Cross-layer Routing on MIMO-OFDM Underwater Acoustic Links

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***Abstract*—UnderWater Acoustic Sensor Networks (UW-ASNs) are experiencing a rapid growth, due to their high relevance to commercial and military applications such as oceanographic data collection, pollution monitoring, offshore exploration, disaster prevention, and tactical surveillance. However, the design of efficient communication protocols for underwater sensor networks is still an open research problem due to the unique characteristics of the underwater acoustic communication channel such as limited bandwidth, high and variable propagation delays, and significant multipath and scattering.**

In this paper, we consider multimedia underwater monitoring applications with heterogeneous traffic demands in terms of bandwidth and end-to-end reliability. Distributed routing algorithms are introduced for delay-insensitive and delay-sensitive applications, with the objective of reducing the energy consumption by i) leveraging the tradeoff between multiplexing and diversity gain that characterizes MIMO links, and ii) allocating transmit power on suitable subcarriers according to channel conditions and application requirements. To achieve the objective above, each node jointly i) selects its next hop, ii) chooses a suitable transmission mode, and iii) assigns optimal transmit power on different subcarriers to achieve a target level of Quality of Service (QoS) in a cross-layer fashion. Extensive simulation results demonstrate that our proposed protocol is adaptive to the unique characteristics of the underwater acoustic communication channel, and achieves excellent performance through local cooperations between transmitter and receiver.

***Index Terms*—Underwater acoustic sensor networks, Routing algorithm, MIMO-OFDM, Cross-layer design, Performance evaluation**

I. INTRODUCTION

In recent years, UnderWater Acoustic Sensor Networks [1] (UW-ASNs) have experienced a rapid growth, due to their high relevance to commercial and military applications such as oceanographic data collection, pollution monitoring, offshore exploration, disaster prevention, and tactical surveillance. However, currently available underwater acoustic technology supports only low-data-rate and delay-tolerant applications. State-of-the-art typical experimental point-to-point acoustic modems use signaling schemes that can achieve data rates lower than $20\,\mathrm{kbit/s}$ with a link distance of $1\mathrm{km}$, while commercially available modems provide even lower data rate waveforms [2][3][4].

Multimedia underwater sensor networks would enable new applications for underwater multimedia surveillance, undersea explorations, video-assisted navigation and environmental monitoring. However, these applications require much higher data rates than currently available with acoustic technology, and more flexible protocol design to accommodate heterogeneous traffic demands in terms of bandwidth, delay, and end-to-end reliability. To accommodate such traffic demands, we propose to leverage the potential of *multiple-input-multiple-output* (MIMO) transmission techniques on acoustic links, leverage the potential of *orthogonal frequency-division multiplexing* (OFDM) to reduce intercarrier interference, and develop a new cross-layer routing protocol to flexibly exploit the potential performance increase offered by MIMO-OFDM links under the unique challenges posed by the underwater environment.

Most impairments of the underwater acoustic channel are adequately addressed at the physical layer, by designing receivers able to deal with high bit error rates, fading, and the inter-symbol interference (ISI) caused by multipath. Conversely, characteristics such as the extremely long and variable propagation delays are better addressed at the medium access control and routing layers. In fact, the quality of acoustic links is highly unpredictable, since it mainly depends on fading and multipath, which are not easily modeled phenomena. Finally, as in terrestrial sensor networks, energy conservation is one of the major concerns, since batteries cannot be easily recharged or replaced. Moreover, the bandwidth of the underwater links is severely limited. Hence, routing protocols designed for underwater acoustic networks must be spectrally and energy efficient.

For these reasons, the objective of this paper is to explore the capabilities of underwater MIMO-OFDM links, and to leverage these from the perspective of higher layer protocols, and in particular at the routing layer, with a cross-layer design approach. In particular, in this work:

1) *We identify how the capabilities of MIMO-OFDM links*, in particular the tradeoff between transmission data rate and link error probability, *impact routing protocol design in underwater networks*;
2) We build on the lessons learnt in developing solutions for UW-ASNs at the medium access control [5] and at the routing layer [6], to *develop a new routing protocol called UMIMO-Routing that leverages MIMO-OFDM capabilities* to enable more flexible and efficient

utilization of the underwater channel with respect to existing protocols. In particular, UMIMO-Routing is fully distributed and the performance targets are achieved through the cooperation of transmitter and receiver. Moreover, following a cross-layer design approach, UMIMO-Routing adapts its behavior to the condition of environmental noise, channel and interference to choose a suitable transmission mode, allocate transmit power on subcarriers, and minimize the energy consumption according to the Quality of Service (QoS) requirements of the multimedia application.

We emphasize that, to the best of our knowledge, our work constitutes the first research effort to develop higher-layer communication protocols for underwater networks with MIMO-OFDM links.

The remainder of this paper is organized as follows. In Section II, we discuss the suitability of the existing sensor routing solutions for the underwater environment. In Section III, we introduce an underwater acoustic MIMO-OFDM transceiver model and discuss the multiplexing-diversity tradeoff. Our proposed routing protocol named UMIMO-Routing is introduced for delay-insensitive applications in Section IV, while we adapt it to meet delay-sensitive applications in Section V. In Section VI, we assess the performance of the proposed solutions through simulation experiments. Finally, in Section VII, we draw the main conclusions.

II. RELATED WORK

A surge in research on underwater sensor networks in the last few years has resulted in increased interest for this cutting-edge technology. Apart from studies concerned with acoustic communications at the physical layer [7], [8], recent research is concentrating on developing solutions at the medium access control (MAC) [9], [10] and network layers of the protocol stack. In [11], we proposed UW-MAC, a distributed MAC protocol tailored for UW-ASNs for which extensive carefully crafted simulations demonstrated that it achieves high network throughput, low channel access delay, and low energy consumption. UW-MAC is a transmitter-based code-division multiple access (CDMA) scheme that incorporates a novel closed-loop distributed algorithm to set the optimal transmit power and code length. In [5], we proposed UMIMO-MAC to adaptively leverage the tradeoff between multiplexing and diversity gain. UMIMO-MAC jointly selects optimal transmit power and transmission mode through the cooperation of transmitter and receiver in a cross-layer fashion. In [12], a hybrid medium access control protocol is described, which includes a scheduled portion to eliminate collisions and a random access portion to adapt to changing channel conditions. In [13], Ahn and Krishnamachari analyze mathematically the performance of the propagation delay tolerant ALOHA (PDT-ALOHA) protocol for underwater networks.

Recent work has proposed routing protocols specifically tailored for underwater acoustic networks. In [6], a new geographical routing algorithms designed to distributively meet the requirements of delay-insensitive and delay-sensitive sensor network applications for the 3D underwater environment is proposed. In [14], a depth-based routing protocol is developed, which does not require full-dimensional location information of sensor nodes and only needs local depth information. In [15], the authors provide a simple design example of a shallow water network, where routes are established by a central manager based on neighborhood information gathered from all nodes by means of poll packets. In [16], the proposed Focused Beam Routing (FBR) protocol, based on location information, considers energy-efficient multi-hop communications in underwater acoustic networks. By coupling routing and MAC functionalities with power control, the next relay is selected at each step of the path. In [17], Harris and Zorzi study tradeoffs in the design of energy efficient routing protocols for underwater networks. In particular, an analysis is conducted that shows the strong dependence of the available bandwidth on the transmission distance, which is a peculiar characteristic of the underwater environment (see also Stojanovic [18]). Other significant recent studies consider delay-reliability tradeoff analysis (Zhang and Mitra [19]), the benefits achievable with cooperative communications (Mitra et al. [20]), and multi-path routing (Zhou and Cui [21]). No previous work, to the best of our knowledge, has investigated routing over acoustic MIMO-OFDM links.

In [22], Zhou et al. consider adaptive MIMO-OFDM with three different transmitter configurations. There is a growing literature on physical layer and coding aspects of underwater MIMO-OFDM communications [23][2][24][25]. However, to the best of our knowledge, no previous paper has addressed the design of higher-layer protocols optimized for underwater MIMO-OFDM communications.

III. SYSTEM MODEL

In this section, we first introduce the communication architecture for three-dimensional underwater sensor networks, and briefly describe the characteristics of underwater acoustic propagation. Then we introduce an underwater acoustic MIMO-OFDM transceiver model, and discuss the multiplexing and diversity tradeoff. Finally, we discuss the impact of frequency-dependent noise and attenuation in MIMO-OFDM communications.

A. Network Architecture

In three-dimensional underwater sensor networks, nodes are deployed at different depths to observe a given phenomenon and report to surface stations, as shown in Fig. 1. Each sensor is anchored to the bottom of the ocean and equipped with a floating buoy. The depth of each sensor can be regulated by adjusting the length of the wire that connects the sensor to the anchor. Underwater sensors are able to relay information to the surface station via multi-hop paths. Existing deployment strategies for underwater sensor networks, as discussed in [26], guarantee that the network topology be always connected. Therefore, we assume that at least one path from every sensor to the surface station always exists, and that higher sensor density increases the number of possible paths. Moreover, one or

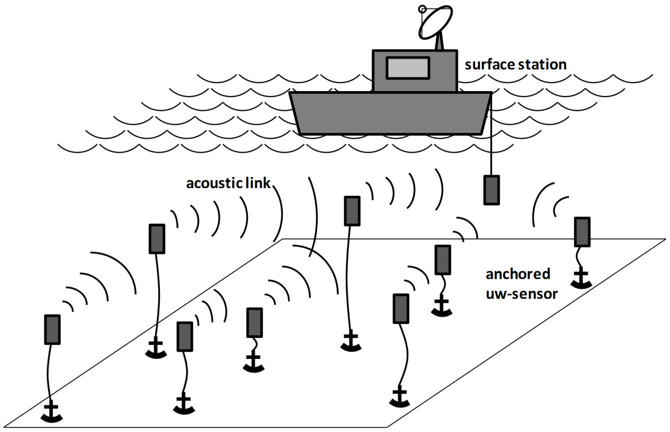

Fig. 1. Architecture of a 3D underwater sensor networks

more surface stations are deployed on the surface of the ocean. Each surface station is equipped with an acoustic transceiver, and it may be able to handle multiple parallel communications with the underwater sensors and surface stations.

B. Underwater Propagation Model

In underwater acoustic communications, the attenuation $A(l,\ f)$ is affected by the frequency f over a distance l, which can be approximated as [18]

$$A(l,f) = l^k \cdot a(f)^l, \tag{1}$$

where k is the geometric spreading, and $a(f)$ is the absorption coefficient expressed by the Thorp's formula:

$$10\log a(f) = \begin{cases} 0.11\frac{f^2}{1+f^2} + 44\frac{f^2}{4100+f} + 2.75\cdot 10^{-4}f^2 + 0.003, & f \geq 0.4 \\ 0.002 + 0.11\frac{f^2}{1+f^2} + 0.011f^2 & , f < 0.4, \end{cases} \tag{2}$$

where $a(f)$ is in dB/km and f is in kHz. The power spectral density (p.s.d.) of the ambient noise in underwater can be expressed (in dB re μ Pa per Hz) as

$$\begin{aligned} &10\log N_t(f) = 17 - 30\log f \\ &10\log N_s(f) = 40 + 20(s-0.5) + 26\log f - 60\log(f+0.03) \\ &10\log N_w(f) = 50 + 7.5w^{1/2} + 20\log f - 40\log(f+0.4) \\ &10\log N_{th}(f) = -15 + 20\log f, \end{aligned} \tag{3}$$

where $N_t(f)$, $N_s(f)$, $N_w(f)$, and $N_{th}(f)$ are the turbulence, shipping, waves, and thermal noise. s represents a shipping activity factor between 0 and 1, and $w[\mathrm{m/s}]$ is the wind speed. Thus, the overall p.s.d. of the ambient noise in underwater is $N(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f)$.

C. Acoustic MIMO-OFDM Transceiver Model

We consider an underwater acoustic sensor network in which each node has M_T transmit elements and M_R receive elements (e.g., hydrophones). When a node sends information to another node, its bit stream is split into M_T sub streams and each sub stream is transmitted by one of the M_T transmit elements. All M_T transmit elements transmit sub bit streams simultaneously to the receiver with range of available subcarriers $[f_1, \cdots, f_N]$ and each subcarrier bandwidth is Δf. Assuming the channel is static within each OFDM subcarrier, the received signals at the receiver can be modeled as

$$\mathbf{y}(f_k) = \sqrt{P(f_k)}\,\mathbf{x}\mathbf{A}(l, f_k) + \mathbf{n}(f_k), \tag{4}$$

where f_k is the central frequency of $k-\mathrm{th}$ subcarrier, $\mathbf{y}(f_k) = [y_1(f_k)\ y_2(f_k)\ \cdots\ y_{M_R}(f_k)]$ is the received signal vector whose component $y_n(f_k)$, $1 \leq n \leq M_R$, is the received signal at receive element n, $\mathbf{x} = [x_1\ x_2\ \cdots\ x_{M_T}]$ is the transmitted signal vector whose component x_m, $1 \leq m \leq M_T$, is the transmitted signal from transmit element m, and $\mathbf{n}(f_k) = [n_1(f_k)\ n_2(f_k)\ \cdots\ n_{M_R}(f_k)]$ is the noise vector whose components are modeled as Gaussian random variables. $\mathbf{A}(l, f_k) = \{a_{m,n}(l, f_k) : 1 \leq m \leq M_T, 1 \leq n \leq M_R\}$ is the channel matrix whose component $a_{m,n}(l, f_k)$ denotes the channel fading coefficient between transmit element m, $1 \leq m \leq M_T$, and receive element n, $1 \leq n \leq M_R$. We assume that the channel matrix is known at the receiver side, but unknown at the transmitter side. The transmitted signal vector $\mathbf{x}$ is assumed to satisfy a power constraint $\sum_{m=1}^{M_T} |x_m|^2 = 1$, i.e., the total transmitted power on $k-\mathrm{th}$ subcarrier is $P(f_k)$ no matter how many transmit elements are deployed at the transmit node.

D. Multiplexing and Diversity Tradeoff

The frequency-dependent attenuation significantly limits the maximum usable frequency and thus the available communication bandwidth [27]. MIMO transmissions is thus an ideal way to increase data rates for underwater acoustic communications, in which independent data streams can be sent out in parallel by multiple transmit elements in the same frequency band. The increased spectral efficiency is termed *multiplexing gain* [28]. At the receiver side, the receiver can demodulate each of the data streams by nulling out the others with a decorrelator [29].

Besides increasing transmission rates, MIMO can also be used to reduce the received signal error probability and hence to improve the communication link reliability. By sending signals that carry the same information through different channels, multiple faded copies of the data information can be obtained at the receiver. Such a redundancy is termed *diversity* [28] and can be quantified in terms of diversity gain d. The average error probability can be reduced in an order of $1/SNR^d$ at high SNR, so the higher the diversity gain, the higher the reliability of the receiver detection.

Therefore, underwater acoustic communications can benefit from MIMO in two aspects: multiplexing gain and diversity gain. Unfortunately, these two gains cannot be optimized independently and there is a tradeoff between them: higher multiplexing gain can be obtained at the price of sacrificing diversity gain, and vice versa. In an RF scenario, for any targeting multiplexing gain r, the maximum diversity gain is [28]

$$d(r) = (M_T - r)(M_R - r), \tag{5}$$

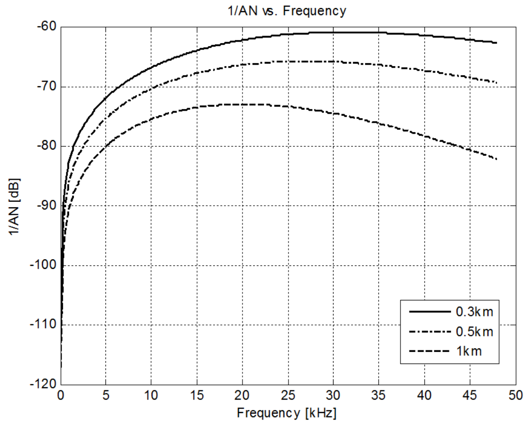

Fig. 2. The factor $1/A(l,f)N(f)$ with different frequencies and distances

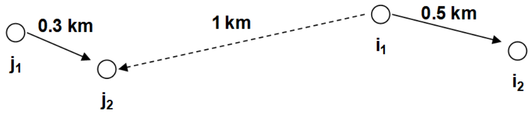

Fig. 3. Communications with difference transmission distances

which depends on the numbers of transceiver elements M_T and M_R.

E. Impact of Frequency-dependent Noise and Attenuation

In the underwater channel, noise is frequency-dependent, and attenuation is both distance- and frequency-dependent. Hence, for a fixed signal power, the signal-to-noise ratio (SNR) at the receiver varies on different carriers. Therefore, we can increase the SNR at the receiver and reduce the interference to neighbors by optimally selecting the transmission frequency. According to (4), the SNR can be expressed as

$$SNR(l, f_k) = \frac{\Delta f \cdot \frac{P(f_k)}{A(l,f_k)}}{\Delta f \cdot N(f_k)} = \frac{P(f_k)}{A(l,f_k)N(f_k)}, \tag{6}$$

which is affected by the AN product, $A(l, f_k)N(f_k)$. The factor $1/A(l, f_k)N(f_k)$ is shown in Fig. 2. As pointed out in [18], there are different optimal frequencies for different transmission distances. Hence, users can select different frequencies according to their transmission distance to achieve the required SNR level and not interfere with each other as shown in Fig. 3. If, for example, i_1 and i_2 are using frequencies centered at 27 kHz, which is the optimal frequency when the distance is 0.5 km, and j_1 and j_2 are using frequencies centered at 32 kHz, even though i_1 is using 32 kHz and interfering with j_2, the interference is limited because their transmission distance is 1 km and the AN product is large at 32 kHz for this transmission distance.

IV. DELAY-INSENSITIVE UMIMO-ROUTING ALGORITHM

In this section, we introduce a delay-insensitive distributed routing algorithm for underwater acoustic networks with MIMO-OFDM links. We first discuss the main factors affecting power consumption. Then we list the constraints to meet the delay-insensitive application requirements. Finally, we derive and analyze the proposed delay-insensitive UMIMO-Routing strategy. The proposed algorithm selects a next hop by jointly considering the transmit power, the packet error rate and the estimated number of hops to the sink.

We consider a network of acoustic devices in a multihop environment, and assume that each sensor node is equipped with $M_T = M_R = M$ transceiver elements. For each packet transmission, each device can encode the information bits to be transmitted in m *parallel independent streams*, with $m \in 1, 2, \cdots, M$. Given the number of independent streams m, and given a family of codes $\mathcal{C}$, a multiplexing gain $r(m)$ and a diversity gain $d(r)$ are defined according to the multiplexing and diversity tradeoff.

Formally, given the number M of transceiver elements at the transmitter and the receiver, and given a set of space time codes $\underline{C} = [C_1, C_2, \cdots, C_P]$, a set of *transmission modes* $\underline{M} = [M_1,\ M_2, \cdots, M_P]$, with P being the size of the space of transmission modes, are defined between a transmitter and a receiver. Each transmission mode M_k is associated to a multiplexing gain r_k, and a diversity gain d_k, with the transmission rate increasing with the multiplexing gain, and the bit error rate decreasing with increasing diversity gain.

As discussed above, the objective of the proposed routing scheme is to satisfy QoS requirements and minimize the energy consumption. The power consumption should be minimized to increase the sensor lifetime and reduce interference to neighboring on-going communications. To guarantee QoS requirements, there are six main factors affecting energy consumption:

1) l_{ij}, the distance between transmitter i and receiver j: a higher transmission power is needed when the distance is large. However, larger distance may reduce the number of hops to the sink and decrease the total power consumption;
2) C^{min}, the required link rate: it is related to the application requirements. A higher power consumption is needed to achieve a higher link rate. Therefore, we may need to select the next hop close to the transmitter when the required link rate is high;
3) r, the multiplexing gain: a higher multiplexing gain achieves a higher link rate, at the expense of reliability or power consumption;
4) d, the diversity gain: a higher diversity gain achieves a higher reliability that can reduce power consumption with a given transmitter-receiver distance, or increase transmitter-receiver distance for a given power consumption;
5) f_k, subcarriers: different subcarriers have different propagation characteristics and interference. Therefore, we can reduce the power consumption by selecting better subcarriers for transmitter-to-receiver transmissions;
6) $I_j(f_k)$, interference on subcarrier f_k observed at receiver j: clearly, a higher transmission power is needed to overcome a higher level of interference.

In the problem formulation, a node i needs to transmit a packet p to a node j. P_i^{max} is the maximum transmit power dictated by hardware constraints at node i. The interference on each subcarrier at node j, $I_j(f_k)$, is overheard from periodic broadcast by node j. We further represent with E_{elec} the distance-independent energy to transmit one bit, where we assume that the energy per bit needed by transmitter electronics and by receiver electronics is the same. The transmit power on each subcarrier and the bit rate are $P_{ij}(f_k)$ [W] and r_b [bit/s], respectively. The link capacity can be expressed as

$$r_b = \sum_{k=1}^{N} \Delta f \cdot \log_2[1 + \tfrac{P_{ij}(f_k)}{A(l_{ij},f_k)[I_j(f_k)+N(f_k)]}], \tag{7}$$

where l_{ij} is the distance between i and j. Therefore, the energy to transmit one bit from node i to node j, E_{ij}, is

$$E_{ij} = 2 \cdot E_{elec} + \frac{\sum_{k=1}^{N} P_{ij}(f_k)}{r \cdot r_b}, \tag{8}$$

where r is the multiplexing gain.

The proposed algorithm allows each node to distributively select the optimal next hop, the optimal transmit power on each subcarrier and transmission mode, with the objective of minimizing the energy consumption. Four constraints are included in the proposed algorithm to meet the delay-insensitive application requirements:

1) The transmit power should not exceed the maximum transmit power. Therefore, $\sum_{k=1}^{N} P_{ij}(f_k) \leq P_i^{max}$;
2) The link rate should be greater than an application-dependent threshold C^{min}. The link rate can be expressed as
$$C = \sum_{k=1}^{N} \Delta f \cdot r \cdot \log_2[1 + \tfrac{P_{ij}(f_k)}{A(l_{ij},f_k)[I_j(f_k)+N(f_k)]}]. \tag{9}$$
According to (7), $C = r \cdot r_b$, which increases with increasing multiplexing gain. However, a higher multiplexing gain requires a higher transmit power for a given target packet error rate since the related diversity gain decreases.
3) The average number of transmissions of a packet sent by transmitter i such that the packet is correctly decoded at receiver j can be expressed as
$$\hat{N}_{ij}^{TX} = \tfrac{1}{1-PER_{ij}}, \tag{10}$$
where PER_{ij} is the packet error rate on link (i, j). PER_{ij} is a function of the transmit power and the interference at node j on each subcarrier, and it can be reduced with a higher diversity gain, as discussed in Section III-D. Therefore, it can be derived as
$$PER_{ij} = \Phi([\tfrac{P_{ij}(f_k)}{A(l_{ij},f_k)[I_j(f_k)+N(f_k)]}]^{-d}). \tag{11}$$
4) The estimated number of hops from node i to the sink S when node j is selected as the next hop can be expressed as
$$\hat{N}_{ij}^{Hop} = \max\Big(\tfrac{l_{iS}}{<l_{ij}>_{iS}}, 1\Big), \tag{12}$$
where $< l_{ij} >_{iS}$ is the projection of l_{ij} onto the line connecting node i with the sink S.

We define S_i as the positive advance set [6], which is composed of nodes closer to sink S than node i, i.e., $j \in S_i$ iff $l_{jS} < l_{iS}$. The next hop of i should be selected from S_i to avoid routing loops. Then we can define the following ”Delay-insensitive UMIMO-Routing” strategy. The next hop, transmission mode and transmit power on each subcarrier are jointly selected by solving the problem below.

$\mathbf{P1}$: Delay-insensitive UMIMO-Routing

Given: i, j, P_i^{max}, C^{min}, $\underline{M}$
Find: $j^* \in S_i$, M^*, $[P_{ij^*}^*(f_k)]$
Minimize: $E_{ij} \cdot \hat{N}_{ij}^{TX} \cdot \hat{N}_{ij}^{Hop}$
Subject to:

$$\sum_{k=1}^{N} P_{ij}(f_k) \leq P_i^{max}; \tag{13}$$

$$\sum_{k=1}^{N} \Delta f \cdot r \cdot \log_2\Big[1 + \frac{P_{ij}(f_k)}{A(l_{ij},f_k)[I_j(f_k)+N(f_k)]}\Big] \geq C^{min}. \tag{14}$$

In the expressions above, E_{ij} is as in (8), $\hat{N}_{ij}^{TX}$ is as in (10) and $\hat{N}_{ij}^{Hop}$ is as in (12). To solve this optimization problem, we can first guarantee (14) by allocating power according to a water-filling principle [30][18]. We increase the total transmit power from 0 to P_i^{max} iteratively by a small amount until (14) is satisfied, and allocate the transmit power on each subcarrier, $P_{ij}(f_k)$, according to the water-filling principle. If we keep increasing the total transmit power, E_{ij} increases but $\hat{N}_{ij}^{TX}$ decreases since PER_{ij} decreases. Therefore, the total energy consumption may be reduced with higher E_{ij}. Then, we can calculate the minimum energy consumption for a given j and a given transmission mode M. Note that the space of solutions to the above problem is limited and the problem can be solved by enumeration - no specialized solver is needed. For example, P_i^{max} is $10\,\mathrm{W}$ and the small amount is $0.1\,\mathrm{W}$. If there are 5 candidate nodes and 2 transmission modes to select from, we only need to calculate at most 10^3 times and then the next hop, transmission mode and transmit power on each subcarrier are selected.

If the multiplexing gain is high, (14) is easily met with lower transmit power. However, PER_{ij} in (11) would be high since the diversity gain is low. On the contrary, higher diversity gain reduces the packet error rate but may not be able to guarantee the target link capacity.

V. Delay-sensitive UMIMO-Routing Algorithm

For delay-sensitive applications, we also propose an algorithm designed to reduce the energy consumption by leveraging the tradeoff between multiplexing and diversity gain according to channel conditions and multimedia application requirements. In this section, we first discuss the different constraints between delay-sensitive and delay-insensitive applications. Then, we derive a delay-sensitive UMIMO-Routing strategy to select a next hop by jointly considering the transmit power and the estimated number of hops to the sink.

Since our delay-sensitive routing algorithm does not retransmit corrupted packets at the link layer, the average number of transmissions in (10) is not needed. However, there are two new constraints that need to be satisfied:

1) The end-to-end packet error rate should be lower than an application-dependent threshold PER_{e2e}^{max}. Since the number of hops between node i and the sink is $\lceil \hat{N}_{ij}^{Hop} \rceil$, the end-to-end packet error rate is $1-(1-PER_{ij})^{\lceil \hat{N}_{ij}^{Hop} \rceil}$ and it should be lower than PER_{e2e}^{max}. Note that corrupted packets would be dropped. Therefore, the packet must be correctly forwarded from the source to node i. If the number of hops between the source and node i is h, $1 - 1^h \cdot (1-PER_{ij})^{\lceil \hat{N}_{ij}^{Hop} \rceil}$ should be lower than PER_{e2e}^{max};
2) The end-to-end packet delay should be lower than an application-dependent threshold T^{max}. The propagation delay from node i to node j is $l_{ij} \, / \, \bar{q}$, where $\bar{q}$ is the sound velocity. Besides, the transmission delay is $L_D \, / \, (r \cdot r_b)$, where L_D [bit] is the packet size. If the estimatetd queueing delay at node j is Q_j, we need to guarantee that the end-to-end packet delay will not exceed the application-dependent delay bound:
$$\frac{l_{ij}}{\bar{q}} + \frac{L_D}{r \cdot r_b} + Q_j \leq \frac{T^{max} - (t_{i,now}^{p} - t_0^{p})}{\hat{N}_{ij}^{Hop}}, \qquad (15)$$
where $t_{i,now}^{p}$ and t_0^{p} are the arrival time of packet p at node i and the time packet p was generated, respectively.

The following "Delay-sensitive UMIMO-Routing" strategy allows transmitter i to jointly select its next hop, transmission mode and transmit power on each subcarrier.

P2: Delay-sensitive UMIMO-Routing

Given: i, j, P_i^{max}, C^{min}, T^{max}, PER_{e2e}^{max}, $\underline{M}$

Find: $j^* \in S_i$, M^*, $[P_{ij^*}^*(f_k)]$

Minimize: $E_{ij} \cdot \hat{N}_{ij}^{Hop}$

Subject to:

$$\sum_{k=1}^{N} P_{ij}(f_k) \leq P_i^{max}; \qquad (16)$$

$$\sum_{k=1}^{N} \Delta f \cdot r \cdot \log_2 \Big[1 + \frac{P_{ij}(f_k)}{A(l_{ij}, f_k)[I_j(f_k) + N(f_k)]} \Big] \geq C^{min}; \qquad (17)$$

$$1 - (1 - PER_{ij})^{\lceil \hat{N}_{ij}^{Hop} \rceil} \leq PER_{e2e}^{max}; \qquad (18)$$

$$\frac{l_{ij}}{\bar{q}} + \frac{L_D}{r \cdot r_b} + Q_j \leq \frac{T^{max} - (t_{i,now}^{p} - t_0^{p})}{\hat{N}_{ij}^{Hop}}. \qquad (19)$$

In the expressions above, E_{ij} is as in (8), $\hat{N}_{ij}^{Hop}$ is as in (12), PER_{ij} is as in (11) and r_b is as in (7). Similar to the delay-insensitive routing algorithm introduced in Section IV, this algorithm still can be solved by enumeration.

VI. PERFORMANCE EVALUATION

We have developed a discrete-event object-oriented packet-level simulator to assess the performance of the proposed cross-layer protocol. MIMO-OFDM links are simulated by incorporating an acoustic MIMO-OFDM link module, which we have developed to assess MIMO-OFDM gains on underwater acoustic links. The physical-layer MIMO-OFDM link module models underwater acoustic signal propagation channel with path loss, multipath and underwater delays. The MIMO-OFDM link module generates bit error rate curves in terms of input parameters such as the link distance, the numbers of transmit/receive elements, choice of space-time codes, transmit power on each subcarrier, acoustic noise level and correlation among different channels.

We evaluate the performance of UMIMO-Routing in a three-dimensional shallow water environment. In addition, we compare it with the Greedy Routing Scheme (GRS) [31]. The GRS is based on geographical distance and it selects among its neighbors the next hop that is closest to the sink, thus reducing the number of hops to the sink. However, UMIMO-Routing not only considers the number of hops to the sink, but also selects the next hop by leveraging the tradeoff between multiplexing and diversity gain that characterizes MIMO links. UMIMO-Routing may select a next hop close to the transmitter to reduce the total power consumption. The knowledge range of GRS is set to $500\,\mathrm{m}$.

We also compare UMIMO-Routing with a version without OFDM to evaluate the performance gain obtained by jointly allocating subcarriers. Finally, to explore the multiplexing-diversity tradeoff, we compare the full UMIMO-Routing protocol with simplified non-adaptive versions of the protocol that transmit at full multiplexing or full diversity. Note that all figures are obtained by averaging over multiple topologies and report 95% confidence intervals. We set the maximum transmission power P^{max} to $10\,\mathrm{W}$ and the data packet size to $250\,\mathrm{Bytes}$. In addition, we consider an initial node energy of $1000\,\mathrm{J}$, a packet inter-arrival time of $5\,\mathrm{s}$, a maximum number of retransmissions equal to 4, an end-to-end packet error rate threshold of 0.05, an end-to-end packet delay threshold of $8\,\mathrm{s}$, and a queue size of $10\,\mathrm{kBytes}$. All nodes are randomly deployed in a 3D shallow water environment with volume of $1500\mathrm{x}1500\mathrm{x}100\,\mathrm{m}^3$. The number of source nodes is 5. Traffic packets are transmitted to any of the 2 surface stations. In the simulations presented in this section, two transmission modes are defined between a transmitter and a receiver, $(\mathrm{d}=2,\ \mathrm{r}=1)$ and $(\mathrm{d}=1,\ \mathrm{r}=2)$, where d is the diversity gain and r is the multiplexing gain. We emphasize, however, that our algorithms can be applied to arbitrary transmission modes, with additional performance gains. In Figs. 4 and 5, we evaluate UMIMO-Routing's scalability with different bit rates by varying the total number of relay nodes in the network in a delay-insensitive application. In Figs. 6 to 8, we show performance results of UMIMO-Routing in a delay-sensitive multimedia application.

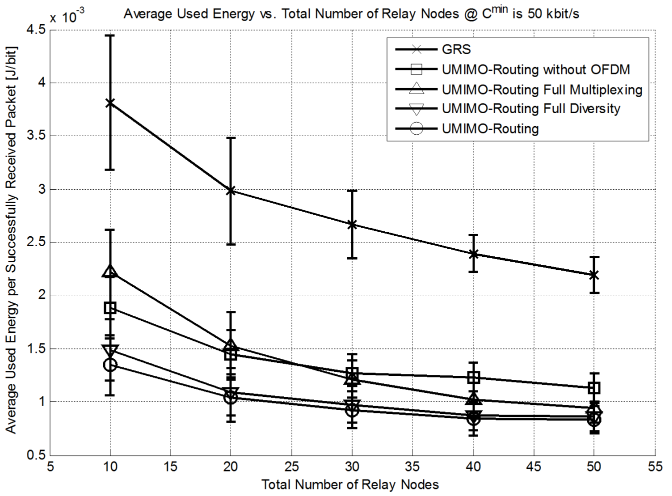

Fig. 4. Average used energy per successfully received packet vs. total number of relay nodes in the network when C^{min} is $50\,\mathrm{kbit/s}$ in a delay-insensitive application

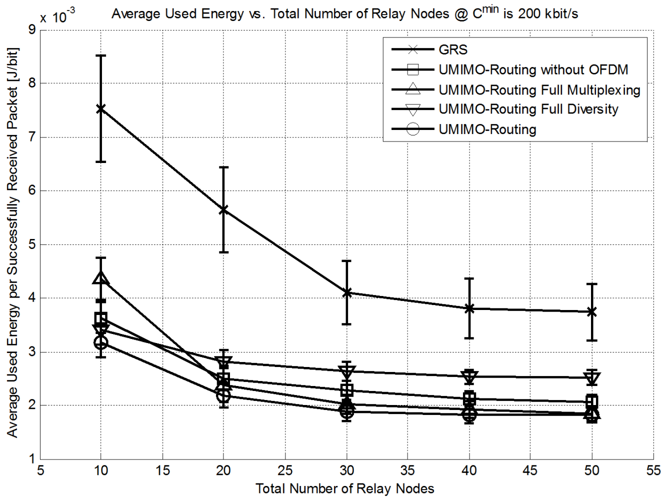

Fig. 5. Average used energy per successfully received packet vs. total number of relay nodes in the network when C^{min} is $200\,\mathrm{kbit/s}$ in a delay-insensitive application

A. Delay-insensitive Applications

First, we set the required link rate C^{min} to $50\,\mathrm{kbit/s}$ to evaluate the performance of UMIMO-Routing in a lower data rate delay-insensitive application. In Fig. 4, UMIMO-Routing is shown to considerably reduce the energy consumption by selecting suitable transmit power compared with GRS. The strategy of GRS focuses on reducing the number of hops to the sink. However, due to the unique characteristics of the underwater acoustic communication channel, GRS wastes more energy to retransmit packets because of large transmitter-receiver distance. Besides, GRS cannot adequately select its next hop and the next hop may have higher interference, which reduces the performance of GRS.

Moreover, when the total number of relay nodes in a given area is small, a transmitter has less choices for its next hop. Usually a transmitter can only choose its next hop with large transmitter-receiver distance. Since UMIMO-Routing Full Multiplexing always selects full multiplexing gain to transmit packets and its diversity gain is small, the packet error rate in (11) is high if the transmitter does not increase its transmit power. Therefore, UMIMO-Routing Full Multiplexing spends more energy when the total number of relay nodes in the area is 10. Besides, UMIMO-Routing Full Multiplexing, UMIMO-Routing Full Diversity and UMIMO-Routing perform almost the same when the total number of relay nodes is large. With more choices of next hops, UMIMO-Routing Full Multiplexing can select a node close to it as its next hop and then reduce the transmit power. E_{ij} in (8) is lower compared with UMIMO-Routing Full Diversity since UMIMO-Routing Full Multiplexing has higher multiplexing gain. On the contrary, UMIMO-Routing Full Diversity can select its next hop with larger transmitter-receiver distance compared with UMIMO-Routing Full Multiplexing since it has higher diversity gain, which reduces the packet error rate. UMIMO-Routing has benefits from both UMIMO-Routing Full Multiplexing and UMIMO-Routing Full Diversity, and it selects its next hop by leveraging the multiplexing-diversity tradeoff. Note that without OFDM, UMIMO-Routing consumes more energy to avoid intercarrier interference since it cannot select suitable subcarriers to transmit packets.

In Fig. 5, we set the required link rate C^{min} to $200\,\mathrm{kbit/s}$ to evaluate the performance of UMIMO-Routing in a higher data rate delay-insensitive application. Since UMIMO-Routing Full Diversity always selects full diversity gain to transmit packets and its multiplexing gain is small, the target link rate in (14) may not be guaranteed if the transmitter-receiver distance is large. UMIMO-Routing Full Diversity selects a next hop closer to the transmitter compared with UMIMO-Routing Full Multiplexing, and it makes the estimated number of hops in (12) higher. Therefore, UMIMO-Routing Full Diversity spends more energy compared with UMIMO-Routing without OFDM, UMIMO-Routing Full Multiplexing and UMIMO-Routing when the total number of relay nodes is large. Besides, the energy consumption of UMIMO-Routing Full Multiplexing is still higher when the total number of relay nodes is 10 because the transmitter-receiver distance is large, and it needs higher transmit power to reduce packet error rate in (11).

B. Delay-sensitive Applications

In Figs. 6 to 8, we set the required link rate C^{min} to $200\,\mathrm{kbit/s}$ to evaluate the performance of UMIMO-Routing in a delay-sensitive multimedia application. In Fig. 6, the average energy used by GRS is shown to be higher than UMIMO-Routing. Since the corrupted packets are dropped without retransmission, the average used energy per successfully received packet is lower compared with Fig. 5. However, GRS does not adequately select its next hop, and the next hop may have higher interference compared with other candidate nodes. Therefore, the average packet dropping rate is higher than UMIMO-Routing, as shown in Fig. 7.

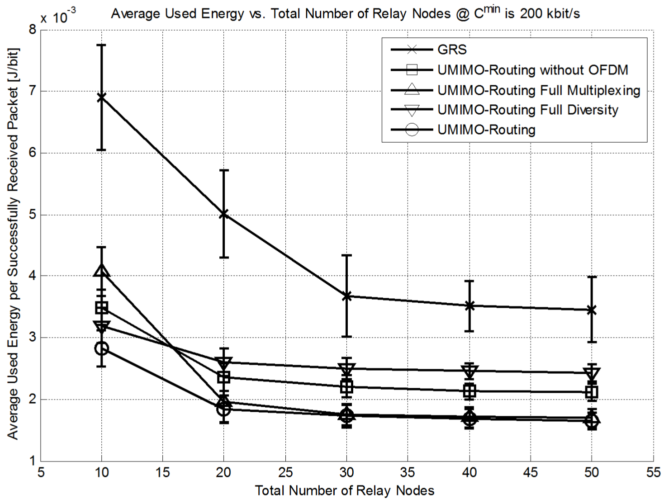

Fig. 6. Average used energy per successfully received packet vs. total number of relay nodes in the network when C^{min} is $200\,\text{kbit/s}$ in a delay-sensitive application

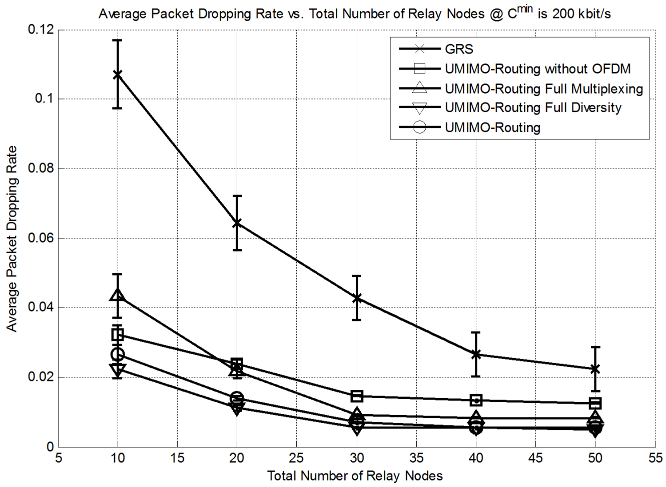

Fig. 7. Average packet dropping rate vs. total number of relay nodes in the network when C^{min} is $200\,\text{kbit/s}$ in a delay-sensitive application

Moreover, UMIMO-Routing Full Multiplexing has higher packet dropping rate compared with UMIMO-Routing without OFDM, UMIMO-Routing Full Diversity and UMIMO-Routing when the total number of relay nodes in the area is 10. The reason is that the transmitter can only choose its next hop with large transmitter-receiver distance and its diversity gain is low. Therefore, the packet error rate in (11) is higher and more corrupted packets are dropped. In Fig. 8, GRS does not adequately select its next hop and the next hop may have higher queueing delay. Thus, GRS has higher average end-to-end delay compared with UMIMO-Routing. Moreover, UMIMO-Routing Full Diversity has lower multiplexing gain and the transmission delay is higher. Its average end-to-end delay is higher than UMIMO-Routing without OFDM, UMIMO-Routing Full Multiplexing and UMIMO-Routing, but it can still guarantee (19).

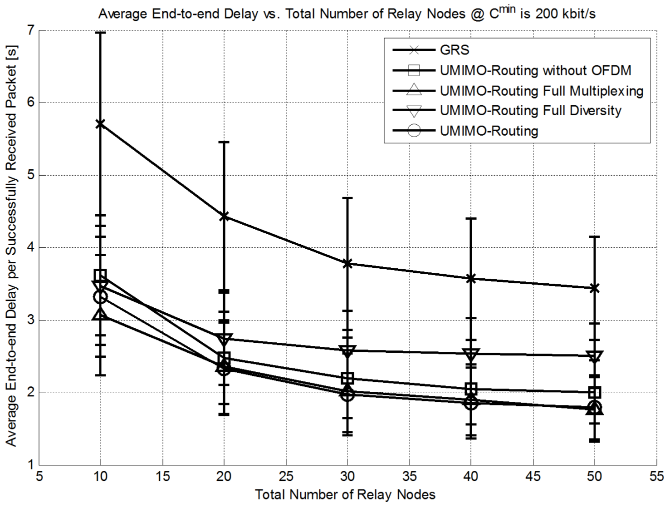

Fig. 8. Average end-to-end delay per successfully received packet vs. total number of relay nodes in the network when C^{min} is $200\,\text{kbit/s}$ in a delay-sensitive application

VII. CONCLUSIONS

We proposed, discussed and analyzed a routing protocol for underwater acoustic sensor networks with MIMO-OFDM links. UMIMO-Routing adaptively leverages the tradeoff between multiplexing and diversity gain, and selects suitable subcarriers to avoid interference. Moreover, in a cross-layer fashion, UMIMO-Routing jointly selects the next hop, transmission mode and transmit power on each subcarrier through the cooperation of transmitter and receiver to achieve the desired level of QoS according to application needs and channel condition. UMIMO-Routing was shown to consistently outperform GRS in terms of energy consumption, packet dropping rate and average end-to-end delay under several different simulation scenarios. With MIMO technology, UMIMO-Routing adequately selects its next hop according to the QoS requirements of different multimedia applications. With OFDM modulation, UMIMO-Routing reduces intercarrier interference and improves the system performance.

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