Ad Hoc Networks 25 (2015) 430–443

Contents lists available at ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

A delay and cost balancing protocol for message routing in mobile delay tolerant networks

Jingwei Miao [a], Omar Hasan [a,*], Sonia Ben Mokhtar [a], Lionel Brunie [a], Gabriele Gianini [b]

[a] University of Lyon, CNRS, INSA-Lyon, LIRIS, UMR5205, F-69621, France
[b] Dipartimento di Informatica, Università degli Studi di Milano, via Bramante 65, Crema 26013, Italy

ARTICLE INFO

Article history:
Received 19 February 2014
Received in revised form 22 July 2014
Accepted 16 August 2014
Available online 22 September 2014

Keywords:
Mobile
Delay tolerant
Routing
Adaptive
Community

ABSTRACT

The increasing pervasiveness of mobile devices with networking capabilities has led to the emergence of Mobile Delay Tolerant Networks (MDTNs). The characteristics of MDTNs, which include frequent and long-term partitions, make message routing a major challenge in these networks. Most of the existing routing protocols either allocate an unlimited number of message copies or use a fixed number of message copies to route a message towards its destination. While the first approach unnecessarily floods the network, the rigidity of the second approach makes it inefficient from the viewpoint of message replication. Hence, the question that we address in this paper is: "how to dynamically allocate message copies in order to strike a balance between the delay and cost of message delivery?". We present a novel adaptive multi-step routing protocol for MDTNs. In each routing step, our protocol reasons on the remaining time-to-live of the message in order to allocate the minimum number of copies necessary to achieve a given delivery probability. Experiment results demonstrate that our protocol has a higher delivery ratio and a lower delivery cost compared to the state-of-the-art Spray-and-Wait and Bubble protocols.

1. Introduction

Mobile Delay Tolerant Networks (MDTNs) are composed of a set of mobile devices, such as cell phones or sensor units, which can communicate with each other via short range wireless protocols (e.g. Bluetooth). A number of networking scenarios have been categorized as MDTNs, such as Vehicular Ad-hoc NETworks (VANETs) [1] and Pocket Switched Networks (PSNs) [2]. The characteristics of MDTNs include frequent and long-term network partitions which makes message routing one of the major challenges in these networks. In order to deal with the intermittent connectivity between nodes (i.e., mobile devices), message routing in MDTNs is often performed in a "store-carry-and-forward" manner [3], in which a node may store and carry a message for some time before forwarding it to another node [4].

In the literature, a number of routing protocols have been proposed for MDTNs. Nevertheless, most of them are inflexible from the viewpoint of message replication. For instance, flooding-based routing protocols [5], which refers to those protocols that always rely on an unlimited number of message copies to route a message, generate a very large number of redundant message copies. This approach can put undue stress on the limited resources of mobile devices. On the other hand, quota-based routing protocols [6,7] allocate a fixed number of message copies for routing a message. The rigidity of this latter approach makes it inefficient, as a fixed number of message copies cannot suit all routing situations.

* Corresponding author.
E-mail addresses: jingwei.miao@insa-lyon.fr (J. Miao), omar.hasan@insa-lyon.fr (O. Hasan), sonia.ben-mokhtar@liris.cnrs.fr (S.B. Mokhtar), lionel.brunie@insa-lyon.fr (L. Brunie), gabriele.gianini@unimi.it (G. Gianini).

http://dx.doi.org/10.1016/j.adhoc.2014.08.008
1570-8705/

To the best of our knowledge, the adaptability of the number of message copies has been addressed only by a few authors. Bulut et al. in [8], routing is divided into multiple periods. In each period, the source node of a message sprays a certain number of message copies into the network. The source node dynamically chooses the allocation of message copies at the beginning of each period, until the message is delivered to the destination node or the Time-To-Live (TTL) expires. The protocol presented by Bulut et al. assumes that all nodes move under the same mobility pattern in a given network space. However, the reality is different. Recent studies [9–11] on the spatial characteristics of human mobility from real world traces demonstrate that humans in real-life tend to roam in smaller sub-regions rather than the whole network space. In addition, the allocation of message copies in [8] relies on the assumption that the source node is aware of the successful delivery of a message at any given instant. However, such an assumption rarely holds in reality, due to the frequent and long-term network partitions faced by MDTNs.

Moreover, Lo and Lu in [12] proposed a routing protocol, named dynamic congestion control based routing. In [12], message replication is controlled by the congestion level (i.e., light load, moderate load and heavy load). In the case of a light network load, the protocol increases the copies of a message by adding a fixed number of replicas. In the case of a moderate load, the protocol decreases the copies of a message. In the case of a heavy load, the protocol does not replicate a message and simply forwards the message to an encountering node.

Thompson et al., in [13], proposed a protocol to deal with congestion in DTNs. The protocol adjusts the replication rates at individual nodes according to the number of message copies in the network and the buffer capability of individual nodes.

In this paper, we present a novel routing protocol in MDTNs, called the Community-based Adaptive Spray (CAS) routing protocol. The goal of this protocol is to allocate the minimum number of message copies for a message while still achieving a high delivery ratio. Our protocol exploits the community structure of human networks. A community is defined as a set of nodes which frequently co-exist and encounter (see Section 3.1). It has been demonstrated in the literature that nodes in a MDTN often form such structures [14].

Our protocol is composed of two major parts. First, a sub-protocol responsible for gathering mobility information about nodes upon encountering each other. This sub-protocol aims at learning/synchronizing the topologies of communities in the network. Second, a sub-protocol responsible for the routing process. Routing is organized around the notion of gateways between communities. Specifically, a gateway towards a community *C* is the node in a given community that has the highest probability to encounter any node in *C*. To route a message towards a given destination node, the source of a message uses the community topology to pre-compute the multi-hop path that traverses the minimal number of communities through their gateway nodes and that has the highest delivery probability. Furthermore, once the routing process is engaged, our routing protocol allocates a given number of message copies at each hop depending on the remaining TTL of the message. The urgency of delivering a message rises as the TTL of the message approaches expiration. The CAS protocol raises the number of message copies in the network in proportion to the remaining TTL in order to increase the probability of message delivery before time runs out. This strategy keeps the number of message copies in the network low while achieving a high delivery ratio.

The contributions of this paper are twofold:

- We propose a novel routing protocol that dynamically allocates message copies according to the remaining TTL of each message.
- The analysis of our protocol shows that it is the generalization of many existing protocols including Direct [15], Epidemic [5], Spray-and-Wait [7], and some community based routing protocols [16]. By generalization, we mean that our protocol can dynamically decide to behave like one of these algorithms in order to better suit the current situation.

This paper is a considerably extended version of our previous work [17]. The major additions to the current paper include the following. First, we demonstrate that our routing protocol can represent a class of routing protocols. Second, we present new experiments to evaluate the performance of our protocol. Additionally, we have also developed an analytical model to compute the cover time of the topology of communities. The details of the analytical model are presented in an extended technical report [18].

The remainder of the paper is organized as follows. Section 2 discusses related work on routing in MDTNs. In Section 3, we introduce the system model and the information maintained by each node. In Section 4, we describe our proposal in detail. The simulations and results are presented in Section 5. Finally, we conclude the paper in Section 6.

2. Related work

In the literature, a variety of routing protocols have been proposed for MDTNs. The protocols can be classified into two broad categories based on the number of message copies utilized in the routing process [15,19,20]: single-copy and multi-copy.

In single-copy routing protocols, such as Direct Delivery [15] and First Contact [21], a single copy for each message exists in the network at any instant. Therefore, these routing protocols achieve the minimum transmission overhead in terms of the number of message copies employed during the routing process. However, due to the frequent and long-term network partitions that characterize MDTNs, these protocols often suffer from low delivery ratio and long delivery latency [22].

In order to guarantee a higher delivery ratio and a lower delivery latency, multi-copy protocols distribute multiple copies of each message in the network. Based on whether the number of message copies of a message is limited or not, multi-copy routing protocols can be further divided into flooding-based [5] and quota-based protocols [6,7].