A joint power control and rate adaptation MAC protocol for underwater sensor networks

Yishan Su\textsuperscript{a,b}, Yibo Zhu\textsuperscript{b}, Haining Mo\textsuperscript{b}, Jun-Hong Cui\textsuperscript{b}, Zhigang Jin\textsuperscript{a,*}

\textsuperscript{a}School of Electronic and Information Engineering, Tianjin University, Tianjin, PR China
\textsuperscript{b}Computer Science and Engineering Department, University of Connecticut, Storrs, CT, USA

\begin{abstract}
In this paper, we propose a new metric to measure the spatial reuse efficiency in networks: the spatial reuse index. We observed that the spatial reuse index in Underwater Sensor Networks (UWSNs) is significantly lower than in RF networks due to the relatively low spreading loss of acoustic signals. As a result, UWSNs generally have much lower network throughput.

To address this problem, we propose an Underwater Power Control MAC protocol (UPC-MAC), which leverages dynamic transmission power adjustment and a novel rate adaptation algorithm to enhance the spatial reuse efficiency. UPC-MAC is a reservation based channel access scheme. It makes use of control packet’s exchanges to collect neighboring nodes’ data transmission requests and channel condition between senders and receivers. With such information, UPC-MAC allows for concurrent data transmissions by applying Nash Equilibrium to transmission power adjustment, which can be done independently on each sender in a distributed way. Furthermore, with the channel information, senders can adjust their data transmission rates by running a rate adaptation algorithm which considers the features of a real Orthogonal Frequency Division Multiplexing (OFDM) acoustic communication system. Simulation results show that UPC-MAC outperforms Slotted FAMA in terms of network goodput and lowers the energy consumption in two representative network scenarios. The simulation results also justify that our rate adaptation algorithm does improve the performance of UPC-MAC.

\end{abstract}

1. Introduction

UWSNs (Underwater Sensor Networks) have gained tremendous attention in recent years because of their wide civilian and military applications such as scientific/commercial exploitation, disaster prediction and coastline protection \cite{1-3}. This motivates more research on a reliable and efficient UWSN designs.

Due to the severe attenuation of radio waves caused by the conductivity of water, acoustic communication has proved to be the only practical method for long range wireless communication in underwater so far \cite{4}. However, underwater acoustic communication also faces grand challenges, such as (a) limited bandwidth: current acoustic communication system is up to 40 km kbps for the range-rate product, (b) long propagation delay: the speed of sound underwater is approximately 1500 m/s, which is $2 \times 10^4$ times slower than the speed of radio, (c) high energy consumption: most existing commercial acoustic modems are battery powered and have to be recharged after working continuously for several days.
All aforementioned constraints to underwater acoustic communication highly degrade network performance making MAC protocol design a daunting challenge. Many MAC protocols dedicated to UWSNs have been proposed in the last decade. All of these MAC protocols fall into three categories: random access [5,6], reservation based [7–9] and schedule based MAC protocols [10]. Among most of the proposed MAC protocols for UWSNs, reservation based MAC protocols such as Slotted FAMA [7] have been shown to have a better performance with heavier traffic loads [11]. With the exchange of control packets, they can effectively alleviate collisions and achieve a relatively high network throughput.

However, most of the existing reservation based MAC protocols try to increase the throughput of the network only by carefully scheduling the packet transmission. They do not consider the spatial reuse, which is the total number of concurrent transmissions that can be accommodated in the network [12]. Usually, the capacity of the network depends on the capacity of each link and the number of links which transmit data simultaneously. As a result, reusing spatial resource is an efficient way to increase the network throughput.

In [13], the authors show that traditional reservation based protocols are inefficient in spatial reuse because of a relatively low spreading loss of the acoustic signal in underwater. They also show that in underwater environments, an RTS/CTS handshake scheme becomes ineffective when the distance between a communication pair is larger than 22% of the maximum transmission range. By contrast, in RF based networks, an RTS/CTS handshake scheme retains effective as long as a communication pair is closer than 56% of the maximum transmission range. To better reuse the spatial resource, power control has been proposed and extensively studied in wireless networks, which serves the purpose of both better spatial reuse efficiency and power saving. In addition, to deal with the change of transmission power and improve the reliability of the network, rate adaptation provides a critical mechanism to trade between sending data rate and robustness.

In this paper, to illustrate our motivation, we first define a spatial reuse index as a metric for spatial reuse efficiency and compare it between UWSNs and RF networks. We then present related work on power control and rate adaptation. Then we incorporate a distributed power control scheme into a new proposed reservation based channel access protocol to allow every node to allocate its transmission power by collecting the channel information and the nodes data transmission requests. The purposes are twofold. Firstly, the interference range can be reduced for a better spatial reuse efficiency. Secondly, the transmission power level can be reduced to achieve a better energy efficiency. Specifically, based on the collected channel information, an optimization problem, whose objective is to maximize the overall network throughput while preventing nodes from using unnecessarily high power, can be formulated to manage the transmission power. The optimal data transmission power for each node can be calculated by solving an Nash Equilibrium (NE) equation for a given utility function. Finally, based on the optimal transmission power and the channel information, we can adjust the data transmission rate of acoustic modems to guarantee a reliable data transmission and save energy. This rate adaptation algorithm is based on a real underwater Orthogonal Frequency Division Multiplexing (OFDM) communication system features [14].

With the power control algorithm and corresponding rate adaptation algorithm, UPC-MAC allows for as many concurrent communications as possible which highly improve the performance of the networks in terms of network goodput and energy consumption.

This paper is an extended version of our conference version [15]. In [15], we proposed the basic idea of for UPC-MAC as a powerful scheme to improve the spatial reuse efficiency. However, one main drawback of [15] is that the transmission rate of senders is assumed to be equal with varying Signal to Interference plus Noise Ratio (SINR), which does not tally with the actual situation.

To deal with the signal variation resulting from the transmission power adjustment and guarantee the system performance, we develop a novel SINR based rate adaptation algorithm with a consideration of the hardware design of underwater OFDM modem. By implementing the rate adaptation algorithm, the new version UPC-MAC cannot only be better applied to real systems but also achieves a better system performance.

The rest of the paper is organized as follows. In Section 2, we briefly introduce the difference of spatial reuse in RF networks/UWSNs. In Section 3, we present related works of power control and rate adaptation scheme. In Section 4, we propose a power control MAC protocol, UPC-MAC, which employs a game theory based power allocation algorithm. After that, we introduce a rate adaptation algorithm considering the features of a real acoustic OFDM communication system. In Section 5, we provide simulation results and analysis on the performance of UPC-MAC compared with a classic reservation based MAC protocol, Slotted FAMA. Finally, our main conclusions and future works are drawn in Section 6.

2. Spatial reuse in UWSNs and RF based networks

In this section, we will discuss the major difference in spatial reuse efficiency between UWSNs and RF networks, which is also the motivation for our new power control MAC protocol.

In wireless network, a requirement of MAC protocols is that they should allow as many simultaneous and successful transmissions as possible in different spatial areas to improve the throughput/goodput of the network. This ability is known as spatial reuse [16]. In both RF based networks and UWSNs, spatial reuse is an efficient way to improve the throughput of a network. However, these concurrent communications will increase the probability of collisions. To quantify the spatial reuse efficiency and compare it between the RF network and UWSN, we define a spatial reuse index $\Omega$ as Eq. (1)

$$\Omega = \frac{d_{tr}}{d_{in}} = \frac{d_{tr}}{\max(d_{i})|_{i = 1}^{N-1}}$$

where $d_{tr}$ is the transmission range; $d_{in}$ is the maximum interference range; $N - 1$ is the number of senders which
can interfere with the receiver. It is obvious that a larger $\Omega$ indicates a better spatial reuse efficiency.

Here we define the interference range as a distance to a receiver that, if some nodes send packets within this distance, will cause collision to an on-going reception of the receiver. In order to avoid collisions, the Signal to Interference plus Noise Ratio ($\text{SINR}$) should be larger than a decoding threshold, noted as $\text{SINR}_\text{th}$ as Eq. (2),

$$\text{SINR} = \frac{p_i \cdot h_i}{\sum_{j=1}^{N-1} p_j \cdot h_j + \sigma^2} \geq \text{SINR}_\text{th}$$

where $p_i/p_j$ is the transmission power of the original sender/interfering senders; $h_i/h_j$ is the channel gain between the original sender/interfering senders to the receiver; $N - 1$ is the number of senders which can interfere with the receiver; $\sigma^2$ is the thermal noise.

In this paper, for UWSN, we apply the channel gain $h$ as Eq. (3) [17],

$$h = \frac{1}{A_0 d^k a(f)}$$

where $A_0$ is a unit-normalizing constant; $k$ is the spreading factor; $d$ is the distance between the sender and the receiver and $a$ is the absorption coefficient.

Substituting $h_i$ and $h_j$ by Eq. (3) and ignoring the thermal noise, Eq. (2) yield Eq. (4),

$$\text{SINR}_{\text{UWSN}} = \frac{p_i/A_0 d^k a(f)^k}{\sum_{j=1}^{N-1} p_j/A_0 d^k a(f)^k} \geq \text{SINR}_\text{th}$$

where $k$ is the spreading factor of a typical value $k = 1.5$ [18].

For RF networks, we apply the attenuation model, by ignoring the thermal noise, as Eq. (5). The $\text{SINR}_{\text{RF}}$ is shown in Eq. (6),

$$h = \frac{1}{d^k}$$

$$\text{SINR}_{\text{RF}} = \frac{p_i/d_i^k}{\sum_{j=1}^{N-1} p_j/d_j^k} \geq \text{SINR}_\text{th}$$

where $k$ is the spreading factor of a typical value $k = 4$ [19].

From Eqs. (1), (4) and (6), we can observe that $\Omega$ depends on the number of interfering nodes, the transmission power and the distance between them. Here we use an example to illustrate the difference between an RF network and UWSN. We assume in a network, there is one sender $S$, one receiver $R$ and one interfering sender $I$. For UWSN, the frequency of the signal is set as: $f = 15$ kHz. For both networks, we assume the transmission power of all nodes are the same. The results of different spatial reuse index are shown in Fig. 1.

As shown in Fig. 1, $\Omega_{\text{RF}}$ is always higher than $\Omega_{\text{UWSN}}$ with the same decoding threshold. Fig. 2 shows the ratio of collision area of UWSN network and RF network. The ratio is calculated by collision area in UWSN divided by that in RF network with the same decoding threshold. Fig. 2 indicates that with the same transmission power, the collision area in UWSN is much larger than that in RF network. Therefore, the spatial reuse efficiency is lower in UWSNs than in RF networks.

The inefficiency of UWSN in spatial reuse results from the lower signal spreading factor $(k = 1.5)$ compared to that in the RF network $(k = 4)$. Since acoustic signal fades slower than RF signal, the unnecessary high transmission power can result in a larger collision area. An effective method to reduce the collision area is to avoid using unnecessarily high transmission power by implementing a power control scheme. An example is shown in Fig. 3, where node A and C are senders as well as node B and D are the destinations of A and C respectively. The small solid circles are the transmission ranges and the larger circles are the interference ranges. Fig. 3(b) demonstrates the advantage of power control, which allows two concurrent transmissions without collision.

3. Related work

Before we present solutions on a joint power control and rate adaptation algorithm for UWSNs, we introduce some related work on both power control and rate adaptation in this section.
3.1. Power control

Based on RTS/CTS scheme in the context of IEEE 802.11, some power control schemes have been proposed [20,21]. Most of these solutions adopt a maximum power level for exchanging RTS/CTS packets and a minimum necessary power level for transmitting DATA and ACK packets. Gomez and Campbell in [22] analyzed the advantages of applying transmission power control (TPC) in wireless multi-hop networks. In this paper, they concluded that per-link transmission range adjustment outperforms global range transmission adjustment by 50% in terms of throughput. However, most of those protocols only consider one link’s communications. They neglect the tradeoff between the energy consumption and the network capacity which is related to the spatial reuse.

To improve the spatial reuse efficiency, authors in [23] address this problem based on SINR constrained with a physical interference model. The proposed algorithm can select a subset of senders/receivers and allocate a power level with the object of maximizing the number of concurrent communications. The authors in [24] also tried to allow spatial reuse of the medium by allowing communication at minimum propagation ranges. In [25], the authors presented a cross-layer design for the multiple access problem in contention-based wireless ad hoc networks. The proposed protocol introduced two alternating phases, namely scheduling and power control.

However most of existing power control scheme for wireless network cannot be applied to UWSNs directly. For example, two phase scheme in [25] may introduce extra time consumption; most parameters in [23] may rely on a complex cross-layer protocol design.

For UWSNs, Josep Jornet and Milica Stojanovic in [26] introduced a distributed power control scheme which aims to minimize per bit energy consumption. The proposed scheme requires the knowledge of both the positions of all other nodes and channel information. However, the dynamic of the network and variation of the channel state may weaken the performance.

3.2. Rate adaptation

Rate adaptation is the process of dynamically switching data transmission rates according to dynamic channel conditions. Most of the existing rate adaptation scheme can be divided into two categories: probing based and SINR based.

Probing based rate adaptation, such as [27,28], assume that an increase of packet loss means a deterioration of the channel quality. Then the sending rate should be reduced by switching to a more moderate modulation scheme. However, considering the cost of retransmitted a packet in underwater environment, including the energy and time consumption, the loss based rate adaptation is not ideal for UWSNs. In addition, loss based rate adaptation algorithms usually rely on the statistic result of a certain number of transmitted packets. However the relatively low data generation rate in UWSNs may not allow for a precise statistical result.

On the other hand, SINR based rate adaptation algorithm which characterizes the channel quality by exploring physical layer information would give a better guideline for rate adaptation. In [29], a rate adaptation mechanism adopted by the receiver instead of by the sender was proposed for WLAN. The channel quality estimation and rate selection is performed on a per-packet mode via the received SINR. In another approach [30], a systematic measurement-based study was conducted to show that SINR is a good prediction tool for channel quality. Furthermore, a corresponding design of practical rate adaptation algorithm SGRA was proposed. SGRA adapts sending rate via SNR to frame delivery ratio (FDR) relationship which is measured in a real world environment. However, due to some unique design and parameters’ setting of underwater acoustic modem, most of the existing rate adaptation algorithm cannot be applied directly in UWSNs. For example, for an underwater OFDM modem, adaptive modulation and coding technique (AMC) is applied for rate adaptation [31].

Based on the analysis above, we find that few work on power control and rate adaptation have been studied for UWSNs. Driven by this observation, we will present our
solution on power control and rate adaptation algorithm in the next section. The proposed solution aims to maximize the network throughput by considering the tradeoff between energy consumption and the network capacity. As for the related rate adaptation algorithm, an SINR based solution which considers the features of a real OFDM acoustic communication system is adopted.

4. UPC-MAC protocol

In this section, we will first introduce the basic idea of UPC-MAC. After that, we will formulate an optimization problem for a power control game and a rate adaptation algorithm is proposed based on the underwater acoustic OFDM modem.

4.1. Protocol overview

UPC-MAC is a reservation and slotted based MAC protocol. Here we define 4 types of packets: Request to Send (RTS), Channel State Information (CSI), DATA and Acknowledgement (ACK). In UPC-MAC, time is slotted and each packet should be transmitted at the beginning of a time slot. Similar to [7], the length of one slot is \( s + c + a \), where \( s \) is the maximum propagation delay; \( c \) is the transmission time of a CSI packet and \( a \) is a guard time to compensate for possible clock drifts. We assume that the channel gain is stationary during a short period, which is long enough for the transmission of a few control packets and one data packet.

Here we use an example to show how UPC-MAC works. There are two pairs of senders and receivers, says \( A \rightarrow B \) and \( C \rightarrow D \), in the network. These four nodes are within the maximum transmission range of each other (one-hop network). Here we use \((\text{TYPE})_{\text{sender-receiver}}\) to denote a packet and \( h_{\text{sender-receiver}} \) to denote the channel gain between the sender and the receiver. At the beginning of a slot, \( A,C \) wish to send a packet destined to \( B,D \) respectively.

In UPC-MAC, when a node requires sending a packet, it will wait until the beginning of the next slot and then transmit an RTS packet if the channel is idle. In this case we define the slot when the RTS packets are sent as the first slot. Therefore, at the beginning of the first slot, \( A,C \) send \( \text{RTS}_{A-B}, \text{RTS}_{C-D} \) with the maximum power level, respectively. All the destinations \( B,D \) will receive both of these packets. An RTS packet contains the transmission power level and packet priority. Then, according to the sending and receiving power levels of these packets, node \( B \) can calculate the channel information: \( h_{AB}, h_{CB} \) with Eq. (7); and node \( D \) can calculate the channel information: \( h_{AD}, h_{CD} \). With Eq. (7), receiving nodes can calculate the channel gain based on the sending and receiving power of the signal directly.

\[
    h_i(dB) = p_r(dB) - p_s(dB)
\]  

Fig. 4. UPC-MAC state machine.
where $h_i$ is the channel gain, $p_i$ is the receiving power of the packet which can be calculated by advanced attenuation model and $p_i$ is the transmission power of the packet.

In this paper, Eq. (8) [17] is applied for attenuation as a case study, which can be replaced by any other advanced model.

$$h = 1/A_0d^d\kappa(f)^d$$

where $A_0$ is a unit-normalizing constant; $k$ is the spreading factor; $d$ is the distance between the sender and the receiver and $\kappa$ is the absorption coefficient.

At the beginning of the second slot, the receiving nodes $B$ and $D$ will send a CSI packet respectively with the channel information they got in the first slot. For example, $B$s CSI packet containing the channel information $h_{AB}, h_{CD}$ will be sent to $A$ and this packet can be overheard by node $C$. Node $D$ will send a similar packet to its destination node $C$ which can be overheard by node $A$. At the end of the second slot, node $A$ and node $C$ can set up a channel state matrix $H$ with the CSI packets they collected. Each source node will have an $N \times N$ channel state matrix $H$ as Eq. (9) ($N$ is the number of senders).

$$H = \begin{cases} h_{AB} & h_{CD} \\ h_{CB} & h_{CD} \end{cases}$$

Then each of the sender will use power control algorithm to allocate their transmission power on a DATA packet distributedly. Finally, if a receiver can receive the DATA packet correctly, it will send an ACK packet with the same power as the DATA packet they received. If a node is denied to send a data packet, it will retransmit an RTS packet in the slot after the ACK’s transmission. The state machine of UPC-MAC protocol is shown in Fig. 4.

Based on this scheme, a sender will adjust its transmission power of the DATA packet with a consideration of other nodes transmission request. Finally, more concurrent transmissions can be conducted with a power allocation algorithm, which is shown in the next subsection alongside spatial reuse efficiency can be improved.

4.2. Protocol details

We have given the overall picture of UPC-MAC. In this subsection, we will discuss the detailed design of UPC-MAC.

4.2.1. Power control algorithm

Once a node gets the channel state matrix $H$, it can use a power control algorithm to allocate its transmission power for its DATA packet. In the network, nodes can be treated as rational and selfish users who intend to maximize their individual utilities in a self-interested manner. To optimize the overall network performance, we design a game theory based algorithm to allocate the transmission power. Our goal is in twofold: maximize the network throughput and reduce energy consumption. To fulfill our goals, we define a utility function as Eq. (10). There are two parts including the utility and pricing factors in the utility function. The achievable capacity is approximated by Shannon capacity theory [32]. With an assumption that the available bandwidth $B$ of each user is equal, we omit the bandwidth $B$ when we solve the optimization problem. Therefore, Eq. (10) can be transformed to Eq. (11). The first term of (11) denotes the relationship between capacity of a link and the power. The second part reflects the transmission power on this link. It is a linear function that represents the price for consuming a specific amount of power. $x_i$, the pricing factor with a constant value for all links, denotes the bit price of one unit consuming power which is in unit of [bit/Watt].

$$u_i(p_i, p_{-i}) = B_1 \log(1 + \text{SINR}) - x_i \cdot p_i$$

$$u_i(p_i, p_{-i}) = \log \left( 1 + \frac{h_i \cdot p_i}{\sum_{j=1}^{N-1} h_j \cdot p_j + \sigma^2} \right) - x_i \cdot p_i$$

where $p_i$ denotes transmission power on the link $i$. $p_{-i}$ denotes transmission powers on all the links except link $i$ and $x_i$ is a positive pricing factor.

Therefore the optimization problem can be formulated as (12) and (13):

$$\max u_i(p_i, p_{-i}) \text{; for all } i (1 \leq i \leq N)$$

s.t.

$$p_i \in S_i = [0, P_{\max}] (1 \leq i \leq N)$$

$$\text{SINR}_i \geq \text{SINR}_{th} (1 \leq i \leq N)$$

where $P_{\max}$ is the maximum transmission power determined by hardware design; SINR$_{th}$ is the decoding threshold of the acoustic modem.

The optimization problem can be solved by game theory, and the solution, if feasible, is the one that achieves Nash Equilibrium (NE). Although NE does not always exist, delightedly we can prove that it does exist in our problem. As stated in [33], NE exists only if the following two conditions are satisfied:

1. $S_u$, the set of transmission power for each sender, is a nonempty and convex subset of some Euclidean space.
2. $u_i$, the utility function for each sender, is a continuous and quasi-concave function for independent variable $p_i$.

The first condition is readily satisfied. To prove the second condition is also satisfied, we take the second-order derivation of $u_i$:

$$\frac{\partial^2 u_i}{\partial p_i^2} = -\frac{h_i^2}{(h_i \cdot p_i + \sum_{j=1}^{N-1} h_j \cdot p_j + \sigma^2)^2}$$

Since $\frac{\partial^2 u_i}{\partial p_i^2} < 0$, the second condition is satisfied. Therefore NE exists.

Table 1

<table>
<thead>
<tr>
<th>Mode</th>
<th>Modulation</th>
<th>Payload per block (bytes)</th>
<th>Rate (kb/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>BPSK</td>
<td>38</td>
<td>1.38</td>
</tr>
<tr>
<td>Mode 2</td>
<td>QPSK</td>
<td>80</td>
<td>2.90</td>
</tr>
<tr>
<td>Mode 3</td>
<td>QPSK</td>
<td>122</td>
<td>4.42</td>
</tr>
<tr>
<td>Mode 4</td>
<td>16QAM</td>
<td>364</td>
<td>5.94</td>
</tr>
<tr>
<td>Mode 5</td>
<td>16QAM</td>
<td>248</td>
<td>8.99</td>
</tr>
</tbody>
</table>
The transmission power of each sending node is defined as the players response function as Eq. (15). The best response of each node is the transmission power that maximizes its utility function and satisfies constraint (13).

\[
\frac{\partial u_i}{\partial p_i} = -\frac{h_i}{(h_i \cdot p_i + \sum_{j=1}^{N-1} h_j \cdot p_j + \sigma^2)} - x = 0
\]  

(15)

Solving Eq. (15) gives:

\[
p_i = \frac{1}{x_i} \sum_{j=1}^{N-1} h_j \cdot p_j + \sigma^2
\]

(16)

In order to guarantee \( p_i \leq P_{\text{max}} \), we choose \( x_i = \frac{1}{r_{\text{max}}} \).

To get the matrix expression, we rearrange the terms in Eq. (16) and get a new expression (17).

\[
p_i \cdot h_i + \sum_{j=1}^{N-1} h_j \cdot p_j = \frac{h_i}{x_i} - \sigma^2
\]

(17)

For all the sending nodes, Eq. (17) can be denoted as the following matrix form expression:

\[
H \cdot P' = G
\]

(18)

where \( H \) is the \( N \times N \) channel state square matrix; \( P' \) is the unique NE solution; \( G = [g_1, g_2, \ldots, g_n]^T \) is an \( N \times 1 \) vector, where \( g_i = \frac{h_i}{x_i} - \sigma^2 \). Then \( P' \) can be solved by:

\[
P' = H^{-1} \cdot G
\]

(19)

If the obtained \( p_i \) does not satisfy the constrain (13), it means that the transmissions cannot be conducted concurrently. In that case, the protocol will deny the sending request with the lowest sending priority. Then senders will rerun the power allocation algorithm.

4.2.2. Rate adaptation algorithm

By implementing the power control scheme, we allow for as many concurrent transmissions as possible. However, SINR at the receiver side will change significantly after transmission power is adjusted. To deal with the signal variations, transmission rate should be tuned accordingly. The basic idea of rate adaptation is to estimate the channel condition then adaptively select the best rate out of multiple available transmission rates. For example, the data rate should be increased when the channel state is above a certain threshold to prevent the channel from being underutilized or the data rate should be decreased to achieve a lower bit error rate (BER) performance.

Another advantage of implementing a rate adaptation algorithm for UWSNs is that a proper transmission rate can improve the energy efficiency. Specifically, most energy for underwater sensor nodes is consumed by data transmissions. The total energy for a data transmission mainly depends on the time duration of the transmission rather than the transmission mode it chooses. If the transmission rate can be increased, the sending time can be reduced and finally the energy will be saved. These features motivate us to develop a rate adaptation algorithm coupling with our power control scheme in UPC-MAC.

To adjust the transmission rate according to receiving SINR, adaptive modulation and coding (AMC) technique can be applied in underwater systems. In a typical AMC procedure, a sender will choose a suitable transmission mode with a reported channel condition which is mainly acquired by exchanging control packets. Motivated by the above discussion, in UPC-MAC, since SINR information is already available at the senders, we incorporate a rate adaptation algorithm to UPC-MAC. In this work, we adopt the five transmission modes available on real underwater modem characteristics, specifically, with a newly emerged underwater OFDM modem [14].

An OFDM modem is capable of working at one of the five modes. All the five modes in this modem use LDPC channel codes in GF(4) with different modulation schemes and code rates [31] as shown in Table 1. In OFDM modems, each packet is composed of multiple blocks. The details of the packet format can also be found in [14]. The working mode of OFDM modems is essentially decided by the current SINR, which reflects the current channel condition. In other words, with a higher SINR, modems can choose a more aggressive mode with a higher data rate; otherwise, modems choose a more conservative mode with a lower...
data rate. Inspired by this conclusion, we proposed a method of rate adaptation for underwater OFDM Modem in Eq. (20),
\[
R_t = \begin{cases} 
0, & \text{SINR} < \beta_0 \\
M_k, & \beta_{k-1} \leq \text{SINR} \leq \beta_k, (1 \leq k \leq 4) \\
M_s, & \beta_5 \leq \text{SINR}
\end{cases}
\]  
(20)
where \(R_t\) is the adopted transmission mode; \(M_k\) is one of the five modes of OFDM modems and \(\beta_k (\beta_{k-1})\) is the upper (lower) threshold for setting the modem mode to \(M_k\).

To make the rate adaptation scheme work, we have to decide on all \(\beta_k\). This is achieved with the help of the results from [31]. Fig. 5 shows that given a certain mode, the relationship between SINR and the yielded Block Error Rate (BLER). Therefore, given a predetermined desired BLER, we can decide the thresholds to adopt different modes. As an example, in Fig. 5, given the desired BLER equal to \(10^{-2}\), when SINR is less than \(\beta_0\), UPC-MAC adopts modem mode 0; while when SINR is between \(\beta_0\) and \(\beta_1\), modem mode 1 is adopted.

4.3. Discussion

Besides the overall designs illustrated above, there are some special problems that should be discussed including a special channel state matrix and hidden/exposed terminal problem.

4.3.1. Special channel state matrix

As introduced in the protocol overview section, a channel state matrix should be an \(N \times N\) square matrix. However, in some circumstances, the matrix may not be a square matrix. For an example, in Fig. 7, nodes A and B initial transmissions to the same destination D, and C initial a transmission to F at the same time. Then node D may successfully receive \(RTS_{A\rightarrow D}\) and \(RTS_{B\rightarrow D}\) within the same slot (if two RTS packets collide, A, B will back off to retransmit their requests). At this situation, after receiving these two packets, D will first check priority of the packets and choose the packet with a higher priority, says A, as the potential sender. Then it will set \(h_{BD} = -1\). If \(RTS_{A\rightarrow D}\) and \(RTS_{B\rightarrow D}\) have the same priority, D will choose the one that comes earlier.

Once node B receives the matrix with \(h_{BD} = 0\) as in Eq. (21), it knows that its request is declined this time. Then the matrix can be transferred to a \(2 \times 2\) square matrix as Eq. (22) which can be solved by the proposed power allocation algorithm.
\[
H = \begin{bmatrix} h_{BD} & h_{BF} \\
-1 & h_{HF} \\
h_{CD} & h_{CF} \end{bmatrix}
\]  
(21)
\[
H = \begin{bmatrix} h_{BD} & h_{BF} \\
h_{CD} & h_{CF} \end{bmatrix}
\]  
(22)

4.3.2. Hidden/Exposed terminal problem

As hidden terminal and expose terminal are two major challenges in MAC protocol design, we will discuss how UPC-MAC handles these two problems in the following part.

Hidden terminal: As defined in [34], a terminal is hidden when it is within the range of the intended receiver of a packet but out of range of the sender. As shown in Fig. 6, where A is sending a packet to B and C cannot overhear A transmission. If C sends a packet during this time, there will be a collision at node B. In this case, node C is a hidden terminal.

In UPC-MAC, a sender will send an RTS packet and wait for a CSI packet to decide whether to send a DATA packet or not, which is similar to most reservation based MAC protocols. By exchanging of the control packets, node C knows node A will talk to B and it will defer its transmission. Then, the collisions potentially caused by a hidden terminal can be avoided.

Exposed terminal: Let us consider another situation shown in Fig. 6. We assume that node A wants to send a packet to node B and node D wants to send a packet to node C.

In a traditional RTS/CTS based MAC protocol, node A sends an RTS and waits for B to reply a CTS. Meanwhile, node D could transmit transmits an RTS to C just before A sends the RTS to node B. After receiving the RTS from node D, C transmits a CTS. As overhearing this CTS packet, B will keep silent and not reply A, although concurrent transmissions from node D to node C would not have interfered with transmission from A to B. Here we define node B as an exposed terminal.

However, for UPC-MAC protocol, we use CSI packets to replace CTS packets, which means that node B may not prevent its transmission of \(CSI_{B\rightarrow A}\) packet after receiving a \(CSI_{C\rightarrow D}\) packet from node C. For this case, in the first slot, node B will receive an \(RTS_{A\rightarrow B}\) packet, and it will send a \(CSI_{B\rightarrow A}\) packet in the second slot. With this \(CSI_{B\rightarrow A}\) packet, sender A knows that B receives no other RTS packet except \(RTS_{A\rightarrow B}\), so it knows that the data packet which will be transmitted in the next slot will not cause any collision at node B.

Based on the analysis above, we can conclude that UPC-MAC is able to handle both hidden terminal and exposed terminal problems effectively.

5. Simulation results

In this section, we evaluate the performance of UPC-MAC protocol and compare it with Slotted FAMA (SFAMA). The performance metrics are (a) the network goodput, which is measured as the number of successful data transmissions per unit time; (b) end-to-end delay, which is measured as the average delay of a certain number of packets; (c) the relative frequency of concurrent communications, which is measured as the ratio between the number of concurrent communications and the number of total transmissions, and (d) relative energy consumption which is measured as the ratio between the energy consumption of UPC-MAC and that of Slotted FAMA for the same number of transmitted packets.

The following simulations are conducted by Aqua-sim simulator, which is an NS-2 based simulator for UWSNs [35]. We modify some modules in Aqua-sim so that we can adjust the transmission power, the transmission rate and corresponding transmission range. The simulation
parameters are in accordance with the hardware specifications of the underwater OFDM modems which are listed in Table 2.

5.1. One hop network scenario

In the one-hop network scenario, each node is within the maximum transmission ranges of all the other nodes in the network. In other words, all the exchanged control packets sent with the maximum power can be received by each terminal. We model this scenario in our simulation as follows. Six sensor nodes are deployed in an area of $2000 \text{ m} \times 3000 \text{ m}$ and further divided into six square areas with $1000 \text{ m} \times 1000 \text{ m}$. Each sensor node is deployed in the middle of a square field as shown in Fig. 7 (as in many monitoring applications, each sensor node is anchored by a buoy for monitoring a certain area). Nodes $A, B, C$ are source nodes and nodes $D, E, F$ are destinations. Each source node generates packets according to a Poisson process with a rate $\lambda / (\text{packets} / \text{s})$. For each generated packet, the destination is randomly selected from $D, E, F$.

Fig. 8 depicts the network goodput with varying packet generation rate for the two target MAC protocols, Slotted FAMA and UPC-MAC. To show the effect of applying the rate adaptation algorithm, we also compare UPC-MAC with and without the rate adaptation (RA) algorithm in Fig. 8. This figure shows that UPC-MAC achieves about 20% improvement in network goodput over Slotted FAMA when both of them reach the maximum goodput at a 100B packet length. For a longer packet length scenario, UPC-MAC can achieve about 15% improvement at 500B packet length. This improvement comes from the concurrent communications of UPC-MAC. We can also observe that UPC-MAC with rate adaptation algorithm achieves a similar goodput performance compared to the protocol without rate adaptation. The reason is that even when UPC-MAC adopts rate adaptation algorithm, it does not shorten the time slot used for data transmission nor change the frequency of the concurrent communications. These two main factors affecting the goodput of the network. By contrast, in the one-hop network scenario, Slotted FAMA does not enable any concurrent communication to avoid possible collisions. Since the frequency of concurrent communication mainly depends on the network topology and the traffic pattern of the network, different packet lengths yield similar frequency of concurrent communications, as shown in Fig. 10(a) and (b). The reason that packet length has little impact on the frequency of concurrent communication is that even the longest packet, which is a 500B packet, can still be sent in one slot according to the data rate of the OFDM modem. Therefore the relative frequency of concurrent communication only depends on the senders’ positions and their packet sending frequency. However, the packet length does affect the goodput, as shown in Fig. 8, where a larger packet length leads to a higher goodput.

From Fig. 10(a) and (b) we can also conclude that when the packet generation rate reaches 0.1 packet/s, the relative frequency of concurrent transmissions becomes stable. It is because this is the maximum number of concurrent transmissions that can be handled. At this situation, the number of transmissions cannot be increased by adjusting the power level. That is to say that all the senders make a full use of spatial resource. Thus, the goodput curve becomes flat when the packet generation rate reaches 0.1 packet/s. Due to the same reason, the curves in Fig. 8 depicts the same trend.

Since the end-to-end delay is another critical performance of network, we compare it between UPC-MAC and SFAMA (50 packets/ delay are compared). Fig. 9 shows that
UPC-MAC can achieve a better end-to-end delay performance compared to SFAMA at two different packet lengths. The reason is that some simultaneously transmitted packets reduce queueing delay which further results in a shorter end-to-end delay in UPC-MAC. We also observed that, all these four curves start from about 30 s. Such delay mainly results from the delay of hand-shaking process of both protocols.

5.2. Multi-hop network scenario

Since multi-hop UWSNs are generally more useful for underwater applications, it is necessary to evaluate the performance of the UPC-MAC in such a generic scenario.

As shown in Fig. 11, we are now looking at a multi-sink network. Sinks $D_1 - D_3$ are deployed on the surface of the water. Other nodes are deployed in the 3-D area. We assume that three bottom nodes, $S_1 - S_3$, are data sources and $R_1 - R_6$ are relay nodes. Given the observation that the performance of UPC-MAC are related to the network topology, we evaluate the two protocols in a dense and a sparse topology respectively. Similar to the one-hop network, each sensor node is deployed in the middle of each cubic field with the size $1000 \times 1000 \times 1000$ m for a dense topology and $1500 \times 1500 \times 1500$ m for a sparse topology. Each source node generates packets according to a Poisson process with a rate $\lambda$ (packets/s).

The network goodput is shown in Figs. 12 and 13 with varying packet generation rates for the two target MAC protocols, Slotted FAMA and UPC-MAC (both with/without
RA are depicted). As the same trend of one-hop network, this figure shows that UPC-MAC achieves a better network goodput performance compared to Slotted FAMA at different packet lengths in both dense and sparse networks. The difference observed between our one-hop and multi-hop network topology is a larger increase in goodput, namely 68% at 100B and 48% at 500B of the packet length in the dense network; 52% at 100B and 40% at 500B in the sparse network. It shows that UPC-MAC will benefit more in a large scale network.

By comparing the goodput performance in Fig. 12 and that in Fig. 13, we can conclude that UPC-MAC shows a better performance improvement in a denser network. For example, for 500B data packet, UPC-MAC outperforms SFAMA about by 68% in the dense network compared to 52% in the sparse network. The reason is that, in the dense network, the potential collision between nodes are more frequent than that in the sparse network. The transmission with power control can play a more significant role in dense networks.
The improvements of the network performance also come from better spatial reuse efficiency. But different from one-hop scenario simulation, both UPC-MAC and Slotted FAMA allow concurrent transmissions in this multi-hop network simulation. This is due to the possibility that concurrent transmissions may not cause collisions even though they are transmitted with a fixed maximum power. For example, $S_1 \rightarrow R_1$ and $R_3 \rightarrow D_3$ can send packets simultaneously with the maximum power level. So it is necessary to compare the relative concurrent transmission frequency between SFAMA and UPC-MAC as shown in Fig. 14 with different packet length. These two pairs of comparison figures show that UPC-MAC allows for more concurrent transmission compared to Slotted FAMA with different packet length. These four figures also illustrate that the packet generation rate at which the network reaches its maximum capacity.

Furthermore, we compare the end-to-end delay performance in the two networks. Both Fig. 15(a) and (b) show that UPC-MAC can largely reduce the end-to-end delay of the networks. By comparing Fig. 15(a) and (b), we also conclude that UPC-MAC shows a even better end-to-end improvement in a denser network topology. For example, for 500B data packet, UPC-MAC decrease the end-to-end delay about by 58% in the dense network while 36% in a sparse network.

5.3. Energy consumption

Energy efficiency is the motivation behind our rate adaptation scheme. By implementing the proposed rate adaptation algorithm, UPC-MAC achieves not only a larger network goodput, but also a smaller energy consumption.

$$R_e = \frac{E_{UPC}}{E_{SFAMA}}$$

Fig. 16(a) and (a) plot the relative energy consumption ($R_e$) or normalized energy consumption, which is calculated by Eq. (23). $E_{UPC}$ is the total energy consumption by UPC-MAC. $E_{SFAMA}$ is the total energy consumption by SFAMA without power control.

From both Figures, we observe that (a) Both UPC-MAC with/without RA outperform SFAMA in terms of energy consumption. (b) UPC-MAC with the proposed RA can achieve a better energy efficiency compared to that without RA. However, in Fig. 16, UPC-MAC with/without RA show different trends with increasing packet generation rate. For UPC-MAC with RA, senders should lower their sending power and rate to avoid collisions at a heavy traffic load. A lower sending rate means a longer transmission time which leads to an increased energy consumption even when a lower sending power is adopted. By contrast, for UPC-MAC without RA, senders only reduce their sending power at the same situation. As a result, with an increasing packet generation rate, the energy consumption can be reduced. By comparing the $R_e$ for dense and sparse networks, we observe that UPC-MAC with RA shows more advantages in sparser network. The reason is that UPC-MAC with RA tend to adopt more aggressive transmission mode in sparse network which results in a much lower energy consumption.

6. Conclusions and future work

In this paper, we first define a new metric, spatial reuse index, to introduce the necessity of power control in UWSNs. To address this problem we propose a MAC protocol UPC-MAC to improve the goodput and save energy by power control and rate adaptation. UPC-MAC makes use of control packets to collect sending request and channel condition to adjust the transmission power and data rate. All the nodes can allocate their transmission power and transmission rate distributedly by running a game-theory based power control algorithm and an acoustic OFDM modem based rate adaptation algorithm. This scheme enables as many concurrent transmissions as possible. Simulation results show that UPC-MAC improves the network goodput and save energy both in one-hop and multi-hop networks.

Regarding future works, due to the performance of UWSNs being highly dependent on network’s topology, it is important for us to research a joint design of deployment and power control channel access algorithm. Furthermore, with considering a highly dynamic network, the underwater channel state may not be strictly stable during the packets transmissions. Therefore an implementation of channel estimation algorithm will improve the performance of the proposed MAC protocol.
Acknowledgments

This work was supported in part by the National Natural Science Foundation of China through the Grants 61162003, 61202379 and Qinghai Science and Technology Project No. 2012-Z-902. This work was done in UWSNs lab at UCONN during the visiting scholar program for the doctoral student funded by China Scholarship Council. Thanks Robert Martin for paper revision and grammar check. This paper is an extended version of [15].

References


Yishan Su is a Ph.D. candidate at the school of Electronic and Information Engineering, Tianjin University. Currently, he is working as a visiting student at the Underwater Sensors Networks Lab at University of Connecticut. He received the B.E. and M.S. degree from Tianjin University in 2008 and 2010. His research interests include protocols design and implementation in underwater sensor networks (UWSNs) and delay/disruption tolerant networks (DTN).

Yibo Zhu received the B.Eng. and M.Eng. degrees in computer science, both from Xi’an Jiaotong University, China, in 2006 and 2009, respectively. Currently, he is pursuing the Ph.D. degree and working as a research assistant at the Underwater Sensor Network (UWSN) Lab, University of Connecticut. His main research interests include simulation and MAC/Routing protocol design for underwater acoustic networks. He is a student member of IEEE.
Haining Mo received his M.E. from Computer Science and Technology, Harbin Institute of Technology, Harbin, China in 2006. He is currently working towards his Ph.D. degree in the Department of Computer Science and Engineering at the University of Connecticut. His research interests include reliable data transfer, medium access control and protocol design, implementation and test in Underwater Acoustic Networks.

Jun-Hong Cui received her Ph.D. degree in Computer Science from UCLA in 2003. Currently, she is a Full Professor in the Computer Science and Engineering Department at University of Connecticut (UConn). She also served as the Assistant Dean for Graduate Studies and Diversity of School of Engineering at UConn from 2009–2012. Her research interests cover the design, modeling, and performance evaluation of networks and distributed systems. Currently, her research mainly focuses on algorithm, protocol and system design and development in underwater sensor networks, autonomous underwater vehicle (AUV) networks, and distributed cyber-aquatic systems. She has also been conducting active research on smart health and smart transportation systems. At UConn, she leads UbiNet (Ubiquitous Networking) Lab and UWSN (UnderWater Sensor Network) Lab. More recently, she has been leading the efforts to launch an NSF I/UCRC (Industry/University Cooperative Research Center) on Smart Ocean Technologies, in collaboration with University of Washington. She is actively involved in the community as an organizer, a TPC member, and a reviewer for numerous conferences and journals. She served as an Associate Editor for Elsevier Ad Hoc Networks from 2007 to 2013. She co-founded the first ACM International Workshop on UnderWater Networks (WUWNet’06), which now has become a stand-alone conference. She has been serving as the WUWNet steering committee chair. Jun-Hong received 2007 NSF CAREER Award and 2008 ONR Young Investigator Award. She also received the United Technologies Corporation (UTC) Professorship in Engineering Innovation award at UConn in 2008 and UCLA Engineering Distinguished Young Alumnus Award in 2010.

Zhigang Jin received his B.E. degree from Hebei University of Technology, Tianjin, China, in 1993, M.E. degree from Tianjin University, Tianjin, China, in 1996 and Ph.D. degree from Tianjin University, Tianjin, China, in 1999. He was a visiting professor in Ottawa University, Ottawa, Canada, in 2002. He is currently a professor in Tianjin University, Tianjin, China. His research interests focus on the performance evaluation of traffic and networks, the management and security of the computer networks, and the wireless networks.