A Channel-Sharing Scheme for Underwater Cellular Networks

Taking Advantage of the Long Propagation Delays in The Design of Underwater Half-Duplex Cellular Networks

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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 (radio) 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; that is, they cannot transmit and receive data concurrently.

When the coverage area of a network is large, one may want to consider a cellular type of network architecture. In such an 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, and communications between base stations are established through a separate link. Base stations can be mounted on buoys so as to offer an efficient radio link between distant cells, a global positioning system-positioned reference or a gateway to another network. Two types of communications are possible: from the base station to the nodes (downlink) or from the nodes to the base station (uplink).

In cellular radio systems, different frequency bands are assigned to close cells. The total available bandwidth is divided among the number, N, of cells, which form a cluster. Assuming a 2D geometry with hexagonal cells, the number of cells in a cluster that minimizes the interference is of the form: $N=i^2+ij+j^2$, where i and j are integers.

The attenuation of signals with distance in the underwater environment is slower than in the radio environment, especially at the more commonly used low-carrier frequencies. Consequently, networks with short cell radii may require a large reuse number, which leads to inefficient system operation. However, this limitation can be overcome by means of a hybrid system design in which time scheduling accompanies frequency reuse.

Protocol Description

The long propagation delays in an underwater channel allow simultaneous transmissions between nodes that are a certain distance apart, so that their signals do not interfere. This is achieved by making the packets cross in water, so that each packet reaches its respective receiver at a different time than any of the others. 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.

Consider a shallow-water network of hexagonal cells of radius R, each with a base station in the center and with 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 network relies on a frequency reuse scheme, such that the same band is reused in different cells at least D meters apart (without the loss of generality, spatial reuse based on code allocation in a spread-spectrum system can be assumed instead). The total available bandwidth is divided among N_h cells, which form a cluster similar to that in a conventional cellular system.

The signal quality is measured in terms of the signal-to-interference ratio (SIR), where SIR_0 denotes the minimum ratio required for correct reception. Let N be the minimum number of cells per cluster that a conventional scheme requires to achieve SIR_0, and $N_h<N$ the cluster size chosen for the hybrid scheme. This decrease in N shortens the distance to the interfering cells. Hence, a transmit/receive sleep schedule must be established 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 minimum distance between two co-channel cells is D=R[Sqaure root of] $3N_h$. The time it takes the signal to propagate between the base station and the cell edge, T=R/c, where c=1,500 meters per second, denotes the nominal speed of sound in water. 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, absence of collision can only be guaranteed 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 from it. If the base station knows its nodes' distances, it can lengthen the active interval in the schedule by a factor of X greater than or equal to one. 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.

After the transmission, a waiting period is introduced to allow the interference to pass before commencing a new transmission. The length of this wait-time is set to R [square root of] (($3k_0N_k$)/c), where k_0 should be chosen as the minimum needed to guarantee the absence of harmful interference for the nodes at the cell edge.

The efficiency is given by: $\eta_{hybrid}=\eta_{time}\bullet\eta_{hybrid}=((D-2R)X)/((D-2R)X+D')\bullet(1/N_h)$, where D' is the distance to the farthest interfering cell whose interference must be avoided.

The choice of N_h and k_0 is not an easy one. Due to the nonlinearity of the problem, some configurations provide lower interference, while others exhibit interference peaks during the receiving interval. Hence, the best option for a practical implementation would be to calculate the interference for all combinations and choose the best one.

Case Study

Assuming that the cells are divided into two areas (X=2), the active transmitting interval will have two parts: The first interval, lasting (D-2R)/c seconds, with low interference, will be reserved for nodes farther than R[square root]2/2 from the base station (outer nodes), and the second interval, with strong interference, will be used 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. The schedule for each type of communication is as follows:

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 overlap.

The farthest interfering co-channel cell's interference will reach the edge of the cell at t=(D'-R)/c. The signal only lasts 2(D-2R)/c seconds, but it has to traverse the entire cell, so the interference will not be over until t=(2(D-2R)+D'+R)/c. After that, the outer nodes can again receive without interference. Consequently, the base station should start a new transmission interval at t=(2(D-2R)+D')/c.

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.

If the base station multiplexes its users in time, 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, the improvement 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.

Bidirectional. If 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 is consistent with the unidirectional modes.

Results

A network divided into cells of one kilometer in radius is considered, where nodes transmit at a carrier frequency of 22 kilohertz. The signal attenuates with distance due to spreading at $1/d^{1.5}$ and is subject to absorption at five decibels per kilometer.

Numerical calculations show that in the hybrid scheme with N_h=3, k_0=3 and X=2, the most vulnerable packets are received with an average SIR about three decibels higher than that of the traditional scheme with 16 cells per cluster. This holds for all uplink, downlink or bidirectional cases. The efficiency is also increased by 50 percent.

When distances are short or the center frequency is low, the absorption is 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 an SIR greater than 15 decibels with a cell radius of one kilometer and a carrier at 10 kilohertz. The problem with large clusters comes not only from their low efficiency, but also from the need to divide the already narrow bandwidth into as many sub-bands as there are cells in a cluster. These narrow sub-bands in turn limit the maximum number of users in a cell, reducing the network capacity.

The protocol proposed here 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=4 and k_0=9, this protocol requires only four sub-bands and offers an SIR greater than 15 decibels for both uplink and downlink with an efficiency 70 percent higher than a conventional scheme where N=31.

Conclusions

A channel-sharing protocol based on a cellular type of architecture is proposed for underwater wireless sensor networks. The protocol takes advantage of the long delays and signal absorption in the underwater channel, resulting in increased efficiency of bandwidth utilization when compared to a 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 and thus increasing the bandwidth efficiency. In addition, if the base station knows the distance to each of the users, the efficiency can be further 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 requiring 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, this protocol increases the density of users that can be supported in the network.

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[Fig 1]

Downlink schedule when X=2. All three base stations transmit simultaneously using the same channel. Nodes in the outer region receive their packets with weak interferences.

[Fig 2]

SIR at the base station during the receiving interval of an N_i=3, k_0=3 bidirectional scheme. Maximum number of interfering nodes at minimum distance is assumed.

[Fig 3]

SIR at the cell edge during the receiving interval of an N_i=3, k_0=3 bidirectional scheme.