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TDMA frame design for a prototype underwater RF communication network

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ABSTRACT

Very low frequency electromagnetic communication system is used in a small scale underwater wireless sensor network for coastal monitoring purposes, as recent research has demonstrated distinct advantages of radio waves compared to acoustic and optical waves in shallow water conditions. This paper describes the detailed TDMA and packet design process for the prototype sensor system. The lightweight protocol is time division based in order to fit the unique characteristics and specifications of the network. Evaluations are based on initial beach trial as well as modeling and simulations.

1. Introduction

The recent growing interests in monitoring aqueous environments have led to extensive research on underwater wireless sensor networks (UWSN). Given modern operational requirements and digital communications technology, previous work in Ref. [1] has re-evaluated role of radio frequencies electromagnetic (RF-EM) signals in the underwater sensor networks, where a case study was also conducted on a project entitled Automated Sensing Technology for Coastal Monitoring (ASTEC). The project attempted to use RF-EM waves as the communication medium. This paper will demonstrate in details the protocol and packet design regime for the prototype UWSN proposed in this case.

In order to gather data and consequently quantify the effects of coastal erosion beneath the sea surface, ASTEC project aims to create the world's first automated system for monitoring and forecasting for this purpose. Engineers have classically modeled the submerged beach profile by describing two different zones: near shore zone and offshore zone. The near shore zone is active while the offshore zone is inactive with respect to the movement of sediment, silt, sand etc. In environmental science, coastal erosions can be explicitly indicated by depth of closure (DoC) which is defined as the depth seaward where neither change in bottom elevation nor net sediment exchange between nearshore and offshore can occur significantly [2]; the contour of such closure is approximately parallel to the coastline in most cases.

The UWSN built in this project aim to gather data and consequently quantifies the effects of coastal erosion beneath the sea surface. The primary role of sensors will be to either directly or indirectly measure the movement of sea bed sediments, so as to monitor the DoC. All measurement data will be sent to one destination node (i.e. the sink) on the shore or at any other designated position. The sink will be enabled with the function of Global System for Mobile communications (GSM) which allows all the collected data to be eventually transported to a central office for processing. This enables the remote collection and processing of the data. The system will also gather data regarding the health of the sensor nodes which will also be accessible by the user so enabling the failed nodes to be replaced as needed.

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Although the usability of underwater RF technology has been quite controversial to date, it can offer great potentials in practical applications if all the system parameters are properly tuned. Unlike in acoustic systems where data rates remain relatively constant regardless of the frequency, the data rates of underwater RF communication systems are frequency-dependent and the attenuation of an EM signal increases significantly both with frequency and distance, for instance, higher frequencies although can enable higher data rates, would result in shorter transmission range [3]. Hence, when RF technology is attempted in underwater systems, the choice of operating frequency, bit rate and sensor density requires careful deliberation during the design phase. Based on respective project requirements, each design has to uniquely balance parameters such as antenna design, transmit power, duty cycle, data bandwidth, and local noise source in order to achieve an optimized solution for the specific application. This paper presents a good case of such circumstance with all the system specifications explained.

Section 2 briefly reviews the underwater RF communication characteristics. Section 3 describes the system implementation and network scenario. Section 4 discusses the protocol scheme and key issues. Section 5 demonstrates the detailed packet design process. Section 6 reveals some information of the initial beach trial and evaluates the system with modeling and simulations, and Section 7 concludes the paper.

2. Review of underwater RF communication

Most underwater wireless networks use acoustic wave as the transmission medium nowadays, which is a proven technology for underwater sensor applications with a transmission range of up to 20 km [4], but the chances of getting much more out of acoustic modems are quite remote. Acoustics yields poor performance in shallow water where the transmission can be affected by turbidity, ambient noise, salinity gradients and pressure gradients; in addition, acoustic technology can place an adverse impact on marine life [5]. Another option that may be used for underwater transmission is optical wave, but this only delivers good performance in very clear water, and requires tight alignment due to the demand for the sight and the limitation of very short transmission ranges [6]. The characteristics of optical link have made itself impractical for many underwater applications. The latest research on optical UWSN is still ongoing such as Ref. [7]. Table 1 outlines the three major underwater communication technologies in terms of benefits, limitations and requirements. Compared to acoustic and optical technologies, RF-EM has some distinct advantages that make it suitable for underwater environments.

EM propagation through water is very different from propagation through air because of the high permittivity and electrical conductivity of water medium. Propagating waves continually cycle energy between the electric and magnetic fields, hence high conduction leads to strong attenuation of electromagnetic propagating waves. Plane wave attenuation also increases rapidly with frequency. However it is interesting to consider reversal of roles between acoustic and EM technologies as passing from water to air. In air, acoustic signals are highly attenuated so hundreds of people can hold separate conversations in a crowded conference hall. Radio waves have low attenuation in air so communications must be separated in frequency through careful management of the spectrum. In water the two roles reverse themselves, and it is easy to see the potential benefits of high EM spatial attenuation in a multi-user environment which enables localized communications.

EM signaling, coupled with digital technology and signal compression techniques, has many advantages that make it suitable for niche underwater applications. Comparing to acoustic and optical wave technologies, radio frequency (RF) EM technology allows flexible deployment of underwater wireless sensor network for coastal monitoring applications, where there is a high level of sediment and aeration in the water column. First, both acoustic and optical waves cannot perform smooth transition through air-and-water interface. EM waves can cross water-to-air or water-to-earth boundaries easily; its signal follows the path of least resistance, where both air and seabed paths can extend the transmission range. Second, EM transmissions are tolerant to turbulence that are caused by tidal waves or human activities, as opposed to the case of acoustic and optical waves. Third, EM waves can work in dirty water conditions, while optical waves are susceptible to particles and marine fouling [8]. Fourth, EM operation is also immune to acoustic noise, and it has no unknown effect on marine lives. Research on underwater EM communication is currently ongoing, with examples such as Ref. [9,10]. Table 2 summarizes the advantages of underwater RF-EM technology.

An important consideration for underwater RF-EM performance is its multi-path propagation feature caused by the effects of the water-to-air interface. Propagation loss and the refraction angle are such that an EM signal crosses the water-to-air boundary and appears to radiate from a patch of water directly above the transmitter. The large refraction angle produced by the high permittivity launches a signal almost parallel with the water surface [11]. This effect aids communication from a submerged station to the land and between shallow submerged stations without the need for surface repeater buoys. A similar effect can also be produced at the seabed. Since the conductivity of the seabed is much lower than water, it can provide an alternative low loss, low noise, covert communications path. In many deployments, the single propagation path with the least resistance will be dominant. Should the air path or the seabed path be chosen as the dominant data path, relatively longer transmission range can be achieved as compared to the water path. Hence the multi-path propagation of electromagnetic waves can be advantageous for signal transmission in shallow water conditions.

Magnetic coupled loop antennas are the most compact practical solution for duplex submerged systems. Loop antennas are directional in nature and this property can be exploited to allow selection of a single propagation path. Alternatively, omni-directional antennas can be