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Analytical evaluation of the performance of contact-Based messaging applications☆

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ABSTRACT

Communications in mobile opportunistic networks, instead of using the Internet infrastructure, take place upon the establishment of ephemeral contacts among mobile nodes using direct communication. In this paper, we analytically model the performance of mobile opportunistic networks for contact-based messaging applications in city squares or gathering points, a key challenging topic that is required for the effective design of novel services. We take into account several social aspects such as: the density of people, the dynamic of people arriving and leaving a place, the size of the messages and the duration of the contacts. We base our models on *Population Processes*, an approach commonly used to represent the dynamics of biological populations. We study their stable equilibrium points and obtain analytical expressions for their resolution.

The evaluations performed show that these models can reproduce the dynamics of message diffusion applications. We demonstrate that when the density of people increases, the effectiveness of the diffusion is improved. Regarding the arrival and departure of people, their impact is more relevant when the density of people is low. Finally, we prove that for large message sizes the effectiveness of the epidemic diffusion is reduced, and novel diffusion protocols should be considered.

1. Introduction

The authors in [1] define Mobile Social Networking in Proximity (MSNP), as a wireless peer-to-peer network of opportunistically connected nodes that use proximity as the social relationship. This condition allows the establishment of local communication channels that can be used for applications such as information sharing, advertisement, disaster and rescue operations, gaming, etc. Instead of using the established Internet infrastructure, the communication in mobile opportunistic networks takes place upon the establishment of ephemeral contacts among mobile nodes using direct communication (i.e. Bluetooth or WiFi Direct). Moreover, by relying on properly designed security mechanisms, mobile opportunistic networks can increase the confidentiality and privacy of communications, since direct communications, unlike infrastructure based communication, are more robust to the tracking of the user behaviour.

Based on the concept of opportunistic networks, new contact-based messaging applications have recently been developed. Firechat, as an example, a messaging application meant for festivals, became popular in 2014 in Iraq due to the government restrictions on Internet use[1], and after that during the Hong Kong protests[2]. There are anyway other examples, like Briar (see https://briarproject.org) which is a secure messaging application, or CoCam [2] for image sharing in events. Moreover, several supporting frameworks and architectures are appearing, such as the Haggle project [3], a framework for autonomic and opportunistic

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[1] Kuchler, Hannah; Kerr, Simon. "Private Internet: FireChat app grows in popularity in Iraq". Financial Times, 2014-06-22

[2] Bland, Archie. "FireChat the messaging app that's powering the Hong Kong protests". The Guardian, 2014-09-29.

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computing, or AllJoyn, an open source, general networking framework from the Allseen Alliance (https://allseenalliance.org/). The experience shows that these messaging applications seem to be operative in open places with a moderate to high density of people.

In this paper, we analytically study the performance of these opportunistic contact-based messaging strategies in city squares or gathering points. According to a recent survey [4] analytical modelling and performance evaluation of DTNs and Opportunistic Networks is one of the key challenging problems. A common approach is to combine a network simulation tool with realistic mobility traces. Nevertheless, simulation can be very time consuming and restricted to the limited scenarios of the available mobility traces. Analytical models can avoid these drawbacks providing a fast and broader performance evaluation. Two classes of analytical models have been proposed for modelling this network dynamics: Markovian models [5–10] and deterministic models based on Ordinary Differential Equations (ODEs) [6,11–13]. Analytical models require anyway a precise and concise description of the mobility scenario, that usually assume that the inter-contact times distribution between pairs of nodes are exponentially distributed with a given contact rate [5].

We based our model on *Population Processes*, a method commonly used to model the dynamics of biological population [14]. More specifically to opportunistic networks, Haas and Small [6] presented a model based on epidemiological processes for a network that used animals (whales) as data carriers to store and transfer messages (an approach similar to DTN). Zhang et al. [11] derived ODE equations for the study of the dynamics of various forwarding and recovery DTN schemes, such as epidemic and 2-hop, among others. The authors of [12] introduced a mathematical approach for messages diffusion in opportunistic networks using the Epidemic protocol. This approach is based on well known models for the spreading of human epidemical diseases, e.g. SIR (Susceptible, Infectious and Recovered) models. One of the main conclusions of their analysis (mathematical model and its respective simulation) is that SIR models are quite accurate for the average behaviour of Epidemical DTN.

In [13] the authors propose a detailed analytical model to analyse the epidemic information dissemination in mobile social networks. It is also based on SIR models including rules that concern user's behaviour, especially when their interests change according to the information type, and it can have a considerable impact on the dissemination process. After large simulations, they have demonstrated the accuracy of their model.

Nevertheless, these previous models, do not take into account several social aspects that impact the performance of message dissemination such as: the density of people, the dynamic of people arriving and leaving a place, the size of the messages and the duration of the contacts. We therefore introduce dynamic models that take into account these social aspects, based on Delay Differential Equations (DDEs). DDEs are similar to Ordinary Differential Equation (ODEs), but their evolution involves past values of the state variable. DDEs have been used for modelling population dynamics in many disciplines such as biology, ecology, epidemics [15], and network protocol analysis [16].

For these models we studied their stable equilibrium points and obtained analytical expressions for their resolution. The evaluations performed showed that these models can reproduce the dynamics of message diffusion. We show that when the density of people increases, the effectiveness of the diffusion is improved. Regarding the arrival and departure of people, the impact is more important when the density of people is low. Finally, we prove that for large message sizes the effectiveness of the epidemic diffusion is reduced, and novel diffusion protocols should be considered.

The paper is organised as follows. Section 2 describes the contact-based messaging dissemination approach that we assume. Section 3 presents the models and Section 4 the evaluation of a few scenarios using our approach. Finally Section 5 offers the conclusions.

2. The considered contact-based messaging approach

The class of contact-based messaging applications we are considering in this work is based on establishing a short-range communication directly between mobile devices, and on storing the messages in these devices to achieve their full dissemination. It can be considered a wireless peer-to-peer (P2P) network of nodes that connect opportunistically. No messages are sent or stored in servers, rather, all information is stored on the mobile devices in a given area, i.e., it can be seen as a localised approach instead of a cloud approach.

Message spreading is based on epidemic diffusion, a concept similar to the spreading of infectious diseases, where an infected node (the one that has a message) contacts another node to infect it (transmit the message). Epidemic routing obtains the minimum delivery delay at the expense of increased usage of local buffer and increased number of transmissions. There are different variations of this diffusion scheme (that is, the infection process), that attempt to reduce resource utilisation e.g., 2-hop forwarding [5], probabilistic forwarding [17] and spray-and-wait or multiple copy [7,18].

The diffusion of messages among users is organised in groups. Users can join (and leave) a group, and their members receive the messages that are sent to the group. Thus, the goal is to spread all the messages of the various groups so that they can be received by the subscribed members. The mechanisms for group management are, anyway, outside the scope of this paper.

Message dissemination takes place as follows. Mobile devices have a messaging application that notifies and shows the user the received messages for the subscribed groups. Each node has a limited buffer where the messages in transit can be stored. When two nodes establish a pair-wise connection, they exchange the messages they have in their buffer, and check whether some of the newly received messages are suitable for notification to the user. All nodes that have the messaging application collaborate in storing and forwarding messages.

Typically, not all connections will end with a successful transmission. The effectiveness of a transmission depends on several factors, mainly on contact duration but also on interference, social behaviours such as selfishness, etc. We define an *effective contact* a contact that is successful, i.e., whose duration allows the complete transfer of the designated messages. Assuming a contact rate $\hat{\lambda}$, that comprises all opportunistic contacts, and defining p as the probability of successful transmission, the *effective contact rate* is simply $\lambda = p\hat{\lambda}$.

Regarding contact duration, two approaches can be assumed:

- The devices stop when they need to exchange information. In this case, the owners of the mobile devices control this exchange by waiting until the message transmission is completed. This is a commonly used scheme in several existing short-range messaging protocols such as *Apple iOS Airdrop* and *Google Android Copresence*. We can also consider, that not all user are willing to stop, so reducing the effective contact rate.
- The devices do not stop, so the completion of message transmission will depend on the contact duration. In this case, when the contact duration is lower than the message transmission time, the transmission fails. The success probability p will clearly depend on the users mean speed and communication range. For example, if nodes are expected to be constantly