Available online at www.sciencedirect.com
ScienceDirect
Ad Hoc Networks 7 (2009) 201–218
www.elsevier.com/locate/adhoc

Combining on-demand and opportunistic routing for intermittently connected networks

J. Boice, J.J. Garcia-Luna-Aceves, K. Obraczka *

Department of Computer Engineering, University of California at Santa Cruz, 1156 High Street, Santa Cruz, CA 95064, United States

Received 26 January 2008; accepted 2 February 2008
Available online 19 February 2008

Abstract

While current on-demand routing protocols are optimized to take into account unique features of mobile ad-hoc networks (MANETs) such as frequent topology changes and limited battery life, they often do not consider the possibility of intermittent connectivity that may lead to arbitrarily long-lived partitions. In this work, we introduce the space-content-adaptive-time routing (SCaTR) framework, which enables data delivery in the face of both temporary and long-lived MANET connectivity disruptions. SCaTR takes advantage of past connectivity information to effectively route traffic towards destinations when no direct route from the source exists. We show through simulations that, when compared to traditional on-demand protocols, as well as opportunistic routing (e.g., epidemic), SCaTR increases delivery ratio with lower signaling overhead in a variety of intermittently connected network scenarios. We also show that SCaTR performs as well as on-demand routing in well-connected networks and in scenarios with no mobility predictability (e.g., random mobility). In the latter case, SCaTR delivers comparable reliability to epidemic routing with considerably lower overhead.

Keywords: On-demand routing; Opportunistic routing; Disruption-tolerant networking; Proxies; Intermittent connectivity

1. Introduction

The price, performance, and form factors of sensors, processors, storage elements, and radios today are enabling the development of network-supported applications in very disrupted environments, i.e., environments where end-to-end connectivity is not guaranteed at all times because of either the characteristics of the environment or the normal operation of the network nodes. Examples of such applications and environments include monitoring of disrupted phenomena (e.g., wild fires), object tracking, establishment of on-demand network infrastructure for disaster relief or military purposes (in which case, the ad-hoc network can be disrupted by terrain, weather, and other natural phenomena, as well as jamming, interference, etc.), peer-to-peer vehicular or interpersonal networks [9] with very sparse connectivity, and mobile ad-hoc networks (MANETs) that need not be connected at all times in order to limit interference and contention. In these scenarios, network disconnection is the normal state of operation rather than an exception.

* Corresponding author. Tel.: +1 831 459 4308; fax: +1 831 459 4829.

E-mail addresses: boice@cse.ucsc.edu (J. Boice), jj@cse.ucsc.edu (J.J. Garcia-Luna-Aceves), katia@cse.ucsc.edu (K. Obraczka).

1570-8705/$ - see front matter
doi:10.1016/j.adhoc.2008.02.003

The demand for networking in environments prone to intermittent connectivity poses a challenge because the architects of the IP Internet and MANETs have assumed that physical connectivity exists on an end-to-end basis between sources and destinations for extended periods of time, or at least for the duration of a transaction among communicating parties. This assumption has had profound implications on how communication bandwidth is shared, how routing is accomplished, and how messages are disseminated across computer networks. In particular, routing in packet-switching networks has been based on routing tables that specify the next hop to one or more destinations. Such routing information is derived entirely from topology (or connectivity) information that represents only a snapshot of the state and characteristics of network links at particular instants.

Regardless of the specific mechanisms used in a routing protocol today (e.g., proactive or on-demand routing), computing the routing table entry for a given destination can be viewed as a particular form of searching a database. The routing database can be replicated (as it is done in such topology broadcast approaches as TBRPF [26] and OLSR [8]) or distributed, as in AODV [28] or DSR [19]. Depending on whether the routing database is replicated or distributed, the search algorithm can be centralized (e.g., using Dijkstra's shortest path first algorithm) or distributed (e.g., using a flood search based on route requests and route replies). The routing databases constructed by traditional routing algorithms specify the instantaneous status of a link (up or down), and the value of its parameters such as delay and bandwidth at some specific point in time. The search for routes in such databases produces snapshot paths that have no temporal dimension. Hence, if the network connectivity or link parameters change, multiple paths to destinations may be affected; the only way most current routing protocol can recover is to search for new paths. This time-independent, reactive approach to changes in network connectivity and link parameters works well as long as the disruptions in network connectivity due to environmental or operational reasons are not so frequent and/or long-lived that they prevent the routing protocol from obtaining time-independent paths to intended destinations.

Starting with the work in the Interplanetary Internet Research Group (IPNRG) [5] of the IRTF (Internet Research Task Force), considerable effort has recently been devoted to the study of networks with intermittent connectivity or very long latencies. Perhaps most prominent in this area is the work by the DTNRG (Delay-Tolerant Networking Research Group) [11], which started in 2002 under the IRTF. Section 2 summarizes prior related work on routing in disrupted environments. From our summary of related work, it becomes apparent that no complete solution exists for on-demand routing that incorporates the network topology's time dependency.

In this paper we describe the SCaTR (space-content-adaptive-time routing) framework to enable on-demand routing in MANETs with intermittent connectivity.[1] Section 3 describes SCaTR which we currently implement by extending the ad-hoc on-demand distance vector (AODV) routing protocol [28]. Our current instantiation of SCaTR is such that, if the network is connected, it operates exactly as regular on-demand routing, in this case AODV. However, if no direct route is available from source to destination, a node that is deemed closer to the destination than the source will advertise itself as a *proxy*. In this manner, the resulting protocol does no worse than standard AODV in well-connected environments, and does far better in partitioned networks.

We evaluate SCaTR through extensive simulations comparing its performance against on-demand and epidemic routing under a number of scenarios that address random and predictable node mobility. Section 4 presents our experimental methodology and Section 5 presents our simulation results in detail. They show, for example, that SCaTR's proxies improve delivery reliability in both predictable and random mobility situations, while incurring lower signaling overhead. In predictable mobility scenarios, schedules or trajectories are not assumed to be global knowledge. Instead, the routing algorithm in SCaTR uses mobility histories to improve performance. Further, given enough time, the protocol delivers all possible packets to their intended destinations, achieving high reliability. Section 6 summarizes our contributions and discusses ideas for future work. We start by reviewing related work in the next section.

2. Related work

Disruptive networks (also referred to as delay-tolerant, partitioned or disconnected networks) have recently received considerable attention from

[1] This paper builds on our earlier work presented in [1].