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Ego network models for Future Internet social networking environments ☆

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ABSTRACT

In this paper we present constructive algorithms for generating realistic synthetic ego networks (one of the most important representations of human social networks). These algorithms are based on ego network models derived in the anthropology literature, which describe the key structural properties of ego networks, and the properties of the social relationships between individuals. The main area we consider for applying these algorithms is the study of social networking environments currently under discussion in the research community. In particular, we focus on two relevant examples, i.e. Mobile Social Networks, and Social Pervasive Networks. In both cases, together with the ego network structural properties, it is fundamental to also describe the statistical properties of the contact process between the nodes. To this end, we complement the algorithms with an analytical model that characterises the dependence between the key distributions used in the literature to describe the contact processes. Finally, we validate our algorithms and models, showing that the synthetic ego networks that can be generated matches both structural properties of ego networks, and contact process properties that have been found in real human social networks.

1. Introduction

There is a clear trend in the vast framework of Future Internet research that posits a tight integration between the physical and cyber worlds. This is not only relevant to research areas pertaining to Cyber Physical Systems [1], but spans more widely in all the areas of the Future Internet [2,3] in general, and future pervasive and mobile computing systems [4] in particular. The pervasive diffusion of mobile devices that users carry with them, together with a multitude of devices with networking and computation capabilities spread in the environment, is actually enabling this tight integration. Thanks to networking technologies that can well support mobile users and the flow of information between the cyber and the physical world (such as mesh [5–7] and sensor networks [8]), what happens in the cyber world impacts on the physical world and vice versa. For example, sensor readings coming from distributed sensors (in the physical world) are analysed (in the virtual world), and can trigger actions on actuators (in the physical world again). Social relationships (in the physical world) immediately translate into virtual relationships on Online Social Networks (in the virtual world).

In the perspective of such an integrated cyber-physical world, a key aspect to design efficient Future Internet solutions is understanding the properties of human social relationships. In a broad range of cases, devices in the cyber world are actually proxies of their users in the physical world, which follow them in their daily routines and behaviour (e.g., smartphones constantly carried by users). Therefore, the structures and properties of human social relationships can be naturally translated into relationships between the users' devices, around which networking solutions can be designed. A first element for achieving such an understanding is modelling the mobility of the users, as mobility is very often a strong indicator of social behaviour. This topic, in fact, has recently received increasing attention [9–17]. Beyond that, there is a broader research trend looking at the mutual interplay between the social relationships between users and the design of Internet solutions and platforms. This encompasses several topics, including monitoring users social relationships [18–20], characterising the behaviour of users in social networking platforms [21–24], designing optimised social networking services [25–30].

In this paper we consider two social networking scenarios brought about by cyber physical convergence, Mobile Social Networks (MSNs) and Social Pervasive Networks (SPNs). MSNs are typically formed between users located in a limited area (which can however be as big as a city), and communication among them

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is typically supported through opportunistic networking technologies [31]. Opportunistic networking is an evolution of the legacy MANET paradigm, where the existence of simultaneous end-to-end paths between two endpoints is not necessary in order to enable communication. Exploiting the store-carry-and-forward paradigm [32,33], messages are locally stored at intermediate nodes that are deemed most suitable to bring them closer to the eventual destination(s), until a new node appears (e.g., thanks to mobility), which is an even better candidate for reaching the destinations. A number of research topics are been addressed in the area of opportunistic networking, including forwarding protocols [34–37], privacy-preserving solutions [38,39], resource management and service-oriented systems [40,41], support for participatory sensing [42–44], and characterisation of foundational theoretical properties [45–47]. Some of the solutions investigated in this area exploit information about human social relationships, e.g. for routing protocols [48–50], and data dissemination protocols [51–53], although well grounded models of human behaviour (like those used in this paper) are seldom used.

Social Pervasive Networks are a possible longer-term (with respect to MSNs) evolution of the pervasive networking paradigm enabled by the tight integration of the cyber and physical worlds. Assuming that the diffusion of pervasive technologies will enable, in principle, communication between any two users anytime and anywhere, the resulting network might in fact be formed by edges that correspond to communication channels activated because of a social relationship between two users, and only when those users communicate due to their social relationship. In other words, the network and the communication events between the devices might closely map the corresponding human social network and the interaction patterns of the users. Multi-hop communications will still occur in this type of network, for example to enable diffusion of information among groups of people that do not necessarily have mutual social relationships. Besides being a natural design approach, another advantage of such a design paradigm is that activated communication channels will naturally inherit the trust level existing between their users, which is typically hard to assess in pervasive networks. A notable class of services that would benefit from such a design paradigm are content-centric and data dissemination services, which are considered to be one of the key drivers of the Future Internet [3]. Nowadays, content-centric services are mostly supported by Content Delivery Networks and P2P solutions [54]. Several solutions continue to be proposed for optimising systems based on these paradigms, in particular in the P2P area both for fixed and mobile networks [55–60]. SPNs could be used as a natural substrate for implementing trusted P2P-like content-centric solutions tailored to, for example, disseminating data to interested users in a scalable way. Note that opportunistic networking techniques could be used in SPNs too. Also in SPNs, data exchanges occur only when users bound by a social relationship activate a communication, which is conceptually a similar event to a physical meeting between users in a MSNs, and can thus be used to opportunistically forward messages or spread content. Finally, note that there is significant evidence suggesting that human social networks are almost invariant with respect to the specific technology that mediates social interactions [61,62]. Therefore, current results in the anthropology domain that describe the properties of human social networks are already a solid starting point to investigate the properties of SPNs.

Looking at the two main cases we consider in this paper (MSNs and SPNs) it clearly appears that well grounded models of human social behaviour are needed. We highlight two main features that should be captured by such models. On the one hand, the *structural* properties of human social relationships should be captured, to describe the characteristics of human social networks, and how they can be exploited for enabling efficient communications and data dissemination systems in the virtual world. On the other hand, the *contact processes* between users, and how they depend on the human social structures, should also be modelled, because contact patterns have a very strong impact on the performance of opportunistic networking protocols, and thus on MSNs and SPNs. For example, in the case of MSNs, it is known that key properties on convergence of opportunistic networking protocols depend on the statistical properties of contact patterns [63,64].

Providing models matching these requirements is the original contribution of this paper. In particular, we start from well established models coming from the anthropology literature (Section 3), which describe the structure of ego networks (a very important way of describing human social networks) and the properties of social relationships between individuals. Starting from this model, in Section 4 we propose a constructive algorithm to generate synthetic ego networks which reproduce these structural properties. This algorithm can, for example, be used in simulation to generate realistic synthetic human networks on top of which networking solutions for MSNs or SPNs can be tested.

In Section 5 we complement the algorithm with an analytical model that can be used to decide how to configure the contact processes between individuals. As we discuss at the beginning of Section 5, configuring the contact processes such that they reproduce the statistical properties found in real traces may not be straightforward. This is mainly due to the fact that, for practical reasons, it is difficult to characterise with sufficient statistical accuracy the distributions of inter-contact times between *individual users*. Therefore, it is customary in the literature to use aggregate statistics to characterise real traces, such as the distribution of contact *rate* (the reciprocal of the average inter-contact times between two users) and the distribution of *aggregate* inter-contact times (the distribution of inter-contact times of all pairs considered together). The model presented in Section 5 helps to correctly configure the contact processes between individual users, such that aggregate statistics found in real traces can be reproduced.

In Section 6, we validate the constructive algorithm and the analytical model of inter contact times. This allows us to show that fundamental properties of generated synthetic networks match real data found (i) in the anthropology literature, about the structure of human social networks, and (ii) in the opportunistic networking literature, about the properties of contact processes between users. Therefore, the results of this paper can be used, for example, in simulators, to generate synthetic traces for relevant examples of Future Internet social networks, that correctly reproduce statistical features of human social behaviour and interactions.

2. Related work

This paper is mainly related to two bodies of work. The first one consists in the anthropology literature about models of human social networks. This body of work is described in detail in Section 3. The second body of work consists in the literature about the study of inter-contact times in opportunistic networks.

Chaintreau et al. [63] have demonstrated the fundamental impact of inter-contact times on the convergence properties of opportunistic network forwarding protocols. The authors show that when the inter-contact times of individual pairs present a power law with shape parameter less than or equal to 2, a large family of routing protocols yield infinite delay. The authors also analyse real traces of face-to-face inter-contact times, both originally presented in the paper and collected by others [65–67]. Assuming that the network is homogeneous, they focus on the distribution of aggregate inter-contact times, finding a good fit with a Pareto distribution with shape parameter lower than 2. These results posed