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E^2DTS: An energy efficiency distributed time synchronization algorithm for underwater acoustic mobile sensor networks

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ABSTRACT

Time synchronization plays an important role in wireless sensor network applications and energy conservation. In this paper, we focus on the need of time synchronization in underwater acoustic mobile sensor networks (UAMSNs). Several time synchronization algorithms have been carried out in this issue. But most of them are proposed for RF-based wireless sensor networks, which assume that the propagation delay is negligible. In UAMSNs, the assumption about rapid communication is incorrect because the communication is primarily via acoustic channel, so the propagation speed is much slower than RF. Furthermore, the propagation delay in underwater environment is time-varying due to the nodes' mobility. We present an energy efficiency distributed time synchronization algorithm (called "E^2DTS") for those underwater acoustic node mobility networks. In E^2DTS, both clock skew and offset are estimated. We investigate the relationship between time-varying propagation delay and nodes mobility, and then estimate the clock skew. At last skew-corrected nodes send local timestamp to beacon node to estimate its clock offset. Through analysis and simulation, we show that it achieves high level time synchronization precision with minimal energy cost.

1. Introduction

Wireless sensor networks (WSNs) are widely used in environmental monitoring, target tracking [1], security surveillance, assisted navigation, and many other applications. In WSNs, each node works in a distributed manner and collects the data alone (e.g., sensing the environment). After sensing phrase, the time-sensitive data were sent to cluster header or sink node, and then fused to extract meaningful information. Time synchronization plays an important role in the working process of wireless sensor networks. It will help process and analyze the data correctly and predict future system behavior. For example, in mobile target tracking applications, the distributed system may match the sensing time and sensing location so as to calculate the speed and direction of moving object. In addition, not only would the application layer use time synchronization, other layers such as medium access control and networking layers may also benefit from time synchronization. For example, the Slotted FAMA [2] is an example of MAC protocols that requires time synchronization.

With the usefulness of time synchronization, it has drawn a quite number of attentions from researchers in past few years. In the Internet, NTP is the classical method to provide time synchronization for distributed system [3]. It uses a phase-locked loop to correct the local clock frequency so that the long term average skew error can be kept in a low level. But energy consumption is out its consideration, while energy efficiency is an important issue in sensor networks. Many synchronization protocols have been proposed to solve this issue [4–11]. The assumption of neglect propagation delay in above literature is appropriate for RF-based wireless sensor networks because of the rapid radio communication velocity. This situation is

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different in underwater environment. So a new approach to time synchronization with high precision is required in UAMSNs.

In underwater acoustic mobile sensor networks, the underwater communication mainly uses acoustic channel which differs from radio channel in many aspects. First of all, the acoustic channel has a low propagation speed of approximately 1500 m/s, which are five orders of magnitude lower than that of the radio channels. The high propagation delay can reduce the throughput of the system considerably. Meanwhile the speed of sound in water varies significantly with temperature, density and salinity causing acoustic wave to travel on curved paths [12]. This multivariant speed adds troubles in predicting propagation delay. Moreover, the available bandwidth of the underwater acoustic channel is limited by both range and frequency [13,14]. Within this limited bandwidth, the acoustic signals are subject to time-varying multipath, which may result in severe inter-symbol interference (ISI) and large Doppler shifts and spreads [15], relative to radio channels. These characteristics of the acoustic channel restrict the range and bandwidth for reliable communications [16] and lead to the low data transmission rate.

Following the change of deployment scene and the characteristics of acoustic channel, these time synchronization algorithms which are suitable for RF-based wireless sensor networks could never be directly applied to in UAMSNs. Syed and Heidemann proposed TSHL [12], which is used in high latency acoustic networks. The TSHL assume that all the nodes in networks are static, which is not true in real underwater environments. In some applications for underwater acoustic sensor networks (e.g. monitoring of ocean currents), the nodes have some certain mobility resulted in the mobility of ocean current with a rate of 3–6 km/h (around 0.83–1.67 m/s) [17]. Meanwhile, Autonomous Underwater Vehicles (AUVs) can move automatically with a speed of up to 2.9 m/s [22]. Nitthita et al. propose a cluster-based synchronization algorithm for underwater acoustic mobile networks, called "MU-Sync" [18]. The MU-Sync estimate the clock skew with performing the linear regression twice over a set of local time information gathered through message exchanges. Numerous cluster headers with ideal time need to be deployed in underwater acoustic mobile sensor networks, which may be quite difficult to achieve due to economical reasons.

In this paper, we present an energy efficiency distributed time synchronization algorithm for underwater acoustic mobile sensor networks, called "E^2DTS". The inaccuracy of sound velocity calculated by the Wilsion formula is 0.3 m/s [23], which is nine times less than nodes mobility speed. So the nodes mobility is the main cause of errors in time synchronization. With an assumption of the nearly constant motion in limited time of synchronization stage, we explore the relationship between time-varying propagation delay and nodes mobility. In E^2DTS, a beacon node with ideal time navigates in sensor nodes deployed area and periodically sends the reference message with ideal sending time. E^2DTS uses two phases' message exchanges to estimate the clock skew and offset. In the first phase, each unsynchronized node estimates its own clock skew by eliminating the affection of time-varying propagation delay. In the second phase, each skew synchronized node estimates its clock offset by once message exchange with beacon node. With the help of MAC-level time stamping, the E^2DTS can achieve high level time synchronization precision with minimal energy cost.

The remainder of this paper is organized as follows. In Section 2, we describe the characteristic of underwater acoustic mobile sensor networks and discuss the causes of errors in time synchronization. Then in Section 3, we do a brief survey of recent works for time synchronization in wireless sensor networks, especially in underwater acoustic sensor networks. The details of the E^2DTS are shown in Section 4. Section 5 provides the simulation results which are carried out to compare the proposed scheme with others. And finally, we give our conclusion in Section 6.

2. Background

2.1. Underwater acoustic mobile sensor networks

In UAMSNs, a large number of sensor nodes and vehicles are deployed to perform collaborative monitoring tasks over a given area. Different from terrestrial sensor networks, nodes and vehicles in UAMSNs communicate via acoustic channel. Though there are many means for underwater wireless communications, but acoustic waves are the best one known so far. In spite of good performance in terrestrial sensor networks, radio-frequency (RF) communication is improper for underwater acoustic mobile sensor networks. In underwater environments, RF has a high attenuation rate which seriously limits its communication range, so the propagation range of RF in underwater environments is very short. Long wave RF has longer transmission distance in underwater environment, but it requires high transmission power and large antennae, making it unsuitable for small and energy limited sensor nodes. Optical waves are severely affected by high attenuation rate and scattering in underwater environments. Moreover, transmission of optical signals requires high precision in pointing the narrow laser beams, which are still being perfected for practical use [19].

The acoustic waves are the best means for underwater acoustic mobile sensor networks so far. There are many channel characteristics which are different from that of radio waves and optical waves. The velocity of sound propagation is the first difference between radio and acoustic. The velocity of acoustic propagation is approximately 1500 m/s, which are five orders of magnitude lower than that of the radio propagation. The long propagation delay can reduce the throughput of the system considerably. Sound propagation underwater is principally affected by transmission loss, noise, reverberation and temporal and spatial variability of the channel [19]. Meanwhile the temperature, density and salinity make the speed of sound propagation vary severely by causing acoustic wave to travel on curved paths. This variable speed adds troubles in predicting propagation delay for some applications, such as time synchronization.