Ad Hoc Networks 24 (2015) 161–174

Contents lists available at ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

Modelling mobile opportunistic networks – From mobility to structural and behavioural analysis

Anh-Dung Nguyen [a,*], Patrick Senac [a], Michel Diaz [b]

[a] ISAE-University of Toulouse, 10 Avenue Edouard Belin, BP 54032, 31055 Toulouse Cedex 4, France
[b] LAAS-CNRS, 7 Avenue du Colonel Roche, BP 54200, 31031 Toulouse Cedex 4, France

ARTICLE INFO

Article history:
Received 4 March 2014
Received in revised form 7 July 2014
Accepted 29 July 2014
Available online 7 August 2014

Keywords:
Mobile opportunistic networks
Human mobility model
Small-world structure
Data dissemination

ABSTRACT

In this work, we propose a modelling framework which captures the most fundamental behavioural and structural properties of mobile opportunistic networks from mobility to structural level. First, we introduce Spatio-TEmporal Parametric Stepping (STEPS) – a simple parametric mobility model which can cover a large spectrum of human mobility patterns. STEPS abstracts the fundamental spatio-temporal behaviours of human mobility, i.e., preferential attachment and attractors, by using a power law to drive nodes' movement. We show that the model makes it possible to express key peer-to-peer properties of opportunistic networks such as inter-contact/contact time distributions. Leveraging on the expressive and modelling power of STEPS, we analyse how fundamental structural properties can emerge from the combination of elementary node's mobility behaviour. Specifically, we bring out one sufficient condition of the emergence of the famous small-world structure in opportunistic networks. We also show that this special dynamic network structure improves significantly the communication capacity of opportunistic networks.

1. Introduction

Mobile opportunistic networks are dynamic networks based on nodes' intermittent contacts between mobile devices carried by human users. This type of network, in which the end-to-end path between senders and receivers is not guaranteed and the communication has to rely on the store-move-and-forward paradigm, was shown to be the sole communication means in many extreme situations, especially when an infrastructure-based communication is not possible, for instance, deep space communications, disaster recovery networks, battlefield networks. Moreover, the ever increasing density of mobile wireless devices and sensors that populate the edge of the Internet raises the question of the efficient cooperative use of these vast space of resources by leveraging on the spontaneous communication capacity offered for free by "mobile clouds" of edge devices, e.g., for offloading mobile data, data caching and sharing, etc. Therefore, mobile opportunistic networks pave the way to a pervasive and universal communication environment in which the store-move-and-forward communication can play an important role by its capacity to free users from infrastructure dependence.

Human mobility was known to have a significant impact on performance of opportunistic networks [1,2]. Some statistical properties related to the spatial, temporal and social patterns of human mobility (e.g., scaling laws of the travelled distance, inter-contact/contact time, visiting time, return time, etc.) have been discovered [3]. Unfortunately, the complexity of the human mobility makes it hard to incorporate all these statistical characteristics in

* Corresponding author. Address: ISAE, 10 Avenue Edouard Belin, BP 54032, 31055 Toulouse Cedex 4, France. Tel.: +33 6 28 34 60 94.

E-mail addresses: anh-dung.nguyen@isae.fr (A.-D. Nguyen), patrick.senac@isae.fr (P. Senac), michel.diaz@laas.fr (M. Diaz).

http://dx.doi.org/10.1016/j.adhoc.2014.07.017
1570-8705/

one formal model. In this paper, we introduce Spatio-TEmporal Parametric Stepping (STEPS) – a powerful formal model for human mobility or mobility inside social/interaction networks that can capture not only spatio-temporal and social mobility patterns, but also the structure of human contact network.

In the first part of the paper, we show that preferential location attachment and location attractors are invariants properties and at the origin of the spatio-temporal correlation of human mobility. Indeed, as observed in several real mobility traces, while few people have a highly nomadic mobility behaviour the majority has a more sedentary one. We then assess the expressive and modelling power of our model by showing its capacity of expressing easily several fundamental spatio-temporal and social statistical characteristics of human mobility usually observed in real traces, in particular the truncated power law behaviour of the travelled distance, the pause time between travels and the inter-contact/contact time.

In the second part, with STEPS, we show how fundamental global structural properties can emerge from specific behaviour of mobile nodes. Specifically, we transpose in the framework of mobile opportunistic networks the notion of dynamic small-world structure. The famous experiment of Milgram showed that the human acquaintance network has a diameter in the order of six, leading to the small-world qualification. Watts and Strogatz later introduced a formal model of small-world phenomenon for static graphs [4]. The small-world graph is then qualified as graphs with an exponential decay of the average shortest path length contrasting with a slow decay of the average clustering coefficient. Interestingly, numerous real static networks exhibit such property. From a communication perspective, small-world networks make information diffusion as fast as random networks.

The great majority of studies on small-world networks properties and behaviours focused on static graphs and ignored the dynamics of mobile networks. For example, in a static graph, a data dissemination cannot spread out if the initial data carrier is in a disconnected component of the network; conversely in a mobile network, nodes movements can ensure the temporal connectivity of the underlying dynamic graph. Moreover, a data dissemination can take off or die out depending not only on the network structure and the initial carrier, but also on the time when the data begins to spread. These aspects cannot be captured by a static small-world model.

In order to formalise the dynamic small-world phenomenon, we extend to dynamics networks the notions of dynamic clustering coefficient and shortest dynamic path. By studying the evolution of these metrics from our rewiring process, we show that nomadic nodes (i.e., nodes with no preferential attachment) play the role of bridges between temporal communities, reduce significantly the shortest dynamic path length of mobile network and hence contribute to the emergence of the dynamic small-world structure. We then demonstrate the capacity of STEPS to capture this structural characteristic of mobile opportunistic networks. Finally, we show through formal analysis the impact of this structure on data dissemination speed of mobile opportunistic networks.

The rest of the paper is structured as follows. After an overview of the related works in Section 2, Section 3 formally introduces STEPS and Section 4 shows its capacity to capture salient features of opportunistic networks. In Section 5, after having formally defined the notions of dynamic clustering coefficient and shortest dynamic path length, we analyse various real opportunistic network traces and show the intrinsic properties of opportunistic networks that induce the small-world phenomenon. We show how STEPS can capture these properties and how to explain the emergence of these properties in opportunistic networks in Section 6. Finally we conclude the paper in Section 8.

2. Related works

Human mobility has attracted a lot of attention of not only computer scientists but also epidemiologists, physicists, etc because its deep understanding may help to explain many important issues in these different fields. Traditionally, in Mobile Ad-hoc Networks and Delay-Tolerant Networks researches, the lack of large scale mobility traces made that research initially based on simple formal models such as Random Waypoint and Random Walk (see [5] for a survey). The parameters of these models are usually drawn from an uniform distribution and hence not realistic and even are considered counterproductive in some cases [6].

Recently, available real mobility traces allowed researchers to understand deeper the nature of human mobility. Some statistical spatio-temporal properties of human mobility patterns have been discovered. These properties can be classified as spatial, temporal and social properties [3]. The spatial properties are related to the travelled distance and spatial patterns. The power law distribution of the travelled distance was initially reported in [7] in which Brockman et al. study the spatial distribution of human movement based on bank note traces. Recently, Yves-Alexandre de Montjoye et al. [8] investigated fifteen months of human mobility data for one and a half million individuals and found that human mobility traces are highly unique. Strikingly, they showed that four spatio-temporal points are enough to uniquely identify 95% of the individuals. Xin Lu et al. [9], by analysing the travel patterns of 500,000 individuals in Cote d'Ivoire using mobile phone call data records, also showed that human mobility is highly predictable. Regarding the temporal properties, In [10], Gonzalez et al. show that people have a significant probability to return to a few highly frequented locations. In another study [11], Song et al. show that humans show significant propensity to return to the locations they visited frequently before, like home or workplace. As for the social properties of human mobility, the power law distribution of the inter-contact time was initially studied by Chaintreau et al. in [1]. In [2], Karagiannis et al. extend this result and suggest that the inter-contact time follows a power law up to a characteristic time (about 12 h) and then cut-off by an exponential decay. The power law distribution of the contact duration was also reported in [12].

Existing mobility models can also be classified according to the properties they can capture, i.e., spatial, tempo-