A Channel Sharing Scheme for Underwater Cellular Networks

Borja Peleato and Milica Stojanovic
Massachusetts Institute of Technology
borjapeleato@yahoo.es, millitsa@mit.edu

***Abstract*— We propose a channel-allocation and scheduling protocol for underwater acoustic cellular networks. The protocol exploits both the acoustic path loss and the long propagation delay of the underwater channel to enable efficient use of system resources. By scheduling co-channel transmissions to avoid strong interference, it allows grouping of the cells into small clusters, thus achieving higher efficiency than a conventional scheme based on spatial frequency (or code) reuse alone.**

I. Introduction

Recently, there has been a growing interest in wireless sensor networks for underwater applications. However, acoustic propagation imposes fundamental challenges on the communication system design, making these systems very different from their terrestrial counterparts. In particular, the underwater channel is characterized by low bandwidth and long propagation delay. In addition, the currently available underwater modems are half-duplex, and the power required for transmission is usually much higher than that required for reception.

Sound propagates through water at approximately $c = 1500$ m/s, and is absorbed at a rate

$$A[\frac{dB}{km}] = 0.11\frac{f^2}{1+f^2} + 44\frac{f^2}{4100+f^2} + .000275 \cdot f^2 + .003 \quad (1)$$

where f represents the signal frequency in kHz. For longer distances, the useful bandwidth narrows, and the propagation delays become too long to be neglected (as it is the case in radio environments.)

When the coverage area of the network is large, one may want to consider a cellular type of network architecture. The area is divided into clusters, each containing a number of cells, and the available bandwidth is reused across clusters. Each cell has a base station through which the distributed nodes communicate. Communication between base stations is established through a separate link, enabling the nodes of different cells to communicate with each other. Base stations can be mounted on buoys, so as to offer an efficient RF link between distant cells, a GPS positioned reference, or a gateway towards another network. Two types of communication are possible: from the base station to the nodes (downlink) or from the nodes to the base station (uplink). A duplexing method, such as time or frequency division duplexing (TDD,FDD) can be used to distinguish between the two directions of communication. The method used to enable multiple access between the distributed nodes and the base station is traditionally chosen as time, frequency, or code division multiple access (TDMA,FDMA,CDMA).

In cellular radio systems, the network relies on a frequency allocation scheme to enable spatial reuse of bandwidth. The total available bandwidth is divided among N cells, which form a cluster. Clusters are designed so as to maximize the distance between cells using the same frequency band (co-channel cells.) For a two-dimensional geometry with hexagonal cells, the number N of cells in a cluster must satisfy the following equation [2]:

$$N = i^2 + ij + j^2 \quad (2)$$

where i and j are integers.

In radio networks, the attenuation of the signal is mainly caused by spreading, which grows with distance as d^α, where α is the path loss exponent. Therefore, the co-channel signal to interference ratio (SIR) only depends upon the relative distances between the nodes. As a result, the SIR does not depend on the cell radius, but only on the number of cells per cluster N. In the underwater environment, however, absorption also plays an important role, and the path loss exponent is lower than that of a radio channel. Consequently, both the signal frequency and the absolute distances affect the SIR. Short radii and low carrier frequencies may require a large reuse number N, which leads to inefficient system operation. To overcome this limitation, we propose a hybrid system design, in which time-scheduling accompanies frequency reuse.

The paper is organized as follows. Section II gives the general structure of the proposed scheme. Sec.III presents a case study to illustrate the protocol performance. In Sec.IV, selection of the protocol parameters is addressed. Finally, Sec.V provides numerical examples for the interference level, and Sec.VI summarizes the conclusions.

II. Protocol Description

The long delays in an underwater channel allow simultaneous transmissions within reach of one another, so that the packets cross in the middle without interfering at their respective receivers. This fact provides an advantage over half-duplex radio channels. Theoretically, all the M nodes in a fully connected underwater network can achieve a time efficiency of 1/2, while in a half-duplex radio environment with negligible delays the upper bound would be 1/M. A very simple example of this principle is shown in Fig. 1. A total of nine packets are

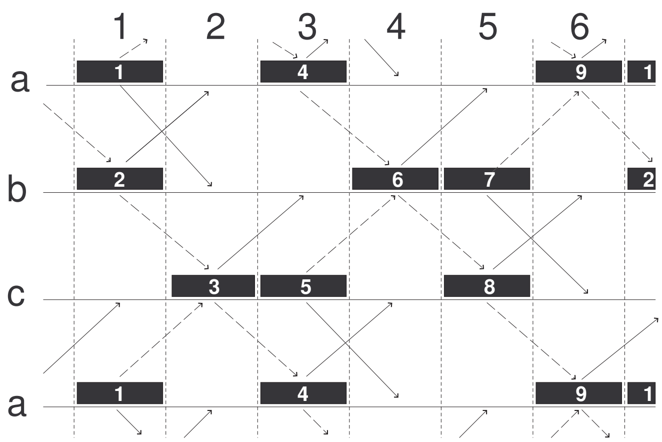

Fig. 1. Period of six time slots in a transmission schedule. Nodes a, b and c are located at the vertices of an equilateral triangle. Slots, packets and propagation delays between any two nodes all have the same duration. Solid lines indicate the destination of each packet, and dashed lines indicate the interference that they create.

exchanged in six time slots, of the same length as the packets. In contrast, only one packet can be transmitted in each slot in a half-duplex radio environment.

By applying this strategy to a cellular network, the interference from the closest co-channel cells can be avoided. In turn, frequency reuse can be performed more efficiently by using fewer cells per cluster.

We consider a shallow water network of hexagonal cells of radius R, each with a base station in the center, and users arbitrarily deployed. All nodes are half-duplex and use the same transmission power. Base stations must be loosely synchronized to a common clock. The link can either be unidirectional (only uplink or only downlink) or bidirectional. The network relies on a frequency reuse scheme, such that the same band is reused after a distance D. (Without the loss of generality, spatial reuse based on code allocation in a spread-spectrum system can be assumed instead.) The total available bandwidth B is divided among N_h cells, which form a cluster similarly as in a conventional cellular system.

We establish a transmit/receive sleep schedule so that the closest co-channel cells do not interfere during the listening period and interferences add up during the remainder of the slot. The sleep period introduces a time inefficiency, but improves the bandwidth efficiency by reducing the number of cells per cluster with respect to that of a conventional scheme.

Let N be the minimum number of cells per cluster that a conventional scheme requires to achieve a certain SIR_0, and $N_h \leq N$ the cluster size chosen for our scheme. The minimum distance between two co-channel cells in our scheme is $D = R\sqrt{3N_h}$. The time it takes the signal to propagate between the base station and the cell edge is given by $T = R/c$. Assuming the same communication direction for both cells (either uplink or downlink), the time needed for the interference to reach the other cell's receiver is at least $(D-R)/c$. If both transmissions start at the same time, we can only guarantee absence of collision for the packets transmitted during the first $(D-2R)/c$ seconds.

When the base station communicates with nodes located close to the cell edge, the signal level is much lower than that received by a node closer to the center. Therefore, the nodes close to the base station can tolerate higher interference levels than those that are far. If the base station knows its nodes' distances, it can lengthen the active interval in the schedule by a factor of $X \geq 1$. The first $(D - 2R)/c$ seconds will be free from strong interference, allowing the base station to communicate with the farther nodes. The rest of the interval will have stronger interference and it will be left for closer nodes. The transmission/reception time is thus set to $X(D - 2R)/c$, where X can be 1 if the distances between the cells and the base station are unknown, or the interference level tolerated is the same for all the nodes.

After the transmission, a waiting period is introduced to allow the interference to pass before starting a new transmission. The distances to the different tiers of co-channel cells are given by

$$R\sqrt{3k \cdot N_h} \tag{3}$$

where k is given in the form (2).

Let us denote by k_0 the greatest k for which the interference needs to be eliminated in order to achieve the required SIR_0. The waiting time is then set to $R\sqrt{3k_0N_h}/c$, the minimum needed to guarantee the absence of harmful interference for the nodes at the cell edge.

The efficiency is given by

$$\eta_{hybrid} = \eta_{time} \cdot \eta_{freq} = \frac{(D-2R)X}{(D-2R)X + D'} \cdot \frac{1}{N_h} \tag{4}$$

where $D' = R\sqrt{3k_0N_h}$ is the distance to the farthest interfering cell whose interference must be avoided. Comparing the efficiency of our scheme when $X = 1$ with that of a conventional scheme, the former is higher only when the conventional scheme requires $N \geq 19$, i.e. for small cells, low frequencies and/or high SIR requirements. If X can be increased, our scheme outperforms the standard cellular system in the majority of scenarios.

III. Case study

We will divide the cells into two areas ($X = 2$). The active transmitting interval will thus have two parts: the first interval lasting $(D - 2R)/c$ seconds, with low interference, will be reserved for nodes farther than $R\sqrt{2}/2$ from the base station (outer nodes), and the second interval, with strong interference, will be used to to communicate with the rest of the nodes (inner nodes). Assuming a uniform distribution of the nodes over the cell, half of them will be in the inner region and the other half in the outer region. Below, we describe in detail the schedule for each type of communication: downlink, uplink, and bidirectional.

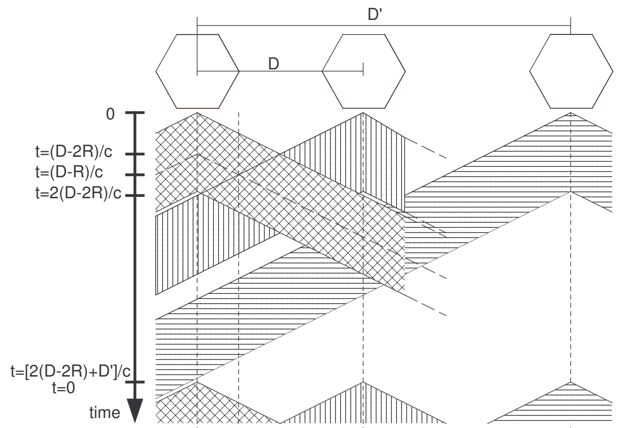

Fig. 2. Illustration of the downlink schedule when $X = 2$. All three base stations transmit simultaneously using the same channel. Nodes in the outer region receive their packets (first half of the transmission slot) without interference.

A. Downlink

All co-channel base stations start transmitting packets for their outer nodes at $t = 0$, and continue doing so until $t = (D - 2R)/c$. At that point, they start transmitting the packets for the inner half of the nodes during another $(D - 2R)/c$ seconds. A node located on the edge of the cell will hear the first group of packets between $t = R/c$ and $t = (D - R)/c$. The interference from the closest co-channel cell will reach it after $t = (D - R)/c$; hence, there will be no overlapping.

The distance to the farthest co-channel cell whose interference needs to be avoided is D' (distance between the centers of both cells). Its interference will reach the edge of our cell at $t = (D' - R)/c$. The signal only lasts $2(D - 2R)/c$ seconds, but it has to traverse the entire cell, so it will not be over until $t = (2(D - 2R) + D' + R)/c$. After that, the outer nodes can start receiving without interference again. Consequently, the base station should start a new transmission interval at $t = (2(D - 2R) + D')/c$. Fig. 2 illustrates the scheme.

In summary, the base station transmits from $t = 0$ to $t = (D - 2R)/c$ to the outer nodes, and from $t = (D - 2R)/c$ to $t = 2(D - 2R)/c$ to the inner nodes. The new transmission interval starts at $t = (2(D - 2R) + D')/c$.

B. Uplink

In the uplink case, the schedule is more complicated. A transmission can originate from any point within a cell, and the base station must receive the packets from outer nodes without interference.

The schedule for the downlink case increased the efficiency by doubling the length of the transmission interval with respect to the one with $X = 1$; similarly, the length of the receiving interval is now doubled. If the base station multiplexes its users in a TDMA frame, it suffices to assign slots during the first half of the $2(D - 2R)/c$ receiving period to outer nodes, and the rest to the inner nodes. Once the receiving period is over, the base station will stay idle for D'/c seconds.

If, on the other hand, the base station assigns a sub-band (or code) to each node, doubling the length of the receiving period does not improve the efficiency because it will only be receiving from half of the nodes at any given time. The improvement then comes from reusing the same code (or sub-band) for two nodes located in different areas (inner and outer.) The schedule is the following: all nodes transmit during $(D - 2R)/c$ seconds, but those located in the outer region start at $t = (R - r)/c$ and those in the inner region start at $t = (D - R - r)/c$, where r is the distance from the node to the base station. After a node stops transmitting, it waits for $(D - 2R + D')/c$ seconds and starts the cycle again.[1]

C. Bidirectional

If time division duplexing for bidirectional communication is needed with half-duplex underwater modems, the preceding two schemes can be alternated. With an idle time of $(D' - R)/c$ seconds after the downlink slot, and $(D' + R)/c$ seconds after the uplink slot, the efficiency does not change.

IV. Protocol implementation

The cell radius is usually limited by the number of base stations or the user density, but it should be chosen as small as possible to maximize the user capacity of the network. The carrier frequency, on the contrary, must be as high as possible to increase the absorption of the interference, but we must not forget that the useful signal will also be more attenuated at a higher frequency.

Once the SIR threshold for correct reception, the cell radius, and the carrier frequency are set, the first step is to find the cluster size that a conventional scheme would require, namely N. This will indicate the nearest layer whose interference can be tolerated. Given the value for N, the direct approach would be to choose N_h and k_0 for the hybrid scheme such that $N_h k_1 \geq N$, where k_1 is the next term after k_0 in the sequence given by Eq.(2).

However, the choice of N_h and k_0 is not an easy one. Due to the non-linearity of the problem, some configurations provide lower interference, while others exhibit interference peaks during the receiving interval. In the conventional scheme, the second layer of interference is usually neglected because it is always $\sqrt{3}$ times farther than the first. In our scheme, on the contrary, both layers can be very close and not all layers contribute with the same number of cells. Consequently, several layers have to be considered, resulting in many variables that have to be taken into account to obtain a general expression for the optimal N_h and k_0. For example, $(N_h, k_0) = (3, 3)$ has the closest layer of co-channel interference at a distance of $6R$ (which corresponds to a conventional scheme with N=12), and the second at a distance of $8R$ (N=21 in a conventional scheme). However, the second layer contributes with 12 cells, while the first one has only 6. If the frequency is low or the

[1] When no downlink is needed, the efficiency can be further increased by having the inner nodes transmit during $t \in ((-R + r)/c, (R - r)/c)$ and finish $2(R - r)/c$ seconds earlier. The waiting period in this case is nearly $T = R/c$ seconds shorter.

cell radius small, the interference from the second layer can be stronger than the one from the first. Hence, the best option for a practical implementation would be to calculate the interference for all combinations of (N_h, k_0) and choose the best one.

N	$\eta_{conventional}$	N_h	k_0	η_{hybrid}
3 4 7		need X >2		
9	11.1%	3	1	13.3%
12	8.3%	4	1	11.5%
13	7.7%	3	3	9.3%
16	6.3%	3	3	9.3%
19	5.3%	3	4	8.3%
21	4.8%	4	3	8.2%
>21		no need to divide the interval ($X = 1$)		

TABLE I

OPTIMAL N_h AND k_0 FOR R=1KM AND f=22KHZ WHEN $X = 2$.

Table I lists the combinations for $X = 2$ which give the best efficiency while keeping the SIR for outer nodes greater than that achieved by the conventional scheme. Cell radius of 1 km and carrier frequency of 22 kHz are assumed.

For very small values of N (under 7), it is impossible to protect all the nodes in the outer half of the cell from interference while keeping the efficiency higher than in a conventional scheme. X should then be increased to 3 (1/3 of the active period is free from interference) or higher.

If more than 21 cells per cluster are needed in a conventional scheme (likely if the cells are small), X can be reduced to 1. The efficiency will be lower, but the base station no longer has to make any distinction between the nodes. Additionally, it would be possible to implement a transmission power control mechanism because the protocol no longer assumes higher power received over short links.

V. RESULTS

This section presents several numerical examples. We assume practical spreading with α=1.5, and absorption according to the expression (1).

We assume that the cell radius is 1 km and the carrier frequency is 22 kHz (absorption occurs at 5 dB/km at this frequency). We will compare the interference level with the (3,3) hybrid scheme to that of a conventional scheme with $N = 16$.

Fig. 3 shows the interference level at the center, side and vertex of a hexagonal cell in the case of downlink transmission. The closest interfering layer during the first half of the active interval will be at least $\sqrt{3 \cdot 12}$ km away (k_1=4). The resulting SIR should be equivalent to that of a conventional scheme with $N = 12$. However, despite the fact that the schedule is designed to avoid interference only from the first two co-channel cell layers (k=1,3), this particular design also avoids the interference from the third layer (k=4). Furthermore, the long gap between the third and fourth layers (k=4 to k=7) enhances the SIR improvement.

The efficiency is given by

$$\eta_{hybrid} = \frac{1}{N_h} \frac{2\sqrt{3N_h} - 4}{2\sqrt{3N_h} - 4 + \sqrt{3N_h k_0}}$$

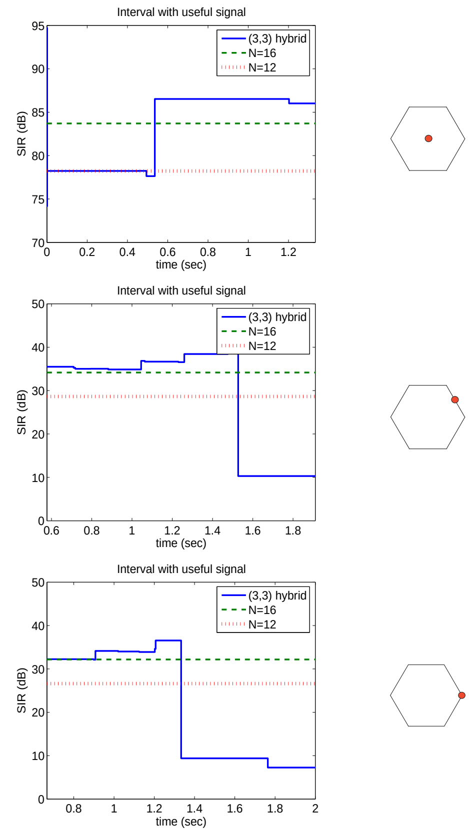

Fig. 3. Downlink SIR at three points of a cell during the receiving interval. The packets for outer nodes are sent during the first half of the interval, while those for nodes closer to the center of the cell are sent during the second half.

The efficiency is 9.3%, which is higher than the 8.3% of an N=12 conventional scheme (a 10% improvement). Compared to an N=16 conventional scheme, the efficiency is improved by 50%. The hybrid scheme also achieves a higher SIR than either of the conventional schemes: there is 3 dB improvement over the N=12 conventional scheme, and a 10 dB improvement over the N=16 conventional scheme.

Additionally, the first plot of Fig.3 shows that the signal to interference ratio in the central region is high during the second half of the interval. Therefore, the inner nodes can also receive their packets without strong interference, thus allowing the base station to reduce its transmission power if necessary. This holds as long as $N_h \leq 4$.

The results for the uplink case are similar. Fig.4 shows the interference level in the worst case (minimum distance to the transmitter in each co-channel cell). During the first half of the receiving period, the base station barely hears any interference. This is the interval during which the weak packets from far nodes arrive, while those from nodes in the inner region will arrive during the second half. It may seem that the interference during the second half of the interval is too high even for the nodes close to the center, but this is mainly due to the fact that we are plotting the worst case. If necessary, the interference could be reduced at the cost of some efficiency by increasing N_h.

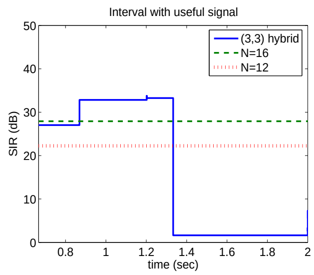

Fig. 4. SIR during the receiving period at the base station (uplink). The useful signal is assumed to be originated at the cell edge. During the first half of the interval, while the interference is weak, packets from outer nodes are received.

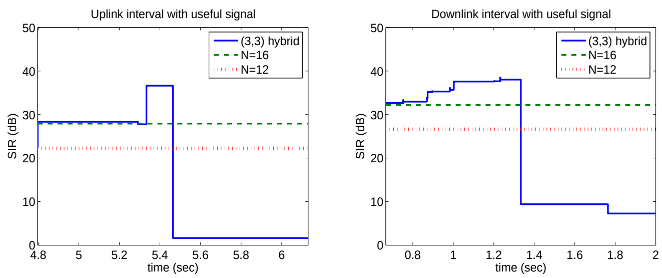

Fig. 5. SIR at the base station (left) and at the cell edge (right) during the receiving intervals of a bidirectional (3,3) hybrid scheme. The cell radius is 1km and the worst case is assumed for the uplink scheme.

Finally, Fig. 5 shows the results for the bidirectional case, which are very similar to the ones already presented.

When distances are short or the center frequency is low, the absorption is nearly negligible. The network must then rely on spreading to attenuate the interference. However, spreading in the underwater environment is slow, and large clusters are usually required. For example, a conventional scheme requires at least 31 cells per cluster to achieve SIR>15dB with a cell radius of 1km and carrier at 10kHz.

Our protocol can provide considerable improvements in such cases. The number of different sub-channels can be as small as necessary and the efficiency is higher. For example, when X=2, $(N_h, k_0) = (4, 9)$ offers SIR>15dB for both uplink and downlink with an efficiency 70% higher than the conventional scheme with $N = 31$.

If the base station does not know the distance to each node, X must equal 1. In such case k_0 can be smaller because by reducing the length of the transmission interval, the overall interference created will also decrease. When X=1, $(N_h, k_0) = (4, 7)$ offers SIR>15dB with an efficiency 7% higher than with the conventional scheme. Smaller cells, higher SIR requirements, or lower frequencies would require larger clusters for the traditional scheme. The efficiency gained with our scheme would then be greater.

VI. Conclusion

A channel sharing protocol for underwater wireless sensor networks based on a cellular type of architecture was proposed. The protocol takes advantage of the long delays and signal absorption in the underwater channel, resulting in an increased efficiency of bandwidth utilization as compared to the traditional frequency reuse scheme. Instead of relying only on frequency reuse over clusters of cells, a timing schedule is assigned to each cell, effectively reducing the number of cells needed per cluster, thus increasing the bandwidth efficiency. In addition, if the base station knows the distance to each of the users, the efficiency can further be increased by exploiting the fact that the nodes closer to the base station can tolerate higher interference levels than those at the cell edge.

Moreover, this scheme can achieve a desired SIR without having to use a large number of cells per cluster, which may be the case with a traditional system. By reducing the size of the cluster or the cell radius and compensating for the SIR loss by means of the schedule, our protocol increases the user capacity, i.e. the density of users that can be supported in the network.

The proposed scheme requires the base stations to be synchronized to a common time base, but only in a very loose way, as the slot lengths are on the order of seconds. It also requires the base stations to be able to estimate the distance to each of the users, which can be done by measuring the round trip delay. If a base station cannot estimate the distance to its users, the achievable efficiency is reduced by a factor of 0.75, making the scheme beneficial only for networks with very small cells or high SIR requirements.

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