Message Ferrying for Constrained Scenarios

Ramesh Viswanathan and Jing (Tiffany) Li[1]
Electrical and Computer Engineering Dept
Lehigh University, Bethlehem, PA 18015
Email: {rav7, jingli}@ece.lehigh.edu

Mooi Choo Chuah
Computer Science and Engineering Dept
Lehigh University, Bethlehem, PA 18015
Email:mcc7@lehigh.edu

***Abstract*— Message ferrying (MF) [2], a viable solution for routing in highly partitioned ad-hoc networks, exploits message ferries to transfer packets between disconnected nodes. This paper studies the delivery quality of service (QoS) for certain urgent messages in the constrained and the relaxed constrained MF systems. Efficient algorithms to compute near-optimal ferry routes are proposed, delay analysis is conducted and the results are compared to the non-constrained scenario.**

***Index Terms*— Message Ferrying Scheme, Disconnected Networks, Sparse Sensor Networks, Traveling Sales Man Problem, Routing, Ad-hoc Networks**

I. Introduction

One existing challenge in mobile communication is to maintain communication links between participating mobile entities. Due to network partitioning, entities may get isolated from network for an unpredicted time. This raises the question of how data can be delivered in a constantly disconnected network. A number of schemes have been proposed to provide communications in highly partitioned networks (e.g. [1][2]).

Message Ferrying (MF) scheme is proposed in [2], where a single or a set of mobile devices called "message ferries" take the responsibility of carrying messages between disconnected nodes. Other network entities called regular node act as a message sources and sinks. MF scheme is a promising candidate in a number of practical applications (e.g.[3]). In non-real time application, it is useful to provide different message delivery services similar to the regular and express mail features offered by the post office. Thus, here we consider two message types: urgent and regular messages. In the constrained scenario (CS), we request that a ferry delivers the urgent messages to the destination immediately after picking them up from the source. In the relaxed constrained scenario (RCS), we allow the urgent messages to be delivered within a certain deadline but not necessarily right after they are picked up.

In section II, we propose our network model. In section III, we discuss in detail how ferry route is determined for the CS and RCS case. Experiment results are discussed in section IV. In section V, we summarize our results.

II. Network System Model

We define hotspot (HS) nodes as regular nodes with the constraint that the HS receiver must be visited shortly after visiting the HS sender. Such a constraint may arise due to delivery deadlines for certain urgent messages or huge packet transfer. The following assumptions are used in the study:

[1]Supported by National Science Foundation under Grant No. CCF-0430634, and by the Commonwealth of Pennsylvania, Department of Community and Economic Development, through the PITA program.

• Regular nodes are stationary, isolated, and randomly distributed in a given region with a single ferry. • The ferry exchanges packets with any regular node only once in each trip and keeps repeating the trip. • Wireless communication range of the ferry or a regular node is negligible compared to the distance between any pair of regular nodes. • Packets are generated at a constant rate. Except for HS sender(s), all other packets are randomly destined across the network. • All packets are of equal size. The wireless link between the ferry and regular nodes are uplink-downlink symmetric, stable and homogeneous for all regular nodes. • No buffer space limitation at the ferry.

III. Ferry Route Design

A. Notations and Problem Formulation

Our goal is to design efficient routes for the ferry such that the average delivery time for all packets is minimized while meeting certain special QoS requirement.

Let $\mathbb{S} = \{1, 2, \cdot, n\}$ denote the set of regular nodes. A ferry route can be mathematically described as an optimized permutation of the regular nodes, $\pi : \pi(1), \pi(2), \cdots, \pi(n)$, where $\pi(i)$ stands for the order at which node i is being visited.

The following notations will be used in the discussion:

- $d_{i,j}$: Distance between a pair of regular nodes i and j.
- v: Ferry's traveling speed.
- w: A single packet transfer time between Ferry and a node.
- $P_{i,j}$: Number of packets destined to node j from node i in a given ferry trip.
- C_i: Total packet collecting time at node i.
- D_j: Total packet dumping time at node i.
- $T_{i,j}$: Ferry's travel time between nodes i and j (including time spent exchanging packets at intermediate node(s)).
- $Q_{i,j}$: Delivery time for an average packet generated by node i to arrive at its destination node j.

Clearly, the packets generated by node i is given by $\sum_j P_{i,j}$ and the packets destined to node j is given by $\sum_i P_{i,j}$. We have

$$C_i = w \sum_j P_{i,j}, \quad D_j = w \sum_i P_{i,j}. \tag{1}$$

Due to the assumption that packets are generated at a constant rate and distributed randomly, $C_i \approx E[C_i]$, $D_j \approx E[D_i]$, and $E[C_i] = E[D_i] = \bar{C}$, where $E[\cdot]$ denotes the statistical mean.

For a given trip using route π, let $\pi^{-1}(k)$ denote the node ID that is visited at order k, where $k = 1, 2, \cdots, n$. For notational convenience, let $\pi^{-1}(n+k) = \pi^{-1}(k)$. The travel time between all pairs of nodes can be efficiently computed as follows ($k = 1, \cdots, n$, $m = 2, \cdots, n-1$):

$$T_{\pi^{-1}(k),\pi^{-1}(k+1)} = \frac{d_{\pi^{-1}(k),\pi^{-1}(k+1)}}{v}, \quad (2)$$

$$T_{\pi^{-1}(k),\pi^{-1}(k+m)} = T_{\pi^{-1}(k),\pi^{-1}(k+m-1)} + C_{\pi^{-1}(k+m-1)} + D_{\pi^{-1}(k+m-1)} + T_{\pi^{-1}(k+m-1),\pi^{-1}(k+m)}. \quad (3)$$

To minimize the delivery delay and to save buffer, upon arrival at any regular node, the ferry will dump the packets that are destined to it before collecting new packets. Since packets are dumped and collected sequentially at a constant rate of $1/w$ packets per second, the average delivery time for a packet addressed from node i to node j is given by

$$Q_{i,j} = \frac{C_i}{2} + T_{i,j} + \frac{D_j}{2}, \quad i=1,\cdots,n,\ j=1,\cdots,n. \quad (4)$$

The cost function, $\mathcal{C}_\Pi$, for a given route, Π, is defined as the average delivery time, averaged over all packets, all senders and all receivers:

$$\mathcal{C}_\pi = E\left[\frac{\sum_{i,j} Q_{i,j} P_{i,j}}{\sum_{i,j} P(i,j)}\right], \quad (5)$$

where the expectation is taken over many rounds of MF trips. By weak law of large number (WLLN), the average over a large number of repeated experiments converges unbiasedly to the true statistical mean. In the following subsections, we discuss different scenarios with the same network topology.

B. The Non-Constrained Scenario (NCS)

The NCS case does not impose any constraint in the MF system. This model will serve as a reference to compare and to evaluate our proposed models.

Since no nodes or packets have priority over others, the design strategy targets minimizing the average delivery delay:

$$\min_\pi \ \mathcal{C}_\pi, \quad \Longrightarrow \quad \min_\pi \ E\Big[\sum_{i,j} Q_{i,j} P_{i,j}\Big]. \quad (6)$$

Due to the uniform randomness, $E[P_{i,j}]$ is a constant for all pairs (i,j), where $i \neq j$, and so are $E[C_i]$ and $E[D_j]$. Hence, equation (6) becomes

$$\min_\pi \ \sum_{k=1}^{n} T_{\pi^{-1}(k),\pi^{-1}(k+1)}, \quad (7)$$

We use heuristic algorithms for the Traveling Salesman Problem (TSP) to find ferry's shortest route. Here we adopt the Lin-Kernighan heuristic (LKH) algorithm [4], [5]. After finding an efficient route using LKH algorithm, we further optimize it using the delay-based 2-opt technique [5].

C. Constrained Scenario (CS)

In the CS case, a large number of urgent messages need to be delivered faster than regular messages from a HS sender to a HS receiver. The simplest way to achieve this QoS is to require that the ferry visit the HS receiver immediately after visiting the HS sender. Let s and r denote HS sender and receiver node ID respectively. We have the following optimization problem:

$$\min_{\pi:\pi(s)=\pi(r)-1} \mathcal{C}_\Pi, \quad \Longrightarrow \quad \min_{\pi:\pi(s)=\pi(r)-1} \sum_{k=1}^{n} T_{\pi^{-1}(k),\pi^{-1}(k+1)}. \quad (8)$$

Again, the TSP algorithm is exploited to determine the best ferry route but with modifications. Since HS nodes are visited immediately after one another, we replace both nodes by a virtual node whose coordinates are the midpoints of HS nodes. This newly generated virtual node along with all other regular nodes serve as an input to the TSP algorithm. After we obtain the shortest path route for the reduced topology, we expand the virtual node into two HS nodes.

D. Relaxed Constrained Scenario (RCS)

In the RCS case, we grant ferry the liberty of visiting a set of nearby regular nodes, termed the HS neighbors, on its way of delivering urgent messages. Such a relaxation of constraint presents a better means of meeting QoS requirement for HS nodes while keeping down the delay for regular nodes.

Assume an $\alpha\%$ of relaxation in the delivery deadline for urgent messages from HS sender s and HS receiver t, the constraint optimization problem can be formulated as

$$\min_\pi \quad \sum_{k=1}^{n} T_{\pi^{-1}(k),\pi^{-1}(k+1)}, \quad (9)$$

$$\text{subject to:} \quad Q_{s,t} \leq T_{th} = (1+\alpha\%)\frac{d_{s,t}}{v}$$

Given the relaxation in delivery deadline, the main design concern is the selection of the HS neighbors. We propose adaptive technique to search for the best HS neighbors. The algorithm starts with a relatively loose neighbor window around the HS nodes with an initial window width:

$$\theta = \min\left(d_{s,t}, \sqrt{v^2 T_{th}^2 - d_{s,t}^2}\right). \quad (10)$$

The window size is reduced successively until no more HS neighbors can be included without violating the QoS constraint. A concise summary of the algorithm is provided in Table I. We conducted experiments with different window shapes, including rectangle, parallelogram, and elliptical shapes. We observe that for a randomly picked HS pair, all three shapes lead to about the same neighbor set with no fundamental difference. Figure 1 presents an optimized route for a HS pair $(42, 17)$ for the CS and the RCS cases. Figure 2-Left illustrates the successive window search approach.

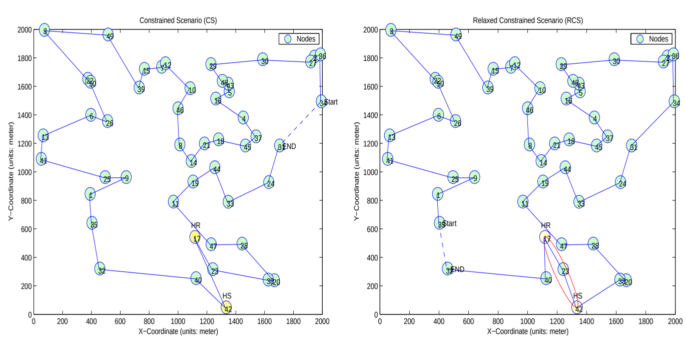

Fig. 1. Ferry route in CS and RCS case.

IV. Preliminary Experimental Results

Below we present experimental results on the MF performance for different cases. We consider $n = 50$ regular nodes randomly distributed in a rectangular area of size 2000m $\times$ 2000m. A single ferry traveling at a speed of $v = 30$ m/s. In each ferry round, all regular nodes generate $400 \pm 5\%$ packets.

TABLE I

FERRY ROUTING FOR THE RELAXED CONSTRAINT SCENARIO

Notations:	
	Regular nodes: $\mathcal{S} = \{1, 2, \cdots, n\}$
	Hotspot nodes: sender s, receiver t, $(s, t \in \mathcal{S})$
	Delivery constraint for urgent messages: T_{th}
Rout A: Within the Hotspot Neighborhood:	
[1]	Use (10) as the window width and determine the initial neighbor set.
[2]	Use the TSP algorithm to compute a directed and open shortest path π^* for the neighbor set that starts from the HS sender and ends at the HS receiver.
[3]	Compute the average $Q_{s,t}$ using (2),(3) and (4) by substituting $\bar{C}$ for C_i and D_i.
[4]	Compare $T_{s,t}$ with the time constraint T_{th}. If $T_{s,t}$ is smaller, declare the nodes in the window as HS neighbors and report π^* as the ferry route in the HS neighbor. Other wise, decrease the window width by excluding one (farthest) node from the neighborhood set, and goto [2].
Rout B: Outside the Hotspot Neighborhood:	
[5]	Replace the HS nodes and their neighbor set in one virtual node whose coordinates are the center of the neighborhood window. Find a closed-loop shortest route for this virtual node and other regular nodes.
The Complete Ferry Route:	
[6]	Insert Route A in the place of the virtual node in Route B to obtain the compete ferry route.
[7]	It is also possible to further conduct 2-opt swap to optimize the route around the HS area, provided that the $T_{s,t}$ remains smaller than T_{th}.

A constant packet transfer time of $w = 0.01$ msec/packet is used and thus $\bar{C} = E[C_i] = E[D_j] = 4$ msec.

In the experiment, we randomly pick a pair of HS nodes, and allot 80% of the packets generated at the HS sender to the HS receiver and the remaining 20% randomly to the rest of $n-2$ regular nodes. For all other nodes, packets are destined randomly but uniformly. In the RCS case, the delivery constraint for the urgent messages is set to be 60% more than the cost for a direct link ($\alpha = 60$). Typically after 2 or 3 rounds of ferry trips, the MF system enters a steady state.

A. Delay Analysis

The cost function in (5) provides the average packet delay, averaged over all network nodes and all packets. Let $\mathcal{H} = \{(s_1, t_1), (s_2, t_2), \cdots\}$ denote all the HS pairs. The average packet delay for urgent messages can be computed using:

$$\mathcal{C}_{\pi,\text{urgent}} = E\left[\frac{\sum_{(i,j)\in\mathcal{H}} Q_{i,j} P_{i,j}}{\sum_{(i,j)\in\mathcal{H}} P(i,j)}\right], \qquad (11)$$

and the average packet delay for all other regular messages can be computed using:

$$\mathcal{C}_{\pi,\text{non-urgent}} = E\left[\frac{\sum_{(i,j)\in\mathcal{H}^c} Q_{i,j} P_{i,j}}{\sum_{(i,j)\in\mathcal{H}^c} P(i,j)}\right], \qquad (12)$$

where $\mathcal{H} = \mathcal{S} \times \mathcal{S} - \mathcal{H}$ denotes the complementary of $\mathcal{H}$, and $\mathcal{S}$ is the set of all nodes.

We have conducted extensive experiments with different node distribution and hotspots to find the average behavior and performance of the system. Figure 2-Right, 3-Left and 3-Right plot the packet delay for the hotspot nodes, the other nodes and all the nodes, respectively, for one specific example of network topology and hotspot designation using the NCS,

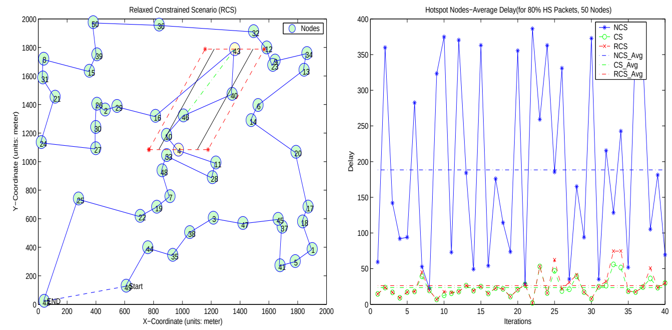

Fig. 2. Left: Window search. Right: Packet delay for Hotspot nodes.

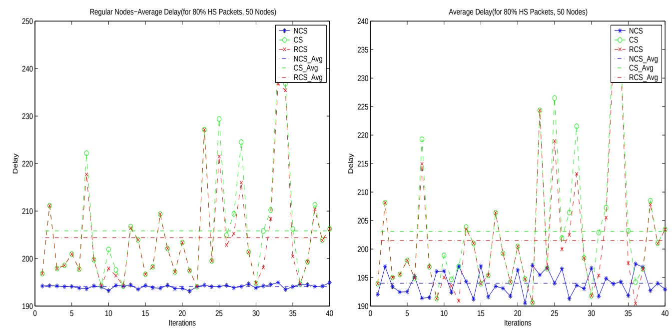

Fig. 3. Packet delay for non-hotspot nodes (Left) and all nodes (Right).

CS and RCS routing. The simulation is repeated for 40 ferry rounds and the average delay values are also plotted. Clearly, we see that the NCS routing targets the overall packet delay and hence provides the shortest global route, at the cost of huge (unsatisfactory) delay between the HS nodes. The CS and RCS routing, on the other hand, trade the global optimality for a considerable improvement of the local QoS.

V. CONCLUSION

We have extended the MF concept for partitioned networks to constrained scenarios. After presenting the base approach using the results from the traveling salesman problem, we discuss how ferry routes can be designed to satisfy the delay constraint for certain hotspot nodes. Simulations and delay analysis show that the proposed strategies are effective with urgent messages enjoying much better delay performance at the expense of a moderate increase in the delivery time of regular messages. Future works could consider finite ferry buffer, wireless communication range and multiple ferries.

REFERENCES

[1] Q. Li and D. Rus, “Sending messages to mobile users in disconnected ad-hoc wireless networks,” MOBICOM, August 1989.

[2] Wenrui Zhao and Mostafa H. Ammar, “Message Ferrying: Proactive Routing in Highly-Partitioned Wireless Ad Hoc Networks,” Proceedings of the IEEE Workshop on Future Trends in Distributed Computing Systems, Puerto Rico, May 2003.

[3] A. Pentland, R. Fletcher, and A. Hasson, “DakNet: Rethinking Connectivity in Developing Nations,” IEEE Computer Society, 2004.

[4] J. Bentley, “Fast algorithms for geometric traveling salesman problems,” ORSA Journal on Computing, 4:387-411, 1992.

[5] K. Helsgaun, “An Effective Implementation of the Lin-Kernighan Traveling Salesman Heuristic,” DATALOGISKE SKRIFTER (Writings on Computer Science), No. 81, 1998, Roskilde University.