Competition and Cooperation between Nodes in Delay Tolerant Networks with Two Hop Routing

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Abstract. This paper revisits the two-hop forwarding policy in delay tolerant networks (DTNs) and provides a rich study of their performance and optimization which includes (i) Derivation of closed form expressions for the main performance measures such as success delivery probability of a packet (or a message) within a given deadline. (ii) A study of competitive and cooperative operations of DTNs and derivation of the structure of optimal and of equilibrium policies. (iii) A study of the case in which the entity that is forwarded is a chunk rather than a whole message. For a message to be received successfully, all chunks of which it is composed have to arrive at the destination within the deadline. (iv) A study of the benefits of adding redundant chunks. (v) The convergence to the mean field limit.

1 Introduction

Through mobility of devices that serve as relays, Delay Tolerant Networks (DTNs) allow non connected nodes to communicate with each other. Such networks have been developed in recent years and adapted both to human mobility where the contact process is between pedestrians [5], as well as to vehicle mobility [7].

The source does not know which of the nodes that it meets will reach the destination within a requested time, so it has to send many copies in order to maximize the successful delivery probability. How should it use its limited energy resources for efficient transmission? Assume that the first relay node to transfer the copy of the packet to the destination will receive a reward, or that some reward is divided among the nodes that participated in forwarding the packet. With what probability should a mobile participate in the forwarding, what is the optimal population size of mobiles when taking into account energy and/or other costs that increase as the number of nodes increase? If it is costly to be activated, how should one control the activation periods?

We propose in this paper some answers to these questions using simple probabilistic arguments. We identify structural properties of both static and dynamic optimal policies, covering both cooperative and non cooperative scenarios.

This paper pursues the research initiated in [2] where the authors already 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. That work has been extended in [3] to model the separable nature of a packet, which is composed of K blocks called chunks. Only once all chunks

R. Núñez-Queija and J. Resing (Eds.): NET-COOP 2009, LNCS 5894, pp. 264–278, 2009.

corresponding to a packet are received, the packet is considered to be available at the destination. The authors of [3] also study adding H redundant chunks such that the packet can be reconstructed at the destination once it receives any K out of the $K + H$ chunks.

In this paper we revisit the work of [2,3] with the following differences. (i) In [3] it is assumed that memory is limited so that a mobile can only carry one chunk. In this paper we restrict to systems that do not have such constraints. (ii) Both problems [2,3] were modeled using a mean field limit. We consider here the exact models and show that the mean field limit serves as a bound for the performance of the original system. The bound becomes tight as the number of mobiles increases.

In [4], a related optimal dynamic control problem was solved in a discrete time setting. The optimality of a threshold type policy, already established in [2] for the fluid limit framework, was shown to hold in [4] for some discrete control problem. A game problem between two groups of DTN networks was further studied in [4]. We complement these in the current work by focusing on other types of game theoretical problems: those concerning competition between individual mobiles. We obtain the structure of equilibrium policies and compare them to the cooperative case.

2 Model

Consider n mobiles, and moreover, a single static source and destination. The source has a packet generated at time 0 that it wishes to send to the destination. Assume that any two mobiles meet each other according to a Poisson process with parameter λ. Whenever the mobile meets the source, the source may forward a packet to it. We consider the two hop routing scheme [1] in which a mobile that receives a copy of the packet from the source can only forward it if it meets the destination. It cannot copy it into the memory of another mobile.

Consider an active mobile with non-controlled transmission rate. Let T_1 be the first time it meets the source and let $T_1 + T_2$ be the first time after T_1 that it meets the destination. Denote

$$q_\rho = \exp(-\lambda\rho), \qquad Q_\rho = Q_\rho(\lambda) = (1 + \lambda\rho)\exp(-\lambda\rho)$$

Consider the event that the mobile relays a packet from the source to the destination within time ρ, i.e. $T_1 + T_2 \leq \rho$. $T_1 + T_2$ is an Erlang(2) random variable and therefore the probability of the above event is $1 - Q_\rho$. Note that $Q_\rho - q_\rho$ is the probability that $T_1 < \rho$ but that $T_1 + T_2 > \rho$.

Control problems. We consider central control, in which the source decides whether to transmit a packet when it is in contact with a mobile, and distributed control, in which the mobiles are those who take decisions, concerning both the transmission of packets to the destination as well as of receiving packets from the source.

As energy is limited or costly, we either limit the number of active mobiles, or we control dynamically the transmission rate. The first case corresponds to