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Performance modeling and analysis of void-handling methodologies in underwater wireless sensor networks

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ABSTRACT

In this paper, we devise an analytical framework for the performance evaluation of communication void-handling algorithms designed for underwater wireless sensor networks (UWSNs). Geographic and opportunistic routing (GOR) have been shown efficient for multi-hop data delivery in UWSNs. However, geo-routing suffers from a serious drawback known as communication void region. The communication void region problem occurs when a source node does not have a neighbor node in closer proximity to the destination that can continue forwarding the packet. Whenever a data packet reaches a node in a void region, the data packet should be re-routed from a void-handling procedure or discarded. In this paper, we model the three main methodologies that have been used for the design of void-handling algorithms for geographic and opportunistic routing protocols in UWSNs. Our proposed analytical framework considers the characteristics of underwater sensor networks, network density and traffic load, underwater environment and acoustic channel, as well as the characteristics of the power control, bypassing void region and mobility assisted void-handling paradigms. The devised analytical framework is aimed to fill the gap in the literature of analytical tools that allow the performance evaluation of the trade-offs of each paradigm along different scenarios of UWSNs. The proposed model provides insights for the further design of void-handling algorithms in different underwater application and sensor network configurations. Numerical results show that the widely used bypassing void region approach is not effectively for moderate- and high-density UWSN scenarios. Conversely, topology control-based approaches (power control and mobility-assisted) are preferable as they create additional links. However, the use of void-handling procedures increased the network energy consumption, which made each paradigm unsuitable for specific scenarios revealed by the proposed modeling.

1. Introduction

Nowadays, underwater wireless sensor networks (UWSN) are promising technology for the monitoring of large areas of submarine environments. Traditionally, a UWSN is composed by autonomous sensor nodes deployed underwater and sonobuoys (sinks) deployed at the surface of the ocean. Each underwater sensor nodes is responsible to monitor and track events of interest in its vicinity. Moreover, they act collaboratively to deliver gathered data to sonobuoys. The sonobuoys are responsible for data collection from the sensors. The applicability of UWSNs ranges among scientific, industrial and military applications, such as ocean exploration and data collection, disaster prevention, seismic and tsunami monitoring, offshore exploration, pollutant content monitoring, and navigation assistance [1–4].

Despite the potential of UWSNs over traditional wire-line instruments, their wide implementation is still costly, and limited by several networking challenges, mostly arising from the use of underwater acoustic channel. Underwater acoustic communication suffers from large and variable delays, high bit errors, temporary losses of connectivity, limited bandwidth capacity, and high energy cost [5,6].

1.1. Motivation

The aforementioned channel characteristics introduce challenges into the design of routing protocols for UWSNs. Because of them, the use of traditional proactive routing is impractical, as it requires the maintenance of an up-to-date routing table to every node in the network; reactive routing is impractical, as it creates

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routing paths on-demand [7]. In this context, geographic and opportunistic (GOR) routing paradigm has been shown promising for UWSNs [8–15].

In the GOR paradigm, there is no need for either the establishment or maintenance of complete routes to the destination, nor the transmission of routing messages to update states. Conversely, a sensor node uses local information about the position or depth of itself and its neighboring nodes to select a next-hop (or a set of them) node, which can advance the data packet towards the destination. However, geographic-based routing protocols suffer from a serious drawback known as *communication void region*. Communication void region occurs whenever the current forwarder node (void node) does not have a neighboring node advancing the data packet towards the destination. Whenever a data packet gets stuck at a void node, an alternative path should be determined, or it will be discarded.

The communication void region problem degrades the performance of UWSNs. Data packets discarded at void nodes can compromise the application, which is already impaired by packet loss relative to the noisy and harsh nature of underwater wireless communication. Moreover, the overhead required for determining and maintaining alternative routing paths from void nodes to the destination increases data packet collision, retransmission, and energy consumption. This serious shortcoming has been widely investigated in radio frequency-based wireless ad hoc networks, as discussed in [16].

1.2. Our contributions

Several void-handling procedures were proposed in geographic routing protocols designed for UWSNs [8,11,17–19]. However, to the best of our knowledge, there is no analytical model for the performance evaluation of void-handling procedures, allowing scientists and practitioners to select the best paradigm when designing a void-handling procedure for the considered scenario of UWSN. This fact is worrying since analytical- and simulation-based extensive and deep studies are needed before a on-the-field UWSN routing protocol test. This is due to the high cost of ship missions for the deployment and maintenance of UWSNs in the ocean.

In this paper, we proposed an analytical framework for the evaluation of the trade-offs of the three different strategies used to design void-handling algorithms for UWSNs: *power control-, bypassing void region-* and *mobility assisted-based* strategies. Our devised analytical framework take into consideration the characteristics of underwater sensor networks, such as network density and traffic load, underwater environment and acoustic channel, such as the noise and signal absorption, as well as the characteristics of the power control, bypassing void region and mobility assisted void-handling methodologies. From our devised analytical framework, one might deeply study the trade-offs of each approach in the desired network scenario and configuration. It can be used to obtain insights for the further design of void-handling algorithms in particular deployments of UWSNs.

In our proposed model, we devise the following performance evaluation metrics: *percentage of nodes in the void region*, which measures the efficiency of geographic data routing in terms of packet delivery, *coverage rate*, which measures the portion of the environment where sensor nodes can sense and deliver data packets using a void-handling procedure when necessary, *network lifetime*, which measures the efforts, in terms of energy, of void-handling techniques to re-route data packets from void regions through void-handling techniques. In addition, the performance of the void-handling techniques will be strictly related to their characteristics when re-routing data packets from void regions. Thus, we analyze the percentage of nodes with long-range communication, moved nodes and number of hops when power control-, mobility assisted- and bypassing-based void-handling technique are used, respectively. This investigation allows us to better understanding in which UWSN configurations each void-handling technique is more suitable.

This work significantly enhances our previous work [20] by making the following contributions:

- Based on our literature review, we propose a thorough classification of void handling algorithms for UWSNs in three main categories: power control-, bypassing void region-, and mobility assisted-based strategies.
- We propose an analytical framework for evaluating the performance and trade-offs of void-handling algorithms in UWSNs. Our model take into consideration the characteristics of the network architecture, underwater acoustic communication and recovery strategies.
- We performed numerical experiments for an extensive performance evaluation of the three commonly used strategies for the design of void-handling algorithms in underwater sensor networks. In our numerical analysis, we considered different network density scenarios, which are a critical factor impacting on the number of void nodes.

Surprisingly, numerical results show that the widely used bypassing void region approach is not effectively for moderate- and high-density UWSN scenarios. Conversely, topology control-based approaches (power control and mobility-assisted) are preferable as they create additional links. However, the use of void-handling procedures increased the network energy consumption, which made each paradigm unsuitable for specific scenarios revealed by the proposed modeling. The results obtained provide important guidelines for the design of energy-efficient geographic routing protocols and void-handling algorithms for underwater sensor networks over several network density and load traffic conditions.

The remaining of this paper is organized as follows. Section 2 presents our proposed classification of void handling algorithms for UWSNs, and reviews the works encountered in the literature. Section 3 describes some preliminary concepts used by our proposed model. Section 4 presents the analytical framework proposed to study the trade-offs of the void-handling algorithms in UWSNs. Section 5 presents the performance evaluation of the analytical model. Finally, Section 6 presents our conclusion and future work.

2. Literature review and void-handling algorithms classification

In this section, we review the void-handling algorithms proposed for geographic and opportunistic routing protocols in underwater wireless sensor networks. Based on the main approach used to overcome void regions, we propose classify void-handling algorithms designed for UWSNs in three major categories: power control-, bypassing void region- and mobility assisted-based approach. However, before surveying these protocols, we properly define the communication void region problem and its related concepts that are recurrently used throughout the text.

Definition 1 (Communication void region)**.** This occurs when the current forwarder node cannot deliver data packets directly to the destination, and does not have a neighbor node closer to the destination than itself to continue forwarding.

Definition 2 (Void node)**.** These are the nodes located within communication void regions. When a packet becomes stuck in the void nodes, it should be either routed using a void handling algorithm, or discarded.

Definition 3 (Void handling algorithm)**.** This is the mechanism employed by the geographic routing protocol to route data pack-