The Necessity for Strong Reciprocators in Mobile Ad Hoc Networks

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Abstract—In civilian mobile ad hoc networks behaviour of network participants in accordance with the collective interest cannot be guaranteed. The cooperation in packet forwarding can emerge if the reciprocal tit-for-tat (TFT) principle is commonly used. This induces the nodes with self-regarding preferences to act cooperatively. However, as demonstrated in this paper, in certain conditions costs of using a reciprocal forwarding are greater than benefits. In such a case, the cooperation can emerge only if nodes with specific behaviour called strong reciprocity are present in the network. This paper analyses such conditions using a nature-inspired evolutionary approach. The computational experiments demonstrate that as soon as at least approximately 70% of nodes follow the TFT-principle in packet forwarding, benefits of its use exceed costs, regardless the forwarding behaviour of the remaining nodes. Consequently, strong reciprocators are not required for sustaining cooperative network. Below that threshold, the need for strong reciprocators depends on the composition of the remaining nodes. In particular, it is positively correlated with the number of unconditionally cooperative nodes as these nodes create incentives for free-riding behaviour.

Keywords—MANETs; cooperation; strong reciprocity; tit-for-tat; trust management; evolutionary game theory; cognitive networks.

I. INTRODUCTION

Communication in mobile ad hoc networks (MANETs) is based on cooperation of its participants. Two distant nodes can exchange packets using intermediate nodes, that act as routers. As most of devices in MANETs rely on batteries, energy-constrained operation constitutes one of nodes’ most important characteristics. In addition, in civilian MANETs nodes may belong to different authorities. Hence, the probability that nodes are going to be reluctant to forward packets in order to conserve their energy is very high. Although, decentralised nature of network control in MANETs introduces additional robustness against the single points of failure [1], it also means that enforcing or providing incentives for cooperative behaviour cannot be done easily. The fact that cooperation in civilian MANETs involves human behavioural factor makes the analysis of the development of the cooperation difficult. Network users differ in preferences. Some of them—as in the canonical model in economics [2]—are rational and self-regarding, i.e. they aim at maximising their own material gains (by maximising the throughput and minimising the contribution to packet forwarding). However, much research has shown that one particular type of other-regarding behaviour—strong reciprocity—is present in social interactions [2], [3]. Strong reciprocators cooperate with others and punish non-cooperators, even if this is costly and provides neither short nor long run benefits [4], [5]. Hence, strong reciprocators incur a cost to create a benefit for the whole network. They should be distinguished from weak reciprocators, willing to cooperate only if they expect long-term net benefits [5], [6].

In general, a cooperative aggregate outcome can be reached if nodes are able to create cooperation incentives for a majority of self-regarding nodes. Recent research has demonstrated that cooperation can be sustained if packet forwarding is based on the norm of reciprocity (direct or indirect), i.e. nodes respond to each other in similar ways by returning forwarding services [7], [8], [9]. Forwarding strategies are typically derived from the tit-for-tat (TFT) principle—capturing the essence of reciprocity. TFT directs a node to reciprocate cooperation and to punish free-riders. The existence of a certain number of nodes following the TFT-based forwarding strategies induces the nodes with self-regarding preferences to act cooperatively. The situation becomes more complicated if cooperation involves indirect reciprocity, which can be characterised as “You relay my packets and someone else will relay yours”. In such a case, in addition to bearing the cost related to packet forwarding (battery use), in some cases, nodes also bear the cost associated with discarding packets (increase of untrustworthiness among other nodes) [10]. Hence, if the cost of punishing free-riders is too high, nobody has the incentive to be the punisher. Most research in the field of MANETs assumes selfishness axiom [11] according to which the nodes aim at maximising their own material gains and expect others to do the same. Consequently, cooperation can by only based on weak reciprocity.

However, recent research in experimental economics challenges the axiom, showing that strong reciprocity can give rise to cooperation in conditions, where “classical” models predict defection [6], [11]. Can cooperation emerge in MANETs if using the TFT-based forwarding strategy is costly? If strong reciprocators willing to bear the cost related
to the use of the strategy are present in a MANET, the answer is yes. We demonstrate, that as soon as the number of such nodes is greater than certain threshold value, the use of the strategy becomes beneficial to nodes with all preference types, i.e. it will also be used by nodes willing to be involved only in self-interested forms of cooperation. Hence, in such a case strong reciprocators are no longer necessary to sustain the cooperation.

This article investigates the conditions, where strong reciprocators are needed to develop cooperation in a MANET. A nature-inspired evolutionary approach is used. Benefits and costs of using a forwarding strategy are measured in fitness terms and the strategy is subject to natural selection, leading to the most successful outcome in given conditions. If the benefits of using TFT exceed the costs, TFT emerges as a choice for nodes with self- and other-regarding preferences. Otherwise, the strategy “do not forward packets” evolves as a solution, meaning that the cooperation can only emerge if strong reciprocators are present in the network.

The paper is structured as follows. The next section discusses related work in the area. Section III presents the model of a MANET used in this work. Section IV introduces the evolutionary methodology proposed as a tool to address the issue. Section V contains specification of parameters and simulation results. The final section summarises the main conclusion.

II. BACKGROUND AND RELATED WORK

Reciprocity-based cooperation requires nodes to use trust systems in order to distinguish selfish nodes from cooperative. Such systems can be extended with reputation systems. The main difference between the two is that, in the former, a node evaluates a subjective view of the entity’s degree of cooperation, while in the latter the view of the whole community is taken into account [12]. Several cooperation enforcement mechanisms (CEMs) based on reciprocity have been proposed in the literature (see e.g. [13], [14], [15], [16], [17]). In particular, the development of cooperation based on direct reciprocity with several forwarding strategies present in the network was analysed in [7], [8], [9]. In these works the authors demonstrate that cooperation is very likely to emerge on the basis of defection-tolerant versions of the TFT principle. It directs to cooperate on the first move and then do whatever the other player did in the previous move [18]. The strategy is based one of the most prevalent social norms—reciprocity [19]. The norm can be either direct or indirect [20]. The former may be characterised as “You relay my packets and I will relay yours”, while the latter can be captured in the principle “You relay my packets and someone else will relay yours” (see example in Figure 1). Direct reciprocity requires nodes to memorise their bilateral packet relaying interactions in the form of personal trust data [21]. On the other hand, indirect reciprocity expects nodes to track packet relaying interactions between other network participants. The information about the status of these interactions is referred to as general trust data [21]. Direct reciprocity can be seen as personal enforcement of cooperation, while indirect reciprocity as general enforcement [22]. In [10] we show that, if cooperation is based on indirect reciprocity and a watchdog-based mechanism [23] is used for data collection, discarding packets (even originated by selfish nodes) can be costly. In such a situation an intermediate node that discards packets pays a cost expressed as a decrease of its trustworthiness perceived among other nodes. Modifications of the trust data collection mechanism can result in minimisation of the cost [10].

The work reported in this section assumes that cooperation based on reciprocity (direct and/or indirect) can be developed using weak reciprocators only. As recent research in experimental economics challenges the selfishness axiom, in this work we analyse the development of cooperation assuming additional presence of strong reciprocators.

III. MODEL OF THE NETWORK

In this work we assume that a reputation system is not present in the network. Nodes only use their own (independent) trust systems.

A. Networking assumptions

The following assumptions are made: the network is self-organising and the network layer is based on a reactive,
source routing protocol; each device is equipped with an omnidirectional antenna with similar radio range, bi-directional communications and promiscuous mode; the topology of the network is unpredictable and changes dynamically; in the absence of network regulation, some network users act in a selfish but not malicious manner; nodes recognise each other and thus can remember their history of interactions.

B. Data collection

To explain reciprocity-based cooperation we assume that trust data collection is based on the watchdog (WD) mechanism introduced in [23]. Two network events—“packet forwarded” and “packet discarded” are used to derive the degree of cooperation of the source of the message. A source routing protocol is assumed to be used, therefore, the list of intermediate nodes is included in the header of the packet. Information regarding the packet relaying behaviour of other nodes (referred to as trust data) is gathered only by nodes directly participating in the communication session. This information is stored in node’s private knowledge base. There is no exchange of ratings between nodes. The communication session involves a source node (sender), a destination node and intermediate nodes forwarding packets from the source to the destination. Trust data collection is performed in the following way: nodes are equipped with a watchdog mechanism that enables them to check whether a packet was delivered to its destination. A node that requests another node to relay a packet verifies by means of a passive acknowledgement whether the requested node actually forwarded the packet. As an example, let us assume that node A originates a message to node D via intermediate nodes B and C. The message is discarded by node C.

A decision mechanism. Nodes collect trust data as described in Section III-B. On the basis of such data an intermediate node $i$ evaluates a degree of cooperation (DOC) of the source nodes (denoted by $s$). The evaluation is based on two characteristics of $s$, namely $\text{req\_acc}_{s|i}$ and $\text{req\_dsc}_{s|i}$, which are the numbers of packets forwarded and discarded by $s$, respectively (the notation $s|i$ means that node $s$ is under the evaluation of node $i$). Then, the node computes DOC of node $s$ (a number from the interval $[0, 1]$):

$$DOC_{s|i} = \frac{\text{req\_acc}_{s|i}}{\text{req\_acc}_{s|i} + \text{req\_dsc}_{s|i}}.$$

To evaluate DOC, node $i$ takes into account from its knowledge base only the $T$ latest records regarding $s$. In the next step node $i$ has to decide whether to accept or reject the packets from $s$:

$$\langle \text{action} \rangle = \begin{cases} \text{forward} & \text{if } DOC_{s|i} \geq minDOC_i, \\ \text{discard} & \text{if } DOC_{s|i} < minDOC_i, \end{cases}$$

where $minDOC_i$ is the minimum DOC value required by node $i$ to provide $s$ with the forwarding service.

We assume that nodes do not distinguish between personal and general trust data (the former takes into account the status of packets originated by a node itself, while the latter considers the status of packets originated by other nodes [21]). That is, both data types are used to evaluate DOCs. Hence, the TFT mechanism defined in this section allows to build cooperation on the basis of direct and indirect reciprocity.

There are two special cases concerning messages received for relaying from unknown nodes. If a node receives a packet in the initial period of the existence of the network (specified by a threshold parameter $t_{unkn}$), the packet is forwarded with a probability $p_1$. As soon as the network is established (i.e. a certain amount of time has passed), the packet from an unknown node is forwarded with a probability $p_2$. The value of $p_1$ is high so that the network could be easily created. On the other hand, the value of $p_2$ is low in order to discourage network participants from whitewashing attack [24]. The attack is defined as a situation, where a selfish node repeatedly rejoins the network under new identities in order to take advantage of cooperative approach towards unknown nodes.
D. Path selection

When a node wishes to send its own packets it first chooses (among all possible paths) the route with the best rating. The rating is calculated as an arithmetic mean of DOC of all nodes belonging to the route. The value of the DOC of an unknown node is specified by the parameter \( DOC_{\text{unkn}} \).

E. Types of forwarding strategies

Three types of forwarding strategies are defined. The first one is the TFT-based forwarding mechanism described in Section III-C. The remaining strategies represent two particular patterns of behaviour that one might expect to be present to some extent in a typical MANET—selfishness and altruism. The strategy representing the first type of behaviour (denoted by ALLD) directs a node to discard all packets received for forwarding. The strategy based on the second behaviour (denoted by ALLC) tells a node to accept all forwarding requests.

IV. EVALUATION METHODOLOGY

Conditions of a network are defined by the distribution of forwarding strategies (TFT, ALLD, ALLC) among participating nodes. In addition, a population representing a set of forwarding strategies (TFT, ALLD, ALLC) among participating nodes. In addition, a population representing a set of forwarding strategies (TFT, ALLD, ALLC) among participating nodes. Hence, the evaluation of a performance of strategies used as a result of spatial location and the structuring effect of relations incurred by the use of trust systems by nodes. Hence, the evaluation of a performance of strategies used as a result of spatial location and the structuring effect of relations incurred by the use of trust systems by nodes.

A. The evolution of strategies of \( S_{POP} \)

The distribution of strategies of nodes that belong to the population of \( S_{POP} \) is subject to changes. The nodes, which belong to this population, are referred to as players. A strategy for a player is the forwarding approach. Each player has the same forwarding strategy \( S \) set composed of \( m \) strategies—\( S = \{ \text{TFT, ALLD, ALLC} \} \) (\( m = 3 \)). Games are played between a source of a packet and the intermediate nodes that can either pass on the packet to the next hop or drop it. Players are divided into \( m \) groups \( i = 1, ..., m \), according to their current forwarding strategies. The state of the population is represented by a vector \( <q_1, q_2, ..., q_m> \) where each \( q_i \) denotes the relative frequency of strategy \( i \) in the population. Payoffs obtained by players using a particular strategy are translated into mean fitness of group \( i \). Strategies are passed through non-overlapping generations. Groups grow from one generation to the next in proportion to their relative fitness. The growth rate of a given strategy is described by replicator dynamics [25]. In consequence, the selection process makes unsuccessful strategies less likely to appear in the outcome.

The overview of the generational process and strategy evaluation in a MANET is shown in Figure 3. The evolutionary discovery of the best strategies starts from a particular initial condition and happens in generations. It comprises of three steps. In the first step, the network is set up and nodes are assigned with forwarding strategies. In the second step they are evaluated in a MANET. The third step updates the strategies of \( S_{POP} \) by means of replicator dynamics. Steps 2 and 3 are repeated producing successive generations of \( S_{POP} \). This generational process is repeated until the outcome (domination of a strategy or of a set of strategies) has been reached. Detailed description of the procedure can be found below.

\textbf{Step 1: specify values of the parameters.}
1) Specify values of the parameters: \( M \) as a number of nodes participating in the network, \( R \) as a number of rounds and \( L \) as the number of \( S_{POP} \).
2) Assign all nodes (\( M \) nodes in the network and \( L \) nodes from the \( S_{POP} \) population) with the forwarding strategies.

In the next step the performance of each node belonging to the population of \( S_{POP} \) is independently evaluated in the network. As dynamics of a typical MANET expressed in terms of mobility and connectivity of the nodes are unpredictable, intermediate and destination nodes are chosen randomly.

\textbf{Step 2: evaluate the strategies of \( S_{POP} \) in the network.}
1) Specify \( l \) (CANDIDATE node) as \( l := 1 \) and inject it to the network.
2) Reset the knowledge base of each node.
3) Specify \( r \) (round number) as \( r := 1 \).
4) Specify \( k \) (source node) as \( k := 1 \).
5) Randomly select node \( u \) (destination of the packet) and intermediate nodes, forming several possible paths from node \( k \) to \( u \).
6) If more than one path is available, calculate the rating of each path according to the procedure described in Section III-D and choose the path with the best rating.
7) Let node \( k \) initiate a communication session (originate a packet). Each intermediate node can either pass on the packet to the next hop or drop it (according to its forwarding strategy).
8) After the completion of the communication session update trust data (as described in Section III-B).
9) If \( k < (M + 1) \), then choose the next node (\( k := k + 1 \)) and go to point 5. Else, go to point 10.
10) If \( r < R \), then \( r := r + 1 \) and go to point 4 (next round). Else, go to point 11.
Final generation (outcome)

Step 1: set the parameters

Step 2: evaluate the strategies

Step 3: update the strategies

Figure 3. Overview of the evolutionary model. Forwarding strategies of the nodes that belong to the population of $S_{POP}$ are subject to changes as the members of the population play the evolutionary game. These strategies are evaluated one by one in the MANET. The strategies of nodes in the MANET define network conditions. They remain unchained (except the strategy of one node (denoted by red colour), used to evaluate the strategies of $S_{POP}$). In the first step the parameters of the network are specified, in the second step performance of each node of $S_{POP}$ is independently evaluated in a MANET, in the third step the distribution of strategies among $S_{POP}$ is updated (generation $g+1$ is obtained) according to their performance in generation $g$. Steps 2 and 3 are repeated until the final outcome is reached (generational process). In the example presented in the figure the TFT strategy constitutes the final outcome.

11) If $l < L$, then $l := l + 1$ and go to point 2. Else, go to Step 3.

Step 3: update the distribution of strategies among the nodes that belong to the population of $S_{POP}$.

1) For each group $i$ calculate its mean fitness ($f_i$) as described in Section IV-B and stop the evaluation procedure.

2) The fraction of population in group $i$ in the subsequent generation ($q_i'$) is given by the following equation:

$$q_i' = q_i \frac{\bar{f}_i}{\bar{f}},$$

where $f_i$ is the mean fitness of group $i$ and $\bar{f}$ is the mean fitness of the whole population calculated as follows:

$$\bar{f} = \frac{1}{m} \sum_{i=1}^{m} q_i f_i.$$

B. Fitness evaluation

Benefits and costs of using a strategy are measured in fitness terms. The fitness of group $i$ in generation $g$ is calculated as the mean fitness of all players that belong to that group. The fitness of player $j$ is calculated as follows:

$$fitness_{j}^{g} = \frac{nps_{j}}{npp_{j} + nr_{j}},$$

where $nps_{j}$ is a number of packets successfully sent by node $j$ (the benefit), $npp_{j}$ is a number of packets forwarded by $j$ (the cost) and $nr_{j}$ is the time node $j$ spent in the network (expressed by the number of rounds played).

This fitness function represents utility of a node with self-regarding preferences, i.e. a node that wishes to obtain highest possible throughput but at the same time it wants to conserve its battery by minimising the number of forwarded packets.

C. Interpretation of the outcome

The evolution of strategies guided by the fitness function representing self-regarding preferences has four possible outcomes—(i) victory of the TFT strategy, (ii) victory of the ALLC strategy, (iii) victory of the ALLD strategy, and (iv) tie between any subset of the strategies. The first two outcomes mean that cooperation will most likely emerge regardless the preferences of participating nodes, as the use of these strategies—TFT in (i) and ALLC in (ii)—is the most beneficial choice to a node. In the first outcome (i), the TFT nodes collectively create strong cooperation incentives, even among self-regarding nodes. The second outcome (ii) means that altruism (unconditional cooperation) constitutes the best choice for a node. However, the collective use of ALLC does not create any incentives for cooperation. The third outcome (iii) means that self-regarding nodes will choose to defect. Therefore, cooperation can be only developed, if a network has a sufficient number of strong reciprocators (bearing the cost of punishing the noncooperative nodes).

V. COMPUTATIONAL EXPERIMENTS

The experiments were carried out according to the procedure described in Section IV. The main goal was to differentiate between the conditions where the use of the reciprocity-based cooperation (represented by the TFT strategy) is costly to a node, and the conditions where the use is beneficial. Several settings of the network varying in the distribution of the strategies were analysed. For each setting, the solution—the outcome observed in the population of $S_{POP}$—was discovered according to the procedure described in Section IV.
A. Specification of the parameters

The specification of the parameters is given in Table I. The number of repetitions (referred to as runs) of each experiment was set to 50. The mean value of the performance of each strategy was calculated over all runs of the experiment. The network simulation time was set to 600 rounds. In the initial generation the TFT, ALLC and ALLD strategies were uniformly distributed among the nodes belonging to the population of the $S_{POP}$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of all nodes in the network ($M$)</td>
<td>31, 61</td>
</tr>
<tr>
<td>size of $S_{POP}$ ($L$)</td>
<td>15</td>
</tr>
<tr>
<td>initial distribution of strategies of CAND.</td>
<td>5 TFT, 5 ALLC, 5 ALLD</td>
</tr>
<tr>
<td>simulation time (number of rounds ($R$))</td>
<td>600</td>
</tr>
<tr>
<td>number of repetitions of each experiment</td>
<td>50</td>
</tr>
<tr>
<td>$minDOC$</td>
<td>0.85–1 (equiprobable)</td>
</tr>
<tr>
<td>number of records taken to evaluate DOC ($T$)</td>
<td>5</td>
</tr>
<tr>
<td>forw. prob. of TFT towards unknown ($p_1$)</td>
<td>1.0</td>
</tr>
<tr>
<td>forw. prob. of TFT towards unknown ($p_2$)</td>
<td>0.3</td>
</tr>
<tr>
<td>$DOC_{unkn}$ of TFT round # 50</td>
<td>0.5</td>
</tr>
<tr>
<td>path length/probability of a given # of hops</td>
<td>1/0.1, 2/0.3, 3–5/0.2</td>
</tr>
<tr>
<td>number of available paths</td>
<td>1–4 (equiprobable)</td>
</tr>
</tbody>
</table>

Table I

SPECIFICATION OF THE PARAMETERS AND SETTINGS OF NODES.

B. Results

Our preliminary experiments demonstrated that the problem of costly punishment by TFT strategy exists only if some nodes unconditionally cooperate in packet forwarding (behaviour represented by the ALLC forwarding strategy). The ALLC strategy can be easily exploited by the ALLD strategy as it does not retaliate. Therefore, if unconditional cooperators are not present in the network, cooperation can emerge without strong reciprocators. In this section we investigate what happens if some ALLC strategies exist in the network.

The example of an outcome of the evolutionary process for the network composed of 31 nodes is illustrated in Figure 4. Among the nodes, 5 used the TFT strategy, 21 the ALLD strategy, 4 the ALLC strategy and 1 node was used to evaluate the strategies of the population of the $S_{POP}$. The ALLC turned out to be the weakest performer, as it did not manage to go beyond the 12th generation in any of the 50 runs of the experiment. As for the two remaining strategies, the popularity of TFT constantly grew until reaching the mean relative frequency of 0.94 after 173 generations (i.e. on average 94% of nodes used TFT in generation 173 and beyond). Therefore, TFT is the winning strategy for this network setting. The remaining 6% of nodes used the ALLD strategy.

The results corresponding to all remaining distributions of ALLC, ALLD and TFT strategies in the network are illustrated in Figure 5. The x-axis shows the relative frequency of nodes using the TFT strategy, while the y-axis represents the relative frequency of nodes using the ALLD strategy. The relative frequency of nodes using the ALLC strategy can be calculated by subtracting the relative frequency of nodes using the ALLD strategy from 1. Two outcomes can be distinguished. In the first one—denoted in the figure by “strong reciprocity”—the ALLD strategy evolved in the evolutionary process as a dominant strategy of the $S_{POP}$. It means that the use of TFT is costly, thus, the strategy will be selected by strong reciprocators only. In the second outcome (denoted by “weak reciprocity”) TFT was the winner, hence reciprocity-based cooperation is a rational choice for nodes with all types of preferences.
The first observation is that the more popular the TFT strategy is in the network, the lower is the cost of using it. If more than approximately 70% of nodes apply it for packet forwarding, benefits are greater than costs, i.e., selection of TFT is beneficial even among those with self-regarding preferences. In such a case the distribution of ALLD and ALLC strategies among the remaining nodes is not relevant. However, below the 70% threshold, the rationale behind the selection of TFT depends on the number of nodes using the TFT strategy and the distribution of ALLD and the ALLC strategies. For instance, in the network, where 40% of nodes already use the TFT strategy, its application is beneficial if at least 33% of the remaining nodes use the ALLD strategy (or equivalently, maximum of 67% of the remaining nodes use the ALLC strategy).

The first general conclusion that can be drawn is that reciprocity-based cooperation (represented by the TFT strategy) can be pursued by self-regarding nodes only if a significant portion of the population already uses the TFT strategy. If the number of nodes following TFT is not sufficient, a cooperative MANET can only be developed in the presence of strong reciprocators (which pay the cost of using the TFT strategy). As soon as a certain number of nodes uses TFT, strong reciprocators do not bear the cost anymore, thus cooperative behaviour will also be followed by nodes with self-regarding preferences. As shown in Figure 5, the number of required nodes using TFT depends on the composition of the strategies of the remaining nodes.

The question remains what happens if the network size is greater? This issue was addressed in the second set of experiments, where the network size was increased from 31 to 61 nodes. The results for various distributions of strategies among the nodes are illustrated in Figure 6. Comparing to the small network case, the outcome is slightly changed as the area corresponding to victory of the ALLD strategy grows slightly (marked in the figure with the yellow zone). Therefore, the increase of the network size augments the cost of using the TFT strategy.

VI. Conclusion

A MANET is an environment without central authority, where participants differ in device types and preferences, demonstrates numerical results for five selected locations on the threshold curve ($l_1$–$l_5$).

<table>
<thead>
<tr>
<th>Location (freq. of TFT,ALLD)</th>
<th># of generations</th>
<th>Fitness of ALLD</th>
<th>Fitness of TFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l_1$ (0.1, 1.0)</td>
<td>130</td>
<td>0.11 (0.011)</td>
<td>0.095 (0.011)</td>
</tr>
<tr>
<td>$l_2$ (0.2, 0.63)</td>
<td>59</td>
<td>0.218 (0.017)</td>
<td>0.211 (0.015)</td>
</tr>
<tr>
<td>$l_3$ (0.4, 0.33)</td>
<td>55</td>
<td>0.293 (0.02)</td>
<td>0.282 (0.013)</td>
</tr>
<tr>
<td>$l_4$ (0.6, 0.03)</td>
<td>40</td>
<td>0.38 (0.02)</td>
<td>0.34 (0.027)</td>
</tr>
<tr>
<td>$l_5$ (0.66, 0)</td>
<td>47</td>
<td>0.355 (0.02)</td>
<td>0.336 (0.031)</td>
</tr>
</tbody>
</table>

Although, the use of forwarding strategies built on the principle of reciprocity captured by the TFT strategy by a certain number of nodes guarantees a cooperative MANET, the question is whether nodes will choose such strategies. Under the common assumption of selfishness axiom, the answer is yes, if costs of using the TFT strategy are greater than benefits. However, recent diverse experiments challenge the axiom, showing that cooperation can also be developed, even if punishing noncooperators is costly, and yields no personal benefits. Strong reciprocators are willing to pay the costs for creating incentives for self-regarding nodes to behave cooperatively. The aim of this article was to assess the conditions, where strong reciprocators are required for sustaining cooperation in a MANET. A distinction between the conditions, where using TFT is beneficial to a node, from the conditions, where using TFT incurs costs greater than benefits was made. Using a nature-inspired evolutionary model based on replicator dynamics and computational experiments, the article demonstrated two factors determining whether strong reciprocators are needed—the number of nodes using the TFT strategy and the number of nodes using the ALLC strategy (unconditional cooperation). The greater number of nodes with the TFT strategy is present in the network, the lower is the cost of using it, thus more efficient incentives for cooperative behaviour are created. As soon as at least approximately 70% of nodes follow the TFT strategy for packet forwarding, benefits of using that strategy exceed costs, regardless the distribution of the strategies among the remaining nodes. Consequently, strong reciprocators are no
longer necessary for sustaining cooperative network. The second factor—the number of nodes following the ALLC strategy—has the opposite effect on the global outcome, as such nodes create incentives for free-riding behaviour. In certain cases the benefits from exploitation of nodes using ALLC strategies are greater than the costs. It means that the cooperation stimulating effect of trust and reputation mechanisms is limited, as free-riding is more advantageous than creating a reputation of being cooperative. Hence, the more ALLC nodes are present in the network, the higher is the cost of building incentives for cooperation, and the greater the demand for the presence of strong reciprocators is created.

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