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Citation: SCIENCE CHINA Information Sciences **57**, 102308 (2014); doi: 10.1007/s11432-013-4957-8

View online: https://engine.scichina.com/doi/10.1007/s11432-013-4957-8

View Table of Contents: https://engine.scichina.com/publisher/scp/journal/SCIS/57/10

Published by the Science China Press

SCIENCE CHINA
Information Sciences

• RESEARCH PAPER •

October 2014, Vol. 57 102308:1–102308:14
doi: 10.1007/s11432-013-4957-8

Energy-aware routing for delay-sensitive underwater wireless sensor networks

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Received February 24, 2014; accepted June 12, 2014; published online June 27, 2014

Abstract The energy reduction is a challenging problem in the applications of underwater wireless sensor networks (UWSNs). The embedded battery is difficult to be replaced and it has an upper bound on its lifetime. Multihop relay is a popular method to reduce energy consumption in data transmission. The energy minimum path from source to destination in the sensor networks can be obtained through the shortest path algorithm. However, because of the node mobility, the global path planning approach is not suitable for the routing in UWSNs. It calls for an energy-efficient routing protocol for the high dynamic UWSNs. In this paper, we propose the modified energy weight routing (MEWR) protocol to deal with the energy-efficient routing of delay-sensitive UWSNs. MEWR is a low flooding routing protocol. It can tolerate the node mobility in UWSNs and achieve a low end-to-end packet delay. MEWR can provide lower energy consumption than the existing low delay routing protocols through the dynamic sending power adjustment. The simulation results demonstrate the effectiveness of MEWR.

Keywords energy, delay, routing, UWSN, node mobility

Citation Zhang S L, Wang Z X, Liu M Q, et al. Energy-aware routing for delay-sensitive underwater wireless sensor networks. Sci China Inf Sci, 2014, 57: 102308(14), doi: 10.1007/s11432-013-4957-8

1 Introduction

With the emphasis on the upsurge in marine economy and the safeguarding of the national marine rights, underwater wireless sensor networks (UWSNs) have become a hot topic. The underwater sensors observe our curious targets, and transmit their local information to the base station (BS). The BS then implements some advanced tasks with the sensors' information.

The routing protocol is a hot research topic for UWSNs. The communication method of UWSNs is different from the terrestrial wireless sensor networks. In the terrestrial wireless sensor networks, the radio wave is employed to implement the communication between sensor nodes. However, the electronic wave will decay quickly in the sea water. For example, the Berkeley Mica 2 Motes have been reported to have only 120 cm communication range in underwater environment at 433 MHz by experiments [1]. Therefore, the acoustic communication is thought of as the only appropriate method in the UWSNs' communication at current time. The propagation speed of acoustic signal is five orders of magnitude

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lower than the radio signal. As a result, the packet delivery in UWSNs will face longer end-to-end packet delay. In some delay-sensitive applications of UWSNs, the routing strategy should seriously consider the propagation delay of a path. In UWSNs, the underwater sensor nodes are powered by the batteries, and it is difficult to replace the exhausted batteries. Therefore, energy conservation is very important in the applications of UWSNs. The routing protocols of UWSNs should also provide low energy consumption. In this paper, we focus on the energy-efficient routing for the delay-sensitive UWSNs.

Because of the high attenuation of long range communication, multihop relay is a common scheme to reduce energy consumption in the data transmission process. When a node has a packet to transmit to the sink, this packet will be routed through some intermediate nodes in the multihop relay process. Because the underwater sensor nodes will move due to the water current, the network topology changes frequently. The routing protocols designed for terrestrial wireless sensor network [2–6] are not suitable for UWSNs because the node mobility is not considered in these protocols. These protocols usually require the processes of path construction, maintenance and recovery. However, these processes are very expensive in high dynamic UWSNs. The existing underwater routing protocols [7–10] that seriously consider the node mobility of UWSNs do not contain the path construction, maintenance and recovery processes. The packets are flooded to the sink with geographic information. However, the sending power of these flooding based protocols are identical among different nodes. The energy can be reduced if we can properly reduce the transmission range. Based on the fact that enough neighbor nodes can hear the packets from the sender, we can decrease the sending power of the sender.

In this paper, we propose the MEWR routing protocol for delay-sensitive UWSNs. The protocol consists of two phases. In the first phase, the senders discover their neighbor nodes. In the second phase, the senders select part of their neighbors as the intermediate nodes and flood the packet to the intermediate nodes. Different intermediate nodes selection schemes can be designed according to different performance metrics. In the energy-aware routing of delay-sensitive UWSNs, the intermediate nodes selection should be based on two principles: low energy consumption and low delay. To design such a scheme, the delay constrained energy minimum routing problem should be solved. The delay constrained energy minimum routing problem is a constrained shortest path (CSP) problem. The problem can be described as a 0-1 integer linear programming (ILP), and it is NP-complete even for only one constraint [11]. The approximate approaches such as ε-approximation and simple metric are proposed to solve the CSP problem of networks. These approaches are only suitable for the route planning for stationary topology network. In MEWR, we employ the idea of simple metric approach and use a mixed metric to evaluate the cost of a link. Our contributions can be concluded as follows:

- We formulate a mixed metric to evaluate the cost of link. The intermediate nodes selected based on the mixed metric can handle the energy and delay of the route at the same time.
- The packets are flooded to part of the neighbors of a node in MEWR protocol. The sending power can be reduced if the neighbors are close to the sender. The flooding can also be reduced.
- The sender will sense the neighbors through a small size probe packet before sending. The influence of node mobility is impaired with small overhead.

For the convenience of the reader, we introduce some notations in Table 1.

The paper is organized as follows: in Section 2, we discuss the related works; in Section 3, we describe our models and assumptions; in Section 4 we describe the energy-aware delay-sensitive routing problem as a 0-1 ILP; in Section 5, we address the MEWR protocol; the simulation results are shown in Section 6; in Section 7, we conclude the paper.

2 Related work

MEWR is a routing protocol. It needs the geographic information of sender, neighbor nodes and sink. There are many geographic routing protocols designed for the dynamic UWSNs [5,7,9,12–14].

VBF [7] is a flooding based low delay routing protocol designed for UWSNs. VBF is easy to achieve and can handle the influence of node mobility. Based on the location information of the sink and neighbors,

Table 1 Notations

Name	Description
(i, j)	The link between node i and node j
e_{ij}	The energy weight of (i, j)
d_{ij}	The link length of (i, j)
c_{ij}	The cost of (i, j)
x_{ij}	The variable that describes whether e_{ij} is selected in the path
X	The multihop relay path, $X = [x_{11}, x_{12}, \ldots, x_{ij}, \ldots, x_{n-1,n}]^{\mathrm{T}}$
ε	$\varepsilon = [e_{11}, e_{12}, \ldots, e_{ij}, \ldots, e_{n-1,n}]$
T	$T = [t_{11}, t_{12}, \ldots, t_{ij}, \ldots, t_{n-1,n}]$
T_d	The delay constraint
Ω	The path set
τ_i	Transmission delay of node i
q_i	Queueing delay of node i
$N(i)$	The neighbor node set of i
$I(i)$	The intermediate node set of i
v	The sound speed
v_{water}	The water current speed
V	The sensor node set
E	The link set

VBF can provide low delay path. Duplicate packets will be received at the sink in VBF. To reduce the flooding, the packet will be held for a certain time. The holding time is determined based on the location of sender, forwarder and receiver. In DBR [9], the packets are flooded to the nodes with a smaller depth. There is also a holding time for each node, the holding time in DBR is based on the depth information. DFR protocol [13] implements the packet flooding in a scoped area. The receiver determines whether to discard the receiving packet or not based on the angle of signal. In [7,9,13], the sending power is the same for all nodes. It does not take advantage of the multihop relay. If there are enough neighbors of the sender, the transmission power does not need to be so large to reach the edge of maximum communication. We can decrease the transmission power to reduce total energy consumption.

In the routing protocols [5,6,12,14–16], the sending power can be controlled based on the location of neighbor nodes. Pompili et al. proposed a routing algorithm for delay-sensitive UWSNs [12]. However, in the model of [12], the node mobility is not seriously considered. Ref. [12] employed a probability model to describe the propagation delay of a link, but the assumption of Gauss distribution of delay remains to be discussed. Zorzi et al. [5] proposed the geographic random forwarding (GeRaF) routing. GeRaF addresses the node mobility. At each hop, GeRaF determines a radius R, and the packet at the current node will be routed to the node within the R. The node that is closest to the destination node inside the range will be selected as the next intermediate node. The approach in [15] is similar to GeRaF, but its implementation is much simpler. In [15], the nodes will agree to relay the packets if they are close to the sink. Ref. [14] proposed the forwarding protocol with both the energy and time considered. Due to the long propagation delay in acoustic communication, the protocol in [14] determines whether the packets are transmitted through an intermediate node or not based on the spatial location of the intermediate nodes. Huang et al. [16] employed the fuzzy logic method to determine the candidate intermediate nodes. The approach in [16] can prevent the growing of the packet forwarding tree so as to reduce flooding. In [17], the sensor nodes were divided into several layers based on their distances to the sink. According to the layer to which the sender belongs, the sender controls its transmission power so that only part of neighbors can hear and relay the packet. However, the geographic routing schemes [5,12,14–17] do not address how to position nodes in a highly dynamic network.

In this paper, we try to find an energy-efficient path for delay-sensitive UWSNs. In MEWR, we adjust the transmission power such that only part of neighbors can hear the data packet. The sending power of

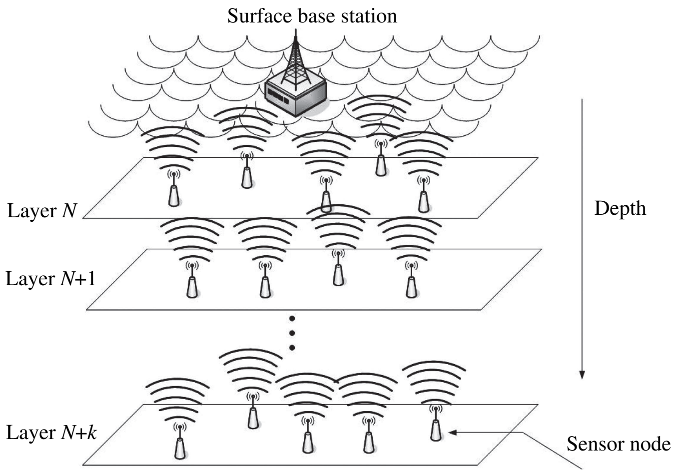

Figure 1 UWSN architecture.

different nodes are different. Compared to [5,12,14–17], MEWR does not need the location information of neighbor nodes but just the distance to neighbors. With the distance information, the sender determines the next hop based on the energy and delay model in UWSNs.

Although our MEWR does not require the global link cost information, our work helps solve CSP problem [18–21]. In MEWR, the determination of intermediate node selection is based on the simple metric approach. Simple metric approach is used to solve the CSP in quality of service (QoS) routing. It combines the constraints with the cost function. The delay of each link is added to the cost of each link as a penalty in this approach. Simple metric approach is based on the lagrangian relaxation [21]. Handler et al. [18] first proposed the method for the CSP problem. Jüttner et al. [19] developed a similar algorithm called lagrange relaxation based aggregated cost (LARAC) for the problem. The convergence of the simple metric approach can be guaranteed [18,19]. Xiao et al. [11] accelerated the search speed of the LARAC with a complexity of $O((m + n\log n)^2)$. Ref. [22] indicated that there exists information lost in the simple metric approach. But [11,19,20] argued the efficiency of the simple metric approach, and proposed some algorithms to overcome the information lost problem.

In this paper, our MEWR employs the idea of mixed metric and formulates the link cost based on the energy and delay of a link. Different from LARAC, the path is not determined at the source node. Because of the node mobility, the network topology changes frequently. It is impossible to determine the optimal path at the source node. In MEWR, we just determine the next hop with the mixed metric in a greedy way.

3 Basic model and assumptions

3.1 Network architecture

A UWSN performs cooperative sampling of the 3D ocean environment. The general architecture of UWSNs is shown in Figure 1.

The UWSN usually consists of a surface sink and many underwater sensor nodes. The sink is located at the surface and implements some advanced tasks with sensors' data. The underwater sensor nodes deployed in the underwater environment report their information to the surface sink. With the installation of buoyancy devices, the underwater nodes can float at different depth to sense the surroundings [23]. The depth of a sensor node can be regulated through the buoy, and the underwater nodes are deployed in layers at certain depths as shown in Figure 1 [8,23]. The topology of a UWSN is not stationary because of the node mobility. In horizontal directions, the sensor nodes will move with the water current, with a speed of 1–3 m/s. In vertical directions, the depth variations are usually negligible [8,10,23].

The nodes are equipped with acoustic modems and they can communicate with each other through acoustic channel. The bandwidth for UWSNs is 1–100 kHz [1]. Acoustic link can be built between two underwater sensor nodes to support the information exchanges.

The energy consumption for each node consists of the transmitter electronics energy to run the transmitter, the receiver electronics energy to run the receiver and the signal amplifier energy to support the long range communication. Because of the high attenuation of the acoustic signal, the signal amplifier dominates energy consumption of a node. Therefore, the transmitter electronics energy and the receiver electronics energy are neglected in this paper. The signal amplifier energy is a function of frequency, distance and medium. We assume that the medium is same in the underwater environment continuously. The attenuation in an underwater acoustic channel is a function of distance d and frequency [24]:

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

where l is the spreading factor, and $a(f)$ is the absorption coefficient. $a(f)$ can be expressed empirically using the Thorp's formula. For frequency above 100 Hz, there holds [25]

$$\log a(f) = 0.011\frac{f^2}{1+f^2} + 4.4\frac{f^2}{4100+f^2} + 2.75\times 10^{-5} f^2 + 0.0003. \tag{2}$$

The signal strength at receiver will be $1/A(d, f)$ of the original signal from transmitter. The sender can control its sending power based on the distance to the receiver.

3.2 Delay in UWSNs

When a sensor node has a packet to send to the sink, the sensor node becomes the source node. According to (1), the attenuation has an exponential relationship with the transmission distance. In order to save energy, multihop relay will be employed in the data transmission. In the multihop relay, the packets are routed from source node to the sink through intermediate nodes. The transmission of the packet from one node to another is counted as one hop. All the nodes inside the communication range of the source node are the candidates for the intermediate nodes.

When a packet is routed from the source node to the sink, there is an end-to-end packet delay. In general, the delay in UWSNs can be divided into the following types:

- Queueing delay—time the packet waits at the routing queues;
- Transmission delay—time to push the packet onto the link;
- Propagation delay—time for a signal to reach its destination.

The queueing delay is determined by the congestion situation of the network. The transmission delay is related to the data transmission rate of a sensor node. Both the queueing delay and transmission delay are similar to that of the terrestrial wireless sensor networks. The propagation delay, on the other hand, is much longer than that of the terrestrial wireless sensor networks. In terrestrial wireless sensor networks, sensor nodes communicate with each other through radio signal at a theoretical speed of 3×10^8 m/s. But in the acoustic communications of UWSNs, the speed of sound in the water is at most 1500 m/s. It makes the propagation delay really considerable.

3.3 Energy-aware routing in delay-sensitive UWSNs

Because the replenishment of batteries in underwater environment might be impossible, it calls for an energy-efficient routing scheme for UWSNs. When a packet is to be sent to the sink, a multihop path should be determined to minimize the energy consumption during the packet relay. In delay-sensitive UWSNs, there is a delay constraint on the end-to-end packet delay. We denote the delay constraint by T_d. When a packet is routed from the source node to the sink, the end-to-end delay should not be over a delay constraint T_d.

In many cases, the energy minimum path cannot satisfy the delay constraint. It can be illustrated through a simple example as shown in Figure 2.

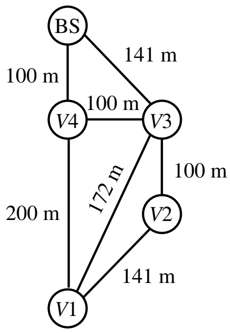

Figure 2 A simple UWSN.

There are four sensor nodes $V1$, $V2$, $V3$, $V4$ and a sink. With the distances between sensor nodes, the communication energy per bit for each link can be calculated through (1). The sound speed is assumed to be 1500 m/s, meaning that the propagation delay of 1 m is $\frac{1}{1500}$ s. The data transmission rate for each node is assume to be 10 kbps and the queueing delay for each node is assumed to be 0.03 s. Suppose $V4$ has a 256-bit length packet to send to the sink with a delay less than 0.3 s. The Dijkstra's algorithm with the energy metric suggests that the path $V1 \rightarrow V2 \rightarrow V3 \rightarrow sink$ is the energy minimum path. The total propagation delay of $V1 \rightarrow V2 \rightarrow V3 \rightarrow$ sink is 0.25 s and the total transmission delay is 0.077 s. Therefore, the path $V1 \rightarrow V2 \rightarrow V3 \rightarrow$ sink has an end-to-end delay of 0.422 s. It means that the energy minimum path cannot satisfy the delay constraint in this example. This example is quite common in the UWSNs. In UWSNs, we usually add some intermediate nodes to reduce the communication energy. But it means longer propagation distance and extra transmission delay. We need to deal with the trade-off between energy and delay.

In this paper, we focus on the energy-aware routing of delay-sensitive UWSNs. We try to find an energy-efficient path whose end-to-end delay is acceptable in the delay-sensitive applications.

4 Routing problem description

A sensor network can be described as an undirected graph $G(V, E)$, where V denotes the node set and E denotes the link set. $(i, j) \in E$ denotes the link between node i and node j. We call the distance between node i and j the link length of (i, j). For convenience, we let the node $1 \in V$ be the source node and node $n \in V$ be the sink in this paper. Due to the limited communication range of an underwater sensor node, one node may not be able to cover an arbitrary node in the network. For two sensor nodes i and j, we call j the neighbor of i if j is covered by i.

Lemma 1. The energy minimum path is equivalent to the attenuation minimum path.

Proof. Suppose node i will send 1-bit data to node j, and the link length of (i, j) is d_{ij}. If the signal strength at the receiver side should be at least β and the attenuation of link (i, j) is $A(d_{ij}, f)$, the communication energy of (i, j) is $A(d_{ij}, f)\beta$. It can be easily found that the communication energy per bit has linear relationship with the attenuation. Therefore, the energy minimum path is equivalent to the attenuation minimum path.

In this paper, we try to find the energy minimum path for the energy-efficient routing in delay-sensitive UWSNs. The energy minimum routing in delay-sensitive UWSNs should deal with two metrics: attenuation and delay. Therefore, we associate each link with two weights: energy weight and delay weight. The energy weight is the attenuation of a link, and the delay weight is the delay of a link. We denote by e_{ij} the energy weight of (i, j) and by t_{ij} the delay weight of (i, j). e_{ij} can be calculated through (1), i.e.,

$$e_{ij} = d_{ij}^{l} a^{d_{ij}}(f), \tag{3}$$

where d_{ij} is the link length of (i, j), l is the spreading factor, and $a(f)$ is the absorption coefficient. t_{ij} consists of three parts: queueing delay, transmission delay and propagation delay. We denote the queueing delay of node i ($i \in V$) by q_i, and the transmission delay of node i by τ_i. If the link length of (i,j) is d_{ij}, the delay weight of (i,j) is

$$t_{ij} = q_i + \tau_i + \frac{d_{ij}}{v}, \tag{4}$$

where v is the sound velocity. τ_i can be calculated with the packet size and the data transmission rate. If the packet size is S and the data transmission rate of node i is r_i, we have

$$\tau_i = \frac{S}{r_i}. \tag{5}$$

Because the distance between two nodes changes frequently, we should note that the energy weight and delay weight are not static in G.

The nodes within the communication of $i \in V$ are the neighbors of i. We denote by $N(i)$ the neighbor node set of i. $N(i)$ contains all the neighbors of i. In the routing process, a sender needs to transmit the packet to the intermediate nodes. Multiple nodes may serve as the intermediate nodes. We denote by $I(i)$ the intermediate node set of i. The node $j \in I(i)$ will assist to relay the packet sent by i. It is obvious that only neighbors of i are candidate for the intermediate nodes. Therefore, $I(i)$ is the subset of $N(i)$. Based on the link weights, the sender i formulates $I(i)$ and broadcasts the packet to the node in $I(i)$.

5 Modified energy weight routing (MEWR) protocol

MEWR is an on-demand routing protocol. No path maintenance nor recovery is required in MEWR. The node only determines the next hop based on the neighbors' location information. MEWR completes the path construction in two phases. The first phase is the path discovery phase. Different from the path discovery process in the conventional routing protocols like DSDV [2] and AODV [4], we do not build a path in discovery phase. The nodes that have packet to transmit just discover their neighbors through a probe packet in the discovery phase. The second phase is the next hop determination phase. In the second phase, the source node chooses some neighbor nodes as the next hop based on the distance to the neighbors. Because of the high dynamic property of UWSNs, the global route planning is meaningless. MEWR employs a greedy approach to determine the next hop. In order to achieve low delay and low energy consumption, we formulate the cost of a link as a mixture of delay metric and energy metric. Then we greedily choose the intermediate nodes with the minimum cumulative link cost. The sensor node recognizes each other through the sensor's unique ID. The number of IDs should be large enough so that each node can be assigned an ID. Considering the scalability of the network, in our protocol, we use a 16-bit sequence to denote the ID.

5.1 0-1 ILP description for static topology routing

Because the next hop determination is a modification of simple metric approach, which is designed for static topology routing, we first give a 0-1 ILP description for static topology routing. The routing problem can be described as a 0-1 ILP problem with the graph G. The packets are routed from source node to the sink along a path. The path is composed by several intermediate nodes and links. We use a 0-1 variable x_{ij} to determine whether the link (i,j) is used. $x_{ij} = 1$ means the link (i,j) is used during packets relay, and $x_{ij} = 0$ means the link (i,j) is not used. Supposing there are n nodes in the network, we define

$$\begin{aligned} X &= [x_{11}, x_{12}, \ldots, x_{ij}, \ldots, x_{n-1,n}]^{\mathrm{T}}, \\ \varepsilon &= [e_{11}, e_{12}, \ldots, e_{ij}, \ldots, e_{n-1,n}], \\ T &= [t_{11}, t_{12}, \ldots, t_{ij}, \ldots, t_{n-1,n}]. \end{aligned}$$

In the routing problem, if we want to use X to describe a connected acyclic path during multihop relay, the elements of X should satisfy the following equations:

Node ID	Depth

Figure 3 Probe packet format.

$$\sum_{j=1}^{n} x_{ij} - \sum_{k=1}^{n} x_{ki} = \begin{cases} 1, & i = 1, \\ 0, & i = 2, \ldots, n-1, \\ -1, & i = n. \end{cases} \tag{6}$$

We define a set $\Omega = \{X|X \text{ satisfies } (6)\}$. $X \in \Omega$ can be thought of as a path in the UWSN routing. In delay-sensitive UWSNs, the end-to-end delay should be less than the delay constraint T_d, i.e.,

$$TX < T_d. \tag{7}$$

The energy minimum routing problem with the constraint (7) can be interpreted as a 0-1 ILP:

$$\min_{X \in \Omega} \varepsilon X, \quad TX < T_d. \tag{8}$$

This problem is a typical CSP problem, and X here means a path during multihop relay.

5.2 Path discovery

Due to the node mobility, the neighbors of a node will change frequently. In the path discovery phase, the source node should determine its neighbors through a probe packet.

When a node has a packet to transmit, a probe packet will be broadcast by the node. The format of probe packet is illustrated in Figure 3.

The packet is a 32-bit packet and it contains the ID and the depth of the sender. As we have mentioned, the neighbors are the nodes within the communication range. All the neighbors of the sender will receive the probe packet. Because the sinks are located above water, the packet should be routed to the nodes with a smaller depth. The neighbor nodes compare their depth with the depth information in the probe packet. If the depth of the neighbor node is smaller than the depth value in the probe packet, a reply will be sent back by the neighbor node. The reply is a 48-bit packet and it contains the ID of the neighbor node, the ID of sender in probe packet and the distance to the sink. In our assumptions, the underwater nodes are able to measure the distance to the transmitter. So the source node can determine its distances to neighbors based on the received replies.

In the path discovery phase, a node needs to wait for the replies before the route determination. The waiting time should be long enough so that all replies from neighbors can be received. The distance to the farthest neighbor is at most the communication range R. Therefore, the waiting time is set to $2R/v$. Although both the location of neighbors and sender will change, the locations will not change too much within the path discovery process. For example, if the sound speed is 1500 m/s, the communication range is 200 m and water current speed is 5 m/s, the maximum moved distance of a node is $\frac{2\times200}{1500} \times 5 = \frac{4}{3}$ m. The path discovery process in MEWR can adapt the influence of node mobility. The detailed process of path discovery phase is shown in Algorithm 1.

Algorithm 1 Phase 1: path discovery phase

Require: the depth of nodes;

```
if i has a packet to send
    broadcast the probe packet;
end if
wait for 2R/v;
for j ∈ N(i)
  if depth_j <depth_i
    send the reply to i;
    add i to N(j);
  end if
end for
```

5.3 Next hop determination

MEWR is an energy-aware routing algorithm in delay-sensitive routing. It is expected that the packet is routed through a low energy consumption path while satisfying the delay constraint. In the network with fixed topology, the route planning problem can be converted to the 0-1 ILP (8). However, the node mobility makes the energy weights and delay weights dynamic. Even though it is the optimal path at current time, the optimum cannot stay for a long time due to the variation of delay and energy metrics. Therefore, we only determine the next hop in MEWR.

The delay constrained attenuation minimum problem is a CSP problem and it is not easy to solve. LARAC algorithm is a fully polynomial routing algorithm designed for the CSP problem [19]. LARAC can generate a near-optimal path for the stationary topology network. We exploit the idea of LARAC to determine the next hop.

Recalling the 0-1 ILP (8), we define two functions

$$f(X) = \varepsilon X, \tag{9}$$

$$g(X) = TX - T_d, \tag{10}$$

where $X \in \Omega$. $f(X)$ means the attenuation of the path X. $g(X)$ can be used to evaluate the delay of the path X. We have a Lagrangian function

$$L(X,\mu) = f(X) + \mu g(X) = \sum_{e_{ij}\in E} (e_{ij} + \mu t_{ij})x_{ij} - \mu T_d, \tag{11}$$

where $\mu \geqslant 0$. Eq. (11) is the *Lagrangian Relaxation* (LR) of the original problem. By (11), the weight changes to $e_{ij} + \mu t_{ij}$. The new weight is the mixture of the energy weight and the delay weight. Multiple performance metrics are converted to a simple metric. In LARAC, a near optimal path can be obtained through adjusting the parameter μ. The value of μ is determined through Newton's method. However, LARAC is not suitable for the path planning for UWSNs. Due to the high dynamic topology, the energy weight and delay weight change frequently. The path obtained through LARAC may not be a path with low energy consumption and low delay after several hops. However, the idea of LR approach provides an approach to solving the low energy routing in delay sensitive UWSNs. In MEWR, we formulate the cost of a link similar to LARAC. The link cost of c_{ij} is denoted by $c_{ij} = e_{ij} + \mu t_{ij}$. When $\mu = 0$, the route is determined with only energy metric. On the other hand, when μ is large enough, the route is determined with only delay metric. μ can be thought of as a penalty coefficient in LARAC. According to the delay requirement in UWSNs, we can control the delay of the path through adjusting μ. Compared to the existing greedy approaches in energy-aware routing, the mixed metric can consider the energy and delay at the same time.

If the node i has a packet to transmit, it first calculates the energy weight and delay weight of a neighbor $j \in N(i)$. Then the link cost of (i,j) is given by $c_{ij} = e_{ij} + \mu t_{ij}$. Similarly, the link costs of (j,n) and (i,n) can also be obtained. Node i will determine the next hop in a greedy way. If $j \in N(i)$ is selected as the intermediate node to relay the packet, the path cost is at least $c_{ij} + c_{jn}$. j is candidate as an intermediate node only if

$$c_{ij} + c_{jn} < c_{in}. \tag{12}$$

Otherwise, direct transmitting the packet from i to the sink is more efficient. We first check whether there is a neighbor that satisfies (12). If yes, selecting the neighbor will achieve lower cost. The node $j \in N(i)$ with the minimum $c_{ij} + c_{jn}$ is considered as the optimal intermediate node. The packet will be routed to this node.

Because the node's location will change after sending the reply packet, the node with the minimum $c_{ij} + c_{jn}$ may not be the best choice at current time. To provide more candidate optimal choices, we take the maximum moved distance of a node into consideration. For $j \in N(i)$, the maximum moving distance after sending the reply packet is $\frac{2R}{v}v_{water}$. So the cost variation of link (i,j) is

$$\Delta_{ij}^{+} = c_{ij} + \left(d_{ij} + \frac{2R}{v}v_{\text{water}}\right)^{l} a^{(d_{ij}+\frac{2R}{v}v_{\text{water}})}(f) + \mu\left(t_{ij} + \frac{2R}{v^2}v_{\text{water}}\right), \tag{13}$$

Sender ID	Receiver ID	Packet ID	d

Figure 4 Ack packet format.

$$\Delta_{ij}^{-} = c_{ij} - \left(d_{ij} - \frac{2R}{v} v_{\mathrm{water}}\right)^{l} a^{(d_{ij} - \frac{2R}{v} v_{\mathrm{water}})}(f) + \mu \left(t_{ij} - \frac{2R}{v^2} v_{\mathrm{water}}\right), \tag{14}$$

where Δ_{ij}^{+} means the link cost maximum increment and Δ_{ij}^{-} means the link cost maximum decrement. The actual cost $c_{ij} + c_{jn}$ with j as the intermediate node is in the range $[c_{ij} + c_{jn} - \Delta_{ij}^{-}, c_{ij} + c_{jn} + \Delta_{ij}^{+}]$. We call this range the 2 hop cost range (2HCR) For each $j \in N(i)$, we can formulate a 2HCR. The node with minimum $c_{ij} + c_{jn}$ has the minimum lower bound in the range, and this node will be selected as the intermediate node. We move j to $I(i)$. The node $k \in N(i)$ whose 2HCR has the overlapped part of the 2HCR of j will also be moved to $I(i)$. The packets from the sender will be routed to the nodes in $I(i)$.

The detailed process of next hop determination phase is shown in Algorithm 2.

Algorithm 2 Phase 2: next hop determination phase

Require: d_{ij}, d_{in}, d_{jn};

Ensure: $I(i)$;

for $j \in N(i)$
  calculate e_{ij} and t_{ij};
  $c_{ij} = e_{ij} + \mu t_{ij}$;
end for
$j = \arg\min_{j \in N(i)} [c_{ij} + c_{jn}]$;
move j to $I(i)$;
for $k \in N(i)$
  if $c_{ik} + c_{kn} - \Delta_{ik}^{-} < c_{ij} + c_{jn} + \Delta_{ij}^{+}$
    move k to $I(i)$;
  end if
end for

After node j receives the packet, an Ack packet will be sent to node i. The format of the Ack packet is illustrated in Figure 4.

The Ack packet is a 64-bit packet and it contains the sender ID, receiver ID, the packet ID and the distance d between sender and receiver. The sender will wait the Ack for $2d/v$. If the sender does not receive the Ack after sending the packet for $2d/v$, the packet will be retransmitted.

6 Simulation results

In this section, we will present the simulation results of our MEWR protocol. The underwater nodes are randomly distributed in a 1000 m×1000 m×1000 m area. The energy consumption of communication can be described as (1). We set the spreading factor at 2 and the absorption coefficient at 1.001. The packet loss ratio of the wireless link is set to 0.3. The sound speed is configured as $v = 1500$ m/s. The sensor nodes will transmit their local data to the BS. We assume that it requires 100 pJ/bit energy to achieve an acceptable signal noise ratio (SNR) at the receiver side. The location of a node can be described with a coordinate (x, y, z). We assume the data transmission rate is 50 kbps. The communication range of each sensor node is set to 500 m. Each node may move from its initial location because of the water current. In the simulations, we assume the water current speed is 3 m/s. The direction of water current is random and it changes every 10 s. As a result, the node will move 3 m with the water current every second. In MEWR, there are four kinds of packets: probe packet, reply packet, Ack packet and data packet. We assume the data packet is 50-byte. The other three kinds of packets are used for route control, and their sizes are much smaller than that of data packet.

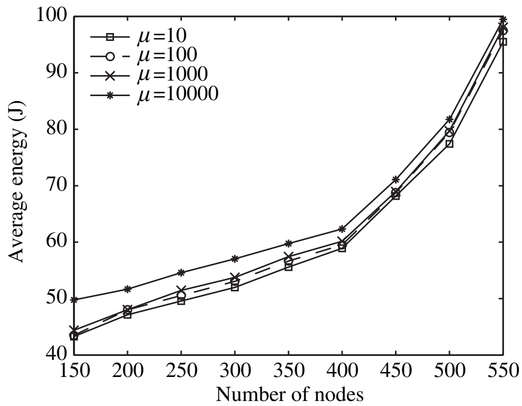

Figure 5 Average energy consumption of MEWR.

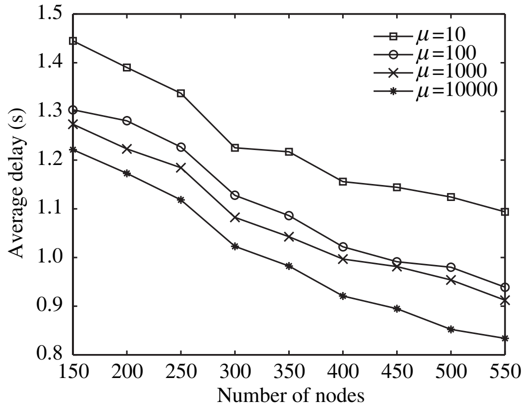

Figure 6 End-to-end packet delay of MEWR.

We compare the MEWR protocol with vector based forwarding (VBF) protocol [7] and depth-based routing (DBR) protocol [9]. VBF and DBR are flooding routing protocols designed for the UWSNs, and they can be implemented easily. In VBF and DBR, there is a holding time for each node to reduce flooding. The holding time of VBF is determined by the adaptive factor. The holding time of DBR is determined by a global parameter δ. In the simulations, we let δ be half of the transmission range. In VBF and DBR, the sending power of a node is fixed. MEWR, on the other hand, will adjust the sending power based on the distance to the intermediate node. In the path discovery phase of MEWR, the probe packets and reply packets are used to sense the neighbor nodes. Therefore, the power for sending probe packets and reply packets is controlled to the maximum power (the power for the signal to reach the nodes on the edge of transmission range). The sending power of Ack packet and data packet will be adjusted based on the distance of a hop.

MEWR is an energy-aware routing protocol for delay-sensitive UWSNs. Energy and delay are two metrics. In the simulations, we use average energy consumption and average delay to evaluate the the performance of MEWR. In MEWR, μ is the unique parameter we need to configure out. To evaluate the influence of μ, we simulate the energy and delay performance of MEWR with different μ. In each simulation, we let 10 nodes be the source node with packets to send to the sink. The sink is located at (500,500,0). The process is repeated for 500 times, and results is the average value of the 500 times simulations. The energy performance is shown in Figure 5, and the delay performance is shown in Figure 6.

In Figures 5 and 6, the four curves depict the energy consumption with different μ. The energy performance and delay performance of $\mu = 0$, $\mu = 100$ are quite similar. The energy consumption of $\mu = 1000$ is larger than that of $\mu = 0$ and $\mu = 100$. The delay of $\mu = 1000$ is smaller than that of $\mu = 0$ and $\mu = 100$. When $\mu = 10000$, there is an increase in energy consumption and a decrease in delay. The results reflect the property of μ. μ can be used to evaluate the importance of delay performance. Larger μ will reject the intermediate nodes with longer delay, and sometimes reduce the number of hops. It increases the energy consumption and reduces the end-to-end delay. In delay-sensitive applications, we can adjust μ to guarantee the real-time constraint of the system. Figures 5 and 6 show the influence of scalability. The energy consumption will increase and the delay will decrease when the nodes increase in number. Through Figure 5, it can be found that the energy consumption will increase more quickly with large scalability network. The situation is caused by more possible intermediate nodes during packet transmission. In MEWR, the nodes which have overlapped 2HCR with the estimated optimal intermediate node are candidate to relay packets. When the network is dense, more nodes may have the overlapped 2HCR. As a result, more nodes are candidate to relay the packet, and the total energy consumption increases more quickly. However, we should still note that the increase is not so obvious. Through Figure 7, we can found the energy increase of MEWR is not so considerable compared to DBR and VBF.

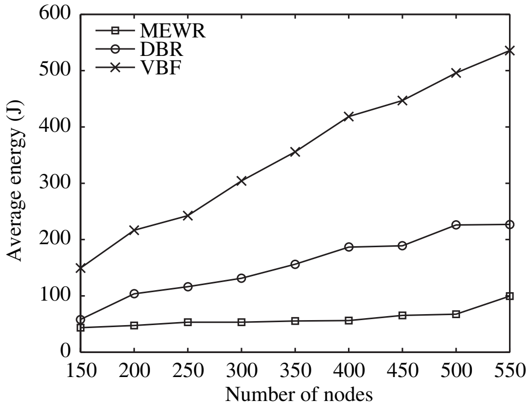

Figure 7 Energy comparison between MEWR and DBR.

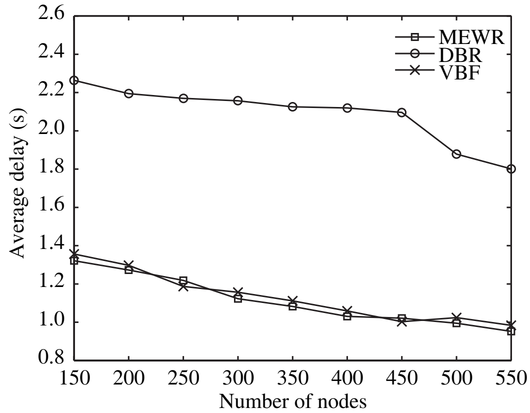

Figure 8 Delay comparison between MEWR and DBR.

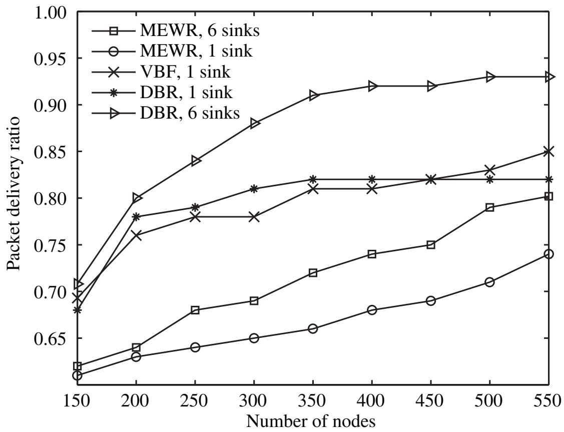

Figure 9 Packet delivery ratio.

The comparisons between MEWR ,VBF and DBR are shown in Figures 7 and 8. In each simulation, we randomly generate 10 source nodes, and these nodes will send packets to the sinks. μ is set to 1000 for MEWR. All simulations are repeated for 500 times, and the values in Figures 7 and 8 are the average energy consumption and delay in the 500 times.

It can be found that MEWR achieves better energy and delay performance. Under different network scalability, the energy consumption of MEWR is much smaller than VBF and DBR. Because the high attenuation of acoustic signal, reducing the communication range can reduce the sending power a lot. In VBF and DBR, the sending power is a fixed value and all the nodes within the communication range can hear the data packets. In MEWR, only the small size control packets are sent with the power to guarantee the neighbors can hear them. The sending power of data packets are controlled to a value that can just support part of neighbors. With the decrease of transmission range, the energy consumption can be reduced a lot. MEWR can achieve smaller end-to-end delay to DBR, and it has similar delay performance to VBF. The reason is that there is no holding time MEWR compared to DBR and VBF. Holding time is used to reduce the flooding in flooding based routing protocols. In MEWR, the flooding is reduced through adjusting the sending power. Although some control packets exchanges in MEWR will increase the end-to-end packet delay, the delay performance of MEWR is good. It can achieve similar end-to-end packet delay to VBF with lower energy consumption.

Although MEWR have good energy and delay performance, it has its own limitations. It can save energy of the network, but it does not give a good packet delivery ratio. The packet delivery ratio is defined as the ratio of the number of distinct packets received successfully at the sinks to the total number of packets generated at the source node. Figure 9 compares the packet delivery ratios between VBF, DBR and MEWR. In one sink scenario, MEWR has a lower packet delivery ratio than VBF and DBR.

The low packet delivery ratio is caused by two reasons: topology change after path discovery phase and low flooding. Because of the node mobility, some transmissions may fail after the path discovery phase of MEWR. Although the slot between path discovery phase and next hop determination phase is small, there exists network topology change, which may cause the transmission failure. MEWR is a low flooding protocol. The low flooding protocol can achieve low energy, but cannot guarantee the robustness. Figure 9 also shows that MEWR has a better packet delivery ratio with 6 sinks than that with only one sink. In the 6 sinks scenario, MEWR can achieve similar delivery ratio to VBF when the number of nodes is large. For the large scale network with multiple sinks, the packet delivery ratio of MEWR is acceptable.

7 Conclusion

In UWSN, energy conservation is an important subject. Due to the high attenuation of acoustic channel, multihop relay will be employed in packet transmission. However, due to the long propagation delay of acoustic communication, the end-to-end packet delay has to be considered in the delay-sensitive applications. Some routing algorithms are designed to generate a low delay path. However, the existing low delay routing protocols require large packet flooding, which increase the energy consumption. In this paper, we propose an MEWR protocol to solve the energy-aware routing problem in delay-sensitive UWSNs. MEWR first uses a small size probe packet to sense the neighbor nodes. Because the node moving will not be too large, the sender can determine its neighbors based on the reply packets. Then the next hop is determined based on the mixed energy delay metric. MEWR can adjust the sending power of the sender and reduce the energy consumption compared to the existing flooding based routing protocols. The end-to-end delay of MEWR is also very low.

Acknowledgements

This work was supported in part by National Natural Science Foundation of China (Grant Nos. 61222310, 61174142, 61071061 and 61374021), Natural Science Foundation of Zhejiang Province (Grant Nos. R1100234 and Z1090423), Program for New Century Excellent Talents (NCET) in University (Grant No. NCET-10-0692), Fundamental Research Funds for the Central Universities (Grant No. 2011QNA4036), Specialized Research Fund for the Doctoral Program of Higher Education of China (Grant Nos. 20100101110055, 20130101110109), and Marine Interdisciplinary Research Guiding Funds for Zhejiang University (Grant No. 2012HY009B).

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