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CARP: A Channel-aware routing protocol for underwater acoustic wireless networks

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ABSTRACT

The paper concerns the definition and performance evaluation of a new multi-hop routing protocol for underwater wireless sensor networks. Our solution, termed CARP for Channel-aware Routing Protocol, exploits link quality information for data forwarding, in that nodes are selected as relays if they exhibit recent history of successful transmissions to their neighbors. CARP avoids loops and can successfully route around connectivity voids and shadow zones by using simple topology information, such as hop count. The protocol is also designed to take advantage of power control for selecting robust links. The performance of CARP has been compared with that of two other protocols for underwater routing, namely, the Focused Beam Routing (FBR) and a flooding-based solution (EFlood). Metrics of interest include packet delivery ratio, end-to-end packet latency and energy consumption, which have been investigated through ns2-based simulations and experiments at sea. The in-field trials have been conducted at two European locations, namely, a Norwegian fjord and the Mediterranean Sea. The tests in the Mediterranean Sea have been performed jointly with the NATO Science and Technology Organization Centre for Maritime Research and Experimentation (STO CMRE), under a collaboration agreement between the University of Roma and CMRE. Our results show that CARP robust mechanism for relay selection doubles the packet delivery ratio of FBR and EFlood. CARP also outperforms FBR and EFlood in terms of energy consumption, and delivers packets significantly faster than FBR.

1. Introduction

Underwater wireless sensor networks (UWSNs) are an enabling technology for many autonomous systems that find application to science, security, and industry. The diversity of aquatic applications ranges from environmental monitoring, pollution control, prediction of and reaction to natural disasters, eco-system analysis, surveillance for defense applications and port safety, off-shore oil and gas industry, aquaculture, geological and oceanographic science, marine, biology and archaeology [1,2]. Most of these applications are currently served by piecemeal networking infrastructures, mostly based on costly underwater cabling or limited, single hop acoustic communications. Recently, however, research on UWSNs has focused on the design of more flexible and performant networks that can cover larger areas of the submarine environment. This is made possible by deploying a variety of sensor nodes capable to transmit their data wirelessly to collections points

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(*sinks*) through multi-hop communications. Sinks may then forward the received information to onshore control stations, usually via RF transmissions.

Challenges to the design of communication protocols for the new, multi-hop UWSN architecture come from the very specific environment where they operate. Long propagation delays, low bandwidth, sound speed variability, slow power signal attenuation, and the rapidly changing conditions of the underwater channel affect UWSNs at all levels of their design and deployment. In particular, MAC and routing protocols face new challenges with respect to their terrestrial counterparts, in that channel access mechanisms and routing techniques are highly affected by the link quality whose variations are less predictable and manageable than that of wireless radio links. Recent trends in protocol design show that cross-layer techniques can impact protocol performance positively, especially in networks with limited resources and/or deployed in challenging environments, like UWSNs [3]. An example of cross-layer routing is provided by the Focused Beam Routing (FBR) protocol, proposed by Jornet et al. in [4]. Control packets (`RTS` and `CTS` as in CSMA/CA-like channel access) are used to reserve the channel, a typical MAC function. The control packets, however, carry also node location information that is used for routing purposes, namely, to select as next-hop relay the node that is closest to the sink. The use of short packets for channel access and relay selection results particularly effective for routing in the challenged UWSNs environment. This is because their transmissions are relatively fast even at the low rates of acoustic modems, and because they are less subject to bit errors and interferences. However, in the quickly varying conditions of the underwater channel, the fact that two nodes can exchange short control packets correctly, may not be sufficient to guarantee that longer data packets are also going to be safely delivered. In other words, protocols like FBR that do not consider link quality information as a criterion for relay selection are still heavily prone to bit errors. This is a problem that affects many other cross-layer solutions (see Section 2).

In this paper, we present a new distributed cross-layer Channel-aware Routing Protocol (CARP) for UWSNs for multi-hop delivery of data to the sink. While still reaping the benefits of cross-layer design (short packets for robust channel access and relay selection), CARP obviates to the drawbacks of other solutions in that link quality is explicitly taken into account for selecting the next-hop node on a route to the sink. History of successful transmissions to neighboring nodes is maintained and used in relay selection. Other characteristics that make CARP relay selection particularly suitable for implementing multi-hop routing in UWSNs include the following: (i) The use of simple topology information (hop count) for routing around connectivity holes and shadow zones, thus avoiding the well-known pitfalls of geographic routing; (ii) considering residual energy and buffer space, and (iii) taking advantage of power control, if available, for selecting transmission powers so that shorter control packets experience a similar Packet Error Rate (PER) of longer data packets.

The performance of CARP has been evaluated through simulations and through trials at sea, measuring metrics such as packet delivery ratio, packet latency and energy consumption. Simulations have been performed by implementing CARP in SUNSET [5], our extension to the ns-2 simulator specifically designed for underwater networking. We used the Bellhop ray tracer [6] and historical environmental data for more realistic modeling of the underwater acoustic channel. Through Bellhop we have been able to compute the frequency-dependent acoustic path loss of each source–destination pair at a given location, as well as the spatially-varying interference induced by all active nodes. The performance of CARP has been compared to that of FBR [4] and of an enhanced version of flooding, called EFlood, where nodes wait for a random time before forwarding the packet (this desynchronizes node transmissions and reduces interferences, improving the performance of common flooding). We consider networks with desirable size (20 nodes), varying traffic and packet size. Experiments at sea have been performed at two European locations, namely, a Norwegian fjord and the Mediterranean Sea, in multi-hop network of realistic size (6 and 8 nodes, respectively). In the trials, the performance of CARP has been compared to that of EFlood. Both simulations and in-field tests show that CARP is an effective solution for transmitting packets through time-varying channels. The protocol is capable of routing around connectivity holes and shadow zones, and of maintaining a high packet delivery ratio for increasing traffic, irrespective of the ratio between transmission and propagation times. Our simulation results show that CARP outperforms both FBR and EFlood with respect to packet delivery ratio, being always able to deliver 80% of the packets, independently of the wide variety of traffic and data packet sizes we considered, in simulations and at sea. At higher traffic FBR and EFlood show instead decreasing performance: EFlood can deliver only up to 35% of the generated packets, and FBR only up to 40%. CARP also consistently outperforms EFlood in trials at sea. The energy saved by CARP is up to 100% than that of FBR, and up to 400% (simulations) and 63% (in-field) than the energy saved by EFlood. In terms of end-to-end packet latency, our simulations show that both CARP and FBR incur longer delays with respect to EFlood, since they both use an handshaking mechanism for channel reservation. CARP, however, significantly outperforms FBR, proving suitable for actual underwater applications.

The rest of the paper is organized as follows. Previous work on underwater multi-hop routing is summarized in Section 2. In Section 3 we describe CARP in detail. Section 4 illustrates experimental results. Finally, Section 5 concludes the paper.

2. Related works

Protocols for underwater communications have recently received noticeable attention [7–10]. Among the first protocols to tackle the problem of finding routes from an underwater sensor node to the sink is the Vector-Based