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Reward-based Incentive Mechanisms for Delay Tolerant Networks

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1. Introduction

Delay tolerant networking (DTN) [1] is an architecture that promotes data transmission even in absence of end-to-end connectivity at a given time. In DTNs, forwarding of a message is performed through mobile nodes in an opportunistic manner.

To cope with intermittent connectivity and to increase delivery rate, DTN routing protocols commonly appeal to multi-copy forwarding, that is the message is replicated to relay nodes and it is delivered if one of the copies reaches the destination.

The two-hop routing scheme [2], which we consider in this paper, allows the source to forward copies of the message to any idle node in contact, and a relay that receives the message from the source can transmit it only to the destination.

However, in DTN applications, when mobile devices are controlled by selfish owners, DTN nodes can be unwilling to spend their own resources serving as relays or can try to gain benefits from cooperation.

Some form of virtual currency is proposed by credit-based incentive mechanisms [3] to encourage communication among different nodes in DTNs. The studies in this work are centred on such type of incentives, namely addressing the reward-based incentive scheme introduced in [4] for two-hop routing. Each node that accepts the message has a certain probability to reach the destination, and the incentive scheme proposes to reward the relay that is the first one to deliver. The success probability and expected reward estimated by a relay depend on certain informations that the source announces to a relay in contact.

This paper investigates the impact of the announced information on the expected reward the source has to pay, and the aim is to find a reward policy for the source that is optimal in costs.

The results are obtained in two cases. First, for two relays and a decreasing density function of inter-contact times between relays and the source (destination), it is shown that the optimal reward policy corresponds with adapting the information the source can give to the relays. This adaptive strategy is shown to be of threshold type. Second, for an arbitrary number of relays and exponentially distributed inter-contact times, it is proved that the expected reward the source has to pay remains the same within fixed setting of informing the relays. The source can, however, reduce the expected reward, by adapting the announced information according to the meeting times with the relays.

2. System Model and Problem Description

The network considered consists of one fixed source node, one fixed destination node and a finite number of relays. The relays move according to a mobility model with i.i.d. inter-contact times between a relay and the source (resp. destination) corresponding to density function f_s (resp. f_d).

The source generates a message at time 0 and attempts to forward it to the destination through the relay nodes by replicating the message, under the two-hop routing scheme.

Forwarding of the message imposes a certain set of costs for a relay node :

1. reception cost, C_r, is a fixed energy cost for receiving the message from the source,
2. storage cost, C_s, is the cost incurred per unit time a relay carries the message,
3. delivery cost, C_d, is the fixed cost for transmitting the message to the destination

As an incentive for cooperation, the source proposes to a mobile node a reward that promises to compensate costs that the node expects to incur if it accepts the message. The source is assumed to be not informed whether the message is delivered by any relay, and continues to offer message copies to relays when encountering. The expected costs and the expected reward estimated by a relay depend on the information the source proposes to the relays.

A mobile node encountering the source knows the time when the transmission process started. In addition, the node may be given the history of forwarding process according one of three settings that the source can use :

1. *full information*, when each mobile node is informed about the number of already existing copies and the corresponding contact times,
2. *partial information*, when each mobile node knows only the number of existing copies,
3. *no information*, when the relays know only their own meeting times with the source.

The reward a relay gets is a random variable depending on the stochastic process describing contacts with the destination. Moreover, the information the relay is given by the source may distinctly affect its estimation of the expected reward.

Thus, within each of three settings and based on the node mobility model, the source needs to determine an amount of reward it should propose to a mobile node when encountering it, and then deploy an optimal policy of informing the nodes in order to reduce the expected reward it should pay for message delivery.

2.1. Two Relays, Decreasing Function of Inter-Contact Times

Consider a case of two mobile nodes. Assume a decreasing density function of inter-contact times between the relays and the source (destination).

For fixed s_1 and s_2, denote by $\mathbf{s}$ the vector (s_1, s_2).

2.1.1. Expected Cost for a Relay

Define $V_i^{(k)}(\mathbf{s})$ as the net cost for relay $i = 1, 2$ under the setting $k \in \{F, P, N\}$, and let $R_i^{(k)}(\mathbf{s})$ be the reward asked by this relay to the source under this setting. Then, the expected cost for relay i takes the form,

$$\mathbb{E}[V_i^{(k)}(\mathbf{s})] = C_r + C_s\mathbb{E}[\tilde{T}_d] + [C_d - R_i^{(k)}(\mathbf{s})]p_i^{(k)}(\mathbf{s}),$$

with $\tilde{T}_d$ being the residual inter-contact time for a relay to meet the destination, and $p_i^{(k)}(\mathbf{s})$ denotes success probability estimated by relay i under the setting k when it meets the source.

2.1.2. Expected Reward Paid by the Source

The expected reward paid by the source for given contact times $\mathbf{s} = (s_1, s_2)$ and under setting k, is as follows

$$R_S^{(k)}(\mathbf{s}) = R_1^{(k)}(1 - p_2(\mathbf{s})) + R_2^{(k)} p_2(\mathbf{s}),$$

where $p_2(\mathbf{s})$ is the probability of success of the second relay given s_1 and s_2.

2.1.3. Adaptive Strategy

It is always beneficial for the source to give information to the first relay independently of s_1.

Proposition 1 $\quad R_1^{(F)}(\mathbf{s}) = R_1^{(P)}(\mathbf{s}) \leq R_1^{(N)}(\mathbf{s}).$

The next proposition says that between the choice of informing a relay that is the second one and not giving this information, it is better for the source not to give this information.

Proposition 2

$$R_2^{(N)}(\mathbf{s}) \leq R_2^{(P)}(\mathbf{s}).$$

Comparing the settings of full information with that of no information, the following proposition shows that for the source the adaptive strategy is of the threshold type.

Define the difference of the success probabilities as a function of s_1 and s_2,

$$g(s_1, s_2) = p_2^{(N)}(s_1, s_2) - p_2^{(F)}(s_1, s_2), \qquad (1)$$

then for the source, it will be better to give information when $g(s_1, s_2) < 0$.

Theorem 1 *There exists* $0 \leq \theta_1 < \infty$ *such that*

1. *if* $0 \leq s_1 < \theta_1$, *then* $g(s_1, s_1 + \nu) \geq 0, \forall \nu \geq 0$*;*
2. *if* $\theta_1 < s_1 < \infty$, *then*
   (a) $g(s_1, s_2) < 0, \forall s_2 \in [s_1, s_1 + \omega(s_1))$,
   (b) $g(s_1, s_2) > 0, \forall s_2 \in (s_1 + \omega(s_1), \infty)$,

where θ_1 *is a solution of the equation* $g(s_1, s_1) = 0$ *and* $\omega(s_1)$ *is a solution of* $g(s_1, s_1 + \nu)$ *with respect to* ν *when* $g(s_1, s_1) < 0$.

2.2. N Relays, Exponential Inter-Contact Times

Assume the inter-contact time between a relay and the source (resp. destination) is exponentially distributed with rate λ (resp. μ).

Proposition 3 *For each setting* $k \in \{F, P, N\}$ *in the model with* N *relays,* $\overline{R}^{(k)} = C_1 + NC_2$*, where* $C_1 = C_d$ *and* $C_2 = C_r + C_s/\mu$.

The average reward that the source has to pay is, thus, the same if the source adheres to a fixed informing mode and depends only on the number of involved mobile nodes. This reward can be, however, reduced by adapting the announced information according to meeting times with the nodes.

References

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