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Improving the transport performance in delay tolerant networks by random linear network coding and global acknowledgments ☆

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ABSTRACT

We propose and study a new set of enhancement features to improve the performance of reliable transport in Delay Tolerant Networks (DTNs) consisting of both unicast and multicast flows. The improvement in reliability is brought in by a novel Global Selective ACKnowledgment (G-SACK) scheme and random linear network coding. The motivation for using network coding and G-SACKs comes from the observation that one should take the maximum advantage of the contact opportunities which occur quite infrequently in DTNs. Network coding and G-SACKs perform "mixing" of packet and acknowledgment information, respectively, at the contact opportunities and essentially solve the *randomness* and *finite capacity* limitations of DTNs. In contrast to earlier work on network coding in DTNs, we observe and explain the gains due to network coding even under an *inter-session* setting. Our results from extensive simulations of appropriately chosen "minimal" topologies quantify the gains due to each enhancement feature. We show that substantial gains can be achieved by our proposed enhancements that are very simple to implement.

1. Introduction

Mobile Ad hoc NETworks (MANETs) aim at making communication between mobile nodes feasible without any infrastructure support. If the spatial density of mobile nodes in a MANET is too low, then an end-to-end path between a source and a destination almost never exists, and two mobile nodes can communicate only when they come within the radio range of each other. Such sparse and/or highly mobile MANETs fall into the class of Delay Tolerant Networks (DTNs) that are characterized by frequent link disruptions and highly intermittent connectivity. There can be several reasons for intermittent connectivity such as limited wireless radio range, sparsity of mobile nodes, limited energy resources, attack, and noise [2].

Apart from sparse MANETs, other examples of DTNs include Inter-Planetary Networks (IPNs) [3] which pertain to *deep-space* communication. Examples of *terrestrial* applications of DTNs include sparse Vehicular Ad hoc NETworks (VANETs) [4], Pocket Switched Networks (PSNs) [5], Airborne Networks (ANs) [6], Mobile Social Networks (MSNs) [7], Under Water Networks (UWNs) [8] and "Data Mules" [9].

In DTNs, due to highly intermittent connectivity, no contemporaneous end-to-end path may ever exist [10], and hence, the nodes must adopt a *Store-Carry-and-Forward* paradigm of routing. A source has to depend on the

☆ This paper is a thoroughly revised and substantially extended version of our earlier work [1].

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mobility of other nodes, which act as "relays", and data packets and ACKnowledgments (ACKs) get transferred between a source and a destination through one or more relays. This inherently entails a large delay. Since the nodes take advantage of the transmission opportunities during contacts with other nodes in order to exchange packets, such forwarding mechanism is sometimes also referred to as *opportunistic routing*.

In reliable transport, a source wishes to ensure that the information it sends arrive correctly and "in order" at the destination. The Transmission Control Protocol (TCP) is by far the most deployed protocol for reliable transport. However, *TCP turns out to be very inefficient for reliable transport in MANETs, because it misinterprets losses due to interference and link failures as losses due to congestion* [11]. This is even worse in the case of DTNs due to intermittent connectivity [12]. Transport solutions for MANETs, that are based on cross-layer signaling [13–15], are not suitable for DTNs, because only opportunistic routing can be performed.

Clearly, the performance of routing and transport in DTNs is very much dependent both on the *mobility of the nodes* and the *packet replication method* [16], and there is a need for transport solutions that could leverage this special characteristics of DTNs. In this paper, we propose and study several "smart" techniques for replicating packets and acknowledgments in order to improve the performance of reliable transport in DTNs, and show their efficacy under a realistic heterogeneous mobility model as well as a homogeneous mobility model.

1.1. Literature survey

Several methods for spreading packets in DTNs have been investigated under opportunistic routing, for example, *spray-and-wait routing* [17], *probabilistic routing* [18], *direct delivery* and *two-hop routing* [19], and *epidemic routing* [20]. Much of the existing literature on DTNs focuses on the routing aspect and relatively fewer pieces of work deal with reliable transport. The literature on transport in DTNs is primarily concerned with deep-space communication [21–27].

The Bundle Protocol [21] specifies a framework rather than a concrete protocol implementation. The "Saratoga" protocol [22] provides an IP-based convergence layer in DTNs supporting store-and-forward of bundles. It performs UDP-based transfer of IP packets with Selective Negative ACKnowledgements (SNACKs). The Licklider Transmission Protocol (LTP) [23] is designed to serve as a DTN convergence layer protocol. It provides retransmission-based reliable transfers over single-hop connections and supports both reliable and unreliable data transmission. The CFDP protocol [24] provides file copy services over a single link and requires all parts of a file to follow the same path to the destination. The Deep-Space Transport Protocol (DS-TP) [25] is based on *Double Automatic Retransmission* to provide proactive protection against link errors. The TP-Planet [26] protocol employs *Additive Increase Multiplicative Decrease* control mechanism and uses time-delayed Selective ACKnowledgments (SACKs) to deal with asymmetric bandwidth. SCPS-TP [27] adopts major TCP functionalities and extends them in order to deal with some of the unique characteristics of deep-space links. Harras and Almeroth [28] probed into issues related to the use of transport in a DTN environment. Fall and MaCanne [29] discussed important issues related to transport performance not specific to DTNs.

Ahlswede et al. [30] initiated the study of network coding. Ho et al. [31] proposed the random linear coding technique. Network coding research originally studied throughput performance without delay considerations for channels with no erasures and no feedback [30,32,33]. The network coding based routing approaches for challenging environments such as DTNs have been widely studied and simulated, and have been shown to provide promising results [34–38]. Widmer and Le Boudec [37] show that the performance of their network coding based routing algorithm is better than that of probabilistic routing. Katti et al. [34] showed that network coding can improve the throughput in unicast wireless communication. Zhang et al. [38] investigated the benefits of using random linear coding with epidemic routing for unicast communications in mobile DTNs, especially *under constrained buffer sizes and intra-session coding*. Network coding has been used not only to minimize the delivery delay [39,38] but also to improve the probability of successful delivery within a given time [40].

In contrast to the large body of work on transport in deep-space DTNs, in [41] the authors proposed a new reliable transport protocol for "terrestrial" DTNs. The reliable transport scheme in [41] is based on random linear coding of data packets and uses a special type of ACKs that indicate the *missing degrees-of-freedom (DoF)* at the destination. The scheme in [41] operates in (re)transmission cycles. If the source does not receive an ACK indicating zero missing DoF within an optimally chosen *cycle timeout*, then a new (re)transmission cycle, with updated optimal parameter settings based on the latest information of missing DoF, is triggered. This process continues until the source receives an ACK indicating zero missing DoF, and thus, reliability is achieved.

1.2. Our contributions

This work is an extension of our earlier work [1] in which we proposed several enhancement features to improve the performance of reliable transport in terrestrial DTNs. In this work, we extend the conclusions of [1] by quantifying the benefits due to each enhancement feature under appropriately chosen "minimal" topologies. We study the performance benefits using a wider range of performance metrics and provide more insightful observations through critical analysis of the simulation results.

Since designing appropriate ACK mechanisms in DTNs is still an open issue [42], we propose and study several enhanced ACK schemes. We propose a novel Global Selective ACKnowledgement (G-SACK) scheme. A G-SACK can potentially contain *global* information about the receipt of packets at each destination in the network. We also study the impact of our enhanced ACK schemes together with random linear network coding.