Ad Hoc Networks 44 (2016) 1–18

Contents lists available at ScienceDirect

Ad Hoc Networks

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

Review Article

Congestion control in disruption-tolerant networks: A comparative study for interplanetary and terrestrial networking applications

Aloizio P. Silva[a,*], Scott Burleigh[b], Celso M. Hirata[a], Katia Obraczka[c]

[a] Instituto Tecnológico de Aeronáutica, São José dos Campos, São Paulo, Brazil
[b] Jet Propulsion Laboratory – NASA/Caltech, Pasadena, CA, USA
[c] University of California Santa Cruz, Santa Cruz, CA, USA

ARTICLE INFO

Article history:
Received 21 February 2015
Revised 31 January 2016
Accepted 1 February 2016
Available online 17 February 2016

Keywords:
Delay and disruption tolerant networks
Interplanetary Networks
Congestion control
Network performance

ABSTRACT

Controlling congestion is critical to ensure adequate network operation and performance. That is especially the case in networks operating in challenged- or extreme environments where episodic connectivity is part of the network's normal operation. Consequently, the "pure" end-to-end congestion control model employed by the Internet is not adequate. Our goal is to study congestion control mechanisms that have been proposed for these so-called disruption tolerant networks, or DTNs. In this paper, we conduct a performance study comparing existing DTN congestion control mechanisms for two main application domains, namely: inter-planetary (IPN) and terrestrial networking applications. Our results confirm that congestion control helps increase message delivery ratio, even in highly congested network scenarios. Furthermore, the results show that existing DTN congestion control mechanisms do not perform well in IPN scenarios. Our study also suggests that good design principles for congestion control in DTN scenarios include: combining reactive and proactive control, using local information instead of global knowledge, and employing mechanisms that are routing protocol independent. One important conclusion from our quantitative study is that there is currently no universal congestion control mechanism that fits all DTN scenarios and applications.

1. Introduction

In the last 10 years, applications such as environmental sensing, habitat monitoring, emergency response, disaster recovery, and bridging the digital divide, to name a few, have raised great interest in so-called challenged network environments. In such environments, also known as delay and disruption tolerant networks, or DTNs, continuous end-to-end connectivity cannot be guaranteed and the communication channel may be subject to arbitrarily long signal propagation delays, lapses in connectivity, and high error rates. Under these conditions, participating nodes must store in persistent storage data they are transmitting or forwarding until a contact opportunity arises, i.e., until the node has a suitable next-hop neighbor that can receive the data.

Congestion control in challenged environments is thus critical to ensure nodes are congestion-free and can serve as relays when needed so messages can be delivered end-to-end. Because DTNs violate the fundamental assumptions underlying the TCP/IP (Transmission Control Protocol/Internet Protocol) protocol architecture, namely the existence of an end-to-end path between nodes and short

* Corresponding author. Tel.: +55 31997755907.
E-mail addresses: aloizio@ita.br, aloizio@soe.ucsc.edu (A.P. Silva), scott.c.burleigh@jpl.nasa.gov (S. Burleigh), hirata@ita.br (C.M. Hirata), katia@soe.ucsc.edu (K. Obraczka).

http://dx.doi.org/10.1016/j.adhoc.2016.02.004
1570-8705/

delays, they cannot employ the Internet's congestion control principles. The technical challenges posed by DTN congestion control combined with its impact on performance motivated a number of research efforts aiming at developing novel congestion control schemes for DTNs [9,15,19,22,29].

Our goal with this study is to understand the performance trade-offs raised by existing DTN congestion control mechanisms and how they behave in a wide range of DTN scenarios. We focus on two types of DTN applications, namely deep space communications, also known as Interplanetary Internet (IPN) [6] and terrestrial applications.[1] Terrestrial DTNs can target a wide range of applications including sensor networks for environmental- and habitat-monitoring, vehicular networking applications, law enforcement and first responder services, to name a few. Our study compares the performance of different congestion control schemes in both IPN and terrestrial scenarios. To our knowledge, this is the first performance study on DTN congestion control examining both interplanetary and terrestrial applications, thus exploring the feasibility of a universal congestion control mechanism.

We also explore the impact of different routing protocols and node mobility models and evaluate the different congestion control strategies using such performance metrics as average delivery ratio, average latency, and overhead. Another goal of this work is to provide insight on good design principles for congestion control schemes so that they can be applied to a variety of DTN scenarios.

The remainder of the paper is organized as follows. In Section 2, we provide an overview of DTN and IPN environments and Section 3 describes the congestion control schemes we studied. Section 4 describes our experimental methodology while Sections 5 and 6 present the results of our comparative study. Section 7 provides a discussion of the results and Section 8 concludes the paper.

2. Background

2.1. Interplanetary internetworking

As described in [2,3,6], an Interplanetary Internet includes the IPN Backbone, IPN External Networks, and Planetary Networks (PNs). The IPN Backbone makes possible the communication among the Earth, other planets, space probes, and spacecraft through satellites. The IPN External Network includes, for instance, spacecraft flying in deep space between planets, space probes, and orbiting space stations. A PN is composed of the PN's Satellite Network and the PN's Surface Network. The former includes links among surface nodes, orbiting satellites, and IPN Backbone Nodes, providing relay services between surface networks and the backbone as well as between two or more parts of the surface network. Surface networks provide communication between surface elements, such as rovers and sensor nodes.

The main challenges affecting IPNs can be summarized as follows [2,8,28,30,32]:

- *Intermittent connectivity:* disconnections can happen due to planetary motion as well as the movement of celestial bodies, spacecrafts, rovers, etc.
- *Long and variable delays:* the deep space connection may have extremely high round-trip latencies caused by astronomical distances, e.g., the round-trip time (RTT) for radio communication from Mars to Earth can take between 3 minutes minimum to 30 min maximum. This happens because the distance between the Earth and Mars varies enormously depending on their relative positions in their orbits around the Sun.
- *High bit error rates:* the uncorrected bit error rate (BER) for deep space radio communication is high (around 10^{-1}) due to extreme environment conditions (i.e., cosmic radiation leads to signal corruption). Strong forward error correction coding is applied to reduce the observed BER to a rate that is on the order of 10^{-5} to 10^{-6}, still far higher than in communications over optical fiber in the Internet.
- *Asymmetric data rates:* the asymmetry in date rates on space links is typically of the order of 1:1000 or higher. Communications channels between spacecraft and the ground are frequently asymmetric in terms of both channel capacity and error characteristics. This asymmetry is a result of various engineering tradeoffs (such as power, mass, and volume), as well as the fact that for scientific missions, most of the data originates at the satellite and flows to the ground. The return link is generally used for commanding the spacecraft, not bulk data transfer [10].

2.2. Terrestrial DTN

Terrestrial DTNs find a variety of applications including (wireless) sensor networks (e.g., for environmental- and habitat monitoring often times deployed in remote regions possibly under extreme conditions), vehicular networks, emergency rescue and disaster relief operations. Similar to deep space networks, some of the main challenges affecting terrestrial networks can be summarized as follows:

- *Intermittent connectivity*
- *Arbitrarily long and highly variable delays*
- *Highly variable bit error rates:* the BER varies according to the environment (e.g., deep-sea sensor networks or military/civilian submarine communication). For example, in a wireless sensor network the BER may be on the order of 10^{-1}–10^{-3} [11,21] but is frequently lower than in the deep space environments.
- *Data rates:* Data rates are frequently symmetric but may be asymmetric in some environments (e.g., underwater communications).

However, unlike IPNs where contacts are typically governed by planetary movement [12], in terrestrial DTNs contacts are not usually scheduled. They are often random also known as "opportunistic".

3. Selected DTN congestion control mechanisms

For our comparative study, we picked a subset of DTN congestion control mechanisms from the schemes

[1] A preliminary version of this work focusing on IPN environments is described in [24].