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# Efficient routing in carrier-based mobile networks

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ABSTRACT

The past years have seen an intense research effort directed at study of delay/disruption tolerant networks and related concepts (intermittently connected networks, opportunistic mobility networks). As a fundamental primitive, routing in such networks has been one of the research foci. While multiple network models have been proposed and routing in them investigated, most of the published results are of heuristic nature with experimental validation; analytical results are scarce and apply mostly to networks whose structure follows deterministic schedule.

In this paper, we propose a simple model of opportunistic mobility network based on oblivious carriers, and investigate the routing problem in such networks. We present an optimal online routing algorithm and compare it with a simple shortest-path inspired routing and optimal offline routing. In doing so, we identify the key parameters (the minimum non-zero probability of meeting among the carrier pairs, and the number of carriers a given carrier comes into contact) driving the separation among these algorithms.

## 1. Introduction

In the last decade, there has been significant research activity in highly dynamic networks, e.g. wildlife tracking and habitat monitoring networks [3,15], vehicular ad-hoc networks [4,28], military networks, networks for low-cost provision of Internet for remote communities [11,21], as well as LEO [23] and inter-planetary networks [5]. As the incurred delays in these networks can be large and unpredictable, they have been named Delay (or Disruption) Tolerant Networks (DTNs). The disruptions and loss of connectivity come from many sources—sparseness [14,22], high and unpredictable mobility [28], covertness, or nodes powering down to conserve energy [15]. Since the connectivity cannot be guaranteed, these networks can be classified as Intermittently Connected Networks (ICNs). As standard Internet and MANET routing protocols cannot be applied in ICNs, this has spawned intense research into communicating primitives in ICNs. Strong motivation also comes from the possibility of exploiting (conceivably maliciously) the ICNs for uses external and extraneous to the mobile carriers that form the network. As pointed out in [6], *"other entities (e.g., code, information, web pages) called agents can opportunistically move on the carriers network for their own purposes, by using the mobility of the carriers as a transport mechanism."*

The high dynamism of DTNs and ICNs cannot be adequately modelled by previous fault-based techniques. In these networks, *"[topology] changes are not anomalies but rather integral part of the nature of the system"* [6,7]. There have been several approaches to model such networks (time-varying graphs [13,26], temporal networks [16], evolving graphs [1,12], graphs over time [19], dynamic graphs [17]), all in essence capturing the network topology as a function of time. While these modelling frameworks allowed characterization of several important concepts related to connectivity over time, they

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are far too general for analytical investigation of performance guarantees of various routing algorithms. On the other hand, the more applied research of routing in ICNs is aimed at modelling and analysing real-life mobility patterns. Often, the real-life traces of a certain mobility scenario are collected, and analysed. However, in order to establish general results, the mobility has typically been modelled using planar random walk, random waypoint or related mobility models. Performance evaluation is in such cases achieved through simulation, analytical results are scarce and limited to these quite restricted and unrealistic mobility models. Clearly, there is a lack of models for ICNs that are simple and concrete enough to make theoretical analysis of communication algorithms tractable, while sufficiently strong to be of practical relevance.

From the simplicity point of view, we find the carrier-based approach of [13] highly desirable. It neatly combines the simplicity of discrete time and space with the ability to capture the inherently local communication. Its main drawback is the deterministic nature, as the mobility patterns in ICNs are often complex, inherently non-deterministic and unknown. One of the main contributions of this paper is an extension of this model to stochastic networks.

A carrier-based network consists of $n$ *sites*, $k$ mobile *carriers* roaming over these sites and an *agent* (or several agents, when considering multiple-copy routing schemes), which is the active entity executing the routing algorithm. The *agent* is always located on some carrier, the sites are resource-less abstractions of geographic locations. The system is synchronous. From the point of view of an agent, a time step proceeds as follows: The step starts with the agent located on some carrier $c$ at a site $v$. All carriers then move to their new destinations, with the carrier $c$ moving to site $v'$ (carrying with it the agent). To conclude the step, the agent can switch to any carrier $c'$ that is at the moment present at $v'$.

In [13] the carriers were limited to deterministically executing cyclical walks, making the network a periodic time-varying graph. We propose to model the carriers as stochastic processes. There are several possibilities to do so, e.g. using the recently introduced Markov Trace Model [10]. In [10] it is shown how to compute the stationary distributions for carrier location based on known Markov Trace Model of their movement. However, the situation is typically reverse: the probability distribution of carrier location can be estimated by sampling/trace collection, while the underlying movement algorithm is unknown. This motivates us to investigate a simpler case of carrier mobility modelled as i.i.d. process where the carrier location at each time step is chosen according to some fixed (per carrier) probability distribution over the sites. The principal question we ask is "How and to what extend can such simple and limited knowledge of the movement patterns be exploited to help routing?"

*Related work—routing in ICNs.* Routing in ICNs is a research area which has seen considerable attention. For deterministic networks, modified shortest path approaches can be used [14], however fundamentally different techniques are needed for stochastic networks. The first routing schemes (so-called *epidemic* routing [27]) for stochastic ICNs were flooding based and hence inherently costly in bandwidth, buffer space and energy consumption. Significant subsequent work [9,15,20,23–25] has been done to improve upon epidemic routing by limiting the spread of the messages to nodes that are estimated to be closer to the destination. Several approaches have been used for this estimation, typically using the previous history of carrier encounters [15,20,23] or specific models of carrier mobility [9,23]. Nevertheless, most of these approaches are inherently multi-copy and to various degrees exhibit the drawbacks of flooding. Furthermore, the typical performance evaluation is experimental comparison with epidemic routing, with little or no theoretical results concerning provable performance bounds. The few single-copy approaches [18,22,25] are either inherently based on the assumption that the movement range of the carriers covers all sites [22] or analytical results are known only for very simple mobility models (random walk) [25]. See [25,29] for detailed discussions of different routing schemes in ICNs and further pointers.

*Our results.* The focus of this paper is investigation of single-copy routing in (synchronous, time and space discrete) ICNs induced by mobile carriers whose mobility patterns are modelled as i.i.d. processes: for each carrier there is a known fixed probability distribution over the sites. Note that some sites can have zero probability in this distribution and thus some pairs of carriers can never meet, which implies a graph structure underlying our model. First, we show that it is sufficient to consider only *greedy* routing algorithms in which the agent always chooses the best available carrier according to some total ordering of the carriers. Such greedy routing is a type of *opportunistic routing* studied before [2,8], however our simple model and knowledge of carrier mobility patterns allows us to find the provably optimal algorithm *AlgOPT*. The algorithm is optimal in the sense that it has the lowest expected routing time (measured as the number of synchronous steps) and gives the best possible competitive ratio with respect to the optimal offline routing algorithm knowing the future moving patterns of carriers (which corresponds to epidemic flooding with unlimited resources).

We provide tight upper and lower bounds of $\Theta(1/p_{\min})$, and lower bound $\Omega(\Delta)$ on this competitive ratio, where $p_{\min}$ is the minimum non-zero probability of meeting among the carrier pairs and $\Delta$ is the maximum (over all carriers) number of carriers a carrier comes into contact with. This allows us to clearly identify the parameters of the carrier movement that drive the performance bounds of routing.

The upper bound is actually achieved even by a simple algorithm *SimplePath*, in which the agent follows a fixed sequence of carriers. This might possibly suggest that the use of *AlgOPT* is not really necessary. As a final result we show that this is not the case as there is an instance for which *SimplePath* is as much as $\Omega(n)$ times worse than *AlgOPT*.

## 2. Model

We consider a system of $n$ sites, and $k$ carriers. Each carrier $c$ is modelled by a sequence of random variables $\{X_c^{(t)}\}_{t=1}^{\infty}$, where $X_c^{(t)} \in \{1, \dots, n\}$ is the site to which the carrier moves in step $t$. In this paper, we consider *memoryless carriers* where

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