Computer Networks 83 (2015) 349–362

Contents lists available at ScienceDirect

Computer Networks

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

Delay-tolerant networks and network coding: Comparative studies on simulated and real-device experiments

Yuanzhu Chen [a], Xu Liu [a], Jiafen Liu [b,*], Walter Taylor [c], Jason H. Moore [d]

[a] Wireless Networking and Mobile Computing Laboratory, Department of Computer Science, Memorial University of Newfoundland, St. John's, NL, Canada
[b] School of Economic Information Engineering, Southwestern University of Finance and Economics, Chengdu, Sichuan, China
[c] Computational Genetics Laboratory, Giesel School of Medicine, Dartmouth College, Hanover, NH, USA
[d] Institute for Biomedical Informatics, Perelman School of Medicine, University of Pennsylvania, Philadelphia, PA 19104-6021, USA

ARTICLE INFO

Article history:
Received 27 December 2014
Accepted 6 April 2015
Available online 29 April 2015

Keywords:
Delay-tolerant network
Network coding
Mobile devices

ABSTRACT

Delay-tolerant networking effectively extends the network connectivity in the time domain, and endows communications devices with enhanced data transfer capabilities. Network coding on the other hand enables us to approach the information capacity of networks by allowing intermediate nodes to process data en route. Both of these were major breakthroughs in mobile and wireless communications in the past decade or so. As reported in this article, we are interested in how network coding interacts with such a challenged networking paradigm as DTN from an experimental perspective. We conducted tests with both real smart mobile devices and computer simulation and found conditions where their results match. This would give us confidence of using computer simulation to study larger delay-tolerant networks with and without network coding at a much manageable cost.

1. Introduction

Data communication networks connect computing devices with wired or wireless links to exchange information. For such networks to scale as the number of devices in it increases, we allow messages to traverse multiple communication links from its source node to the destination. Such a "store and forward" technique is the central idea of how the Internet can support numerous computers. This significantly extends the scope of communication networks spatially. Recently, research on Delay-Tolerant Networking (DTN) [1,15,17,30] has been focusing on how to extend communication networks temporally. As mobile devices and networking technologies become more powerful and efficient, such mobile devices can be used to "store, carry, and forward" data when users roam around. That is, even without cellular or Wi-Fi infrastructure and only relying on short-range radios, e.g. Bluetooth and ZigBee, a number of sparsely deployed mobile devices can be used to transfer data automatically especially when the data are not meant to be time-sensitive. The DTN technology can be useful in many scenarios, such as mobile sensor networks, disaster recovery, and social networking.

The concept of network coding was formulated in the seminal work by Ahlswede et al. [5] in 2000, and the past decade has seen tremendous growth in this area [23]. Its idea breaks away from the principal of traditional multi-hop networking, where intermediate nodes only forward packets but cannot modify their contents, much like cars traveling on a highway. Since bits are not cars anyway, network coding allows intermediate nodes to combine packets mathematically from different input ports just before forwarding them. When treating a packet as a sequence of symbols, even linear network coding defined

* Corresponding author.
E-mail address: ljfwhy@gmail.com (J. Liu).

http://dx.doi.org/10.1016/j.comnet.2015.04.002
1389-1286/

over small Galois fields can introduce a fairly significant throughput gain. The readers are referred to an easy-to-read and yet informative primer by Fragouli et al. [12]. Other benefits of network coding include improved robustness of network operations, higher energy efficiency in wireless radios, and better security against eavesdroppers. Network coding proves to be especially powerful and flexible, and can be exercised along with other revolutionary networking paradigms. For example, it was shown that opportunistic data forwarding in multi-hop wireless networks can further increase the capacity of these networks when intermediate nodes judiciously combine overheard packets and forward them [7,28]. As another example, the resilience to lost or delayed information brought about by network coding turns out particularly effective in DTNs, as evidenced by computer-simulated experiments in Widmer and Le Boudec [27] and Lin et al. [19].

In this research, we evaluate how network coding stacks against various conventional message passing techniques in DTNs using both real Apple iOS devices and in the ONE simulator in a university building. Our goal is to assess to what extent the ONE as one of the best and most widely used simulators for DTN research can mimic the real world. On one hand, we used real mobile devices to measure how message propagate among roaming users over the built-in Bluetooth radios. On the other hand, we enhanced the ONE with a more realistic link layer by adding a few parameters. We are able to claim that the simulator can behave fairly closely to iOS devices with these parameters tuned properly. As part of a bigger research project, we can be confident that the simulator can work in place of real devices for efficient studies of larger-scale networks.

The rest of this article is organized as follows. Next section, we review relevant experimental research on DTN and network coding in this context, and provide background information about the device API and simulation software used in this research. In Section 3, we describe an array of techniques for message passing without network coding. Next in Section 4, move to detail a generation-based implementation of network coding in DTN. We conducted experiments using both real devices and computer simulation. The experimental settings and results are reported in Section 5. Section 6 concludes this article with discussion and future research issues.

2. Background

Here, we review the most relevant research in DTN and network coding in DTN. We also provide a brief description to the tools used in the experiments, a Bluetooth API to the Apple iOS and a DTN simulation software suite in Java.

2.1. Related research

Research on DTN started from the Interplanetary Networking project at JPL [3]. The networking problem in such a scenario considers predictable mobility of space probes and surface stations, where the feedback loop can take a very long time to complete due to both signal propagation delay and obstacles of other celestial bodies. In a more general setting, because the mobility of communication devices can be unpredictable, scheduling networking activities in a deterministic fashion is no longer feasible. A great deal of research has been done on data transfer in such a framework to fulfill the simple goal of moving data from the source to its destination. A number of excellent reviews and vision articles have been published on the architecture and protocol aspects of delay-tolerant networks [15,17,29,30].

The two most important, and yet distinct operations at the Network Layer (Layer III) are data forwarding and routing [18]. Forwarding regulates how packets are taken from one link and put on another. Routing determines which path a data packet should follow from the source node to the destination. The latter essentially feeds control input to the former. Here, we stick to the term of data forwarding although it is also sometimes referred to as routing in literature.

Data forwarding in unpredictable DTN is more or less inspired by Epidemic Routing [26]. There, the authors are interested in transferring messages to their destinations as quickly as possible at the cost of using a considerable amount of network resources consumed by making many copies of the same message. Subsequent work on unicast data, where a message has a sole destination, make more careful tradeoffs between the data transfer performance, in terms of latency and delivery ratio, and resource consumption. For example, Spray and Wait [25] regulates the number of copies a message using a single control parameter.

When assuming that historical contact information would suggest a similar pattern in future, nodes can utilize such observation to construct some sort of utility function to gauge which node in its proximity might help forwarding its messages more effectively. This approach was initially explored in PROPHET [20] and MaxProp [6] most noticeably. When historical contact records are further distilled with social network analysis methods, nodes can make more sophisticated forwarding decisions taking more factors into consideration. This approach is exemplified in BUBBLE-Rap [14], Delegation Fowarding [11], SimBet [10], and CAR [24].

Data forwarding techniques aside, researchers in data communications have also been on a quest for the killer applications of this groundbreaking technology for years [21]. Although such a quest is far from satisfactory, there have been a number of interesting applications in infrastructureless computer networking, such as IPN [3], Haggle [2], ZebraNet [16] and iSNAC [8], to name a few. Among these, iSNAC is a mobile social networking iPad application that focuses on broadcasting messages to help conference attendees to share information effectively.

Subsequent to the seminal work of Ahlswede et al. [5], another important discovery of network coding is its randomized application. As we know, the linear independency of the coefficients used to generate a set of coded packets is a determinant for the receiver to successfully decode for the native packets. This is especially crucial in wireless and mobile networks, where coded packets are subject to