INITIALIZATION

D_{tran}	50Kbps
D_{recv}	50Kbps
P_{tran}	*0.8W*
P_{recv}	*0.05W*
P_l	*0.08W*
P_S	*0.1W*
μ	*0.5 nodes per day*
Td	*7.5 sec*
S_D	*100 bytes*
S_c	*10 bytes*
m	*8*
n	*10*
r	*500 m*

We did analytical study to get the optimal values of T and r_1 . t is coming as 5 sec. The optimal value of T = 60 sec and the optimal value of r_1=456.02 m. The maximum possible value of U = 0.52 L_r with Lifetime = 0.76 × L_r and the successful message delivery ≈ 70%. Here, we have considered the worst case for this analytical case study. We can get the average percentage of successful message delivery by simulation.

We have used NS2 for the simulation. The total simulation time is 65 seconds, which is equal to the duration of one set up cycle and one active cycle of our Model. The sink is fixed at a particular location. For the initial separation of 450 m among the active nodes, the successful message delivery is 75 %. We then varied the initial distance among nodes and analyzed lifetime of network and the percentage of successful message delivery which are plotted in the following graphs.

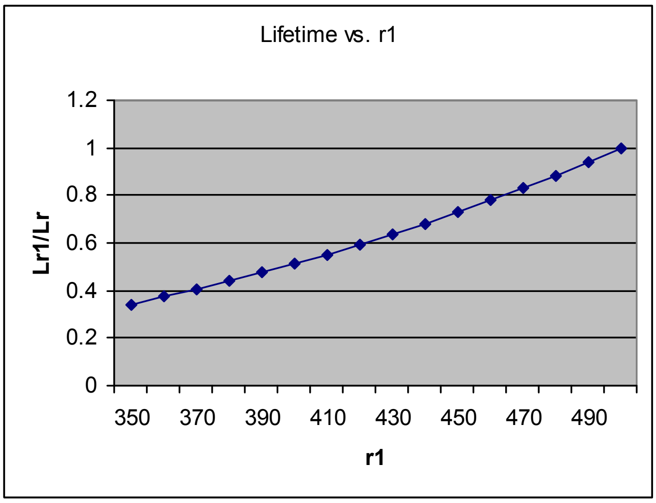

Figure 6. Lifetime vs. r1 graph

VI. CONCLUSION

Underwater communication using long range (1 – 90 Km) acoustic modem is relatively older. But such systems are power hungry and expensive. In this paper, we have mentioned a novel alternative possibility of time-critical underwater communication using short-range (50 – 500 m) low-cost sensors. Our primary goal is that the modem should be inexpensive to make it feasible to purchase and deploy many underwater sensor nodes. Long-range communication can be achieved by multi-hop routing over many individual nodes. In fact, focusing on short-range communication means we can increase the available acoustic bandwidth and also avoid many of the challenges of long-range underwater communication and hence, greatly simplifying the modem design. Besides, we have proposed a novel synchronization protocol that will guarantee total volume coverage, improve the QoS; as well as enhance the lifetime of the entire network.

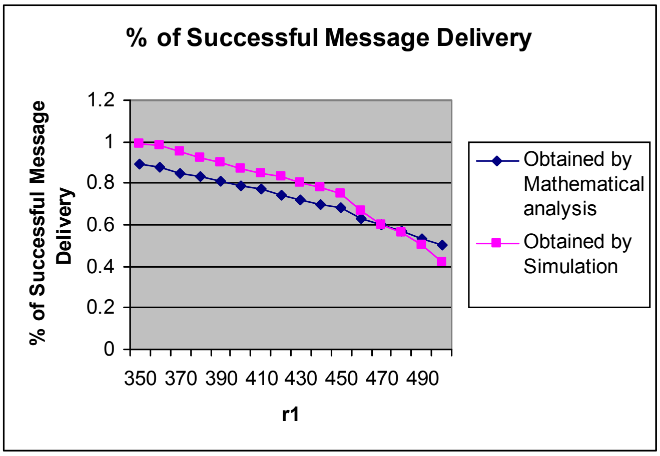

Figure 7. % of Successful Message Delivery vs r1 graph:

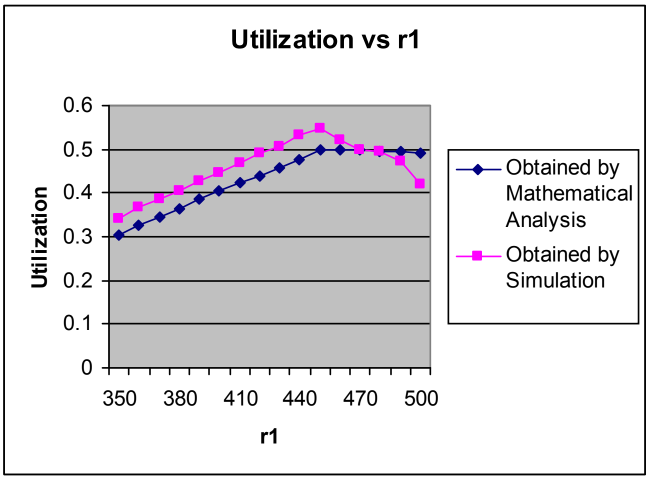

Figure 8. Utilization vs r1 graph

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