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Geographic multipath routing based on geospatial division in duty-cycled underwater wireless sensor networks

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ABSTRACT

In Underwater Wireless Sensor Networks (UWSNs), the geographic routing is a preferred choice for data transmission due to the unique characteristics of underwater environment such as the three dimensional topology, the limited bandwidth and power resources. This paper focuses on underwater routing protocols in the network layer, where underwater sensor nodes can collaborate with each other to transfer data information. The three dimensional underwater network is first divided into small cube spaces, thus data packets are supposed to be collaboratively transmitted by unit of small cubes logically. By taking complex properties of underwater medium into consideration such as three dimensional topology, high propagation delay and path loss of acoustic channel, we propose two novel multi-path strategies called Greedy Geographic Forwarding based on Geospatial Division (GGFGD) and Geographic Forwarding based on Geospatial Division (GFGD). The proposed two algorithms mainly consist of two phases, choosing the next target small cube, and choosing the next hop node in the target small cube. Furthermore, all the sensor nodes in the network are duty-cycled in the MAC layer. Finally, performance analysis is derived, and simulation results illustrate the performance improvement in finding route paths, optimal length of found paths. In addition, energy consumption of route finding is reduced and propagation delay of data transmission is decreased.

1. Introduction

As a promising solution to aquatic environmental monitoring and exploration, UWSNs have attracted significant attention recently from both academia and industry (Han et al., 2012; Partan et al., 2007; Han et al., 2013). Unlike Terrestrial Wireless Sensor Networks (TWSNs), an UWSN is deployed in underwater environment and it is envisioned to enable applications in oceanographic data collection, ocean sampling, pollution and environmental monitoring, offshore exploration, disaster prevention, assisted navigation, distributed tactical surveillance, and mine reconnaissance (Pompili et al., 2006). The subsurface underwater environment of UWSNs is quiet different and complex in many aspects compared with that of TWSNs (Ayaz et al., 2011):

- The main difference between TWSNs and UWSNs is the communication channel. High-frequency radio signals attenuate rapidly underwater. Instead, acoustic communication emerges as a better choice for underwater communications. However, acoustic communication has several handicaps such as low bandwidth, high propagation delay and high bit error rate.
- In UWSNs, all sensor nodes freely drift with ocean current, which results in dynamic network configurations. Therefore, an UWSN is always considered to a dynamic three dimensional (3D) network, while a TWSN is always modeled as a static two dimensional (2D) network.
- UWSNs are much more energy limited compared with TWSNs. On the one hand, underwater sensor nodes often cost much more than regular terrestrial wireless sensor nodes. On the other hand, underwater sensor nodes may need to be left in the ocean for several days or even longer time without power replenishment. In this case, densely deployment is not an affordable choice for UWSNs.

All the above properties cause existing routing algorithms in TWNSs unable to directly be applied in UWSNs. Motivated by these considerations and due to the fact that geographic routing is notable for its special advantages (e.g., it does not require maintenance of routing tables or route construction during the forwarding process), in this paper, we propose two geographic multipath routing

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algorithms based on geospatial division, i.e., Greedy Geographic Forwarding based on Geospatial Division (GGFGD) and Geographic Forwarding based on Geospatial Division (GFGD). First, the studied network is logically divided into Small Cube (SC) spaces. In GGFGD, data packets are greedily forwarded to the sink node, where all the neighbor nodes in the closest SC which have higher residual energy, shorter transmission delay and less path loss can be selected as next hop; while in GFGD, data packets are directionally transmitted to the destination. Based on the sub-cubes and the relative position of the source node and the destination node, some target SCs are firstly selected. Only the neighbor nodes in the selected target SCs are used for data directional transmission. Moreover, we take sleep schedule into account, i.e., duty-cycle (a kind of sensor nodes' sleep schedule aiming at putting the idle listening sensor nodes in the network into sleep state so that the nodes will be awake only when they are needed). In the duty-cycled model, the sensor nodes can collaborate with each other to switch their sleep or wake-up mode, which helps one to save energy consumption and prolong network lifetime.

The remainder of this paper is organized as follows. In Section 2, we review the related literatures from three aspects. In Section 3, we introduce the network model, the energy consumption model and the spacial division model that are used in the process of routing establishing. In Sections 4 and 5, we, respectively, present the GGFGD and GFGD algorithms in detail, then carefully introduce the two phases of each algorithm, separately. While in Section 6 we show the performance results of the two proposed algorithms. Finally, we draw the main conclusions in Section 7.

2. Related work

In this section, we present the existing literatures on multipath geographic protocols and duty-cycle sleep schedule, and then identify the novelty of our work.

2.1. Multipath protocols

Multipath protocols establish more than one path in routing discovery procedure, it utilizes link redundancy to enhance data delivery ratio and improve reliability of UWSNs. Many researchers have proposed multipath protocols in TWSNs (Liang et al., 2011; Kulkarni et al., 2011; Radi et al., 2012; Han et al., 2014), while those protocols cannot be directly applied in UWSNs.

One of the underwater multipath protocols is proposed by Priya and Kumari (2012) named multipath power-control transmission (MPT) protocol. First, the source node initiates a multipath routing process by flooding a "Route Request" message to the destination. Any intermediate nodes which receive this "Route Request" for the first time will forward it. When the destination node receives "Route Request" messages, it will reply "Route Reply" messages reversely along the paths of the corresponding "Route Request" messages. Second, the destination node makes some path selection to decided several optimum paths, thus the data packets are sent along these chosen paths. MPT smartly combines power control with multipath routing to transmit data packets. However, the limitation of this protocol is that "Route Request" message flooding consumes quiet a lot energy, which reduces the applicability of MPT in UWSNs.

Seah and Tan (2007) make use of multipath data delivery to avoid contention near the sink with the virtual sink design involving a group of spatially diverse physical sinks. Sensor nodes can forward data to one or more spatially diverse sinks, to achieve high reliability despite the adverse network conditions. However, the problem of redundant transmission exists, which consumes critical underwater resources.

Chen et al. (2010) propose a new efficient routing protocol named multipath routing (MPR) protocol. In this protocol, multipath is utilized during the path construction from the source node to the destination node, which is composed of a series of multi-subpaths. Each multi-subpath is a sub-path from a sending node to its two-hop neighboring node. The contribution of this work is to minimize propagation delay, while energy consumption is relatively at a high level.

2.2. Geographic protocols

Geographical routing protocols establish source–destination paths based on localization information of sensor nodes, which do not need route discovery process. There have been a lot of geographic routing algorithms proposed in TWSNs (Jumira et al., 2013; Huang et al., 2013; Hamouda et al., 2009; Huang et al., 2011; Zhang and Shen, 2010; Zeng et al., 2009). While considering the complex underwater environment (Akyildiz et al., 2005; Heidemann et al., 2006), routing algorithms in TWSNs are not suitable for UWSNs.

Xie et al. (2006) propose a Vector-Based Forwarding (VBF) routing protocol. VBF is a position-based routing approach: sensor nodes which close to the "vector" will forward the message. VBF adopts a distributed self-adaptation algorithm which allows nodes to weigh the benefits of forwarding packets and thus reduce energy consumption by discarding the low benefit packets. While the limitation of VBF is because of the fixed transmission range of sensor nodes, only the sensor nodes that are within a certain range of the "vector" will forward packets, thus limits its range of application, especially in sparse networks. In addition, VBF also fails in multipath construction. Later, Nicolaou et al. (2007) develop an enhanced version of the VBF protocol, i.e, Hop-by-hop approach (HH-VBF). This protocol consumes less energy and significantly improves the robustness of packet delivery in sparse networks.

Chirdchoo et al. (2009) propose a Sector-Based Routing with Destination Location Prediction (SBR-DLP). They assume that each sensor node knows its own location, and predicts locations of destination nodes, therefore, relaxing the need for precise knowledge of the destinations' locations. This is suitable for mobile UWSNs where sensor nodes can move along with ocean current. However, the location prediction mechanism results in extra energy consumption, which is undesired in underwater circumstances.

Hwang and Kim (2008) propose a Directional Flooding based Routing protocol (DFR) for UWSNs. In DFR, when a node has a packet to send, it floods the packet towards the sink node. However, the set of nodes which participate in packet flooding are limited in a certain range to prevent the packet from being flooding into the whole network. Thus a flooding zone is proposed, which is decided by the link quality and the angle between the sender–forwarder and the forwarder–sink. The limitation of DFR is although it limited the flooding zone in a relatively area, much energy are consumed during the flooding phase.

2.3. Duty-cycled sleep schedule

Early studies (Leong et al., 2006; Karp and Kung, 2000; Kim et al., 2005; Bisnik and Abouzeid, 2007) assume that all nodes are always awake during forwarding. However, such assumptions are not realistic, and clearly less energy-saving. In order to save energy consumption in idle state, a duty-cycled operation is widely used in TWSNs, where each node periodically switches between sleeping mode and awake mode (Lai, 2010). It is expected that higher performance improvement will be achieved if the duty-cycle schedule is taken into consideration.

Similarly, there are not much works focusing on duty-cycle in UWSNs. Ammari and Das (2008) first analyze the k-coverage problem in 3D TWSNs and propose a new model that guarantees k-coverage for a 3D field. Then, a hybrid forwarding protocol for