MULTI-MODE ADAPTIVE MAC PROTOCOL SUITE AND STANDARDIZATION PROPOSAL FOR HETEROGENEOUS UNDERWATER ACOUSTIC NETWORKS

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Abstract: *This paper investigates a multi-mode MAC protocol suite for use in a heterogeneous underwater network. Modems from different manufacturers may employ different physical layers and MAC protocols. If multiple modems operating in the same or overlapping frequency bands are deployed in the same geographic area, they cannot function correctly due to interference. We propose a mechanism to achieve co-existence and communication among such heterogeneous assets. Co-existence is defined as the state where modems of the same type can communicate with each other while minimizing interference with other types. The Communications state is when all modems in one area can communicate with each other. Alien signals are defined as non-decipherable communication signals for any one modem type. The Co-existence mode requires all modems to implement an alien signal detection feature. In this mode, a CSMA based scheme will be used to communicate among modems of the same type, if alien signals are detected, and to allow non-interfering co-existence among different modem types. In order to achieve Communications mode, modems will be required to implement a standardized Physical Layer (along with their proprietary Physical Layer or as the only system and on top of the alien signal detector). Such suitable Physical Layer standards are currently being addressed under the JANUS initiative at NURC. For this mode, we propose using a MACA based protocol suite for the MAC layer. It has a distributed MACA-based mode and a centrally controlled polled mode that nodes dynamically adapt to, depending on deployment and node configurations. Features include autonomous selection of distributed or controlled MAC modes, inter-cell interference mitigation strategies, and provisions for both reliable and unreliable modes. This paper presents some simulation results and mathematical analysis for the two MAC protocol modes.*

Keywords: *Underwater, acoustic networks, adhoc, MAC protocols, standards, MACA*

1. INTRODUCTION

Underwater modems currently utilize diverse physical layer standards and MAC protocols in overlapping frequency bands and do not co-exist or communicate with each other over standardized protocols. Physical Layer protocol standardization attempts are in progress, such as the JANUS initiative at NURC [1]. In this paper, we propose a potential candidate for a standardized MAC protocol suite. We use the term JANUS to refer to protocol standardization aimed at both Physical and MAC layers for underwater networks.

For MAC protocol standardization to take place, underlying physical layer and frequency band allocation standards have to be in place. An initiative that is currently looking at this issue is JANUS. In this paper we assume that such standards are in place and take the next step of addressing the MAC Layer. We assume that the packet structure defined by the Physical Layer standard has a type field that determines the structure of the packet that follows, as well as a checksum field. The MAC protocol could use control packets or data packets and will indicate this using the type field. Based on real implementation trials using ARL's OFDM modems, we recommend that 3 or more bytes should be available in the control packet definition in the Physical Layer standard (excluding type field and checksum) in order to be able to convey sufficient information. Current JANUS proposal for example has 6 bytes (excluding type and checksum fields) in the control packet and hence is sufficient.

We aim for two levels of compliance for the standard, the first is to achieve co-existence and the second level is to achieve communications among heterogeneous assets (sections 2.1 - 2.4). We also look at how nodes can dynamically adapt their physical layer and MAC protocols based on node capability and environment sensing (section 2.5). Performance analysis is presented in section 3. We also look at some key aspects such as FEC, power control etc (section 4) and how to integrate proposals for broadcast beacons such as the JANUS Beacon into a MAC framework (section 4.3). The proposal attempts to provide flexibility for modem manufacturers to choose the level of compliance they are willing to adopt in phases, and to be able to use, innovate and improve their indigenous technologies while conforming to accepted standards.

2. JANUS MAC PROTOCOL SUITE PROPOSAL

2.1. Level-1 MAC – Co-existence, CSMA based

In the co-existence mode, we propose that all modems adopt the same detection preamble scheme for a given frequency band. If that is not possible, modems can implement an alien signal detection feature, i.e., to be able to detect a signal in its frequency band that is not of its Physical Layer type. This could be based on energy detection, for example. There could also be wakeup tones that are also present as part of the preamble structure, such as those being proposed in the JANUS initiative. Energy detection can also be used alongside the detection preamble to monitor the signal following the preamble, to determine end of the packet, for example.

With such a minimal compliance at the Physical Layer, we propose that a suitable variation of the Carrier Sense Multiple Access (CSMA) based MAC scheme be used to communicate among modems of the same type. The carrier sense comes from the ability to detect alien packets as stated above. In this scheme, nodes use a random back-off before transmitting a packet. The details of the back-off procedure are the same as in section 2.3 for RTS packet in MACA-D. In fact this scheme can be viewed as similar to the Basic Access Scheme in 802.11 [2]. CSMA MAC protocols have lower performance compared to many other options, but at this level of minimal Physical Layer compliance, it offers perhaps one of the best solutions to avoid interference between different modem types.

2.2. Level-2 MAC –Communications, MACA based

In order to achieve communications mode, modems will be required to implement a standardized Physical Layer (along with their proprietary Physical Layer or as the only system and on top of the alien signal detector or detection preamble). Such suitable Physical Layer standards are currently being addressed under the JANUS initiative at NURC.

For this mode we propose using a MACA based protocol suite for the MAC layer. It has a distributed MACA-based mode (MACA-D) and a centrally controlled polled mode (MACA-C) that nodes dynamically adapt to, depending on deployment and node configurations as explained later on in section 2.5. In the centralized scheme, we define a cell to consist of a MAC Controller (MC) and the nodes within its control. Many of the centrally controlled MAC protocols use a polling scheme, where the MC polls the client nodes [3]. Some of the distributed protocols are ALOHA, CSMA, MACA [4], FAMA [5] etc. Among distributed protocols, some protocols such as MACA and FAMA involve handshaking using control packets before data transmission. Centrally controlled modes typically perform better than distributed modes by eliminating contention. However, in a generic network environment with heterogeneous nodes, a centrally controlled protocol alone might not usable and distributed modes may be needed. Prior work addressing such large scale ad hoc dynamic underwater networks includes the Seaweb project [6]. The terrestrial IEEE 802.11 family of protocols also use such combined topology suites in the form of Point Coordination Function (PCF) and Distributed Coordination Function (DCF). Level 2 MAC protocol suite is the key focus in this paper and the next two sections discuss this in greater detail.

2.3. Distributed Mode (MACA-D) of Level-2 MAC

Here we look at an enhanced version of MACA that shall form the basis of the distributed mode in the Level-2 MAC protocol suite. This protocol uses RTS-CTS-DATA_TRAIN-ACK sequence similar to those used in other MACA based schemes (note that some protocols use selective ARQ instead of ACK). We shall use DATA to indicate DATA_TRAIN for brevity.

In the RTS contention phase, a node starts off with a uniformly selected back-off time in the range of 0 to W. When the back off timer expires, an RTS is transmitted. Once the RTS is sent off, the CTS timer t_A starts. If the timer expires before reception of the CTS, the RTS back-off procedure starts again. Once the CTS is received, the DATA train is sent off followed by a wait for ACK. If an ACK is not received within the timeout period, the RTS cycle repeats. Reception of RTS/CTS packets and a possible DATA frame while waiting to send RTS triggers Virtual Carrier Sense (VCS), i.e. nodes refrain from transmissions for an appropriate time depending on the control packet received (i.e. waits until a potential CTS can be sent if an RTS is received, or waits long enough for a DATA batch to be sent if a CTS is received). Successful DATA transmission for any one node restarts RTS contention cycle for all.

To handle some nodes missing the winning CTS and interfering with the DATA phase, all nodes monitor for DATA packets. DATA packets have information on packets remaining in the batch. This helps nodes that missed the RTS/CTS to regain VCS with a probability close to 1 after a few DATA packets are sent. Every node overhearing any packet continuously updates its own NAV (Network Allocation Vector) just as in 802.11 [2]. Another option is not to fully rely on decoding DATA packets for DATA based VCS. We can assume that the preamble detection for DATA is the same as the control packets and these packets can thus be detected (though information is not decodable) prompting a back-off or wait. Since the delay between DATA packets in a train is small and fixed, receiving nodes will continuously keep receiving these packets and they wait till the train finishes. The protocol has an additional Early ACK enhancement – a node sends an ACK instead of CTS, if the RTS is repeated for the duplicate packet train. This happens when the previous ACK is lost.

For 802.11 DCF mode, it can be shown that the optimum back-off window is dependent only on the number of neighbours and is directly proportional to it [2]. The authors have verified using independent analysis and confirmed the same finding for MACA-D, but the analysis is omitted here for brevity. Thus the back-off window size is set according to number of neighbours as known by the node over a period of time. For power control, the RTS contains the transmit power used and the CTS suggests power level based on the received SNR.

2.4. Centralized Mode (MACA-C) of Level-2 MAC

In this mode of the protocol suite, an MC controller controls the collision domain or "cell". An RTR (Request-to-receive) initiates all communication sequences for the uplink (towards MC or between nodes in the same cell). All nodes monitor for MC control packets to detect presence of a controlling MC and then switch to the controlled MAC mode. Channels not mentioned in RTR can be assumed to be uncontrolled by the MC and nodes may make use of them as they wish (e.g. using MACA-D). Configuration determines which nodes may operate as a MC (e.g. radio buoys).

For uplink, MACA-C operates in few modes as follows:

RTR-DATA-ACK: The intended node responds with DATA in control channel modulation if it's meant for the MC and uses power control information inferred from RTR's received power, assuming bi-directional validity of power information. MC then closes with ACK. Multiple ACKs may be used to increase receive probability. ACK may include earliest next RTR timing and helps reduce uncertainty.

RTR-RTS-CTS-DATA-ACK: If the destination is another node (not the MC), or if a node wishes to use another FEC scheme, a node sends out RTS once RTR is received. That is followed by CTS-DATA-ACK just as in MACA-D. This mode is quite similar to the protocol discussed in [3]. CTS indicate FEC and power control information as described earlier.

For downlink, MC starts with RTS and uses RTS-CTS-DATA-ACK sequence just as in MACA-D. RTS-CTS-PILOT_DATA-ACK scheme may be used as in MACA-D for downlink channel measurements.

2.5. Dynamic MAC

We propose that a modem assess its neighborhood and switch to an appropriate MAC scheme from the above choices. When modems don't sense dissimilar modems, they could use any physical layer and MAC schemes. This allows the usage of proprietary technologies and protocols in isolated environments. For modems that have only Level-1 compliance, if they detect alien signals (hear a standardized preamble followed by indecipherable packet or based on energy detection) they should automatically switch to Level-1 MAC (co-existence MAC) that uses random back-off.

Level-2 compliance is possible in two ways – modems implement only the standardized Physical layer or they implement the standardized Physical layer alongside any proprietary scheme and have mechanisms to switch between them. For nodes using the compliant Physical Layer and MAC protocol, there is no change in behavior required. For nodes using compliant Physical Layer and non-compliant MAC protocol when in isolation, if they hear packets belonging to the standardized MAC protocol (as identified by the type field), they need to switch to the standardized Level-2 MAC protocol for compliance. Nodes with multiple Physical Layers (one of which is compliant), operating in non-standard Physical Layer in isolation, need to switch to compliant mode upon detecting alien signals. In level-2 MAC, there are two modes MACA-C and MACA-D. The nodes determine the presence of an MC through RTR messages. If they do hear RTR, they use MACA-C. If they do not hear RTR messages, they use MACA-D.

3. PERFORMANCE ANALYSIS OF LEVEL-2 MAC

3.1. MACA-D

Simulation results are shown in *Fig. 1* (basic MACA scheme and one with DATA_VCS and Early ACK enhancements) and depict how the performance improves with packet train length (no FEC or power control is used in simulations).

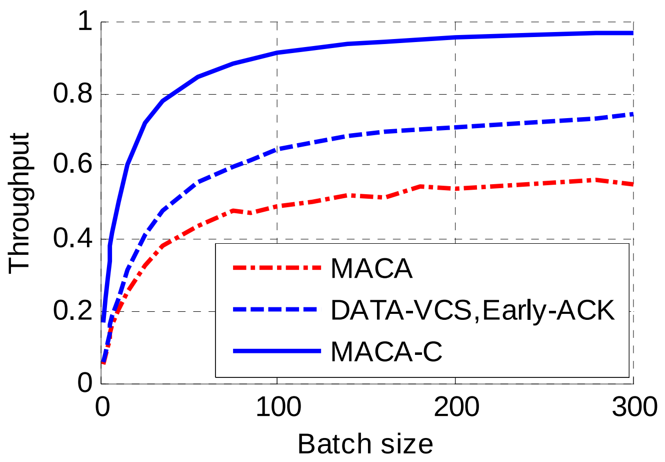

Fig. 1: Performance of MACA-D and MACA-C
(Packet duration L= 0.5 s, detection and decoding probability P= 0.81, one-way latency D= 0.5 s, number of nodes n= 4)

With appropriate batch size selection, the throughput can be over 60% for reliable delivery as seen in *Fig. 1*. Mathematical analysis also confirms these findings but is not included in this paper for brevity. Throughput behaviour is independent of neighbour nodes as shown for 802.11 DCF [2]. Together with the need for dynamic FEC and power control, such a handshaking scheme is very suited to underwater networks.

3.2. MACA-C

Let p be the combined probability of detection and decoding for a control packet, D is average one way propagation delay, L is packet time duration, B is batch size (number of packets in a train). Let the average time period till a successful RTR reception (due to detection and decoding losses) be W_{RTR}. RTR may be lost and the MC will resend RTR (potentially to other recipient nodes). This can be viewed as a geometric distribution with expected number of retries $1/p$. Considering $1/p$ - 1 failures, where time spent includes RTR duration, round trip delay and time for first DATA packet, the successful reception of RTR is given by,

$$W_{RTR} = \left(\frac{1}{p} - 1\right)(L + 2D + L) + L + 2D \quad (1)$$

The total time for batch transmission s including time for packet train BL and time for n ACKs is,

$$s = W_{RTR} + BL + D + nL \quad (2)$$

The average throughput T is as follows and is also plotted in *Fig. 1*. As expected, MACA-C performs better due to lack of contention and associated collisions.

$$T = \frac{BL}{s} \quad (3)$$

4. OTHER ASPECTS OF THE PROTOCOL SUITE

4.1. Dynamic FEC and power control

The packet format is as shown in *Fig. 2* and has two parts – a detection preamble and an information part. A series of such packets constitute a packet train. The information signal could be control packets using a predetermined modulation and Forward Error Correction (FEC) scheme or user DATA in variable modulation and FEC schemes. Adapting the FEC scheme for the DATA train is critical in ensuring optimum data rates. The decoding of control packet RTS could help estimate the BER and the CTS can specify the FEC scheme to use. If such a mechanism to derive BER estimates from control packets is not possible, probe pilot packets (with a known data pattern) may be sent in order to receive feedback from receiver on channel characteristics, for e.g. RTS-CTS-PILOT_DATA-ACK scheme. The receiver of PILOT_DATA indicates channel performance measures in the ACK.

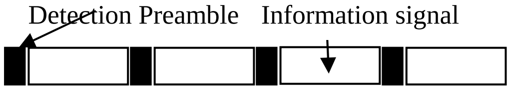

Fig. 2: Packet Train

Power control may be needed to adapt the range required for routing and node connectivity. For such purposes of dynamic FEC and power control, handshaking based MAC protocols such as MACA are well suited [6].

4.2. Inter-Cell or Inter-MC Interference

When there are multiple cells and controlling MCs in a neighbourhood using MACA-C, adjacent cell interference could take place. In scenario 1, as depicted in *Fig. 3,* the MCs are not able to hear each other or neighbouring cell nodes' transmissions. We assume here that all nodes only have single hop range to reach MC using power control.

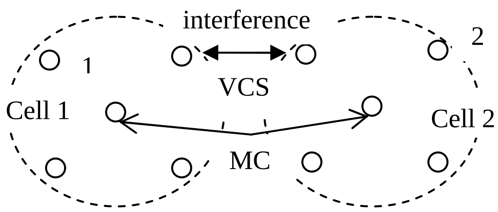

Fig. 3: Neighbouring cells Scenario 1

So it will continue to use MACA-C. But as we can see, nodes from adjacent cells interfere with each other's transmission. They observe VCS as mentioned in section 2.3 and will not reply to MC's RTR. MC will proceed to do communications between nodes such as 1 and 2 away from such interference. Thus parallel communications takes place in neighbouring cells correctly using MACA-C in the face of inter-cell interference that does not involve the MCs.

If MCs discover that their cells are near enough to cause interference, option A is to give up RTR based control and let nodes revert to MACA-D. Option B for MCs is to continue use MACA-C with a back-off for RTR, just as in RTS back-off in MACA-D. The neighbour MCs can hear either the RTRs or the reply RTS, INFO or DATA packets. MCs obey VCS rules for allowing neighbours to complete one communication sequence (till ACK). In option B, the RTR contention will only be between MCs of neighbouring cells unlike in RTS contention involving all nodes in option A. It's possible that since the optimum contention window is directly proportional to participating neighbours [2], the MC based RTR contention needs a shorter contention window and the effective contention period could be lower. Since under normal circumstances, MACA-C gives better performance than MACA-D and RTR back-off based method could solve the problem of neighbouring cell interference, we propose that MCs do not relinquish their roles in favour of MACA-D upon discovery of inter-cell interference, and instead use RTR back-off (option B). This idea needs to be further validated by simulations as part of future research.

4.3. Unreliable Messaging, Broadcasts and JANUS Beacon

In the Level-1 MAC, the random back-off method applies to all packets equally, including unreliable messages and broadcasts. In Level-2 MAC-D and downlink MACA-C, if unreliable short messaging (no ACKs) is required, the same contention logic as RTS can be used to send single short DATA packets using control packet FEC. In other words, DATA is sent in the place of RTS. In MACA-C uplink, RTR-DATA format can be used for unreliable short messaging (no ACKs). Broadcasts are done via these unreliable modes.

Unreliable broadcast mode can be used for beacons such as those proposed in JANUS. JANUS beacon and similar concepts attempts to allow nodes to broadcast useful information about itself to neighbouring nodes. Such broadcast packets need to come under the control of a MAC protocol to avoid interference in a given acoustic frequency band. It’s easy to accomplish such a beacon in the proposal as mentioned above using the general purpose broadcasts.

5. CONCLUSION

We have presented a comprehensive MAC protocol suite to address a diverse and heterogeneous underwater network with multiple levels of compliance which also allows for proprietary schemes to be used in isolation. The MAC protocol in the communications mode has both distributed and centralized operating modes. Some indicative performance results were also shown. The authors have begun sea-trials using the MACA-D component of the protocol suite. Preliminary results are quite promising and are expected to be published in the near future. Nodes self regulate the operation modes and topology according to self capability and capabilities of neighbouring nodes. The key vision is a self-organizing network, with nodes able to dynamically adapt to any scenario through environment discovery. We note that many of the details of the protocol are still open. Here we only attempt to provide a good direction and once there is acceptance for the fundamental ideas, then the next step of detailed standardization needs to take place.

6. ACKNOWLEDGEMENTS

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