Ad Hoc Networks 10 (2012) 1379–1398

Contents lists available at SciVerse ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

DECADE: Distributed Emergent Cooperation through ADaptive Evolution in mobile ad hoc networks

Marcela Mejia [a,b,*], Néstor Peña [b], Jose L. Muñoz [c], Oscar Esparza [c], Marco Alzate [d]

[a] Universidad Militar Nueva Granada, Bogotá, Colombia
[b] Universidad de los Andes, Bogotá, Colombia
[c] Universitat Politècnica de Catalunya, Barcelona, Spain
[d] Universidad Distrital, Bogotá, Colombia

ARTICLE INFO

Article history:
Received 13 March 2011
Received in revised form 27 September 2011
Accepted 20 March 2012
Available online 18 April 2012

Keywords:
MANET
DSR
Trust models
Game theory
Emergent behavior
Adaptation

ABSTRACT

The scarce resources of a mobile ad hoc network (MANET) should not be wasted attending selfish nodes (those nodes that use resources from other nodes to send their own packets, without offering their own resources to forward other nodes' packets). Thus, rational nodes (those nodes willing to cooperate if deemed worthy) must detect and isolate selfish nodes in order to cooperate only among themselves. To achieve this purpose, in this paper we present a new game theoretic trust model called DECADE (Distributed Emergent Cooperation through ADaptive Evolution). The design of DECADE is shown by first, analyzing a simple case of packet forwarding between two nodes, and then the results are extended to bigger networks. In DECADE, each node seeks individually to maximize its chance to deliver successfully their own packets, so that the cooperation among rational nodes and the isolation of selfish nodes appear as an emergent collective behavior. This behavior emerges as long as there is a highly dynamic interaction among nodes. So, for those cases where the mobility alone does not suffice to provide this interaction, DECADE includes a *sociability parameter* that encourages nodes to interact among them for faster learning and adaptability. Additionally, DECADE introduces very low overhead on computational and communication resources, achieving close to optimal cooperation levels among rational nodes and almost complete isolation of selfish nodes.

1. Introduction

Mobile Ad Hoc NETworks (MANETs) are formed by wireless mobile devices with limited battery power, computation capacity, and memory space. These devices communicate among them through multi-hop routes, without relying on any communication infrastructure [1]. For a MANET to function appropriately, each node must be willing to contribute with its own resources and, in exchange, should be able to use other nodes' resources. However, in this environment there could be selfish nodes. Selfish nodes use resources from other nodes of the network to send their packets without forwarding packets of these other nodes [2]. To avoid this unfair situation, MANETs have to use an enforcement mechanism.

The contributions of this paper are the following. First, we propose a cooperation enforcement mechanism called DECADE (Distributed Emergent Cooperation through ADaptive Evolution) for MANETs based on a source routing protocol like DSR (Dynamic Source Routing) [3]. DECADE is based on trust and game theory. DECADE differs from similar models in its completely distributed nature, in which cooperation becomes an emergent property that evolves from the individual learning and adaptive behavior of each node. We present an extensive set of simulations that show how DECADE achieves almost optimal cooperation

* Corresponding author at: Universidad Militar Nueva Granada, Bogotá, Carrera 11 No. 101-80, Colombia. Tel.: +57 3002083542.
E-mail address: angela.mejia@unimilitar.edu.co (M. Mejia).

1570-8705/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.adhoc.2012.03.017

values among rational nodes and almost total isolation of selfish nodes, with high efficiency and fast convergence. Second, we conduct an analytic study of our model on a simplified two-node scenario, proving analytically the optimal results of our previous work presented in [4]. Both the analysis method based on dynamical systems theory and the analysis results stating the weakness of the prisoner's dilemma for trust modeling in MANETs are significant contributions of this paper. Third, we make a more extensive study of the model in [4] noticing how, under low mobility conditions, the rational nodes need to explore its environment more aggressively. Finally, we propose the "sociability factor" as one possible way to achieve this exploratory behavior. Sociability is necessary in low/medium mobility scenarios, in which it is not easy to obtain timely knowledge about other node's behavior. We show that our sociability parameter encourages more interactions among nodes and effectively improves environment perception.

There are two kinds of selfish misbehaviors at the network layer of an ad hoc network [5]: selfish routing misbehavior, when a "silent node" does not participate in route discovery, and selfish forwarding misbehavior, when a node fully participates in the route discovery phase but refuses to forward packets for others. DECADE, like most cooperation enforcement systems in the literature, is designed to cope with selfish forwarding nodes. The silent nodes, however, can be encouraged by DECADE to participate, since they need to gain reputation in order to transmit their own packets.

The rest of the paper is organized as follows: Section 2 summarizes the main cooperation enforcement models in the literature for MANETs, emphasizing those that are based on game theory and providing a comparison with DECADE. Section 3 analyzes the simplest case of two nodes taking turns to send packets using the other one as a relay. We modify the payoff table of the prisoner dilemma in order to make it more robust to the uncertain environment of a MANET, leading to the Forwarding Dilemma model. In Section 4, this forwarding dilemma is extended to the environment of a bigger network that has both rational and selfish nodes. After describing the game model, we briefly review the distributed cellular/bacterial evolution algorithm (which was extensively presented in [4]). In Section 5, we analyze the effects of low/medium mobility and we introduce the sociability parameter as a way of encouraging the interactions among nodes for a better environment estimation. Finally, Section 6 concludes the paper.

2. State-of-the-art

Models for cooperation enforcement in MANETs can be broadly divided in two categories according to the techniques they use to enforce cooperation [6]: credit-based models and trust models. The main drawback of credit-based models is that they require the existence of either tamper-resistant hardware or a virtual bank, heavily restricting their usability for MANETs. On the other hand, models in which trust is the base for cooperation are envisioned as the most promising solutions for MANETs because these models do not have the restrictions of credit-based models.

Trust models can frustrate the intentions of selfish nodes by coping with observable misbehaviors. If a node does not behave cooperatively, the affected nodes, reciprocally, may deny cooperation. Generally speaking, in a trust model, an entity called the Subject S commends the execution of an action a to another entity called the Agent A, in which case we say that $T\{S{:}A, a\}$ is the trust level that S has on A with respect to the execution of action a [7]. This trust level varies as the entities interact with each other; i.e., if the Agent A responds satisfactorily to the Subject S, S can increase the trust level $T\{S{:}A; a\}$. On the other hand, if the subject S is disappointed by the agent A, the corresponding trust level could be decreased by some amount. In this sense, a trust model helps the subject of a distributed system to select the most reliable agent among several agents offering a service [8]. To make this selection, the trust model should provide the mechanisms needed for each entity to measure, assign, update and use trust values. Several trust models have been proposed in the literature for improving the performance of MANETs. In [9], there is a classification of trust-based systems according to the theoretical mechanisms used for trust scoring and trust ranking. Following this classification, we can further divide the trust-based proposals in approaches based on social networks, information theory, graph theory and game theory.

In proposals based on social networks like CONFIDANT [10], improved CONFIDANT [11], CORE [12] or SORI [13], the nodes build their view of the trust or reputation not only taking into account their own observation but also considering the recommendations from others. In addition to the previous ones, there are some trust models based on social networks that also use cluster-heads [14–17]. The cluster-head is a node who is elected to play a special role regarding the management of recommendations. An example can be found in [14]. The problem of the previous proposals is that the calculation and measurement of trust with recommendations in unsupervised ad-hoc networks involves the complex issue of rating the honesty of recommendators. Although there are efforts like [15–17] that try to alleviate this problem, it is still a hard difficulty for systems that use recommendations.

Regarding the proposals based on information theory, one of these is [7], in which the authors proposed a trust model to obtain a quantitative measurement of trust and its propagation through the MANET. However, the proposal is theoretical and it does not include an implementation specification. [18] describes a trust inference algorithm in terms of a directed and weighted Trust Graph, T, whose vertices correspond to the users in the system and for which an edge from vertex i to vertex j represents the trust that node i has in node j. However, covering the whole graph is still a highly complex computational problem.

Finally, there are several proposals that use game theory. These proposals can be further divided into cooperative and non-cooperative games [19]. In cooperative games, users form coalitions, so a group of players can adopt a certain strategy to obtain a higher gain than the one it may be obtained making decisions individually. In