# Energy-efficient Reliable Broadcast in Underwater Acoustic Networks[*]

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## ABSTRACT

Underwater acoustic networks have the potential to support a large variety of applications, such as environmental and equipment monitoring. However, underwater protocol design is in its infancy. Although there has been some work in routing and MAC layer protocols, they only address some of the challenges. A fundamental primitive that has not yet been researched for underwater networks is reliable broadcast. Reliable broadcast is required by many different applications, such as in-network node reprogramming. In this paper, we present three reliable broadcasting protocols (SBRB, FSBRB, and DBRB) that address the specific challenges of the underwater channel. We also compare our approach to two standard reliable broadcast protocols through extensive simulation, and show that our protocols provide significant gains in terms of both energy consumption and time to complete the broadcast. Moreover, our results demonstrate the importance of addressing the peculiar relationship between bandwidth and distance exhibited by an underwater acoustic channel.

## Categories and Subject Descriptors

C.2.1 [**Computer–Communication Networks**]: Network Architecture and Design; C.2.2 [**Computer–Communication Networks**]: Network Protocols

## General Terms

Algorithms, Design, Performance

## Keywords

Underwater sensor networks, acoustic communications, reliable broadcast, bandwidth–distance relationship.

## 1. INTRODUCTION

Underwater acoustic sensor networks have the potential to support a large variety of applications, from monitoring environmental factors, such as underwater seismic events or weather conditions, to helping in the control of mining equipment, or to supporting ship navigation. The development of protocols to support these applications is presently in its infancy. Due to the deep differences between the underwater and the terrestrial radio propagation environments, it is still not clear whether the knowledge gained for radio protocols can be reused for designing underwater communications.

While there has been some work performed towards the development of medium access control and routing protocols, a fundamental networking primitive, broadcast, has yet to be explored. Broadcast protocols are necessary for a number of vital network functions, such as route dissemination, neighbor discovery, and propagation of data. In some applications (*e.g., tsunami* detection), data may be broadcast (*e.g.,* to reach a a number of relevant destinations in the area, such as weather control stations) or routed to the destination using multiple paths (in order to achieve a higher probability of correct delivery). Additionally, some network applications require a reliable broadcast of information (*e.g.*, in-network reprogramming of nodes). However, the implementation of reliable broadcasting on underwater acoustic sensors may be not straightforward, as acoustic modems have much higher communication costs than their terrestrial counterparts [1], potentially making traditional methods prohibitively expensive.

Fortunately, the underwater acoustic channel has other unique properties that can be leveraged to design new reliable broadcast protocols that are not available to standard radio networks. In particular, a relationship exists between the distance bridged by activating a certain link and the bandwidth available for communication over that link. As the distance increases between nodes, the frequency band available for communication is both reduced and shifted toward lower frequencies [2]. Furthermore, the power control flexibility of typical underwater devices is much larger than in traditional radio-based sensor nodes, allowing communication range variances on the order of tens of kilometers.

The main contribution of this work is the design of three reliable broadcast protocols (called SBRB, FSBRB and DBRB) for underwater acoustic environments. While the methods we employ are somehow inspired by the large amount of expertise that has been gathered in terrestrial radio networks, there is still a lot of ground to cover to devise methods to implement efficient broadcasting, given the peculiar underwater channel features. In particular, we devise a way to leverage the bandwidth–distance relationship in order to reduce the number of transmissions required to complete the broadcast, with the further goal of minimizing both the overall energy consumed and the total time it takes to complete the broadcast. It is important to account for both of these metrics in the underwater environment, due to the already high base costs of communication and extremely long propagation delays. We test our solutions

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through extensive simulation, comparing against two versions of a traditional reliable multicast protocol, initially designed for the radio environment.

The rest of this paper is as follows. Section 2 presents a model of underwater acoustic channels, highlighting the bandwidth–distance relationship. Section 3 details the descriptions of five reliable broadcast protocols. Section 4 presents the results of our simulation study. Section 5 gives an overview of the related work in the underwater environment. Finally, Section 6 presents some conclusions and future directions.

# 2. DATA RATE AND PROPAGATION DELAY IN UNDERWATER CHANNELS

Two factors have an important impact on the performance of any reliable broadcast protocol, namely, the data rate supported by the channel and the signal propagation delay. As these two features are very different in underwater environments, with respect to radio characteristics, any evaluation of broadcast protocols should take them fully into account. In particular, one of the protocols we propose is specifically designed to take full advantage of the bandwidth variation with distance. Therefore, in this Section, we quickly summarize the relevant channel models. More detailed descriptions of the models have been presented in a number of other sources [2–4].

## 2.1 Propagation Delay

Acoustic signals propagate in water at much lower speeds than radio signals in air. Additionally, the propagation speed is dependent on the depth of the nodes. From the point of view of broadcast protocols, the propagation speed affects both the time before a node can learn about a lost packet and the time it takes for the entire broadcast to be completed. The underwater propagation speed in $\mathrm{m/s}$ has been accurately modeled by Urick as follows [3]:

$$\begin{aligned} c(t,S,z) &= 1449.05 + 45.7t - 5.21t^2 + 0.23t^3 \\ &+ \left(1.333 - 0.126t + 0.009t^2\right)(S-35) \\ &+ 16.3z + 0.18z^2, \end{aligned} \tag{1}$$

where $t$ is one tenth of the temperature of the water in degrees Celsius, $z$ is the depth in meters, and $S$ is the salinity of the water. The most important factor in (1) is the temperature of the water. For oceans, the temperature typically ranges between $2\,^\circ\mathrm{C}$ and $22\,^\circ\mathrm{C}$ [5]. The salinity, instead, is in the interval $[32, 37]$ parts per thousand $(\mathrm{ppt})$ with an average of $35\,\mathrm{ppt}$ [6].

## 2.2 Bandwidth–Distance Relationship

The peculiar bandwidth–distance relationship of the underwater acoustic channel derives from the dependency on frequency exhibited by both the attenuation and the noise power profiles. In turn, the SNR of a received transmission depends on the frequency according to the following equation:

$$SNR(\ell,f) = \frac{P/A(\ell,f)}{N(f)\Delta f}, \tag{2}$$

where $f$ is the frequency, $P$ is the transmitted power, and $\Delta f$ is the noise bandwidth at the receiver. The product $A(\ell,f)N(f)$, determines the frequency-dependent part of the SNR at a specific distance $\ell$. The available bandwidth at a given distance can be derived by first choosing the frequency $f_0$ at which the SNR is maximum for that distance, and then using the $3\,\mathrm{dB}$ bandwidth definition to derive the upper and lower frequency limits (note that the frequency response is skewed [2], so that $f_0$ is not the actual center frequency).

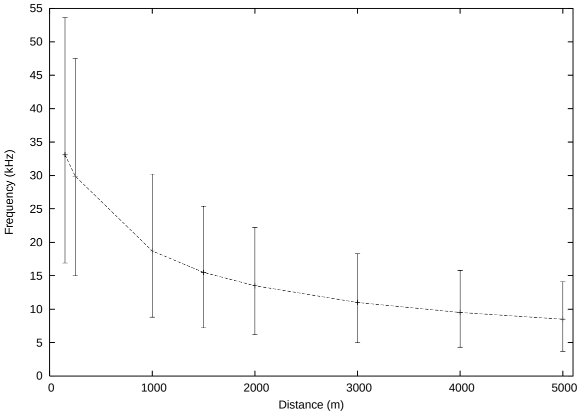

**Figure 1: The effect of distance on the available bandwidth.**

Urick models the attenuation $A(\ell,f)$ in terms of the spreading loss and the spreading coefficient $k$ for distance $\ell$ and frequency $f$ as follows [3]:

$$A(\ell,f) = \ell^k a(f)^\ell, \tag{3}$$

where the first term is called the spreading loss and the second term the absorption loss. The spreading coefficient defines the geometry of the propagation (*i.e.*, $k = 1$ for cylindrical, $k = 2$ for spherical, whereas $k = 1.5$ models the so-called practical spreading [3]). The $a(f)$ term is modeled using Thorp's formula [7].

The ambient noise in underwater environments is affected by four components: turbulence ($N_t$), shipping activities ($N_s$), wind-driven waves ($N_w$), and thermal noise ($N_{th}$). The following formulae give the power spectral density of the four noise components in dB re $\mu\mathrm{Pa/Hz}$ as a function of frequency in $\mathrm{kHz}$ [8]:

$$\begin{aligned} 10\log N_t(f) &= 17 - 30\log f \\ 10\log N_s(f) &= 40 + 20(s-0.5) + 26\log f \\ &\quad -60\log(f+0.03) \\ 10\log N_w(f) &= 50 + 7.5\sqrt{w} + 20\log f \\ &\quad -40\log(f+0.4) \\ 10\log N_{th}(f) &= -15 + 20\log f, \end{aligned} \tag{4}$$

representing turbulence, shipping, wind and thermal noise, respectively. The shipping factor $s$ ranges between $0$ and $1$ for low to high activity, and $w$ represents the wind speed in $\mathrm{m/s}$. The overall noise power spectral density for a given frequency $f$ is the sum of all linear-scale terms:

$$N(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f). \tag{5}$$

The different components impact the noise power spectral density at different frequencies. For example, in the frequency ranges encountered for distances over tens of meters, the turbulence and shipping components have very little effect, whereas the other two can become dominant.

Figure 1 plots $f_0$ and the available bandwidth as a function of the distance between nodes in $\mathrm{m}$, highlighting the shift of $f_0$ toward the lower frequencies, as well as the bandwidth reduction experienced at longer distances. Notice also that the bands are often not completely overlapping, making it possible to choose frequency intervals available only at short or long distances for implementing simultaneous communication in two bands.

# 3. RELIABLE BROADCAST PROTOCOLS

In this section, we begin by presenting two base-line protocols, called SRB and FSRB, and our three broadcast protocols, called

SBRB, FSBRB, and DBRB. Reliable broadcast protocols have been studied in detail in both the wired [9] and radio-based [10, 11] network environments. The main problem for reliable broadcast protocols is to efficiently correct errors affecting different parts of the message at different nodes, while avoiding retransmission storms. One way to solve this is to use forward error correction (FEC) to encode the block of packets. Then, the FEC block itself can be transmitted either proactively, or reactively, in the event of a loss. Packet FEC block codes are characterized by the number of segments of an encoded block of data that are required to successfully decode the entire message. For example, consider a Reed-Solomon code [12]. If $k$ segments of data are encoded into a block of $n$ packets, then a node can correct up to $\frac{n-k}{2}$ errors or $n-k$ erasures (*i.e.*, errors known to have taken place). Therefore if, *e.g.*, CRC codes are used to check the correctness of the received packets, a node can reconstruct the whole message from any $k$ out of the $n$ segments.

However, FEC cannot guarantee reliability. If the error rate of the channel increases beyond the corrective ability of the code, retransmission must be resorted to. Hybrid FEC/ARQ schemes for multicast and broadcast have been used in both wired and wireless environments [13] to help reduce retransmissions. In fact, in a single stream of packets, different nodes may lose different packets: in that case, FEC reduces the implosion of retransmission requests, and ARQ handles the losses FEC was not able to compensate for.

The following subsections detail three protocols we evaluated for reliable broadcast in underwater environments. The first and second protocols have two versions each, one without FEC and one using hybrid FEC/ARQ. The third protocol always makes use of FEC. For each protocol, we refer to the entire content of the broadcast as the *broadcast message*. Each broadcast message is divided into a number of packets, depending on the minimum transmission unit of the acoustic modem and the size of the message. Each packet contains a header with unique packet numbers and the total number of packets making up the broadcast message. We also consider some restrictions on what it means to reliably broadcast a message to all nodes in a network. First, we assume that no partitions exist in the network. Second, we do not consider node failures. Node failures essentially have two effects on reliable broadcast performance: the failed node will not receive the message, and a network partition could result. Since neither condition can be solved via a broadcast protocol, we believe these assumptions are reasonable.

## 3.1 Simple Reliable Broadcast (SRB)

The first protocol, Simple Reliable Broadcast (SRB), is not specifically suited to the underwater environment and is used as our base-line for experiments. With SRB, every node, upon receiving the broadcast message, re-broadcasts it to all its neighbors. In the event that one or more packets in a message are not received by a node, the node waits until no broadcast packets are overheard for a pre-defined time interval, and broadcasts a retransmission request to its neighbors. Upon receipt of this request, the neighbors contend for the channel by randomly choosing a backoff time in the interval. The node whose timer expires first retransmits the packets. The delay in requesting retransmissions allows time for the normal rebroadcasts from neighboring nodes to correct the transmission errors at the cost of some delay, that is indeed kept local, and does not significantly impact the dissemination delay. Channel contention at the MAC layer for SRB and all other protocols in this paper use a carrier-sense collision avoidance (CSMA) MAC layer protocol similar to the one proposed in [14]. This protocol was developed to minimize collisions in the underwater environment.

If the error rate of the channel (either due to noise or collisions) is sufficiently high, such that retransmissions are consistently required, FEC is a good solution to achieve higher reliability without increasing the overall traffic. In the FEC version of SRB (FSRB) each message is encoded before packet transmission begins. We assume that the same encoding mechanism is used by each node; this minimizes the computational cost of message forwarding, as a node that receives all of the encoded packets does not need to decode and then re-encode the message before repeating the broadcast. Hence, SRB ensures reliability only by retransmission requests, whereas FSRB employs FEC to correct errors and resorts to retransmissions only if FEC fails.

It should be noted that with SRB and FSRB, every node repeats the broadcast. This potentially adds a number of transmissions that are not necessary in reasonably dense networks (*i.e.*, where nodes have multiple neighbors). Indeed, it has been shown that, for current radio devices, the most energy-efficient broadcast strategy is to use the maximum transmit power and to reach the greatest number of neighbors with each transmission [15]. In underwater acoustic networks, however, transmitting to the longest possible distance at the highest power is not the most energy-efficient solution [4]. The protocol described in the next Section addresses this problem by leveraging the bandwidth–distance relationship exhibited by the acoustic channel.

## 3.2 Single-Band Reliable Broadcast (SBRB)

Essentially, Single-Band Reliable Broadcast expands SRB by employing long range communication to notify all neighbors that a broadcast has started, and then using shorter-range transmissions to send the messages to neighboring nodes. If any node does not receive the whole broadcast after a time interval, it asks its neighbors for retransmissions as specified hereon.

When a node wants to originate a broadcast, it sends a long-range signal in the appropriate frequency range at a high power level, notifying the greatest possible number of nodes of the forthcoming transmission. It should be noted that all communications other than the broadcast initiation signal take place in a high-frequency, low-power band, and thus do not collide with these long range notification signals. Along with the high power used to notify the new broadcast, this significantly reduces the probability that any notification signal will be lost.

After advertising the beginning of the broadcast, the source uses the larger bandwidth and lower power enabled by short-range communications to send the broadcast to its nearest neighbors. Once a node successfully receives the entire message, it contends for the channel to begin its own transmission using its short range bandwidth and power. If the node loses the contention and receives the broadcast from one of its neighbors, it does not attempt to forward the message any more. If the node wins the contention, it sends the first packet of the message to notify the nearest neighbors then switches to the long-range bandwidth and sends a broadcast notification to communicate to all other nodes that the broadcast is making progress. Once this message is sent, the node completes the broadcast transmission on the short-range band. Finally, if the node loses the contention, but does not hear the broadcast message being forwarded by any neighbor, it re-contends for the channel to transmit the broadcast.

If any segments of the broadcast should be lost, the node waits for the channel to be idle for a certain time interval and then sends a retransmission request to its neighbors, as in SRB. In case a node has received the long range broadcast notification, but no broadcast packets, it waits a longer time interval, then requests the broadcast from its neighbors and resets the timer. If a second long timeout occurs, it expands its transmission radius and requests the broadcast message again. This process continues until some node having the broadcast message receives the request and initiates a retransmission.

Note that, similar to SRB, SBRB achieves reliability through retransmission requests, whose impact is reduced through longer timeouts and slowly expanding request reaches. For this reason, SBRB is more likely to be affected by losses (fewer redundant transmissions of the broadcast message are sent). Hence, FSBRB, the FEC-enhanced version of SBRB, should exhibit much better performance. Similar to FSRB, FSBRB encodes the message prior to initiating the broadcast.

## 3.3 Dual–Band Reliable Broadcast (DBRB)

The final protocol, Dual–Band Reliable Broadcast (DBRB), operates similarly to SBRB, except that instead of sending short broadcast message notifications on the long distance, high power band, it uses this band to send some FEC data that can be used by nodes to correct errors. Every node that repeats the broadcast sends some redundant data using the long distance band. As a consequence, after a small number of sensors have retransmitted the broadcast, many nodes throughout the network are likely to possess sufficient redundancy to reconstruct the message completely. This allows the amount of redundancy sent on the long distance links to be tuned, with the aim to spend less energy and yet ensure a reasonable error-correction ability. However, this protocol requires some priming time, as there might be insufficient redundancy available to correct errors on the first forwarders, that in turn tend to require retransmissions more frequently.

# 4. SIMULATION RESULTS

To test the performance of the five protocols described above, we implemented them in a simulator we designed to test underwater networks. Our simulator fully accounts for the model of the underwater channel as described in Section 2.

A carrier-sense collision avoidance (CSMA) MAC layer protocol similar to the one proposed in [14] was used for channel access. It provides mechanisms to effectively operate in the presence of the long delays found in the underwater environment. This protocol maintains a low number of collisions per packet, except in very high traffic situations. Hence, most of the packet error events in the network come from collisions, with only a small portion being accounted for by ambient noise.

In addition to modeling the error due to noise and attenuation, as well as MAC layer collisions, we use an additional parameter in the MAC layer that allows us to increase or decrease the packet loss probability, in order to test the protocols over a wide range of error rates.

We used a topology generation algorithm that randomly places nodes in a $5\,\mathrm{km} \times 5\,\mathrm{km} \times 5\,\mathrm{km}$ network, and then adjusts node placement to make a fully connected network given the transmission range. We generated many scenarios by varying this range between $100\,\mathrm{m}$ and $2\,\mathrm{km}$. Additionally, we varied the number of nodes placed in the network between $40$ and $700$.

We model the acoustic modem after the WHOI micromodem specifications [16], with transmit powers between $10\,\mathrm{W}$ and $50\,\mathrm{W}$. The short-range frequency band used is $22\,\mathrm{KHz}$–$55\,\mathrm{KHz}$ whereas the long-range frequency band spans from $4\,\mathrm{KHz}$ to $13\,\mathrm{KHz}$. We used $96\,\mathrm{byte}$ packets and varied the number of packets per broadcast message from $1$ to $20$. Additionally, for protocols using FEC, we fixed the error correcting ability to a single packet of the broadcast message. Further optimizations for the broadcast protocols include adding adaptive FEC to tune the correction capabilities as the error rate on the channel changes.

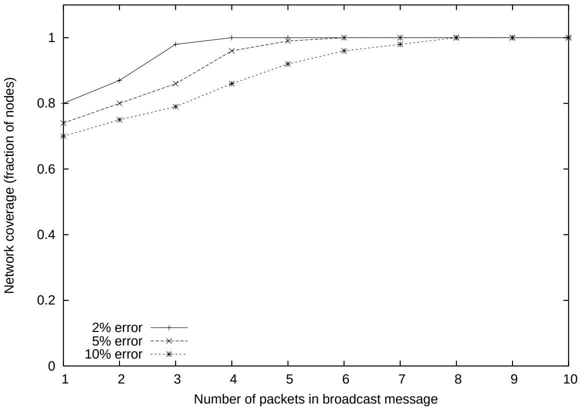

**Figure 2: Coverage,** $512$ **nodes**

All experiments represent the averages over $40$ runs with different random topologies generated for each run. For all experiments, we maintained $95\%$ confidence intervals between $1\%$ and $2.5\%$ of the averages.

## 4.1 Coverage

There are two components to a fully reliable broadcast protocol. The first concerns whether a node node, once it receives one packet of the broadcast, receives the entire broadcast message successfully. The second concerns whether all nodes in the network receive the broadcast message. This latter concern we call *coverage*. In any wireless network, without pre-knowledge of all of the nodes in the network, it is impossible to guarantee full coverage. Reliable broadcast protocols in this environment can only promise statistical coverage. The protocols in this work deal with this situation. The network coverage of a reliable broadcast protocol is complete only if all nodes in the network are reached. As a sample situation, consider a node that is placed on the edge of the network and has only one neighbor. If that node fails to receive a broadcast packet from it's only neighbor, there is no way for it can know that a broadcast is being propagated, and thus it will never request a retransmission. Additionally, there is no completely sure way for the sender to know if a node in the network has not received its broadcast. For our protocols, once a receiving node obtains part of a broadcast, it will receive the entire broadcast, through the use of either FEC or repeated retransmissions. Having multiple packets make up a single broadcast message increases the chances that the entire network will be covered, by increasing the probability that each node will receive at least one packet of the message.

Figure 2 depicts the fraction of nodes that successfully receive the broadcast message using SBRB as a function of the number of packets making up the broadcast message for different error probabilities. For all error rates tested, the fraction of nodes receiving the broadcast message converged to one after the number of packets was increased to $9$. For the remainder of experiments presented in this paper, the broadcast message size was held constant at $10$ packets (the FEC encoded messages where $12$ packets).

## 4.2 Varying the Error Rate

In the next set of experiments, we varied the error rate of the channel to see its effects on the energy consumption needed to complete the broadcast and the time from the initiation of the broadcast

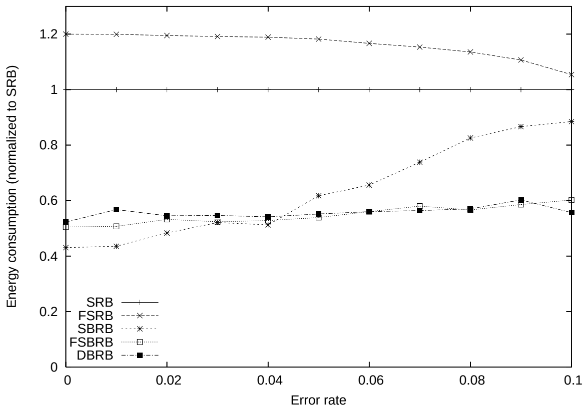

**Figure 3: Energy consumption,** $100\,\mathrm{m}$ **min transmission range**

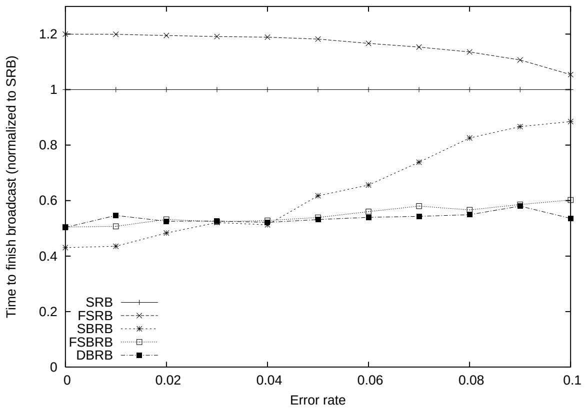

**Figure 4: Completion time,** $100\,\mathrm{m}$ **min transmission range**

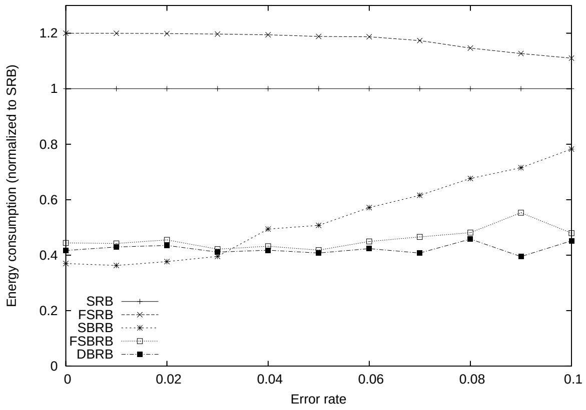

**Figure 5: Energy consumption,** $500\,\mathrm{m}$ **min transmission range**

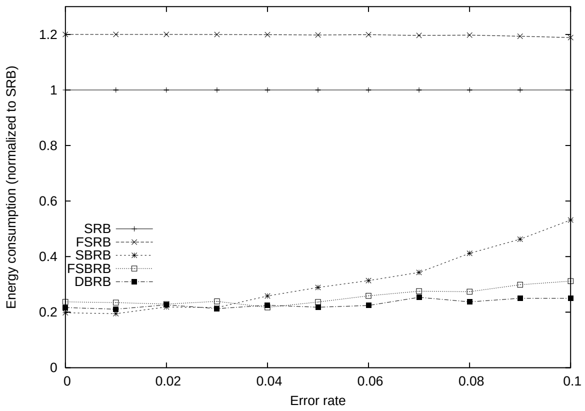

**Figure 6: Energy consumption,** $1.2\,\mathrm{km}$ **min transmission range**

to when the last packet is received. In this section, we present results from $4$ different network densities. Each of these network densities requires a different minimum transmit power that can be used and still have a connected network. In turn, this power translates to a minimum distance that must be covered with each transmission for keeping the network connected. This parameter is important, since it affects the energy cost of each transmission in terms of energy, as both the transmit power and the transmission time are increased at longer distances.

Figures 3 and 4 depict the energy consumption and time to completion, respectively, as the error rate on the channel is increased. For both graphs the y-axis is normalized to the performance of SRB. The key to notice is that for error rates lower than about 3%, SBRB outperforms FSBRB and DBRB by 8% to $5\%$. At higher error rates, the savings from using FEC become critical and FSBRB and DBRB begin to outperform SBRB. In all cases, the gains achieved by leveraging the bandwidth–distance relationship for SBRB, FSBRB, and DBRB produce considerable savings, consuming around $40\%$ to $50\%$ of the energy required by SRB and FSRB. As one would expect, the time to completion follows roughly the same curve, since energy increases in these cases are directly related to the need for more transmissions. Additionally, the delay increase incurred in SBRB for using the long-range band for notification is completely dominated by the total number of transmissions needed to complete the broadcast. This is not the case in networks tested with $5$ to $20$ nodes, where the added times for the longer range transmissions could be seen in the graphs; however, SBRB and DBRB still outperformed SRB and FSRB by no less than $16\%$. Since the time results are along the same lines as the energy results for all experiments in this section, we omit them due to space considerations.

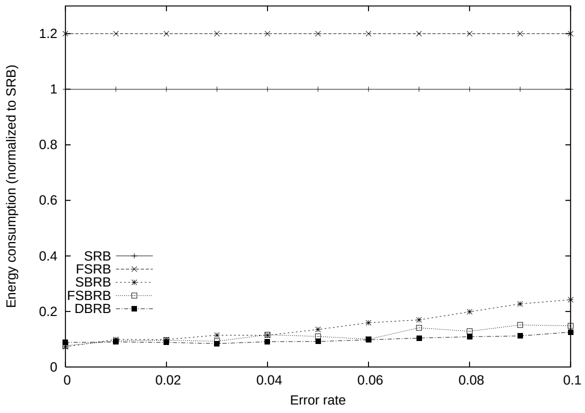

**Figure 7: Energy consumption,** $2\,\mathrm{km}$ **min transmission range**

Figures 5 to 7 depict the energy consumption normalized to SRB for minimum transmission ranges of $500\,\mathrm{m}$, $1.2\,\mathrm{km}$, and $2\,\mathrm{km}$, respectively. As the transmission range required to avoid network

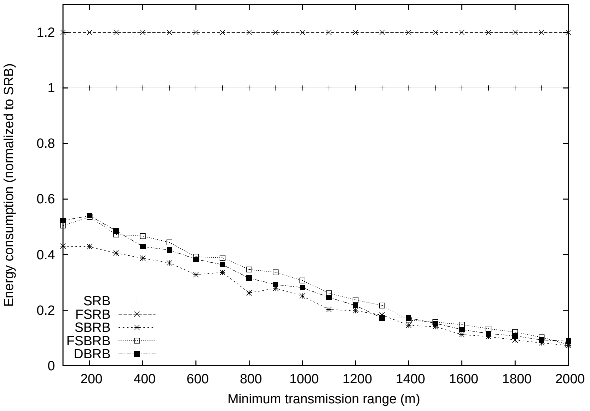

**Figure 8: Energy consumption,** $0.00$ **error parameter**

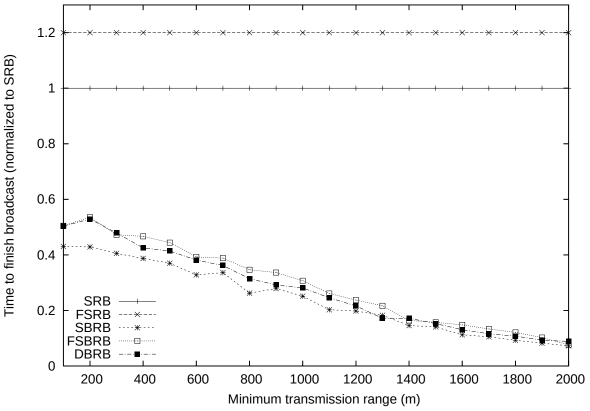

**Figure 9: Completion time,** $0.00$ **error parameter**

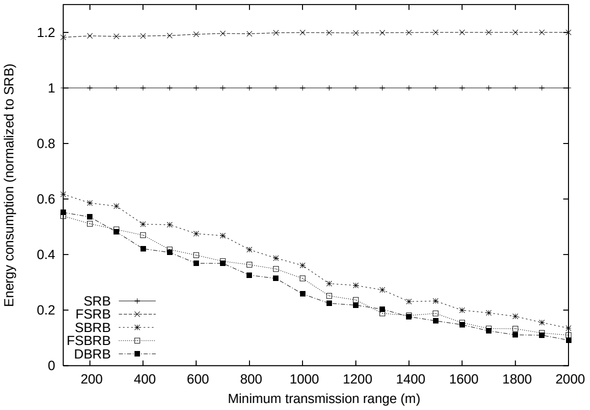

**Figure 10: Energy consumption,** $0.05$ **error parameter**

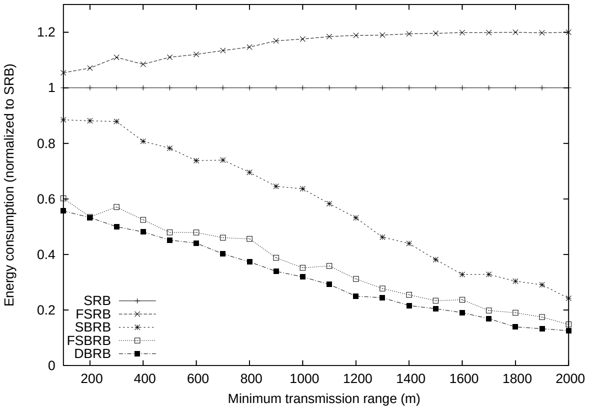

**Figure 11: Energy consumption,** $0.10$ **error parameter**

partitions increases, SRB performs progressively worse. This is directly due to the large number of transmissions still needed and the increase in the cost of transmissions. Furthermore, at higher error rates and longer distances, DBRB begins to outperform FSBRB by about 3%. This suggests that, at longer minimum distances, if an adaptive FEC were used by DBRB, significant improvements over FSBRB could be realized.

### 4.3 Varying the Minimum Transmission Range

To more accurately view the effects of minimum transmission ranges on the performance of the various protocols, in this section, we present results that vary the transmission range for different average error rates.

Figures 8 and 9 depict the energy consumption and time to completion respectively, as the minimum transmission range to avoid network partitions is increased. For both graphs the y-axis is normalized to the performance of SRB. The first thing to notice is that minimum transmission range has no effect on FSRB, because every node repeats the message. As the transmission range increases, the total cost for sending a message increases; therefore, SBRB, FSBRB, and DBRB all save increasingly more energy as compared to SRB as the minimum transmission range increases, due to their ability to minimize the number of transmissions required to complete the broadcast. As with the results in the previous subsection, the time results follow the energy trends as expected, and are thus omitted for the rest of the experiments in this Section.

Figures 10 and 11 depict the energy consumption as a function of the minimum transmission distance for error parameters of 5% and 10% respectively. It is worth noting that the increasing separation between SBRB, FSBRB, and DBRB as error rate increases is not affected by changes in minimum transmission distance. In other words, no matter what minimum transmission distance, if the error rate is high, DBRB outperforms the other protocols by an average of 3%.

## 5. RELATED WORK

The use of acoustics for underwater communication has received increased interest in recent years. While the main use of acoustic waves is still sonar detection and ranging, as well as telemetry [17], relatively recent efforts have proven that reliable links can be set up in water, using signal processing techniques that provide good communication efficiency or speed [18–21].

While there are still many open issues in building underwater acoustic networks [22], some papers have contributed to the design of MAC protocols for underwater networks. A discussion of deterministic multiple access schemes for underwater networks was presented in [23]. A more comprehensive comparison of such schemes in clustered environments has been more recently carried out in [24]. Other protocols have been more specifically tailored to the underwater acoustic channel features. For example, Slotted FAMA [25] focuses on collision avoidance. It sets up shared synchronization among the sensors, whereby the time is divided into slots sufficiently long to accommodate for the maximum round-trip time in the network. Transmissions are preceded by an RTS/CTS handshake, and may take place only at the beginning of a slot, ensuring that the channel is sensed busy when another transmission is going on. PCAP [26] also pursues collision avoidance. It makes the duration of a handshake predictable, by inserting proper waiting intervals before the transmission of the CTS. This delays the setup of the link enough to "simulate" the maximum propagation delay between the two nodes. In turn, this allows the transmitter to carry out other tasks while waiting for the receiver to reply. The approach in [27] is quite different, as collision control is sought instead of avoidance. The nodes preemptively perform an RTS/CTS exchange and wait before transmitting data. During this wait time, the recipient may hear another RTS meant for another node and could be able to warn the transmitter in time to avoid the collision. Also, if the transmitter hears another RTS during the waiting time, it delays its transmission for the same reason. The protocol in [27] cannot avoid collisions completely. However, the reduced length of the waiting times ensures a globally greater throughput, outperforming Slotted FAMA. Moreover, there is no need to maintain the nodes synchronization. Another protocol specifically tailored to underwater acoustic networks is UWAN–MAC [14]. It is designed to save energy through very low duty cycles, and focuses on collision avoidance through a sort of adaptive TDMA. Each node has an awake/sleep schedule and transmits when awake. Upon synchronizing with their neighbors through special packets, the nodes know when to wake up to hear nearby transmissions. All data packets carry schedule information so as to reduce the total overhead. HELLO packets are used to recover from erroneous synchronizations, such as waking up and hearing no transmission by the intended sender. The authors in [1] argue that the difference between transmit and receive power can be exploited in underwater networks and discuss how to manage idle time in that light. The conclusion is that near-optimal energy performance can be reached if ultra-low power transducer wakeup modes could be implemented. On a similar line of thought, Tone-Lohi [28] tries to avoid collisions by sending very short busy tones, that could be heard by other nodes during idle channel monitoring.

From the point of view of routing, most of the literature is focused on the adaptation of terrestrial radio protocol to the underwater environment. For example, Vector-Based Forwarding [29] lets nodes compute the angle of arrival of an overheard acoustic signal to understand their position with respect to a cylindrical area connecting the source to the destination. If a node is inside such an area, it is allowed to forward the packet. To achieve the maximum advancement, the eligible forwarders delay their operations proportionally to their distance from the sender, so that nearby nodes refrain for a longer time and can overhear the packets forwarded by farther neighbors. Segmented Data Reliable Transport (SDRT) [30] employs FEC to guarantee error protection. Each node encodes and forwards data continuously using a simplified version of Tornado codes, until some positive feedback is received. To avoid wasting too much energy, packet transmissions are "windowed:" the packets inside the window are transmitted at full rate, whereas a lower rate is used for those outside the window. Each receiver must decode the whole block of data before transmitting again. In [31], the authors deploy a framework for addressing delay-sensitive and -insensitive applications, involving Reed-Solomon packet coding and scheduling of packets according to their delay requirements. The focus of the investigation is on the impact of the long delays and stronger attenuation of the acoustic channel on packet routing. The variation of the available bandwidth with distance is taken into account in [4]. The conclusion is that there exists an optimal hop distance from an energy consumption point of view. Moreover, the authors infer that routing protocols should be designed to match such a distance, or if possible, to approach it from below (choosing closer neighbors), considering linear as well as 3-dimensional topologies.

Notice that even though [30, 31] rely on packet FEC as we do, they only transmit over a single channel that is suited to all nodes in the network. Unlike [30, 31], the approach we take in this paper is different. We devise different techniques to exploit the change in the available bandwidth with varying distance to convey FEC toward all nodes, with the aim to perform reliable broadcasting in an underwater sensor network.

# 6. CONCLUSIONS AND FUTURE DIRECTIONS

Underwater acoustic networks have characteristics that are very different from their terrestrial, radio-based counterparts. One of the most important differences is the relationship between the available bandwidth and the transmission distance. In this paper, we present the design of three reliable broadcast protocols that leverage this relationship to outperform standard, radio-based broadcast approaches in terms of energy consumption and time to complete the broadcast. Our three protocols, Single-Band Reliable Broadcast, FEC Single-Band Reliable Broadcast, and Dual-Band Reliable Broadcast each leverage the ability to use small bands to transmit long distances to alert nodes that broadcasts are to be expected. Then, by reducing the transmission range and selecting only certain nodes from each neighborhood to repeat the broadcast, the protocols dramatically reduce the total number of transmissions required.

Our extensive simulation study demonstrates that both FSBRB and DBRB yield significant gains in terms of energy consumption and time to completion, as compared to the other protocols. Additionally, DBRB performs the best when the error rates are high.

Future work includes investigating the use of adaptive FEC in FSBRB and DBRB. Our results suggest this optimization should produce even larger savings, though it is unclear whether DBRB or FSBRB would perform the best. Additionally, FEC coding schemes that are not block codes may allow significant advantages for both protocols.

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