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A Joint Time Synchronization and Localization

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ABSTRACT

Time synchronization and localization are basic services in a sensor network system. Although they often depend on each other, they are usually tackled independently. In this work, we investigate time synchronization and localization problems in underwater sensor networks. We propose a joint solution for localization and time synchronization, in which the stratification effect of underwater medium is considered, so that the bias in the range estimates caused by assuming sound waves travel in straight lines in water environments is compensated. By combining time synchronization and localization, the accuracy of both are improved jointly. Additionally, an advanced tracking algorithm IMM (interactive multiple model) is adopted to improve the accuracy of localization in the mobile case. Furthermore, by combining both services, the number of required exchanged messages is significantly reduced, which saves on energy consumption.

I. INTRODUCTION: In recent years, Underwater Sensor Networks (UWSNs) has attracted significant attention [1], [2], [3]. Among the services UWSNs can provide, time synchronization and localization are very critical, because most UWSNs applications benefit from or require these two services. For instance, TDMA (Time Division Multiple Access), one of the commonly used medium access control (MAC) protocols, often requires precise synchronization among sensor nodes. Additionally, most geographic routing algorithms assume the availability of location information [4], [5]. Although localization and synchronization services are closely related, they are usually studied independently. This is mainly because localization is traditionally studied from the signal processing point of view in radio networks, and synchronization is mainly studied from protocol design point of view. However, especially in UWSNs, localization and synchronization are closely "bonded". Since the ranging is estimated based on time of arrival (TOA) or time difference of arrivals (TDOA) in UWSNs, many localization algorithms rely on the time synchronization services. For example, in TOA, a popular localization algorithm, synchronization is a prerequisite. On the other hand, knowledge of location helps time synchronization because it can be used to estimate propagation delays. Furthermore, both localization and time synchronization require a sequence of message exchanges among the nodes. Based on these bonds relationships, we believe that localization and time synchronization could be solved jointly, with two major benefits. First, a joint strategy would save energy, since localization and synchronization can use only one set of message exchanges instead of two. This is important for energy constrained network systems like UWSNs. Second, a joint solution can help to improve the accuracy of both services. However, to the best of our knowledge, there is no work has explored the joint design of synchronization and localization in UWSNs. Additionally, in UWSNs, all current localization algorithms assume the straight line transmission of acoustic waves. In fact, due to the sound speed variation with depth in the water environment, called “stratification effect”, the real transmission path usually bends. This will severely affect the ranging estimation, and in turn affect localization accuracy. In this paper, we propose a joint solution for localization and synchronization, called JSL for UWSN, JSL is a four phases scheme in which, time synchronization and localization are performed at different phases. During iterations, the output of synchronization is fed back as the input of localization, and the output of localization is fed back as the input of synchronization. In this way, synchronization and localization are interleaved and can benefit each other by improving the accuracy of both. During the localization phase, unlike other algorithms that assume sound waves travel in straight lines in the water environment, JSL compensates the stratification effect when performing the underwater acoustic ranging, so that the propagation delay estimation will be significantly improved.

II Related Work

Although there are significantly growing interests in UWSNs in the past several years, the research on time synchronization for UWSNs is still relatively limited. TSHL [8] is designed for high latency networks, which can manage long propagation delays and remain energy efficient. TSHL combines one-way and two-way MAC-layer message delivery. TSHL works well for static underwater sensor networks, but it cannot handle mobile scenarios as it assumes constant propagation delays among sensor nodes. MU-Sync [9] is proposed to synchronize nodes in a cluster based UWSNs. Although MU-Sync aims to solve sensor node mobility issue in UWSNs, it requires relatively high message overhead. Furthermore, MU-Sync uses half of the round trip time to calculate one way propagation delay, which causes extra errors, especially for fast moving situations or when ordinary nodes respond to cluster head after experiencing a long time duration. Mobi-Sync [13] is a time synchronization scheme for mobile underwater acoustic sensor networks. Mobi-Sync distinguishes itself by considering spatial correlation among the mobility patterns of neighboring UWSNs nodes. This enables MobiSync to accurately estimate the long dynamic propagation delays. However, Mobi-Sync only works for dense network as it is based on spatial correlation. TSMU [14] is a pairwise synchronization method. It effectively utilizes Doppler effects and incorporates the relative speed of the transmitter and receiver to improve the dynamic propagation delay estimation. Additionally, Kalman filter and the calibration process are exploited to further enhance synchronization accuracy. However, TSMU only show its performance with linear kinematic model, which limits its practical applicability. Traditionally, localization algorithms are either rangebased or range-free. In this work, we focus on the rangebased localization algorithms. Ranging techniques are either communication-based or connectivity-based. GPS Intelligent Buoys (GIBs) [15] and PARADIGM [16] use underwater GPS. Those to-be-localized sensor nodes need to communicate with the surface buoys, because of which, the time synchronization is a base for them in order to convert time information into range information. [17] tries to avoid time synchronization by using half of the round-trip time to estimate the propagation delay. It requires a sensor node to communicate with multiple surface buoys, which may introduce a heavy load of traffic in the network. A silent positioning scheme is proposed [18] which does not depends on time synchronization. Instead, all the sensor nodes get localized by passively listening to the beacon messages exchanged among anchor nodes, so that it requires four noncoplanar anchors that can mutually hear each other. Usually, connectivity-based method is only used when there is no direct communication between nodes and sensors, where range estimation is estimated based on network connectivity. [19] proves that euclidean method performs the best in anisotropic topologies, but with more cost on computation

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and communication. In [20], it proves that with short communication range among anchor nodes, euclidean method can be adopted for 3D underwater localization. [21] relaxes this limitation by proving it is also working when the anchor nodes communication range is long. However, both [20] and [21] are suffering from heavy traffic due to using flooding mechanism. [22] introduced "SLMP", which applies some prediction schemes to localization algorithm to reduce its overhead. In SLMP, anchor nodes conduct linear prediction by taking advantages of the inherent temporal correlation of underwater object mobility pattern. While each ordinary sensor node predicts its location by utilizing the spatial correlation of underwater object mobility pattern, weighted-averaging its received mobilities from other nodes. However, because the prediction is based on temporal and spatial correlations, the algorithm only works in dense network.

III. DESIGN CHALLENGES

In order to achieve effective time synchronization and localization in UWSNs, following four critical challenges have to be addressed. 1) Stratification Effects: Underwater acoustic localization usually relies on TOA measurements, which are converted into range estimates. However, the water medium is inhomogeneous and the sound speed varies depending on several parameters, such as temperature, pressure and salinity. As a result, sound waves do not necessarily travel in straight lines. Ignoring this stratification effect could lead to considerable bias in the range estimates. 2) Long Propagation Delays: Any software based time synchronization approaches using message exchanges have to face several uncertainties which could affect accuracy. Those uncertainties include sending time, accessing time, transmission time, propagation time, reception time, interrupt handling, encoding time, decoding time and byte alignment time [6], [7]. In UWSNs, among these uncertainties, the propagation time is dominant due to the low propagation speed of acoustic signals. Such long propagation latencies heavily affect the accuracy of time synchronization algorithms which assume instant synchronization message reception [8], [9]. Therefore, in order to achieve more accurate time synchronization in UWSNs, estimating and compensating the long propagation delay is a must do job. 3) Sensor Node Mobility: While terrestrial sensor networks are usually static, sensor nodes in an underwater environment often have passive mobility caused by water currents or proactive mobility coming with mobile platforms, which makes localization challenging. This is because in such a situation, it is difficult, if not impossible, to estimate the real time distance between two sensor nodes, which will in turn affect localization accuracy. The mobility also complicates time synchronization by causing continuous changes of propagation delays. However, most of the existing time synchronization schemes use half of the round trip time to calculate one way propagation delay. Due to node mobility, the propagation delays on the way to and from nodes are not necessarily identical, especially when nodes move at a high speed. Therefore, to improve the time synchronization accuracy, the sensor node mobility should be considered. 4) Energy Constraints: Underwater sensor nodes are usually powered by batteries, for which it is not easy to replenish. Therefore, the life time of a sensor node is restricted by the limited power supply. For this reason, synchronization and localization overhead needs to be carefully controlled. Synchronization or localization protocols requiring frequent message exchanges are not suitable in UWSNs.

IV CONCLUSION

In this paper, we presented JSL, a joint solution for time synchronization and localization. To our best knowledge, it is the first localization scheme which compensates the stratification effect in the underwater environment. Furthermore, synchronization and localization are closely coupled and help each other to improve the accuracy of each other. An advanced tracking algorithm IMM is adopted to further improve accuracy. Our simulation results show that JSL can achieve high accuracy for both synchronization and localization. In the future, we plan to design a network-wide synchronization and localization scheme based on JSL. After one ordinary node is synchronized and localized, it will become a reference node to help to synchronize and localize other ordinary nodes. In this way, the scheme can be used in a large scale network.

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