Prediction Assisted Single-copy Routing in Underwater Delay Tolerant 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. Many existing DTN routing protocols adopt multi-copy replication and/or are incognizant of mobility models. Hence they are not suitable for networks with extremely stringent resources and time-varying mobility models such as underwater sensor networks. In this paper, we propose a generic prediction assisted single-copy routing (PASR) scheme that can be instantiated for different mobility models in underwater sensor networks. PASR employs an effective greedy algorithm which captures the features of network mobility patterns, and provides guidance on how to use historical information. We demonstrate the superior performance of PASR through simulation.**

I. Introduction

Many routing protocols have been proposed to deal with the lack of contemporaneous end-to-end paths in delay tolerant networks (DTNs) [1], [2], [3], [4], [5]. These protocols, however, have the following limitations. First, many protocols are designed for specific mobility models. For instance, [4], [6], [7] propose protocols social networks; [8], [9] focus on random waypoint and random walk models; and the protocols in [10] are for networks with pre-determined node trajectories. Although some other protocols are for general mobility models, they are not mobility cognizant [11]. Since the underlying mobility dominates the contact and inter-contact pattern [12], these mobility incognizant protocols can have superior performance for one model while much degraded performance for another model [11]. Another drawback of most existing routing protocols is that they use multi-copy replication that allows multiple replicas of a packet to exist in a network simultaneously. These protocols establish several virtual spatial temporal routes (either using flooding [1], [11], [13] or controlled flooding [6], [14]) to increase delivery probability and decease end-to-end delay. On the other hand, they exhaust network resources (such as bandwidth and power) much more quickly than single-copy routing strategies.

The above limitations make existing DTN routing protocols unsuitable for underwater sensor networks (UWSNs), an area that has attracted significant attention from both academia and industry [15], [16]. Due to node mobility and sparse node deployment, UWSNs can be treated as DTNs [17]. 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 patterns in an UWSN can vary dramatically over time depending on the environment. These two characteristics render existing multi-copy based DTN routing protocols unsuitable for UWSNs.

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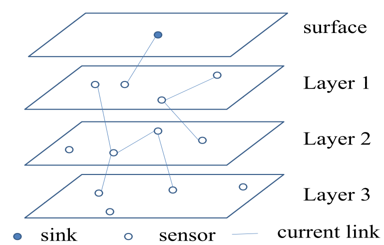


Fig. 1. A simple example of a three-layer underwater sensor network.

In this paper, we propose a generic scheme, *prediction assisted single-copy routing* (PASR), for UWSNs. PASR can be instantiated to efficient single-copy routing protocols under different mobility models. Our main contributions are: (1) propose a small-scale trace-based greedy algorithm, named *aggressive chronological projected graph* (ACPG) to capture the network mobility properties and the common characteristics of near optimal routes, (2) design a heuristic prediction assisted single-copy routing protocol based on the guidance from ACPG, and (3) evaluate this generic scheme in UWSNs with three different mobility patterns through comprehensive simulation. Our simulation results show that ACPG indeed captures different mobility patterns and provides effective guidance to instantiate PASR protocols, that achieve close to optimal results and outperform other existing schemes.

The rest of this paper is organized as follows. We first introduce the network model in Section II. We then present the greedy algorithm ACPG and compare it with an optimal algorithm in Section III. Section IV describes and evaluates the generic prediction assisted single-copy routing scheme PASR and how to instantiate PASR in UWSNs with different mobility models. Finally, Section V discusses related work, and Section VI concludes the paper and proposes future research directions.

II. Network Model

We consider a data collection underwater sensor network, which consists of M layers. Multiple underwater sensors are deployed in each layer, which can passively move with water currents in the horizontal plane and vibrate slightly in the vertical direction. This kind of deployment can be achieved by simple buoyancy control of underwater sensors at certain depths [15]. Fig. 1 shows a simple example of such a network with three layers. For simplicity, we assume that one data sink is anchored in the middle of the water surface.

Since underwater sensors float with currents, their movements are driven by the movement of water and are tractable to some extent. We adopt the kinematic model [18] to describe the mobility. The movement is constrained in the horizontal plane and independent of the depth. The mobility model can be approximated as

$$\begin{cases} V_x = k_1 \lambda v \sin(k_2 x)\cos(k_3 y) + k_1 \lambda \cos(2k_1 t) + k_4 \\ V_y = \lambda v \cos(k_2 x)\sin(k_3 y) + k_5 \end{cases} \tag{1}$$

where V_x and V_y are the instantaneous velocities on the X and Y axes respectively; $k_i(i = 1, \ldots, 5)$, λ and v are variables related to the environment, such as tides and bathometry.

Further we assume the network operates in a slotted manner, each slot of duration T. Sensors in the lowest layer generate packets to be transmitted to the sink using nodes in the middle layers as relays. All sensors use store-and-forward mechanism; a packet received or generated in a slot can be forwarded in later slots. Each sensor broadcasts a short *hello* message to its neighbors at the beginning of each slot to declare its existence and exchange necessary information. Each sensor is equipped with a buffer that can accommodate W packets and a battery that can transmit P packets. Sensors work in a half-duplex mode (i.e. they cannot transmit and receive simultaneously), and transmit or receive data at the rate of λ packets per second. The objective is to deliver packets to the sink with minimum delay at low energy consumption.

III. Aggressive Chronological Projected Graph

We first propose a greedy algorithm named *aggressive chronological projected graph* (ACPG) to capture the network mobility properties and the common characteristics of near optimal routes. ACPG compresses the evolving network topology and connectivity to a single graph $G(V, E)$ chronologically, efficiently finds routes from the graph in a slot by slot manner, and characterizes the underlying mobility pattern.

A. Construction of $G(V, E)$

We assume the network contains M layers and N nodes in each layer (excluding the sink on the surface). We also model a super source v_s that generates packets and distributes them to the corresponding sources without delay, and a super sink v_d (the sink on the surface) to collect all packets. The slots are indexed as $0, 1, 2, \ldots$. Thus, we can construct a graph $G(V, E)$. Vertex $v_{ij} \in V \ \ (i = 1, \ldots, M, j = 1, \ldots, N)$ is the jth node in the ith layer, and edge $(v_{ij}, v_{kl}) \in E$ represents the connection between these two nodes during a certain time slot t. To differentiate edges in different time slots, we use (u, v, t, C) to represent an edge in G, where u and v are the connecting nodes in slot t and C is the capacity of that connection. The edge set E is initialized to be empty and updated in ACPG at each time slot.

Node $v \in V$ can be in two status: *inactive* or *active*. A node is active if there exists one route from the super source to it in G; otherwise, it is inactive. Initially, only the super source v_s is *inactive*. Each node v also maintains the following information:

- U_v: the upstream node. Node u is the upstream node of v iff $(u, v, t, C) \in G$ has the smallest value t among all edges associated with v. Two nodes are *mutual upstream nodes* if they are the upstream nodes of each other.
- $I_v(i)$: the maximum number of packets that can be transmitted or received during the ith slot, initialized to be λT.
- $C_v(i)$: the available storage in the ith slot, initialized to be buffer size W.
- P_v: the residual power for transmissions, initialized to be battery capacity P.

B. Operations of ACPG

The operations of ACPG at each slot t, $t > 0$, include two routines: (1) *edge projection*, during which connections in a time slot are projected to G as edges; and (2) *routes reservation and graph update*, during which routes are discovered and G is updated.

During edge projection at time slot t, only the necessary connections will be projected to G. We say a connection between nodes u and v is necessary if either u or v is active during that slot. Connections between two inactive nodes do *not* need to be projected as edges since they will not be used in any route. After the projection of $(u, v, t, C) \in E$, both u and v become active and update their upstream nodes. If multiple connections in different time slots have been projected to edge $(u, v) \in E$ up to the current slot t, only the one with the lowest time slot value is *available* on graph G and can be used for route discovery until it is replaced by the next earliest edge.

The second routine finds possible routes up to slot t, reserves the resources and updates G. If $v_d \in G$ is active, there must exist at least one flow from the super source v_s, whose route can be traced back along the upstream nodes from v_d. We then reserve the necessary resources with the route capacity, which is the minimum node capacity or edge capacity along the route. After reservation, nodes whose batteries are exhausted and edges whose capacities are reached become dead, and hence are removed from G. Afterwards, related nodes update their upstream nodes. The removal of nodes or edges may cause other connecting edges outdated. We define an outdated edge as an edge $(u, v, t', C) \in E$ if u and v are mutual upstream nodes. An outdated edge shall be deleted since it is impossible to be utilized in any route.

These two routines operate alternately until all traffic demands are satisfied. Through the aggressive route discovery along the earliest available edges, ACPG not only quickly finds low delay routes with significantly reduced complexity, but also summarizes the characteristics of the greedy routes, which reflect the properties of the underlying mobility pattern (see Section IV-C).

Fig. 2 shows an example of the projected graph at slot 9, where we only mark the tuple (t, C) on an edge (overlapped edges are arranged chronologically while only the first edge is available for route discovery). There are possible flows on the graph since v_d is active. Following the upstream nodes, we can build the first route ($v_d \stackrel{9}{\leftarrow} v_{12} \stackrel{7}{\leftarrow} v_{22} \stackrel{3}{\leftarrow} v_{31} \stackrel{1}{\leftarrow} v_s$) with

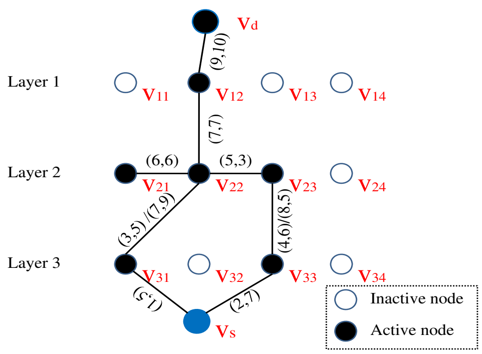


Fig. 2. An example of projected graph for 12 nodes in 3 layers.

capacity of 5 packets and delay of 8 slots, where $\overset{i}{\leftarrow}$ represents the packet is transmitted in the ith slot. After reserving the resources on nodes and edges on the route, edge $(v_{31}, v_{22}, 3, 5)$ is removed and node v_{22} changes its upstream node to v_{23}. Then we can find another route $(v_d \overset{9}{\leftarrow} v_{12} \overset{7}{\leftarrow} v_{22} \overset{5}{\leftarrow} v_{23} \overset{4}{\leftarrow} v_{13} \overset{2}{\leftarrow} v_s)$ with capacity of 2 packets and delay of 7 slots. This route exhausts edge $(v_{22}, v_{12}, 7, 2)$, so we remove edge $(v_{22}, v_{12}, 7, 2)$ and the outdated edge $(v_{12}, v_d, 9, 3)$, and make v_{12} and v_d inactive.

C. Performance of ACPG

We evaluate the performance of ACPG by comparing it with optimal solutions from integer linear programming (ILP) (which is omitted due to space limit, more details are found in [19]). The ILP formulation is based on an expanded space-time graph. It, however, may not be able to provide feasible solutions (because not all traffic demands can be satisfied). ACPG, on the other hand, is a greedy algorithm that aggressively searches for routes using the earliest available edges. As we shall see, it not only achieves close to optimal solutions, but also characterizes the properties of the near optimal routes according to the mobility pattern.

We consider a three-layer underwater sensor network. Each layer covers a $600m \times 600m$ horizontal area and the distance between two adjacent layers is $90m$. Four nodes are initially randomly deployed in each layer and move following the deterministic mobility model described in equation (1) (i.e. $k_4 = k_5 = 0$). The small-scale simulation is due to the high complexity of ILP (the proposed ACPG is scalable, we investigate larger networks in Section IV). Each sensor has buffer size of 30 packets and transmission range of $100m$. Sensors in the 3rd layer start generating packets from the 500th second to the 1000th second with the rate of one packet per second in a round-robbin manner. The simulation length is 3000 seconds and the slot interval is chosen to be 10 seconds. We vary the power capacity from 500 to 100 transmissions, while $unlimit$ means both the buffer and power capacities are not constrained.

Fig. 3 compares the performance of ILP and ACPG. The curves are plotted based on the average results of 10 runs and the numbers associated with the solid line in Fig. 3(a) indicate the number of runs in which ILP obtains feasible solutions. ILP is not feasible if not all traffic demands can be satisfied given the trace, while ACPG provides solutions that deliver as many packets as possible and characterizes the routes. We observe that ILP and ACPG overlap for both delivery ratio and average delay in the unlimited condition, indicating that ACPG can perform as well as the optimal algorithm when there are no power, buffer and bandwidth constraints. It is interesting to note that ILP fails to provide feasible solutions in more and more runs when the power capacity decreases, while ACPG provides good solutions with only slightly lower delivery ratio and higher average delay. Especially when the power capacity is as low as 100 transmissions, ILP provides no feasible solutions for all the runs, while ACPG provides results for almost 60% of all packets. ACPG again overlaps with ILP if we exclude all unfeasible runs in ILP.

In summary, for all the scenarios we investigate, ACPG provides results close to the optimal ones. Moreover, ACPG can capture the characteristics related to the mobility pattern and guide the prediction assisted single-copy routing design (see Section IV). Hence, ACPG can be executed in a short training period to provide guidance in real environments.

IV. Prediction Assisted Single-copy Routing

In this section, we propose *prediction assisted single-copy routing* (PASR), that utilizes ACPG in a training period to capture the characteristics of the mobility pattern, and provide guidance on route selection. Based on the guidance, PASR chooses appropriate historical information to predict future contacts to build single-copy routing schemes. In the following, we first present the generic scheme of PASR, then describe how to instantiate PASR to construct two specific protocols for underwater sensor networks with different mobility patterns.

A. How PASR Works?

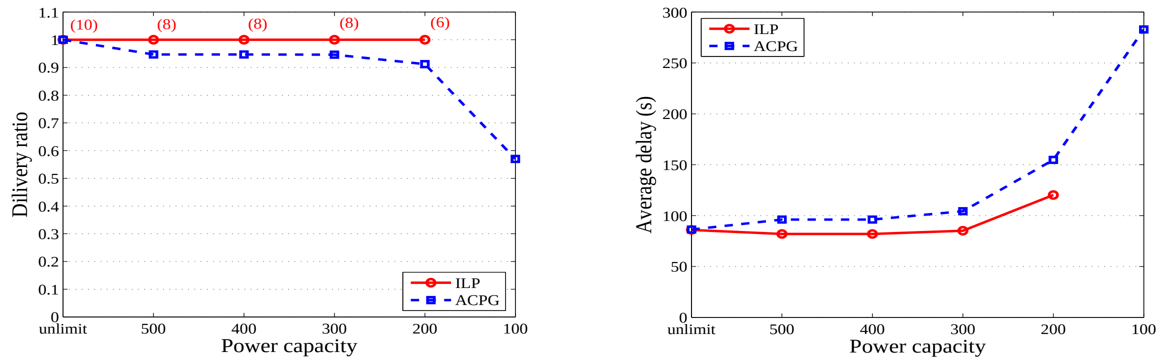
1) Historical information: If the mobility pattern is stable for a long time, the history can tell the future. The most widely used historical information includes:

- Recent trajectory: the geographic locations just visited.
- Average contact duration: the average duration of a contact.
- Average inter-contact duration: the average duration between two contacts. A contact coupled with the next inter-contact interval is called a *period*.
- Last contact time: the last time two nodes contacted.
- Contact frequency (or contact probability): the average contact frequency with another node or a landmark.

Not all the above information is available in a network or related to the mobility pattern. ACPG captures what historical information predicts the future under the current mobility model.

2) Guidance from ACPG: The following properties of routes and node contacts, which are closely related to the underlying mobility pattern, can be captured by ACPG:

- Geographic preference: this is defined as the common feature of geographic locations that the greedy routes prefer. It is useful in geographic-related networks where nodes prefer certain geographic areas, or in landmark-based networks where nodes visit some landmarks often.
- Contact periodicity: this describes whether any pair of nodes have periodic contacts. Two nodes may have



(a) Delivery ratio.

(b) Average delay.

Fig. 3. Comparison of ILP and ACPG.

strict/weak contact period with fixed/variable contact and inter-contact durations. This periodicity may not last for the whole network lifetime.

- Inter-contact time distribution: e.g., uniform or exponential distribution. It can be obtained through curve fitting.
- Contact probability: the contact probability with another node or one landmark in a certain time interval.

3) Predict the future: After ACPG characterizes the mobility pattern, it suggests what historical information can be used for prediction.

- If the guidance exhibits geographic preference, a node can use it to determine whether to forward packets to a neighbor or not. For example, if the current neighbor will travel to a location which is preferred in ACPG with high probability, then it is qualified to be the next relay.
- If mobility shows contact periodicity, we can utilize the average contact duration and average inter-contact duration to estimate the future periods using linear prediction, and utilize the last contact time to estimate the next contact time with high accuracy.
- If the inter-contact time follows some well-known distribution, then the last contact time can be used to predict whether a node is approaching or departing away from another node. Several models have been exploited in [12].
- If a node contacts another node or landmark with a certain probability, the future contacts may be modeled as a semi-markov process as described in [4].

In summary, ACPG connects history and future through proper information selection and prediction. Hence, efficient PASR can be instantiated following this procedure. Please refer to our technical report [19] for more details.

B. Instantiating PASR

We next describe how to instantiate PASR for different mobility models. For illustration, we consider three mobility models in an underwater sensor network. This network consists of 3 layers and 15 nodes in each layer (in addition, the surface layer has one sink in the middle). Each layer covers a $800m \times 800m$ square area and the distance between two adjacent layers is $40m$. Each node has a buffer of 100 packets, a transmission range of 50m and a transmission rate of 50 packets per second. The power capacity varies from 300 to 30 transmissions, and the slot duration is 10 seconds.

B.1. UWSN in Regular Currents

The first mobility model we investigate assumes all nodes in the network float with the regular currents following equation (1) with $k_4 = k_5 = 0$. We first obtain guidance about the underlying mobility pattern from ACPG, then propose a PASR protocol accordingly.

1) Guidance from ACPG: Since our network consists of three layers which can be treated as three geographic areas and nodes move with regular currents, we focus on two properties: geographic preference and contact periodicity.

The geographic preference in this network means nodes in which layer are preferred. Results from ACPG show that most nodes highly prefer forwarding packets to an upper layer node directly even when having previous contacts with many nodes in the same or lower layers. Thus we obtain the first guidance: an upper layer node is more preferred than other layer nodes.

The contact periodicity for a pair of nodes is declared if a certain contact period repeats more than 4 times within 150 slots. We find that more than 80% of pairs observe periodicity with various period duration. This leads to the second guidance: nodes have varying periodic contacts. We shall note that ACPG only indicates periodicity, the period durations for different pairs are different.

2) Protocol following ACPG: Based on the above guidance, we propose a specific PASR for this network, *energy efficient history prediction assisted routing* (EEHPA). This scheme includes two essential operations: *prediction update* and *per-contact forwarding decision*.

For the prediction, each node u maintains its own prediction vector (PV), which is a vector of tuples (i,v,D_v), where i is the prediction slot, v is the best relay in this slot and D_v is the expected delay through this relay to the sink. PV is recursively updated through the neighbors' PVs and the predicted future contacts with these neighbors. Since the guidance indicates weak periodicity, we choose the previous two periods (two contact durations and two inter-contact durations) to estimate the future periods using linear prediction. PV, when its value changes, can be piggybacked to the *hello* message at the beginning of each slot and the update is not frequent owing to the sparse connectivity in DTNs.

Forwarding decisions are made based on the PV and the guidance from ACPG every time a node encounters neighbors. Since results from ACPG indicate that few nodes forward packets to a lower layer, we only allow forwarding to nodes in the upper or the same layer for simplicity. We take node u to illustrate the decision. When u contacts v, it searches its PV for the expected delay D_v through v and the minimum expected delay $D_{v'}$ through the predicted best relay v'. Then node u makes positive forwarding decisions to v under two conditions: (1) $D_v \in [D_{v'}, D_{v'} + \delta_1)$; and (2) $D_v \in [D_{v'} + \delta_1, D_{v'} + \delta_2]$ and node v is in the upper layer. The parameters δ_1 and δ_2 are called *prediction error tolerances*, whose values are small with accurate predictions or large otherwise.

B.2. UWSN in Currents with Randomness

The second mobility model we exploit involves random movements by following equation (1) with non-zero k_4 and k_5. The randomness models the impact from environment, which may lead to estimation errors and prediction errors in real systems. PASR can tolerant these errors to some extent since ACPG just captures the general properties of the majority of nodes, who exhibit similar mobility patterns. In this setting we still use EEHPA.

B.3. UWSN in Irregular Currents

The last mobility model incorporates irregular currents which will significantly change the underlying mobility pattern. Through this setting, we can evaluate whether ACPG discovers this change and react correspondingly.

We assume that nodes in the first two layers will be affected by an irregular water current, which drifts nodes away from the center of the network area. The nodes affected switch between the regular current and irregular current every 10 seconds. To provide connectivity to the sink, one node is anchored in the middle of the first two layers, which are not affected by the irregular current.

After executing ACPG in a training period under this mobility, we find that, affected by the irregular current, most nodes in the bottom layer route packets to the center area through nodes in the same layer to take advantages of anchor nodes. We also notice that only the nodes in the same layer have contact periodicity. Thus we obtain the following two guidance from ACPG: (1) a node in the same layer is preferred; and (2) only predict for nodes in the same layer.

Therefore, we modify EEHPA to obtain a new PASR, named iEEHPA, according to the new guidance. In iEEHPA, we adopt the techniques and operations in EEHPA, but only predict future contacts for nodes in the same layer in the prediction update phase, and prefer nodes in the same layer in the forwarding decision phase.

C. Performance Evaluation

To evaluate the performance of the instantiated PASR protocols described eariler, we allow nodes in the bottom layer randomly generate 300 packets from the 500th second with the total generation rate of one packet per second. Due to the limited space, we focus on single-copy schemes and use Epidemic routing as a reference for multi-copy schemes. In each mobility model, we compare instantiated PASR protocols with the following schemes:

- ACPG: serves as the lower-bound.
- EEPA: *energy efficient prediction assisted* routing. It differs from EEHPA by precise predictions using the deterministic terms in equation (1). This is an idealized scheme for UWSN since we do not know the precise mobility model in practice.
- First Contact (FC): The single-copy routing by forwarding packets to the first node encountered without any prediction [2], [9]. If multiple nodes are contacted at the same time, one in the upper layer is preferred.
- Epidemic: a flooding based scheme [1]. To save energy, we allow epidemic ACK to be broadcasted through the network, which is used to delete useless copies.

To compare performance, we adopt the following metrics:

- Delivery ratio: the ratio of packets delivered.
- Average delay: the average delay for all delivered packets.
- Average energy consumption: the average number of transmissions needed to successfully deliver a packet.

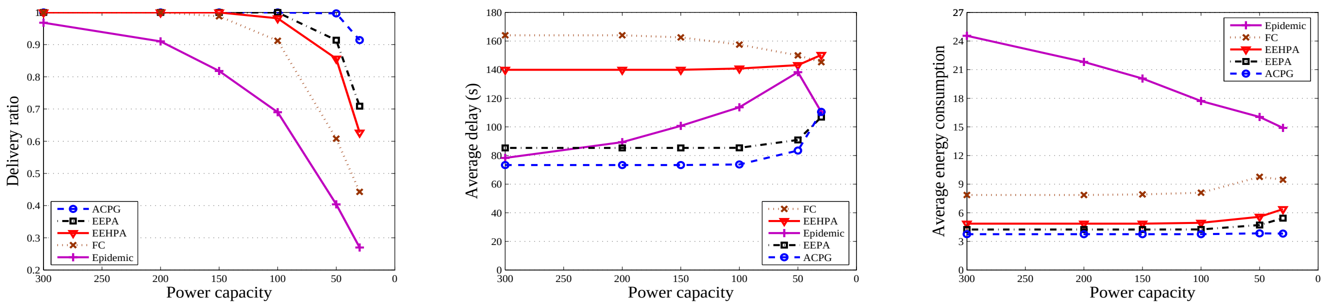
We compare various routing schemes in Fig. 4. When the network resources change from loosely to stringently constrained, it is not surprising to see that the delivery ratio of Epidemic drops rapidly to 0.3 when the power capacity is 30. This is because Epidemic uses too much energy during the flooding as shown in Fig. 4(c) and exhausts sensors quickly. This indicates that Epidemic is not suitable for resource constrained networks. Meanwhile, FC performs better than Epidemic with higher delivery ratio, but it degrades quickly especially from the power capacity 100 to 30 since the aimless forwarding not only delays the packets, but also wastes energy. ACPG provides the best results under all criteria. With the guidance from ACPG, the performance of both EEPA and EEHPA approaches the results of ACPG. It is interesting to notice that EEHPA only causes a slightly higher delay than EEPA since its prediction based on historical information is not as precise as EEPA. Moreover, it is noticed that the average delay for all delivered packets increases when the power capacity becomes constrained. This is because the network is even sparser when nodes die owing to the restricted power capacity, causing very long delays for some packets.

We also demonstrate that EEHPA can tolerant large randomness under the second mobility model and the modified iEEHPA outperforms other schemes significantly in the third irregular currents mobility model. This indicates that the PASR protocols are mobility cognizant and suitable for various underlying mobility models based on guidance from ACPG. Please refer to our technical report [19] for more details.

V. Related Work

Deterministic routing is applicable to DNTs when complete information is available. Merugu *et. al.* build a space-time graph to select routing paths using dynamic programming and shortest path algorithm [20]. Jain *et. al.* formulate a linear programming problem upon the availability of all knowledge oracles [2].

In most networks, it is impossible to obtain complete information in advance, thus only heuristic routing is suitable. Epidemic [1] is a representative multi-copy routing scheme by replicating a packet to any node in the network. To avoid flooding in Epidemic, many other multi-copy schemes propose to limit the number of copies in the network. Spyropoulos *et. al.* present spray and wait [11], in which a certain number



(a) Delivery ratio. (b) Average delay. (c) Average energy consumption

Fig. 4. Performance comparison of various routing schemes in UWSN with regular currents.

of copies of a packet are replicated. Spyropoulos *et. al.* and Xue *et. al.* extend spray and wait with better distribution schemes in [21] and [22] respectively. Lindgren *et. al.* propose PROPHET to limit the number of copies [6], in which a node only forwards a packet to the neighbors who have higher probabilities to reach the packet's destination in a short time. In addition, Jones *et. al.* utilize the contact history to find routes with minimum estimated expected delay [23]. Wu *et. al.* propose a scheme that forwards packets to relays with increasing utility [14]. Wang *et. al.* study the tradeoff between data deliver ratio/delay and transmission overhead theoretically, and an efficient data delivery scheme using nodal delivery probability as the forwarding criteria [24].

Only few studies focus on single-copy routing. Spyropoulos *et. al.* discuss several basic single-copy routing protocols in [9]. Yuan *et. al.* present predict and relay based on the prediction of the probability distribution of future contact times [4]. They assume nodes only move around a set of landmarks following a time-homogeneous semi-markov model.

VI. Conclusions and Future Work

In this paper, we present a generic scheme prediction, assisted single-copy routing (PASR), for UWSNs. We first propose ACPG, which is a greedy algorithm that provides results close to optimal and characterizes the properties of the underlying mobility pattern. We then design online heuristic protocols by choosing appropriate historical information and forwarding criteria based on the guidance from ACPG. We investigate an UWSN with various mobility patterns and randomness using two instantiated PASR schemes, EEHPA and iEEHPA. Simulation results show that ACPG captures the properties of various mobility patterns and provides corresponding guidance, and the instantiated PASR schemes outperform others.

As future work, we will pursue the following three directions: (1) compare our schemes with other multi-copy schemes and study the tradeoffs between using single copy and multiple copies, (2) explore more mobility prediction technologies suitable for underwater sensor networks, and (3) examine PASR under different mobility models.

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