Delay Tolerant Networks in Partially Overlapped Networks: A Non-cooperative Game Approach*

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Abstract. Epidemic forwarding protocol in Delay Tolerant Networks maximizes successful data delivery probability but at the same time incurs high costs in terms of redundancy of packet copies in the system and energy consumption. Two-hop routing on the other hand minimizes the packet flooding and the energy costs but degrades the delivery probability. This paper presents a framework to achieve a tradeoff between the successful data delivery probability and the energy costs. Each mobile has to decide which routing protocol it wants to use for packet delivering. In such a problem, we consider a non-cooperative game theory approach. We explore the scenario where the source and the destination mobiles are enclosed in two different regions, which are partially overlapped. We study the impact of the proportion of the surface covered by both regions on the Nash equilibrium and price of anarchy. We also design a fully distributed algorithm that can be employed for convergence to the Nash equilibrium. This algorithm does not require any knowledge of some parameter of the system as the number of mobiles or the rate of contacts between mobiles.

1 Introduction

Delay tolerant mobile ad-hoc networks have gained attention in recent research. Instantaneous connectivity is not needed any more and messages can arrive at their destination thanks to the mobility of some subset of nodes that carry copies of the message. A naive approach in forwarding a message to the destination consists in the use of an epidemic routing strategy, in which any mobile that has the message keeps on relaying it to any other mobile that arrives within its transmission range and which does not still have the message. This would minimize the delivery probability at a cost of inefficient use of network resources in terms of energy used for transmission. The need for a more efficient use of network resources has motivated the use of more economic packet forwarding strategies such as the two-hop routing protocols, in which the source transmits copies of its message to all mobiles it encounters, but these relay the message only if they come in contact with the destination. The performance of the two-hop forwarding protocol along with the effect of the timers have been evaluated in [1]. In this paper we consider an alternative approach that offer a way of studying the successful delivery probability and energy consumption. This paper aims to provide a scheme which maximizes the expected delivery rate while satisfying a certain constant on the number of forwardings per message. To do this, we assume that each mobile may decide which

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routing protocol it wants to use for delivering packets. We restrict the case that only two routing protocols are available to mobiles: epidemic routing and two-hops. This scheme allows us to exploit the trade-off between delivery delay and resource consumption. The higher number of users use epidemic (resp. two hops) routing , the higher (resp. lower) probability of success and the higher (resp. lower) consumption of resource.

In our study we assume that each mobile like to find the routing protocol that maximizes his utility function. But, as this utility depends on the action of the other mobiles, the system can be described as a non-cooperative game. We show that this game has at least one Nash equilibrium, and we designed a distributed algorithm to reach it. This algorithm is implemented at each node, allowing the system to reach the Nash equilibrium in a completely distributed way. Since the estimation of some parameters of the system, is very difficult in DTN, due to the lack of persistent connectivity, the proposed algorithm also allows the nodes to converge to the Nash equilibrium without any information.

Delay Tolerant Networks (DTNs) have recently attracted attention of the research community. Delay Tolerant Networks (DTNs) are sparse and/or highly mobile wireless ad hoc networks where no continuous connectivity guarantee can be assumed [2, 3]. There are several results of real experiments on DTNs [6, 11, 13]. In [10], the authors studied the optimal static and dynamic control problems using a fluid model that represents the mean field limit as the number of mobiles becomes very large. In [9], the optimal dynamic control problem was solved in a discrete time setting. The optimality of a threshold type policy, already established in [8] for the fluid limit framework, was shown to hold in [9] for the actual discrete control problem. A game problem between two groups of DTN networks was further studied in [9].

2 The Model

We consider two overlapping network regions, where source and destination nodes are each in distinct regions. By network region we mean a region with moving nodes that can establish a connection between them. We assume that nodes have random waypoint mobility (see [7]) which is confined to the region it is associated . In context of DTN the transportation of data relies mainly on mobility, so the overlapping region plays an important role. Overlapping regions are the only place where nodes can exchange data from one region to another. Consider that network region S_1 contains a source S, and N_1 mobile nodes, and that network region S_2 contains the destination node d and N_2 mobile nodes. Since source and destinations are in different regions, data can be transported from source to destination by mobile nodes only through the overlapping region $\hat{S}$. Let us parameterize the overlapped(normalized) region, denoted by $\tilde{S} = \hat{S}/\max\{S_1, S_2\}$. Notice that the overlapping region $\tilde{S}$, when parameterized reduces to (assume $S_1 = S_2$ for simplicity) the following special cases : “Unified network”, i.e., when $\tilde{S} = S_1 = S_2$, and “Overlapped network” when $0 < \tilde{S} < 1$.

We assume that each mobile node is equipped with some form of proximity wireless communications device. The network regions are assumed to be sparse, so that, at any time instant, nodes are isolated with high probability. Communication opportunities arise whenever, due to mobility patterns, two nodes get within mutual communication

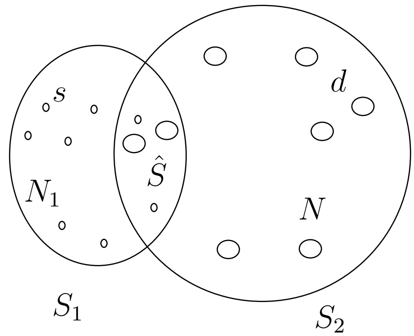

Fig. 1. Overlapped Network Region $\hat{S}$

range. We refer to such events as "contacts". The time between subsequent contacts of any pair of nodes is assumed to follow an exponential distribution. The validity of this model for synthetic mobility models (including, e.g., Random Walk, Random Direction, Random Waypoint) has been discussed in [1]. In [7], the authors derived the following estimation of the pairwise meeting rate λ :

$$\lambda = \frac{2wRE[V^*]}{S}, \tag{1}$$

where w is a constant specific to the mobility model, $E[V^*]$ is the average relative speed between two nodes and R is the range. Let λ_1 (resp. λ_2) be the rate of meeting of any pair of nodes in region S_1 (resp. S_2). Let λ_S denote the rate of meeting between the source and a node in region S_2. From (1), we have

$$\lambda_1 = \frac{2wRE[V_1^*]}{S_1}, \ \lambda_2 = \frac{2wRE[V_2^*]}{S_2} \text{ and } \lambda_s = \frac{2wRE[V_s^*]}{S_1}.$$

Similarly, the rate of meeting between a node (resp. source) in S_1 and a node in S_2 is given by $\lambda_{12} = \frac{2wRE[V_{12}^*]}{\hat{S}}$, $\lambda_{s_2} = \frac{2wRE[V_{s_2}^*]}{\hat{S}}$,

where V_{s_2} is the average relative speed between source and a node in region S_2. There can be multiple source-destination pairs, but we assume that at a given time there is a single message, eventually with many copies, spreading in the network. For simplicity we consider the message originated at time t = 0. We also assume that the message that is transmitted is relevant only during some time τ. The message contains a time stamp reporting its generation time, so that it can be deleted at all nodes when it becomes irrelevant.

A mobile terminal is assumed to have a message to send to a destination node. We consider in this paper two types of routing in DTN networks: epidemic routing and two-hop routing. In this paper we study the competition between individual mobiles in a game theoretical setting. Each mobile can decide whether to use epidemic or two-hop routing, depending on which strategy maximizes his utility function. We assume that the source node S stays in region S_1 while the destination node d stays in region S_2. Naturally, the nodes in S_1 needs to forward the packet to the nodes in S_2. Hence, the nodes in S_1 are of "Epidemic" type only, while nodes in S_2 may be of either type.

Consider that there are N_1 mobiles among the total N_{tot_1} in region S_1 which participate in forwarding the packet using epidemic routing. We assume that N mobiles among N_{tot} in region S_2 can choose between epidemic and two-hop routing. Let N_e^0 (resp. N_t^0) be the number of mobiles that always use epidemic (resp. two-hop) routing. Then, we have:

$$N_{tot} = N + N_e^0 + N_t^0$$

The source in region S_1 has a packet generated at time 0 that wishes to send to the destination d in region S_2. In region S_2, let N_e (resp. N_t) be the number of users that use epidemic routing (resp. two-hop routing). Let $X_e(t)$ (resp. $X_t(t)$) be the number of mobile nodes (excluding the destination and source) that use epidemic routing (resp. two-hop) and have at time t a copy of the packet. Denote by $D_i(\tau)$ the probability of a successful delivery of the packet by time τ. Then, given the process X_i (for which a fluid approximation will be used), we have the probability of successful delivery of packet as:

$$P_{succ}(\tau) = 1 - e^{\left(-\lambda_d \int_0^\tau (X_e(t)+X_t(t))dt\right)} \tag{2}$$

where λ_d denotes the inter-meeting rate between the destination and a node in S_2. Consider that on successful delivery of the packet is rewarded with $\bar{\alpha}$ which is shared among all the participating nodes. Let the reward is shared among the two region as α_{S_1} for region S_1 and α for S_2, where $\bar{\alpha} = \alpha_{S_1} + \alpha$. In region S_1 there are only epidemic type user, the reward is shared equally among $X_1(\tau)$ users. While in region S_2, the reward α is further shared as α_e (resp. $\alpha_t = \alpha - \alpha_e$) among the mobiles that have at time τ a copy of the message and use epidemic (resp. two-hop) routing. Hence, the utility U_e (resp. U_t) for a player using epidemic (resp. two-hop) routing is given by

$$U_e(N_e) = \Big(\frac{\alpha_e P_{succ}(\tau)}{X_e(\tau)} - \beta\tau\Big)\mathbb{P}_1(\text{ resp. } U_t(N_e) = \Big(\frac{\alpha_t P_{succ}(\tau)}{X_t(\tau)} - \gamma\tau\Big)\mathbb{P}_1) \tag{3}$$

where β and γ are the energy cost ,and $\mathbb{P}_1(t) = 1 - e^{-\int_0^t (\lambda_{s_2} + \lambda_{12}X_1(s) + \lambda_2 X_e(s) ds)}$ which denotes that the probability of receiving a packet by time t.

2.1 Fluid Approximation

We consider the following standard fluid approximation (based on mean field analysis)

$$\frac{dX_1(t)}{dt} = (\lambda_s + \lambda_1 X_1(t) + X_e(t)\lambda_{21})(N_1 - X_1(t)), \tag{4}$$

$$\frac{dX_e(t)}{dt} = (\lambda_{s_2} + \lambda_{12} X_1(t) + X_e(t)\lambda_2)(N_e - X_e(t)), \tag{5}$$

$$\frac{dX_t(t)}{dt} = (\lambda_{s_2} + \lambda_{12} X_1(t) + X_e(t)\lambda_2)(N_t - X_t(t)). \tag{6}$$

The essage is spread directionally, which means that nodes from region S_1 can forward the packet to nodes in S_2, while the reverse is not allowed,so $\lambda_{21} = 0$. On solving the ODE's given in eq. (4)-(6) using the suitable initial conditions, we obtain

$$X_1(t) = \frac{\lambda_s N_1 \left(1 - \exp\left(-t\left(\lambda_s + \lambda_1 N_1\right)\right)\right)}{\lambda_s + \lambda_1 N_1 \exp\left(-t\left(\lambda_s + \lambda_1 N_1\right)\right)}\,, \tag{7}$$

$$X_e(t) = \frac{N_e\left[\psi(t)\left(1 - N_e\int_0^t \frac{\lambda_2}{\psi(u)}du\right) - 1\right]}{\psi(t)\left(1 - N_e\int_0^t \frac{\lambda_2}{\psi(u)}du\right)}, \tag{8}$$

$$X_t(t) = N_t\Big(1 - \exp\Big[-\lambda_{12}\int_0^t X_1(u)du + \lambda_2\int_0^t X_e(u)du + t\lambda_{s_2}\Big]\Big). \tag{9}$$

where $\psi(t) = \exp\left(\int_0^t \left(\lambda_{s_2} + \lambda_{12}X_1(u) + \lambda_2 N_e\right)du\right)$.

3 The DTN Game

As explained before, there is but a single choice for the nodes in region S_1, i.e., to participate or not in epidemic forwarding. However in region S_2, a node can choose between participating or not, and, if so, it can choose between epidemic forwarding or two hop forwarding to deliver the packet to destination. Every mobile would like to find the strategy that maximizes his individual utility. But, as his utility depends on the actions of the other mobiles, the system can be described as a non-cooperative game. As the game is symmetric, a Nash equilibrium (NE) N_e^* is given by the two conditions:

$$U_e(N_e^*) \geq U_s(N_e^* - 1) \text{ and } U_t(N_e^*) \geq U_e(N_e^* + 1)$$

The previous definition means that no user using epidemic routing (resp. two-hop routing), has an incentive to use two-hop routing (resp. epidemic routing). The existence of the Nash equilibrium is guaranteed by [12].

4 Stochastic Approximation for Nash Equilibrium

In this section we introduce a distributed method to achieve the Nash equilibrium in the case where some parameters (i.e., N, λ and λ_s) are unknown. We show that simple iterative algorithms may be implemented at each node, allowing them to discover the Nash equilibrium in spite of the lack of information on such parameters. Note that the estimation of N, λ and λ_s, is very difficult in DTN because of the lack of persistent connectivity. This distributed algorithm proposed in [5] was proved, for a fixed number of players, that if it converges, it will always do to a Nash equilibrium. In order to increase the speed of convergence, each user decides to stop his update mechanism after reaching a given threshold [4]. It is not a global convergence criteria, as we can find in centralized algorithms, but an individual convergence criteria that let each user stop calculations. The algorithm is based on a reinforcement of mixed strategies and players are synchronized in such a way that the decision of all players (playing pure strategy) induce the utility perceived for each one.

The algorithm works in rounds. Each round corresponds to the delivery of a message by the source. Let $N_e(t)$ be the number of players that use epidemic routing at round t.

At each round t, each user i chooses epidemic routing over the set $C = \{e, t\}$ of strategies, with probability p_t (and chooses the two-hop routing with probability $1 - p_t$). The utility perceived by user i at round t depends on his action and on the actions of the other mobiles. This utility u_t^i is expressed as follows:

$$u_t^i = \mathbb{1}_{\{c_t=e\}} \cdot U_e(N_e(t)) + \mathbb{1}_{\{c_t=t\}} \cdot U_t(N_e(t)) \tag{10}$$

Then, each player updates his probability according to the following rule (see Algorithm 1):

$$p_t^i = p_{t-1}^i + b \cdot \left(\mathbb{1}_{\{c_t=e\}} - p_{t-1}^i\right) \cdot u_t^i, \tag{11}$$

Figure 3.b shows the evolution of the probabilities and the convergence to Nash Equilibrium for a set of 10 players, using a treshold of convergence at $\epsilon = 10^{-6}$.

5 Global Optimum Repartition and Nash Equilibrium

In this section, we are interested in the network efficiency as the maximization of the global optimum of the system. We want to optimize the overall network energy-efficiency with respect to the aforementioned degrees of freedom. For this purpose, we consider the optimal social welfare, which is well known in game theoretic studies, and compare it with the performance achived at Nash Equilibrium.

The following simulations allow us to see the range of values for different parameters which minimizes the gap in total utility between the Nash equilibrium and the global optimum. For different rates of λ_s and different values of the reward on epidemic routing α_e, we compute the price of anarchy, using the total utility at the global optimum repartition and at Nash Equilibrium.

The social welfare of the network is measured by the total utility of the system expressed by

$$W_s = X_e(\tau)U_e(N_e) + X_t(\tau)U_t(N_e) \tag{12}$$

and the price of anarchy is measured as follows:

$$PoA = (W_s^{Opt} - W_s^{NE})/W_s^{Opt} \tag{13}$$

where W_s^{Opt} (resp. W_s^{NE}) is the social welfare at the global optimum (resp. at the Nash Equilibrium.)

Through the different simulations for several set of values for the main parameters of our DTN network, we observe the network stability and efficiency. In figure 2 we plot the evolution of the number of users infected using either two hops or epidemic routing. As we can notice, the rate of infection of users using epidemic routing increases with the inter-meeting rate in the second region before reaching a stability point, that is mainly influenced by the relevant time of packet delivery which increases the probability of success and makes the infection rate independent on λ_2. This rate is always bigger with the surface of overlapping and the reward on using epidemic routing. We observe the same behavior for the infection rate of users using two-hop routing, except that the infection rate become smaller with the reward on using epidemic routing. Figure 3.a present on the other hand the price of anarchy (PoA) at Nash Equilibrium. For small

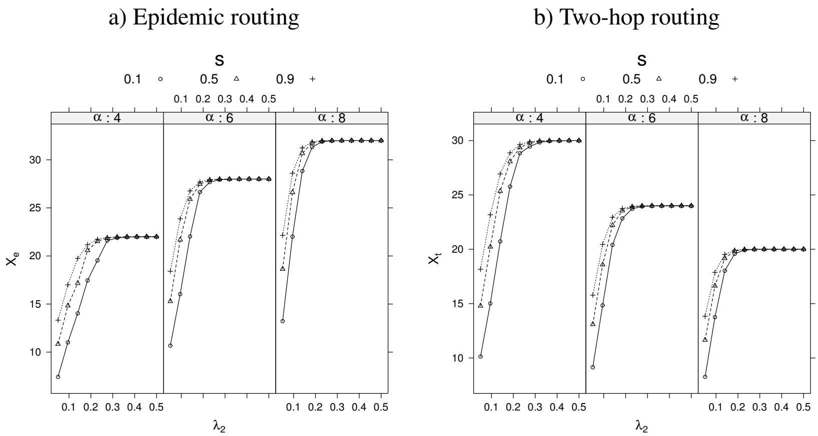

Fig. 2. Infected users using epidemic or two-hop routing

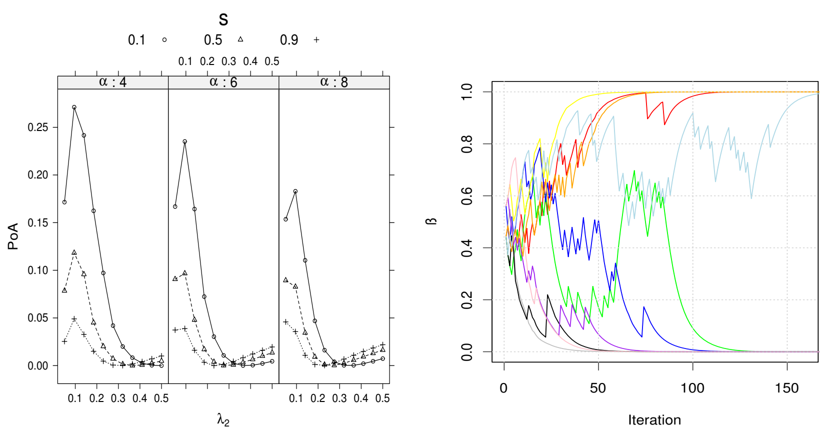

Fig. 3. a) Price of anarchy depending on λ_2 b) Convergence to Nash Equilibrium

values of the inter-meeting rate λ_2 in the second region, the PoA takes it highest values and is almost independent on $\tilde{S}$. The optimality of the Nash equilibrium (obtained when the PoA is near or equal to zero) is achived for small values of λ_2 by increasing α_e or $\tilde{S}$.

6 Conclusion

This paper presents a framework to analyse the tradeoff between the successful data delivery probability and energy costs. We formulate the problem as a non-cooperative game in which each mobile has to decide which routing protocol it wants to use for packet delivering: Epidemic routing or Two-hop routing. We explore the scenario where the source and the destination mobiles are enclosed in two different regions, which are partially overlapped. We showed the impact of overlapping area on price of anarchy and Nash equilibrium. To complete this contribution, we plan to analyze the system when there are new arrivals to the area of interaction and mobiles within this area will be active for a limited period of time. This configuration makes the system dynamic in the number of mobiles, a more realistic approach to a DTN case.

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