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Design and Performance Evaluation of Underwater Data Dissemination Strategies using Interference Avoidance and Network Coding

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***Abstract*—The long propagation delays of the underwater acoustic channel make traditional Medium Access schemes impractical and inefficient under water. This paper introduces and studies Interference Avoidance and Network Coding for Medium Access protocol design aiming to cope with the underwater channel constraints and achieve efficient data transmission under water. Network Coding can exploit the broadcast channel to send different information to several receivers simultaneously. With Interference Avoidance the long propagation delay can be used to communicate in full-duplex mode. Alone and combined these concepts could increase channel utilisation as well as improve energy efficiency of the network nodes. The main goal is to investigate the potential benefits of new strategies for data dissemination over a string topology scenario. Comprehensive simulations prove the feasibility of Interference Avoidance and Network Coding improving the system efficiency when compared with CSMA/CA.**

I. Introduction

Communications in the marine environment employ acoustic waves, since radio and optical waves experience high dampening under water [1]. The underwater acoustic link differs significantly from traditional radio communications. Long latency, large propagation losses and limited bandwidth are the main channel characteristics. Most commonly used Medium Access Control (MAC) schemes from terrestrial radio communications are prone to severe limitations in terms of efficiency and scalability when deployed under water [2].

Strong efforts in research have fuelled the development of new MAC protocols for underwater communications. Many rely on intelligent collision avoidance with improved handshaking contention design. Despite the system efficiency gains, the approach of advanced contention-based protocols is still insufficient due to the long propagation delays. Interference Avoidance and Network Coding are emerging strategies that can be used in novel MAC schemes to exploit the unique features of the underwater acoustic channel and increase the efficiency of data transmission.

This paper focuses on the design and performance evaluation of an improved Medium Access scheme incorporating Interference Avoidance (IA) and Network Coding (NC) based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). The reference scenario is the string topology network, see Fig. 1. The main contributions are the following:

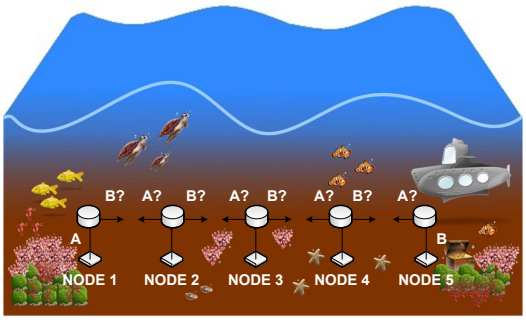


Fig. 1. The reference scenario: an underwater string topology network.

- Design and possible implementation of IA and NC as an extension to CSMA/CA.
- Simulation results of IA and NC on throughput and energy efficiency compared with pure CSMA/CA.

The remainder of the paper is organised as follows. Section II provides an overview of the related work. In Section III IA and NC are described and some practical hints are given to implement these new techniques. Section IV presents the performance analysis of the proposed MAC techniques with respect to CSMA/CA. Conclusions are drawn in Section V.

II. Related Work

Several works are available in the literature targeting improved MAC protocols for underwater networks.

In [3] Slotted FAMA is proposed, which is a contention method based on Floor Acquisition Multiple Accesses (FAMA) [4]. Despite achieving collision avoidance, S-FAMA presents drawbacks in terms of throughput performance due to the lengthened time slots. To improve throughput performance, [5] presents another handshaking protocol named Multiple Access Collision Avoidance (MACA) [6] with packet trains for Multiple Neighbours (MACA-MN). Likewise, [7] introduces and studies the MACA for Underwater (MACA-U) protocol which is an adaptation of terrestrial MACA for multi-hop underwater networks. Reference [8] employs the

maximum propagation delay to avoid collisions and MAC level pipelining to increase efficiency. Reference [9] applies shorter delay to avoid collision when the communicating nodes are close to each other thus overcoming the throughput degradation caused by the maximum propagation delay. Some of these MAC protocols rely on advanced collision avoidance schemes to improve system efficiency, while others include ACK and retransmission mechanisms. However, the protocols which employ improved handshaking approach lead to larger propagation delays which limit the throughput and the end-to-end latency. Consequently, additional strategies should be considered to significantly improve the system efficiency.

Novel MACA-based MAC protocol with Delay Tolerant (MACA-DT), introduced in [10], can enhance the system efficiency by using adaptive silent time and simultaneous handshake technique. The new Funnelling MAC (FMAC-U) [11] utilises an improved three-way handshake mechanism and Carrier Division Multiple Access (CDMA) technology to enhance the system efficiency. In [12] a data-centric multi-hop MAC protocol employs multiple collision domains to limit transmission interference, and dynamic collision-free polling to offer efficient handshake. These inspiring works show that system efficiency gains are possible when improved handshaking design is merged with additional MAC techniques. Nevertheless, they do not take energy efficiency metrics into account when the performance of proposed MAC protocols is evaluated. Energy consumption is a major design requirement in order to prolong the battery lifetime of network nodes.

An Efficient Medium Access Control Protocol for underwater Acoustic Sensor Network, called UWAN-MAC, is proposed in [13]. UWAN-MAC relies on energy efficiency as the main performance metric. By synchronised power-sleeping techniques, it achieves a distributed, scalable and energy-efficient MAC protocol. Reference [14] introduces a Reservation-based MAC protocol, called R-MAC, which focuses on energy efficiency and fairness. R-MAC schedules the transmissions of control and data packets to avoid data packet collision. In [15] they present T-Lohi a new class of distributed and energy-efficient media-access protocol for underwater acoustic sensor networks. By exploiting short tones and a low-power receiver T-Lohi can reduce the energy consumption while achieving high throughput. Reference [16] exploits the possibility of concurrent transmissions, similar to Interference Aware (IA) MAC [17], where Delay-aware Opportunistic Transmission Scheduling (DOTS) reduces the probability of collisions in order to improve the system efficiency.

The above MAC protocols enhance the system efficiency in terms of some parameter. However, they still suffer from inefficient data transmission due to the long underwater propagation delay. A new approach should treat the unique features offered by the underwater acoustic channel as an improvement opportunity rather than a drawback or constraint. Therefore, the proposed strategies consider IA and NC as new approaches to fully exploit the properties of the underwater channel with focus on energy, throughput and delay.

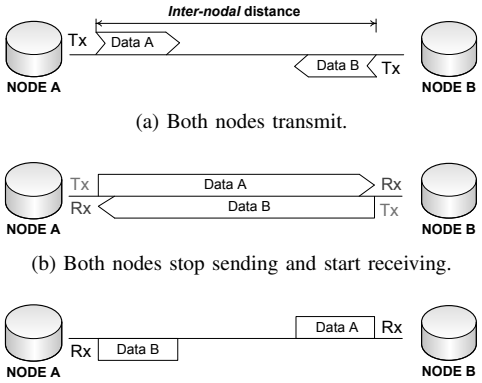
III. Proposed Techniques

This section provides a description of the analysed Multiple Access solutions, by first introducing Interference Avoidance (IA) and Network Coding (NC), and then providing general design considerations. CSMA/CA with RTS/CTS is considered as reference for implementation of the proposed concepts.

A. Interference Avoidance

The concept of IA exploits concurrent transmissions and reception of information based on the knowledge of the propagation delay. As a general assumption, nodes cannot send and receive simultaneously. In stationary networks, where nodes are fixed or move very slowly, the propagation delay between a pair of nodes can be assumed constant. If a node could determine it, it could set the maximal packet length in accordance with the long inter-nodal propagation delay. Neighbouring nodes having packets to exchange would be able to concurrently transmit these. The approach can also be extended to the case of more nodes. Fig. 2 and Fig. 3 provide an example of the basic approach involving two and three nodes, respectively.

In Fig. 2, the transmission of data packets between two nodes, A and B, is displayed. First, both nodes start sending their packets to one another, Data A and B, respectively. Data are transmitted until the maximal packet size is reached where the packet length corresponds to the propagation delay. Then, both nodes start receiving data from each other which takes place for a time equal to the propagation delay.



(a) Both nodes transmit.

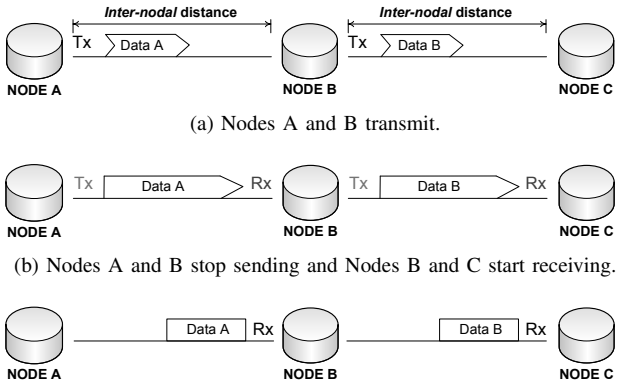
(b) Both nodes stop sending and start receiving.

(c) Both nodes have almost received the packet.

Fig. 2. Simultaneous data packet exchange between a pair of nodes using Interference Avoidance.

Fig. 3 depicts the data transmission among three nodes, A, B and C. First, Nodes A and B transmit their packets, Data A and B, to Nodes B and C, respectively. When the maximal packet length is reached, Nodes A and B stop transmitting and Nodes B and C start receiving concurrently until the reception process is completed.

This idea is based on the inspiring work in [18], where a local and opportunistic approach is proposed to exploit the possibility of concurrent bidirectional transmissions between a sender and receiver, thus improving throughput and latency. In particular, bidirectional concurrent data packet exchange



(a) Nodes A and B transmit.

(b) Nodes A and B stop sending and Nodes B and C start receiving.

(c) Nodes B and C have almost received the packet.

Fig. 3. Concurrent data transmission among nodes using Interference Avoidance.

is employed, where a pair of nodes is allowed to transmit multiple rounds of transmissions to each other for every successful handshake. However, in [18] data packets have a shorter duration than the inter-node propagation time, whereas the approach proposed in this paper considers the packet transmission time and inter-node propagation time to be the same. This allows for more efficient schemes and can provide advantages in more complex scenarios.

Exploiting full-duplex communication between node pairs can improve channel utilisation, end-to-end latency and energy efficiency of network nodes. Energy consumption is of primary concern in underwater networks as nodes are battery-powered and deployed in hard-to-access areas where batteries might not be recharged or replaced. Thus, IA can prolong the network lifetime by fully leveraging the limited capacity of batteries.

This novel approach could be incorporated to CSMA/CA which represents a well-known protocol. To this end, some design considerations should address: (i) the redefinition of RTS/CTS exchange to allow intelligent collisions; (ii) the estimation of the propagation delay between nodes; and (iii) the insertion of a guard bits sequence at the beginning and/or at the end of packets to reduce synchronisation dependence.

B. Network Coding

Network Coding [19] considers that nodes are not restricted to forward data but can also process incoming information flows. The idea of NC relies on the combination of independent flows when transported throughout the network. Two different approaches to NC have been considered; linear, and physical-layer network coding. Linear network coding (NC) [20] refers to the output flow obtained at a given node as the combination of its input flows by linear coding operations. Physical-layer Network Coding (PNC) [21] exploits the additive nature of the channel and is applied to EM signal reception and modulation. The coding operation is obtained by the collision of incoming signals. Information decoding requires correct reception of several combined packets, and thus it is not always possible to immediately extract information from a single packet. This represents a minor constraint of PNC for the target scenario where all nodes require all the information as will be discussed later. Fig. 4 and Fig. 5 show an example of each approach.

In Fig. 4, a sender has to transmit packets b_1 and b_2. There are two receivers, which are interested in both packets. First, the source node sends b_1 and b_2 to Nodes A and B, respectively. Then, they send the data packets which are received separately by Node C and receivers 1 and 2. Using network coding, Node C linearly combines both packets by the XOR function and transmits the resulting information on the middle link. Finally, Node D sends the combination of packets to the final receivers, which can decode the remaining packets by the XOR operation, thus improving the overall throughput of the network.

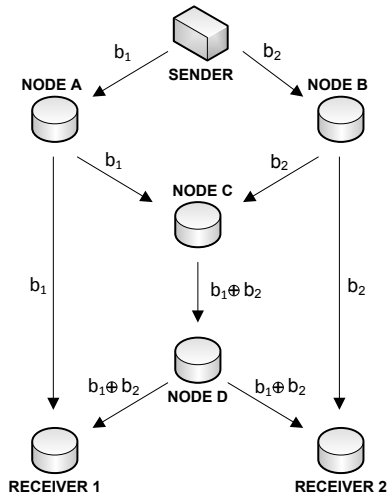


Fig. 4. Network Coding in the canonical butterfly network.

Fig. 5 depicts a transmission of data packets between two end nodes by exploiting the broadcast channel of the central node. The left node holds b_1 and is interested in b_2. The right node holds b_2 and is interested in b_1. First, both end nodes send their packets to the central node. After simultaneous reception of both signals, the central node decodes the combination of the two packets using proper modulation techniques and broadcasts the resulting information to its neighbours. Finally, each end node extracts the required packet.

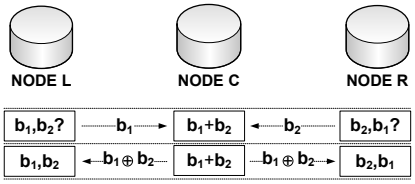


Fig. 5. End-to-end data transmission with Physical-layer Network Coding.

The deployment of NC is a challenging task as nodes must support additional functionality which increases the complexity of the approach compared to traditional store-and-forward networks. The following sections demonstrate that the implementation of NC as an extension of CSMA/CA can significantly enhance the performance of underwater networks. This aspect is also acknowledged in other works [22] [23].

C. Combining Interference Avoidance and Network Coding

This paper proposes to combine IA and NC approaches to fully exploit the properties of the underwater acoustic channel and achieve efficient data transmission from time and energy perspectives. The proposed techniques are the combination of IA and NC (IA+NC) and the combination of IA and PNC (IA+PNC).

Figures 6 to 8 illustrate the packet exchange among 5 nodes string network for each considered MAC method by first introducing the general case of CSMA/CA, and then identifying the specific features of combined techniques. Only the starting phase of the transmission is considered and it is assumed that RTS/CTS ensure no collisions in pure CSMA/CA and enable intelligent collisions for the combined solutions. A box below each node depicts the data stored in it at a given time. The arrows represent data packets transmission. At the right of each figure, the time of the dissemination process is counted in time slot.

CSMA/CA (Fig. 6): In $T = 1$ packets a_1 and b_1 are simultaneously sent from nodes 1 and 5 to nodes 2 and 4, respectively. Since both transmissions are out of range, they will not interfere. Packet a_1 is then sent from Node 2 to Node 3 in $T = 2$. After that, Node 4 transmits b_1 to Node 3. Packet a_1 is later sent from Node 3 to Node 4. Node 3 forwards b_1 to Node 2 in $T = 5$. Finally, a_1 and b_1 are concurrently delivered to the end nodes. The process is repeated for a_x and b_x which represent successive packets. In the next figures a_x and b_x also indicate the possibility of additional simultaneous transmissions if nodes have more packets to send.

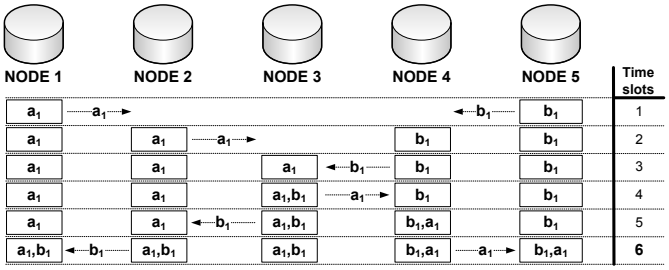


Fig. 6. Data dissemination process of CSMA/CA in the string network.

IA+NC (Fig. 7): With IA Node 1 could transmit an additional packet (a_x) in $T = 2$ while Node 2 is sending a_1 to Node 3. The same operation is performed in $T = 3$ with packets b_1 and b_x. Using NC in $T = 4$, Node 3 combines packets a_1 and b_1 and broadcasts the combination ($a_1 \oplus b_1$) to nodes 2 and 4 whereas a concurrent transmission could take place from either Node 2 or Node 4 to Node 3 by exploiting IA, a_x is shown as an example. While nodes 2 and 4 are forwarding b_1 and a_1 to the end nodes in $T = 5$, these last could send other packets (a_x and b_x) to nodes 2 and 4 by IA.

IA+PNC (Fig. 8): Exploiting PNC in $T = 2$, a_1 and b_1 are simultaneously sent from nodes 2 and 4, respectively, to Node 3. By IA at the same time, additional packets (a_x and b_x) could be concurrently transmitted from nodes 1 and 5 to nodes 2 and 4 respectively. While Node 3 is broadcasting the collision of packets ($a_1 \oplus b_1$) in $T = 3$, both Node 2 and Node 4 could exploit IA to simultaneously send a packet (a_x and b_x) to Node 3.

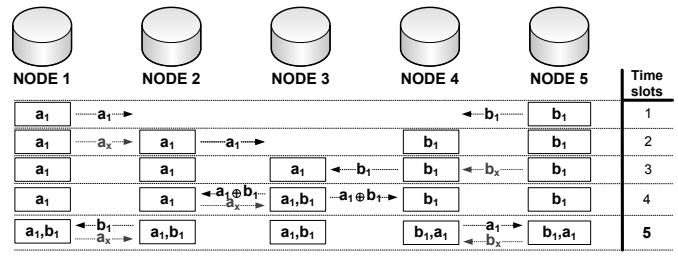


Fig. 7. Data dissemination process of IA+NC in the string network.

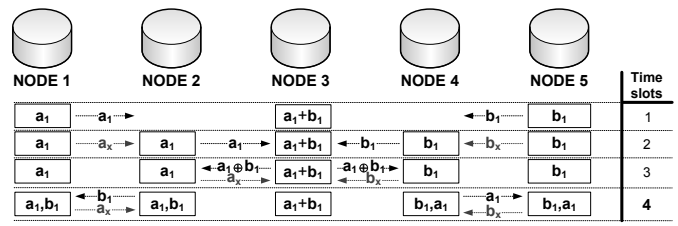


Fig. 8. Data dissemination process of IA+PNC in the string network.

IV. Performance Evaluation

This section analyses the performance of the proposed Medium Access strategies using IA and NC for data dissemination over a string topology network scenario. The performance analysis considers a slightly modified CSMA/CA approach. As a general assumption, the impact of RTS/CTS handshakes is restricted to enable or prevent concurrent transmissions for enabling collision avoidance. However, the presence of these messages is not counted in the assessment. The following MAC techniques are considered: CSMA/CA, IA, NC, PNC, combination of IA and NC (IA+NC) and combination of IA and PNC (IA+PNC).

A. Simulation Setup

Simulations are built in Python. The aim of the simulations is to measure the potential benefits of proposed MAC techniques in more realistic environments. The simulation scenario consists of k nodes, which are aligned either vertically or horizontally. Nodes are fixed and the coverage of each node is one hop. Two data sources at the edges of the string disseminate two information flows, A and B, through the network. Flow A is transmitted by the left end node and flow B is sent by the right end node. The dissemination process is completed when the target nodes have received all the packets. Fig. 1 shows an example of 5 nodes in the string network.

The simulation framework relies on a basic operation subject to: (i) the local priority of packets, where flow A has priority with respect to B and packet number has priority over flow; (ii) the random channel access; (iii) the random packet erasures with fixed probability; and (iv) the inability of nodes to send and receive simultaneously.

The simulation settings are described by the parameters in Table I. Data rate and Bit Error Rate are based on commercial acoustic modems specifications [24]–[26]. Power consumption of transmit, receive, idle and sleep modes is obtained from [25]. The maximum packet size is set so the transmission time of a packet is equals to the propagation delay between the nodes. This ensures the highest gain when IA is employed but also requires that the inter-node distance is known. Packet Error Rate is given by the simple Bernoulli model as in [27]. Besides, the number of iterations per simulation ensures that the 95% of confidence intervals are within $\pm 2\%$ of the values shown.

TABLE I
SIMULATION SETTINGS

Data Rate	9600 bps
Length of Links	1000 m
Speed of Sound	1500 m/s
Propagation Delay	$666{,}\hat{6}$ ms
Maximum Packet Size	800 bytes
Packet Transmission Time	$666{,}\hat{6}$ ms
Transmit mode Power Consumption	2 W
Receive/Idle mode Power Consumption	0.8 W
Sleep mode Power Consumption	8 mW
Bit Error Rate	10^{-5}
Packet Error Rate	0.062
Network size (nodes)	2, 3, 4, 5, 8, 10, 20 and 30
Traffic (packets, half per source)	2, 4, 10, 20, 50 and 100
Number of iterations per simulation	100

B. Simulation Results

Fig. 9 and Fig. 10 show the time required by considered MAC techniques so that all nodes of a certain size network can receive a given number of packets disseminated by the end nodes of the system. The x axis represents the amount of packets disseminated through the network which is common to all figures and the y axis shows the duration of the dissemination process in time slots. Two representative samples of string network length are considered; 3, and 8 nodes respectively. Notice that the node density of underwater networks is expected to be smaller than that of radio networks due to the long propagation delays and the hard physical deployment. Overall, as the number of packets at the sources increases, the dissemination time increases.

Fig. 11 depicts the energy saving of proposed strategies normalised with respect to the energy consumption of CSMA/CA when the dissemination process of a given number of packets through 5 nodes string network is completed, i.e. all nodes have received all packets. The energy metric is based on the total amount of energy consumed throughout the network for each strategy which is then used to calculate the energy reduction in percent compared to CSMA/CA, as shown in the y axis. It is assumed that nodes stay in idle state after transmission and reception and only transition into a sleep mode when they have no more packets to send and do not expect any additional packets. In general, as the density of packets grows in the network, the energy saving increases especially in the combined techniques.

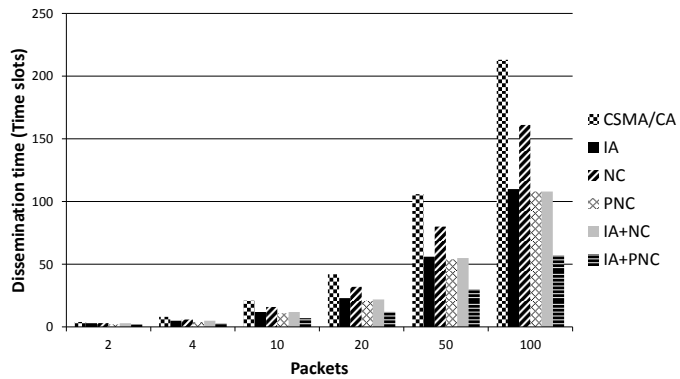


Fig. 9. Duration of dissemination process of different number of packets in a 3 nodes string network according to the MAC techniques under evaluation.

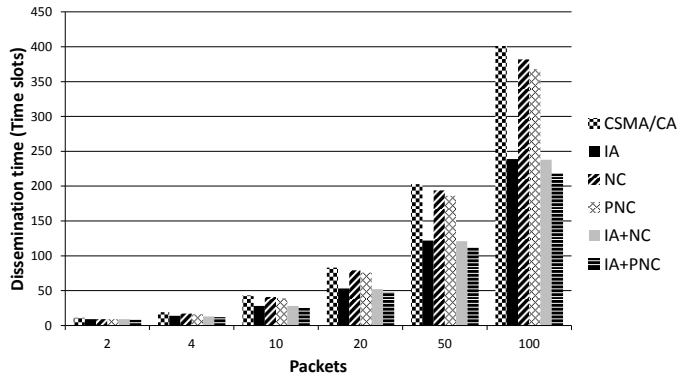


Fig. 10. Duration of dissemination process of different number of packets in a 8 nodes string network according to the MAC techniques under evaluation.

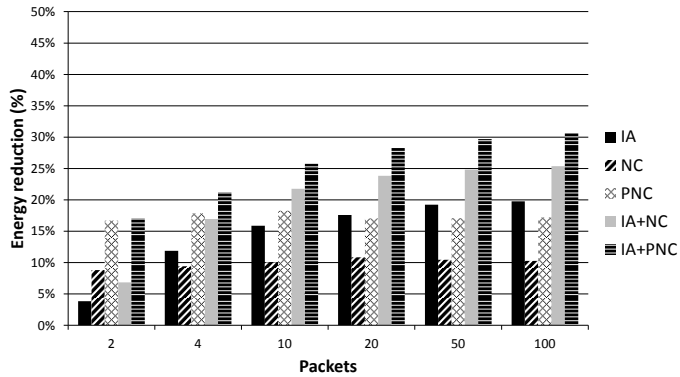


Fig. 11. Energy saving of proposed techniques compared to CSMA/CA in the dissemination process of several packets over a 5 nodes string network.

Presented results demonstrate the potential benefits of IA and NC on the channel utilisation and the energy efficiency of data transmission under water, significantly improving the achieved performance of CSMA/CA. According to Fig. 9, the advanced techniques provide shorter overall dissemination times with respect to CSMA/CA depending on the amount of packets, when the network comprises a small number of nodes. For instance, IA+NC and IA+PNC can reduce the data dissemination time 50% and 70% respectively for 100 packets compared with CSMA/CA, while achieving higher energy efficiency, see also Fig. 11. In larger networks, see Fig. 10, the improvement of combined techniques is remarkable. The

reduction in dissemination time is maintained over the 50% for 100 packets, whereas the energy gains represent the 25% and 30% for IA+NC and IA+PNC respectively when compared with CSMA/CA as observed in Fig. 11. IA helps to reduce the overall dissemination time and becomes more efficient when the number of nodes and packets increases but IA+NC achieves better energy efficiency while keeping high throughput. IA+PNC always performs better in terms of time and energy though its applicability for the target scenario might be limited, since relay nodes cannot extract the individual data packets when incoming signals are combined. Thus, IA+PNC is more appropriate for end-to-end data transmission, where relay nodes do not require the transported information.

A combination of IA and NC represents a viable alternative solution for future underwater acoustic networks to improve the system efficiency in terms of throughput and energy consumption.

V. Conclusions

This paper proposes and investigates the feasibility of the emerging concepts Interference Avoidance and Network Coding for Medium Access in underwater communications. The objective is to enhance the efficiency of underwater communication systems with focus on channel utilisation and latency. The new approaches utilise the underwater channel characteristics by exploiting the long propagation delay and the broadcast channel to enable full-duplex communication. Presented simulations prove the potential of such strategies to improve the throughput and reduce the energy consumption. The combined solution of these concepts is especially promising as it provides the highest gain, where the combined approaches achieve a reduction of up to 50% and 70% in data dissemination time and 25% and 30% in consumed energy when compared to the traditional CSMA/CA.

In future works we will move from these promising results in underwater networks towards the feasibility study and possible implementation of proposed techniques in radio communication systems. Overall, we plan to: (i) implement Network Coding and Interference Avoidance at the network layer; (ii) improve reliability of energy measurements by real testbeds, for instance, measure the total consumed energy throughout the network and the time to first node (or a given percentage of nodes) death; and (iii) provide a real throughput and energy assessment of practical implementations according to the testbed results.

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References

[1] L. Liu, S. Zhou, and J.-H. Cui, "Prospects and problems of wireless communication for underwater sensor networks," *Wireless Communications and Mobile Computing*, vol. 8 (8), pp. 977–994, Oct. 2008.

[2] M. Stojanovic, "Underwater wireless communications: Current achievements and research challenges," *IEEE Oceanic Engineering Society Newsletter*, vol. 41 (2), pp. 10–13, Spring 2006.

[3] M. Molins and M. Stojanovic, "Slotted FAMA: a MAC protocol for underwater acoustic networks," *IEEE OCEANS'06, Singapore*, pp. 1–6, May 2007.

[4] C. L. Fullmer and J. J. Garcia-Luna-Aceves, "Floor Acquisition Multiple Access (FAMA) for packet-radio networks," *ACM SIGCOMM*, pp. 262–273, 1995.

[5] N. Chirdchoo, W.-S. Soh, and K. C. Chua, "MACA-MN: a MACA-based MAC protocol for underwater acoustic networks with packet train for multiple neighbors," *IEEE VTC, Singapore*, pp. 46–50, May 2008.

[6] P. Karn, "MACA a new channel access method for packet radio," *ARRL/CRRL Conference*, pp. 134–140, 1990.

[7] H.-H. Ng, W.-S. Soh, and M. Motani, "MACA-U: a media access protocol for underwater acoustic networks," *IEEE GLOBECOM'08, New Orleans, Lousiana, USA*, pp. 833–838, Dec. 2008.

[8] X. Guo, M. Frater, and M. Ryan, "An adaptive propagation-delay-tolerant MAC protocol for underwater acoustic sensor networks," *IEEE OCEANS'07 - Europe*, pp. 1–5, June 2007.

[9] B. Peleato and M. Stojanovic, "Distance aware collision avoidance protocol for ad-hoc underwater acoustic sensor networks," *IEEE Communications Letters*, vol. 11 (12), pp. 1025–1027, 2007.

[10] W. Lin, E. Cheng, and F. Yuan, "A MACA-based MAC protocol for underwater acoustic sensor networks," *Journal of Communications*, vol. 6 (2), pp. 179–184, April 2011.

[11] G.-Y. Fan, H. Chen, L. Xie, and K. Wang, "Funneling media access control MAC protocol for underwater acoustic sensor networks," *Journal of Zhejiang University - Science C*, vol. 12 (11), pp. 932–941, 2011.

[12] M. Yang, M. Gao, C. H. Foh, J. Cai, and P. Chatzimisios, "DC-MAC: A data-centric multi-hop MAC protocol for underwater acoustic sensor networks," *IEEE ISCC'11, Kerkyra, Greece*, pp. 491–496, July 2011.

[13] M. K. Park and V. Rodoplu, "UWAN-MAC: an energy-efficient MAC protocol for underwater acoustic wireless sensor netwroks," *IEEE Journal of Oceanic Engineering*, vol. 32 (3), pp. 710–720, July 2007.

[14] P. Xie and J.-H. Cui, "R-MAC: an energy-efficient MAC protocol for underwater sensor networks," *IEEE WASA'07*, pp. 187–198, Aug. 2007.

[15] A. A. Syed, W. Ye, and J. Heidemann, "T-lohi: a new class of MAC protocols for underwater acoustic sensor networks," *IEEE INFOCOM'08*, vol. Pheonix, AZ, pp. 231–235, April 2008.

[16] Y. Noh, P. Wang, U. Lee, D. Torres, and M. Gerla, "DOTS: a propagation delay-aware opportunistic MAC protocol for underwater sensor networks," *IEEE ICNP'10, Kyoto, Japan,*, pp. 183–192, Oct. 2010.

[17] D. Shukla, L. Chandran-Wadia, and S. Iyer, "Mitigating the exposed node problem in IEEE 802.11 ad hoc networks," *IEEE ICCCN'03, Dallas, TX*, pp. 157–162, Oct. 2003.

[18] H.-H. Ng, W.-S. Soh, and M. Motani, "BIC-MAC: bidirectional-concurrent MAC protocol with packet bursting for underwater acoustic networks," *IEEE OCEANS'10, Seattle, United States*, pp. 1–7, Sep. 2010.

[19] R. Ahlswede, N. Cai, S.-Y. R. Li, and R. Yeung, "Network information flow," *IEEE ToIT*, vol. 46 (4), pp. 1204–1216, Jul. 2000.

[20] S.-Y. R. Li, R. W. Yeung, and N. Cai, "Linear network coding," *IEEE ToIT*, vol. 49 (2), pp. 371–381, Feb. 2003.

[21] S. Zhang, S. C. Liew, and P. P. Lam, "Physical-layer network coding," *in Proc. ACM 12th Mobicom 2006*, pp. 358–365, Sep. 2006.

[22] D. E. Lucani, M. Médard, and M. Stojanovic, "A lower bound to transmission power for multicast in underwater networks using network coding," *IEEE ISITA'08, New Zealand*, pp. 1–6, Dec. 2008.

[23] M. Chitre and W.-S. Soh, "Network coding to combat packet loss in underwater networks," *ACM WUWNet'10, Woods Hole, Massachusetts, United States*, pp. 1–6, Sep. 2010.

[24] Model ATM-885 from Teledyne Benthos *http://www.benthos.com/*.

[25] Model UWM 2000 from LinkQuest Inc *http://www.link-quest.com/*.

[26] Model AquaNetwork from DSPCOMM *http://www.dspcomm.com/*.

[27] J. Daladier and M. Labrador, "An adaptive logical link layer protocol for underwater acoustic communication channels," *IEEE OCEANS'09, Biloxi, Mississippi*, pp. 1–8, Oct. 2009.