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Deployment Strategy Analysis for Underwater Cooperative Wireless Sensor Networks

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Abstract— **Wireless sensor networks (WSNs) are widely used for underwater environment monitoring. Because of the harsh underwater environment, WSNs face the challenges of erroneous communication, lower lifetime, less robustness, and cost constraints. In this paper, we propose a cooperative WSN which uses a cooperative coded OFDM (COFDM) system and network coding to deal with the shadowing phenomenon present in the underwater communication channel. The proposed scheme is cooperative spatial-domain coding combined with the LDPC-coded OFDM system. The designed system is analyzed using random and grid deployment strategies for the required number of sensors, bit-error rate (BER), and cost of the network.**

Keywords— **Wireless sensor networks, Deployment, Underwater communication, LDPC, OFDM, Network coding, UWSN.**

I. INTRODUCTION

Underwater acoustic communication has widespread applications in monitoring of the underwater environment, military/oceanic surveillance, underwater navigation, observation of radiation leaks, and exploring the underwater resources. These applications require sophisticated underwater sensor networks, therefore, reliable and robust underwater communication systems are needed to be deployed [1], [2].

In the present underwater communication systems, acoustic wave is the major carrier due to its low attenuation characteristic [3]. However, the slow propagation speed (1500 m/s in normal condition) of acoustic waves leads to long delay spread. Further, the underwater acoustic channel (UAC) is time varying according to changes in temperature, geometry of the channel, roughness of the sea surface, and spatial position determined by the sea current etc. In particular, multipath delay spread due to reflections at the sea surface and bottom causes inter-symbol interference (ISI) and frequency selective fading. Hence, these factors lead to system performance falloffs [4], [5].

The authors in [1], [6], and [7] describe challenges such as noise, Doppler spreading effects, multipath fading, and shadow zones, in the design of underwater acoustic sensor networks, along with a detailed characterization of UAC. It is still considered a significant research problem to design an underwater acoustic sensor network system that performs robustly over the UAC, which exhibits many challenges as mentioned above. The purpose of this paper is to propose an underwater COFDM scheme for wireless underwater sensor networks and show its robust performance against the challenging UAC problems under different deployment strategies. The envisioned network is a wireless sensor access network where multiple sensors inside shallow water transmit to a buoy on the sea surface.

In order to analyze the deployment strategies for underwater WSNs (UWSNs), we limit our discussion to deployment schemes for the UWSN. Sensor deployment planning is very important for the performance of wireless sensor networks. Node deployment provides the base for efficient network operation such as topology control, routing, localization, coverage, and connectivity. Along with these, it also helps in minimizing the power consumption in order to prolong the network lifetime.

Other notable works on node deployment for UWSNs include, [8] which deals with finding an optimal path for multihop routing, used to deliver data from underwater sensor nodes to data collectors onshore. A distributed node deployment strategy in which the nodes are initially deployed in a 2-D bottom grid and then adjust their positions to random depths in order to minimize the sensing overlaps among themselves was presented in [9]. A recent work in [10] deals with the impact of node deployment strategies on localization performances when the nodes are deployed in a 3-D environment.

In the case of 2-D UWSNs, the sensors could be deployed according to a pre-planned location map, or they could be spread randomly from the water surface over the entire area of concern. We consider static sensor nodes which do not change their positions with respect to the coverage area. Considering these scenarios, our coverage problem becomes a static coverage problem. Therefore, we will focus on static coverage techniques to fully cover the area of interest [11], [12], [13]. Another important issue related to the performance of sensor networks is the connectivity of each component in the network

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i.e., sensors and a common destination (buoy for UWSN). The transmission range of a sensor in the network is different from sensing range. Therefore, connectivity of the network is a separate problem and there exists many different solutions for it such as pure-connectivity [14] and routing algorithm based (RAB) connectivity [15]. Connectivity of the network is designed in order to ensure that the sensed data is transmitted timely and efficiently to the buoy.

II. DEPLOYMENT OF SENSOR NODES

The underwater WSN can be deployed in two types of communication architectures, i.e., two-dimensional (2-D), where sensors are deployed at the bottom of the sea, and three-dimensional (3-D), where the sensors can float at different depths to cover the entire volume of water [1]. As mentioned above, we consider a static and 2-D deployment scheme for our UWSN, which is relatively easier to deploy and operate. We use the *k*-coverage parameter, which means that every point in that region falls within the sensing range *r* of at least *k* sensors. Since the underwater acoustic sensors are expensive devices and have a high cost of operation and maintenance, our deployment target is to achieve *1*-coverage.

An optimal deployment strategy to cover a 2-D rectangular area using the minimum number of sensors is to use a triangular-grid [16], as shown in Fig. 1. In order to achieve full coverage, the coverage ratio, η (covered area/target area) should be 1, which can be achieved by adjusting the distance *d* among sensors, such that $d = \sqrt{3}r$. This makes the uncovered areas zero and minimizes the overlapping areas. Using (3) in [16], the minimum number of sensors *U*, required to cover a target area, $l\times h$, to satisfy a given coverage ratio η is computed as, $U(l,h,d,r) = \left\lceil \frac{l-d}{d} + 1 \right\rceil \times \left\lceil \frac{2\sqrt{3}h - 6d + 4\sqrt{3}r}{3d} + 1 \right\rceil$. Therefore, the minimum number of sensors necessary to provide *1*-coverage in an area of 100×100 m^2 for $r = 20$ m, is 12.

Next is to estimate the number of redundant sensors required to ensure network robustness to node failures within a pre-determined observation period. Let us assume that all the nodes have the same failure rate, the node failures occur according to Poisson distribution, and are independent of each other. Then the number of redundant sensors required to compensate for Poisson-distributed node failures is given in (18) of [16], as $\sum_{u=0}^{\Delta U} \frac{(\lambda T)^u e^{-\lambda T}}{u!} \ge \Gamma$, where λ is the sensor failure rate, *T* is the observation time in days, *u* is the number of sensors that may fail during the time *T*, and Γ is the probability that no more than ΔU failures occur in the observation time *T*. For example, for an average failure every one month ($\lambda = 1/(365/12)$) by a sensor and success probability, $\Gamma = 0.95$, there will be about six sensor failures during a period of three months [16]. Therefore, to ensure network connectivity and provide *1*-coverage in an area of 100×100 m^2, for $r = 20$ m and observation period of three months, we need to deploy 18 sensors instead of 12.

Finally, to ensure connectivity of the network, we use the argument given in [14], which says that, $\Theta(\log U)$ neighbors are necessary and sufficient for a sensor network to be

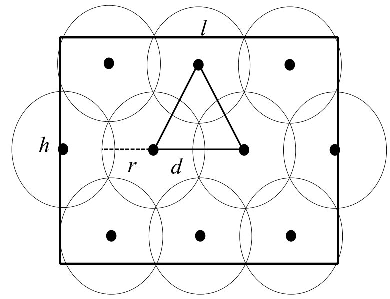

Figure 1. 2-D triangular grid deployment of sensors in an $l \times h$ area.

asymptotically connected. It is proved that the range of this number is between $0.074\log U$ and $5.1774\log U$. Therefore, for a network of 12 or 18 nodes, we choose the minimum number of connected neighbors required to be 5. So, a total of 6 nodes form a cooperation group.

Although the triangular-grid deployment seems to be a cost-effective solution in terms of the number of sensors needed to provide coverage and connectivity in a given area of interest, it may not be an effective solution for underwater area monitoring when cooperative communication is used to enhance the performance of the network. Apart from that, deploying and maintaining a triangular-grid structure in the underwater environment for a longer period of time may turn out to be costly as compared to the randomly deployed network. In this paper, we study the effects of random and triangular-grid deployment schemes of 2D static deployment strategies when using cooperation among sensor nodes that communicate to a buoy on the sea surface.

III. SYSTEM MODEL

The suggested COFDM system employs a regular LPC ($N = 256, j = 4, k = 8$) code [17] and the OFDM system parameters are summarized in Table I. At the receiver, a discrete-time signal **r** is obtained after the necessary OFDM reception processing, as follows,

$$\mathbf{r} = \mathbf{H}\mathbf{s} + \mathbf{n} \quad (1)$$

where **n** is an i.i.d. Gaussian noise vector; $\mathbf{n} \sim \mathcal{N}^{N\times 1}(0, \sigma^2)$, **r**, **s**, and **n** are each an $N \times 1$ vector; **H** is an $N \times N$ diagonal matrix whose diagonal entries are the transfer-function coefficients $(H_1, H_2, H_3, ..., H_N)$ of the UAC multiplied by the lognormal gain *g*; and **s** is the transmitted BPSK signal from the sensor.

We adapt the two-phase user-cooperation scheme [18]-[20] for our design of the underwater acoustic WSN. This approach simultaneously exploits the diversity benefit from the frequency and spatial domains. Each sensor relays the OFDM modulated data for its neighboring sensors, which helps overcome the frequency-selective fading.

Our approach is different from the one proposed in [18] in that it does not need to decode the symbols received at the relay, rather it just detects the binary codeword and then re-encodes the data to send it to the destination in the second phase. Apart from that, we also employ a detailed channel code

TABLE I. OFDM SYSTEM PARAMETERS

Parameter	Value
Carrier frequency	7 kHz
Transmission bandwidth : BW	10 kHz
Maximum Doppler spread : $B\tau_{max}$	4.744 Hz
Coherent time : $T_C = 1/\ B\tau_{max}$	210 ms
Maximum delay spread : τ_{max}	25 ms
Coherent bandwidth : B_C=1/τ_{max}	40 Hz
Number of sub-carriers : N	256
Sub-carrier bandwidth : $\Delta f = BW/N$	39.0625 Hz
Valid symbol duration : $T_D = 1/\Delta f$	25.6 ms
CP period : $T_{CP} \geq \tau_{max}$	25 ms
OFDM symbol duration : $T_S = T_D + T_{CP}$	50.6 ms

and propose a joint channel-network code decoding scheme, which will be published in [21]. The following protocol describes our proposed channel-network code design.

Channel-Network Code Protocol:

Step 1: In the broadcast phase, each node *i*, broadcasts an *N*-bit LDPC-COFDM symbol of duration T_S to all the other nodes in the cooperating group, and the destination *D* by using TDMA mechanism.

Step 2: The sensor nodes receive the OFDM-modulated symbols. A receive-set $\Re(j) \subseteq \{1, 2, \cdots, U\}$, stores the indices of the sensors whose transmissions are received correctly at node *j*, where *U* is the total number of cooperating sensor nodes.

Step 3: In the relay phase, each node *i*, randomly selects a small number of codewords from its receive-set $\Re(i)$, computes their checksum by using a low-density generator matrix (LDGM) code [22] and forwards it to the destination, *D*.

Step 4: The destination node *D*, decodes the combined channel-network code received from each transmitting node, *i*, in both the broadcast phase and the relay phase.

The source-symbols transmitted in the first phase constitute the systematic symbols and the relay-symbols transmitted in the second phase constitute the parity symbols of the channel-network code. Hence, a set of *U* nodes complete the transmission of one channel-network codeword of length *2NU* by the end of the second phase. The codeword received at the destination is rate 1/4, since we use rate 1/2 LDPC code in the broadcast phase and rate 1/2 spatial code in the relay phase, resulting in the overall network code rate to be reduced.

IV. PERFORMANCE ANALYSIS

In this section, we aim to analyze the BER of the designed network code by considering random and triangular-grid deployment strategies for the UWSN. The coding gain obtained by the use of a channel code is well-understood but in the case of the designed network code, we need to consider

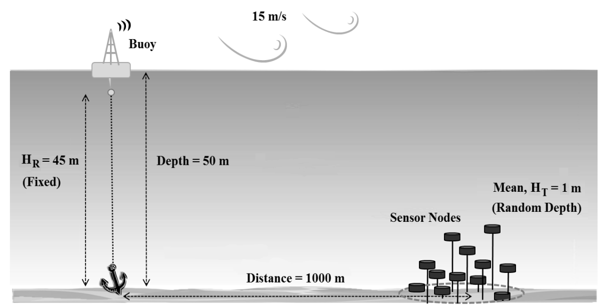

Figure 2. Underwater WSN scenario for simulation

other factors such as the energy spent by sensors in the formation of the network code, the cost of deployment and operation, and the effect on network lifetime. Our aim is to see the network coding gain by using the proposed channel-network code and the effect of deployment strategy on the BER performance as well as on the network lifetime.

A. Simulation Settings

To analyze the BER, we assume the underwater sensor nodes to be distributed at the sea-bottom, as shown in Fig. 2. The number of sensor nodes considered is 12 and 18 according to the calculations done in Section II. These nodes are at an average 1 m height from the sea bottom within a 100 × 100 m^2 area. In the case of random deployment, the depth and position of each node is generated randomly uniform with mean 1 for every OFDM symbol transmission, and time varying channel responses between the nodes and buoy. Similarly, for the case of triangular-grid deployment, the position of each node is generated in the form of a triangular-grid. However, the buoy position is fixed at 5 m below the sea surface. Other factors affecting the channel are; a maximum sea surface wind speed of 15 m/s, water depth of 50 m (considering the 44 m average depth of the Korean Western Sea), and an average distance of 1000 m between the node and buoy. The lognormal random distribution is set with mean 1 and variance 2. Each node has a transmission range of 1000 m and a data rate of 7 kbps. The data packet size is set to 32 bytes. Each node sends 1 packet of data in the broadcast phase and 1 packet of data in the relay phase, towards the buoy.

B. Random vs. Grid Deployment

In this section, we will compare a randomly deployed network with that of a triangular-grid in terms of energy consumption and BER performance. As shown in Fig. 3(a), for example, a triangular-grid deployment covers the whole target area by using minimum number of required sensors, while random deployment of sensor nodes may result in uncovered sections of the target area, as shown in Fig. 3(c). In order to cover the whole area of interest by using random sensor deployment, sensors with much larger sensing radius r_2 can be used, which will increase the amount of sensing energy consumed by the network as compared to the sensors with initial sensing radius r_1, as shown in Fig. 3(c). Similarly, if the number of sensors, with the same sensing radius, is increased to cover the whole area of interest, with random deployment, and cope with sensor failures, the amount of sensing energy consumed will increase proportionally, as shown in Fig. 3(d).

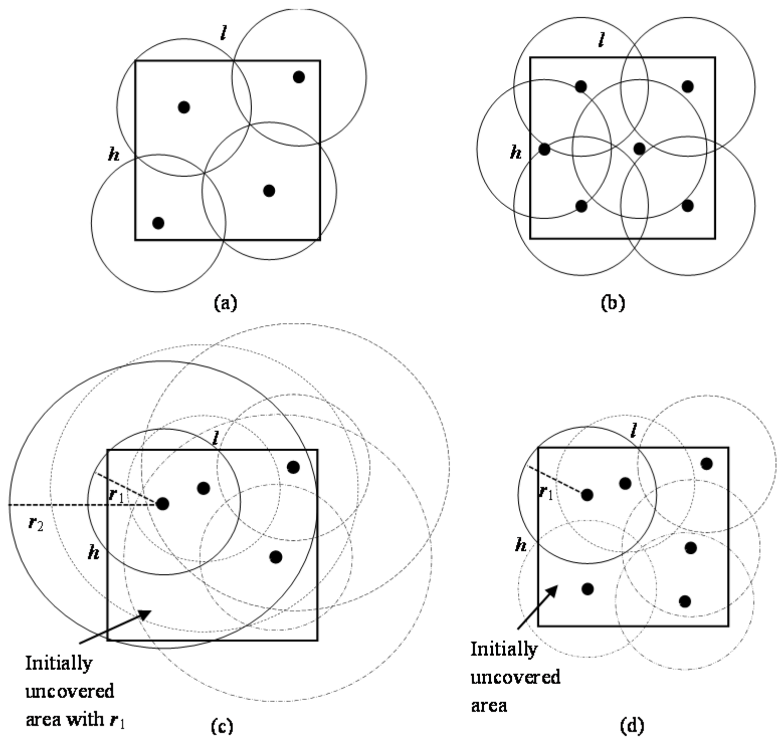

Figure 3. Triangular-grid and random deployment of sensor nodes. (a) Fixed deployment using minimum number of sensor nodes. (b) Fixed deployment with redundant nodes to cope with failures. (c) Random deployment showing the initial sensing radius r_1 with uncovered area and increased radius r_2 to cover the whole area of interest. (d) Random deployment with redundant nodes to cover the whole area of interest and cope with failures.

When using a fixed deployment of sensors with redundant nodes to cope with failures in the area of interest, the resulting node distribution is as shown in Fig. 3(b).

As we consider the sensor nodes deployment to be static, increasing the sensing radius does not affect the performance at the destination. As shown in Fig. 3(c), even though the sensing radius is increased but the sensor positions are kept the same, thus, the communication channel to the destination remains probabilistically the same. Therefore, this strategy does not significantly improve the quality of the received signal at the destination. On the other hand, increasing the number of sensors used in both random and triangular-grid deployment may affect the signal quality at the destination positively, as the relayed signal has more paths to the destination. Therefore, we expect the performance of the system with more nodes per unit area to be better than that with fewer nodes.

Let the energy per bit in the transmitted codeword be defined as E_b in joules and N_0 be the noise power spectral density of the AWGN given in (1). The ratio E_b/N_0 then gives us a normalized measure of the SNR. Fig. 4 shows the BER performance of the proposed channel-network code with random and fixed triangular-grid deployment of sensor nodes in an area of 100×100 m^2. For comparison purpose we also show direct communication to the buoy without using cooperation for both uncoded and LDPC-COFDM. The results show that although the COFDM scheme is able to deal with the frequency-selective fading, it suffers from performance degradation under the lognormal shadowing effect present in the UAC. Therefore, the LDPC-COFDM direct communication scheme achieves a 10^{-3} BER point at ~18 dB E_b/N_0. A fixed deployment of 12 nodes shows lower BER than that of random deployment by achieving the 10^{-3} BER point at ~1 dB lower E_b/N_0. Similarly, 18 nodes with fixed deployment show a better BER than that of random deployment. Overall, 18-node deployment shows a better BER performance as compared to 12-node deployment by ~2 dB. Therefore, we can safely say that random deployment is preferred over triangular-grid deployment for an underwater acoustic WSN, because random deployment is easier and cheaper to deploy and maintain over a period of time, and it performs slightly better in terms of BER, as compared to the triangular-grid deployment.

Comparing the BER performance of the direct and cooperative communication scheme proposed in this paper, we can see a benefit of ~12 dB in SNR which is very significant and can offset the increase in energy consumption as a result of the cooperation among sensors and increased decoding complexity of the proposed channel-network code.

V. Conclusion

This paper proposes a channel-network code protocol for the underwater acoustic WSN and studies its effects on two deployment schemes, that of random and triangular-grid deployment. The results show that the proposed channel-network code can achieve a significant benefit of ~12 dB in SNR as compared to the direct communication. The comparison of deployment schemes also shows that random deployment of the underwater acoustic WSN is preferred over

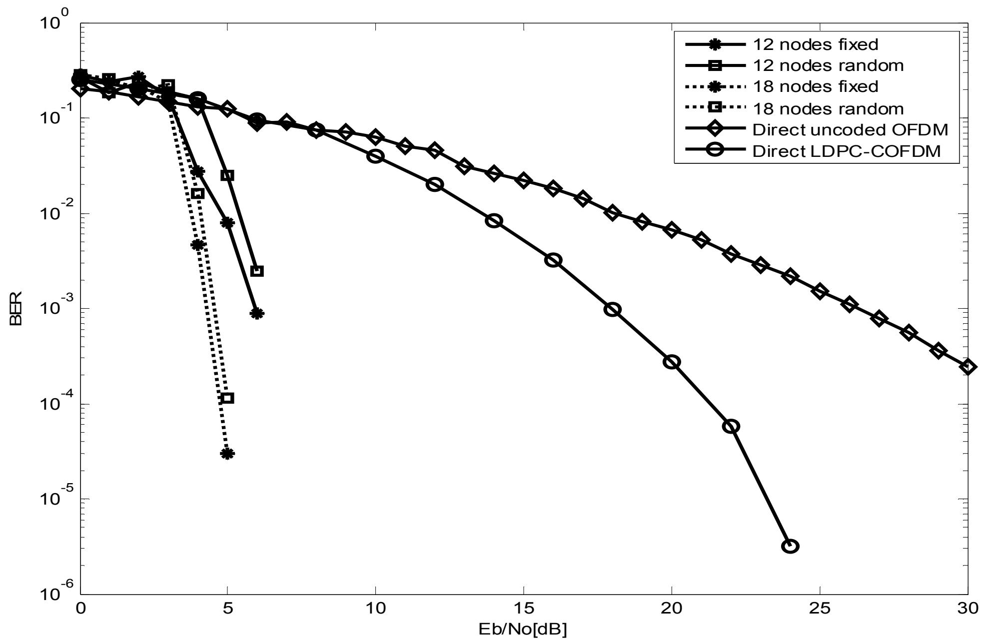

Figure 4. BER performance of the proposed channel-network code with random and traingular-grid deployment schemes.

the triangular-grid deployment in terms of BER and cost of deployment.

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