Ad Hoc Networks 34 (2015) 144–156

Contents lists available at ScienceDirect

Ad Hoc Networks

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

A novel void node recovery paradigm for long-term underwater sensor networks

Rodolfo W.L. Coutinho [a,b], Azzedine Boukerche [b], Luiz F.M. Vieira [a], Antonio A.F. Loureiro [a,*]

[a] Department of Computer Science, Federal University of Minas Gerais, Belo Horizonte, MG, Brazil
[b] PARADISE Research Laboratory, University of Ottawa, Ottawa, ON, Canada

ARTICLE INFO

Article history:
Received 1 March 2014
Received in revised form 24 October 2014
Accepted 24 January 2015
Available online 21 February 2015

Keywords:
Underwater sensor networks
Topology control
Geographic routing
Local maximum problem

ABSTRACT

Aquatic environment corresponds to more than 70% of the Earth's surface mostly still unknown and unexplored. Underwater wireless sensor networks have recently been proposed as a way to observe and explore these environments. However, the efficient data delivery is still a challenging issue in these networks because of the impairments of the acoustic transmission. To cope with this problem, we present a novel geographic forwarding protocol and two topology control mechanisms for long-term non-time-critical underwater sensor networks. The proposed routing protocol considers the anycast network architecture in the data forwarding process. The proposed centralized topology control (CTC) and the distributed topology control (DTC) mechanisms organize the network via depth adjustment of some nodes. Simulation results show that with these mechanisms, the data packet delivery ratio achieves more than 90% even in hard and difficult scenarios of very sparse or very dense networks, and the end-to-end delay and energy consumption per delivered packet are reduced.

1. Introduction

Aquatic environment is a fascinating place representing more than 70% of the Earth's surface mostly still unknown and unexplored. For a long time, undersea research was largely limited to the surface or the nearby water, given the wireline instruments limitations [1]. Recently, underwater wireless sensor networks (UWSNs) have been suggested as a powerful technology for gathering data and monitoring lakes, rivers, seas, and oceans [2,3]. In this network, sensor nodes deployed underwater monitor environmental variables such as water temperature, pressure, conductivity, turbidity and certain pollutants, and then report relevant collect data for any one of surface sonobuoys (sinks) through acoustic multihop communication. The sonobuoys equipped with both acoustic and radio communication, collect data from sensor nodes through acoustic communication and offload them to a monitoring center by means of radio communication (WiFi or satellite communications).

Yet, underwater monitoring is a difficult task due to the underwater acoustic communication characteristics. Underwater acoustic communication has a high propagation delay due to the speed of acoustic signals in water which is about 1500 m/s, severely limited available bandwidth, and high and dynamic packet loss probability, which leads to lots of retransmissions, a high energy consumption, and lower reliability [4]. As a result of the unique characteristics of the acoustic communication, the conventional reactive and proactive routing protocols used in terrestrial wireless sensor networks are not suitable for UWSNs because of the overhead to maintain routing tables updated and the delay for on-demand route discovery.

* Corresponding author.
E-mail addresses: rwlc@dcc.ufmg.br (R.W.L. Coutinho), boukerch@site.uottawa.ca (A. Boukerche), lfvieira@dcc.ufmg.br (L.F.M. Vieira), loureiro@dcc.ufmg.br (A.A.F. Loureiro).

http://dx.doi.org/10.1016/j.adhoc.2015.01.012
1570-8705/

Furthermore, the high energy cost of acoustic transmission makes these approaches impractical for underwater networks. In these scenarios, position-based or geographic routing is preferable as it does not require the establishment or maintenance of complete routes.

Geographic routing in UWSN uses the position information or the depth information to route packets towards the destination. Every node aware of its geographical location forwards packets to a locally optimal next-hop node closest to destination. This strategy makes geographic routing protocols simple and scalable. Moreover, there is not additional communication overhead since source node requires to know only 1-hop neighbor locations and the location information of the destination, to select the next-hop. The main disadvantage of geographic routing is the local maximum node problem, also called communication void region. The communication void region occurs whenever the sender is the closest node to the destination. The node located in a communication void region is called void node. Whenever a packet gets stuck in a void node, the routing protocol should attempt to route the packet using some recovery method or discard it [5].

Some studies in the field have invested efforts to cope with the communication void problem (please refer to Section 2). Most of them use message transmission-based procedures where an explicit path should be discovered and maintained to circumvent the void region. Here, we advocate that instead of using message-based procedures, the depth adjustment of some nodes can result in a network topology more suitable for the use of the geographic routing protocol where void nodes are reduced or even eliminated. Using this approach, we have an initial energy cost that depends on the depth adjustment technology to move the nodes to new locations. This cost is diluted in the long-term of network operation, i.e., the energy per delivered packet is amortized. Furthermore, according to the application, the gain in the network performance can justify paying this cost.

In this paper, we propose a geographic routing model for underwater sensor networks. The proposed routing protocol (Section 4) considers the anycast nature of the underwater sensor network, where sea surface sonobuoys are the destination of the gathered data collected by the underwater sensor nodes, during the data packet forwarding process. The proposed protocol uses the distance from the nodes to their closest sonobuoy to forward data packets using a greedy strategy. Thus, neighbors that have the smallest distance for some sonobuoy will be selected as the next-hop forwarder.

Moreover, we propose two topology control mechanisms based on the depth adjustment of some nodes aiming to organize the network topology for better use of the greedy forwarding strategy and to significantly reduce the impact of the local maximum node problem in the network performance. We consider only scenarios where nodes can move on the vertical axes, not an undefined position (x, y) as occurs with current solutions. We present a centralized topology control (CTC) algorithm in Section 5 that determines which nodes do not have a path to a sonobuoy (isolated nodes) and which ones are in a communication void region and, then, compute new depth to them. Moreover, we present a distributed topology control (DTC) algorithm in Section 6 where each node locally determines if it is in a communication void region and computes its new depth to overcome this problem.

Simulation results (Section 8) show that nodes moved to new locations can effectively participate in the data forwarding process, improving significantly the network performance as compared with the traditional underwater sensor networks routing protocol. Both the geographic routing protocol and the proposed topology control mechanisms are effective solutions to increase the fraction of the data delivered packet in UWSNs, which was higher than 95% for CTC and 80% for DTC, representing a gain of 25% when compared with analyzed routing protocols, even in hard and difficult scenarios of very sparse or very dense networks. Moreover the fraction of the sensing coverage area and the energy consumption per delivered packet were improved. In addition, we discuss the related work in Section 2, present the network model in Section 3, and conclude the paper in Section 9.

2. Related work

Data collection and routing in underwater networks are important issues and have been investigated using different approaches. For instance, Bölöni et al. [6] and Basagni et al. [7] have used autonomous underwater vehicles (AUVs) to retrieve the information from the nodes through optical communication. They have proposed models to the value of information (VoI) and scheduling strategies for the nodes decide when and how much information to transmit, given the path of the AUV.

In this work, we consider a SEA swarm architecture where the nodes should through multihop acoustic communication delivery the packet to some sonobuoy (sink) at surface. In the following, we present some proposals addressing the same architecture.

Xie et al. [8] proposed the VBF routing protocol where packets are routed along a virtual "routing pipe" formed by the vector from the sender and destination location information. When a node receives a packet, it determines its distance to the forwarding vector and, then, forwards the packet if this distance is less than a predefined threshold.

Depth-Based Routing (DBR) [9] protocol considers the depth information of the nodes to greedily route packets upward to be received by some sink deployed at the water surface. Upon receiving a packet, a node compares its own depth with the depth of the previous sender. If the node is closer to the water surface, it is a qualified candidate to forward the packet.

In both VBF and DBR routing protocols, the packet will be discarded if the receiver node is not qualified to forward it. Nevertheless, since the packet forwarding decision is based only on whether the node is qualified or not according to their rules, high density scenarios can result in redundant and unnecessary transmissions overloading the acoustic channel. Moreover, they do not employ any recovery procedure to cope with the maximum local problem, which significantly degrades the network