Analysis of Message Delivery Delay in Geographic DTN Routing

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***Abstract*—In this paper, we derive the average message delivery delay in a geographic DTN routing with multiple mobile agents, whose mobility patterns are given by random walk on a graph and message routing algorithm is the Random algorithm. A geographic DTN routing aims at realization of message delivery among multiple (generally, geographically-dispersed) geographic locations on a field without necessity of specific communication infrastructure by utilizing mobility of mobile agents. We model the behaviors of mobile agents as multiple random walks on a graph. Our analysis reveals the effect of system parameters — the number M of mobile agents on the field and the number K of message loads at a geographic location — on the average message delivery delay.**

I. Introduction

In this paper, we derive the average message delivery delay in a geographic DTN routing, where every mobile agent moves according to random walk on a graph and loads/unloads messages at visiting geographic locations using Random algorithm.

A geographic DTN routing aims at realization of message delivery among multiple (generally, geographically-dispersed) *geographic locations* on a field without necessity of specific communication infrastructure by utilizing mobility of *mobile agents*. On the field, there exist multiple geographic locations (i.e., fixed nodes) and mobile agents (i.e., mobile nodes), and messages are transferred among geographic locations using store-carry-and-forward operations of mobile agents.

In the literature, fundamental characteristics of geographic DTN routing with five routing algorithms (Random, Nearest, Farthest, Distant and AOD (Angle Of Deviation)) have been studied through simulation experiments [1].

In this paper, we derive the average message delivery delay of geographic DTN routing with Random algorithm by modeling the behaviors of mobile agents as multiple random walks on a graph. Our analysis reveals the effect of system parameters — the number M of mobile agents on the field and the number K of message loads at a geographic location — on the average message delivery delay.

The organization of this paper is as follows. Section II briefly explains the concept of geographic DTN routing and Random algorithm. Section III describes our analytic model used throughout this paper. Section IV derives the average message delivery delay by modeling mobile agents' behaviors as multiple random walks on a graph. Section V concludes this paper and discusses future works.

II. Geographic DTN Routing and Random Algorithm

In this section, we briefly explain the concept of geographic DTN routing. Refer to [1] for more detailed description.

A geographic DTN routing aims at realization of message delivery among multiple (generally, geographically-dispersed) *geographic locations* on a field without necessity of specific communication infrastructure by utilizing mobility of *mobile agents*. There exist multiple geographic locations and also multiple mobile agents (i.e., mobile nodes) on the field, and messages are carried by mobile agents for *message* delivery among geographic locations.

Every geographic location generates *messages* destined for other geographic locations. We assume that multiple mobile agents autonomously and irregularly visit geographic locations one and another. A mobile agent can *load* a message at its visiting geographic location, carry multiple messages while it moves, and *unload* one or more carrying messages at its visiting geographic location.

There exist a huge number of possible geographic DTN routing algorithms depending on the combination of various factors: message generation patterns and buffer sizes of geographic locations, mobility, mobility controllability, buffer sizes of mobile agents, type and capacity of wireless communications between a geographic location and a mobile agent, and availability of positional information of mobile agents (e.g., GPS (Global Positioning System)).

In this paper, we focus on a case where people carrying portable devices such as smartphones autonomously move among geographic locations. Therefore, we assume that mobile agents' mobility are uncontrollable (i.e., a geographic DTN routing algorithm has no control over people's mobility), and the capacity of wireless communication is limited (i.e., the bandwidth for message transfer between a geographic location and a portable device is finite). On the contrary, we assume that the buffer sizes of geographic locations and mobile agents (e.g., portable devices) are sufficiently large. We also assume that the positional information of mobile agents are available to a geographic DTN routing algorithm.

Geographic DTN routing algorithms can be roughly classified by their *message loading* mechanism (i.e., how messages are copied/moved from *a geographic location*) and *message unloading* mechanism (i.e., how messages are copied/moved from *a mobile agent*).

In this paper, we focus on the simplest algorithms, Random algorithm, which should be the baseline for other complex geographic DTN routing algorithms.

Random algorithm is the minimal and the simplest algorithm, which randomly performs both message loading and message unloading. When mobile agent m visits geographic location v, the number K of messages are randomly chosen from the buffer of geographic location v. Those messages are moved to the buffer of mobile agent m.

If mobile agent m has one or more messages destined for geographic location v in its buffer, those messages are moved to the buffer of geographic location v.

III. Analytic Model

We model the field comprising of multiple geographic locations and paths connecting those geographic locations as an undirected graph $G = (V, E)$ where vertices and edges correspond to geographic locations and paths, respectively. Let A be the adjacency matrix of G, $d(v)$ be the degree of vertex v.

We model mobile agent's behavior in geographic DTN routing as a discrete random walk on graph G. At every slot, mobile agents randomly and synchronously move one of their neighbor vertices in G. Namely, a mobile agent on vertex v at slot k randomly moves to one of neighbor vertices of vertex v with probability $1/d(v)$ at slot $k+1$.

Every mobile agent performs message delivery using Random algorithm. When a mobile agent visits a geographic location, it performs the following operations: (1) randomly moves the number K of messages from geographic location' buffer to mobile agent's buffer (message loading), and (2) moves, if any, all the messages destined for the current geographic location from mobile agent's buffer to geographic location's buffer. In our analysis, it is assumed that the buffer of mobile agents are sufficiently large.

In this paper, we focus on geographic DTN routing with the number M of mobile agents. The starting vertex of mobile agent m at the initial state ($k = 0$) is denoted by s_m. We assume that, at the initial state, all messages are initially placed in the buffers of their originating geographic locations. Namely, no additional message is generated at $k > 0$. Let $n_{u,v}$ be the number of messages generated at u and destined for v. Let $n_u\,(\equiv \sum_{v\in V} n_{u,v})$ be the total number of messages stored at geographic location u.

IV. Analysis

First, we focus on the case with a single mobile agent ($M = 1$).

Hitting time, which is the expected number of slots for mobile agent starting its random walk from vertex s to reach vertex t at first, is given by the following equation [2].

$$H(s,t) = 2\,|E| \sum_{k=2}^{|V|} \frac{1}{1-\lambda_k} \left(\frac{v_{k,t}^2}{d(t)} - \frac{v_{k,s}\, v_{k,t}}{\sqrt{d(s)\, d(t)}} \right)$$

where λ_k and $v_{k,i}$ are k-th eigenvalue of $N = D^{1/2}\, A\, D^{1/2}$ ($\lambda_1 = 1 > \lambda_2 \ldots \lambda_{|}V|$) and i-th element of k-th eigenvector corresponding to λ_k. D is the diagonal matrix with diagonal entries $1/d(1) \ldots 1/d(|V|)$.

For delivery of a message from geographic location u to geographic location v, the following three conditions must be satisfied: (1) the mobile agent starting its random walk at $k = 0$ arrive geographic location u, (2) a message destined for geographic location v is loaded (i.e., chosen by Random algorithm) by the mobile agent, and (3) the mobile agent delivers the message to geographic location v. Hence, the average massage delivery delay from geographic location u to geographic location v is given by

$$D_{u,v} = H(w,u) + \sum_{i=1}^{\infty} p_{u,v}(i)\,(i-1)\,R_u + H(u,v),$$

where $p_{u,v}(i)$ is the probability that a message destined for geographic location v is loaded at the i-th visit of geographic location u. Also, R_u is the mean recurrence time at geographic location u (i.e., the expected number of slots between two successive arrivals of the mobile agent at geographic location u). Then,

$$u, v | u \neq v, n_{u,v} > 1.$$

With Random algorithm, the mobile agent visiting at geographic location u moves (at most) the number K of messages randomly chosen from available messages at the buffer of geographic location u. So, we have:

$$p_{u,v}(i) = \begin{cases} \frac{K}{n_u} & \text{if } i\,k \leq n_u \\ \frac{\max(n_u-(i-1)\,K,0)}{n_u} & \text{otherwise} \end{cases} \qquad (1)$$

Since the visiting probability of the mobile agent at geographic location u is given by $\frac{d(u)}{2\,|E|}$, the mean recurrence time R_u is given by its reciprocal; i.e., $R_u = \frac{2\,|E|}{d(u)}$.

Second, we consider the case with multiple mobile agents ($M > 1$).

Let $H^M(\{s_1, \ldots, s_M\}, v)$ be the hitting time of multiple random walks (i.e., the expected number of slots for any of M mobile agents starting their independent discrete random walks from vertices $s_1, \ldots, s_M$ to reach vertex v at first). It is known that the hitting time of M random walks on graph G can be calculated from the hitting time of a single random walk on another graph $G^M = (V', E')$ [3]. $G^M = (V', E')$ is defined as

$$V' = \{(v_1, \ldots, v_M) | v_1, \ldots, v_M \in V\} \qquad (2)$$

$$E' = \{((u_1, \ldots, u_M), (v_1, \ldots, v_M)) | (u_1, v_1), \ldots, (u_M, v_M) \in E\}. \qquad (3)$$

Let $A_v\,(\subset V')$ be the set of all vertices in G^M, which contain any vertex $v \in V$.

$$A_v = \{(u_1, \ldots, u_M) | (u_1, \ldots, u_M) \in V', \exists i\; u_i = v\} \qquad (4)$$

The hitting time of M random walks, $H^M(\{s_1, \ldots, s_M\}, v)$, is given by the time for a single random walk on G^M starting from vertex $(s_1, \ldots, s_M)$ to arrive at first any of vertices in A_v [3].

Hence, the average message delivery delay from geographic location u to geographic location v is given by

$$D_{u,v} = H^M(\{s_1, \ldots, s_M\}, u) + \sum_{i=1}^{\infty} p_{u,v}(i)\,(i-1)\,R_u + H(u,v).$$

Since R_u is the expected number of slots between two successive arrivals of any pair of M mobile agents at geographic location u, R_u is approximately given by

$$R_u \simeq \frac{\sum_{v\in A_u} H^M(v, A_u \setminus \{v\})}{|A_u|}, \qquad (5)$$

where $H^M(v, S)$ is the time for a single random walk on G^M starting from vertex v to arrive at first any of vertices in S.

V. Conclusion

In this paper, we have derived the average message delivery delay in geographic DTN routing with Random algorithm. We have modeled the behaviors of multiple mobile agents with discrete-and-independent random walks on a graph.

Our future work includes extensive simulations under realistic scenarios to validate our approximate analysis, and extension of our analysis to incorporate more realistic geographic DTN routing such as multiple-copy routing algorithms, geometry-aware routing algorithms, and other mobility patterns than the random walk.

Acknowledgments

This work was partly supported by JSPS KAKENHI Grant Number 25280030.

References

[1] M. Seki, K. Ogura, Y. Yamasaki, and H. Ohsaki, "Performance comparison of geographic DTN routing algorithms," in *Proceedings of the IEEE Signature Conference on Computers, Software, and Applications (Student Research Symposium) (COMPSAC 2015)*, pp. 617–620, July 2015.

[2] L. Lovász, "Random walks on graphs: a survey," *Combinatorics, Paul Erdos is eighty, Keszthely*, vol. 2, pp. 1–46, 1993.

[3] K. Efremenko and O. Reingold, *Approximation, Randomization, and Combinatorial Optimization. Algorithms and Techniques: Proceedings of 12th International Workshop, APPROX 2009, and 13th International Workshop, RANDOM 2009*, vol. 5687, ch. How Well Do Random Walks Parallelize?, pp. 476–489. Springer Berlin Heidelberg, 2009.