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Topology control models and solutions for signal irregularity in mobile underwater wireless sensor networks

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ABSTRACT

Underwater wireless sensor networks (UWSNs) have been developed for a set of underwater applications, including resource exploration, pollution monitoring, and tactical surveillance. The topology control techniques of UWSNs and terrestrial wireless sensor networks are significantly different because of the particularity of underwater environments and acoustic communication. In underwater environments, signal irregularity phenomenon affecting network protocols is more prone to exhibit, and anchored sensor nodes towed by wires move within a spherical crown surface randomly. However, most previous efforts about topology control either have not been made on signal irregularity in mobile underwater wireless sensor networks, or the proposed irregularity models are too idealistic to reflect reality. The current study constructs a more authentic signal irregularity model, which can be degenerated into a variety of special cases easily, and three representative topology control objectives ((K_S, β)-Coverage, (K_C, α)-Connectivity, and efficient consumption) are concluded. A topology control algorithm for signal irregularity (TCASI) is designed for this topology control problem. The results prove the convergence of TCASI and polynomial complexity as well. The performance of the algorithm is analyzed through simulation experiments that indicate a well-constructed topology, where (K_S, β)-Coverage and (K_C, α)-Connectivity can be achieved while optimizing energy consumption as much as possible.

1. Introduction

Underwater wireless sensor networks (UWSNs) (Akyildiz et al., 2005; Jawhar et al., 2011) are the enabling technology for various underwater applications, and the interest in UWSNs is growing. There are plenty of applications in underwater environments such as ocean resource exploration, pollution monitoring, and tactical surveillance. UWSNs consist of underwater sensors (anchored nodes and surface sinks) that perform collaborative monitoring tasks over a 3D space. Acoustic communications (Zhou et al., 2012; Saleh et al., 2007) are the typical physical layer technology in underwater networks. Anchored nodes are equipped with floating buoys that are inflated by pumps. The depth of the anchored node is regulated by adjusting the length of the wire, and anchored nodes are prone to drift off their static positions in compliance with the spherical crown mobility pattern (Liu et al., 2012) (see Appendix). The given phenomenon is observed by anchored nodes in charge of relaying data to surface sinks, as shown in Fig. 1, which illustrates a 3D mobile UWSN. The measurements of environmental events are monitored by anchored nodes locally, and transferred to one of the surface sinks by multi-hops. Ultimately, the measurements are aggregated at a LEO satellite from all surface sinks for future processing.

Signal irregularity is a common phenomenon in WSNs and UWSNs. Signal irregularity is caused by various factors, such as antenna directions, transmitting power, antenna gains, battery status, signal-noise-ratio threshold, and obstacles, among others (Ababneh, 2009; Zhou et al., 2006). Particularly, a variety of obstacles are distributed in underwater environments, thus, signal is easier to be reflected, diffracted, or scattered in propagation. Consequently, an irregularity phenomenon is more prone to exhibit in UWSNs. Signal irregularity directly or indirectly affects network protocols, such as the MAC, routing, localization and topology control. Therefore, signal irregularity is a non-negligible issue, especially in UWSNs.

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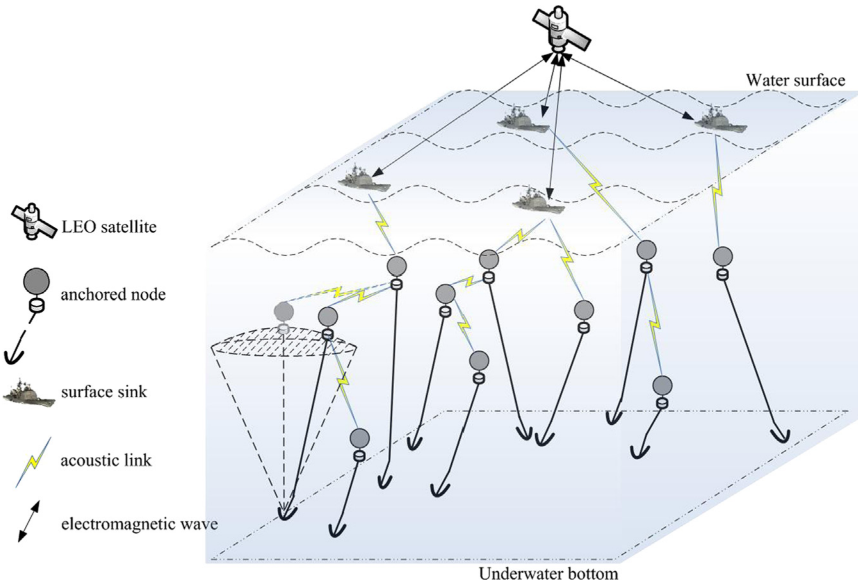

Fig. 1. Architecture of a Mobile UWSN.

Another inevitable issue of UWSNs is node mobility. Every anchored node moves within a spherical crown surface under the resultant force of current wallop, anchored wire pull, and buoyancy force. More seriously, accurate and real-time positions of nodes cannot be afforded through a localization system, such as GPS, which is attributable to the constraints of deployment cost, antenna size, power consumption and underwater environments. Another crucial topic is how to improve the topology deterioration or damage caused by mobility.

Practically, sensor nodes may be heterogeneous and equipped with different devices, which give rise to different maximum radii (both sensing radius and communication radius). Moreover, the sensing radius and the communication radius depend on sensor and transceiver modules (RF chips), respectively. The two kinds of radii should be considered as independent with each other, and thus signal irregularity[1] must include both sensing irregularity and communication irregularity. In this regard, the present research accounts for both coverage and connectivity issues (Zhu et al., 2012; Wang et al., 2012), which are necessary for 3D monitoring. Full coverage ensures the environment detection at all depths. Global connectivity ensures at least one communication path from any node to surface sinks. However, the requirements for coverage and connectivity of diverse applications vary. For example, stronger environmental monitoring and invulnerability may be necessary in military applications; conversely, the demands are not so strong in non-emergency applications, such as natural ecology monitoring. In particular, probabilistic coverage and connectivity problem are more appropriate to numerous acoustic detection applications. To consider a more general UWSNs topology control problem, a model integrating (K_S,β)-Coverage (Ammari, 2012; Sengupta et al., 2012) and (K_C,α)-Connectivity (Atay and Bayazit, 2008; Law and Yen, 2007) will be constructed for analysis in the current study (Section 3). Most existing works can be regarded as a special case of this model with $K_S=1$, $K_C=1$, and $\alpha=1$, $\beta=1$.

Moreover, the battery power of nodes is limited. Usually, batteries cannot be easily replaced underwater, and solar energy is hardly being exploited. As a result, another primary objective of UWSNs is to reduce energy consumption and increase network lifetime (Dietrich and Fressler, 2009; Kosar et al., 2011). In the literature, UWSN lifetime is defined as the time that all alive nodes cannot form a topology fulfilling (K_S,β)-Coverage and (K_C,α)-Connectivity.

Based on the characteristics of underwater acoustic communication, UWSN topology control includes several other typical objectives such as propagation delay, bandwidth, and transmission success rate. The problem of multi-objectives topology control in UWSN appears in an early work (Liu, 2010). The present study concentrates on signal irregularity and neglects other objectives temporarily. Therefore, topology control based on signal irregularity for mobile UWSNs is defined as the art of coordinating the decisions of mobile nodes regarding their communication and sensing ranges to generate a network topology with the desired properties ((K_S,β)-Coverage, (K_C,α)-Connectivity), while exerting the optimization of energy consumption.

The remainder of the current study is organized as follows. Section 2 introduces some related works. Section 3 formulates the topology control problem in mobile UWSNs. Section 4 proposes a topology control algorithm for signal irregularity TCASI. Section 5 analyzes TCASI from the aspects of convergence, complexity, necessary number of deployment nodes, number of asleep nodes, and energy consumption. Section 6 discusses the performance evaluation of TCASI. Finally, Section 7 provides some conclusions. This work is the extension of Liu and Liu (2013), the algorithm is discussed from three special cases, and more analysis and simulations have been made and provided in this paper.

2. Background

2.1. Coverage or connectivity problem

The problem of topology control for WSNs and UWSNs has been studied extensively. The early representative topology control algorithm LMST (Local Minimum Spanning Tree) was proposed by Li et al. (2003). In LMST, each node built its local minimum spanning tree independently and

[1] In this paper, irregularity on both sensing range and communication range is collectively referred to as signal irregularity.