Imitation as the Simplest Strategy for Cooperation

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***Abstract*—Ad hoc networks comprise independent cooperative nodes which work together to constitute a system having a value greater than the sum of the values of the individual components. The nodes cooperate to gain access to the medium or to establish a messaging infrastructure by relaying foreign packets. However, when nodes in an ad hoc network operate autonomously without a central authority, they tend to defect, e.g., do not forward each other's packets following the game theoretic analysis. External mechanisms may preserve and enforce cooperation in network in return of additional operational costs or security overheads. However, low power devices may lack computational power that is required to implement the system. Recent works in evolutionary game theory have shown that cooperation may survive in a lattice structured biological network without any enforcement. The spatial structure of the network may allow the survival of the cooperative nodes when they imitate the dominant surrounding strategy. Imitating strategy helps low power devices adapt dynamically to the environment rather than giving deterministic and static decisions. In this work, we apply the imitation strategy to ad hoc networks which have geometric random network structure different from the lattice structured networks. Simulations show that simple imitation strategy allows cooperation to be spread over the network.**

***Index Terms*—Cooperation, Wireless Ad Hoc Networks, Prisoner's Dilemma, Forwarder's Game, Evolutionary Game Theory, Network Reciprocity**

I. INTRODUCTION

THE main motivation of wireless ad hoc networks is to compose networks that operate without depending on any infrastructure. The nodes in a network cooperate to establish a messaging infrastructure in which all the nodes can send and receive packets at any direction. In such a network, where the degree of cooperation is a metric for connectivity, it is obvious that the performance of the network depends on the collaborative effort of the nodes. Therefore, it is crucial to sustain the cooperation to raise the operational value of the network.

However, except from the networks which are dedicated for a certain goal such as rescue operations, wireless ad hoc networks may comprise selfish nodes. Each node aims at improving its application performance which can be defined as improved end-to-end throughput with a longer lifetime. In the scenario depicted in Fig. 1, both sources, the laptops of Alice and Bob, prefer sending their packets to the respective destinations over a neighbor node to conserve energy which may lead to prolonged lifetime. However, this cooperation results in additional power consumption for the relay node. Since the relay node's aim is to increase its lifetime and bandwidth, it may not consent to be exploited by the neighbor nodes. This strategic situation is defined as Prisoner's Dilemma in game theory [1]. In Prisoner's Dilemma, the incentive to defect is higher than the cooperation strategy. Therefore, none of the nodes relay the foreign packets if there are no external enforcements. In the literature several external enforcement mechanisms are investigated to preserve cooperation in autonomous networks like credit exchange and reputation dissemination. Nevertheless, as mentioned in Section II, all these external mechanisms incur additional overhead on the operation of the network and devices. The additional signaling and especially hardware requirements for security such as the tamper proof hardware requirement challenges the low power devices.

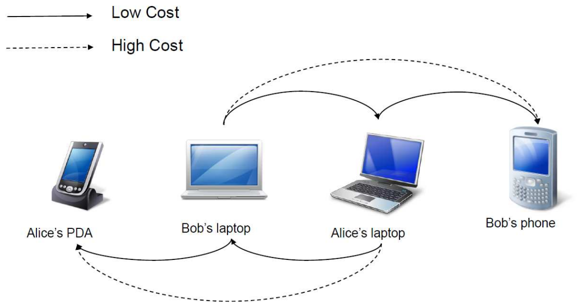


Fig. 1. Simple relaying scenario where direct link depicted as a dashed arrow may not exist or leads to higher energy consumption. If the nodes cooperate they can use each other as a hop, whereas if they defect they have to use the direct links.

Due to the constraints of the low power devices simpler strategies are required which can still maintain cooperation in the network. Imitation strategy which is inspired by *Network Reciprocity* [2], determines the forwarding strategy according to the fitnesses of the immediate neighbors. When the device joins the network, it gathers the fitnesses of the cooperators and the defectors, then perform the fittest strategy. If the defectors are dominant in that part of the network, the device also defects not to be exploited by others. On the other hand if the cooperators are dominant, even if the device still has the choice to be a defector, it becomes a cooperator. Defection may still have larger fitness value compared to cooperation, however dominance of cooperators ensures that being cooperator still has benefits. Moreover, in the future when new nodes join the network, they also become cooperator with higher possibility. As a result, the operational value of the whole network improves.

Although network reciprocity sustains cooperation in lattice structured biological networks [2], [3], what about the ad hoc networks where the network degree is not constant and the network expansion pattern is not the same? In this work, we apply the imitation strategy to ad hoc networks. After defining the strategy, invasion of the cooperators is investigated. Simulation results show that cooperators can reproduce. The rule for the survival of the cooperators is that the ratio of the benefit to cost should be larger than the network connectivity degree. The benefit is obtained as a result of the altruistic act of the cooperator and the cost is serving that altruistic act. In forwarders game presented in Fig. 1, benefit is the successful packet transmission and depends on the significance of the application while cost is the consumed energy for processing and transmission. Furthermore, the imitation strategy can be protected against frauds by distributed algorithms.

The rest of this paper is organized as follows: In Section II the mechanisms that sustain cooperation in a network are given. After summarizing the external enforcement mechanisms, Section II-D explains the imitation strategy. In Section III, the imitation protocol is described and in Section IV a realistic network update strategy for the wireless ad hoc networks is investigated. Lastly, Section V and VI summarize the work done and present the future challenges.

II. RELATED WORKS

A. Cooperation in Nature

Biologists observe the evolution of the cooperation in nature among the animals as well as humans even if the strategic game is a Prisoner's Dilemma. It is argued that independent individual components in a cooperative system work together to create a value greater than the sum of the values of the individual components. The mechanisms of the evolution of cooperation, emerged from Evolutionary Game Theory, are [4]:

- *Kin Selection*: Individuals cooperate if they are genetic relatives of each other. If Alice and Bob are close siblings, then they are expected to help each other.
- *Direct Reciprocity*: Cooperation may emerge among the unrelated individuals if there is a possibility of future interaction where the altruistic behavior may be required in reverse direction. When Alice and Bob meet frequently and both require help from each other, then the possibility of future interaction motivates them to cooperate.
- *Indirect Reciprocity*: Individuals help each other if the peer's reputation is larger than some threshold. Assume that Bob is well known with his altruistic behavior and has a high positive reputation. When Bob meets Alice, Alice offers her services to him since Bob helps everyone and consequently she increases her reputation.
- *Network Reciprocity*: Not all the populations are well-mixed. In most of the populations the interactions are limited to a portion of the population which means that the decision on the cooperation or defection is done with respect to local information.
- *Group Selection*: The cooperator groups have higher rate of growing and splitting into two since they have higher total fitness. Whereas inside the group, defectors easily invade the group.

Wireless ad hoc networks can be considered as a population with a Prisoner's Dilemma game where the cooperation is relaying a foreign packet and defection is dropping all the packets that are not destined to itself. If it can be shown that cooperation evolves among the nodes of the network naturally, we no longer need to employ external cooperation enforcement mechanisms.

In the following sections, among the five rules of evolution of cooperation, firstly the most investigated ones, Direct Reciprocity and Indirect Reciprocity are explained with their constraints. Later, Network Reciprocity strategy is introduced as the simple imitation strategy.

B. External Mechanisms and Indirect Reciprocity to Enforce Cooperation

The external mechanisms can be grouped into two, the credit-exchange (also known as virtual-currency or micropayment) systems and reputation-based (indirect reciprocity) systems [5]. In reputation-based systems, nodes collect reputation information of neighbor nodes regarding their tendency on forwarding foreign packets and also share this information with the rest of the network [6], [7], [8], [9]. Packets of the nodes with a good reputation are forwarded by its neighbors and the packets of the defective nodes are ignored. Besides signaling overheads in distribution of the reputation, it is also hard to estimate the node behavior due to interference and collisions. Wireless medium is open to interference and collisions which are out of the control of the relaying node. Unfortunately, such packet drops might lead to a decrease in the reputation of a node.

Among credit-exchange systems, [10] is a budget counter mechanism. The budget increases when a node forwards a foreign packet and decreases when the node's own packet is forwarded by other nodes. The benefit of forwarding a packet is an increase in budget which is spent in order to send its own packets. At the end, the node has to cooperate and forward the foreign packets to be able to send its packets. Similarly, there are many other works [11], [12], [13] that achieves cooperation by employing credit-exchange. For security and trust, tamper-proof hardwares, centralized entities or encryption based systems are proposed.

These mechanisms sustain cooperation in a network. However, they incur overhead, additional control signaling which uses in-band resources and consume energy. There has to be certain authentication mechanisms to prevent the frauds on the network. Central entities may be required for coordination.

C. *Possibility of Future Interactions (Direct Reciprocity)*

In one shot Prisoner's Dilemma, the equilibrium is defection. However, what happens if there is a future punishment in case of a defection? Repeated interactions among the nodes may increase the level of cooperation and the future punishment possibility changes the behavior of the defector node towards cooperation. In Fig. 1, suppose that the laptop of Alice wants to send her packets over the laptop of Bob. Bob is aware that in the future he will need the help of Alice for relaying his packets. Therefore, Bob cooperates with Alice and relays the packets to the PDA of Alice. As the number of interactions increases, cooperation may be favored.

The repeated forwarders game can be defined as *Iterated Prisoner's Dilemma (IPD)*. In an IPD game, if there is a non-zero probability that there may be a future interaction with a neighbor node, then the nodes cooperate in the game. The forwarders game designed as an IPD, is extensively investigated in [1], [14]. The behavior of selfish nodes in a large randomly generated static network topology is depicted. The requirements for a full cooperative network is given in [1]. Firstly, a node should have a dependency loop with all of the sources for which it forwards packets. Secondly, the maximum forwarding cost for the node on every route where it is a forwarder must be smaller than its possible future benefit averaged over the number of routes. In other words, the gain you achieve in future should exceed the present costs.

D. *Imitation as the Simplest Strategy for Cooperation*

The repeated game's success in spreading cooperation over the network highly depends on the possibility of future interaction of a node with the same neighbor node. Reputation and credit-exchange systems require resource consuming signaling among the devices. For low power devices, there is a need for a simple strategy which can dynamically adapt to the surrounding and can promote cooperation on the network.

Evolutionary game theory has another explanation for the survival of cooperators in a network, *network reciprocity*. In evolution, the fittest individual survives and its siblings invade the network. In Prisoner's Dilemma, since the defection is the strict Nash Equilibrium, it is also the evolutionary stable strategy and expected to invade the network. However, in [2], [4] it is argued that when the network has a spatial structure, cooperators can establish clusters and survive; they may even invade the network.

III. IMITATION PROTOCOL

Assume a fully connected network of a mixture of cooperator and defector nodes. When a new node joins, it always computes the fitness of the defectors is larger than the cooperators. However, in a loose structure like lattice or random graphs according to the surrounding cooperator population, the new node may determine that cooperators have larger fitness and chooses cooperation. The death-birth update strategy of a network with constant neighbor degree is analyzed in [2]. In death-birth update strategy at each step a random death occurs and the neighbors compete for the empty site in proportion of their fitness. Assume a node with k neighbors where i of them are cooperators. The payoff of the cooperator node is $bi - c(k-i)$ where b is the benefit obtained from a cooperative node and c is the cost of the altruistic behavior that a cooperative node has to pay. The payoff of a defector node is bi when it has i cooperator neighbors, it does not pay any costs since it has no altruistic act. After a birth, the new node decides its strategy according to its neighbors' fitnesses. The probability of choosing the cooperation strategy is $\dfrac{F_c}{F_c + F_d}$ where F_c and F_d are the sum of the payoffs of the cooperator and defector neighbors, respectively.

The new node needs to know the fitness values of every device around it to determine the strategy. When the node joins the network while trying to discover its neighbors, it may also get the fitnesses of the neighbors. Then, it is easy to find the fittest strategy by using the fitnesses. However, the nodes may share tampered values to manipulate the decision and the low power device cannot employ heavy protocols based on complicated encryption techniques.

Consistency check can be a solution for the fraud detection. The new node requests the list of cooperators and defectors from each neighbor besides their fitness values. Since most of the first hop neighbors are also neighbors of each other, the lists they provide should be consistent. Even in this case, a cooperator node may exaggerate the number of its cooperator neighbors by adding some new ones. However, by estimating the average density of the network with local information [15] and may be assuming that the nodes are uniformly distributed, new arriving node can put boundaries on the number of neighbors and consequently on fitness values. Although this is not an exact solution, a boundary on the fitness values is enforced.

IV. SURVIVAL OF COOPERATORS WITH IMITATION STRATEGY

When the network follows the death-birth process and the degree k is almost constant (e.g., as in lattice) and $\dfrac{b}{c} > k$ then the cooperators can survive [2]. However, the assumptions for this analysis are arguable for wireless ad hoc networks. Firstly, the degree of the network is assumed to be almost constant which is not the case in wireless ad hoc networks. Secondly, the topology update strategy, the authors employ death-birth update scheme in which a new child is born at the same place after a death on the network. The parents of the child node are the fittest ones among the neighbors of the dead individual. We may assume that in a wireless ad hoc network when a new node joins the network, it determines its strategy among its new neighbors and choose the fittest strategy. However, the update strategy may not be the same. In a wireless ad hoc network, we expect that nodes randomly leave the network and in random time a new node appears at a random place. Therefore, the analytical results obtained in [2] have to be reconsidered for wireless ad hoc networks.

The death-birth update strategy is not the appropriate network expansion method for the wireless networks. In wireless

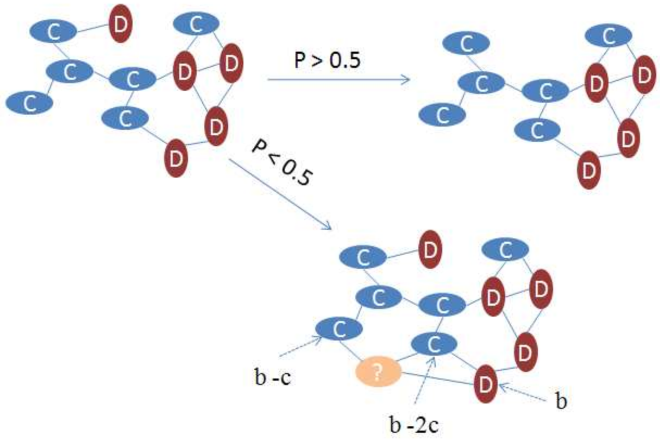


Fig. 2. An iteration of the random update strategy. The birth location and dead node selection is done randomly.

networks the nodes join the network at random times and appear at random locations, therefore the structure, degree of the network changes frequently. The size of the network vary over time, due to geometric random graph structure the node degrees are highly variable.

A. *Experiment*

In order to verify the survival of the cooperators in wireless ad hoc networks, we design an experiment with random update strategy which resembles the wireless network structure more. In MATLAB environment, a geometric random network with path-loss channel is deployed in an area and its network size, giant component size, the ratio of the cooperators are examined throughout the generations.

The random update strategy is depicted in Fig. 2. The vertexes represent the nodes of a wireless ad hoc network and the nodes are connected to other nodes with the edges if the nodes are in the range of the communication distance of the nodes. The cooperators, which are represented with blue elongated ellipse, pay cost c (e.g., the energy consumption for forwarding the packet) for each neighbor to receive benefit b. The defectors, which are denoted with red narrow ellipse, only receive benefits and does not incur associated link costs. The sum of the link costs and benefits is the payoff R for a node and the fitness is given by $1-w+wR$, where w measures the intensity of selection. Strong selection means $w = 1$. Weak selection means $w \ll 1$. In 'random-update' strategy at each step either a death or birth occurs with equal probabilities. In the case of a death (upper right graph), a random node leaves the network (i.e., dies) and its neighbor's payoff values are re-computed. In birth (lower right graph), a new node appears in a random location (i.e., node with a question mark). The new node's behavior is determined according to the fitnesses of its neighbors, it becomes a cooperator with a probability $\dfrac{F_c}{F_c+F_d}$. In the example presented in Fig. 2, the total fitness of all adjacent cooperators and defectors are $F_c = 2(1-w)+(2b-3c)w$ and $F_d = 1-w+bw$, respectively. Further details on the simulation parameters are presented in Table I.

TABLE I
SIMULATION PARAMETERS

Parameter	**Value**
Simulation environment	MATLAB
Height of the deployment area	100 m
Width of the deployment are	100 m
Transmission range	10 m
Number of nodes deployed initially	400
Initial connectivity degree (k)	≈ 11
Cost of altruistic act (c)	1
Benefit from the altruistic act (b)	$0.01, 0.1, 1, 10, 100$
Node placement	Uniformly distributed
Number of events (death and birth)	10^5
Choosing the node to leave the network	Uniform Random
Birth location	Uniform Random
Number of Repetitions	20
Intensity of selection w	0.01

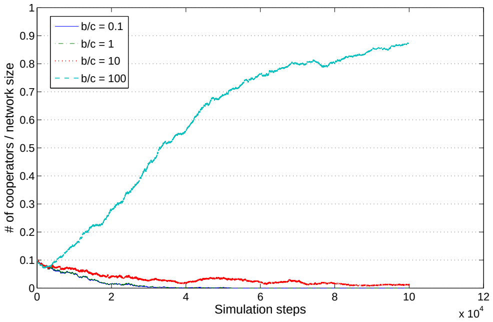
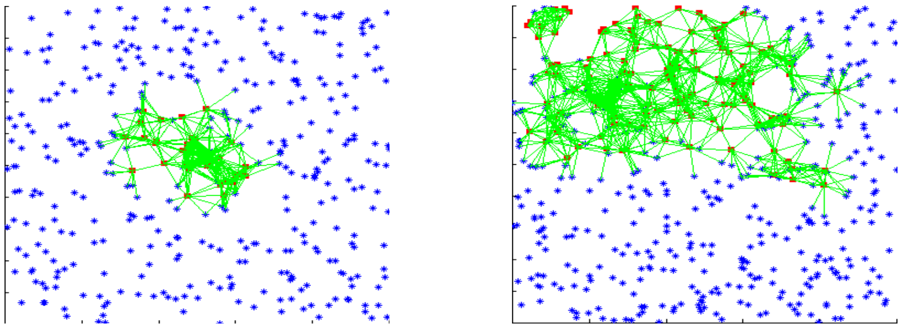


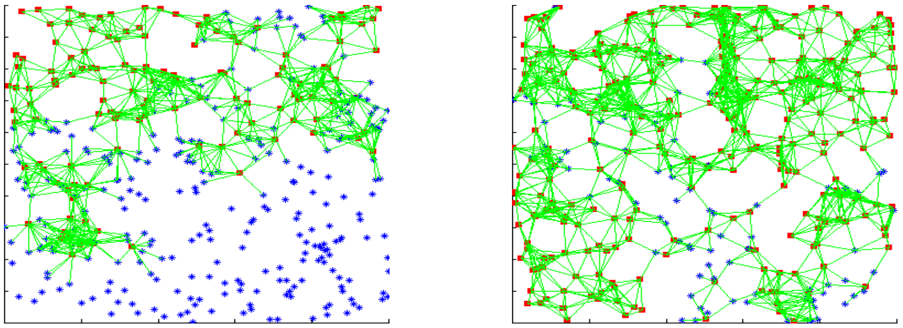
Fig. 3. Change in the ratio of cooperators over time.

B. *Results*

In Fig. 3 the change in the ratio of cooperators to the network size is depicted throughout the generations. Initially, 400 nodes are randomly deployed and 10% of the nodes are chosen as cooperators. When the b/c ratio is 100 where it is $\gg k(\approx 11)$, the ratio of the cooperators rapidly increases. For the other values of b/c, since they are lower than the k, they converge to zero, however, the speed of the convergence is low for values close to the k like 10. For further comprehension, assume that there is no cost ($c = 0$) then there is no difference between the fitnesses of the cooperators and the defectors. In such a case, the selection only depends on the size of the groups. When we introduce cost, the number of cooperators should be high enough to compensate the loss. Therefore, when the b/c ratio is low where the cost has more effect on the fitnesses, the outcome is obviously the loss of the game for the cooperators. Whereas when b/c ratio is high, the effect of the cost is low and it is more possible for cooperators to invade. In between when the b/c is almost k, the probability of selecting cooperation becomes more dependent on the birth location. The number of cooperators should be high to overcome the defectors.



(a) Step $1x10^3$ (b) Step $20x10^3$



(c) Step $40x10^3$ (d) Step $80x10^3$

Fig. 4. Snapshots of the evolution of the cooperators (red boxes), the defectors (blue stars) and the operational links are the green lines. Initially, 10 % of the network is cooperators which are deployed to the center of the area. The mean connectivity degree is ≈ 14 at the beginning of the simulation, but it varies due to the random update strategy. Considering the results in Fig. 3, the b/c ratio is chosen as 25, larger than the mean network degree.

In order to observe the steps of the cooperators invading the network, some of the intermediate steps of the scenario summarized in Table I are captured. The only difference is that the cooperators are clustered at the center, thus it is easier to track the movements of the cooperators as a cluster. The intermediate frames in which the all the operational links are shown in Fig. 4. Although, a few steps are shown, it can be observed that cooperators tend to live in clusters. They survive when they are close to each other.

When we further inspect the network, it is observed that the cooperators and their defector neighbors establish a giant component. Giant component is a significant connectivity metric and indicates largest connected component inside the network. The nodes attached to the giant component have access to the largest portion of the network. Though the giant component can be observed in Fig. 4(d), the size of the giant component is given with more details in Fig. 5. In this simulation the network size is kept constant, the death and birth events occur one by one instead of tossing a coin. The reason is that the variance of the network size has a significant effect on the giant component size and we only want to point out the change in giant component, not the whole network size. Since the cooperation propagate in clusters, the giant component is easily established. As a result, a backbone is established rapidly.

When the b/c ratio is close to network degree (between 10-15), the variance on the size of the giant component increases as can be seen in Fig. 5. The more b/c ratio gets closer to the network degree, the more the chance of sustaining the cooperation depends on the location of the births and deaths.

When the population size varies randomly, in other words deaths and births appear randomly, we still observe the growth of the giant component. Fig. 6 depicts the ratio of giant component to the network size. When b/c is large, the size of the giant component grows, cooperative nodes survive and even invade the network throughout the new generations.

V. DISCUSSION

In this work, we approach the forwarding game from the evolutionary game theory perspective. It is assumed that when a new node joins the network, it decides its strategy according to the fittest strategy among its neighbors. As a result, when the network has a spatial structure and the benefit to cost ratio is larger than the mean degree of the network, the cooperators have the chance to survive among the defectors. For dense networks, the benefit to cost ratio has to be large. As the density increases, the benefit must also be larger.

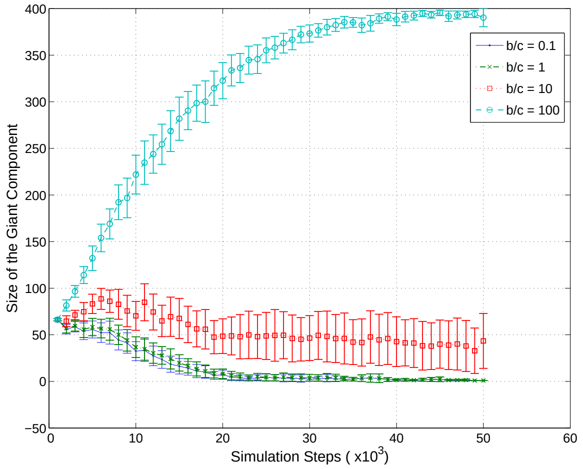


Fig. 5. The change of the size of the giant component throughout the simulation. In order to keep the network size constant, the death and birth events occur one by one instead of tossing a coin.

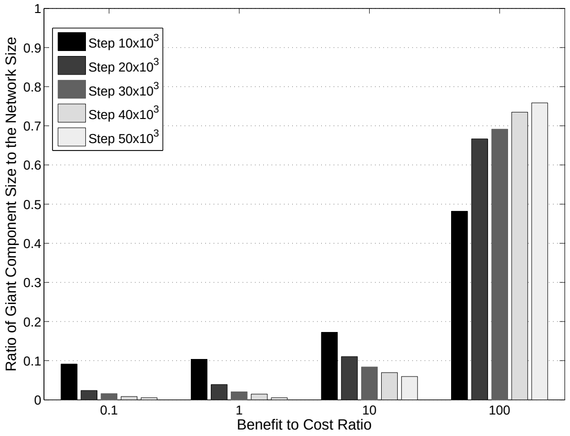


Fig. 6. The ratio of the giant component size to the network size depicted in several steps throughout the lifetime of the network with different b/c ratios.

A. Benefit and Cost

Sustaining cooperation on the network strongly depends on the high benefit to cost ratios. How can we increase the benefit or reduce the cost?

Adding intermediate hops between the source and the destination is a key method in reducing the cost of the source. The energy consumed to transmit a packet over a link increases with at least the square of the link distance. Therefore, if the distance is reduced to half with an intermediate hop, the energy consumed is also reduced by three quarters. Imagine that when a node chooses to cooperate, it incurs the additional cost by relaying neighbor's packets. However, with the help of cooperative neighbors, the cost also declines three quarters. Which means that the cooperator may still improve the benefit to cost ratio.

Apart from the energy concern, there may be cases that there is no direct link between the source and the destination. In such a case, the existence of a intermediate hop determines whether the application on the node will function or not. Hence, the benefit may be invaluable.

Besides the energy cost, depending on an infrastructure for voice communication or Internet access, we incur a monetary cost. Consider the ad hoc voice communication in the existence of an infrastructure. Cooperating means that your phone will relay your neighbor's conversations. The neighbors do not pay anything for their communication, and it is also the same for you. The benefit is the reduction of cost of using an infrastructure network for voice communication. Furthermore, as in the Open Mesh Project [16], the benefit is having a citizen-owned communication network which guarantees the privacy of the clients.

VI. CONCLUSION

The power of the ad hoc networks is due to the cooperation among the nodes. The nodes forward other node's packets and enhance network performance. However, neither all the ad hoc networks are managed by a central authority nor they are established in an emergency case. Ad hoc networks may also be established by selfish, autonomous nodes that have diverse goals in the network. When there are conflicting goals, it is hard to sustain cooperation among the nodes. This phenomenon can be described as a Prisoner's Dilemma in game theory. If the nodes cooperate, the overall network performance improves. However, nodes choose the defection strategy by behaving rationally.

In the literature, some external mechanisms are proposed to compel nodes to cooperate. These mechanisms maintain cooperation by punishment or exchange of services. Considering the constraint nodes the problem with these mechanisms is the power requirement of additional messaging, security and computation.

Low power devices may employ a simple imitation strategy. The nodes decide their cooperation or defection strategy according to the fittest strategy among their neighbors. To show the power of the imitation strategy, a network of low power devices employing imitation strategy is simulated. It is shown that in an ad hoc network cooperators can survive and even invade the network if the ratio of the benefit obtained by the cooperator nodes to the cost in result of the altruistic effect is larger than the network degree.

The authors of [2], compute the linear relation between the necessary requirements for cooperation as $b/c > k$ for lattice networks. Though, it is not the case in wireless ad hoc networks, it is shown in Section IV-A that there is still a relation between the b/c ratio and the degree k. As a future work, the coefficients of the relation should be investigated analytically. Moreover, even if the relation is identified thoroughly, there should be a quantization step for the benefit and cost values.

VII. ACKNOWLEDGMENT

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