Exploring Architectural Challenges in Scalable Underwater Wireless Sensor Networks

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Abstract

The use of sensor networks in aquatic environments has been quite limited, partially due to the harsh underwater environments and associated high system costs. Nevertheless, cost-effective and resource-efficient ***Underwater Wireless Sensor Networks*** *(UWSNs) will bring significant benefits to numerous aquatic applications. The unique properties of underwater environments raise many new challenges in building an efficient UWSN. We will discuss several architectural challenges and possible research topics in this paper.*

1. Introduction

Although sensor networks have been deployed in a broad range of terrestrial applications [1-4], underwater use of sensors and sensor networks has been quite limited due to the harsh environment and associated high costs. Recently, there has been a growing interest in Underwater Wireless Sensor Network (UWSN) due to its advantages and benefits in a wide spectrum of applications in aquatic environments [5-6], such as lakes, ponds, rivers, and oceans. Potential applications of UWSNs include environmental monitoring and data collection, disaster early warning, tactical surveillance, military target detection, unmanned off-shore exploration, and underwater construction.

Compared to land-based wireless sensor networks, UWSNs have two unique properties: acoustic communication channels and the mobility of sensor nodes. Since radio frequency (RF) signals do not propagate well in water, acoustic channels are taken as the sole means for communications among underwater sensor nodes. Compared to RF signals, acoustic signals have much longer latencies (five orders of magnitude) and lower bandwidths. The second property is passive mobility of sensor nodes, which results in dynamic networking structure. Empirical observations suggest sensor nodes will move at the speed of 3-6 kilometers per hour with an effective diffusivity of from 10^{-3} to 10^{3} cm^2/s in the vertical and from 10^{-3} to 10^{5} cm^2/s in the horizontal. To ensure reliable and efficient data transmitting and forwarding, UWSNs must identify the sensor nodes' locations periodically, and adapt the network configuration accordingly.

The aforementioned properties of UWSNs raise special challenges that affect all essential components of UWSNs, including communication mechanisms, networking protocols, sensor node, and resource management. It is necessary to revisit various aspects of sensor node design and consider all the features in UWSNs to build a better optimized system in the new underwater environment.

The rest of the paper is organized as follows. We will describe some architectural challenges in UWSN designs in Section 2, and summarize in Section 3.

2. Challenges in UWSN system designs

2.1. Workload characterization

A typical underwater sensor node consists of a sensor probe, an acoustic modem, a controller, storage, battery, and an interface circuitry that connects all the components with the controller. Although the structure is similar to that of land-based sensor nodes, underwater sensor nodes need different designs of their components because of the unique properties of underwater environments and the distinct requirements of aquatic applications. For example, high-precision localization algorithms, needed for underwater sensor nodes to calculate their positions, impose heavy workloads on microcontrollers. As for the applications, long-term environment monitoring require little computational capability, large memory, and a long operation time; while short-term target detection applications demand more computational capability and real-time response. When building underwater sensor nodes, the first thing we need to study is the new workloads of UWSNs. It is

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also important to investigate the impact on sensor node design of the different application requirements and to seek a common architecture that meets the requirements.

2.2. Energy-efficient node design and resource management

One primary challenge of deploying a dense, distributed, and scalable UWSN is the limited energy resources on individual sensor nodes. Power and energy optimizations are especially critical for UWSNs because 1) acoustic communications will consume more energy than RF channels, and 2) energy harvesting is much more difficult because major harvesting sources such as solar and wind energy are not available in the underwater environment.

On the one hand, UWSNs face new challenges to achieving long operation times. For example, due to the dynamic nature of UWSNs, network configuration algorithms have to run periodically and, very often, at a rate not slower than data sampling rate. Thus, energy-efficient configuration algorithms and scheduler need to be designed. On the other hand, the underwater environment may facilitate some power-saving mechanisms. For example, the microcontroller in a sensor node can go to the sleep mode during idle time and wake up to the active mode when necessary. Since the wakeup process takes time, the node shall be put in the sleep mode only when the idle time is long enough reaching a breaking point. Due to the long delay of acoustic communications, underwater sensor nodes may enter the sleep mode more frequently.

To maximize the lifetime of UWSNs, we need to achieve energy efficiency at both the sensor node and network levels. Within each sensor node, the methods include proper assignments of tasks to components and the energy-efficient implementations of the components. At the network level, it is critical to manage resource efficiently. The possible solutions include strategies that balance the trade-offs between energy consumptions and other metrics. For example, network routing protocols can trade energy for robustness; in applications like target detection, it can be power-saving to perform preliminary computations among *local* nodes that are close to each other and to transmit only useful data or results back to the processing center.

2.3. Lifetime estimation

The lifetime of UWSNs is one of the main design goals. Different underwater applications may have different requirements on lifetime. Accordingly, these requirements give us guidelines to determine certain design parameters, such as density of sensor nodes and battery capacity, at the design time.

Estimating the lifetime of sensor networks prior to the design and deployment of an actual network requires an analytical method and model which coarsely captures the behavior of underwater sensor networks. The model should be generic and parameterized, combining both the physical medium-specific (acoustic communications) and networking aspects in UWSN. Conversely, after the energy estimation model is derived, power optimization consideration can be woven into the design of network protocols (such as medium access control, routing, and transporting), topology (such as the distance between nodes, number of nodes in a cluster, number of tiers in the hierarchical networking architecture), and working parameters (such as acoustic frequency, data query frequency, etc.) in order to materialize a cost-effective and energy-efficient USWN.

3. Summary

In this paper, we briefly examined the architectural and system design issues for UWSNs. We believe that the low-power design and efficient resource management will remain the major challenges for UWSN designs. The unique features of UWSNs raise new challenges, but they also create opportunities to explore power-saving mechanisms. In order to extend the lifetime of UWSNs, power efficiency should be pursued at both the node and network levels. Moreover, an accurate lifetime estimation model is necessary for UWSN designs and can help determine important design parameters to prolong lifetime.

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