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Practical Bloom filter based epidemic forwarding and congestion control in DTNs: A comparative analysis

Ali Marandi [a], Mahdi Faghih Imani [b], Kavé Salamatian [c,*]

[a] Department of Computer Engineering, Khorasgan (Isfahan) Branch, Islamic Azad University, Isfahan, Iran
[b] Department of Computer Engineering Science and Research Branch, Islamic Azad University, Tehran, Iran
[c] University of Savoie, LISTIC, F-74000 Annecy, France

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ABSTRACT

Epidemic forwarding has been proposed as a forwarding technique to achieve opportunistic communication in delay tolerant networks (DTNs). Even if this technique is well known and widely referred, one has to address several practical problems before using it. Unfortunately, while the literature on DTNs is full of new techniques, very little has been done in comparing them. In particular, while Bloom filters have been proposed to exchange information about the buffer content prior to sending information in order to avoid redundant retransmissions, up to our knowledge no real evaluation has been provided to study the tradeoffs that exist for using Bloom filters in practice. A second practical issue in DTNs is buffer management (resulting from finite buffers) and congestion control (resulting from greedy sources). This has also been the topic of several papers that had already uncovered the difficulty to acquire accurate information mandatory to regulate the data transmission rates and buffer space. In this paper, we fill this gap. We have been implementing a simulation of different proposed congestion control schemes for epidemic forwarding in ns-3 environment. We use this simulation to compare different proposed schemes and to uncover issues that remain in each one of them. Based on this analysis, we proposed some strategies for Bloom filter management based on windowing and describe implementation tradeoffs. Afterwards, we propose a back-pressure rate control as a well as an aging based buffer managing solution to deal with congestion control. By simulating our proposed mechanisms in ns-3 both with random-waypoint mobility and realistic mobility traces coming from San-Francisco taxicabs, we show that the proposed mechanisms alleviate the challenges of using epidemic forwarding in DTNs.

1. Introduction

Delay tolerant networks (DTNs) like Wireless sensor networks, vehicular networks (VANETs), and spontaneous networks are characterized by several major challenges such as intermittent and transient connectivity, volatile links and long delays, that make particular methods and mechanisms mandatory for transmitting over them. In DTN applications, data forwarding follows opportunistic approaches based on store-carry and forward scheme, *i.e.* relay nodes store packets and carry them until an appropriate forwarding opportunity arises. The forwarding decision might be based on the identity of an encountered node when there are information on the likelihood of future contacts, *e.g.* in Prophet [1] where the message with the highest likelihood of being delivered by the encountered node to its final destination is forwarded. However, in several cases such future contacts information are not available, *e.g.* in very dynamic environments where past cannot be used to predict the future like some VANET scenarios, or even at the initial stage of any DTN scenarios where there is not yet enough historical information to direct the forwarding decision. In these situations, DTN routing techniques like Prophet are not usable and only epidemic forwarding is applicable. This has motivated techniques like spray and wait [2] or spray and focus [3] that begins by a first stage of epidemic forwarding limiting the spread of each message to L copies and followed by a stage of waiting or routing to reach the final destination.

"Opportunistic forwarding" consists of deciding which packet to forward only based on information exchanged between encountering about their buffers' content. "Epidemic forwarding" [4] is differentiated from other opportunistic forwarding approaches by not making the forwarding decision based on destinations of messages as no information is available about future contact (besides the case where the encountered node is the destination of some

* Corresponding author.
E-mail address: kave.salamatian@univ-savoie.fr (K. Salamatian).

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packets and these packets are sent in priority). Packets will be eventually delivered to their destinations by epidemic forwarding, since one of carriers will likely encounter the destination.

Indeed the major issue and challenge of epidemic forwarding is to control the redundancy and to avoid useless transmissions. In order to achieve this Vahdat et al. [4] proposed to exchange between nodes a summary bitmap indicating which packets are already present in encountering nodes buffers. However, this idea is not practical because the nodes need to be informed of an ordered list of all messages circulating in the network in order to interpret the bitmaps. Building and diffusing this list seems impracticable especially in an asynchronous multi-source/multi-destination scenario. Therefore, the proposed summary bitmaps is in fact a list of received packet IDs and its exchange can impose a relatively large overhead. Vahdat et al. [4] suggested therefore using a *Bloom filter* in order to substantially reduce the space overhead associated with the summary vector. Despite this approach being known from a long time, there is a relatively small number of works that describe practically how to implement Bloom filter based epidemic forwarding and discussed the involved trade-offs. In particular, one needs to deal with defining in a distributed way Bloom filters and how to achieve good transmission overheads vs. transmitted redundancy trade-offs. One of the aims of this paper is to discuss this issue.

In addition, epidemic forwarding and more generally DTN opportunistic forwarding schemes have to address some practical challenges in order to be usable. A major issue in all networks is congestion control that happens when the rate of input packets is larger than what the network can accommodate. This issue is more vital in DTNs as packets are likely to stay in buffers for a longer time than in traditional networks. A large part of the literature has assumed unlimited buffers and showed good performance for epidemic forwarding, however the performance is strongly affected by limited buffers, as nodes have to drop packets when their buffers become full. Therefore, congestion control and buffer management are of vital importance in DTNs and influence directly the performance. The issue of congestion control has been studied extensively in the Internet and traditional networks. But due to lack of continuous end-to-end connectivity in DTNs, classical congestion control approaches are not applicable there. Therefore, we need particular congestion control mechanisms for DTNs that base their decisions only on local information. Another issue is relative to buffer management and deciding what to store in buffers and what to drop. This issue is closely related to indicating packets received at destinations in order to not forward them and to free the space occupied by them. Both buffer management and congestion control have been the subject of different papers each addressing only a small subset of the large set of challenges an epidemic forwarding scheme has to address. To our knowledge no comparative analysis of the schemes proposed in the literature, has been implemented, and more globally no one of the previous works have tackled together with the above three challenges: distributed Bloom filter design, congestion control and buffer management.

In this paper, we will first describe a distributed Bloom filter buffer content exchange scheme that could be used for any opportunistic forwarding scheme (either epidemic or not). We also propose a global framework that integrates most of previous work done on congestion control and buffer management of epidemic forwarding in DTNs. The framework consists of three mechanisms: a back-pressure based injection rate control that controls the rate of injection of new packets from sources in order to ensure that a fast source is not submerging its neighborhood, a buffer management scheme that discards oldest packets and frees space in buffers following a packet aging similar to [5], and a flow control scheme similar to the one implemented in [6] that prevents congestion by postponing message transfers to congested node until adequate resources are available. Most techniques proposed in the literature can be reduced to particular instantiation of different parameters of the above three steps. We implemented the framework in the *ns-3* simulation environment. This enables us to do a comparative analysis of different proposed schemes over the same scenarios and to analyze their strengths and shortcomings. The comparative analysis is done over both random waypoint mobility, and real mobility traces coming from San Francisco taxis. This comparative analysis will lead us to propose a combination of all three mechanisms that achieve a better performance over the simulated scenarios.

In a nutshell the contributions of this paper are as follow. We first present an in-depth analysis of Bloom filtered based epidemic forwarding, discuss the alternatives and present practical way of implementing it. Up to our knowledge while proposing Bloom filter has a long history, no proposition implementable in practice have been provided. This paper fills this gap. A second contribution is relative to the three stage framework, *i.e.*, source injection rate control, buffer management, flow control, proposed for categorizing different DTN congestion control schemes. This framwework provides a taxonomy of the different congestion control schemes that help in understanding the strengths and weaknesses of each proposed scheme. While solutions belonging to each single stage have been proposed, the framework leads to proposing a new congestion control scheme combining elements from existing schemes that cover each of the shortcomings of the individual schemes. The last contribution of this paper is relative to the application of the developped framework to simulate and compare the performance of several of the proposed DTN congestion control schemes. Up to our knowledge no such large scale comparison have been done in the literature. In addition to the trivial interest of making a comparison to know which scheme has the best performance, our comparative analysis provides a marginal benefit analysis of the different stage of congestion control, showing that this is the node to node flow control that has the largest impact by increasing delivery and reducing strongly packet drop caused by congested buffers.

The rest of this paper is organized as follows. Section 2 describes related work. Then we describe in Section 3 windowing based Bloom filter management strategies. Next, in Section 4 we discuss the importance of congestion control and buffer management and propose some mechanisms to deal with it. Section 5 presents our congestion control framework. Afterwards, we present a simulation based comparative analysis of different schemes and show how to improve them by combining the three mechanisms. Finally, Section 7 concludes the paper.

2. Related work

Epidemic forwarding was initially proposed in [4]. In order to use better the scarce communication resources in DTNs and to avoid useless transmissions, Vahdat and Becker proposed to exchange between nodes a summary bitmap indicating which packets are already received in nodes. However, as explained before this idea is not practical as building and diffusing an ordered list of all messages circulating in the network seems impracticable especially in an asynchronous multi-source/multi-destination scenario, resulting in exchanging in most implementations of DTNs a list of received packet IDs in place of a bitmap, and imposing a relatively large overhead to exchange this information. Vahdat et al. [4] already suggested to use a *Bloom filter* to reduce the overhead associated with the summary vector. However despite this approach being known from a long time, there is a relatively small number of works that describe how to implement and describe the involved trade-offs of designing a distributed Bloom filter