Assessing the vulnerability of DTN data relaying schemes to node selfishness

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***Abstract*—Delay tolerant networks rely on the mobility of their nodes and sequences of their contacts to transfer data. Proposed data forwarding mechanisms represent different trade offs between data transfer speed and network resource consumption, most of them assuming perfect cooperation among network nodes. Nevertheless, nodes may exhibit *selfish* behavior, in particular when they are constrained with respect to energy, computational power, and/or storage space. In this paper, we *analytically* assess the performance of two popular data relaying alternatives, the unrestricted and two-hop relay schemes, when nodes behave selfishly while forwarding data. Our results suggest that the performance advantage of unrestricted relaying over two-hop relaying decreases both with the number of selfish nodes and the intensity of their selfishness, irrespective of whether nodes defer from relaying deterministically or probabilistically. We use our model to quantify the vulnerability of the two relaying schemes to node selfishness but also drive remediation actions against it.**

***Index Terms*—DTN, selfish nodes, performance evaluation**

I. Introduction

Delay Tolerant Networks (DTNs) represent a fundamentally different networking paradigm with relaxed requirements on information delivery. The mobility of network nodes enables the opportunistic transfer of data despite the lack of end-to-end paths. Proposed message forwarding algorithms in literature (for example, see [1] and [2]) trade-off message delivery delay with the number of message copies eventually placed in the network, which is closely related to the per-node transmissions and occupied buffer space.

Most studies in literature so far have assumed that nodes are willing to cooperate in the content dissemination process, whereas fewer have consider scenarios with no cooperation at all. In between lies a range of scenarios, where some or all network nodes may exhibit various degrees of *selfishness* in the data forwarding process, in particular when operating under energy and storage resource constraints.

Our work aims at assessing the vulnerability of data relaying schemes to node selfishness. Selfishness in our context can be expressed in two ways. Firstly, nodes may deny copying and storing data, which are destined to a third node and of no interest to them. Secondly, even if they accept to acquire such data, they may refuse to *infect* another node with them, *i.e.*, relay data to other nodes. Apparently, both strategies reflect concerns for energy consumption and storage space occupation. This behavior may be exhibited either deterministically or probabilistically by a subset or the full set of network nodes.

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We focus our attention on two popular data relaying alternatives, the unrestricted-relay and two-hop relay schemes. In Section II we model the relaying process in the presence of selfish nodes as an absorbing two-dimensional Continuous Time Markov Chain (CTMC) and use it to derive the expected message delivery delay. Comparing it with the one achieved under full-cooperation with the same scheme, we can derive a measure of performance deterioration, which we call *deceleration factor*. Our numerical results in Section III demonstrate that: a) although the unrestricted relay scheme continues transferring data faster in absolute terms, its performance, under the same selfishness intensity, deteriorates faster than the two-hop scheme; b) both of them feature *inherent resilience* to node selfishness in that their performance deteriorates slowly with the number of selfish nodes for moderate selfishness levels. Finally, we give an example of how our model could be used to instrument remediation actions against the network performance degradation due to selfishness.

II. Modelling message delivery under node selfishness

In both data relaying schemes nodes take advantage of their mobility to spread the data in the network. Our assumption in this paper is that the meeting time epochs of each node pair follow a Poisson distribution of intensity λ giving rise to exponentially distributed intermeeting times between nodes. This assumption has been shown to hold in [3] under the random waypoint and random direction mobility models and for communication ranges R small enough with respect to a square network area A. More interestingly, the parameter λ is related therein to the actual mobility model parameters through $\lambda = c \cdot \frac{\nu \cdot R}{A}$, where ν is the mean relative velocity between nodes and the constant $c = 1(1.368)$ for the random direction(random waypoint) mobility model, respectively.

Upon a contact that would nominally result in node infection, selfishness is exhibited in two ways: a node already possessing some data item *does not forward* it to another node not availing it with probability p_{nf}; or, a node that has not yet acquired the item *does not copy* it with probability p_{nc}. The probabilities p_{nf} and p_{nc} effectively *mark* the Poisson process of meeting time epochs, therefore preserving the exponential distribution of "useful" contacts, *i.e.,* contacts that result in a new node infection. The deterministic variants of both types of selfishness are obtained for $p_{nf}(p_{nc}) \rightarrow 1$.

With K out of the $N-1$ relay nodes (probabilistically) selfish, the progress of data transfer from the source towards the destination node under both relaying schemes can be described

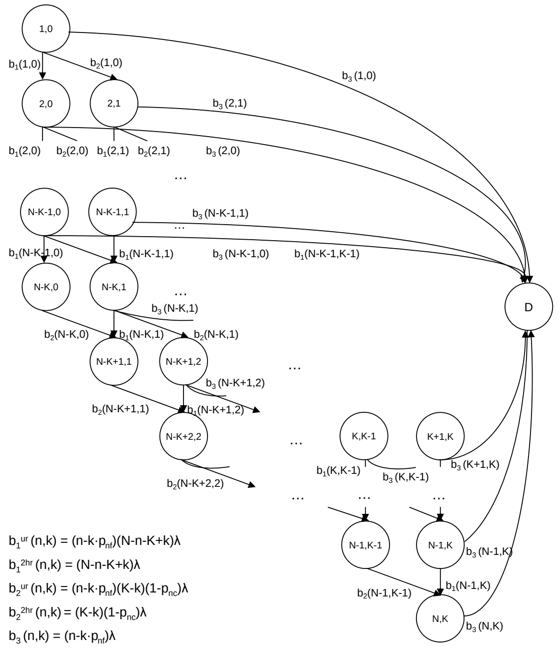


Fig. 1. The CTMC for the unrestricted (ur) and two-hop relay (2hr) message spreading schemes. At the bottom-left part of the figure, we list the relevant transition probabilities for the two schemes as functions of the states (n,k).

by two-dimensional pure-birth processes $\big(n(t),k(t)\big)_{t\geq 0}$ for the numbers of all and selfish-only infected relay nodes, respectively, at time t. These are absorbing Continuous Time Markov Chains (CTMCs) with a finite number of transient states W and one absorbing state D, denoting infection of the destination. The generator matrix $\mathbf{Q}$ for both chains could be written in the general form:

$$\mathbf{Q} = \begin{pmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{R} & \mathbf{T} \end{pmatrix}$$

In $\mathbf{Q}$, the sub-matrix $\mathbf{T}$ is a $W \times W$ matrix with elements $\{T_{ij}\}$ denoting the transition rates amongst transient states; the sub-matrix $\mathbf{R}$ is the $W \times 1$ matrix holding the transition rates from transient states towards the absorbing state D; finally, there are two submatrices with zero elements: the one is the all-zero $1 \times W$ vector of transition rates from the absorbing state to the W transient states, whereas the second one degenerates here to a single zero element corresponding to the negative sum of outbound transition rates from the absorbing state towards the transient states. The transition rates $\{q_{ij}\}$ for each chain differ depending on the relaying algorithm, as shown in Fig. 1 and detailed in the next paragraphs.

A. Message delivery under unrestricted relaying

With unrestricted relaying there are no constraints on the number of message replicas in the network [1]. Under full cooperation, the scheme features minimum spreading delay but only at the expense of maximal resource consumption.

The resulting non-zero state transition rates are given by

$$\begin{cases} T_{ur}\{n+1,k|n,k\} = (n-k\cdot p_{nf})(N-n-K+k)\lambda \\ \qquad\qquad for \;\; k\in[0,K],\; n\in[1,N-1],\; n-k\in[1,N-K-1] \\ T_{ur}\{n+1,k+1|n,k\} = (n-k\cdot p_{nf})(K-k)\cdot(1-p_{nc})\lambda \\ \qquad\qquad for \;\; k\in[0,K-1],\; n\in[1,N-1],\; n-k\in[1,N-K] \\ T_{ur}\{n,k|n,k\} = -\sum_{\{p,q|p\neq n\|q\neq k)\}}(T\{p,q|n,k\}+R\{p,q|n,k\}) \\ \qquad\qquad for \;\; k\in[0,K],\; n\in[1,N],\; n-k\in[1,N-K] \end{cases}$$

and those of the column vector $\mathbf{R}$[1]

$$R_{ur}\{D|n,k\} = (n-k\cdot p_{nf})\lambda \;\; k\in[0,K],\; n\in[1,N],\; n-k\in[1,N-K]$$

Note that the state (n,k) holds the numbers of all and selfish-only infected nodes *excluding (including)* the destination (source) node. The number of transient states is $W = (K+1)\cdot(N-K)$.

B. Message delivery under two-hop relaying

The scheme was first proposed in [4]. Contrary to unrestricted relaying, intermediate relay nodes can only be infected by the source and can themselves infect only the destination node. This two-hop relay strategy aims at limiting the number of transmissions in the network at the expense of higher message transfer delay. The non-zero state transition rates of the submatrix $\mathbf{T}$ are now given by:

$$\begin{cases} T_{2hr}\{n+1,k|n,k\} = (N-n-K+k)\lambda \\ \qquad\qquad for \;\; k\in[0,K],\; n\in[1,N-1],\; n-k\in[1,N-K-1] \\ T_{2hr}\{n+1,k+1|n,k\} = (K-k)(1-p_{nc})\lambda \\ \qquad\qquad for \;\; k\in[0,K),\; n\in[1,N-1],\; n-k\in[1,N-K] \\ T_{2hr}\{n,k|n,k\} = -\sum_{\{p,q|p\neq n\|q\neq k)\}}(T\{p,q|n,k\}+R\{p,q|n,k\}) \\ \qquad\qquad for \;\; k\in[0,K],\; n\in[1,N],\; n-k\in[1,N-K] \end{cases}$$

whereas the transition rates towards the absorbing state D, in matrix $\mathbf{R}_{2hr}$ remain the same as for $\mathbf{R}_{ur}$.

With $\mathbf{X} = -\,\mathbf{T}^{-1}_{ur(2hr)}$ denoting the fundamental matrices of the two absorbing CTMCs and $\mathbf{e}$ the initial probability vector, with all entries equal to zero except for that corresponding to the entry state $(n=1,k=0)$, the expected message delivery delay before the process reaches the destination is given by $\overline{D} = \mathbf{e}\cdot\mathbf{X}\cdot\mathbf{1}$, where $\mathbf{1}$ is the $1\times W$ all-one vector.

III. Numerical results

We use our models to quantify the deterioration of the DTN performance in the presence of selfish nodes. Our metric in this respect is the *deceleration factor* $F_D(N,K)$, defined as the ratio of the expected message delivery delay in the presence of K selfish nodes versus that achieved with the same scheme and number of relay nodes under full co-operation:

$$F_D(N,K) = \frac{\overline{D}(N,K)}{\overline{D}(N,0)}. \tag{1}$$

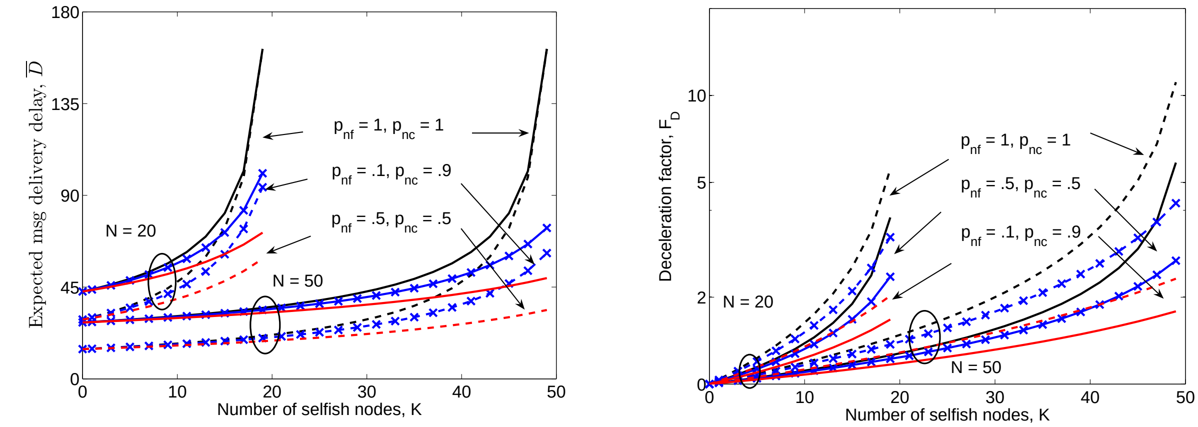
For the unrestricted and two-hop relay schemes the expected message delivery delays under full cooperation are given by

$$\overline{D}_{ur}(N,0) = \frac{1}{\lambda N}\sum_{i=1}^{N}\frac{1}{i} \quad \overline{D}_{2hr}(N,0) = \frac{1}{\lambda}\sum_{i=1}^{N}\frac{(N-1)!}{(N-i)N^i}.$$

If not otherwise stated, we consider nodes that meet each other with rate $\lambda = 0.37\; contacts/hr$. This practically corresponds to nodes with transmission range equal to $50m$ moving at a speed uniformly spread in $[0.5, 2.5]$ m/sec according to the random direction (random waypoint) model in a square area of 1 km side length (circle of radius $\frac{1}{\pi}$ km).

The expected message delivery delays achieved by the unrestricted and two-hop relay schemes are compared in Figure 2(a). The unrestricted relay scheme always outperforms the

[1]The notation $T(R)\{m,l|i,j\}$ denotes the rate of transition from state (i,j) to state (m,l).



(a) Expected message delivery delay.

(b) Deceleration factor.

Fig. 2. Performance of unrestricted (dashed lines) vs. two-hop (solid lines) relaying vs. number of selfish nodes.

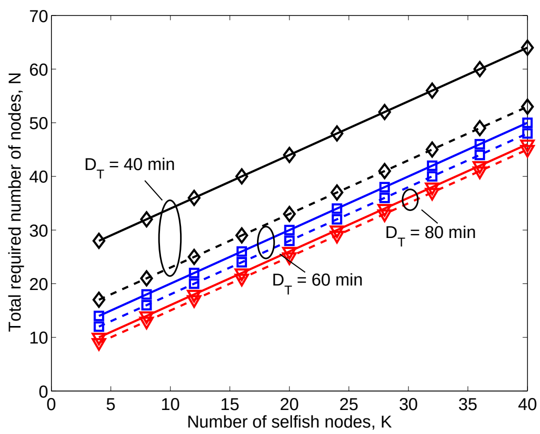


Fig. 3. Required number of network relay nodes vs. number of deterministically selfish nodes for various target expected delays under unrestricted (dashed lines) and two-hop relay (solid lines) schemes.

two-hop scheme for given $\{p_{nf}, p_{nc}\}$ values taking advantage of its more aggressive data relaying strategy. However, the performance lag between the two relaying schemes decreases both with the number of selfish nodes K and the intensity of node selfishness and disappears for $K = N - 1$ deterministically selfish nodes. This is where $\overline{D}$ gets for both schemes its worst-case value of $\frac{1}{\lambda}$; namely, it equals the mean intermeeting time between the source and destination nodes, irrespective of the number of relay nodes in the network.

The order of the two schemes is reversed in the plots of deceleration values in 2(b). The relative performance degradation for the unrestricted relay scheme is steadily higher demonstrating its increased vulnerability to node selfishness. Nevertheless, both schemes appear quite resilient to selfish behavior, at least when this is probabilistic. For example, when $\{p_{nf} = p_{nc} = 0.5\}$ the degradation remains below a factor of two even for 70% of the nodes behaving selfishly. Noteworthy is the dependence of $\overline{D}$, and subsequently F_D, on p_{nf} and p_{nc}: for fixed $p_{nf} + p_{nc}$ sum, $\overline{D}$ gets minimal when p_{nf}=p_{nc}. [2] Moreover, the performance is the same for (p_{nf}, p_{nc}) and (p'_{nf}, p'_{nc}) value pairs satisfying p'_{nf}=p_{nc} and p'_{nc}=p_{nf}.

[2]Note that for given sum $p_{nf} + p_{nc}$ the aggregate probability of selfishness $p_m = 1 - (1 - p_{nf})(1 - p_{nc})$ is minimized when p_{nf}=p_{nc}.

Besides standing in agreement with simulation results in literature reporting empirically the resilience of DTN relaying schemes to node selfishness [5], [6] the model can be used to drive remediation actions. Consider, for example, that some target expected delay value D_T has to be preserved due to content aging concerns. Although the performance deterioration in the presence of selfish nodes could be partially compensated with increasing either the nodes' velocity or their transmission range, both actions assume some capability to control the nodes. Instead, one way to preserve the target delay without interfering with selfish nodes is through the introduction of additional robotic nodes with controlled mobility patterns. Whereas, in the general case, the trajectories of those nodes could be optimized for the given task [7], improvement can already be achieved by letting them move in (pseudo)-random mobility patterns. Figure 3 suggests that a small number of those nodes could suffice to preserve performance even in the worst-case scenario of deterministically selfish nodes. As the target expected delay is relaxed, the number of nodes required by the two relaying schemes tend to coincide.

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