Indonesian Journal of Electrical Engineering and Informatics (IJEEI)
Vol. 10, No. 1, March 2022, pp. 199~218
ISSN: 2089-3272, DOI: 10.52549/ijeei.v10i1.3633

A Collision Avoidance Based Energy Efficient Medium Access Control Protocol for Clustered Underwater Wireless Sensor Networks

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Article Info

Article history:

Received Jan 3, 2022
Revised Mar 14, 2022
Accepted Mar 31, 2022

Keyword:

Collision avoidance
DESERT simulator
Energy efficiency
Medium Access Control (MAC) Protocol
Transmission power control
Underwater Wireless Sensor Network (UWSN)

ABSTRACT

Underwater Wireless Sensor Networks (UWSNs) are typically deployed in energy-constrained environments where recharging energy sources and replacing batteries are not viable. This makes energy efficiency in UWSNs a crucial directive to be followed during Medium Access Control (MAC) design. Multiplexing and scheduling-based protocols are not ideal for UWSNs because of their strict synchronization requirements, longer latencies, and constrained bandwidth. This paper presents the development and simulation analysis of a novel cross-layer communication-based MAC protocol called Energy Efficient Collision Avoidance (EECA) MAC protocol. EECA-MAC protocol works on the principle of adaptive power control, controlling the transmission power based on the signal strength at the receiver. EECA-MAC enhances the conventional 4-way handshake to reduce carrier sensing by implementing an enhanced Request to Send (RTS) and Clear to Send (CTS) handshake and an improved back-off algorithm. Simulation analysis shows that the measures taken to achieve energy efficiency have a direct effect on the number of packet retransmissions. Compared to the Medium Access with Collision Avoidance (MACA) protocol, EECA-MAC shows a 40% reduction in the number of packets that are delivered after retransmissions. This reduction, coupled with the reduced signal interference, results in a 16% drop in the energy utilized by the nodes for data transmission.

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1. INTRODUCTION

Underwater Wireless Sensor Networks (UWSNs) are wireless sensor networks that are deployed in an underwater environment. UWSNs are used extensively in applications such as oceanographic data collection, pollution monitoring, offshore exploration, disaster prevention, assisted navigation and tactical surveillance applications [1]. Typical wireless sensor networks counteract battery depletion by either replacing batteries or applying solar recharging.

These approaches cannot be applied to UWSNs since the deployment environment makes it difficult to access and replace the batteries. Solar recharging is not feasible, especially in deep-water deployments where sunlight is scarce. The combination of acoustic communication and underwater deployment imposes peculiar undesirable characteristics on UWSNs such as increased end-to-end latency, severe multipath, high Bit Error Rate (BER) and increased energy consumption [2]. These factors rule out the direct application of traditional WSN protocols to UWSNs, necessitating a deeper relook at the development of communication architectures, especially MAC and routing protocols.

1.1. Medium Access Control in UWSNs

The primary goal of a good MAC protocol is to regulate access to the communication medium, which is typically shared among multiple communicating entities. It should also be able to support the QoS requirements of the application that is using the network. In [3], the authors state that the fundamental tasks of the MAC layer are to avoid collisions and to provide fair medium allocation among the nodes. The authors also state that MAC plays a large part in the energy efficiency of the network. This is important because this layer in the network software stack manages the hardware that controls the transmission (transceiver). Figure 1 shows a high-level classification of the principles based on which MAC protocols are designed.

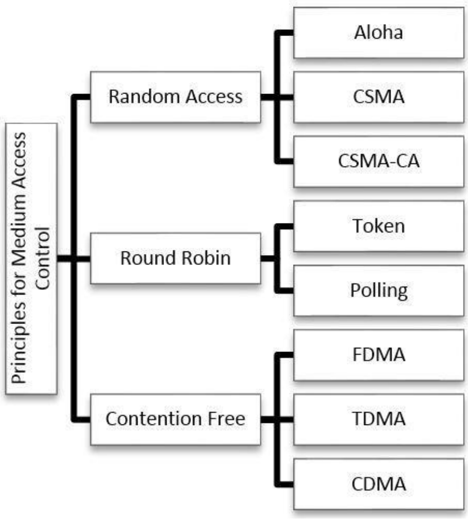

Figure 1. Principles of medium access control

It is evident from existing literature [4] that due to the characteristics of the underwater communication medium, dedicated channels are not suited for transmitting data. Frequency Division Multiple Access (FDMA) based techniques are not preferred due to the unavailability of requisite bandwidth. Time Division Multiple Access (TDMA) schemes may be used, but they need tight synchronization between the nodes. In a contention-based MAC design, it is possible to have simple negotiated, intermediate negotiated and fully negotiated approaches [5]. Carrier Sense Multiple Access (CSMA) is an example of a simple negotiated approach. T-Lohi [6] is an example of an intermediate negotiated approach. Both these approaches are susceptible to the exposed node problem. Contention-based MAC involves sensing the carrier to check for availability before transmission.

Medium Access with Collision Avoidance (MACA) [7] is a 4-way handshake protocol that optimizes carrier sensing by including the length of the data sent in the RTS control packet. The 4-way handshake ensures that MACA can handle the problems of both exposed node and hidden node. These advantages come at the cost of increased utilization of bandwidth for operations not directly connected with the actual transmission of data.

Based on the fore-mentioned issues, it is reasonable to opine that these characteristics of MACA protocol offer an impetus for research studies directed towards the development of schemes for enhancing the energy efficiency of accessing the communication medium in UWSNs.

1.2. Cross Layer Communication for Energy Efficiency

A typical sensor node, irrespective of whether it is installed underwater or on land, expends energy in one of three functionalities: sensing data, processing data and data communication. Sensor networks typically have a low duty cycle, with the nodes being powered only while sensing information. While not sensing, the nodes are not powered, resulting in minimum energy utilization. The data processing aspect is governed by sensor hardware, eliminating software based energy efficiency methods. Thus, the only phase or stage where energy efficiency can be optimized is during the communication phase of operation.

During the communication phase, UWSNs incur undesirable energy expenditure during carrier sensing, exchange of control packet and packet retransmissions due to collisions. These processes are controlled by the MAC layer, implying that if a MAC protocol is designed to optimize them, then the energy consumption of the network is reduced substantially.

The principle of cross-layer development can be applied during protocol development for UWSNs. Cross-layer design is a variant of the traditional method of communication within a node. Traditionally, the network software architecture of a node allows communication only between the adjacent layers. Cross-layer development allows the exchange of information between any two or more communication interfaces of the nodes. This allows developers to optimize communication, keeping in view the application and system requirements. Cross-layer interaction among the physical, data link and network layers balances performance, thereby maximizing energy savings and network lifetime [8].

1.3. Overview of MACA based Protocols in UWSNs

The fundamental idea of MACA was based on the three-way RTS-CTS-DATA handshake of CSMA-CA. If a third party node hears an RTS or CTS not meant for it (xRTS or xCTS), transmission is deferred for a random number of time slots. This duration is fixed by including a timestamp in the header of the RTS and CTS, as opposed to carrier sensing. Irrespective of the status of the carrier, the back-off time always reduces after consecutive attempts at transmission. MACA was expanded to include an Acknowledgement (ACK) during the control packet exchange in [9], creating the MACA protocol for Wireless LANs (MACAW). The control packet exchange of MACAW is shown in Figure 2. Another MAC protocol that can be classified in the same category is the Floor Acquisition Multiple Access (FAMA), which lengthens transmission delay of RTS-CTS exchange so that the protocol can function in environments of lengthy propagation delay [10]. Both these protocols are designed for terrestrial packet radio-based transmissions.

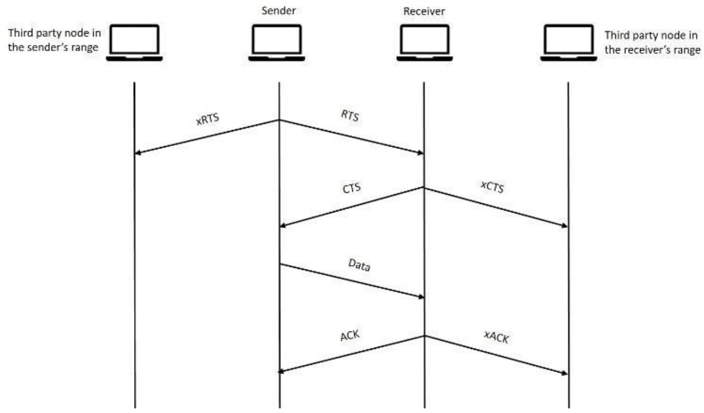

Figure 2. Control packet exchange of MACAW

One of the first attempts at adapting FAMA to the underwater environment was in [11] where the authors created time slots for communication and showed that this method reduced the need for long control packets. Simulation studies of Slotted FAMA show that smaller control packets result in reduced energy consumption. The paper also addresses the tradeoff between excessive connectivity (which leads to more collisions) and a lower transmission range that has lesser collisions but more hops to reach the destination.

Slotted FAMA was enhanced in [12], with the creation of Distance Aware Collision Avoidance Protocol (DACAP). In this protocol, the authors make a distinction between energy expended while transmitting a packet and while receiving it. DACAP is optimized for networks with unequal transmit and receive power requirements. The duration of the handshake is reduced, but this does not affect the receiver sensitivity since the nodes are located within communication range of each other. This allows DACAP to function in an unsynchronized manner.

In [13], the authors present an adaptation of the MACA protocol for UWSNs called Media Access Protocol for Underwater Acoustic Networks (MACA-U). The protocol enhances the state transition rules, packet forwarding strategy and back-off algorithm. In MACA-U, the node stops sensing the channel when it hears a third party RTS or CTS. Every node has a queue for two kinds of data; one is the data generated by the node itself and the other for which the node acts as a relay. The relay data is prioritized at a higher level.

The simulation results of MACA-U show that it maintains a stable throughput compared to conventional Aloha and operates at a 20% higher throughput than MACA. This stability in throughput means that MACA-U is an ideal candidate for the dense deployment of nodes in a UWSN.

Another adaptation of MACA is presented in [14] where the authors utilize packet trains that are intended for different neighbours during the exchange of control packets. This protocol is called a MACA based MAC protocol with packet trains to Multiple Neighbors (MACA-MN). The authors propose that the packet trains lead to better utilization of channel and reduces the overall packet delay. Another advantage of MACA-MN is that it does not require synchronization between sender and receiver.

The authors of [15] propose a MACA-based MAC protocol with Delay Tolerance (MACA-DT). MACA-DT incorporates two novelties, namely adaptive silent time and simultaneous handshake. Once the protocol is initiated, MACA-DT executes a simultaneous handshake algorithm among all the nodes to determine the propagation delay. This is called the initialization phase, after which each node is aware of the time taken to reach every other node. Subsequently, this propagation delay is used to calculate the back-off time (silent time) used when a control packet of third party is sensed. The authors propose that time is adaptive based on propagation delay instead of fixed. The results of simulations show that MACA-DT offers a better throughput compared to MACA and MACA-U because of the adaptive silent time.

The authors of [16] propose a MACA-based Adaptive Packet Train (MACA-APT) protocol designed specifically for underwater acoustic networks. The authors attempt to offset the long propagation delay by transmitting packets consecutively to multiple receivers. This paper also dwells upon a stop and wait ARQ mechanism that is integrated with the protocol. The simulation analysis of MACA-APT shows that size of the packet train has a direct impact on the efficiency and throughput of the network.

1.4. Gaps in Existing Literature

The literature reviewed in the previous section, as well as other papers about MACA based MAC protocols, are directed typically towards increasing the throughput of the network. This was achieved mostly by (i) optimizing the handshake process or (ii) reducing the contention window of the protocols. The review also highlights significant shortcomings in the topic of enhancing MACA based protocols for transmission power control. It is pertinent to emphasize that reducing transmission power results in a reduction of interference in the acoustic medium, resulting in a decreased number of packet retransmissions. This will contribute to significant energy savings in the network. The primary emphasis of this paper is to:

- Enhance MACA to reduce carrier sensing
- Apply principles of adaptive power control to MACA to reduce interference
- Quantify the reduction in retransmissions and savings in battery power due to it

1.5. Scope and Organization of the Paper

This paper presents a novel Energy Efficient Collision Avoidance (EECA) MAC protocol. EECA-MAC protocol is based on the MACA protocol which is enhanced by applying PHY and MAC cross-layer interactions. These enhancements result in a significant reduction of interference due to third party communication, reduced carrier sensing and decreased packet retransmissions.

The rest of the paper is structured as follows: Section 2 describes the design of the EECA-MAC protocol, including the specifications and flowcharts used. Section 3 discusses the deployment scenario and subsequently presents the simulation results and comparative analysis of the EECA-MAC protocol. Section 4 concludes the paper by summarizing the research findings and presenting a glimpse of the proposed future work.

2. DESIGN OF ENERGY EFFICIENT COLLISION AVOIDANCE MAC PROTOCOL

The EECA-MAC protocol is designed to achieve energy efficiency by reducing the number of retransmissions of data packets. The approach followed in this paper is to reduce the interference to the data communication by performing adaptive control of transmit power. This section details the design of the EECA-MAC protocol and its illustration through a set of flowcharts.

2.1. Network Architecture

The UWSN considered here consists of nodes that are classified as sensing-only, data-haul nodes and sinks. Sensing-only nodes are the static nodes responsible for sensing information and broadcasting it to the data-haul nodes. The data-haul nodes are mobile nodes, analogous to cluster heads, capable of movement and control two aspects of the communication: They receive data from the sensing-only nodes in their cluster. This is performed by moving horizontally within the cluster. The data-haul nodes also create a multi-hop ad-hoc network among themselves, by sending data collected from their clusters towards the sink.

A single cluster is shown in Figure 3. The UWSN uses a layered style of deployment, with anchored sensing nodes deployed in layers with the data-haul nodes for each cluster deployed 200 m above the cluster. Normally, communication between two nodes is successful at an inter-nodal distance of 250 m. The EECA-MAC protocol insists that the data haul nodes be mobile while the sensing nodes are to be static. There are multiple sinks in the network architecture and transmission is deemed successful if the data reaches any one of the sinks.

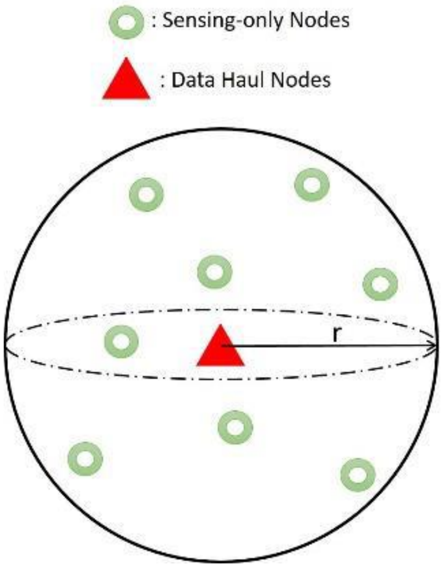

Figure 3. A single cluster consisting of sensing nodes and one data haul node

2.2. Cross-layer Interaction

Two features of EECA-MAC are implemented using cross-layer data exchange between the MAC and PHY layers. The Received Signal Strength Indicator (RSSI) of the RTS is echoed to the transmitter so that the transmission power can be controlled. This feature requires a cross-layer communication of RSSI from the MAC to PHY layer at the transmitter. Another feature of EECA-MAC is the reduced carrier sensing when any node receives an xCTS. All the CTS packets contain the expected frame count of the data to follow. Upon reception of an xCTS packet, a node can back-off from carrier sensing for a sufficient duration to allow the data transfer to complete; this duration can be calculated using the frame count. Once this duration is calculated at the MAC layer, it is communicated to the PHY layer so that the transceiver does not process the packets received in that interval. These cross-layer communications are shown in Figure 4 and Figure 5.

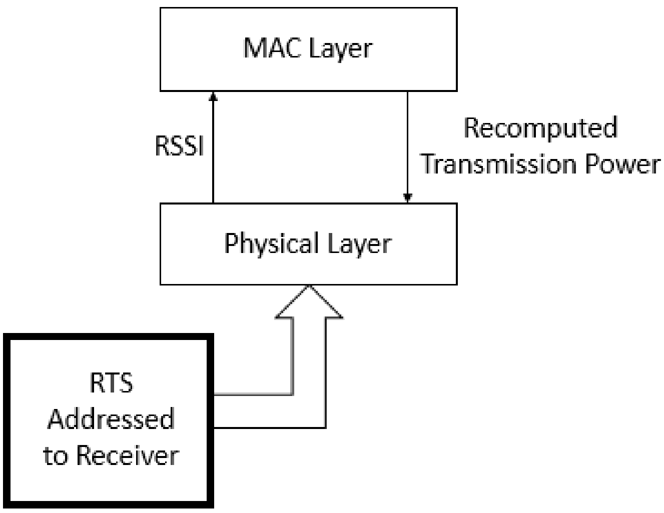

Figure 4. Adjustment of transmitter power based on RSSI at receiver

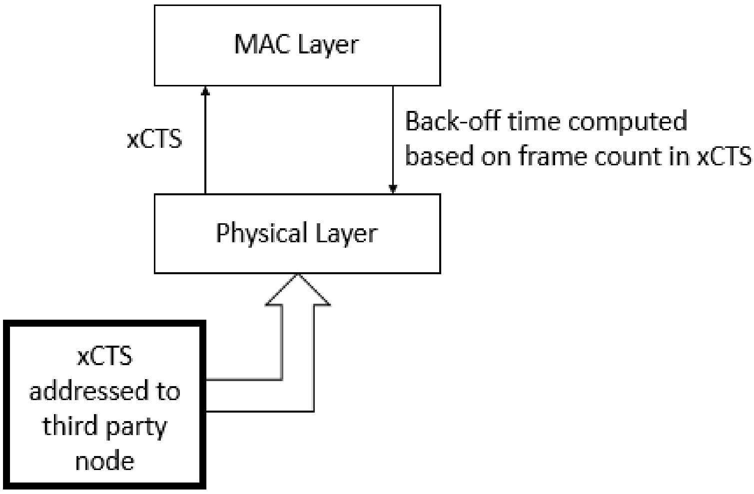

Figure 5. Calculation of back-off time based on frame count in xCTS

2.3. Overview of EECA-MAC Protocol

The distinguishing characteristics of EECA-MAC protocol are listed in this subsection. These characteristics are used as specifications for the low-level design of the protocol.

- EECA-MAC will be developed along the principles of contention-based access, since contention-free approaches necessitate extensive synchronization and localization
- EECA-MAC will be based on MACA. The RTS packet will have information about the amount of data that is expected to be transmitted
- EECA-MAC will use the fully negotiated 4-way handshake. This enhanced handshake comprises RTS, CTS, Data and Acknowledgement. Use of the 4-way handshake eliminates the problems of exposed terminal and hidden terminal to a large extent
- EECA-MAC will control the power of the transmitter, based on the RSSI. The RSSI will be inserted into the CTS packet; this RSSI is subsequently used for transmission power control
- EECA-MAC will perform adaptive power control. Nodes will be able to reduce their transmitter power just sufficient to reach the intended receiver. The sleep duration is decided by the length of the data field in the RTS that is overheard

2.4. Enhanced Four-Way Handshake

RTS and CTS packets are used as a part of the 4-way handshake procedure. These packets are enhanced and will be called Enhanced RTS (E-RTS) and Enhanced CTS (E-CTS) respectively. RTS is created and frame count is inserted into it leading to E-RTS. This is transmitted (allowing for re-transmissions) and then the system waits for corresponding E-CTS.

For E-CTS, initially a normal CTS packet is created. The RSSI of the received E-RTS is inserted into this packet. This is used for the control of transmission power on the transmitter side. The E-CTS is completed by inserting the frame count that was in the received E-RTS.

When the E-RTS packet is transmitted, all other nodes will remain in silent mode. The intended destination node will reply with an E-CTS. In the EECA-MAC protocol, this exchange is used to control transmit power of the source and other nodes and also to inform the third party nodes for how long they have to remain silent. To achieve these purposes, E-RTS includes a field containing how many frames will be transmitted. E-CTS echoes this information as well as the RSSI of the received signal.

Figure 6 shows the transmission of E-RTS and corresponding E-CTS respectively. Figure 7 shows the case of the intended receiver receiving the E-RTS, creating the E-CTS and transmitting it.

Once the E-RTS and E-CTS exchange is complete between the intended sender and receiver, data communication can take place. This phase, followed by acknowledgement, is the enhanced 4-way handshake mechanism of the EECA-MAC protocol. The acknowledgement is for the frames only and not for the packets or application. This protocol uses the sliding window acknowledgement scheme. The transmission of data is shown in Figure 8.

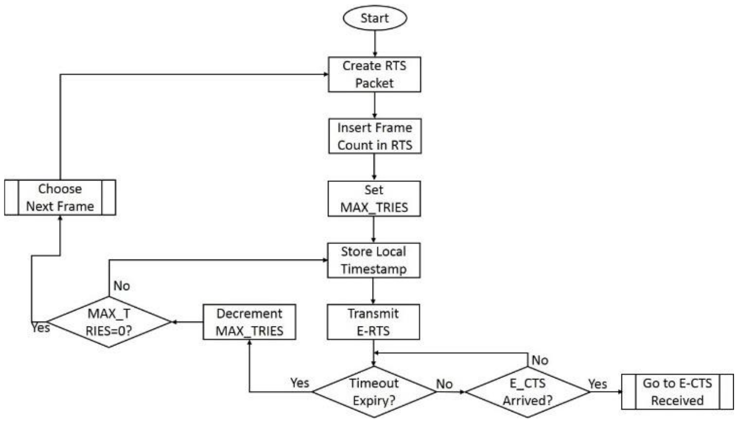

Figure 6. Creation and transmission of E-RTS

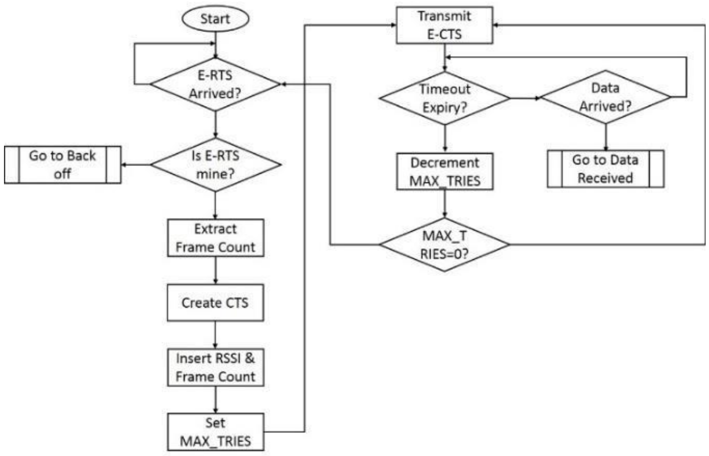

Figure 7. Creation and transmission of E-CTS

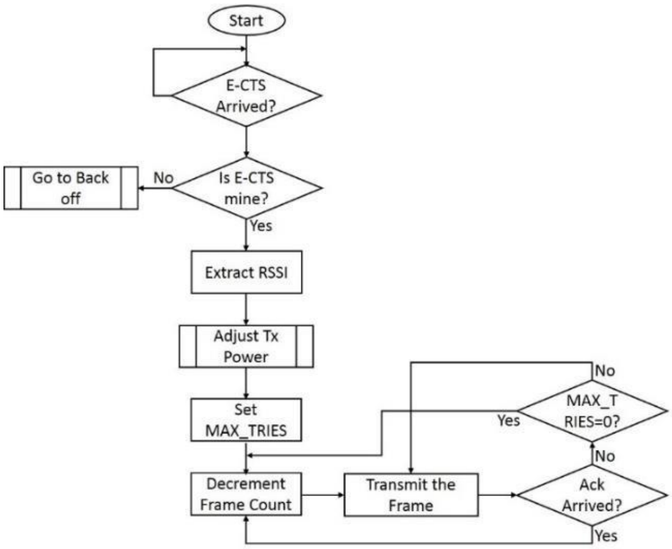

Figure 8. Transmission of data

2.5. Mechanism of Back-off

In medium access, a node has two reasons to back off and not utilize the channel. The first reason is when it receives an xRTS or xCTS. Along similar lines, EECA-MAC protocol performs a back-off if it receives a third party E-RTS or E-CTS. The back-off when a third party RTS is received is rather simplistic: The node will listen to the channel for a corresponding E-CTS. If the E-CTS is not heard, the node can transmit its E-RTS (if needed).

The reception of a third party E-CTS is more crucial. This implies that there will soon be data in that range. Therefore, the node that receives an E-CTS has to defer transmission till the ongoing data transmission is complete. The amount of time that the node has to defer its transmission can be calculated using the frame count in the overheard E-CTS. This is another aspect of power saving in EECA-MAC protocol; the node does not need to sense the channel during the entire time duration of the back-off. This process is shown in Figure 9.

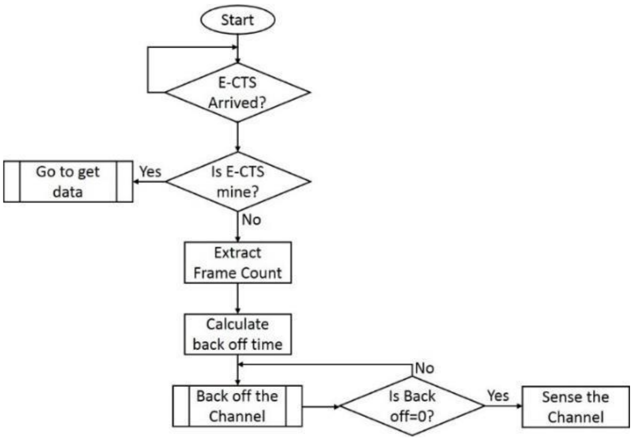

Figure 9. Sensing xCTS

The enhanced 4-way handshake and the back-off mechanism of EECA-MAC ensure lesser interference in the medium thereby increasing energy efficiency by ensuring a reduced number of retransmissions. This results in improved conservation of the battery power of each node, thereby optimizing the uninterrupted active time of the network without recharge of the battery. The energy model of EECA-MAC protocol is described in the next section.

2.6. Energy Model of the EECA-MAC Protocol

Consider M to be the total number of packets transmitted of which N is the number of packets that require retransmission. This makes the total number of transmissions to be $(M+N)$.

If P_T is the power utilized by the node per packet of transmission, the total power utilized for all the transmissions is given by:

$$P_{TT} = P_T(M + N) \quad (1)$$

Due to the measures for energy efficiency incorporated, there is a reduction in the transmission power which is defined as the modified transmission power P_{TT}^M represented by:

$$P_{TT}^M = P_T(M + N') \quad (2)$$

Here, N' is the number of packets that require retransmission after the incorporation of measures to achieve energy efficiency. Eqn. (1) and Eqn. (2) imply that there is a reduction in transmission power from P_{TT} to P_{TT}^M since the number of retransmissions is reduced from N to N'.

Let p $(0 < p < 1)$ indicate the reduction in the number of retransmissions due to the features of the EECA-MAC protocol. Essentially, p is a scaling factor for N, which is the number of packets that require retransmissions.

$$p = N'/N \quad (3)$$

By factoring p into Eqn. (2), the modified total transmission power, P_{TT}^M, will become:

$$P_{TT}^M = P_T(M + pN) \quad (4)$$

Eqn. (1) and Eqn. (4) are used to calculate the reduction in total transmission power, ΔP_{TT}.

$$\Delta P_{TT} = P_{TT} - P_{TT}^{M} = P_T(M+N) - P_T(M+pN)$$

$$\Delta P_{TT} = P_T N(1-p) \tag{5}$$

From Eqn. (5), it is clear that the value of p lies between 0 and 1. p=1 will be the original scenario with N retransmissions and as p tends to 0, there will be an improvement in the ΔP_{TT} value.

If there is a reduction in the number of retransmissions, it naturally follows that there will be a proportional reduction in the total time to transmit the packets. If T is the time required for transmission of one packet using MACA protocol, then the total time to transmit M+N packets is:

$$T_{tot} = T(M+N) \tag{6}$$

Since the number of retransmissions is reduced to N', the total time taken for transmitting packets also reduces by a factor of p as in Eqn. (3). The modified total transmission time of the EECA-MAC protocol is:

$$T_{tot}^{M} = T(M+N') = T(M+pN) \tag{7}$$

Eqn. (6) and Eqn. (7) are used to calculate the reduction in total transmission time, ΔT_{tot}.

$$\Delta T_{tot} = T_{tot} - T_{\text{tot}}^{M} = T(M+N) - T(M+pN)$$

$$\Delta T_{tot} = TN(1-p) \tag{8}$$

Here again, it is obvious that a reduction in the number of retransmissions results in the saving of time the node spends on the transmission of data. A reduction in transmission power and time implies a reduction in the utilization of RF energy, resulting in increased residual energy.

$$\Delta E_{Util} = \Delta P_{TT} * \Delta T_{\text{tot}} = \{P_T N(1-p)\}\{TN(1-p)\}$$
$$\Delta E_{Util} = P_T T N^2 (1-p)^2 \tag{9}$$

3. SIMULATION ANALYSIS OF EECA-MAC PROTOCOL

Network Simulator 2 (NS2) is one of the most widely used open-source platforms to simulate wired and wireless networks. For simulating underwater acoustics, un-modified NS2 is inadequate because (i) Cross-layer communication is needed (ii) The Physical layer for an underwater network is not implemented in the source packages of NS2. One of the most important extensions to NS2 was proposed in [17] where NS2 is extended to facilitate cross-layer communication and multiple radio interfaces. This extended NS2 framework is called Multi InteRfAce Cross Layer Extension for ns2 (MIRACLE). The NS2-MIRACLE framework was improved by adding a PHY implementation that could be used in underwater networks. This is called the World Ocean Simulation System (WOSS) [18]. To simulate EECA-MAC, the DESERT Underwater Framework [19] is used. DESERT incorporates NS2-MIRACLE and WOSS, making it an ideal simulator for the study proposed in this paper. This section presents the simulation results of the EECA-MAC protocol.

The results presented in this section are divided into three parts. In the first part, the results of the energy efficiency calculation are presented. Specifically, these results quantify the reduction in retransmission of packets, reduction in transmitter power and the resulting decline in the energy utilized by the nodes when EECA-MAC is used, compared to the unenhanced MACA protocol. The second part of the results aims to compare the energy consumption of EECA-MAC with Reservation based MAC (R-MAC) originally proposed in [20] by reproducing the scenarios presented in it. The authors believe that this comparison validates the implementation of R-MAC in the DESERT simulator, while simultaneously benchmarking the energy consumption profile of EECA-MAC with R-MAC. The last set of results presents an exhaustive set of simulations that compare the performance of EECA-MAC with R-MAC and DACAP. The protocols will be evaluated in terms of their Packet Delivery Ratio (PDR), latency and energy consumption.

3.1. Analysis of Energy Efficiency of EECA-MAC

To analyze the parameters contributing to the energy efficiency of the EECA-MAC protocol, a scenario is developed that has three clusters, each with one cluster-head and ten sensor nodes as shown in Figure 10. Each sensor node will transmit 100 packets to its respective data haul node. The simulation parameters are listed in Table 1.

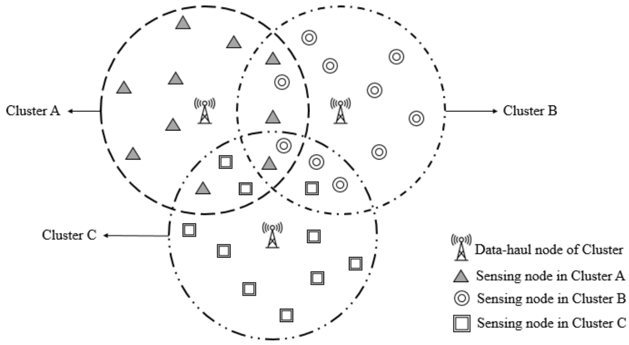

Figure 10. Scenario for analysis of energy efficiency

The network was simulated by transmitting 500 packets in total. The number of packets delivered on the first transmission and subsequent retransmissions with MACA, EECA-MAC, R-MAC and DACAP is tabulated in Table 2. For the received packets, the percentage of packets received is calculated separately for the first transmission and retransmissions. The reduction in the number of retransmissions in EECA-MAC can be attributed to the adaptive power control. This power control leads to lesser interference and packet collisions, thereby diminishing the number of packet retransmissions.

Table 1. Simulation Parameters for analysis of energy efficiency

Parameter	Value
Number of clusters	3
Number of sensor nodes in each cluster	10
Number of packets transmitted by each sensing node	50
Packet size	250 Bytes

Table 2. Number of packets received on the first transmission and subsequent retransmissions

Protocol	Total Packets Received	Packets Delivered on First Transmission	Packets Delivered on Retransmissions (N)
MACA	490	355	135
DACAP	484	388	96
R-MAC	488	397	91
EECA-MAC	496	414	82

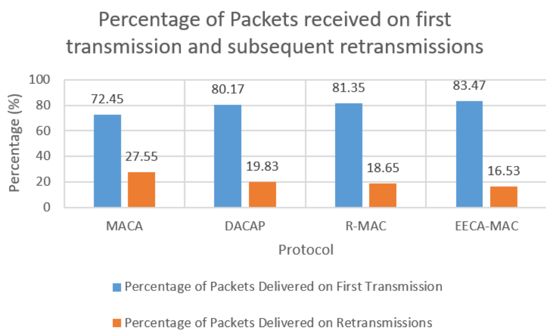

Figure 11. PDR for packets received on the first transmission and subsequent retransmissions

EECA-MAC protocol is developed by considering MACA as the base reference and subsequently enhancing it. This section presents a quantitative comparison of MACA and EECA-MAC protocols in terms of savings of transmission power, latency and RF energy utilization. The graph in Figure 11 shows a reduction of 39.26% in the number of retransmissions required for packet delivery.

To analyze the reduction in the transmission power, let the average transmission power for a single packet is $P_T(W)$. The total number of transmissions in the first attempt (M) is 500, and the number of packets that require retransmission (N) is shown in Table 2. The total transmission power P_{TT} is calculated using Eqn. (1).

$$P_{TT} = P_T(M + N)$$

Here, N=135 is the number of packets requiring retransmission in the MACA protocol.

$$P_{TT} = 635P_T \quad (10)$$

When EECA-MAC is applied to the simulation scenario, it is seen from Table 2 that the packets delivered on retransmissions reduce to 82. This implies that:

$$N' = 82$$

Since $p = N'/N$ from Eqn. (3), $N = 135$ and $N' = 82$:
$p = 0.6074$

This shows that the EECA-MAC protocol uses only 60.74% of the total retransmissions used by MACA to transmit 500 packets. This implies a 39.26% reduction in retransmissions to deliver packets. Considering $N = 500$ and $N' = 82$,, the modified total transmission power of the EECA-MAC protocol is obtained by applying Eqn. (2).

$$P_{TT}^{M} = P_T(500 + 82) = 582P_T \quad (11)$$

Using Eqns. (10) and (11), the reduction in transmission power is:

$$\Delta P_{TT} = P_{TT} - P_{TT}^{M}$$

$$= 635P_T - 582P_T$$

This reduction in transmission power can be normalized as:

$$\Delta P_{TT} = \frac{P_{TT} - P_{TT}^{M}}{P_{TT}} * 100$$

$$\Delta P_{TT} = \frac{635P_T - 582P_T}{635P_T} * 100$$

$$\Delta P_{TT} = 8.35\% \quad (12)$$

From Eqn. (12), it is concluded that a 39.26% reduction in retransmission translates to a reduction of 8.35% of the total power for the successful transmission of 500 packets.

The reduction in end to end latency is calculated on similar lines. The average end-to-end delay of a packet is found to be 0.58 s based on the simulations carried out using the DESERT underwater framework. This value is taken to be T, the average time taken for one packet transmission using MACA protocol. This value is substituted in Eqn. (6) to calculate the total time required to transmit 500 packets, of which 135 packets need retransmissions.

$$T_{\text{tot}} = T(M+N) = 0.58(500+135) \quad (13)$$
$$T_{tot} = 368.3s$$

The EECA-MAC protocol requires 82 retransmissions (N'), giving a modified transmission time of:

$$T_{\text{tot}}^{M} = T_{\text{tot}}\,(M+N') = 0.58(500+82) \quad (14)$$
$$T_{\text{tot}}^{M} = 337.58 \text{ s}$$

Using Eqns. (13) and (14), the reduction in total transmission time is:

$$\Delta T_{tot} = T_{\text{tot}} - T_{\text{tot}}^{M} = 368.3 - 337.58 \quad (15)$$
$$\Delta T_{tot} = 30.74 \text{ s}$$

Any reduction in transmission power and/or transmission time results in a reduction in the RF energy expended by all the nodes in a network. The RF energy utilized is expressed as a product of power and time. The energy utilized for the data transmission using MACA protocol is:

$$E_{Util} = P_{TT} * T_{\text{tot}} = 635P_T * 368.3 \text{ s}$$

$$E_{Util} = 233.87 P_T kJ \quad (16)$$

Since the number of retransmissions is reduced, P_{TT}^{M} and T_{tot}^{M} can be used to calculate the energy utilization (E_{Util}^{M}) when the EECA-MACA protocol is used.

$$E_{Util}^{M} = P_{TT}^{M} * T_{tot}^{M} = 582P_T * 337.58 \text{ s} \quad (17)$$
$$E_{Util}^{M} = 196.472 P_T \text{ kJ}$$

The normalized savings in RF energy, defined as η_E, is given as:

$$\eta_E = \frac{E_{Util} - E_{Util}^{M}}{E_{Util}} * 100 = \left(\frac{233.87P_T - 196.472P_T}{233.87P_T}\right) * 100$$
$$\eta_E = 16\%$$

The simulation results show a reduction of 16% in the energy utilized by the nodes, making the EECAMAC protocol more energy efficient than the MACA protocol. This reduction is brought about because of a reduction in the number of packets requiring a retransmission by a factor of almost 40%. This is made possible by the measures taken in the design of EECA-MAC to make it more energy-efficient such as adaptive power control and reduced carrier sensing.

3.2. Energy Consumption Profile of EECA-MAC and R-MAC

This section presents a comparison of the energy consumption profile of EECA-MAC and R-MAC protocols. The network topologies for this comparison are based on those presented in [20], which proposed R-MAC. To measure the energy consumption under different traffic(data) rates, the topology shown in Figure 12 is used in the simulation study. The network consists of four nodes sending data to a sink. The nodes are not equidistant from the sink. The data rate of transmission varies in discrete steps from 0.02 to 0.24 packets per second. The size of each packet is 60 bytes.

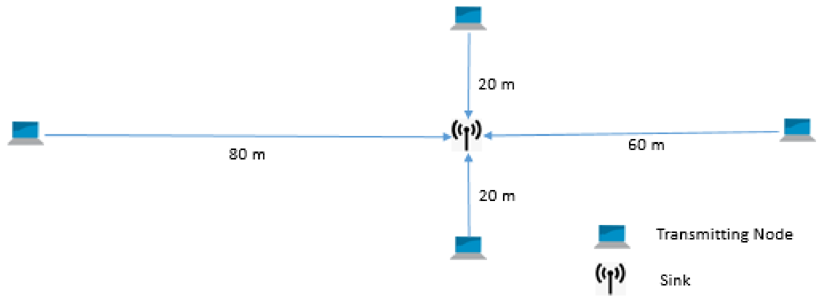

Figure 12. Network Topology-1 with varying data rate

For the network scenario (Topology -1) shown in Figure 12, the simulation results are presented in Figure 13. The simulation results of R-MAC obtained using the DESERT Underwater Framework proposed in this paper are compared with analogous results present in [20] which also invoked R-MAC protocol. In Figure 13, the results obtained with the EECA-MAC protocol are also presented. From the results of Figure 13, it is seen that there is an excellent agreement between the results of [20] and DESERT implementation of R-MAC. Compared to the results of R-MAC, the results obtained through the EECA-MAC protocol show significant reduction in the profile of energy consumption. Since the EECA-MAC protocol performs adaptive power control, there is a relative reduction of almost 35% in the energy consumed. The EECA-MAC protocol controls the transmitter power during the RTS-CTS exchange. This results in the transmitter being able to just reach the receiver instead of overshooting the range (distance between the transmitter and receiver).

Another aspect of the energy profile presented in [20] is the energy consumed to transmit one data packet. For this scenario, the network topology is configured to allow all the transmitting nodes to hear one another as shown in Figure 14. The energy consumption per packet with varying data rates is measured and analyzed. The nodes are not equidistant and they are closer to the sink compared to the previous scenario stated in Figure 12.

For the simulation, the data rate of transmission varies in discrete steps from 0.02 to 0.24 packets per second. The size of each packet is 60 bytes

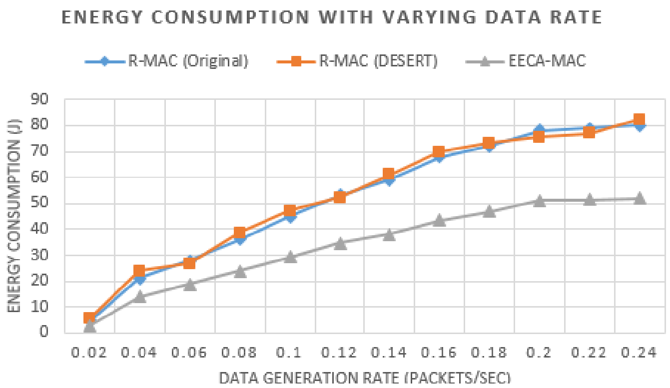

Figure 13. Variation of energy consumption with change in data rate

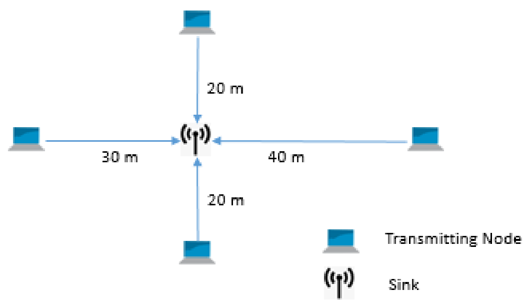

Figure 14. Network Topology-2 for per-packet energy consumption

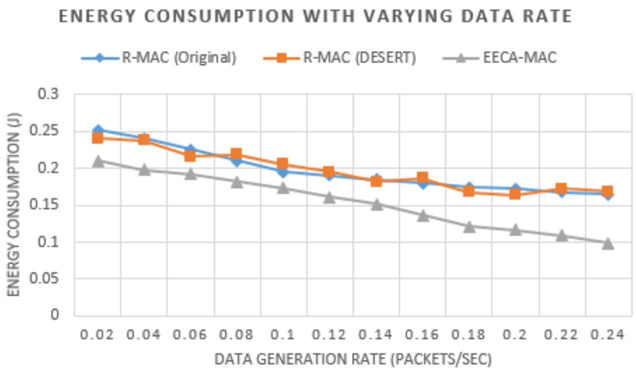

Figure 15. Energy consumption to transmit one packet

The simulation results for the scenario (Topology -2) shown in Figure 14 are presented in Figure 15. In the results shown in Figure 15 also, there is a very good agreement between the R-MAC results of [20] and the DESERT implementation of R-MAC of this paper. It is also seen that the performance of EECA-MAC is progressively better than R-MAC with the increase in the data rate. The underlying reason for this attribute is that the EECA-MAC protocol reduces the interference more effectively since it does not sense the channel frequently. Only when the channel is sensed and found to be free, the RTS-CTS exchange of EECA-MAC controls the transmitter power with the available information on RSSI at the destination node.

3.3. Details of the Scenario Created for Performance Analysis of EECA-MAC Protocol

A multi-sink architecture is considered with 10% of the deployed nodes acting as sinks. To evaluate the MAC protocols, a common routing protocol, Distributed Geographic Routing [21] is used. Table 3 summarizes the deployment scenario highlighting the simulation parameters used in this paper.

Table 3. Simulation parameters for performance analysis

Parameter	Default	Minimum	Maximum
Coverage Area (m)	3000*3000*3000	--	--
Number of Nodes	30	5	50
Traffic (kbps)	40	10	100
Packet Size (Bytes)	500	--	--
Mobility (ms-1)	0.75	0.5	2
Mobility Model	--	Random Waypoint	Random Waypoint
Routing Protocol	Distributed Geographic Routing		

3.4. Performance of EECA-MAC with Variable Node Density

In this set of simulations, the density of the nodes is changed. The performance graphs of the different MAC protocols in terms of Packet Delivery Ratio (PDR), latency and energy consumption are presented in Figure 16 to Figure 18 respectively.

Figure 16 shows the variation of PDR with node density. At lower node densities, it is seen that there are not enough nodes to form a multi-hop path to the sink node. This results in lower PDR at low node densities. On the other hand, as the node density increases beyond a threshold, gradual degradation of PDR is noted when R-MAC and DACAP are used. This can be attributed to the higher level of interference resulting from more nodes in proximity to each other. EECA-MAC is not affected by this, since it progressively reduces the transmitter power as the node density increases. This allows EECA-MAC to function more effectively, with a 10% to 15% increase in the PDR.

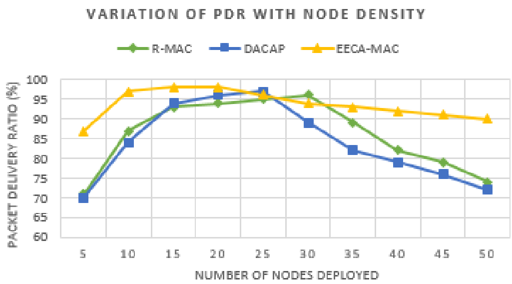

Figure 16. Variation of PDR with node density

Figure 17 shows the variation of latency with node density. As discussed previously, since the nodes are unable to reach the sink node at low node densities, the three protocols start with high latencies. As the connectivity gets better with more nodes being available to route through, the latency reduces.

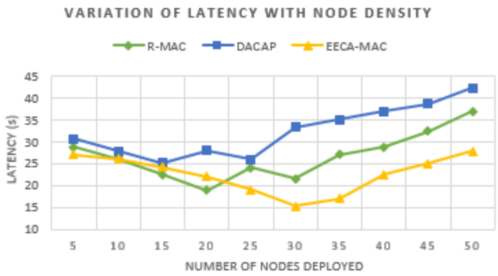

Figure 17. Variation of latency with node density

However, as the node density increases, the number of retransmissions increase since the traffic and packet collisions escalate. This causes a significant increase in the end-to-end latency, especially for the DACAP. DACAP is designed to tolerate extensive latencies and thus, does not resort to retransmissions quickly. EECA-MAC, being least susceptible to interference and collisions, does not need many retransmissions; operating at about 20% to 25% lesser latency than the other protocols.

During the communication phase, UWSNs incur undesirable energy expenditure during carrier sensing, exchange of control packet and packet retransmissions due to collisions. The adaptive power control and reduced carrier sensing of EECA-MAC protocol bring out significant savings in the residual energy of nodes. The results of Figure 18 show that EECA-MAC outperforms both DACAP and R-MAC, reducing the energy consumption by almost 30%.

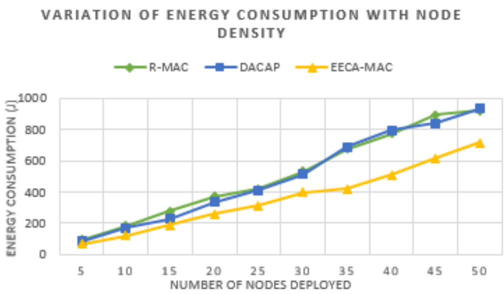

Figure 18. Variation of energy consumption with node density

3.5. Performance of EECA-MAC with Variable Data Rate

In this set of simulations, the data rate is changed. The performance graphs of the different MAC protocols in terms of PDR, latency and energy consumption are presented in Figure 19 to Figure 21 respectively.

Figure 19 shows the variation of PDR with change in data rate. Since the underwater acoustic communication medium is generally bandwidth-constrained, it cannot support very high data rates. It is seen that PDR deteriorates quite rapidly once the data rate reaches 60 kbps. Since this is a medium dependent phenomenon, all the protocols considered in this study exhibit similar behaviour.

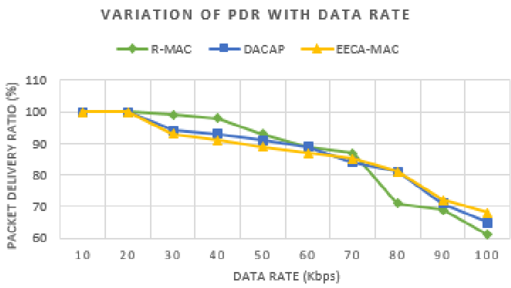

Figure 19. Variation of PDR with data rate

The variation of latency with change in data rate is presented in Figure 20. It is observed that EECA-MAC performs at par with the other protocols. Since there is no major impact of interference and packet collision on latency, EECA-MAC protocol is not significantly better than the other two protocols from the perspective of latency. It is worth noting that reduced carrier sensing also does not have a significant effect on latency. It is to be noted that EECA-MAC misses a few slots available for communication due to not sensing the carrier often enough.

In terms of energy efficiency, EECA-MAC increases the residual energy of nodes; saving about 15% of the energy consumption as shown in Figure 21. This factor is almost the same irrespective of the data rate and can be attributed to consistently transmitting at a lower transmitter power than R-MAC and DACAP.

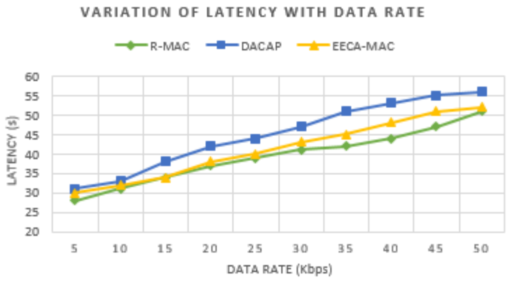

Figure 20. Variation of latency with data rate

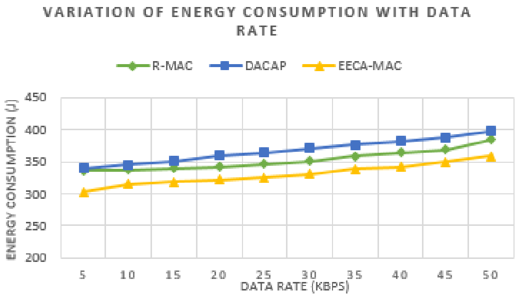

Figure 21. Variation of energy consumption with data rate

3.6. Mitigation of Interference in EECA-MAC

This section presents a formulation highlighting and substantiating the feature of adaptive power control resulting in decreased collisions which in turn leads to minimization of interference and enhancement in the energy efficiency of the EECA-MAC protocol.

The range of a communication link, denoted by R, is determined through the Friss Transmission formula [22] given by:

$$R = \left(\frac{\lambda}{4\pi}\right)\sqrt{\frac{P_T G_T G_R}{P_R}} \quad (18)$$

Where,

P_T = Transmit power at the source node
P_R = Received power at the destination node
G_T = Gain of source (transmit) node
G_R = Gain of destination (receive) node
λ = Wavelength

For a given P_T, P_R, G_T, G_R and λ, $'R'$ is constant. When P_T is set to the maximum allowable power $P_{T\max}$ at the source node, Eqn. (18) becomes:

$$R_{Max} = \left(\frac{\lambda}{4\pi}\right)\sqrt{\frac{P_{T\mathrm{m}}\, G_T G_R}{P_R}} \quad (19)$$

Eqn. (19) gives the maximum range R_{Max} allowed between source and destination nodes for communication.

When P_T is variable and can be controlled at the source node, then it is a scenario of communication with adaptive transmit power, P_{TCNL}. Eqn. (19) becomes Eqn. (20). R_{CNL} is the adaptive range that is set as the instantaneous distance between the source and the destination nodes.

$$R_{CNL} = \left(\frac{\lambda}{4\pi}\right)\sqrt{\frac{P_{TCNL}G_T G_R}{P_R}} \qquad (20)$$

In a wireless network, the distance between the source node and its neighbour node or the distance between the source node and the destination node usually varies and R_{CNL} is known. Knowing R_{CNL}, one can calculate the required P_{TCNL} called the adaptive transmit power, given by Eqn. (21).

$$P_{TCNL} = \frac{P_R 4^2 \pi^2 {R_{CNL}}^2}{G_T G_R \lambda^2} \qquad (21)$$

In the context of the research carried out in this paper, $R_{CNL} < R_{\max}$ and hence $P_{TCNL} < P_{T\max}$.

If there are more nodes apart from the source and destination and if the internode distances (distances between the source node and additional nodes other than the destination node) exceeds R_{CNL}, then no communication is possible between the source node and the referred additional nodes for the calculated P_{TCNL}. This implies that despite the presence of spatially separated additional nodes in the cluster, there can be no communication between the source node and other nodes except the destination node. This results in reduced collisions and therefore the interference is minimised.

Figure 22 shows a scenario with partially overlapping clusters and spatially separated nodes. The transmission or communication range of the source node without adaptive power control is R_{MAX}, and the node is expending P_{TMax} of transmission power to reach the destination node. This is not withstanding that the source and destination nodes are separated by a distance of d which is lesser than R_{MAX}.

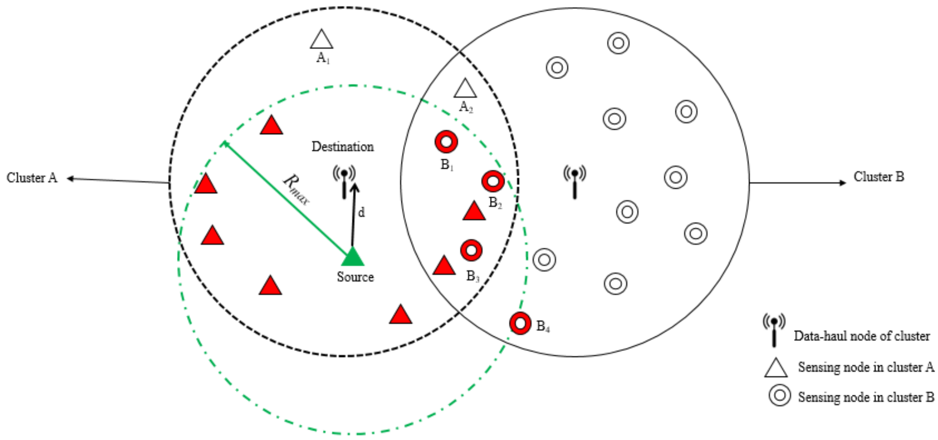

Figure 22. Interference range of source node without adaptive power control

The communication range of the source node in cluster A has a detrimental effect on the sensing nodes B_1, B_2, B_3 and B_4 of cluster B since they are within the maximum range of the source node of cluster A. These nodes can potentially cause interference to the communication in cluster A.

Figure 23 shows the scenario where the range of the source node of cluster A is reduced to R_{CNL} such that the transmitter power of the source node is set to P_{TCNL} which is just sufficient to establish the link with the destination node. This reduces the collision domain of cluster A drastically and also allows the sensing nodes B_1, B_2, B_3 and B_4 from cluster B to communicate with their own data-haul node without causing interference to the ongoing communication in cluster A. Hence Figure 23 clearly depicts the reduction of interference due to the referred adaptive transmit power control at the source node.

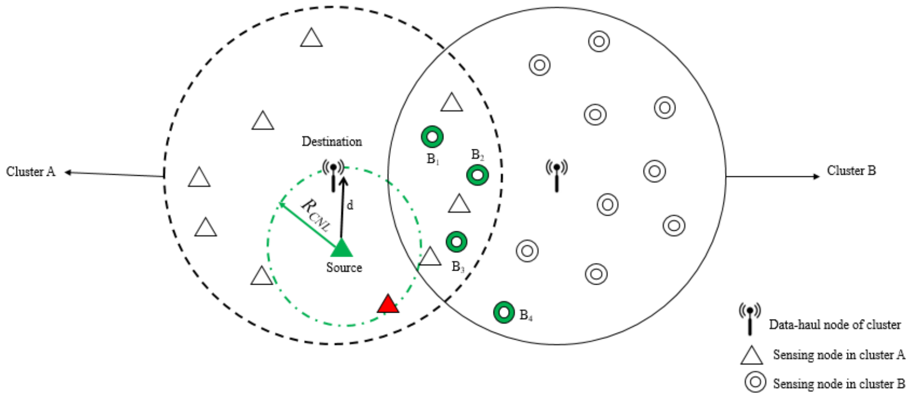

Figure 23. Interference range of source node using adaptive power control

3.7. Characterization of Underwater Acoustic Wave Propagation

In this section, a brief discussion about various factors affecting the speed of sound in seawater is presented.

The speed of sound in seawater is dependent on temperature, salinity and depth. The empirical formula for determining the speed of sound in seawater is given in [23] as:

$$c = 97.3 + (4.95 - 0.055T + 0.00029T^2 - 0.010S) + 0.016D \quad (22)$$

Where,

T = Temperature in $_o$C
S = Salinity in PPT
D = Depth in meters

The velocity of sound continuously varies with depth. The underwater environment factors such as water depth, salinity, conductivity, temperature and pressure pose a significant challenge in underwater wave propagation and communication. With an increase in the depth, salinity and pressure in the water increase. However, the temperature decreases. The acoustic wave propagation is affected by the variation of environmental factors resulting in variable propagation delay, noise, the velocity of sound, multipath fading, attenuation, absorption and spreading loss [24]. Acoustic wave propagation is also affected by the viscosity of water and its chemical composition resulting in absorption loss of sound waves. The absorption loss is also a function of salinity, pressure, temperature and frequency.

Signal to Noise Ratio (SNR) is the signal strength related to background noise. Noise in underwater decreases the signal strength during the propagation between source and receiver. For shallow water, the SNR is more at a lower frequency and decreases with an increase in frequency. The SNR in dB [25] is given by:

$$SNR = SL - TL - NL + DI \quad (23)$$

Where,

SL = Acoustic signal level in dB expressed as:

$$SL = 169 + 10\log_{10}(P) - \alpha_s r - 20\log_{10}\left(\frac{d}{2}\right) - 10\log_{10}\left(r - \frac{d}{2}\right)$$

P = Radiated signal power in watts
α_s = Absorption co-efficient in dB/m
r = Range in m
d = Depth in m

TL = Transmission loss
NL = Noise level for Shallow water (typically 70 dB)
DI = Acoustic Transducer Array Gain

4. CONCLUSIONS AND FUTURE WORK

This paper presented the design, development and simulation analysis of the EECA-MAC protocol, which is an energy-efficient collision avoidance MAC protocol. EECA-MAC is a contention-based protocol developed using MACA principles. The time the protocol EECA-MAC spends sensing the carrier is drastically reduced as compared to other MACA-based MAC protocols. EECA-MAC protocol is energy efficient since it carries out adaptive control of transmit power based on the RSSI of the received signal. The developed EECA-MAC protocol is also capable of backing off from the channel when other transmissions are ongoing, thereby reducing collisions and increasing energy efficiency.

It is seen that the measures taken to reduce interference and increase energy efficiency have proved to be effective and efficient. A comparison with traditional MACA protocol shows that the EECA-MAC protocol exhibits a reduction of almost 40% in the number of packets that require to be retransmitted to ensure successful data transmission. This corresponds to about 8% reduction in total power for the successful transmission of 500 packets and a 16% drop in the energy utilized by the nodes, contributing to an increase in the overall lifetime of the network.

The authors propose to incorporate the EECA-MAC protocol into an enhanced software stack for communication in UWSNs with a focus on energy efficiency. The measures incorporated in the design of EECA-MAC can also be adopted into any MACA based protocol to make it more energy efficient.

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