International Journal of Innovative Technology and Exploring Engineering (IJITEE)
ISSN: 2278-3075 (Online), Volume-8 Issue-12, October 2019

Hybrid Cross Layer Fault Resilient Energy Efficient Data Transmission for Underwater Acoustic Sensor Networks

Vidyalakshmi K,M.Siddappa,B.Shanmukha

Abstract: Under water acoustic sensor network is the unique case of wireless sensor network in which the physical characteristics limits the capability of sensor network due to various problems like Doppler-spreads, medium significnt delay, Double-side spreading, limited bandwidth and frequency-selective fading. Ensuring QOS is very challenging problem in acoustic sensor networks. In this work, a QOS centric hybrid routing protocol with consideration of fault resilience is proposed. The solution use the parameters of the network at all Application Layer, Network Layer, MAC Layer, and PHY Layer, which are the different layers of IEEE 802.15.4 protocol stack, thus calculating Node selection score which helps in identifying the best forwarding node for a constrained reliable data transmission. The solution involves dynamic link quality estimation, congestion awareness, packet injection ratio estimation and physical switching that cumulatively ensures fault-resilient and QoS delivery over acoustic sensor network.

Keywords : Error Correcting Codes, Fault tolerance service, Reed-Solomon, Super Cluster, Under water sensor network, Wireless Sensor Network.

I. INTRODUCTION

Under water acoustic sensor networks (UASN) has gained popularity with increasing applications in marine life monitoring, oil line and tsunami monitoring. Even though UASN are similar in many aspects to terrestrial wireless sensor network, there is major difference regarding channel usage in UASN. While traditional wireless network use radio signal, UASN use acoustic signal due to radio signal attenuation in under water environment. Compared to radio signals, acoustic signals perform well in under water communication. As there is a replacement of communication characteristics from speed of light to the speed of sound, the propagation speed is five orders of magnitude less than that of the radio frequency. This causes variable delay and lower data rate in UASN. The data rates hardly exceeds from 40 kb/s at a range of 1km.

Revised Manuscript Received on October 30, 2019.
* Correspondence Author
Mrs.Vidyalakshmi K*, Assistant Professor in the department of Computer Science and Engineering at BGS Institute of Technology, BG-Nagar, Mandya, Karnataka, INDIA
Dr.M.Siddappa,Professor and Head, Dept. of Computer Science and Engineering and aslo is the Dean Academics at Sri Siddhartha Institute of Technology, Tumakuru, Karnataka,INDIA
Dr.B.Shanmukha, Associate Professor in the department of Mathematics at PES College of Engineering Mandya.

While most terrestrial sensors nodes are static, underwater sensor nodes can move due to different underwater activities, as during normal conditions a node can move 2-3 m/sec with water currents. Energy efficiency must also be a major criteria in
designing UASN as battery replacement for underwater environment is not that very easy, due to effort and time. Senor nodes do fail with higher probability in case of UASN due to the oceanic salt water environment and damage due to marine life. A energy efficient high reliability fault resilient solution to address the above challenges is the motivation for this work. We propose a Fault Resilient Energy efficient Cross layer Hybrid Solution (FREC-HS) to address the QoS challenges in UASN. This approach ensures the selection of a energy efficient fault-resilient high reliable path selection for QoS delivery over UASN. It is accomplished by exploiting the features of cross-layer architecture of IEEE 802.15.4 protocol stack with usage of transmission power control, error coding, selective multipath propagation and network topology adaptive routing. The proposed FREC-HS is implemented in NS2 and tested for UASN conditions. Through simulation measurements, QoS is found to be far better in proposed solution compared to the existing works in the literature.

II. RELATED WORK

The survey is conducted in three categories of fault tolerance, energy efficiency and cross layer solutions

A. Fault tolerance

Ye et al. [1] developed a fault-tolerant routing protocol in cluster based WSNs for reliable data transmission. In their model at first they performed non-uniform multi layer clustered network topology that could prohibit the inter cluster load imbalance problem significantly. Their overall model exhibited that the applied clustering approach could minimize energy exhaustion while maintaining maximum possible network reliability. To perform Cluster Head (CH) selection they applied FIS model that quantifies each node for its suitability for being CH. Furthermore, to ensure security they applied rollback model. Nader et al. [2] proposed a Autonomous Underwater Vehicles (AUV) based solution to overcome the faults due to network holes and disconnected segments. The solution proposed mobile sink to cover the network holes and deploy the fixed sensor nodes that could replace the faulty
nodes of the network.

A strategy was proposed to find the faulty nodes that could replace failed nodes. An energy-aware multi hop cluster-based fault-tolerant load balancing hierarchical routing protocol for WSNs was given by Beldjehem et al.[3]. Salient feature of this solution is that it applied hierarchical fuzzy based clustering to avoid cluster overlapping that permits efficient data forwarding. Hu et al., [4] proposed fault-tolerant routing model for heterogeneous WSNs comprising resource constrained nodes as well as resource rich super nodes. Authors have proposed Immune Cooperative Multi-Particle-Swarm Algorithm (ICMPSA) that helps in swift route-recovery amongst K disjoint paths connecting source to the nearest super node and super node to the sink. Afsar et al. [5] developed Fault-Tolerant Service (FTS) for clustering based routing in which at first the overall nodes are divided into groups using Energy-Efficient Distance-based Clustering scheme. It is then followed by FTS applied to ensure reliable data gathering. They proposed FTS model that comprised three sequential phases: fault detection, fault diagnosis and fault recovery.

B. Energy efficiency

Making use of optimized channel coding parameters Grasielli et al. [6] was able to address the energy-efficient communication problem, where two-layer encoding scheme was considered by including Forward Error Correction (FEC) codes as well as Fountain Codes (FC) for UAN scenarios without any feedback channels. The requirement of minimum energy consumption in underwater acoustic channel for transmitting one bit of information was investigated by De Souza et al [7]. Employing binary FSK modulation usage and also the convolutional error correcting codes, the authors have optimized the Signal-to-Noise Ratio (SNR), operation frequency and code rate when a target Frame Error Rate (FER) was to be achieved and the results have shown that the correct choice of code rate has a very great impact on overall energy consumption and thus the lifetime of underwater communication devices. Inclusively, correct choice of code significantly increases transmission range. De Souza et all [8] investigated total energy required to transfer an information bit over a multi-hop underwater acoustic network successfully taking into consideration number of retransmissions occuring, optimum number of hops, the SNR and code rate.The authors have also analysed that in total energy consumption, the impact of delay constraints by permitting limited or unlimited retransmission. A larger amount of energy savings is established when the parameters mentioned above are mutually optimized for any given link distance. Though the effect of the multiple hops is of greater advantage, permitting small number of retransmissions finally will lead to major energy savings. Daniel et all [9] examined the energy consumption by employing fountain codes of underwater network, whose major thought was to transmit, undetermined amount of coded bits so as to gurantee the given target FER at the receiver which doesn’t need retransmissions. For such target FER, the authors also have optimized SNR, the carrier frequency and also the code rate. The analysis has clearly proved that the use of FC reduces consumption of energy by 30%. Fatma et all [10] made a detailed analysis on effect of underwater characteristics, balancing the energy consumption among all underwater sensors. Among all underwater sensors, the authors have given a balanced routing strategy with deployment pattern which determines the total load weight for each possible next hop, which leads to fairness in energy consumption, which gave the solution to energy holes problem and thus improved network lifetime. Rui Hou et all [11] proposed an Energy-balanced Unequal Layering Clustering (EULC) algorithm which highly improved energy efficiency of the acoustic sensors.This algorithm designs UASNs with unequal layering that is based on node depth which provides solution to “hot-spot” issue via the construction of clusters of different sizes within the same layer.Through simulation the authors have proved that as the energy is balanced in UASN nodes, the life time is prolonged. Tayyaba Liaqat et all [12] gave a Depth-Based Energy-Balanced Hybrid (DB-EBH) routing protocol for UWSNs. DB-EBH is also a hybrid approach like EBH that is based both on direct and multi hop communication whereas it considers linear random deployment of nodes which picks priority neighbor node for forwarding data on depth from sink basis. Degan et all [13] analyses and proposes an energy balanced routing method which is based on Forward-Aware Factor (FAF-EBRM), in which awareness of link weight and forward energy density is considered for next-hop node. Henceforth for local topology a spontaneous reconstruction mechanism is designed. Experimental results has shown that FAF-EBRM outperforms LEACH and EEUC, balancing the energy consumption, which may prolong the function lifetime assuring high QoS of WSN. For acoustic 3D Under Water Sensor Networks (UWSNs), an Energy Efficient logical Cubical layered Path Planning Algorithm (EECPPA) as well as Multiple Sink EECPPA (MSEECPPA) was proposed by. M. Aslam et al [14]. Both EECPPA and MSEECPPA algorithms are quite fully distributed and highly adoptive in execution of logically divided 3D networks into the multiple cubes. The proposed models are very flexible during the location variations of the sensors and has better ability to reconfigure logical cubes with respect to size within 3D cubical UWSNs. A multiple group of leading nodes named CHs is selected by these multiple logical cubes. The iterative executional operation of EECPPA and MSEECPPAA is being classified as; Network Dimensional Phase (NDP), Network Settling Phase (NSP) and Network Transmission Phase (NTP). Multiple cubical layers are constructed in NDP, in NSP leading nodes are selected near reference point of logical cube's boundaries and actual communications of the nodes occurs in NTP. MSEECPPA algorithm selects the suitable relaying nodes called multiple sinks to utilize the multi-hoping mechanism which increases the lifetime of longer distance nodes from the Base Station (BS).

C. Cross layer solution

For under water acoustic sensor networks a cross-layer MAC protocol was proposed by Xueyuan Su et al. [15] which could interact with price-based rate allocation scheme at network layer. In wireless medium to reflect accurately clique constraint, a price which is based on clique is being generalized which acts as the congestion signal, that controls end-to-end rates of the multi hop flows. Later on MAC protocol will schedule transmission of contention-free packet of single-hop in individual maximum clique.

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Chao Lv et all [16] proposed underwater acoustic channel access method which was Time Division Multiple Access TDMA based that could improve the utilization of channel in a dense mobile underwater wireless sensor networks. A pre-verified template that is minimizing the amount of slots which aims to decrease end-to-end delay is being assigned to the time slot of each node in UA-MAC. Inclusively a piggyback based protocol is being implemented to schedule and synchronize network. For UWSNs a novel cross-layer Routing Protocol which was based on Network Coding (NCRP) that makes use of network coding as well as cross-layer design to forward the data packets greedily to the sink nodes efficiently was proposed by Hao Wang et all [17]. This protocol will take the complete advantages of multicast transmission and will decode the packets jointly along with the encoded packets that is being received from different multiple potential nodes in the entire network.To extend the life cycle of the network the transmission power is optimized. Roberto Petroccia et all [18] gave an adaptive cross-layer routing protocol for Underwater Acoustic Networks which is quite self-adaptive and fully distributed. This protocol also supports multiple coded modulation schemes and the crosslayer information usage to interact with the physical layer. In order to select the usage of the relay node, link quality information along with that of energy and topological data is exploited. Guangjie Han et all [19] proposed A cross layer solution which jointly combined VBF routing algorithm along with residual energy consideration and the data retransmission to make an optimized decision to know whether a node is forwarding the data or not.

From the survey, it is clearly seen that we do not find a single solution addressing the fault tolerance and energy efficiency with consideration for quality of service at same time. Designing a solution with optimization of multiple conflicting objectives of fault tolerance with energy efficient at same time without compromising on quality of service is under water wireless sensor network is a challenge.

III. PROPOSED SOLUTION

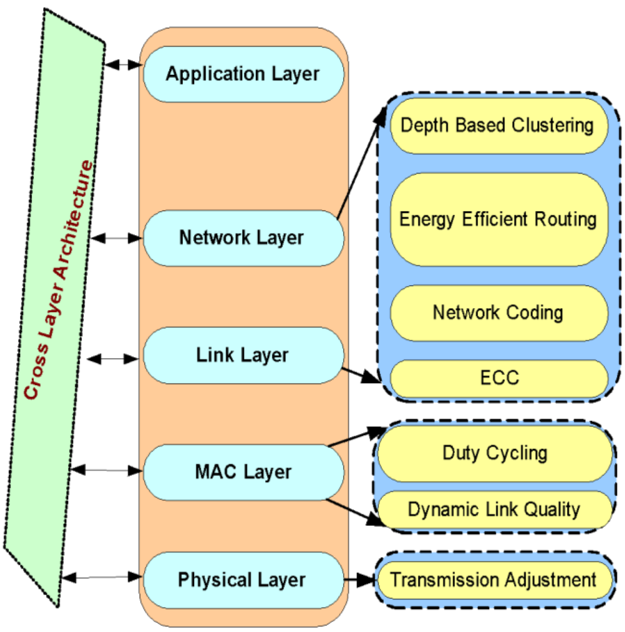

Fig. 1. Hybrid Solution

Fig. 1 shows the architecture of the proposed solution. The proposed FREC-HS involves solutions at Physical, MAC, Link and Network Layers to achieve the following objectives:

1. Energy efficiency and increasing the life time of the network
2. Fault resiliency by handling node faults
3. Increase in the delivery ratio

A. Network Layer

Depth based clustering topology is adopted in FREC-HS. Fig. 2 shows two level clustering architecture based on the depth of deployment of nodes is proposed.

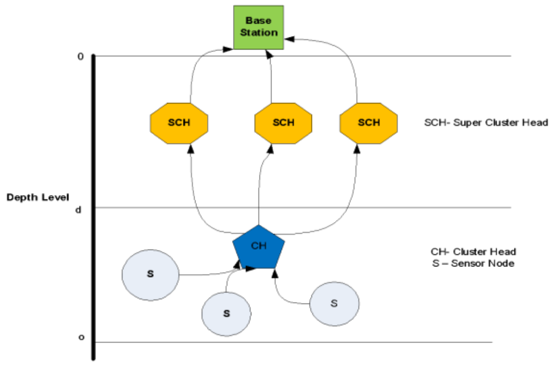

Fig. 2. Two level clustering architecture

Table-I: Nodes at three levels

Level 0	Sink nodes are at level
Level 1	The neighbor nodes who maintain relative position even in presence of movement till a depth level 'd' from the surface of water and energy above a threshold are in Level 1. Also called as Super Cluster Head (SCH).
Level 2	Rest of nodes which are not in Level 0 and Level 1 are in Level 2. Among the Level 2 nodes, density based clustering is done and the node that has the highest energy at lower depth is selected as CH nodes.

The level 1 nodes are bidirectional and can relay the packet but the level 2 nodes are unidirectional. The life time of this network can be modeled as shown below in (1).

$$LT = \frac{E}{(E_T+E_R+E_P)\times\left\{2\times\frac{1}{\sqrt{2\pi}}e^{\frac{-x^2}{2}}\right\}\times NH} \tag{1}$$

Where

E : is nodes initial energy

E_T : is the consumption of energy for transmission

E_R : is the consumption of energy for reception

E_P : is the consumption of energy for listening an internal process

NH: is the number of nodes in path between source to sink

Level 2 nodes sense data and transmit to its corresponding Level 2 CH. This Level 2 CH, aggregates the packets and sends that aggregated packets to its nearby Level 1 SCHs which does network coding on packets received from CH and sends to sink.

Turbulence is usually higher at lower depth in the region of Level 1 and use of network coding at this level to achieve higher packet delivery ratio.The network coding is implemented at lower energy consumption as follows: The SCH mix the packet from different CH and sends the composite packet to base station.

At base station decoding is done to recover packets and redundant packets are dropped. A simple XOR based network coding is applied at SCHs, so as not to increase the number of packets and generate redundancy without any additional energy consumption. Data from two different cluster heads are XOR and sent to base station. At base station, all received packets are assembled and XOR is done to recover the original packets.

The number of Super clusters (SC) to which the data from CH is sent is controlled on the basis of current residual energy of CH node which is achieved by controlling, transmission power of the CH at the physical layer. Fig.3 shows the flow of packets from node at Level 2 to sink.

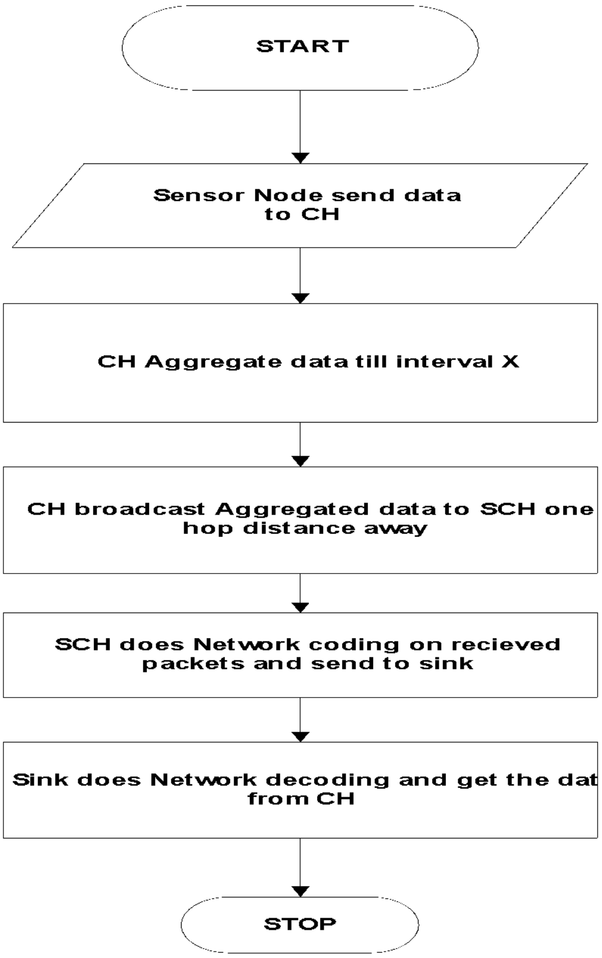

Fig. 3. Flow chart of forwarding algorithm

The use of network coding helps to achieve higher packet delivery ratio by introducing redundant path for data delivery at shallow depths where packet delivery ratio is lower due to turbulence. The pseudo code of this procedure is given below.

```
Procedure HandleAtCH
Input: interval , member nodes
Output: Aggregated Data
For j = 1: |member nodes|
   Tot(j)□0
    For i=1: interval
        If data(j,i)>Tot(j)
          Tot(j)=data(j,i);
        end
    End
End
Agr □ mean(Tot)
Send Agr to nearby SCH
Procedure HandleAtSCH
Input: Aggregated values from CH
Output: Data transmitted to sink
Ag□ 0
For j = 1 : |Aggreated values|
      Ag□ exor(Ag, Agr(j));
End
```

B. Link Layer

At link layer use of Error Correcting Code (ECC) is proposed to solve the problem of retransmission and energy wastage due to retransmission. Each Level 2 sensor node, sends the event sensed to Level 2 CH node using DPSK modulation. The data that is sent from Level 2 sensor node to Level 2 CH is sent with ECC to restore data in case of errors at CH without a need for retransmission. Compared to an uncoded system, the performance is better provided by the use of ECC over noisy channel for the same or low SNR, Reed Solomon (RS) code is considered as the better choice for WSN, which has maximum energy efficiency in proper channel conditions as shown in Fig.4.

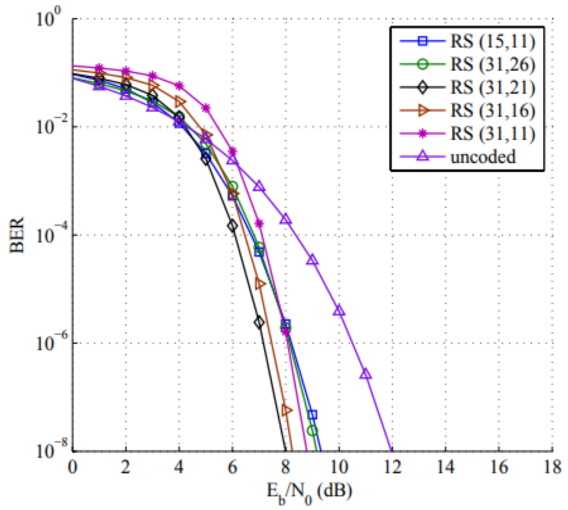

Fig. 4. BER vs SNR

The energy consumption at node due to RS(n,k) is given as in (2)

$$E = E_{RS}(q^2 - 1)log_2(q^2)|mE_T + (m-1)k \quad (2)$$

The energy consumption is measured for different k,n values in RS and is given in the Table-II.

Table-II:Energy Consumption vs RS code

RS code	Power consumption (nW)
RS(15,11)	200
RS(31,26)	125
RS(31,21)	150

RS(31,16)	275
RS(31,11)	450

From the results, RS(31, 26) gives satisfactory performance in terms of Bit Error Rate (BER) and has lower power consumption.

So RS (31, 26) is used for error correction from sensor node to CH.

C. MAC layer

Duty cycling and dynamic link quality based forwarding are two solutions adopted at MAC Layer. For the density based cluster created at Level 2, the level 2 nodes are allocated non conflicting duty cycle with CH node being a exception. Duty cycle time is allotted in proportion to the residual energy of node. But the traditional way of centralized duty cycle decision is not suitable for UWSN, since it involves frequent communication. We propose a distributed decision making by allowing each node to transmit with probability which is based on their residual energy as shown in (3).

$$\square = \frac{1}{1-e^{-\gamma \frac{E_0}{E_i}}} \quad (3)$$

Where

E_0 is nodes ini tial energy

E_i is nodes current residual energy

γ is performance tuning parameter

In this method as the energy level decreases, the transition probability decreases. Dynamic link quality is parameter used for selection of sink by the SCH among the multiple sinks available. Each SCH node calculates link quality in terms of packet delivery ratio achieved over a period of time using Mean Exponentially Weighted Moving Average as shown in (4).

$$\square = \alpha * \square + (1 - \square) * DR \quad (4)$$

Where

$\square$ is the link quality

α is in range of 0 to 1

DR is the packet delivery ratio achieved is last interval

The CH calculates the link quality for each reachable sink and selects the sink whose value is above a threshold.

D. PHYSICAL Layer

Transmission range adjustment is the solution adopted in physical layer for achieving energy efficient data forwarding. The transmission range is approximated as weighted function of residual energy and connectivity of the node. Node density can be measured as the number of unique hello broadcasts received at the node as shown in (5).

$$T = w_1 \frac{1.25}{\sqrt{\rho}} + w_2 E_i \quad (5)$$

Where

$w_1 + w_2 = 1$

$\square$ is the node density

IV. RESULT AND DISCUSSION

The proposed FREC-HS solution was simulated in NS2. Simulation was conducted with following parameters as given in Table-III.

Table-III: Configuration Parameters

Parameters	Values
Number of Nodes	50 to 250
Communication range	100m
Area of simulation	1000m*1000m
Node distribution	Random distribution
Simulation time	30 minutes
Interface Queue Length	50
MAC	802.11
Number of Base station	1
Location of Base station	Moving on surface
Initial energy of nodes	100 joules
Node movement	2-5 m around a center point

The proposed work is compared against [1] and [4]. The performance is measured with respect to Packet Delivery ratio, Network overhead as well as Life time.

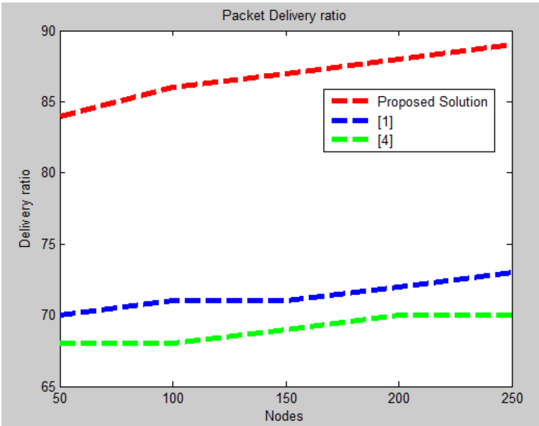

Fig. 5. Packet Delivery Ratio

Fig. 5 gives the packet delivery ratio measured for different number of nodes in all three solutions and is plotted. Packet delivery ratio is being measured by sensor nodes at level below d send packet at Constant Bit Rate (CBR) of 5 packets per seconds and the delivery ratio is measured at sink. From results, it is clearly seen that the packet delivery ratio is quite higher in present work compared to that of [1] and [4].

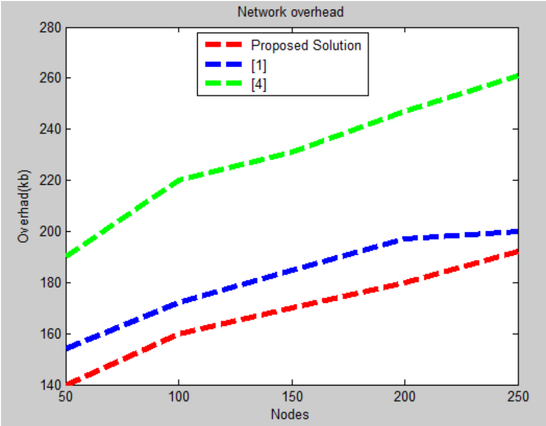

Fig. 6. Network Overhead

Fig. 6 shows the network overhead measured for different number of nodes in the network and is plotted.

The network overhead is measured in terms of total number of bytes and is transferred in the network for about a second. From the results network overhead is comparatively lower in present work compared to [1] and [4].

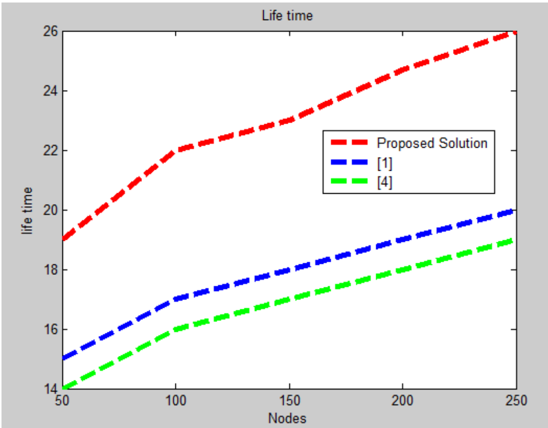

Fig. 7. Life time

Fig.7 shows that Life time measured as the time at which first node energy reduces to zero. Life time is measured for different size of network and plotted. From the results, life time is higher in proposed solution compared to [1] and [4].

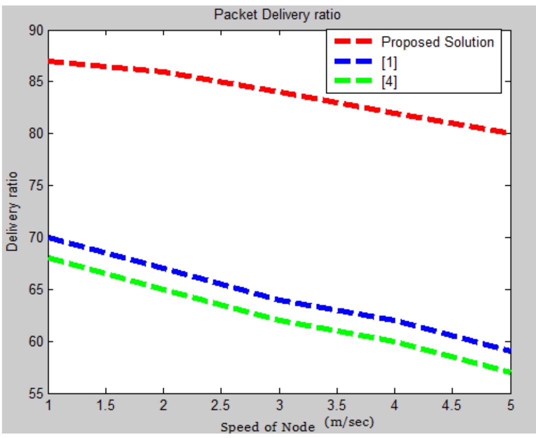

Fig. 8. Packet Delivery Ratio vs Speed

Fig. 8 gives the packet delivery ratio measured for different speed of sensors (due to water movement) and the result is plotted. From the results, its seen that the packet delivery ratio is quite higher in present work for different speed of nodes, compared to [1] and [4].

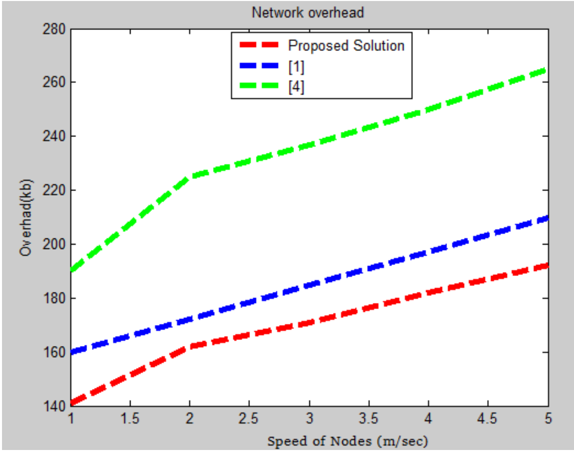

Fig. 9 . Overhead vs speed

Fig. 9 shows that the network overhead measured for different speed of sensors and the result is plotted. From the results, the network overhead increases as the speed increases but the increase is lower in case of present work when compared to [1] and [4].

V. CONCLUSION

Under water sensor network is important for many environmental monitoring and alerting system.In such systems reliability of network with respect to high packet delivery ratio as well as life time of the network is a critical requirement. In our work, a hybrid cross layer solution is proposed that ensures high packet delivery ratio with low energy consumption. The proposed work performs better than the existing works with respect to packet delivery ratio, life time as well as network overhead. Due to use of network coding and error correction, retransmissions are avoided in the network. Due to multipath transmission, the packet delivery ratio is higher. Duty cycling and transmission power adjustment has resulted in less energy consumption and increased life time in the proposed work.

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AUTHORS PROFILE

Mrs.Vidyalakshmi K received B.E. degree in 2005 at Sri Siddhartha Institute of Technology, Tumakuru, Karnataka, India and M.Tech degree in 2011 at National Institute of Engineering, Mysuru, Karnataka, India. She is now the Research Scholar of VTU-RRC, Belagavi, Karnataka, India. She is working as Assistant Professor in the department of Computer Science and Engineering at BGS Institute of Technology, BG-Nagar, Mandya, Karnataka, India and has a teaching experience of 14 years. She has in her credit one research paper published in National Conference and one research paper published in International Conference (IEEE), which has received the best paper award. She also has published one research paper in reputed International Journal and the same has been published as a chapter in a book called HCMC.

Dr.M.Siddappa received his B.E. degree in 1989 from Mysore University Karnataka, India and M.Tech degree in 1993, from Mysore University, Karnataka, India. He received his Ph.D. degree in 2010 from Dr. MGR University, Tamilnadu, India. He is currently working as Professor and Head, Dept. of Computer Science and Engineering and aslo is the Dean Academics at Sri Siddhartha Institute of Technology, Tumakuru, Karnataka. His general research interests lie in the areas of Data structure and algorithm, Artificial Intelligence and Intelligent Systems, Computer Networking. His recent focus has been on underwater acoustic communications and networking. He has a teaching experience of about 26 years and has published more than 20 papers in reputed International Journals and has more than 20 conference publications in his credit. He has visited Louisiana State University, USA, California University, UC Berkeley, Sanfrancisco, USA and Wuhan University, Wuhan,China on research basis. He has a life membership for IJERIA, India, Indian Society for Technical Education, New Delhi, India and for Computer Society of India, India.

Dr.B.Shanmukha recevied his M.Sc degree in 1992 from Bangalore University, Karnataka, India, M.Phil degree 1994 from Bangalore University, Karnataka, India and Ph.D. degree in 2004 from Bangalore University, Karnataka, India. He is currently working as Associate Professor in the department of Mathematics at PES College of Engineering Mandya. His area of specialization is Graph Theory, and has special interest in networks and communication. He has a teaching experience of 26 years. He has in his credit more than 6 papers published in National and International conferences and more than 10 papers published in reputed International Journals. He has attend many Induction training programmes, seminars and workshops. He has a life membership of Indian Society for Technical Education, New Delhi, India, and for Ramanujam Mathematical Society, Tamilnadu, India.