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ARCUN: Analytical approach towards Reliability with Cooperation for Underwater WSNs

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Abstract

Cooperative routing is a hybrid approach utilizing routing techniques and cooperative communication to improve the communication quality of single-antenna sensor nodes. It exploits the broadcast nature of wireless medium and transmits cooperatively using nearby sensor nodes as relays. In this research, a cooperative transmission scheme is proposed for UnderWater Sensor Networks (UWSNs) to improve the network performance called ARCUN. The protocol is an energy-efficient and high-throughput routing scheme for UWSN. Potential relays are selected from a group of neighbor nodes that utilize signal-to-noise ratio and distance computation of the underwater channel. Optimal role of cooperation provides load balancing in the network and gives profound improvement in network stability period and packet delivery ratio.

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1. Introduction

UWSN forms a promising technology for enabling and enhancing several key applications in UnderWater (UW) research. These networks are constituted with very small-sized sensors that are equipped with a single antenna. A sensor node controls its depth through a bladder apparatus and a pressure gauge. The swarm is escorted by sinks present at the water surface, equipped with both acoustic and radio communications. The sensor node examines local UW activities and reports its data to one of the sinks present at the water surface using acoustic multi-hopping. The research is focused here to design an efficient routing protocol that transmits data reliably from an UW sensor to one of the sinks. However, the task is challenging due to limited energy and bandwidth resources and presence

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of noisy environment. An UW channel has limited bandwidth and its propagation latency is five times higher than the radio channel. These limitations create packet collisions which make UWSN vulnerable to congestion. Hence, minimizing the redundant transmissions is considerable for not only minimizing congestion but also to reduce energy consumption.

Cooperative routing is one of the solutions to this problem, through which information loss is avoided by exploiting broadcast nature of wireless link. It makes use of multi-cast mode in which a single source node transmits its data to more than one node by exploiting more than one links at the same time. Designing an efficient cooperative routing protocol may lead to a significant increase in network throughput. Cooperative routing in wireless networks has attracted researchers to exploit the broadcast nature of the wireless medium for the design of energy-efficient routing schemes. It allows more frequent data gathering due to support of neighbouring nodes, hence data loss is least expected. The final destination node, hence, combines the received signals using Fixed Ratio Combining (FRC) technique to obtain diversity against the harmful fading.

2. Related work and Motivation

An efficient technique in localization-free category is Depth-Based Routing protocol (DBR)\(^1\), based on data forwarding through low-depth sensor nodes. Energy-Efficient Depth-Based Routing scheme (EEDBR)\(^2\) is a constructive framework for maximizing the network lifetime by utilizing both depth and residual energy of the sensor nodes. It minimizes the end-to-end delay along with better energy consumption of the low-depth nodes. Both of these techniques attempt to deal with minimizing the load on medium-depth sensor nodes in dense conditions. There is a lack of load balancing in these protocols due to unequal load distribution among the nodes. H2-DAB\(^3\) implements the dynamic addressing scheme among sensor nodes without requiring the localization information. Another efficient scheme R-ERP2R\(^4\) employs the routing metric based on the physical distances between the nodes and exercises it to accomplish higher throughput in UWSN. It also provides the energy efficient solution for data forwarding along with better link quality.

In\(^5\), a communication path based routing protocol by the name of Relative Distance Based Forwarding (RDBF) is presented whose focus is to provide transmission efficient, energy-saving, and low delay routing. Only a small fraction of nodes are involved in forwarding process, which reduces the energy consumption and end-to-end delay. In\(^6\), the authors have addressed the problems of localization by expressing UW transmission loss via the Lambert W function. Real device implementation demonstrates the accuracy and efficiency of the proposed equation in distance calculation, computation stability, and shorter processing time.

Another study proposes a clustering scheme in\(^7\) that promises to overcome the UWSN confines by resolving the transmission of redundant data in the network. The protocol works in rounds, with each round consisting of four phases; utilizing suitable mechanisms in each round. The proposed clustering scheme reduces network consumption, increasing network throughput. The research paper in\(^8\) recommends an Adaptive Mobility of Courier nodes in Threshold-optimized Depth-based (AMCTD) routing protocol to maximize the network lifetime of UWSN. Optimal weight computation not only provided the global load balancing in the network, but also gave proficient holding-time calculation for the neighbors of source nodes.

In ARCUN protocol, we propose a mechanism to route data through UW networks with minimum path-loss over the link. The proposed scheme uses a cost function to select the most appropriate route to sink. This cost function is calculated on the basis of their distance from the sink and their residual energy. The channel for acoustic link is described by path loss model in terms of frequency and distance. Data packets from nodes arrive at sink which further communicate with the base station through radio frequency link. The presented scheme leads to enhance the reliability of the channel through cooperation. Cooperative diversity, obtained with single antennas, is especially useful when time, frequency, and spatial diversity through multiple antennas are not feasible. This motivated us to introduce cooperation scheme in UW environment, and study its impact on system performance.

3. ARCUN: The Proposed Protocol

Multi-hop communication is used as the maximum transmission range of a sensor node is not long enough to cover the entire network.
3.1. Network Topology

Sensed data from the source node S is gathered at one of the sinks D. It is considered that nodes except for sink nodes are energy constrained. Network is assumed to be composed of heterogeneous nodes, as shown in the figure 1, with each node having only one antenna. Relay nodes R1, R2 and R3 are advanced nodes having more energy than the normal nodes. Source nodes are transmitting the data to the higher level nodes as well through the relay nodes. The process goes on till the data reaches D at the surface of the water. Relay nodes have the dual responsibility of data relaying of the neighbor nodes and the transmission of their own data. In case of normal delivery, data from S always follows the relay node path in a cooperation mode but if the relay node link is not reliable or the relay node is dead, then there is a direct link path available for the data transfer.

![Multi-hop routing](image)

3.2. Initialization Phase

Three different types of tasks are performed in this phase. Each node is informed about its neighbors, location of sinks on the surface of water and all the possible routes to various sinks are also evaluated. Sensors update their depth to its neighbors and sinks when each node broadcasts an information packet containing its node identity, depth and energy status. Employing hello packets transmission, each node identifies its neighbors in transmission range and maintains the separate queue of neighbors under depth threshold to identify the finest forwarder for its data transmission. Each node calculates its weights using the formula given below:

$$W_i = \frac{\max(\rho(d_{S_iR_i}, f), \rho(d_{S_iD_i}, f)) + \max(R.E_{R_i}, R.E_{D_i})}{\min(|d_{S_iR_i}|^2, |d_{S_iD_i}|^2)}$$

(1)

where $\rho(d_{S_iR_i}, f), \rho(d_{S_iD_i}, f)$ are the SNR of the corresponding node’s links from $S_i$ to $R_i$ and $S_i$ to $D_i$ respectively, $R.E$ is the residual energy of the corresponding nodes, $d_{S_iR_i}$ and $d_{R_iD_i}$ are the distances between the corresponding source to its relay and immediate destination respectively.

3.3. Co-operation Phase

A two-phase transmission scheme is utilized in cooperation phase. In phase 1, a source $S_i$ forwards its data to both relay $R_i$ and destination $D_i$ simultaneously; whereas in phase 2, $R_i$ re-transmits the received data to $D_i$. Information received at $R_i$ and $D_i$ from source in phase 1 can be expressed mathematically as:

$$y_{S_iR_i} = \sqrt{P_1} h_{S_iR_i} x_{S_i} + N_{S_iR_i}(f)$$

(2)

$$y_{S_iD_i} = \sqrt{P_1} h_{S_iD_i} x_{S_i} + N_{S_iD_i}(f)$$

(3)

where $P_1$ is the transmitted power at the source, $x_{S_i}$ is the transmitted information symbol from $S_i$, $h_{S_iR_i}$ and $h_{S_iD_i}$ are the co-efficients of the UW channel from $S_i$ to $R_i$ and $S_i$ to $D_i$ respectively, modeled as Gaussian random variable with zero mean and variance $\sigma^2$ expressed as $CN(0, \sigma^2)$. The channel variance $\sigma^2$ is:

$$\sigma^2 = \eta d_{ij}^{-a}$$

(4)
where \( d_{ij} \) denotes the distance between any two nodes \( i \) and \( j \), \( \alpha \) is the propagation loss factor and \( \eta \) is a constant whose value depends on the propagation environment. \( N_{S,R_i} \) and \( N_{S,D_i} \) are the noise components introduced in the links from \( S_i \) to \( R_i \) and \( S_i \) to \( D_i \), respectively.

In phase 2, the relay forwards the amplified symbol with power \( P_2 \) to the destination. The received signal then can be modeled as:

\[
y_{R,D_i} = \sqrt{P_2' h_{R,D_i} x_{S_i}'} + N_{R,D_i}(f)
\]  

where \( P_2' = P_2 \) if the relay receives the transmitted symbol correctly, otherwise \( P_2' = 0 \). \( x_{S_i}' \) is the signal which is received at the destination node after passing from \( S \rightarrow R \) link which may be attenuated and may not be the same as \( x_{S_i} \). Destination node \( D_i \) aggregates the received signals from \( S_i \) and \( R_i \). Total transmitted power received at \( D \) is \( P \) such that \( P_1 + P_2 = P \).

3.4. Relay Selection Phase

Selection of relay node relies on instantaneous channel conditions and the weight factor computed in equation (1). The source node finds an optimal relay among its neighbors by comparing their weights. The neighbor having the highest value of \( W_i \) is elected as the relay and after receiving the packet it waits for holding time before upward data transmission. It discards the packet on receiving the same packet from any other neighbor node or the direct link from the source during the holding time duration. If a corresponding destination node receives the packet, it transmits acknowledgment to other neighbors of source node to eliminate needless forwarding by any other neighbor node. Relay nodes continue to forward the packet of the source node until it reaches to one of the sink at the surface of the water.

If multiple relay nodes are available in the path and a source node has a sink node as its next-hop node, then a relay node will never trigger co-operation. It will help to maximize the minimum residual energy left after data transmission. This can be accomplished through the following condition:

\[
\begin{cases}
\text{if } E_{re}(S_i) > E_{re}(R_i), & \text{then direct transfer} \\
\text{else } E_{re}(S_i) \leq E_{re}(R_i), & \text{then relay path}
\end{cases}
\]

3.5. Relay Strategy

The relay node \( R_i \) multiplies the received signal from \( S_i \) by an amplification factor \( \beta \) before forwarding it to \( D \) i.e. \( y_{RD} = \beta(y_{SR}) \). If \( P_s \) and \( P_r \) are the transmission powers at \( S \) and \( R \), respectively, then the factor \( \beta \) can be written as:

\[
\beta = \sqrt{\frac{P_r}{P_s |T_{SR}|^2 + N(f)^2}}
\]  

The gain provides amplification at \( R \) to counter the effect of the channel fading and prevents the relay gain from saturating when the \( S-R \) link undergoes deep fade. As power is defined as energy per unit time, hence expressing the transmission powers of \( S \) and \( R \) in terms of energy, equation (6) can be expressed as

\[
\beta = \sqrt{\frac{E_r}{E_s |T_{SR}|^2 + N(f)^2 \Delta t}}
\]  

Fading is generally independent of time, therefore \( N \Delta t \equiv N \), and \( \beta \) can be re-written as

\[
\beta = \sqrt{\frac{E_r}{E_s |T_{SR}|^2 + N(f)^2}}
\]  

Hence, accordingly the signal received at destination \( D \) in phase 2 can be re-written as

\[
y_{RD} = \sqrt{P_2' h_{RD} \beta x_{S_i} N_{RD}}
\]

The amplitude of the received signal i.e., \( S \) to \( D \), \( S \) to \( R \) and \( R \) to \( D \) is considered here as Rayleigh distributed and links are assumed to be independent of each others transmissions.
3.6. Attenuation and Propagation Delay

For UW links, link distance $d$ and signaling frequency $f$ both have their own impacts on the attenuation function denoted by $A(d, f)$. Consequently, the received signal has an SNR expressed as $\rho(d, f)$. For a distance $d$ (km) from a source to a destination at a frequency $f$ (kHz) and spreading coefficient $k$, the attenuation $A(d, f)$ is described by Urick\textsuperscript{10} given as

$$A(d, f) = A_0 d^k a(f)^d$$

where $A_0$ is a normalizing constant. $k$ is spreading factor whose value is $k = 1.5$ for practical spreading. The absorption coefficient $a(f)$ is described by the Thorps formula as\textsuperscript{11}

$$10 \log a(f) = 0.11 f^2 + \frac{44 f^2}{4200 + f} + \frac{2.75 f^2}{10^4} + 0.003(forf > 0.4)$$

and

$$10 \log a(f) = 0.002 + \frac{0.11 f}{1 + f} + 0.011 f \quad (for f < 0.4) \quad [dB/km]$$

3.7. Noise in UWA Channels

UW communication is affected by turbulence ($N_t$), shipping ($N_s$), waves ($N_w$) and thermal noise ($N_{th}$) which are modeled by Gaussian statistics as described in\textsuperscript{13}:

$$N(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f)$$

where

$$10 \log N_t(f) = 17 - 30 \log f$$

$$10 \log N_s(f) = 40 + 20(s - 0.5) + 60 \log (f + 0.03)$$

$$10 \log N_w(f) = 50 + 7.5 \sqrt{w} + 20 \log f - 40 \log (f + 0.4)$$

$$10 \log N_{th}(f) = -15 + 20 \log f$$

where $s$ is shipping activity factor, whose value ranges between 0 and 1 for low and high activity, respectively; and $w$ is the wind velocity ranging from $0 - 10 m/s$.

3.8. SNR in UWA Channels

The SNR of an emitted UW signal with unit transmit power $\hat{p}(t)(watts)$ at the receiver is given by:

$$SNR(d, f) = \rho(d, f) = SL - A(d, f) - N(f) - DI$$

Assuming omni-directional antennas, directivity index $DI = 0$. The Source Level (SL) is given by:

$$SL = \frac{20 \log I}{1 \mu Pa}$$

where $I$ is the intensity at 1 m from the source in watt/m$^2$, given by:

$$I = \frac{\hat{p}(t)}{2 \pi H}$$

where $H$ is the water depth in meters. Signals in UW channels ($T_d$) experience frequency and link length dependent path-loss which is more complicated than radio channels and is modeled as\textsuperscript{11}

$$T_d = 10 \log_{10} d + 10^{-3} a(f)d$$

where $a(f)$ has the relation as given in equations (11) and (12). First term of the equation (21) stands for power consumptions of signals transmitted from source to destination in wireless channels. Second term corresponds to absorptions of traveling waves power in UW caused by mechanical nature of acoustic waves\textsuperscript{13}.
3.9. Outage Formulation in UW Acoustic Channel

Channel capacity of a Gaussian channel with infinite bandwidth presents an upper limit for the amount of information being transmitted successfully over a communication path. This can be expressed by the Shannon-Hartley theorem: \[ C(d, \rho) = \log_2(1 + \rho(d, f)) \] where \( C(d, \rho) \) (bits/sec) is the channel capacity dependant on both frequency and distance. If the transmission rate at each node is \( R \) (bits/sec), then the signal is considered to be transmitted successfully over fading channels if:

\[ C(d, \rho) \geq R \]

This condition is used to assess the quality of incoming signal at the receiver side. In contrast to equation (23), outage occurs when the transmission rate \( R \) exceeds \( C \), i.e.

\[ \text{Outage} = C(d, \rho) < R \]

It is assumed here that probability of error is approximately nil when channel is not in outage. Hence, the outage probability \( P_{\text{outage}} \) is given by:

\[ P_{\text{outage}} = P\{ C(d, \rho) < R \} \]

\[ P_{\text{outage}} = P\{ \log_2(1 + \rho(d, f)) < R \} \]

3.10. Reliability in UW Acoustic Channel

There are a variety of techniques for prevention of losing data when the channel is in outage. Here, reliability of a link is obtained by isolating diversity through routing, and then results be applied in combination with other diversity techniques. The event of reliable end-to-end transmission from S to D is the one in which all transmissions are successful. The end-to-end Reliability \( \mathfrak{R} \) is defined as the probability of this event. Hence, \( \mathfrak{R} \) can be written as:

\[ \mathfrak{R} = 1 - P_{\text{outage}} \]

3.11. Combining Strategy

Each node D implements a diversity combining technique to combine the received signals coming from S and R. In FRC, instead of just adding up the incoming signals, they are weighted with a constant ratio. This ratio should reflect the average channel quality and influences on channel due to noises. In case of a single-relay node, FRC can be expressed as

\[ y_d = k_1 y_{SD} + k_2 y_{RD} \]

where \( y_d \) represents the combined output signal at the destination node D, \( k_1 \) and \( k_2 \) are the weights of the two links. These weights are a function of power and channel co-efficients and their ratio can be expressed as

\[ \frac{k_1}{k_2} = \sqrt{\frac{P_1 h_{SD}}{P_2 h_{RD}}} \]

An optimal value of the weights ratio is 2 : 1 in case of AF technique. Where

\[ k_1 = \frac{\sqrt{P_1 h_{SD}}}{N_0} \]

\[ k_2 = \frac{\sqrt{P_2 h_{RD}}}{N_0} \]

If the transmitted symbol \( x_s \) has an average energy of unity, then the SNR of the FRC output is

\[ \rho = \frac{P_1 |h_{SD}|^2 + P_2 |h_{RD}|^2}{N_0} \]
4. Performance Evaluation of ARCUN

To evaluate the performance of ARCUN, it is compared with the existing schemes AMCTD and EEDBR. In the simulation with 10 sinks deployed on the surface of the water, 225 nodes are randomly deployed in the network. The transmission range of sensor node is 250 meters. In each round, all alive nodes transmit threshold-based data towards sink. After equal intervals of time, nodes compute their distance from the neighbor nodes. The nodes transfer their data to the upper layer using cooperation of neighbor nodes till the data reaches the sink. The introduction of cooperation and variations in depth threshold make ARCUN scheme as a feasible contender for data-critical applications.

Figure 2(a) illustrates that ARCUN scheme improves the stability period of network by avoiding the forwarding of unnecessary data along with maintaining lower transmission loss. Simulations show that the first node in EEDBR dies after 1000 secs, in AMCTD it dies after 1100 secs whereas in our scheme it dies after 3000 seconds thereby increasing the stability period. Due to the introduction of cooperation scheme, load balancing is achieved thereby increasing the stability period. The cooperating nodes share the load of data forwarding of distant transmissions. When the network becomes sparse, number of neighbors decreases quickly in EEDBR causing network instability. In AMCTD, the consideration of two forwarding attributes; depth and residual energy, causes a trade-off between the network lifetime and transmission loss which is not suitable for reactive applications. Lifetime of ARCUN is increased due to lower throughput by responsive network. In our suggested scheme, employment of Thorps energy model specifies the detailed channel losses which are useful for selective data forwarding in responsive networks. Increase in stability period also confirms reduction in redundant transmissions.

Packet Delivery Ratio (PDR) is the ratio of data packets received at destination to those generated by the source. The plots in figure 2(b) show the PDR comparison of ARCUN with that of AMCTD and EEDBR. Performance of the EEDBR is reduced whereas the delivery ratios of AMCTD and ARCUN show a similar pattern of plots; although the drop in PDR in ARCUN is much less than that of AMCTD. When the inter-arrival time of packets is less, higher traffic is sent from source nodes. This increases the rate of packet collision leading a lower PDR. ARCUN scheme improves the possibility of successful reception of data packets on multiple paths and then combining at the receiving node. EEDBR has higher loss than other techniques as it employs distant propagations as well as multiple forwarding and hence a lower PDR. In AMCTD, channel loss conditions are better than EEDBR, as the weight function computations consider both depth and residual energy of forwarding nodes, therefore the propagations remain stable.

Figure 2(c) describes the comparison between the path-loss (dB) of ARCUN with the other two schemes. In our scheme, path-loss of links is much reduced because the use of cooperation makes the data forwarding much better with the help of relay nodes and load balancing is also achieved. ARCUN is mainly concerned with the requirement of time-critical applications and hence addresses the problem of path-loss reduction by utilizing cooperation and depth difference between data forwarders.
5. Conclusion

In this work, we have suggested ARCUN routing protocol to maximize network lifetime and reduce energy consumption in UWSNs. Utilization of cooperation and SNR enhances the stability period and packet delivery ratio especially for delay-sensitive applications. The transmission schemes without cooperation are based on channel estimation. These try to improve the received packet quality at receiver node. However, transmission using a single link can be affected with the changes in the channel quality. Relay selection mechanism considers the instantaneous path conditions and distance among neighbors to relay packets successfully to destination in constrained UWSN. Variations in depth threshold increase the number of eligible neighbors, thus minimizing critical data loss. Optimal weight computation and role of cooperation not only provides the load balancing in the network, but also gives proficient improvement in the network stability period.

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