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Generic prediction assisted single-copy routing in underwater delay tolerant sensor networks

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ABSTRACT

One challenge in delay tolerant networks (DTNs) is efficient routing, as the lack of contemporaneous end-to-end paths makes conventional routing schemes inapplicable. Although many DTN routing protocols have been proposed, they often have two limitations: many protocols are not mobility cognizant, so they only suit specific mobility models and become inefficient when the environment changes; some protocols employ multi-copy replication to accommodate mobility diversity for increased delivery probability or reduced delay, but they usually do not perform well in resource constrained networks. Due to the unique characteristics of underwater sensor networks (UWSNs), efficient DTN routing becomes even more challenging. In this paper, we propose a generic prediction assisted single-copy routing (PASR) scheme that can be instantiated for different mobility models. PASR first collects a short-duration trace with network connectivity information and employs an effective off-line greedy algorithm to characterize the underlying network mobility patterns, depict the features of best routing paths and provide guidance on how to use historical information. Then it instantiates prediction assisted single-copy online routing protocols based on the guidance. As a result, the instantiated protocols are energy efficient and cognizant of the underlying mobility patterns. We demonstrate the advantages of PASR in underwater sensor networks with various mobility models.

1. Introduction

Many routing protocols have been proposed to deal with the lack of contemporaneous end-to-end paths in delay tolerant networks (DTNs) [1–8]. These protocols, however, have the following limitations. First, many protocols are designed for specific mobility models [9–12]. For instance, the protocols in [13,14,7,15,16] are for networks in social environments; the protocols in [17,18] focus on random way point and random walk mobility models; and the protocol in [11] is for networks with pre-determined node trajectories. Although some other protocols are designed for general mobility models, they are not mobility model cognizant [19]. Since the underlying mobility dominates the contact and inter-contact pattern [20], these mobility incognizant protocols can have superior performance for one model while much degraded performance for another model [19]. Another drawback of most existing routing protocols is that they use multi-copy replication, which allows multiple replicas of a packet to exist in a network simultaneously. These protocols establish several virtual spatial temporal routes (either using flooding [4,19,21] or controlled flooding [15,22]) to increase delivery probability and decease end-to-end delay. On the other hand, they exhaust network resources (such as bandwidth, storage and power) much more quickly than single-copy routing strategies. Thus, multi-copy routing

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schemes always lead to poor performance in resource stringent networks.

Underwater sensor networks (UWSNs), an area that has attracted significant attention from both academia and industry [23–27], can be treated as DTNs [28] due to node mobility and sparse deployment. Compared to other DTNs, UWSNs are extremely resource stringent since acoustic communication, the most practical communication method for UWSNs, has very limited bandwidth and very high power consumption. Furthermore, the mobility pattern in an UWSN can vary dramatically over time depending on the environment. These two characteristics render existing DTN routing protocols, especially multi-copy replication schemes, unsuitable in UWSNs. Therefore, an efficient single-copy routing scheme, which can also be self-adaptive to the varying mobility, is desirable.

In this paper, we propose a generic scheme, *prediction assisted single-copy routing* (PASR), for UWSNs to achieve minimum delivery delay at low energy consumption. PASR can be instantiated to efficient single-copy routing protocols under different mobility models. PASR consists of two phases, *learning phase* and *routing phase*. In the learning phase, PASR collects a short-duration trace with network connectivity information and employs an effective off-line greedy algorithm to characterize the underlying mobility patterns, depict the common features of best routing paths and provide guidance on how to use historical information. In the routing phase, it instantiates a prediction assisted single-copy online routing protocol based on the guidance. Our main contributions are: (1) we propose a short-duration trace-based greedy algorithm, named *aggressive chronological projected graph* (ACPG) in the learning phase and analyze the computational complexity; (2) we design a generic scheme on instantiating heuristic prediction assisted single-copy routing protocols based on the guidance from ACPG in the routing phase; and (3) we evaluate this generic scheme in UWSNs with three different mobility patterns through comprehensive simulation. Our simulation results show that ACPG indeed captures the relationship between historical information and best routing paths under different mobility patterns and provides effective guidance to instantiate heuristic single-copy routing protocols, that achieve close to optimal results and outperform other existing schemes. A preliminary version of this paper appeared in [29].

The rest of this paper is organized as follows. We first discuss related work in Section 2. We then introduce the network model and convert it to an extended space time graph in Section 3. Afterwards, we present the greedy algorithm ACPG and compare it with an optimal algorithm in Section 4. Section 5 describes the generic scheme PASR and how to instantiate prediction assisted single-copy routing protocols in UWSNs for different mobility models. Section 6 presents performance evaluation. Finally, Section 7 concludes the paper and proposes future research directions.

2. Related work

Since many types of networks (e.g., planet networks [30], sensor networks [24], village networks [31], vehicle networks [11]) can be treated as delay tolerant networks, much effort has been put on the challenging routing problem and many schemes have been proposed. Depending on whether the complete information of the networks is available or not, DTN routing can be categorized as *deterministic routing* and *heuristic routing*.

2.1. Deterministic routing

Deterministic routing schemes are to optimize a certain performance metric (e.g., shortest average delay, highest delivery ratio, minimum energy consumption, longest network lifetime and so on) when complete information is available. The complete information may include the location of nodes, the contacts between nodes, the power or storage status of nodes, the traffic demands and so on. Based on the complete information, deterministic routing schemes can achieve the optimal results in respect to a certain performance metric. Merugu et al. built a space time graph to select routing paths using dynamic programming and shortest path algorithm in [32]. Jain et al. formulated a linear programming problem upon the availability of all knowledge oracles in [5].

The rigorous requirement on the complete information of networks makes all algorithms above not practical in real networks, since even missing partial information can significantly increase the complexity [5]. Different from above schemes, we propose a practical prediction assisted scheme. In this scheme, we apply an off-line deterministic algorithm on a short-duration trace to guide the design of online heuristic routing schemes.

2.2. Heuristic routing

In most networks, it is impossible to obtain complete information in advance, thus only heuristic routing is suitable. According to how many replicas of a packet can exist in the network simultaneously, we classify existing heuristic routing schemes into two categories: *multi-copy routing* and *single-copy routing*.

2.2.1. Multi-copy routing

Multi-copy routing means that a node can replicate a packet on multiple relay nodes and expect any of them can reach the destination quickly. Epidemic [4] was a representative multi-copy routing scheme. To minimize the end-to-end delay, Epidemic replicated a packet to every node in the network. However, this flooding scheme consumed too many resources and made itself infeasible in harsh network environments. To avoid unconstrained resource consumption, many other multi-copy routing schemes that limit the number of copies have been proposed. These schemes forward packets according to some criteria, i.e. utility function, forwarding probability and so on. Harras et al. proposed several controlled flooding schemes in [21], such as basic probabilistic, time-to-live, kill time and passive cure. Spyropoulos et al. presented spray and wait [19], in which a certain number of copies of a packet were replicated to the first encountered nodes. This scheme only strictly controlled the total number of copies, but did not choose the relay nodes wisely, causing