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Mathematical modeling of delivery delay for multi-copy opportunistic networks with heterogeneous pairwise encounter rates

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ABSTRACT

This paper proposes an analytical model that captures the expected pairwise delivery delay in an opportunistic network when the source can generate multiple copies of the message. This model allows for the encounter rates among nodes to be heterogeneous, and it is completely independent of the forwarding scheme. The model is validated through simulation experiments performed with ns-3 and a multi-copy simulator specifically developed for this work. Along with the results, this paper also presents a discussion of the variability of the encounter rates over time and its influence on the accuracy of the proposed model.

1. Introduction

In recent years, much attention has been paid to a class of networks called *Challenged Networks*, which are characterized by the difficulty in their end-to-end communication caused by the intermittent connectivity among nodes. Most scenarios include mobile wireless nodes whose mobility may restrict or even prevent the exchange of data among them. In addition, the nodes composing such networks may have low energy resources, which can lead to short transmission ranges that further restrict their communication. In these networks, routing protocols that assume an end-to-end connectivity between the source and destination do not work. Therefore, an overlay architecture called Delay-Tolerant Networking (DTN) [9] was designed to cope with this challenging environment. In this architecture, DTN nodes use the *store-carry-forward* paradigm in which nodes keep copies of the messages for posterior forwarding as soon as a new point-to-point connection is established [13].

Among the wide range of DTN networks, there is a class that uses the node mobility as an advantage instead of a drawback. In challenging environments, node mobility can provide occasional opportunities for new contacts between nodes. The exchange of data among them follows an *opportunistic forwarding protocol*, which is based on the opportunistic encounters

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among the nodes composing an *opportunistic network* [18]. A typical opportunistic network scenario is a DTN network whose nodes are wireless personal devices carried by humans.

The main idea behind opportunistic forwarding protocols is that the network's behavior has a high level of unpredictability and the nodes need to forward messages whenever an *opportunity* arises in order for the message to reach its final destination. Opportunistic forwarding increases the frequency with which the nodes exchange messages, thus enabling the delivery of messages to the final destination to occur sooner. The more opportunistic encounters that the nodes make, the lower the point-to-point and end-to-end delivery delays will be. The definition of what characterizes an opportunistic encounter may vary, thus giving rise to the various protocols that have been proposed in the literature over the years [5,6]. For example, an ordinary contact between two nodes, which means that they are within each other's range and are capable of exchanging messages, may be considered as an opportunity to forward a message. In other cases, the protocol may impose forwarding rules that must be satisfied before the event is considered a forwarding opportunity. For example, the node only forwards the message if the contacted node has a probability of meeting the destination higher than a certain threshold.

Despite the large variety of protocols, a critical issue in opportunistic forwarding is the lack of a general mathematical model for the performance evaluation and protocol analysis. Mathematical modeling is a powerful tool to analyze the dynamics, provide predictions and perform quantitative evaluations of a system. For a model to be applied to a wide range of scenarios, it needs to be as general as possible. In other words, it needs to have as few predetermined assumptions as possible. This is a challenging task, especially due to the network heterogeneity and node mobility. The importance and challenges of the mathematical modeling for opportunistic forwarding are also mentioned by [4,5,13] and several others.

The analytical framework proposed in [2] takes an interesting approach towards developing a more general model for opportunistic forwarding. Regarding the analytical modeling for such opportunistic networks, the most commonly used assumptions in the literature are that the inter-meeting times are exponentially distributed and that the mobility of nodes is homogeneous, which means that the nodes have the same pairwise encounter rates. The authors of [2] propose a *single-copy* model by relaxing those common assumptions. The authors consider that the mobility of nodes may be heterogeneous (the nodes may have different pairwise encounter rates) and do not restrict the distribution of the inter-meeting times to an exponential distribution. Additionally, their framework can be applied to any opportunistic forwarding scheme. To the best of our knowledge, it is the most general performance evaluation model for opportunistic forwarding so far. The drawback is that the model is restricted to a single-copy process. Therefore, only a single copy of each message exists in the network at any time since none of the nodes can duplicate the message in the forwarding process.

The present work presents a new approach for this framework where there is no restriction on the number of copies created by the source. Our motivation is to alleviate the challenge of developing a general model for opportunistic forwarding. Although such a framework is a powerful tool within its context, it presents the restriction of only being adequate for single-copy schemes. However, multi-copy schemes are important means of reaching lower delivery delays. Therefore, it is important to eliminate this constraint by allowing for multiple copies in the network.

In this direction, the main contribution of this paper is the presentation of a *multi-copy model* for the expected delivery delay in opportunistic networks with heterogeneous mobility, regardless of the specific opportunistic forwarding rule in use. The proposed multi-copy model is validated via simulation using two simulation tools: a multi-copy simulator specifically developed for this work and the ns-3 network simulator. The experimental results of both are compared with the analytical predictions. The obtained results show the good accuracy of the multi-copy model.

Moreover, this work also contributes with the analysis of the modeling framework regarding one of its main assumptions, which is that the pairwise encounter rates are considered to be fixed over time. Since we often have to work with scenarios where the encounter rates vary over time, it is important to discuss what happens to the model's predictions when this premise is not satisfied. Therefore, through the analysis of the obtained results, we discuss the influence of the encounter rates' variability over time on the modeling results. Additionally, we define a metric for this variability. With the development of a multi-copy simulator, we are able to analyze both scenarios in a controlled simulation environment, including the case where the rates are fixed and the case where they vary over time. The multi-copy simulator results are also compared with the ns-3 simulator results.

The remainder of this paper is organized as follows. A selection of related works is presented in Section 2. Section 3 introduces the single-copy model for opportunistic forwarding that inspired this work. The multi-copy model is presented in Section 4 and is followed by its validation and results in Section 5. Finally, the conclusions and perspectives of this work are presented in Section 6.

2. Related works

Over the last decade, there have been many efforts to model opportunistic forwarding. In this section, we give a brief overview of the works related to analytical modeling in this area.

A large number of important contributions regarding the modeling of opportunistic forwarding are related to epidemic routing [22], such as [8,10–12,15,20,23–26]. This protocol assumes that the process of forwarding messages in an opportunistic network is similar to the propagation of an infectious disease. Since it was one of the first proposed protocols, there are many opportunistic protocols that are epidemic-based.