Energy Efficient Multi-Path Communication for Time-Critical Applications in Underwater Sensor Networks

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ABSTRACT

Due to the long propagation delay and high error rate of acoustic channels, it is very challenging to provide reliable data transfer for time-critical applications in an energy-efficient way. On the one hand, traditional retransmission-upon-failure usually introduces very large end-to-end delay, thus is not proper for time-critical services. On the other hand, common approaches without retransmission consume lots of energy. In this paper, we propose a new multi-path power-control transmission (MPT) scheme, which can guarantee certain end-to-end packet error rate while achieving a good balance between the overall energy efficiency and the end-to-end packet delay. MPT smartly combines power control with multi-path routing and packet combining at the destination. With carefully designed power control strategies, MPT consumes much less energy than the conventional one-path transmission scheme without retransmission. Besides, since no hop-by-hop retransmission is allowed, MPT introduces much shorter delay than the traditional one-path scheme with retransmission. We conduct extensive simulations to evaluate the performance of MPT. Our results show that MPT is highly energy efficient with low end-to-end packet delays.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]; C.2.2 [**Network Protocols**]

General Terms

Performance, Design, Algorithms

1. INTRODUCTION

As an emerging area, underwater sensor network has attracted rapidly growing interests in last several years [1, 6, 13, 24]. On the one hand, underwater sensor networks enable a wide range of aquatic applications, such as oceanographic data collection, pollution monitoring, offshore exploration, disaster prevention, and tactical surveillance applications. On the other hand, the adverse underwater environments pose grand challenges for efficient communication and networking.

In underwater environments, radio does not work well due to its quick absorption in water, thus acoustic channels are usually employed. The propagation speed of acoustic signals in water is about 1.5×10^3 m/s, which is five orders of magnitude lower than the radio propagation speed (3×10^8 m/s). Moreover, underwater acoustic channels are affected by many factors such as path loss, noise, multi-path fading, and Doppler spread. All these cause high error probability in acoustic channels. In short, underwater acoustic channels feature long propagation delay and high error probability. In such harsh network scenarios, it is very challenging to provide energy efficient reliable data transfer for time-critical applications (such as pollution monitoring and submarine detection). First, conventional retransmission-upon-failure approaches are hard to satisfy the delay requirements. To give a simple example, if two nodes are separately by 500 meters, the propagation delay between them will roughly be $\frac{500}{1500} = \frac{1}{3}$ second. Even one time retransmission-upon-failure will additionally introduce a delay of at least $\frac{1}{3} \times 2 = \frac{2}{3}$ second[1], which is quite large for some time-critical applications. Thus, to meet certain delay requirements, less or no retransmissions are preferred.

On the other hand, however, with less or no retransmissions, we usually need to increase the transmitting power of every node to reduce end-to-end packet error rate in order to meet a certain communication reliability, as often leads to more energy consumption, thus degrading the energy efficiency of the network. As its terrestrial counterpart, underwater sensor network is energy-constrained since underwater nodes are typically powered by batteries, for which replacement or recharging is very difficult if not impossible [1, 6]. Therefore, minimizing the overall energy consumption becomes one of the most important design considerations for such networks. In summary, a new transmission scheme with low delay and high energy efficiency is desired for time-critical applications in underwater sensor networks.

In this paper, we propose a new scheme, called **Multi-path Power-control Transmission (MPT)**, for time-critical applications in underwater sensor networks. MPT is a cross-layer approach. It combines power control with multi-path routing and packet combining at the destination. Distributed power control strategies at the physical layer are used to improve the overall energy efficiency. In MPT, there is no hop-by-hop retransmission, as contributes to low end-to-end delays.

In an underwater sensor network, with high probability, multi-path routing protocols can find multiple paths between any two nodes because of the relatively high node density (this assumption holds even stronger in the multiple-sink underwater network architecture [6, 30], which will be further discussed in Section 3). Different paths will experience independent fading if they are node-disjoint. MPT smartly utilizes this property to provide "multi-path macro-diversity". Specifically, in MPT, the source node transmits

[1]Here we assume that once a node receives an incorrect packet, it will send an NAK back to the sender to ask for retransmission. Besides the retransmission of the packet, we also need to consider the propagation time for the NAK message.

MobiHoc'08, May 26–30, 2008, Hong Kong SAR, China.

the same packet along multiple paths to the same destination. And the transmission power at each intermediate nodes along each path is controlled by the source nodes based on the path characteristics. Multiple copies of the packet (some of these copies may be corrupted during transmission) will arrive at the destination along different paths, and the destination then recovers the original packet by combining the received copies. Packet combining techniques such as those in [32, 9, 14] can be used here.

Multi-path schemes are commonly believed to be beneficial to load balance and network robustness [35, 12, 7], but they are usually not considered energy efficient since more nodes will be involved in a multi-path scheme than in a one-path scheme. In this paper, contrary to the common intuition, we show that in underwater fading environments, for time-critical applications, if multi-path schemes are properly combined with power control at the physical layer and packet combining at the destination, significant energy savings can be achieved while with low end-to-end delays.

Our contributions in this work are three-fold. First, we propose a novel and effective transmission scheme, MPT, for time-critical applications in underwater sensor networks. It can improve the overall energy efficiency across the whole network with low end-to-end delay and high reliability. Second, for MPT, we formulate an optimization problem to optimize the energy distribution across the whole network. We propose an efficient iterative approximation algorithm to solve this complex problem. Third, contrary to the common belief, our simulation results show that if properly used, multi-path can actually reduce the total energy consumption in underwater fading environments with low end-to-end packet delays.

The rest of this paper is organized as follows. In Section 2, we briefly review some related work. In Section 3, we describe the network model. Then in Section 4, we present MPT in detail. After that, we formulate the energy optimization problem and describe our iterative approximation algorithm in Section 5. Finally, we present simulation results in Section 6 followed by our conclusions in Section 7.

2. RELATED WORK

In this section, we first summarize some recent work on underwater sensor networks. Then we briefly review some typical approaches for energy efficiency in wireless sensor networks. After that, we discuss some relevant work on multi-path routing as well as packet combining.

As a new research area, underwater sensor network has received significant research interests for the last several years. Almost every layer of the protocol stack has been tackled: medium access control (MAC) ([28, 25]); multi-hop routing ([26, 38]); localization ([5, 10]), to name a few. Different from previous work, our work in this paper proposes an energy efficient cross-layer approach for time-critical applications in underwater sensor networks.

For wireless sensor networks, generally two ways are employed to improve the overall energy efficiency. One is to devise sleeping schemes for sensor nodes [39, 3, 8]. In these schemes, sensor nodes strategically change between sleeping mode and active mode. Since nodes in sleep mode consume much less energy than in active mode, these schemes can save energy by keeping nodes in sleeping mode as long as possible. The other way is to apply power control at the physical layer to reduce the overall energy consumption for one communication event [20, 16, 37, 19]. In this type of schemes, sensor nodes can dynamically adjust their power levels during the communication process according to channel status and network conditions. Essentially, our MPT scheme belongs to the second category, but it can be combined with any sleeping scheme from the first category.

Multi-path routing has drawn extensive attention in wireless sensor networks. The dense node deployment in wireless sensor networks makes multi-path routing a natural and promising technique to cope with the unreliable network environments. Research efforts have been made using multi-path routing to improve the robustness of data delivery [35, 40], to balance traffic load and power consumption among nodes [12, 36], to reduce end-to-end delays and the frequency of route discoveries [7, 23], and to improve the network security [21, 17], etc. The focus of our work in this paper is not to propose a new multi-path routing protocol. Instead, our research leverages existing multi-path routing protocols to make end-to-end transmission more energy efficient.

The basic idea of packet combining is to combine multiple corrupted copies of one packet to recover the original one. In [32], the authors propose a way to merge two or more non-coded packets to correct errors. It is shown that with packet combining at the receiver side, the original packet can be correctly recovered even if every individual received copy of this packet is corrupted. The authors of [9] extend the packet combining scheme into multi-hop scenarios and investigate its performance in wireless sensor networks. Through experiments, they show that the packet combining scheme can achieve promising results even in multi-hop wireless networks. In [14], the authors propose a multi-path packet combining scheme for wireless multi-hop networks. Based on an analysis on the delay characteristics of multi-path transmission, they show that the optimal number of paths exists that minimizes the average end-to-end packet error rate under certain delay constraints. In our work, we also propose a simple packet combining strategy for our MPT scheme. But our main contribution does not lie in packet combining and any other packet combining techniques can be easily incorporated into our scheme.

3. NETWORK MODEL

In this paper, we consider the following *multi-sink* underwater sensor network model: underwater sensor nodes with acoustic modems are densely distributed in a 3-D aqueous space, and multiple gateway nodes with both acoustic and RF modems are strategically deployed at the water surface. Each underwater sensor node can monitor and detect environmental events locally. As shown in Fig. 1, when an underwater sensor node has data to report, it first transfers the data toward one or multiple surface gateway nodes (each is also referred to as a sink) through acoustic links. Then these surface gateway nodes relay the received data to the control center through radio links. Compared with the acoustic links in water, surface radio links are much more reliable, faster and more energy efficient. Considering that radio signal propagation is orders of magnitude faster than acoustic signal propagation, it is safe to assume that surface gateways can send packets to the control center in negligible time and with relatively small energy consumption (acoustic communications consume much more energy than radio communications [6]). In this way, all the surface gateways (or sinks) form a *virtual sink*.

This multi-sink network architecture is helpful in traffic balance and multiple-path finding, as has been studied and analyzed in [30, 41, 15]. For our MPT scheme, this multi-sink architecture can effectively help to find more paths to the (virtual) sink (since any surface gateway is counted as a sink) and can greatly reduce the packet collision probability in the MAC layer. Later, in our simulation part, we will show the impact of the surface gateways on the network performance.

4. MPT DESCRIPTION

MPT can be divided into the following three parts: *multi-path routing*, *source initiated power-control transmission*, and *destination packet combining*. First, the source node (any underwater sensor node in our network model can be a source node) initiates a multi-path routing process to find paths from the source to the destination (in our network model, the control center can be the destination). Through this route-finding process, the source will get to

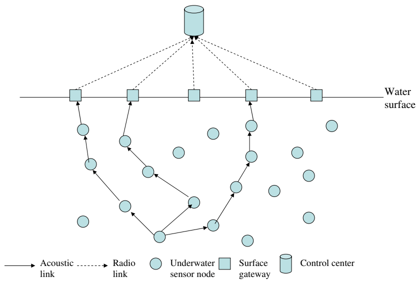


Figure 1: Network model

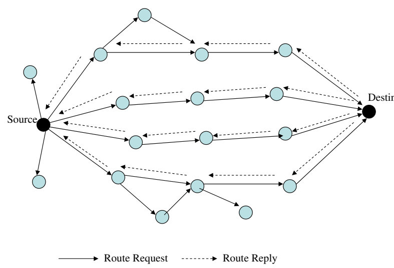


Figure 2: Basic procedure of multi-path routing

know some network parameters such as path length and the number of available paths. Based on this knowledge, the source node selects some paths and calculates the optimal transmitting power for each node along the selected paths. Then, it sends the same packet along the selected paths. Intermediate nodes on these selected paths will relay the packet with specified transmitting power parameters (carried in the packet header). When the destination receives all copies of the packet (some copies may get corrupted), it performs packet combining to recover the original packet.

In the following, we describe each part of MPT in detail.

4.1 Multi-path Routing

We assume that some multi-path routing protocols such as those in [22, 18] are available. The basic procedure of multi-path routing is illustrated in Fig. 2. When the source node has some packets to send, it will flood a "Route Request" message to the destination. Any intermediate nodes who receive this "Route Request" for the first time will forward it. When the destination receives "Route Request" messages, it will reply with "Route Reply" messages reversely along the paths of the corresponding "Route Request" messages. The destination can also make path selection. For example, it can select node-disjoint paths and send "Route Reply" back on them. After the source node receives the "Route Reply" messages, the routes between the source and the destination are established.

From the received "Route Reply" messages, the source node gets to know some path characteristics, such as the number of available paths, m, and the hop lengths of the paths. Based on this information, the source node will determine the optimal number of paths, m^*, and select m^* paths from m available paths. It also needs to calculate the optimal power level that every intermediate node on these paths should use for packet transmission. In Section 5, we will show how the source node makes these decisions.

4.2 Source-Initiated Power-control Transmission

In this phase of MPT, the same packets sent from the source node are transmitted by the intermediate nodes along all the selected paths using the specified transmission power. The packet format

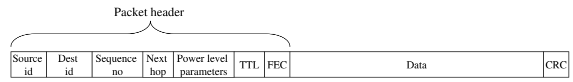


Figure 3: Packet format

is shown in Fig. 3. Every packet should include the source identification (Source id), the destination identification (Destination id), as well as the packet sequence number (Sequence no), next hop, and TTL (time to live) in the packet header. The source node should also include power parameters in the packet header. These parameters (Section 5.5 will specify the parameters) are used to determine the required power level that every intermediate node should use to relay the packet. In addition, we assume some coding schemes with strong error correction capability, such as forward error coding (FEC), are used in the header of every packet. In this way, the header part of every packet can be decoded correctly with high probability. Since the packet header is usually much smaller than the data part, the overhead incurred in the header error correction process is almost negligible. For the large data part, we do not use any error correction coding schemes because of their inefficiency in fading environments [9]. But some error detection coding schemes, such as cyclical redundant checking (CRC), are still used in the data part to check data errors.

When an intermediate node receives a packet, it will decode and check the header part. If the header is correct or can be recovered by the adopted FEC scheme, this node will relay the whole packet to its next hop with the specified power level without further checking the data part[2]. Otherwise, it will simply drop the packet.

4.3 Destination Packet Combining

At the destination, after it receives one copy of the original packet from one path (the data part of this copy may be corrupted during the transmission process), it will first check whether this copy is correct or not. If there is no error with this copy, it means that the destination successfully receives the original packet. Otherwise, the destination will keep this corrupted copy in its buffer. After receiving multiple corrupted copies of the original packet, the destination will combine these copies to recover the original one.

In MPT, we use a simple packet combining technique, which is illustrated in Fig. 4. Assuming the destination receives m^* copies of the same packet from m^* paths, for the i-th bit in this packet, it determines its output b_i as

$$b_i = \begin{cases} 1 & \sum_{k=1}^{m} b_{ik} > \frac{m^*}{2}, \\ 0 & \sum_{k=1}^{m} b_{ik} < \frac{m^*}{2}, \end{cases} \quad (1)$$

where b_{ik} denotes the kth copy of the ith bit. To simply put, when the bits in the majority of the copies are "1", then the corresponding bit of the original packet is decoded as "1"; otherwise, it is decoded as "0". We choose this "majority voting" method mainly because of its simplicity. It should be noted that [32, 9] propose more complicated packet combining schemes, and these schemes can further reduce packet error rate. However, these schemes need to search through all detectable error patterns in order to recover the original packet, as will introduce significant processing delay and increase the complexity of the destination node, especially when the data packet is large. On the other hand, our simple "majority voting" scheme has a constant processing delay and is simple to implement. Our simulation results in Section 6 show that even this

[2] Since packet combining is performed at the destination, corrupted data Packets are still useful for packet recovery and thus should be relayed.

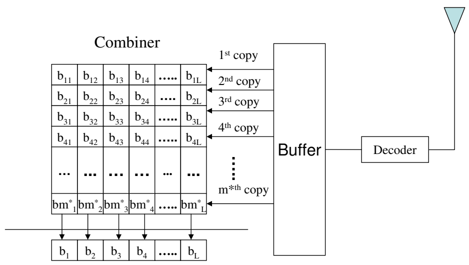


Figure 4: Packet combining at the destination

simple packet combining technology can still achieve significant performance improvement.

5. OPTIMIZING ENERGY DISTRIBUTION

In this section, we will first describe the channel model and formulate the energy distribution optimization problem. We will then show how the source node optimally distributes energy along one path and multiple paths. Finally, we summarize the overall energy distribution process.

5.1 Channel Model

We adopt the acoustic channel model proposed in [34]. For an underwater acoustic channel, its average path loss is given by

$$A(d, f) = d^a \beta(f)^d, \tag{2}$$

where d is the distance of the acoustic channel; a is the spreading factor ($1 \leq a \leq 2$); and $\beta(f)$ is the absorption coefficient which is determined by the frequency of the acoustic channel f. In this paper, we assume that all nodes work in the same frequency band. Thus, $\beta(f)$ will be the same for all nodes.

As in [33, 4], we assume Rayleigh fading for underwater acoustic channels in our analysis. Further more, we use BPSK (Binary Phase Shift Keying) modulation, which is widely used in the state-of-the-art acoustic modems [11]. Thus in our system, one symbol carries information of one bit. The energy consumption for one symbol actually equals to the energy consumption for one bit. Our analysis can be easily extended to other modulations.

5.2 Problem Formulation

In MPT, given m available paths, n_i hops on path i ($1 \leq i \leq m$), and the required end-to-end packet error rate (PER), P_{req}, the source node needs to distribute transmission energy for each hop along the m path in order to minimize the overall energy consumption for one packet transmission. This problem can be formulated as follows:

$$\begin{aligned} \min \quad & \sum_{i \in (1,2,\ldots,m)} \sum_{j \in (1,2,\ldots,n_i)} E_{ij} L \\ s.t. \quad & P_e \leq P_{req}, \\ & 0 \leq E_{ij} \leq E_{\max}, \end{aligned} \tag{3}$$

where L is the packet length in bits; E_{ij} is the average transmitting energy per bit of the jth hop on the ith path [3]; P_e is the average end-to-end packet error rate (PER); and $E_{\max}$ is the maximal transmitting energy per bit of every node, which is stipulated by the system hardware constraints.

In Eq. (3), the first constraint specifies that the average end-to-end PER, P_e, should be smaller than the system requirement P_{req}. The second constraint is to guarantee the transmitting energy per bit of every node will not exceed its maximal allowable transmitting energy per bit $E_{\max}$. In this paper, we ignore the energy consumption for data receiving and processing. This is because in underwater acoustic communication, data receiving and processing consumed much less energy than data transmitting [11].

The above optimization problem is hard to solve because of the following reasons: 1) with the import of the packet combining technique, the expression for the end-to-end PER, P_e, is quite complicated and not convex; 2) In (3), there are $\sum_{i \in (1 \ldots m)} n_i$ variables involved, as will increase the computation complexity of the source node.

In order to solve this complicated optimization problem, we divide the solving process into two steps. In the first step, we do optimal energy distribution among all available paths. This optimal distribution needs to guarantee that the average end-to-end PER requirement can be satisfied. In the second step, we do optimal energy distribution among all nodes along each selected path.

Next, we will first derive the optimal energy distribution for one path and get the relationship between the average energy consumption per bit for one path and its average end-to-end bit error rate(BER). Then, based on the results from one path, we will come to the energy optimization among multiple paths with certain end-to-end PER requirement.

5.3 Optimal Energy Distribution along One Path

Considering path i, its jth hop acoustic link can be treated a Rayleigh fading channel with additive white Gaussian noise (AWGN) on top of an average path loss which is proportional to ${d_{ij}}^a \beta(f)^{d_{ij}}$, where d_{ij} is the distance of the jth hop on path i. Then the average received signal noise ratio (SNR), $\bar{\gamma_{ij}}$, can be written as

$$\bar{\gamma_{ij}} = G \frac{E_{ij}}{N_0 {d_{ij}}^a \beta(f)^{d_{ij}}}, \tag{4}$$

where N_0 is the one-sided AWGN spectral density at the receiver, and G is a constant that is defined by the signal frequency, transducer gains, and other parameters. As such, the instantaneous received SNR, γ_{ij}, has the following distribution [31]:

$$f(\gamma_{ij}) = \frac{1}{\bar{\gamma_{ij}}} e^{-\frac{\gamma_{ij}}{\bar{\gamma_{ij}}}}. \tag{5}$$

Conditional on each instantaneous value of γ_{ij}, we have an AWGN channel. The approximate closed-form bit error rate (BER), $p^b_{ij}(\gamma_{ij})$, for uncoded BPSK signal in such an AWGN channel is provided as follows [27]:

$$p^b_{ij}(\gamma_{ij}) = \frac{1}{\sqrt{2\pi}} \int_{\sqrt{2\gamma_{ij}}}^{\infty} e^{-t^2/2} dt. \tag{6}$$

By averaging (6) over the Rayleigh fading channel, the average BER, P^b_{ij}, for one-hop transmission is obtained as [31]

$$P^b_{ij} = \int_0^\infty p^b_{ij}(\gamma_{ij}) f(\gamma_{ij}) d\gamma_{ij} \approx \frac{{d_{ij}}^a \beta(f)^{d_{ij}} N_0}{4 G E_{ij}}. \tag{7}$$

Eq. (7) specifies the average BER P^b_{ij} for the jth hop on path i. Since error propagation will occur in a multi-hop network scenario, we use a Markov chain to analyze the BER for multi-hop networks. We assume each single hop transmission is communication over a binary symmetric channel. Then, the one-step transition matrix of the Markov chain $\mathbf{K}$ is given by

$$\mathbf{K} = \begin{bmatrix} 1 - P^b_{ij} & P^b_{ij} \\ P^b_{ij} & 1 - P^b_{ij} \end{bmatrix}. \tag{8}$$

[3]Here, we assume that E_{ij} is independent of the packet length, which is a reasonable assumption for un-coded packets.

Due to the assumption of equally likely bits, the average end-to-end BER of path i from the source to the destination is given by

$$\begin{aligned}
\mathrm{P}_i^b &= \Pr(\hat{b}=0|b=1) \\
&= (0,1)\prod_{j\in(1,\dots n_i)}\begin{pmatrix}1-P_{ij}^b & P_{ij}^b\\ P_{ij}^b & 1-P_{ij}^b\end{pmatrix}(1,0)^T \\
&= \frac{1}{2}[1-\prod_{i\in(1\dots ni)}(1-2P_{ij}^b)].
\end{aligned} \quad (9)$$

Thus, to minimize the average energy consumption for one packet transmission with average end-to-end BER, P_i^b, for path i, we need to solve the following optimization problem

$$\begin{aligned}
\min \quad & \sum_j E_{ij}L \\
s.t. \quad & \frac{1}{2}[1-\prod_{j\in(1\dots n_i)}(1-2P_{ij}^b)] \le P_i^b \\
& P_{ij}^b = \frac{N_0 {d_{ij}}^a \beta(f)^{d_{ij}}}{4GE_{ij}}.
\end{aligned} \quad (10)$$

We use Lagrange method to solve Eq. (10) and get the following theorem (due to space limit, we skip the proof of this theorem. Interested readers can find more details in our technical report [42]).

Theorem I: For path i, with average end-to-end BER P_i^b, the optimal energy distribution along this path should satisfy

$$\frac{E_{ij}}{E_i} = \frac{G_{ij}}{G_i}, \quad (11)$$

where E_{ij} is the average energy consumption per bit of the jth hop in path i; E_i is the average energy consumption per bit along path i; $G_{ij} = {d_{ij}}^{\frac{a}{2}}\beta(f)^{\frac{d_{ij}}{2}}$, and $G_i = \sum_{j\in(1\dots n_i)} G_{ij}$. In addition, E_i and P_i^b have the following relationship

$$P_i^b = \frac{1}{2}(1-e^{\frac{-A_i}{E_i}}), \quad (12)$$

where

$$A_i = \frac{N_0}{2G}\sum_{j\in(1\dots n_i)} {d_{ij}}^{\frac{a}{2}}\beta(f)^{\frac{d_{ij}}{2}} \sum_{j\in(1\dots n_i)} {d_{ij}}^{\frac{a}{2}}\beta(f)^{\frac{d_{ij}}{2}}. \quad (13)$$

With Theorem I, given P_i^b, the source node can calculate the optimal transmission energy for each hop along path i.

5.4 Optimal Energy Distribution over Multiple Paths

Given m available paths, the overall energy consumption per packet, E, can be written as

$$E = \sum_{i=(1..m)} E_i L, \quad (14)$$

where E_i is the energy consumption for one bit along path i and L is the packet length in bits. Before presenting the energy distribution optimization problem for multiple paths, we first derive the average end-to-end packet error rate (PER), P_e, as follows.

Recall that we employ packet combining at the destination node. We use U to denote the event that at least one copy of a packet from m paths arrives correctly, $\overline{U}$ to denote that all individual copies are corrupted, and V to denote the event that our packet combining technique can successfully recover the original packet. Then the average end-to-end PER, P_e, can be written as

$$\mathrm{P}_e = (1-\Pr(V|\overline{U}))\times\Pr(\overline{U}). \quad (15)$$

We also know that

$$\Pr(\overline{U}) = \prod_{i=(1..m)}(1-(1-P_i^b)^L), \quad (16)$$

where P_i^b is the average end-to-end bit error rate (BER) of path i. Then we can get

$$\Pr(V|\overline{U})) = \{\sum_{k=\lfloor\frac{m}{2}+1\rfloor}^{m}\underbrace{[(1-P_1^b)\dots\dots(1-P_k^b)P_{(k+1)}^b\dots\dots P_m^b+\dots\dots\dots]}_{\binom{m}{k}}]\}^L. \quad (17)$$

Now we can formulate the optimization problem of minimizing the overall energy consumption per packet as follows:

$$\begin{aligned}
\min \quad & E = \sum_{i=(1,2,\dots.m)} E_i L \\
s.t \quad & \prod_{i=(1\dots m)}(1-(1-P_i^b)^L)\times(1-\{\sum_{k=\lfloor\frac{m}{2}+1\rfloor}^{m} \\
& \underbrace{[(1-P_1^b)\dots(1-P_k^b)P_{(k+1)}^b\dots P_m^b+\dots]}_{\binom{m}{k}}\}^L) \le P_{req}, \\
& P_i^b = \frac{1}{2}(1-e^{-\frac{A_i}{E_i}}) i\in(1,2\dots m), \\
& 0\le E_i \le \eta_i E_{\max} \quad i\in(1,2\dots m).
\end{aligned} \quad (18)$$

In Eq. (18), the first constraint is to specify the system requirement on end-to-end PER. The second constraint describes the relationship between the average energy consumption per bit E_i and the average end-to-end BER P_i^b for each path. The third constraint is to guarantee the transmitting energy per bit of every node will not exceed its maximal allowable transmitting energy per bit. η_i is a constant. Based on Eq. (11), it is calculated as

$$\eta_i = \min_j \frac{G_i}{G_{ij}}. \quad (19)$$

Eq. (18) is hard to solve directly because its first constraint is too complicated and not convex. Next, we propose an iterative approximation algorithm to solve it.

5.4.1 *Iterative Algorithm for Multi-path Energy Distribution*

We have noted that the complexity of Eq. (18) mainly lies in its first constraint. Thus, we focus on simplifying it in order to solve the optimization problem efficiently.

First, we set

$$C = \{\sum_{k=\lfloor\frac{m}{2}+1\rfloor}^{m}\underbrace{[(1-P_1^b)\dots\dots(1-P_k^b)P_{(k+1)}^b\dots P_m^b+\dots]}_{\binom{m}{k}}]\}^L. \quad (20)$$

Then, Eq. (18) can be written as

$$\begin{aligned}
\min \quad & E = \sum_{i=(1,2,\dots.m)} E_i L \\
s.t. \quad & \prod_{i=(1,2,\dots m)}(1-[1-\frac{1}{2}(1-e^{-\frac{A_i}{E_i}})]^L) \le \frac{P_{req}}{1-C}, \\
& 0\le E_i\le \eta_i E_{\max} \quad i\in(1,2\dots m),
\end{aligned} \quad (21)$$

which can be converted into

$$\begin{aligned}
\min \quad & E = \sum_{i=(1,2,\ldots,m)} E_i L \\
s.t. \quad & \sum_{i=(1,2,\ldots m)} ln(1 - [\frac{1}{2}(1 + e^{-\frac{A_i}{E_i}})]^L) \leq ln(\frac{P_{req}}{1 - C}), \\
& 0 \leq E_i \leq \eta_i E_{\max} \quad i \in (1, 2 \ldots m).
\end{aligned} \tag{22}$$

For now, we assume that C is a constant. Later, in our algorithm, we will show how to update C iteratively.

We use Taylor series expansion to the left side of the first constraint in Eq. (22). Then, by using Jensen's inequality, Eq. (22) can be approximated as follows:

$$\begin{aligned}
\min \quad & E = \sum_{i=(1,2,\ldots,m)} E_i L \\
s.t. \quad & -[\sum_{i=(1,2,\ldots m)} \frac{(1 + e^{-\frac{A_i}{E_i}})}{2(1 - x_i)^{\frac{1}{L}}}] \leq -m^{\frac{L-1}{L}} \times \\
& [\sum_{i=(1,2,\ldots m)} (ln(1 - x_i) + \frac{x_i}{1 - x_i}) - ln(\frac{P_{req}}{1 - C})]^{\frac{1}{L}}, \\
& 0 \leq E_i \leq \eta_i E_{\max} \quad i \in (1, 2 \ldots m),
\end{aligned} \tag{23}$$

where x_i ($i \in (1, 2, ..m)$) is the Taylor expansion point for every additive item $ln(1 - [\frac{1}{2}(1 + e^{-\frac{A_i}{E_i}})]^L)$ of the first constraint in Eq. (22). We update it iteratively in our algorithm to refine our results. The objective function of Eq. (23) is linear and its first constraint can be easily proved to be monotonically decreasing and convex when $E_i \geq \frac{Ai}{2}$.

To simplify the optimization problem, we set $E_i \geq \frac{A_i}{2}$. The rationale is as follows: when $E_i \leq \frac{A_i}{2}$, from Eq. (12), we know that the corresponding end-to-end BER of path i, $P_i^b \geq \frac{1}{2}(1 - e^{-2}) = 0.4323$, which is quite high for BER and is only slightly smaller than the worst case $P_i^b = 0.5$ when $E_i = 0$. Thus the probability that the optimal solution falls in $[0, \frac{A_i}{2}]$ is quite small. Therefore, setting $\frac{A_i}{2}$ as a lower constraint for E_i will not degrade the system performance much.

Then Eq. (23) can be converted into the following convex optimization problem and can be solved efficiently by the interior point method [2].

$$\begin{aligned}
\min \quad & E = \sum_{i=(1,2,\ldots,m)} E_i L \\
s.t. \quad & -[\sum_{i=(1,2,\ldots m)} \frac{(1 + e^{-\frac{A_i}{E_i}})}{2(1 - x_i)^{\frac{1}{L}}}] \leq -m^{\frac{L-1}{L}} \times \\
& [\sum_{i=(1,2,\ldots m)} (ln(1 - x_i) + \frac{x_i}{1 - x_i}) - ln(\frac{P_{req}}{1 - C})]^{\frac{1}{L}}. \\
& \frac{A_i}{2} \leq E_i \leq \eta_i E_{\max} \quad i \in (1, 2, \ldots, m).
\end{aligned} \tag{24}$$

Now we show our complete iterative algorithm in Algorithm 1. Clearly, our iterative algorithm includes three iterations. In the outmost iteration, we change the number of the paths and calculate the optimal energy distribution accordingly. In the middle iteration, we update x_is in order to refine our results. In the inner iteration, we update C iteratively. We have proved that **our iterative algorithm converges in finite time**. Due to space limit, we skip all proof details in this paper. Interested readers can find proofs in our technical report [42].

Algorithm 1 *Iterative Algorithm*

Sort all m paths according to their A_i and have $A_1 \leq A_2 \leq A_3 \ldots. \leq A_m$.
$k = 1$ //Initilize the counter of the paths
repeat
  $x_i = 1 - P_{req}, i \in (1, 2, ..k)$ //Initialize the Taylor expansion points
  repeat
    $E_{current,k} = \sum_{i \in (1,2,\ldots,k)} n_i E_{\max} L$ //$E_{current,k}$ is used to store the minimal energy consumption per bit with k paths. And it is initialized to its maximal value
    $C_{current} = 0$ //C is initialized to 0
    repeat
      Solve Eq. (24) and get the corresponding optimal energy distribution $(E_1, E_2, E_3, \ldots E_k)$ and BER $(P_1^b, P_2^b, P_3^b, \ldots.P_k^b)$ of the selected k paths
      $C_{prev} = C_{current}$
      With $(P_1^b, P_2^b, P_3^b, \ldots.P_k^b)$, calculate $C_{current}$ according to Eq. (20)
    until $|C_{prev} - C_{current}| < \delta_1$ //δ_1 is a predefined threshold
    $E_{prev,k} = E_{current,k}$
    $E_{current,k} = \sum_{i=(1,2,\ldots k)} E_i L$
    $x_i = [\frac{1}{2}(1 + e^{-\frac{A_i}{E_i}})]^L, i \in (1, 2, ..k)$
  until $|E_{current,k} - E_{prev,k}| < \delta_2$ //δ_2 is a predefined threshold
  $k = k + 1$
until $k > m$ //Finish all m paths
Compare all $E_{current,k}, k \in (1, 2, ..m)$ and select the smallest one, which corresponds to the final solution

Our algorithm includes multiple convex optimization processes. Although the computational complexity of convex optimization is hard to judge, efficient interior-point algorithm can be used here. Further, it should be noted that every intermediate solution of our algorithm can satisfy the the system end-to-end PER requirement, though they are not optimal. Thus, in practice, we can stop our algorithm whenever the required energy efficiency is reached. In Section 6, we will explore the trade-off between energy efficiency and computational complexity in our algorithm

5.5 Overall Energy Distribution Process

Considering the optimization algorithm discussed in this section, now we summarize the overall energy distribution process as follows:

1) Through the source-initiated multi-path routing process, the source node gets to know all needed information such as the number of available paths, the number of hops for each path, and the per-hop distance.

2) At the source node, the iterative algorithm is performed for multipath energy distribution. Then for every selected path, the source node sends out messages with two additional fields in the packet header. One field is to specify the optimal overall energy along this path, E_i, and the other is to specify G_i.

3) For each intermediate node j along path i, it has recorded its distance to its next hop in the path during the routing process. According to Eq. (11), it calculates its transmitting energy as follows:

$$E_{ij} = \frac{G_{ij}}{G_i} \times E_i. \tag{25}$$

Then it transmits packets with energy E_{ij} per bit.

4) At the destination, after it receives a copy of a packet, it first judges whether this copy is correct or not. If correct, this packet

will be passed to the application layer without any delay. Otherwise, it will wait for other copies and do packet combining to recover the original packet.

6. PERFORMANCE EVALUATION

In this section, we evaluate the performance of MPT through simulations.

6.1 Simulation Settings

Based on NS-2, we implement a simulation package for underwater sensor networks. Following the multiple-sink underwater sensor network model, the simulated network settings are as follows: 512 underwater sensor nodes are deployed in a 3-Dimensional space of $4000m \times 4000m \times 2000m$; and 36 surface gateways are deployed in a 2-Dimensional area of $4000m \times 4000m$ at the water surface. Additionally, we have a control center, to which all surface gateways relay the received packets, and this control serves as the destination node. The transmission range of underwater sensor nodes is set to $600m$ and the data rate is set to be 10Kbps. We use the same broadcast MAC protocol as in [38]. In this MAC protocol, when a node has packets to send, it first senses the channel. If the channel is free, it broadcasts the packets. Otherwise, it backs off. Packets will be dropped if the node backs off 5 times. Since there is no collision resolution in this broadcast MAC protocol, the performance of our scheme might be degraded. But for underwater sensor networks with low data generation rate, the collision probability will be very small. Thus, in our simulations, we set the data generation rate as 1 packet every 10 seconds to minimize the effect of MAC protocols. Further, the packet size is set to be 200 bytes. As for the routing protocol, we modify AODV (Ad hoc On-Demand Distance Vector) [29] and make it support multiple path routing. Each simulation lasts for 10000s. Thus, each node generate about 1000 packets in each simulation. We run simulations for 100 times, and take the average as our final results.

For comparison, we implement two other schemes in the same underwater network settings. One scheme is one-path transmission with power control but without retransmission (referred to as *one-path without retransmission* for short), and the other scheme is one-path transmission with retransmission and power control (referred to as *one-path with retransmission* for short). In the one-path without retransmission scheme, first, through a routing process(the routing process is the same as the previous multi-path scheme), the source node can find the most energy-efficient path and transmits its packets with power control to guarantee the end-to-end packet error rate. No retransmission is performed upon transmission failure. For the one-path with retransmission scheme, it works as follows: first, the source node finds the most energy-efficient path by its routing process and then transmits packets with power control along this path. Retransmission is allowed upon failure (i.e., if the sender does not receive an ACK for a packet from the receiver after time t_r (in our simulations, we set $t_r = 1s$), it will retransmit the packet). We set the maximal times of retransmission, n_r. After retransmitting a packet for n_r times, a node will simply drop this packet.

For the one-path without retransmission scheme, the optimal energy distribution problem has been actually solved in Section 5.3. For the one-path with retransmission scheme, we have also formulated and solved the optimal transmitting energy distribution problem. Due to space limit, we will not include the solving procedure in this paper (interested readers can find more details in our technical report [42]). But we will present the performance comparison between these two schemes and MPT in the next subsection.

For all schemes, we measure two metrics: *average energy consumption per packet* and *average end-to-end packet delay*. For the first metric, due the huge energy consumption of the one-path without retransmission scheme, to better present the comparison results, we covert the original energy consumption per packet E, measured in micro joules, mj, into log scale: $10 * log(E/1mj)$. The second metric is measured in seconds.

6.2 Results and Analysis

6.2.1 Impact of End-to-End PER Requirement

Fig. 5 shows the impact of end-to-end PER requirement (i.e., P_{req}) on various schemes. From this figure, we can observe that with the increase of P_{req}, the average energy consumption per packet decreases sharply. Compared with one-path without retransmission, MPT always consumes much less energy. When we compare MPT with the one-path with retransmission scheme with different n_r (the maximum number of retransmissions), MPT has comparable energy efficiency when P_{req} is small. When the end-to-end PER requirement is low (i.e., when P_{req} is large. In our simulations, when P_{req} is greater than 0.1), MPT has better energy efficiency than the one-path with retransmission scheme. The energy benefits of MPT come from the following two aspects. First, MPT takes advantage of multiple paths to transmit the same packet simultaneously. Even if one path is in deep fading and fails its transmission, other paths can perhaps transmit the packet correctly. This actually provides some "macro-diversity" benefits in the network scale. Second, with packet combining at the destination, even if all paths are in relatively bad conditions and all received copies of the packet are corrupted, the destination still has some probability to recover the original packets.

As for the average end-to-end packet delay, MPT has slightly higher delay than one-path without retransmission. This is mainly due to the packet combining delay at the destination. Compared with one-path with retransmission, MPT has much lower end-to-end delay. For example, MPT has an average end-to-end packet delay of about 5 seconds smaller than that of the one-path with retransmission scheme with $n_r = 3$. This is because of the long propagation delay in underwater sensor networks, which makes the retransmission quite time-consuming.

In short, from this set of simulation results, we can conclude that MPT can find a better trade-off between energy efficiency and end-to-end packet delay. In most practical network settings, MPT can achieve high energy efficiency with small end-to-end delay under certain end-to-end PER requirements.

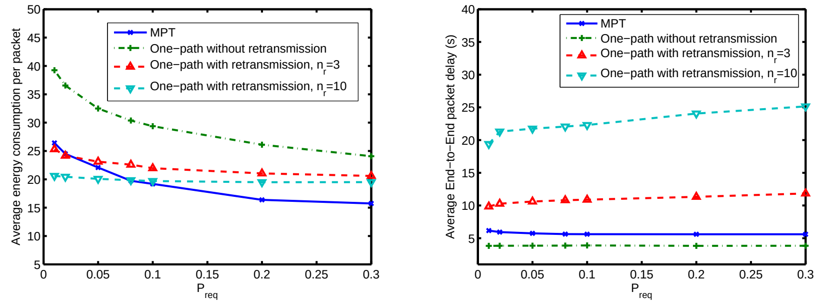
6.2.2 Impact of Node Density

Now we gradually change the average node density of the network[4] by changing the maximal transmitting range of every node from 450 to 750. The resulting average node density varies from 4 to 18. In this set of simulations. we set P_{req} to 0.05.

Fig. 6(a) clearly shows us that with the increase of node density, the average energy consumption of all schemes decreases. This is because more and better paths to the destination (i.e., the control center) will be found with the increase of node density. But the decrease will slow down in the high node density region. This is mainly due to the fact that in the high node density region, most usable energy efficient paths have already been found and continuing increase the maximal transmission range will not help much in energy consumption reduction. Besides, for MPT, very high node density (18 in the figure) will introduce more collision (due to multi-path routing), as will slightly degrade the energy efficiency in practice.

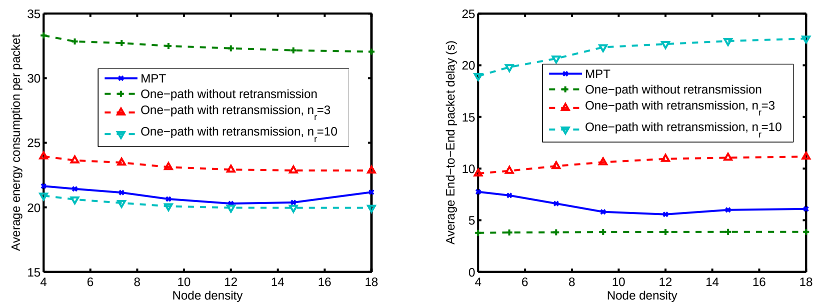
Fig. 6(b) shows the results for the average end-to-end packet delay with varying node density. From this figure, we can see that in the low node density region (from 4 to 12 in the figure), the average end-to-end packet delay of MPT decreases with the increase

[4]The average node density is defined as the average number of one-hop neighbors of a node. Two nodes are neighbors if they can reach each other with their maximal transmitting power.



(a) Average energy consumption per packet (b) Average end-to-end packet delay

Figure 5: Performance with varying end-to-end PER



(a) Average energy consumption per packet (b) Average end-to-end packet delay

Figure 6: Performance with varying node density

of node density. This is because more paths with shorter end-to-end delay are found with the increase of node density. However, in the high node density region, the delay of MPT increases slightly. This increase is mainly brought by the backoff in the MAC layer. But since the data generation rate is very low, the contention in the MAC layer is not significant. Thus, the increase in delay here is just minor. For the one-path with retransmission, the delay is increased gradually with the lifted node density. This is due the following: when there are more nodes in the network, the contention in the MAC layer caused by retransmission becomes more significant, which contributes to higher delays.

6.2.3 *Impact of Surface Gateways*

As discussed in Section 3, one important network parameter of MPT is the number of surface gateways. With more surface gateways, every sensor node has a better chance to find more paths to the destination (i.e., the control center). Thus, better energy efficiency could be achieved. On the other hand, however, with more surface gateways and thus more available paths, higher collision probability will be introduced and thus more energy and time will be wasted in the collision resolution process. In this set of simulations, we investigate the impact of surface gateways on the performance of MPT. We change the number of surface buoys from 4 to 64 and measure the average energy consumption per packet and the average end-to-end packet delay for various P_{req}. The results are plotted in Fig. 7.

Fig. 7(a) shows us that with the increase of surface gateways, the average energy consumption per packet decreases. And the decreasing rate slows down with the further increase of surface gateways. This is because of the higher collision probability introduced by more surface gateways, as is discussed in the early part of this subsection.

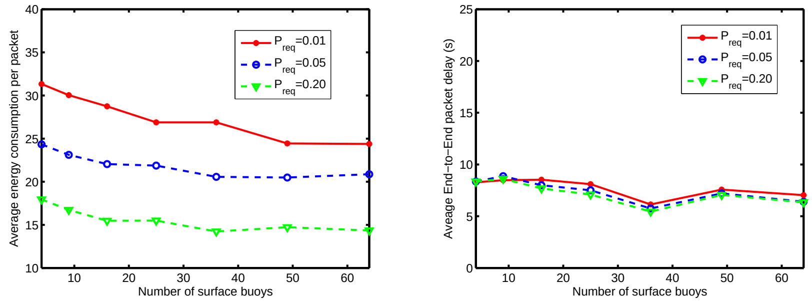
From Fig. 7(b), we can see that though the average end-to-end packet delay is not changed significantly with the number of surface gateways, there is some obvious impact. The variation in the figure is because the following: on the one hand, with more surface gateways, every node has higher probability to find shorter paths to the destination, as contributes to a shorter end-to-end packet delay. On the other hand, however, with more surface gateways and more available paths, higher collision probability will be introduced and thus more time will be wasted to revolve collision. From Fig. 7(b), we can observe that in our simulation settings, when the number of surface gateways gets to 36, the end-to-end delay reaches its minimum.

6.2.4 *Convergence Property*

In this set of simulations, we investigate the convergence property of our proposed iterative algorithm for MPT. From Algorithm 1, we can see the two pre-defined thresholds δ_1 and δ_2 are two critical parameters for the performance of the algorithm. Due to space limit, we only show the impact of δ_1 in this paper. Interested readers can find more results in our technical report [42]

We change δ_1 from 5×10^{-4} to 2×10^{-2}, and measure the average energy consumption per packet as well as the number of iterations performed in the iterative algorithm. The later metric mainly represent the computational complexity involved in the algorithm. The results are plotted in Fig. 8.

Fig. 8(a) clearly shows us that with the increase of δ_1, the average energy consumption per packet increases. This can be easily explained as follows: with the increase of δ_1, our iterative algorithm will deviate away from the optimal point and thus the average energy consumption will increase. We can also identify the critical points for different P_{req}. For example, when P_{req} is 0.05, δ_1 at 0.005 is good since a smaller δ_1 does not help to improve the performance much. On the other hand, with the increase of δ_1, from Fig. 8(b), we can see that the number of iterations will decrease,



(a) Average energy consumption per packet (b) Average end-to-end packet delay

Figure 7: Performance with varying number of surface gateways

sharply at the start and then slow down. When P_{req} is 0.05, and δ_1 is 0.005, the number of iterations is less than 15, which means the complexity of the algorithm is not high. Thus, in practice, we can control the tradeoff between the computation complexity and the energy consumption by changing this value of δ_1.

Fig. 8(b) also shows us that our algorithm converges well fast. Averagely, no more than 45 iterations are needed even when $P_{req} = 0.01$ and $\delta_1 = 0.0005$.

7. CONCLUSIONS

In this paper, we propose a novel Multi-path Power-control Transmission scheme, MPT, for time-critical applications in underwater sensor networks. MPT combines the power control strategies with multi-path routing protocols and packet combining at the destination. Without retransmission at the intermediate nodes, MPT can achieve low end-to-end packet delay. With power control at the physical layer, MPT can achieve relatively high energy efficiency. For time-critical applications in energy constrained underwater sensor networks, MPT is a promising transmission scheme for a good balance between packet delay and energy efficiency.

Future Work: We would like to pursue our future work in two directions: 1) Explore MPT in other long-delay and error-prone networks; 2) Implement MPT in real underwater sensor network testbeds and investigate practical design parameters.

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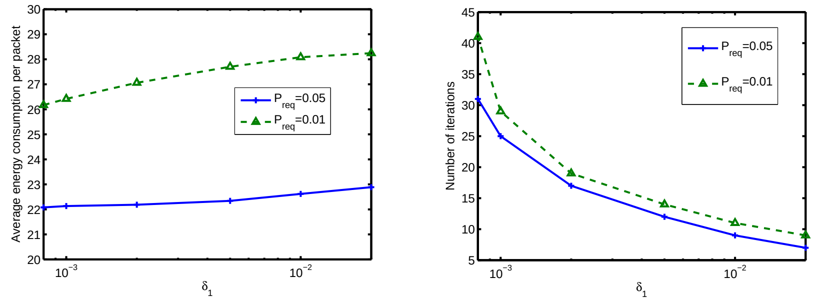

(a) Average energy consumption per packet (b) Average number of iterations

Figure 8: Performance with varying δ_1

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