A multi-channel MAC protocol for AUV networks

Shiraz Shahabudeen, Mandar Chitre, Mehul Motani

***Abstract*— This paper presents results from a study on using multiple communication channels simultaneously for effective networking in a small AUV network. AUVs can be highly mobile, leading to time-varying inter-node distances and a dynamic network topology. We try to exploit this mobility by using multiple acoustic modems operating at different frequency bands and suited for different ranges. We utilize a MAC protocol based on MACA that uses RTS / CTS / DATA / ACK handshaking along with carrier sensing. Data packet trains are used to greatly enhance the performance of this protocol and results show that this feature makes it a very viable protocol for underwater networks in general. The protocol exchanges AUV position information and uses this information to allocate traffic to the different modems. The study is oriented towards the use of multiple AUVs in highly co-operative missions where effective peer to peer data exchange is vital. The term "channel" is used to represent very different capability modems, and is different from the standard context of multi-channel communications where a single transceiver has the option to choose between multiple channels, as in FDMA or CDMA. In our model, we have multiple and very different transceivers being used simultaneously. We name the protocol MACA-MCP since it utilizes Multiple Channels and Positioning information.**

***Index Terms*—adaptive clustering, multi-channel, medium access control, position information, underwater vehicle networks**

I. Introduction

COMMUNICATIONS in an underwater network comprising of Autonomous Underwater Vehicles (AUV), fixed sensor nodes and control vessels are commonly implemented using acoustic links. Typical acoustic modems used to establish these links operate at low data rates and ranges up to a few kilometers. At much shorter ranges of tens to hundreds of meters, higher performance communication links can be established using high frequency acoustics. If more than one of the nodes is at the surface, traditional radio links in air also become feasible. As AUVs move around during a collaborative mission, the inter-node separations may vary from few tens of meters to several kilometers. In this paper we explore the possibility of effectively using such multiple communication channels in an AUV network. The key objective is to maximize throughput and overall data rate per node using multiple channels.

A large body of literature is available on medium access control (MAC) in wireless networks. Random access protocols such as ALOHA, CSMA, MACA, FAMA and variants thereof have been extensively studied in underwater acoustic networks. Orthogonal protocols such as TDMA, FDMA and CDMA have also been explored [1]. In this paper we explore the use of multiple communication channels using random access protocols. The simplest random access protocol is ALOHA. It is well known that by adding carrier sense (CS), the performance of ALOHA can be improved. It was shown in [2] that MACA or FAMA based protocols (referred to as MAC2, a variant of the standard MACA protocol in that paper) using short RTS/CTS packets help improve performance further by eliminating the cost of large packet collisions. This type of algorithm has been the basis of many recent algorithms for underwater networks [3], [4], [5]. However as explained in [5], FAMA in its original form is quite unsuited to underwater networks and a FAMA based MAC for an AUV network was simulated there using a single channel.

The general idea of utilizing multiple communication channels or bands simultaneously in AUVs was discussed in [6]. However the MAC protocols for the different channels were not integrated in this paper. The modems were meant for different applications and no unification at the MAC level was described. Single transceiver, multi-channel adaptive clustered communications are quite popular in terrestrial networks [7]. Orthogonal "channels" using CDMA, FDMA or TDMA are employed to perform adaptive and self-optimized clustered communications.

The term "channel" is used here to represent very different capability modems, and thus this study is different from the common context of multi-channel communications, where a single transceiver has the option to choose between multiple channels as in FDMA or CDMA. The channels in our study refer to multiple modems or transceivers with varying data rates and range capability that can be used simultaneously. The words modem, transceiver and channel are used interchangeably in this paper.

In this paper we use a protocol similar to MACA and

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FAMA on multiple communication channels in an AUV network and study its performance. An efficient data packet train and position information exchange is used to enhance the protocol's performance. We measure end-to-end acknowledged data delivery to characterize true end-to-end throughput. Realistic modem characteristics in terms of Bit Error Rate (BER) and packet detection probabilities, as well as reasonable AUV motion models are used in the simulations. This gives us a good indicative measure of the system's performance. A Data Link Layer (DLL) architecture based on queuing is used to interface to multiple physical layers and provide a seamless standard interface to the network layer. We shall refer to the protocol described in this paper as MACA-MCP.

II. Multi-channel Modelling

A. BER performance modeling

Medium range acoustic underwater modems typically have an optimal performance range and performance reduces at both shorter and longer distances. For example, an OFDM modem developed at the ARL and tailored for shallow water applications, exhibits a U-shaped BER curve with an optimal range at about 800 meters where the BER is at its lowest [8]. At shorter ranges below 400 meters the performance reduces due to lengthening of the multi-path channel while at longer ranges above 1.2 km the performance reduces due to reducing signal-to-noise ratio (SNR). This will be referred to as the medium range modem or the MR-channel in this paper.

Short range acoustic modems that operate up to a few hundred meters range but at much higher data rates are also possible as part of an AUV communication system. Such modems typically operate at much higher frequencies and larger bandwidths compared to the medium range modems. Such a modem will be referred to as the short range modem or the SR-channel. The SR modem has also been assumed to demonstrate a similar behavior as the MR modem, i.e. its performance drops slightly at very short ranges.

Similarly we also use a long range (as compared to the MR modem range) modem, which operates up to about 2km and assumed to be on a lower frequency band orthogonal to MR and SR. A much lower data rate than the MR modem is chosen for this model. This will be referred to as LR channel.

We capture the behavior of three such modems by the BER curves in Fig. 1.

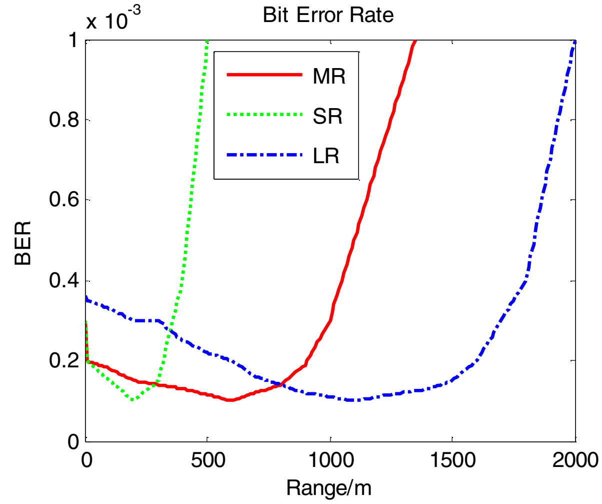

Fig. 1. Coded BER curves for all channels. The BER is modelled as having a rapid increase after their maximum range in this study. At lower ranges the BER increases slightly as compared to each channel's optimum range.

B. The packet train model and packet loss ratio

The data packet train model is shown in Fig. 2. Each packet train is preceded by a detection preamble used to detect the packet. D is the probability of detection of a packet. For simplicity we do not account for the time duration of the detection preamble in the simulations. Each packet has equal probability of success once the train preamble is detected.

Detection Preamble	Packet 1	Packet 2	…	Packet N

Fig. 2. Packet Train

In a packet train with N packets and a detection preamble, the Packet Loss Ratio denoted by R is as defined in (1), where B is the packet size in bits and E is the bit error rate.

$$R = 1 - D\left(1 - E\right)^{B} \quad (1)$$

The PLR-curve in Fig. 3 uses (1) and shows the variations in overall packet loss with range. The final values for packet loss shown here are consistent with the order of packet loss ratios that have experimentally observed by ARL in underwater modems at sea.

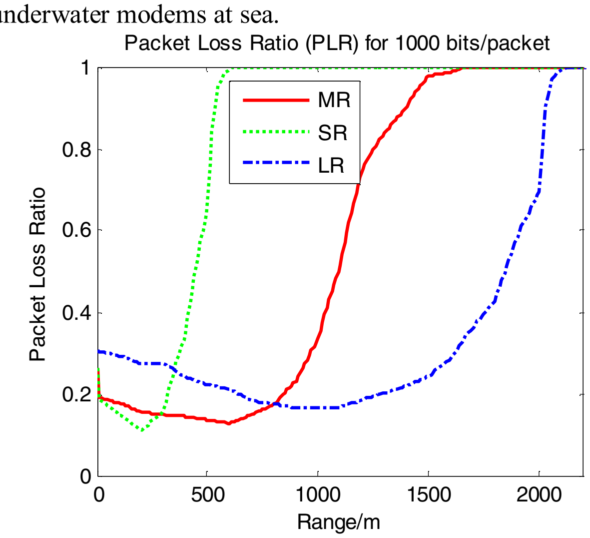

Fig. 3. PLR curves for all channels for 1000 bits per packet. At the optimum range, the packet loss is about 15%.

It should be noted that the definitions of SR and MR channels used here in terms of their BER and performance ranges are quite arbitrary. For applications with different overall mission area, multiple modems with different optimal regions can be chosen. The techniques and algorithms used here can then be applied.

III. Network Architecture and Algorithms

A. The physical layer

The half-duplex physical layer used is similar to that described in [2]. However, no queuing is done to packets coming from the DLL. Queuing at the physical layer makes it harder for the DLL to have good control over the protocol in terms of determining when to send a packet. The physical layer does not accept the DLL packet if transmission is in progress, but accepts and transmits if a reception is in progress, i.e. aborts the reception in favour of the transmission. However, it informs the DLL about ongoing receptions (carrier sense) and the DLL may use that information to avoid transmissions while a reception is in progress.

B. Network layer and data transmission model

The network layer used in this study is currently not involved in routing, but acts as a data generator at each node. When routing is added to the protocol stack, this layer will implement it and a separate application layer will be used. At each node, data is generated at a rate sufficient to fully load the DLL queuing system and send packets to randomly selected nodes. It is assumed that there is data to be sent to all other nodes at all times, i.e. the system is fully loaded. This assumption is consistent with delay tolerant applications such as file transfers between all nodes.

C. The overall architecture

A single network layer is connected to three physical layers via a unifying DLL as shown in Fig. 4.

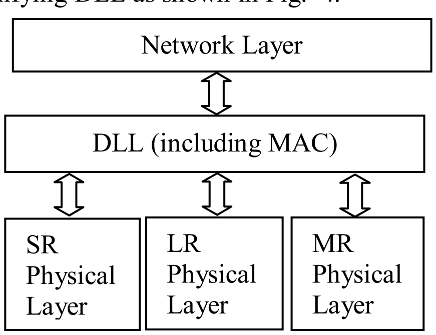

Fig. 4. Network Stack Architecture

D. The basic DLL algorithm

The basic algorithm used in MACA-MCP is adapted from MACA and FAMA. It uses RTS / CTS / DATA / ACK exchange with increasing back-off and virtual carrier sense similar to MACA as well as physical carrier sense as used in FAMA. However, it does not follow the restrictions on RTS and CTS time durations imposed by FAMA [9]. Here RTS and CTS packets are much shorter than the transmission latencies and round-trip delays. In underwater networks it's not practical to put the same requirements on RTS and CTS durations due to the high latencies in transmission [5]. Short RTS and CTS are also needed to minimize collision probability.

E. The packet train based enhancement

Here we look at an enhancement to the basic algorithm described above which is used in MACA-MCP. The use of data packet trains greatly improves the performance of the hand-shake protocol and examples of this idea can be found in [5] and [9]. The RTS contains information on how many data packets are intended for transmission as a single packet train. Once the transmitter receives the CTS, it sends the data packet train. At the receiver, an efficient ARQ method of sending an ACK only at the end of the train indicating all received packets is used and transmitter re-transmits lost data. Increasing back-off timers are used on failed RTS to reduce further collisions. This ACK concept used is different from both [5] and [9] where each data packet indicates whether there is subsequent data and an ACK follows every data packet.

We look at the packet train benefit more closely. As shown in [5], the classic hidden node collision problem of MACA is shown in Fig. 5. The packet train in this case is a single large DATA packet. In such an RTS collision the entire DATA packet is lost and for re-transmission, the complete RTS/CTS/DATA/ACK exchange has to be repeated needlessly wasting bandwidth.

However, when packet trains are used, the RTS collisions only affect some of the packets in the train and the ACK will indicate this. By using fairly large number of packets in the train, efficiency can greatly be improved as the results show in section V.

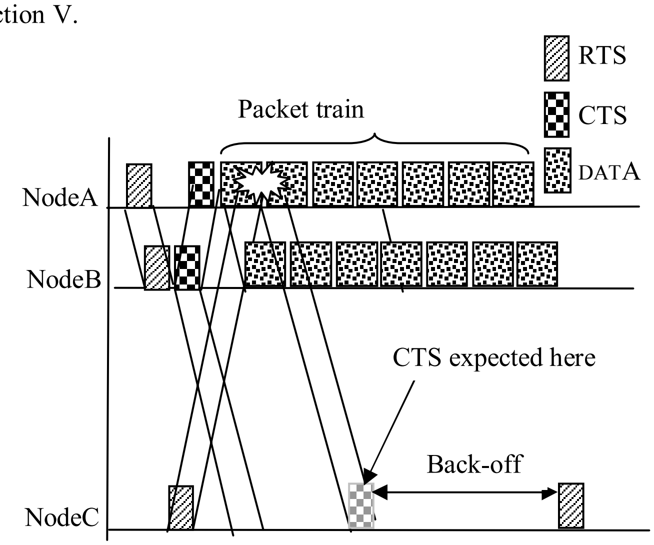

Fig. 5. MACA with DATA packet train improvement

F. DLL architecture and MACA-MCP

There is a queuing system at the DLL with separate queues for each recipient node. Incoming packets are stored in a queue for each destination node. After a packet is queued, RTS is initiated over available channels.

On top of the performance gains from the use of packet trains, we introduce position information exchange to synergize multiple physical layers. Each RTS and CTS contains the position information of the transmitter as well as the latest available position information for its neighbors. In this study, the number of neighbor positions send was set to two. All nodes listen to all packets irrespective of destination and extract the position information contained in all the RTS and CTS packets. Each node maintains a table of position information on all its peers including the time of last update. This position information is gathered and shared by the multiple channels.

When a channel is free based on physical and virtual carrier sense, a modem chooses a node to send data to, based on whether the recipient is within its ideal range. It also uses position information to identify nodes that are certainly out of range and not choose them. If information is outdated for all nodes, then the node is chosen in a round robin fashion to ensure fairness.

IV. SIMULATION SETUP

A discrete event simulation tool based on Omnet++ [10] has been developed and used for this study. All packet lengths are in given in bits. The data rates used are 2400 bps for MR modems, 7200 bps for SR modem and 720 bps for LR modem. Each simulation run is for 4000 seconds and ten runs are averaged for the results in section V.

A. Modelling of AUV node motion

We used a simplified scenario for the study – a group of eight AUVs on a collaborative mission in a 2 km × 2 km search area and moving about independently using a variant of the random direction mobility model with reflecting boundaries [11] as shown in Fig. 6. The nodes move in a straight line at a constant velocity between updates. Updates are done at regular time steps (1 second) and during each update, each node has a small probability of random direction change limited to + or – 45 degrees. Motion is also bounded with in the square mission area of 2km x 2 km. At the boundaries, nodes alter course as if it were reflected off. The inter-node distances can vary with time from a few meters to more than a kilometer. A speed of 2 m/s has been used.

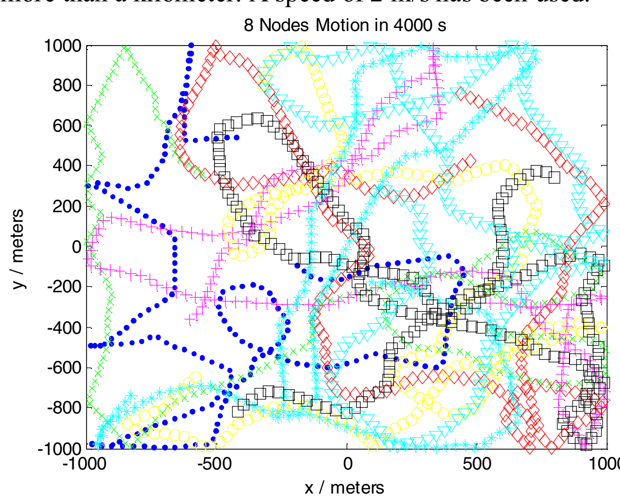

Fig. 6. AUV nodes motion during one realization of the simulation

We have tested each modem at their optimum range regimes and with no motion. This was to confirm correct behavior and performance of each modem independently when node separations are on average, within their range limits. In their range regime, the modems do work properly using the same protocol. As expected, simulations did show that motion degrades the performance of a single modem when used independently. The degree of degradation depends on the exact motion ranges used and the motion model and is not quantified here. This can be attributed to the fact that in the middle of a RTS/CTS/DATA/ACK exchange, the nodes could go out range and this becomes an additional error contributing factor.

B. Some factors affecting performance

The factors that impact performance mainly are AUV motion, BER, packet detection probability and collisions. In this study we have a fixed motion range and characteristics, a fixed BER behavior and a fixed packet detection probability. Collisions are related to timeouts and retry timers used in the protocol. RTS and CTS packet lengths are quite critical to each channel's performance in MACA-MCP protocol. These control collision performance to a great extent. Reducing these control packet sizes, along with better tuning of back-off timers etc are needed to minimize collisions. We have chosen heuristic values for these parameters based on our simulations, but they were not fully optimized rigorously. Another factor is the data packet size. An optimum packet size needs to be chosen for the best performance. The number of packets in a train is another very important factor. The following studies show the effects of train size. Packet size is fixed at 1000 bits.

V. SIMULATION RESULTS

We present results from numerical simulation of MACA-MCP protocol in a small AUV network.

A. MACA-MCP effective data rate performance

Fig. 7 shows the effective data rate per node for the system in different scenarios. Data rate per node is computed by the traffic generating Network Layer as in (2). Average Acknowledged means those data bits for which the RTS/CTS/DATA/ACK was completed.

$$\text{Data rate per node} = \frac{\text{Average Acknowledged data bits}}{\text{Simulation time}} \qquad (2)$$

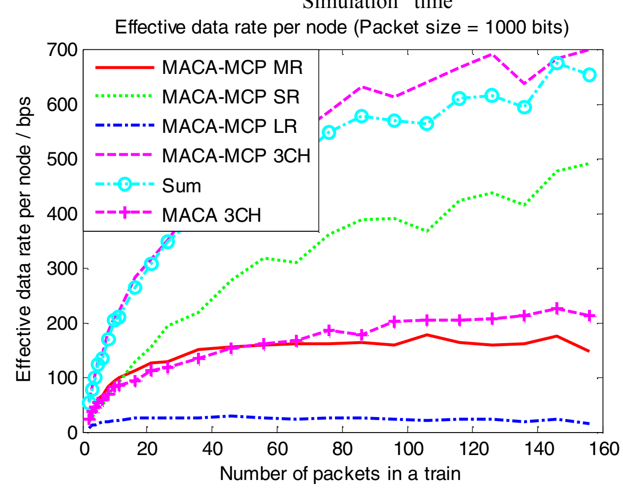

Fig. 7. Effective data rates for the different protocols as a function of packet train size.

Three scenarios use MACA-MCP protocol on a single channel (labeled MACA-MCP MR, MACA-MCP SR, MACA-MCP LR) and one uses all three channels simultaneously (labeled MACA-MCP 3CH). The "Sum" is the arithmetic sum of the three channels using MACA-MCP individually. "MACA 3CH" shows the data rate when all channels are simultaneously used using MACA protocol with the packet train enhancement, but no position information is utilized.

By comparing the MACA 3CH and MACA-MCP 3CH we see that the MACA-MCP is able to increase overall data rate per node by about 300%. This is the key result. Using position information effectively to divide the traffic across the multiple channels helps bring about this significant improvement.

Another interesting result is that the SR modem data rate is much higher than that of the MR or LR modem. Of course, due to the fact that the SR modem has three times the data rate of the MR modem, one expects higher data rate when the modems are operated separately in their own ideal ranges. Here, despite the fact that the test range for the AUVs are four times longer than the maximum range of the SR modem, on average it is about to communicate effectively to immediate neighbors within its range and achieve a high effective bit rate per node. Thus in a similar scenario if one needed to design a single modem system, an SR modem could be the choice. However, it should be noted that this performance characteristic is a function of the test range, the number of nodes used and the nature of clustering behavior in a given scenario as discussed in section C below.

By comparing "MACA-MCP 3CH" with "Sum" we see that when all three channels are used simultaneously, overall throughput is better than the sum of the individual throughputs ("Sum") of three channels using MACA-MCP individually. The gain is of the order of 10% in the scenario used here. This synergy comes about through the position information gathering and sharing mechanism across the modems. Each channel's performance improves by getting cross-channel position information.

The effect of packet train concept has also been shown in the above results. Larger number of packets in a train can improve performance up to a certain limit. However, we do not attempt to quantify the optimal packet numbers in a train in this paper.

B. MACA-MCP throughput performance

Here we look at the throughput performance of MACA-MCP protocol using one modem only, all three channels simultaneously and the MACA protocol without position information using three channels. This is shown in Fig. 8. Throughput calculation is as in (3) where "Data rate per node" is as defined in (2). "Total bit rate used" refers to the bit rate of a single modem in the case of protocol using single modem and the combined bit rate of all modems used for multi-channel protocol. This is the throughput for the network as a whole.

$$\text{Throughput} = \frac{\text{Data rate per node}}{\text{Total bit rate used}} \times \text{Number of nodes} \qquad (3)$$

We see that MACA-MCP has up to about 60% throughput when used with a single channel in MR and SR channels. In the LR channel only mode, the maximum throughput seems to be about 30% only for the simulation scenario we have used here, in terms of number of nodes and operating range. Data in the single modem mode can only be sent to some peers that are with in range, but as the AUVs move around, a node should be able to reach almost any other node over a period of time. This will affect the average transmission latencies. We have not studied average latencies in this paper.

In the complete 3 channel mode, the MACA-MCP protocol can achieve above 50% efficiency for optimal packet train size. Destinations should usually be available on at least the LR modem and thus there is greater connectivity in the 3 channel mode at any given time. MACA without position info over 3 channels has at best about 17% throughput only.

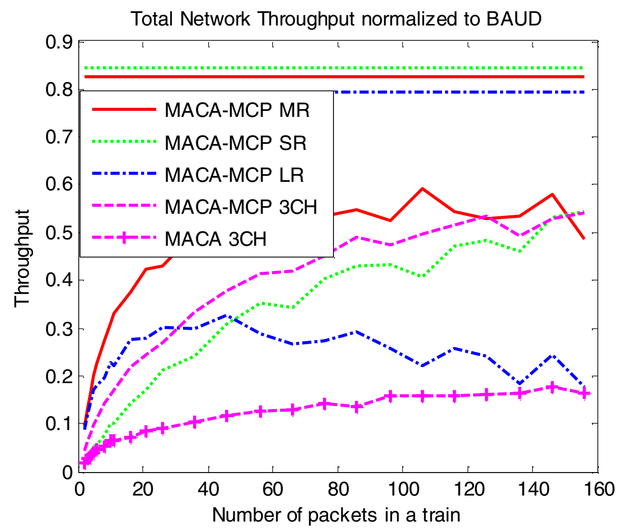

Fig. 8. Network throughput normalized to individual BAUD

The flat lines on top show averaged theoretical throughput for each modem considering only packet detection probability and BER, in their ideal range. In other words, in a point-to-point one-way transmission, in each of the modem's ideal range regime, this is the throughput performance one expects. There are no losses due to collisions and nodes going out of range. There are no losses due to protocol overheads like handshaking, retry timers etc.

Another perspective is obtained on the same result when we normalize to this theoretical averaged point to point data rate shown as flat lines in Fig. 8. This normalization excludes the effects of BER and packet detection probability and helps look at the pure network effects on the throughput. These effects now include motion, collisions and protocol overheads like handshaking and timeout losses. We see that the loss due to the network effects is about 30% and the MACA-MCP protocol is quite efficient.

C. Adaptive clustering behavior

The MACA-MCP protocol effectively achieves a node clustering behavior as shown in Fig. 9. Dashed lines show possible MR channel connections, solid lines show possible MR connections and dash-dot line shows possible LR connections. As each node preferentially chooses to transmit to nodes on the appropriate channel depending on inter-node distances, in steady state with sufficient position information at each node, such a highly clustered scenario should arise in the network.

The key difference as compared to [7] is that parallel and simultaneous communication is possible using multiple modems as opposed to using a single channel at any node at a given time. The scheme can also be viewed as having a rudimentary level of inherent automatic power control at each node since the multiple modems have different ranges and modems are chosen based on receiver range.

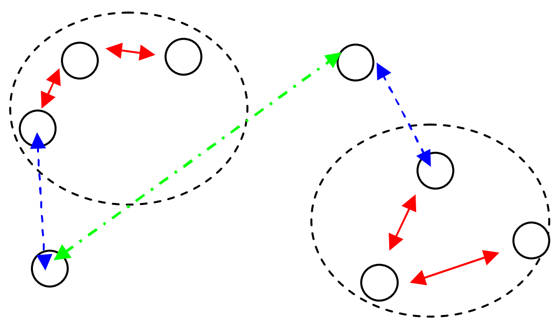

Fig. 9. Node clustering behavior

VI. Conclusion

We have presented a preliminary study on using multiple modems optimized for different ranges simultaneously in an AUV network. We have developed a unified DLL algorithm that allows synergistically using multiple physical layers. A variation of the MACA protocol called MACA-MCP has been developed with performance enhancements through packet trains and position information exchange. This achieves a self-organizing clustered network behavior that leads to good efficiency and data rates per node in the underwater AUV network as shown through simulations.

High speed SR modems should definitely be considered in AUVs to augment the MR or LR modem as they can improve the overall throughput using the MACA-MCP protocol.

The basic concept is also scalable in the sense that the definitions of operating range used here for SR, MR and LR modems etc are arbitrary and the system designer can design point-point modems to cater to different range regimes and suit the multi-channel concepts here to very different overall mission ranges.

The network layer will need to use novel and efficient routing techniques to exploit this DLL algorithm to achieve full connectivity. This will be looked into as part of future work on AUV networks at ARL.

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