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Modeling opportunistic communication with churn

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ABSTRACT

In opportunistic networking, characterizing contact patterns between mobile users is essential for assessing feasibility and performance of opportunistic applications. There has been significant efforts in deriving this characterization, based on observations and trace analyses; however, most of the previously established results were obtained by studying contact opportunities at large spatial and temporal scales. Moreover, the user population is considered to be constant: no user can join or leave the system. Yet, there are many examples of scenarios which do not fully adhere to the previous assumption and cannot be accurately described at large scales. Urban environments, such as smaller city districts, are characterized by highly dynamic user populations. We believe that scenarios with varying population require further investigation. In this paper, we present a novel modeling approach to study operation of opportunistic applications in scenarios where the population size is subjected to frequent changes, that is, it exhibits *churn*. We examine two location-based content sharing schemes: a purely opportunistic case and an infrastructure-supported content sharing scheme, for which we provide stochastic models based on stochastic differential equations (SDEs). We validate our models in five scenarios: a city area, subway station, conference, campus, and a scenario with a synthetic mobility model and we show that the models provide good representations of the investigated scenarios.

1. Introduction

Opportunistic communication in urban areas is a promising solution for infrastructure-free location-based services and content sharing. The topic of urban opportunistic networking has resulted in a large body of research, with a majority of studies basing their results on scenarios where a fixed number of mobile users roams inside a closed area, following certain mobility patterns. However, the size of the geographical space where the communication happens plays a significant role. As the region of interest shrinks—consider a small urban district, rather than an entire city—the assumption of a closed population will no longer hold: there will eventually be users arriving into the area, staying inside for a while and leaving. The population of users is no longer constant and such a system is known as a system with open population (*open system* in short), or in the networking parlance, a system with *churn*. Neglecting the effect of churn in specific scenarios can be hazardous.

Understanding contact patterns between humans and modeling these patterns realistically is essential for designing opportunistic communication schemes and evaluating their performance. While the research towards this aim has thrived over the past years, there has been little work considering opportunistic systems with churn. In such systems, user population is in constant change, thus previously obtained results (e.g., the distribution of inter-contact times) may not be reliable. This study takes a step towards increasing our understanding by characterizing user interactions in such dynamic systems.

Our initial work towards that aim has first been presented in [1]. Herein we extend our study by investigating an additional scenario and providing more detailed analysis. In particular, we examine the effects of node churn on opportunistic communication in the context of content sharing. By means of stochastic differential equations (SDE), we model and evaluate two schemes: the first scheme considers purely opportunistic communication and the second assumes some fixed infrastructure. These scenarios set the scene for the modelling approach which, we envision, can be adapted for a variety of other applications.

The second objective of this study is to gain insights on how user heterogeneity can be tackled in a more tractable way than has been done before. Departing from the traditional assumptions on the homogeneous contact patterns, the recent modeling attempts have resulted in notable contributions such as the works [2,3]. In [2], the authors propose an analytic framework for evaluating performance of delay tolerant networks in terms of delivery delays, allowing different contact patterns for each pair of nodes

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in the system. The framework requires exact knowledge of the connectivity properties in a specific scenario and it relies on the exponential assumption for inter-contact times. More comprehensive is the performance modeling framework of Boldrini et al., [3], assuming general inter-contact times distributions. However, both frameworks are limited to closed populations.

The main contributions of this study are the following:

- We establish stochastic models for two epidemic content spreading schemes and we validate our models by means of simulation.
- We investigate five mobility scenarios including: realistic simulator-based traces, two sets of real-life traces and synthetic mobility. Then, we analyze the scenario-specific distributions of the contact rate and node sojourn time, and we compare these empirical distributions with modeling assumptions.
- We study contact patterns in systems with churn and provide an approximation of the contact rate for the system in the transient state.
- Based on the proposed modeling approach, we demonstrate an estimation method for the system parameters.

This paper is organized as follows. In Section 2 we describe the first content sharing scheme and present our modeling approach. Validation of this model is given in Section 3. The model for the second opportunistic application is developed in Section 4 and validated in Section 5. We review related work in Section 6 and summarize our most important findings in Section 7.

2. Opportunistic location-based content sharing: distributed case

First we consider an opportunistic service for sharing geographically localized contents. The service is targeted to mobile users in urban areas, where as an example of content type one can think of local news, tourist information, transportation schedules, traffic alerts, and the like. Content is geographically tagged to the region of relevance either explicitly e.g., given a set of geo-coordinates of a polygon that confines the region or the center and radius of the anchor zone [4], or implicitly by specifying geographic areas such as "central train station". Outside of the boundaries of the locale, content is considered irrelevant and will not be distributed.

The area of interest is characterized by frequent user arrivals and departures. We assume that mobile users are pedestrians equipped with mobile devices. Applications on user devices use services of a publish/subscribe middleware [5] to publish new contents, or to find peers within communication range and download or forward contents. Content can be classified into different distribution channels, however for the purpose of our study, we assume all users are subscribed to a single channel. Assume that initially there is a single user with a content item who wants to share it with other users in the area, without support of infrastructure. In addition to obtaining content, all nodes are willing to support further content spreading by contributing some amount of their resources for a limited time. This results in a fully distributed, purely opportunistic content sharing scheme. This scheme employs the *virtual storage effect* [6], and has also been referred to as *floating content* [7] or *hovering information* [8].

Users following certain mobility patterns will enter the area, move inside for a while and eventually leave. Since their movements are not bounded to the area, the feasibility and performance of such opportunistic scheme strongly depends on user mobility and contact patterns.

We are interested in answering questions such as:

1. Under what conditions the content is likely to persist in the area (that is, *survive*) for longer time, relying solely on the nodes' capability to store the content and forward it to other, intermittently encountered nodes?
2. What is the availability of the content, i.e., how many nodes currently carry and share the content item, and how many others have downloaded it?

The modeling approach we propose herein provides answers to the posed questions.

2.1. Measuring node interaction

Before delving into modeling, let us define relevant contact metrics. For characterizing closed systems, inter-contact time between specific node pairs has become a standard metric for representing node contact patterns. In open systems however, inter-contact times become immaterial as most node pairs have none or few contacts. We instead define contact rates as follows.

Definition 1. Contact rate of a single node in an open system is defined as the total number of contacts that the node established during its stay normalized by its sojourn time, i.e., the number of contacts per unit time.

The mean contact rate of the system, c, is obtained from the individual contact rates measured over a longer time interval. In particular, we denote by c_N the mean contact rate measured in a system with the average population of N nodes.

Definition 2. Consider a snapshot of the system when the population equals N. The total contact rate Λ_N is given by $\Lambda_N = \frac{N}{2} c_N$.

Definition 3. Pairwise contact rate η is the rate at which two arbitrary nodes come into contact with each other.

The total contact rate alternatively can be represented via the rate η_N, as $\Lambda_N = \frac{N(N-1)}{2} \eta_N \approx \frac{N^2}{2} \eta_N$. Note that we use index N to indicate that rates Λ_N and η_N depend on the current population size.

2.2. Stochastic model

To study phenomena such as *content survival* and to find the probability of this event, or to estimate the size of population that will carry the content, we can observe a stochastic system comprising three populations: nodes that currently carry and share the content, nodes that still have not obtained the content and nodes that stopped spreading the content. The evolution of this stochastic system can be analysed by considering stochastic processes of node arrivals and departures and the contact process between nodes. However, multivariate stochastic systems often do not easily lend themselves to analysis, due to multiple variables (in our case three) and many interacting factors that drive transitions between states. A common approach for studying complex system behaviour, which will also be utilized in our study, is by modeling by *stochastic differential equations* [9]. This approach has been used in mathematical epidemiology, where models are often referred to as *compartmental models*. Different population categories are called *compartments* and nodes within the same compartment are considered indistinguishable from one another with respect to their mobility and connectivity characteristics. By epidemic terminology, we denote as *susceptible* nodes who have not obtained content, *infected* are nodes who are still sharing the content, and those who have the content but are no longer participating in spreading are denoted as *recovered* nodes. Thus, in our model we will have compartments of: susceptible (S), infected (I) and recovered (R) nodes, Fig. 1. We will also refer to a content transfer event as an *infection*.

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