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A game-theoretic approach to optimize ad hoc networks inspired by small-world network topology

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HIGHLIGHTS

- We propose a RGSWN model to control the topology of Ad Hoc networks.
- The model is an integration of small network modeling and game theoretic strategy.
- The model achieves good tradeoff between power consumption and network performance.
- Our repeated game strategy significantly enhances fault tolerance of networks.
- Our model is insightful for designing an efficient and robust ad hoc network.

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ABSTRACT

Nodes in ad hoc networks are connected in a self-organized manner. Limited communication radius makes information transmit in multi-hop mode, and each forwarding needs to consume the energy of nodes. Insufficient communication radius or exhaustion of energy may cause the absence of some relay nodes and links, further breaking network connectivity. On the other hand, nodes in the network may refuse to cooperate due to objective faulty or personal selfish, hindering regular communication in the network. This paper proposes a model called Repeated Game in Small World Networks (RGSWN). In this model, we first construct ad hoc networks with small-world feature by forming "communication shortcuts" between multiple-radio nodes. Small characteristic path length reduces average forwarding times in networks; meanwhile high clustering coefficient enhances network robustness. Such networks still maintain relative low global power consumption, which is beneficial to extend the network survival time. Then we use MTTFT strategy (Mend-Tolerance Tit-for-Tat) for repeated game as a rule for the interactions between neighbors in the small-world networks. Compared with other five strategies of repeated game, this strategy not only punishes the nodes' selfishness more reasonably, but also has the best tolerance to the network failure. This work is insightful for designing an efficient and robust ad hoc network.

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1. Introduction

Ad hoc networks are wireless communication networks for the transmission of data which do not rely on pre-existing infrastructures, such as communication base stations and routers. Nodes in an ad hoc network can be any kind of device, such as a phone, computer or sensor. Each node takes part in routing data packets by forwarding data for other nodes. Determining how the packets should be routed through the network is made dynamically. Thus information transmission needs the cooperation between nodes. There are many conflicting objectives that need to be optimized the overall power consumption, the fluctuations in power consumption per node or usage (for fairness), the robustness to churn (nodes coming and going), robustness to free-riding/exploiting other agents, the speed of updating the network, etc. [1].

An ad hoc network is, in many aspects, a complex system—the spatial distribution and duration of the links, etc. are all non-trivial consequences of the protocol determining the network. The underlying mathematical structure to study this system is network or graph. The theory of complex networks has vitalized the analysis of the topology of ad hoc networks, the optimization of the rules for their formation, and the prediction of their characteristics. One typical example of complex networks is small-world networks—networks with shorter average path length and larger clustering coefficient than purely random networks [2]. Compared to a random network, a small-world network topology would save energy, reduce end-to-end delay and optimize network performance of an ad hoc network. There are many ways to build such models, for example, adopting agents with multiple-radio which owns different radio frequencies to build long- and short-range connections [3]; using directional beamforming for creating short cuts between nodes which significantly reduces path length while maintaining connectivity [4,5]; and introducing super nodes which have more power, storage capacity and data handling capabilities to build super links [6]. In 2002, Helmy et al. introduced the idea of small-world networks into the research on wireless networks, and verified that small-world networks are also suitable for wireless networks with spatial attributes [7–10]. Refs. [11–17] built small-world models of ad hoc networks by adopting nodes with multiple-radio. Based on the models, they studied routing and resource allocation algorithms, capacity analysis [12–15], and channel allocation [16,17].

Ad hoc networks are distributed, self-organized and packet switching. Data transmission in the networks requires cooperation between nodes. Rational nodes, constrained by their own resources, may choose some behaviors that damage network performance. Obviously, even if there were even a small amount of selfish nodes in wireless ad hoc network system, the overall performance of the network would be greatly reduced.

Many strategies of game theory have been used in ad hoc networks to find incentives to suppress the node's selfishness. The most classic strategy is Tit-for-Tat, which has been frequently used as cooperation pattern between nodes in ad hoc networks. More strategies have been proposed to improve the performance of networks. Stern Tit-for-Tat strategy (STFT) resolves selfish behaviors by sternly punishing selfish nodes, which makes these nodes shift from selfish behavior to cooperative behavior for fearing punishment [18]. Guo et al. proposed a game model for the indirect trust information obtaining process, which can increase the availability and efficiency of trust manage system. This strategy makes networks finally achieve the stable condition [19]. An enhanced Tit-for-Tat model based on reputation was designed in Ref. [20], which is possible to encourage rational nodes to participate in cooperation rather than solely rely on punishment measures. Niu et al. adopted the Worst Behavior Tit-for-Tat strategy (WBTFT) to monitor behaviors of nodes so as to take measures to adjust the worst performance of the nodes [21]. Peng et al. constructed an Enhancing Tit-for-Tat strategy (ETFT) based on Peer-to-Peer (P2P) network environment, which executes a strict Tit-for-Tat strategy for punishing the selfish nodes [22]. However, the above researches on Tit-for-Tat strategy assumed that the network was fault-free. If data transmission of some nodes failed because of node failures, adjacent nodes would punish each other and thus get into an unstable state, which would reduce the network performance. Therefore, in our earlier study, we proposed the Mend-Tolerance Tit-for-Tat strategy (MTTFT) to tolerate occasional network failures [23]. This strategy sets a judgment period and a penalty period and forgives selfish nodes at the end of the penalty period. Thus it could maintain the stability of networks as much as possible.

In this paper, by integrating approaches of constructing small-world networks and performing repeated games in ad hoc networks, we propose a Repeated Game in Small World Networks model (RGSWN). This model has the potential to enhance network performance from different aspects. We first construct ad hoc networks with small-world feature by adopting nodes with multiple-radio [3]. This is realized by assuming that each node is equipped with two radio frequency (RF) modules, which send radio signals of larger and smaller frequency, thus agents have long and short communication distance respectively [11]. Then we use the MTTFT strategy for repeated game to deal with the interactions between neighbors in the networks. We compare the performances of the networks under the MTTFT strategy with other five strategies.

2. Methods

2.1. Basic assumptions for the ad hoc networks

This paper focuses on the relationship between neighbors in ad hoc networks. If all the neighbors in the network are in the cooperative state, the constructed network is also in the cooperative state [24]. In this work, we make following assumptions about ad hoc networks:

1. The system time is discrete. The length of a time slot is enough for completing the data transmission, meanwhile the routing and connectivity within a time slot is unchanged.