IMPLEMENTATION OF A CHANNEL-AWARE ROUTING PROTOCOL IN THE NETWORK SIMULATOR FOR UNDERWATER ACOUSTIC COMMUNICATION NETWORKING

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ABSTRACT

Over two-thirds of the earth's surface is occupied by water, however, the level of research in the field of Underwater Wireless Sensor Networking (UWSN) does not necessarily commensurate with the size and potential. Importantly, the underwater acoustic channel is susceptible to signal degradation as a result of the dynamic and harsh state of the environment such as high propagation delay and limited channel bandwidth. The above challenges are the motivation behind the Implementation of The Channel-aware Routing Protocol (CARP) in Underwater Wireless Sensor Networking. CARP [1] is a cross-layer routing paradigm that collaboratively leverages the link quality estimation between neighboring sensor nodes and the hop counts from the sink to determine the next relay node for packet forwarding. In this work, CARP was implemented in Aqua-Sim-NG, an ns-3-based underwater wireless sensor network simulator that simulates underwater acoustic channels with high fidelity. The goal of this work is the optimization of routing performance in underwater acoustic communication networking.

INTRODUCTION

Underwater wireless acoustic networking is a technology-based platform for a large array of emerging applications that includes oceanographic information aimed at the enablement of scientific explorations, seismic monitoring for prediction purposes, as well as the transmission of other underwater information-bearing signals. This requires setting up a range of multi-hop networks of strategically-placed sensor nodes for the transmission of data amongst collection points known as sinks. Such sinks are located at the surface level of the ocean to receive and send data through radio frequencies to control stations located onshore. The deployment of underwater wireless networks is hindered by factors peculiar to the environment they are situated. The changing conditions of such environments provide an enabling environment for the manifestation of challenges that impact on underwater networking, especially routing protocols and medium access control (MAC) which largely differs from its terrestrial counterpart (Syed et al, 2008). These challenges are solved through the development of cross-layer techniques capable of positively affecting the networks. A good example of a cross-layer approach is Focused Beam Routing (FBR) where control packets (RTS/CTS) as in CSMA /CA-like channel access are used in channel reservation and carry node location information that is used to select next hop relay, which is the neighbor closest to the sink. The use of short packets for channel access and relay selection is particularly effective for routing in challenging underwater wireless networks. This paper presents a cross-layered multi-hop delivery system for underwater networks, using short packets of robust channel access and relay selection known as Channel-Aware Routing Protocol (CARP). CARP is also designed to leverage modern power control by selecting transmission powers in such a way that shorter control packets experience a similar packet error rate (PER) to longer data packets. The power increase is made for the transmission of data packets after the handshake process which is when the relay selection has been completed to increase the delivery likelihood of data packets. In comparison, CARF outperforms Depth-Based Routing (DBR) in terms of throughput efficiency, energy consumption, and the latency of its end-to-end packets. The following highlights some of the key contributions of this project in the wireless communications of data packets from the source nodes to the sink in the underwater acoustic channel as found below:

I. Design, development, and integration of the Channel-aware routing protocol in the Aqua-Sim Next Generator simulator

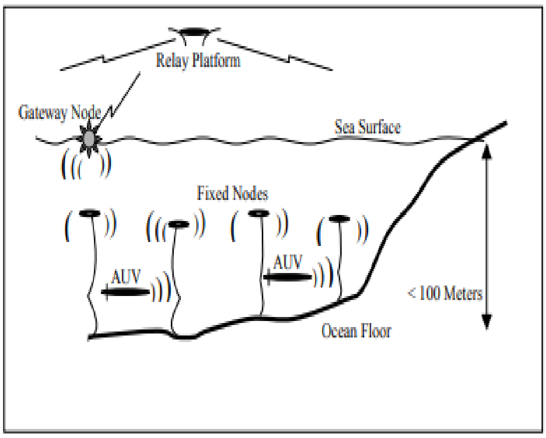
II. II. Integration of a cross-layer routing protocol into the existing routing modules of the simulator framework

III. III. Provision of comprehensive codebase documentation on GitHub for researchers in Underwater Wireless Sensor Networking who intend to build upon the existing routing CARP routing protocol

RELATED WORKS

The underwater channel is very harsh and dynamic which depicts the unpredictability of channel status that directly affects the performance of data transmission. Existing routing protocols that are in use leverage limited metrics in determining the next hop, thus the relay node which is used to forward the packets toward the destination from the sink.

A typical underwater wireless network comprises mobile and fixed sensor platforms having one or more gateways. The node serving as the gateway is equipped with an acoustic modem for the purpose of interfacing with other sensor platforms across the network, as well as a high-speed interface. This interface may be very high frequency (VHF), ultra-high frequency (UHF) high frequency (HF), or w fiber tether.



Representation of a Typical underwater acoustic network

Xie et al (2004), presented Vector-Based Forwarding (VBF), a protocol that attempted to tackle the challenges of routing underwater sensor nodes to the sink. In VBF, every packet contains the positions of the sender, forwarder, and target also called the destination. It is assumed that every node participating in VBF is aware of its position information which is provided by some location algorithm. In the event a node is unaware of its location information, the relative distance to the forwarder and angle of arrival (AoA) could be used in determining the position of the node. However, its success is dependent on correctly determining the radius of the forwarding pipe. Three position fields (SP, TP, and FP) act as coordinates of the sender, target, and forwarder respectively. In order to handle node mobility, each packet contains a RANGE field. When a packet reaches the area specified by its TP, this packet is flooded in an area controlled by the RANGE field. The forwarding path is specified by the routing vector from the sender to the target. Each packet also has a RADIUS field, which is a predefined threshold used by sensor nodes to determine if they are close enough to the routing vector and eligible for packet forwarding.

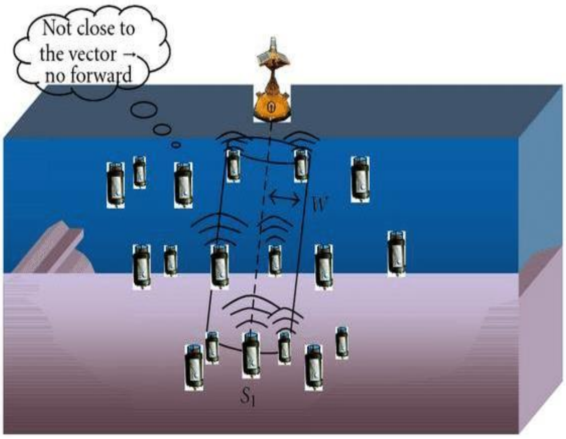


Figure one: Vector-Based Forwarding (Source: Kumar and Singh, 2014)

According to Xie et al (2010), the Depth-Based Routing protocol makes use relative depth of sensor nodes from the sensor nodes to determine the forwarding path toward the destination. Shortcomings range from node might not be in the direction of the destination, does not factor the channel status to determine which node works best, on-demand routing protocol which contributes to latency and reduced throughput efficiency, etc. DBR leverages the general underwater network architecture, based on the depth information of each sensor, it forwards data packets greedily toward the sink. It has a field in the packet header which records the depth of the forwarding sensor node. It is important to note that the depth information is regarded as the vertical distance from itself to the water's surface. Yan et al (2013), noted that DBR being a multiple path routing protocols would likely generate redundant packets during packet transmission, which is why the packet sequence number embedded in the packet header is essential to minimize broadcast and collisions. In DBR, each node adopts a priority Queue Q1 and packet history buffer Q2 to achieve minimization in redundant packet transmission. Every node places a packet destined for forwarding in Q1, after the expiration of the holding time the packet is forwarded. Other qualified nodes with longer distances from the sink have a longer holding time.

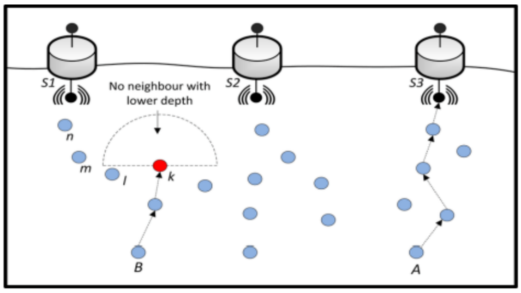


Figure two: Diagramatic representation of the void in Depth-Based Routing (Source: Ghoreyshi et al, 2017)

OVERVIEW OF THE Channel-Aware Routing Protocol

The channel-Aware routing protocol (CARP) can be described as a type of wireless ad hoc network routing protocol that selects the best communication channel by considering the unique attributes of different wireless channels. This protocol depends on the availability of several quality wireless channels for ensuring routing actions. CARP uses certain metrics to determine the best channel for sending data packets to the destination node (Peleato and STojanovic, 2007). The metrics include signal strength, interference level, and packet loss rate. Also, the quality of the wireless channels varies based on differences in distances, interference, and other obstacles. It is important to note that CARP is an on-demand and reactive routing protocol as this process is always initiated anytime a node decides to forward a packet. Moreover, it does not require management of state information as every attribute required during the route discovery process is only at the point of need.

How the CARP Works

The following enumerates the routing procedures using CARP below:

I. Broadcast of HELLO packet by the sink node

II. II. Exchange of PING packet by the sending node during the relay selection process

III. III. Reply from neighboring nodes with a PONG packet during the waiting time δ

IV. IV. Selecting of relay node based on the results of the PONG packet

V. V. Forwarding of packets by the sender node VI. Data acknowledgment from the receiving node

VI. VII. Update of hop count information by the sender to dynamically be in sync with the unpredictable nature of the underwater environment

The protocol's algorithm ensures that the nodes acquire hop count which is the spatial distance from the sink. In line with the above-mentioned procedures, the algorithm behind each process would be further explained in subsequent paragraphs.

```
<i>. Sink broadcast HELLO packet (p) to all its neighbors
<ii>. Each packet contains <src, numPkt>. Since it is emanating from the
sink HC(X) is 0
<iii>. At every node the following occurs:
If HC^t(x) < HC^(t-1)(x)
      Hop = HC^t(x) + 1
      forward (p)
else
      Hop = HC^(t-1)(x)
      forward (p)
```

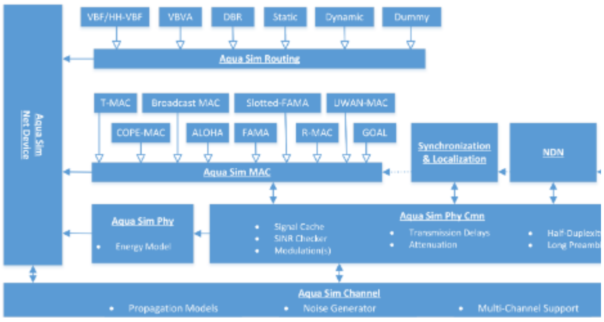
Figure three: Broadcast of Hello Packet

During the relay selection process, nodes exchange PING and PONG packets which possess fields used in determining which of the neighboring nodes become the next hop used in advancing the packet toward the destination. A source node sends a PING packet while a neighboring node responds with a PONG. The waiting time is dependent on the modem's nominal transmission range and acoustic signal propagation speed in water which is continuously updated by using the actual round-trip time of the PING and PONG packet exchange.

Generally, cross-layer protocols as a result of the handshake mechanism for joint channel access and relay selection such as CARP determine the next hop relay based on the correct exchange of control packets. However, it is important to understand that CARP is designed to leverage power control to obtain similar PER for both data and control packets. The power used to send PING is computed to obtain a PER corresponding to a given channel BER, once a relay has been selected, the power is increased so the corresponding PER is similar to that of PING /PONG exchange through which the relay has been determined.

AQUA-SIM

Aqua-Sim is an ns-3-based simulation tool that is used for analyzing underwater networks. It can be used to simulate a variety of underwater wireless protocols through the provision of a graphical user interface that is used to configure network parameters, define network typologies, and also get visual images of the simulation results. Aqua-Sim adopts a modular architecture that allows users to customize the simulation environment by adding preferred modules such as fixed, mobile, and sink nodes. Aqua-Sim was previously developed on ns-2, but as a result of numerous routine releases and enhancements on ns-2, this led to the evolution of ns-3 in 2008. In order to address various constraints introduced by ns-2 which was the underlying framework for Aqua-Sim, Aqua-Sim Next Generation was introduced which is a network simulator based on ns-3.



The architecture of Aqua-Sim Next Generation (Source: GitHub - rmartin5/aqua-sim-ng: Aqua-Sim on NS3)

The objective of the revamp was to improve memory management via the use of smart pointers, adopt proper packet handling techniques, and overall performance improvements. It should be noted that the APIs of ns-2 and ns-3 differ significantly. However, Aqua-Sim Next Generation's architecture is based on the net device of each individual node responsible for the facilitation of interactions with the channel layer. Invariably, modules that are isolated can be used to adopt synchronization support with the MAC protocols for better management of packet handling during simulation. Some advantages of Aqua-Sim Next generation include the following:

- It is a simulator driven by the tracing of discrete events
- It supports mobile and 3D networks
- Its simulation has a high degree of accuracy
- It supports a complete protocol stack from the physical to the application layer

Implemented Protocols in Aqua-Sim NG

1. Media Access Control (MAC) Layer

a. ALOHA

b. Broadcast MAC

c. GOAL: a geographical routing MAC protocol that combines VBF and handshake scheme.

d. Slotted-FAMA: Floor Acquisition Multiple Access protocols that combine carrier sensing with a handshake mechanism.

2. Routing Layer

a. VBF: vector-based forwarding

b. HH-VBF: hop-by-hop VBF

c. Dynamic routing: distance vector which uses the hop count information

d. Static Routing: creates predefined routes on the routing table

e. Dummy Routing: suitable for testing purposes which only forwards packets to the upper and lower layers

RESULTS

An effective CARP protocol is made up of the under-listed files:

1. **aqua-sim-header-routing.h**: This file contains the Aqua-Sim Routing Header. Header files contain the declaration of methods stating the specific class attached to the routing protocol in question. For simplification purposes, the classification of all routing protocols is a derivative of the base public header class which is responsible for virtual functions such as frame serializations, deserialization of bits in the wire, as well as the acquisition of the size of serialized bits for extracting the packet data. With respect to the CARP module, the tag 'CarpHeader is declared a derivative of the public headers base class, and it contains the methods of setting and retrieving the origin of the sender and the destination, obtaining the hop count of the sink node, determine values of the queue capacity of the node's buffer, and also assign tags to packets in order to distinguish between packets used for quality estimates.

2. **aqua-sim-header-routing.cc**: This file contains the main code of the aqua-sim header routing, indicating the number of functions available in the file; the only difference is that the functions are more detailed herein.

3. **aqua-sim-routing-carp.h**: This file contains the CARP proprietary header file, detailing the declarations of the protocol state from neighbor discovery to packet forwarding. In this file, a constructor and destructor of the class were declared to initialize all class variables to null. A map container was used to create a logic between the address of every node and its neighbors. A typeid library was used to keep track of the class attributes during runtime, and methods for the HELLO broadcast for both the sending and receiving node were declared, the same way for the PING control packet and the PONG packet. The base aqua-sim routing file functions as an enabler for neighbors to send acknowledgment after receiving the PONG packet while also being useful for determining the sender's relay node by using a smoothing factor from respective neighbors.

4. **aqua-sim-routing-carp.cc**: This file contains all the methods and variables declared in the CARP routing module header file, including the main file as well as the aqua-sim routing header files that are shared amongst other routing protocols of the simulator. The main protocol states in this file are the HELLO broadcast, PING multicast, PONG unicast, and DATA forwarding.

To broadcast the HELLO packets to neighbors, the sink makes use of SendHello at the initialization stage of the algorithm. The RecvHello module is used by neighbors to receive the broadcast, which subsequently leads to the updating of the hop counts information from the sink after which the SendHello is invoked for the subsequent broadcast of HELLO packets. A map container is used by the PING module to send PING packets. Sending of PING packets to all neighbors is made possible through the SendPing and RecvPing methods. Information received from the HELLO broadcast is utilized by the sender to multicast PING packets to all neighbors while the packet is received using the RecvPing whose only function is to call the SendPong module. The SendPong method is used by the neighbor to send a PONG packet with information on originating address, a destination address, hop count, buffer, and link quality estimate from the best neighbor towards the destination. The sender makes use of the RecvPong module to receive PONG packets from neighbors while invoking the SetNextHop module which redirects the address of the node with the highest link quality estimate. It is important to note that the PONG methods are used to select the next relay node based on the node with the maximum packet-to-success ratio based on correctly delivered packets at the time of transmission.

Data forwarding is made possible using the existing Recv method that is from the AquaSImRouting class. In a situation where a packet is received by a node, checks are made to ascertain if the packet is DATA, and destination address verification is undertaken. Data packets are sent to the application layer using the SendUp method. The boolean return type is used for terminating the process upon forwarding and moving packets to an upper layer to avoid an implementation loop. The aforementioned files were used for developing codes to successfully build CARP in Aqua-Sim Next Generation simulator. This is shown below:

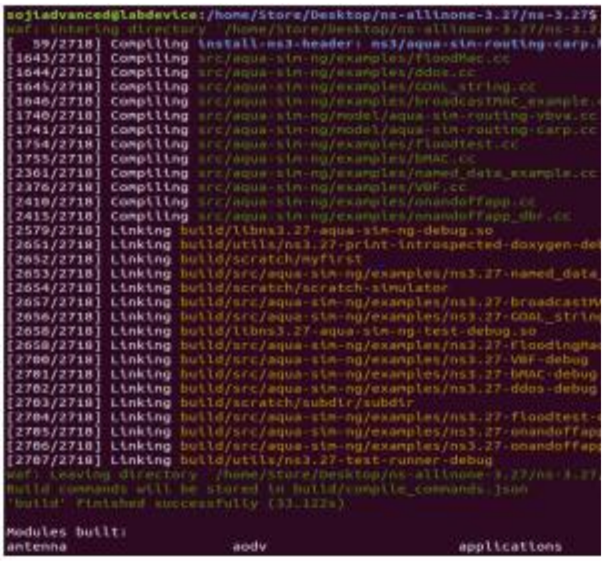


Figure four: Screenshot of the built CARP module in Aqua-Sim Next Generation Simulator

Figure five: Successfully developed module using Aqua-Sim Next generation in NS-3

Evaluation of the CARP protocol performance is made possible by using a network topology of distributed sensor nodes ranging from three to eight with a single sink so as to obtain the packet delivery ratio and throughput for a multi-source node setup and a single-source node setup as demonstrated in the topology below.

Single Source Node Typology

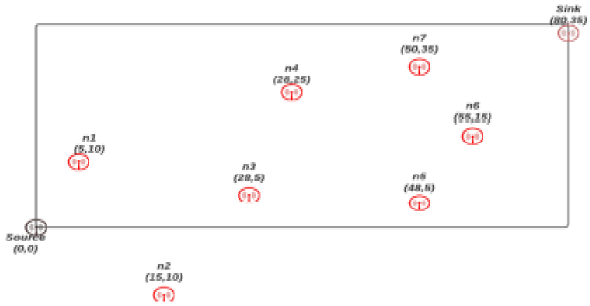


Figure six: Representation of the Single Source Node Typology

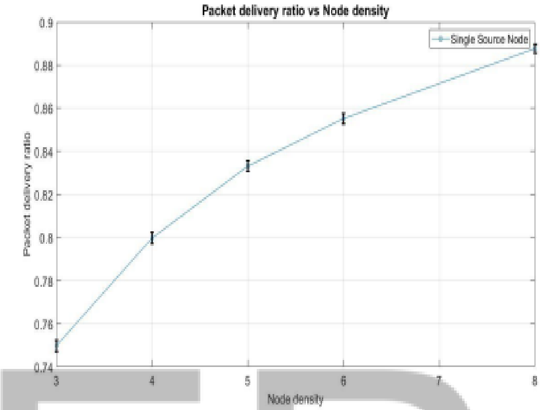


Figure seven: Packet delivery ratio indicating node density variations s using SFAMA-MAC protocol.

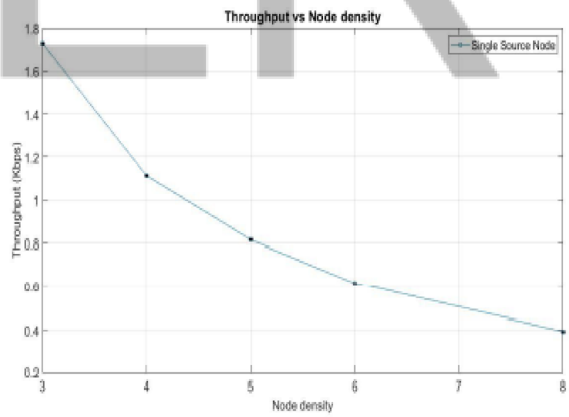


Figure eight: Packet delivery ratio indicating node density variations using ALOHA MAC protocol

Multiple Source Node Typology

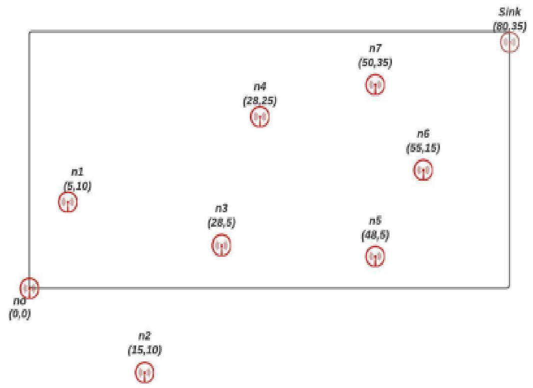


Figure nine: Representation of multiple source node

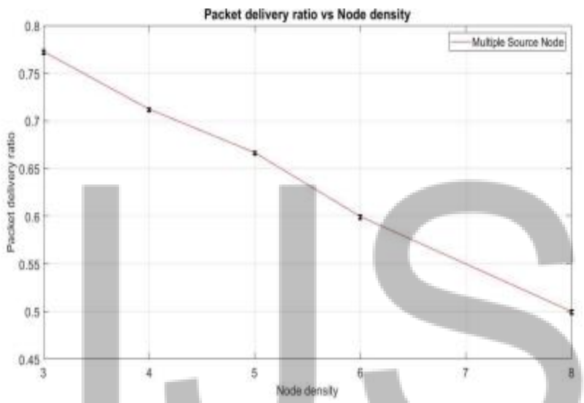


Figure ten: Packet delivery ratio indicating node density variations using SFAMA-MAC protocol

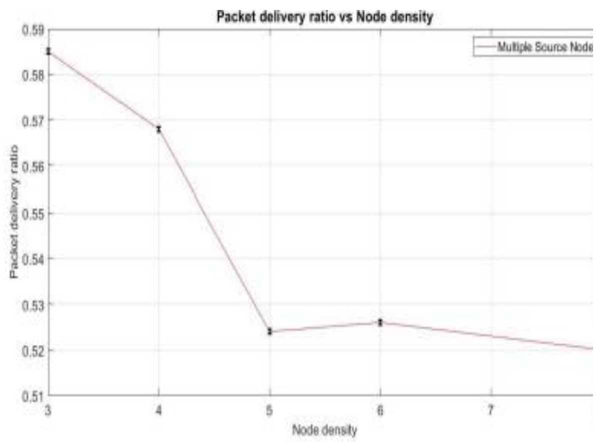


Figure eleven: Packet delivery density indicating node density variations using ALOHA MAC protocol

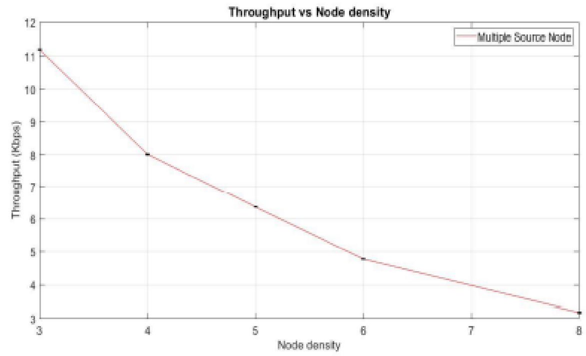


Figure twelve: Throughput indicating node density variations using the SFAMA MAC protocol

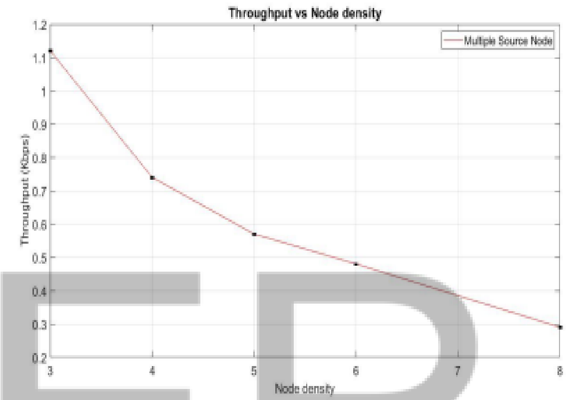


Figure thirteen: Throughput indicating node density variations using ALOHA MAC protocol

DISCUSSION OF SIMULATION RESULTS

In order to reduce the packet collisions generated during the simulations, the Slotted Floor Acquisition Multiple Access (SFAMA) protocols was adopted since it leverages the mechanism of handshake for channel reservation. In figure seven, the single node network typology using SFAMA MAC protocol node density was increased to bridge the path between the source and destination which increased the packet delivery ratio. However, the ALOHA MAC protocol indicated a downward trend in packet delivery ratio as a result of frequent packet colliding. This resulted from poor allocation of shared media, with several nodes simultaneously transmitting packets.

Also, the sink (destination) experienced delivery of more bytes using the SFAMA MAC protocol, and this had a significant impact on the throughput as shown in figure seven. In the ALOHA MAC protocol, however, there was a gradual reduction in the throughput, with fewer bytes received at the destination. The standard deviation of the values obtained after ten iterations while obtaining the packet delivery ratio for each node density value was very minimal. For multisource node network typology, packet collisions in the network were increased by rapid transmission emanating from the source nodes, which greatly affected the packet delivery ratio as shown in figure ten. With the adoption of the SFAMA MAC protocol, the vast collisions which would have led to an increment in the node density were cushioned. This was achieved with the use of the handshake mechanism amongst the nodes.

Suggestions for Future Research

Based on the work that has been carried out and the results achieved, a number of assumptions were made during the development of CARP in Aqua-Sim-NG which introduced some constraints in the computation of the best factor via the link quality estimation. Further studies could be conducted through the extension of the CARP module to develop a model that better captures the variation of the simple topology information and further computes the lq values of the sender's neighbors. These are elucidated below.

I. Gradual variation of the smoothing factor used during the link quality estimation to accurately predict the value that closely relates to the dynamic nature of the underwater environment
II. Performance evaluation of the CARP routing protocol benchmarked with existing routing protocols in Aqua-Sim NG. E.g VBF, DB

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