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Barter trade improves message delivery in opportunistic networks

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ABSTRACT

In opportunistic networks, selfish nodes can exploit the services provided by other nodes by downloading messages that interest them, but refusing to store and distribute messages for the benefit of other nodes. We propose a mechanism to discourage selfish behavior based on the principles of barter. We develop a game-theoretic model in which we show that the proposed approach indeed stimulates cooperation of the nodes. The results show that, in practical scenarios, the message delivery rate considerably increases, if the mobile nodes follow the Nash Equilibrium strategy in the proposed mechanism compared to the data dissemination protocol when no encouraging mechanism is present.

1. Introduction

An opportunistic network is a mobile ad hoc network where the transfer of messages from their source to their destination is performed by the intermediate mobile nodes in a *store-carry-and-forward* manner. This means that the intermediate nodes carry the messages and pass them on to other intermediate nodes when they have a connection (e.g., when they are in vicinity).

Such networks can complement traditional personal wireless communications systems, such as cellular networks, in applications where local information needs to be distributed to a set of nearby destinations based on their interest in the information.

As a motivating example, let us consider a touristic city, such as Rome or Paris, where it would be beneficial for the tourists to be able to share information concerning the various touristic sights. A possible solution would be to set up an on-line bulletin board where tourists can post messages of potential interest for other tourists. However, this solution needs a service provider that runs the bulletin board service, and each tourist must have wireless Internet access for posting and downloading messages. The business model behind this solution would likely require the tourists to pay for both the service usage and the network access.

An alternative solution could benefit from the proliferation of Bluetooth capable personal devices such as mobile phones, PDAs, and MP3 players. These devices can communicate with each other when they are in vicinity even without any user intervention. Touristic information can then be distributed in a store-carry-and-forward manner by using these devices and by exploiting the mobility of the tourists themselves. This would result in a city-wide opportunistic network.

A potential problem in opportunistic and in delay-tolerant personal wireless networks is that the quality of the service provided by the system heavily depends on the users' willingness to cooperate. In particular, the users may act selfishly meaning that they download messages from other users that are interesting for them, but they deny storing and distributing messages for the benefit of other users. As shown in [1], if the majority of the users behave selfishly, then the message delivery rate decreases considerably and the quality of service provided by the network decreases accordingly.

The problems identified in [1] are the motivation for proposing a mechanism that encourages the users to carry other users' messages even if they are not directly

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interested in those messages. Our proposed mechanism is based on the principles of *barter*: the users trade in messages and a user can download a message from another user if he/she can give a message in return. We expect that it is worth for the users collecting messages even if they are not interested in them to exchange them later for messages that they are interested in. Thus, the messages are expected to disseminate faster in the network.

We analyze our proposed solution using game-theoretic techniques. We show that it is worth for the users collecting and disseminating messages even if they are not interested in them, which means that our approach indeed discourages selfishness. The results show that, in practical scenarios, the message delivery rate considerably increases, if the mobile nodes follow the Nash Equilibrium strategy in the proposed mechanism compared to the data dissemination protocol when no encouraging mechanism is present.

This paper is a considerably extended version of our previous work [2]. The differences between the two papers are manyfold. We have rebuilt the system and the game model to be more realistic, and we extended the simulation sets, too. In this paper, we present new contributions and a more detailed analysis of the results.

The remainder of the paper is organized as follows. In Section 2, we analyze the system without any incentives and determine the scenarios where stimulating mechanism should be introduced. In the same section, we introduce the system model that is used to analyze the system with and without encouragement. We describe our barter based approach, and we also extend the system model with the barter mechanism in Section 3. For the analysis of the effects of selfish behavior on the system augmented with the barter mechanism, we introduce a game-theoretic model in Section 4. In Section 5, we show and interpret the results of the barter game. We summarize the related work in Section 6. Finally, we conclude this paper in Section 7.

2. System analysis

In this section, we introduce our system model, which is general enough to represent different applications, and it is particularly well adapted for the example touristic scenario described above. Because of the complexity of the model, we use simulations instead of analytical tools. We show that there are scenarios where the message delivery has large latency because the mobile nodes are selfish in a sense that they only store and forward messages that they are directly interested in. The aim of the analysis is twofold: (1) to prove that an incentive is required in the network to increase the message delivery rate and decrease the message delivery latency, and (2) to give a reference with which we can compare our subsequent solution.

2.1. System model

In our model, the users are placed in an arbitrary field. They own devices that have capabilities to communicate with other devices within their radio range. We consider the case when the devices communicate via wireless links, however, or analysis can be extended to wired communication too. The used wireless technology can be Bluetooth, Wi-fi or any suitable wireless techniques. The messages are generated and disseminated among the devices/users in the considered system, but each user is interested only in a small subset of the messages. The dissemination process is based on the store-carry-and-forward principle. A user and her device together is the *mobile node*, and we assume that the message destination has no impact on the user's movement.

Each message has a type for each mobile node. For simplicity, we distinguish only two types: primary messages and secondary messages. A message is a primary message for a given mobile node, if the mobile node is interested in the content of the message and secondary if the mobile node is not. Note that a message may have different types for different mobile nodes, as different mobile nodes are interested in different contents.

These messages are generated by special nodes which we call *message nodes*. In our system model the time is slotted, and the message nodes generate new messages with a fixed average rate: ϱ messages per time step. The message nodes are static and each one stores only the most recently generated message, which can be downloaded at the cost of communication by any mobile node that passes by the message node.

A message has two main properties: the first one is the *popularity* attribute and the second one is the *discounting characteristic*. The popularity attribute $0 < \zeta \leqslant 1$ describes the probability that a randomly taken mobile node is interested in the message. We assume that message nodes do not generate irrelevant messages, hence we consider $\zeta > 0$.

Each message has some value for each mobile node. The value of a message is determined by its age. For simplicity, we assume that primary messages of the same age have the same value for the mobile nodes. Without loss of generality, we assume that the value of a primary message at the time of its generation is one unit, and this is discounted in time, because messages lose their value over time. This is usually the case in the applications that opportunistic networks are envisioned for. The discounting characteristic is described with a function: $\delta(t)$. The discounting function determines the value of the messages over time. Obviously, it is difficult or impossible to find a discounting function which suits to each application. Therefore, we defined three different monotonely decreasing discounting functions. We express these function in Eqs. (1)–(3) and we plot them in Fig. 1. In the first case, the message value decreases linearly, in the second case, the messages devaluate exponentially, and in the last case, the messages lose their value suddenly, similarly to a step function.

$$\delta_0(t) = \begin{cases} 1 - \frac{t}{500} & \text{if} \quad t < 500, \\ 0 & \text{else}, \end{cases} \tag{1}$$

$$\delta_1(t) = 0.995^t, \tag{2}$$

$$\delta_2(t) = 1 - \frac{1}{1 + 1000 \cdot (1 - \frac{1}{20})^t}, \tag{3}$$

When two mobile nodes get in the vicinity of each other, they interact in the following way: