Computer Networks 114 (2017) 80–94

Contents lists available at ScienceDirect

Computer Networks

journal homepage: www.elsevier.com/locate/comnet

Propagation control of data forwarding in opportunistic underwater sensor networks

Linfeng Liu[a,b,*], Ping Wang[a], Ran Wang[a,c]

[a] School of Computer Engineering, Nanyang Technological University, Nanyang Avenue 639798, Singapore
[b] School of Computer Science and Technology, Nanjing University of Posts and Telecommunications, Nanjing 210003, China
[c] School of Computer Science and Technology, Nanjing University of Aeronautics and Astronautics, Nanjing 211106, China

ARTICLE INFO

Article history:
Received 31 January 2016
Revised 16 December 2016
Accepted 16 January 2017
Available online 18 January 2017

Keywords:
Opportunistic underwater sensor networks
Opportunistic forwarding
Energy consumption
Propagation delay
Data delivery ratio

ABSTRACT

Opportunistic underwater sensor networks (OUSNs) are developed for a set of underwater applications, including the tracking of underwater creatures and tactical surveillance. The data forwarding objectives of OUSNs differ significantly from those of wireless sensor networks or delay-tolerant networks due to their large energy consumption and large propagation delay underwater. This paper begins with a description of the underwater movement, which consists of the regular movement impelled by external force and the autonomous movement controlled by nodes. Then, a topology determined model is provided to generate a power-law distribution structure, where the communication links that are overlong or are close to the space boundary can be avoided. Finally, a proactive opportunistic forwarding mechanism (POFM) is proposed to minimize the energy consumption from data forwarding. In POFM, at the start of each time slot, each node without data decides whether to request for data or not independently. In particular, the probabilities of nodes requesting for data are calculated according to a dynamic percolation analysis, which suggests the nodes with larger degrees or at earlier time slots should be given larger probabilities. The performance of POFM is analyzed through simulation experiments that produce preferable tradeoff results, indicating that POFM has a minor energy consumption with a guaranteed delivery ratio and a limited propagation delay.

1. Introduction

Recently, interest in applying wireless sensor networks (WSNs) [1] into environments to enable/enhance applications such as resource exploration and pollution monitoring has grown. Traditional WSNs consist of large numbers of sensor nodes that are randomly distributed in their detecting fields and vicinities. These nodes are sometimes assumed to be static or to move in a limited range [2]. However, in many practical applications, the movement ranges of nodes are relatively large, such as those in delay-tolerant networks [3], vehicular sensor networks, and pocket switched networks [4]. Accordingly, opportunistic mobile sensor networks (OMSNs) [5–7] are introduced for these types of networks, which are composed of mobile sensor nodes. OMSNs can achieve large-scale sensing at a lower cost compared to a ubiquitous static infrastructure of sensing devices. Nevertheless, due to the node mobility, the available contacts between nodes become scarce and short, which may lead to the unsteadiness of routing paths. Opportunistic underwater sensor networks (OUSNs) are a special case of OMSNs. OUSN technology enables various underwater applications, especially including the tracking of underwater creatures [8] and tactical surveillance [9]. In OUSNs, nodes with autonomous migration ability can move almost arbitrarily. Thus, the future trajectories of nodes are almost unpredictable. As depicted in Fig. 1, the measurements of environmental events are monitored by sensor nodes tied on mobile underwater vehicles (such as whales or submarines) and then transferred to a surface sink through multi-hops. Ultimately, the measurements are aggregated at a LEO satellite or a base station for future processing [10]. Data forwarding in OUSNs is defined as the art of finding and utilizing dynamic paths composed of intermittent contacts for multi-hop data transfer. Data forwarding in OUSNs has several challenges:

1) Energy Consumption. The battery energy of nodes is limited. Batteries usually cannot be replaced easily underwater, and solar energy is rarely exploited. Thus, one aim of OUSNs is to reduce the energy consumption.

2) Propagation Delay. Both electromagnetic waves and laser waves are unsuitable for underwater transmission. Acoustic

* Corresponding author at: School of Computer Engineering, Nanyang Technological University, Nanyang Avenue 639798, Singapore.
E-mail address: liulinfeng@gmail.com (L. Liu).

http://dx.doi.org/10.1016/j.comnet.2017.01.009
1389-1286/

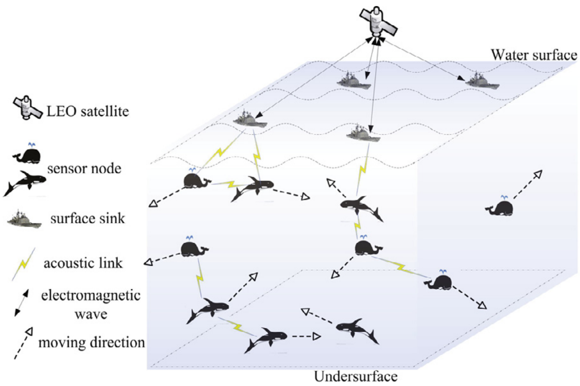

Fig. 1. Architecture of an OUSN.

communication [11] is the typical physical layer technology in OUSNs. Under such case, another distinguishing feature of OUSNs is propagation delay since acoustic waves transmit much slower than electromagnetic waves (the speed of acoustic waves is approximately 1500 m/s).

3) Delivery Ratio. Due to the intermittent links, the data delivery from a source node to a destination node cannot be guaranteed even when the epidemic forwarding is adopted for data routing. It also remains an important issue to improve the delivery ratio.

4) Dynamic Topology. Underwater nodes always move irregularly because of the sophisticated underwater environments (e.g., water current and swimming underwater creature). Given that nodes are mobile, any links between the nodes can generate or disappear over time. Thus, the topology changes constantly, so generated data may not be able to transfer along one single path.

Propagation control is vital for the opportunistic forwarding of OUSNs. The number of nodes carrying data will increase over time, and the propagation velocity (the increased number of existing data copies at every time slot) determines whether the data can be delivered under the restrictions of delivery ratio and delay. The appropriate regulation of propagation velocity for different nodes (with different degrees and positions) or at different time slots will be beneficial to the reduction of the energy consumption. Consequently, the propagation control of opportunistic forwarding is an inevitable issue in OUSNs.

This research explores the data forwarding problem which aims at minimizing the energy consumption subject to the delivery ratio and propagation delay constraints. To observe the propagation process, a dynamical percolation model is constructed, and through analyzing the model, it is shown that the delivery is more possible to achieve if the nodes with larger degrees are given larger transition probabilities (more prone to request for the data) or if the propagations at earlier slots are given larger velocities. Applying these conclusions, a proactive forwarding algorithm is provided to make a tradeoff among energy consumption, propagation delay and delivery ratio via setting proper transition probabilities.

The remainder of this paper is organized: Section 2 discusses related studies; in Section 3, we provide a mathematical network model to describe the data forwarding problem; the proactive opportunistic forwarding mechanism (POFM) is proposed in Section 4; Section 5 gives a POFM analysis from the aspects of complexity, energy consumption, delivery ratio and influence of moving-out probability; Section 6 discusses the performance evaluation of POFM; finally, Section 7 supplies the conclusions.

2. Related work

2.1. Opportunistic forwarding in DTNs

Extensive studies has been carried out on the problem of opportunistic forwarding for DTNs (Delay-Tolerant Networks) and mobile sensor networks. The early representative algorithm proposed in [12] was Epidemic Forwarding (EF), where random pair-wise exchanges of messages among mobile nodes ensured the maximum delivery and the minimum delay. However, numerous redundant message copies were generated gradually in the transmission. To reduce the overhead of flooding-based schemes (such as EF), Spyropoulos et al. [13] put forward the Spray-and-Wait algorithm, where a certain number of copies were firstly thrown into the network. Delivery was accomplished when one of the copy-holders arrived at the destination. In [14], a distributed adaptive opportunistic routing scheme that used a reinforcement learning framework was proposed. The scheme can opportunistically route the packets even in the absence of reliable knowledge about channel statistics and network models. Radunovic' et al. [15] proposed an optimization framework for opportunistic routing, which was eased by network coding. The framework was used to define notions of credits associated with a number of packets in a generation. A primal-dual algorithm was then adopted as the basis for deriving a practical protocol.

2.2. Prediction method in opportunistic forwarding

There also exist some studies considering the data forwarding based on mobility prediction or contacting prediction, which is most common method in opportunistic forwarding techniques. For instance, in [16], MaxProp prioritized both the schedule of packets transmitted to other peers and the schedule of packets to be dropped. Each node should keep track of the probabilities of contacting other nodes. Subsequently, contacting history updated the probabilities. LeBrun et al. proposed the Motion Vector (MoVe) [17], which applied movement speed information to make intelligent opportunistic forwarding decisions. MoVe leveraged knowledge regarding the relative speeds of a mobile router and its neighboring nodes to predict the closest distance from trajectories. In MoVe, nodes move in piece-wise linear fashion, following city street structures. The decision of forwarders relies on velocities of nodes, that is, the best result may be achieved if movements of nodes are rarely changed. Niu et al. [18] developed the Predict and Spread (PreS) routing algorithm, in which an adaptive markov chain is adopted to model the node mobility patterns and capture the social characteristics. The simulation results suggested that PreS can improve delivery ratio and reduce delivery latency when proper parameters were set. In [19] the routing algorithm Predict and Relay (PER) for delay-tolerant networks was introduced. PER was based on the assumption that nodes usually move around a set of well-visited landmark points and that node mobility could be predicted if sufficient history information was provided. In spite of that, the regular mobility hypothesis of the above research is unsuitable for OUSNs.

2.3. Data forwarding in OUSNs

Relevant research has also been conducted to solve the data forwarding problem in underwater sensor networks. In [20], a network-coding-based protocol named Multiple Paths and Network Coding was proposed, and three disjoint paths were established for different groups of packets. Lee et al. [21] presented the Hydraulic Pressure based Anycast Routing Protocol (HydroCast) for reliable underwater sensor event reporting to one of the surface sinks. HydroCast selected the proper subset of forwarders that maximized