Explosions in Pocket Switched Networks

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1 Introduction

Effective forwarding in a delay tolerant network (DTN) is strongly dependent on particular aspects of the setting, such as the size of the physical space involved, and the degree to which contact and mobility patterns are predictable. We are concerned with understanding forwarding in a setting that has not been extensively studied to date: human-carried mobiles moving in a restricted space with high node and contact density. This situation corresponds to individuals at conferences, around office spaces, and in social settings. Networks in these environments are examples of Pocket Switched Networks (PSNs), in which both mobility and multihop forwarding can be used to support communication.

We believe that in order to design effective forwarding algorithms for PSNs, it is necessary to start by understanding the opportunities for forwarding that exist. While some work has already studied the performance of various forwarding algorithms in PSNs [1, 6], there is little understanding to date on the *nature* of the forwarding problem in such settings. In particular, little is known about the kinds of paths (making use of both mobility and multiple hops) that exist in PSNs.

This paper is the first to study the paths that are available for forwarding in PSNs. We use as examples of the PSN setting measurements of contacts between Bluetooth-enabled Intel iMotes at recent Infocom and CoNext conferences [5]. We develop an efficient method to enumerate all paths of interest between nodes (iMotes) and apply it to these traces to capture all paths of interest for a set of randomly generated messages.

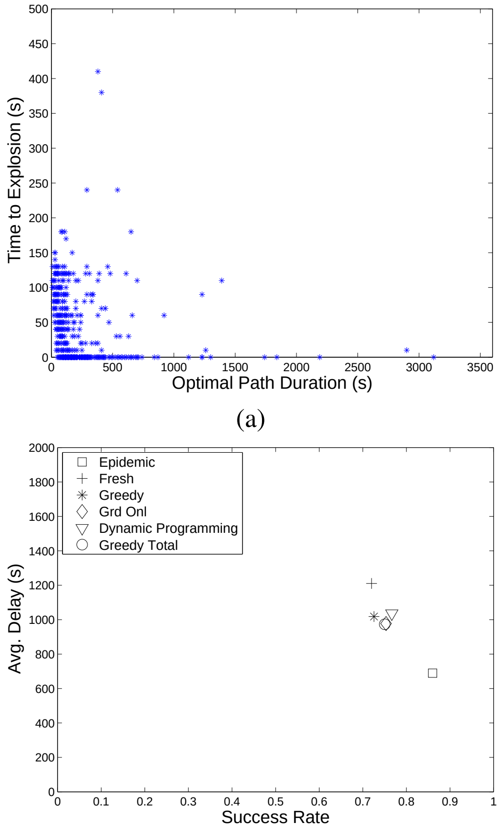
The most striking property of the collection of paths we obtain is the presence of a phenomenon we term *path explosion.* Path explosion refers to the case in which, once the first path reaches the destination the number of subsequent paths grows rapidly with time, so there exist many near-optimal paths. We find that path explosion occurs for the large majority of messages in our datasets.

To explore this effect we build an analytic model describing how paths are created in a homogeneously mixing population and we use it to show how path explosion arises [3]. However our homogeneous model does not explain all aspects of the phenomena observed in our data. In order to understand the nature of forwarding paths more accurately, we show that it is critically necessary to take into account the different contact rates exhibited by different nodes in the population. We find that it is useful to characterize the source and destination as either high contact rate (‘in’) nodes or low contact rate (‘out’) nodes. We show that when the contact rates of the source and destination nodes are taken into account, that the empirical properties of paths and the path explosion process can be understood more completely.

Using our traces, we evaluate a range of different forwarding algorithms [7, 2, 4] that are appropriate for DTNs. We find the surprising result that forwarding algorithms with very different strategies nonetheless show remarkably similar performance in terms of message delivery success rate and average message delivery delay. In fact we find that the particular choice of routing algorithm does not have a strong impact on delay or success rate for our data. We show that these results can be understood in the context of the path explosion phenomenon. Furthermore, understanding the presence of path explosion, and the particular details of how it occurs between combinations of ‘in’ and ‘out’ nodes, allows us to understand how efficient message delivery can take place in these settings.

2 Path Properties and Implications on Routing

A forwarding algorithm solves a decentralized search problem—it searches for a short path between a source and destination node, starting at a given point in time. This path exists in space and time, and its duration is the amount of time between message generation and message delivery. The main focus of our work is trying to understand this solution space of paths that are available for use by a forwarding algorithm. In order to accomplish this, we formally define the notion of valid paths and develop a dynamic-programming based algorithm to enumerate such paths. For a message between a source (s), destination (d), we will use T_n to denote the time at which the n^{th} path reaches the destination, in order of increasing delivery time. We refer to T_1 as the optimal path duration. Our results show that for many messages, the duration of the op-



(a)

(b)

Figure 1: (a) Optimal path duration vs. Time to Explosion,(b) Average Delay (sec) vs Success Rate

timal path can be quite long (thousands of seconds). However a key result is that in the vast majority of cases, once the first path reaches the destination a very large number of additional paths reach the destination soon thereafter – typically tens or a few hundreds of seconds later. We refer to this phenomenon generically as *path explosion.*

For the purposes of this study we define the 'time to explosion' (T_E) as the elapsed time between the arrival of the first path and the arrival of the 2000^{th} path, i.e., $T_E = T_{2000} - T_1$. The number 2000 is not sacrosanct; we believe that 2000 paths are sufficient to cover paths that forwarding algorithms could take.

Each point in the Figure 1 (a) corresponds to (T_1, T_E) for a single message (note the difference in scale on the x and y axes) for Infocom 2006 dataset. There are two key inferences that can be drawn from the figure. First, we see that path explosion exists; for these messages there exist at-least 2000 paths and these paths arrive soon after the optimal path (T_1). Second, there is no clear relationship between optimal path duration and time to explosion; there are many cases in which the optimal path reaches the destination quickly but the path explosion occurs comparatively late, and there are many cases in which the optimal path reaches the destination late while the path explosion occurs quickly thereafter.

Using analytic models and empirical data analysis we develop an understanding of the factors that affect T_1 and T_E. We show using our analytical model that under the assumption of homogeneous contact rates, the path explosion is exponential in nature. However the model does not explain the lack of clear relationship between T_1 and T_E. To explain this we rely on the inhomogeneity of contact rates of nodes. More details can be found in [3].

An interesting aspect of our results is the similarity in performance of the variety of different forwarding algorithms. This is illustrated in Figure 1 (b). This implies that most of the algorithms find one of the many sub-optimal paths, and as they are plenty of them, this gives rise to similar performance. We are able to develop an explanation for this phenomenon based on our understanding of path explosion and different contact rates.

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