Emergence of Cooperation in Decentralized Wireless Networks

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***Abstract*— The paper investigates the mechanisms for promotion of cooperation in decentralized wireless networks. The main objective is to determine whether cooperation can emerge in these networks in the same way it emerges in biological systems. The approach is motivated by recent results in evolutionary biology which suggest that cooperation can be favored by natural selection, if a certain mechanism is at work. We are interested in promoting cooperation based on simple rules, in contrast to most of the approaches which enforce cooperation by using complex algorithms and require strategic complexity of the network nodes. We present a model of a wireless network as a graph, and associate benefits and costs with the strategy that the network users follow at a certain time instant (cooperation or defection). We define fitness function based on the amount of power each node has to transmit and allow the users to update their strategy based on the observed change of fitness. The objective is to demonstrate that cooperative behavior, if introduced by chance, can persists over time in the wireless network.**

I. Introduction

Wireless communication has two fundamental properties. The first one is that the receive power decays exponentially as a function of the distance between the users, which puts stress on the power consumption; the second one is the broadcast nature of wireless communication, which leads to interference between the users. With the increase in the number of subscribers and growth in data traffic in wireless networks, these two features gain on importance and have a strong adverse effect on the network performance in terms of throughput and energy consumption.

The study of the fundamental limits of communication networks suggests that cooperation among the users in wireless networks could potentially overcome these effects. In this context, techniques such as cooperative diversity [1], [2] and interference alignment [3] have been proposed.

However, the performance analysis of wireless networks is often based on simplifying assumptions. As a general rule, the cost of establishing cooperation in wireless networks is not properly taken into account when deriving the performance limits of different cooperative schemes. Indeed, it may happen that the benefits of cooperation are overshadowed by the cost of establishing cooperation at first place. Additionally, very often a central infrastructure/control is assumed, which is not always the case.

Having in mind the potential of cooperation, one of the main questions to be solved is how cooperation can be established in the network. This question is of particular importance in networks which are largely decentralized, i.e. lack a central infrastructure, such as mobile ad-hoc networks. As cooperation comes at a cost for the network users, in a network which lacks centralized control, some users may decide not to cooperate.

Cooperation in decentralized networks is usually established by complex algorithms [7], [8] which usually promote/enforce cooperation based on reputation tables about the users behavior. In contrast to the present approaches which rely on complex algorithms in order to enforce cooperation, we are interested in cooperation which emerges as a result of the system evolution. This approach is inspired by recent results in evolutionary biology which suggest that cooperation plays an important role in evolving systems. Additionally, some of the key results in evolutionary biology show that cooperation can also be favored by natural selection, if certain mechanism is at work [5], [6]. By drawing an analogy between evolving biological systems and wireless networks we will try to identify the mechanisms which are able to promote cooperation in decentralized wireless networks, in the way cooperation is established in the biological systems.

II. Cooperation in biological systems

Recent results in biology [4]–[6] show that cooperation has played a fundamental role in many of the major transitions in biological evolution and is essential to the functioning of a large number of biological systems. Observations show that cooperative interactions are required for many levels of biological organization ranging from single cells to groups of animals. Human society, as well, is based to a large extent on mechanisms that promote cooperation. In the following we will shortly address the concept of cooperation in biology and revisit the candidate mechanisms which explain the emergence and stability of cooperation.

A. Emergence of cooperation

It is well known that in unstructured populations, natural selection favors defectors over cooperators. There is much current interest, however, in studying evolutionary games in structured populations and on graphs [5]. In [5] the authors

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describe a simple rule that is a good approximation for different graphs, including cycles, spatial lattices, random regular graphs, random graphs and scale-free networks. The conclusion is that natural selection favors cooperation, if the benefit of the altruistic act, b, divided by the cost, c, exceeds the average number of neighbors, k, $b/c > k$. The intuition behind is that in this case cooperation can evolve as a consequence of social viscosity even in the absence of reputation effects or strategic complexity.

B. Mechanisms which explain the emergence of cooperation

Candidate mechanisms in biology which are able to explain the emergence and stability of cooperation are kin selection, direct reciprocity, indirect reciprocity, network reciprocity, and group selection [6].

Among the candidate mechanisms which promote cooperation based on natural selection, we identify network reciprocity as the most relevant for wireless communication networks. Network reciprocity explains the emergence of cooperation in a population which is not well mixed. The approach of capturing this effect is evolutionary graph theory, which allows the study of how spatial structure affects evolutionary dynamics.

The argument for natural selection of defection is based on a well-mixed population, where everybody interacts equally likely with everybody else [5]. This approximation is used by all standard approaches to evolutionary game dynamics. But real populations are not well mixed. One approach of capturing this effect is evolutionary graph theory. According to this model, the individuals of a population occupy the vertices of a graph, where the edges determine who interacts with whom. Additionally, the users are assumed to be plain cooperators and defectors without any strategic complexity. In this setting, the experiments show that cooperators can prevail by forming network clusters, where they help each other. The resulting network reciprocity is a generalization of spatial reciprocity [6].

III. Emergence of Cooperation in Wireless Networks

Some theoretical approaches to the evolution of cooperation in biological systems are based on reciprocal altruism and on the iterated Prisoner's dilemma [4], which assume that individuals can adopt complex strategies that take into account the history of their interactions with other individuals. However, many of the most fundamental instances of cooperation in biological systems involve simple entities for which such assumptions are not realistic.

Similarly, we will also be interested in defining simple rules which can promote cooperation in wireless networks. This is in contrast to most of the present approaches which rely on complex algorithms and reputation tables in order to enforce cooperation in the network. Our objective is to promote cooperation by relying on simple strategies, i.e. by imposing a limited set of rules which mimic the principles of evolution, and let the systems evolve in time.

The question we ask is the following? Can cooperation arise in communication networks by evolution? If yes, which mechanism should be at work? It seems that network reciprocity is a promising candidate for promotion of cooperation in communication networks. Indeed, when wireless networks are described as graphs, an analogy can be drawn with populations which are not well mixed. The reason for this is that, given a power constraint, one user can interact only with the nodes which are in the range of his transmission, forming a cluster of potential cooperators.

In order to investigate the effects of the application of this kind of mechanism to wireless communication networks, we define a relatively simple network model which, however, captures both the essence of wireless communication networks and the graph models used in evolutionary game theory. We simulate the emergence of cooperative behavior in a communication network in order to explore whether rules such as natural selection can favor cooperation in these networks.

A. Network model

We model the network as a graph where the users represent the nodes and the edges are related to interactions between the nodes. The objective of each network node is to be power efficient, i.e to minimize the amount of power it spends for packet transmission. As in game theory, we assume two types of nodes, cooperators and defectors. Additionally, we make the following assumptions. First, we assume that the power decays exponentially as a function of the distance to the transmitter (source). Hence, if the transmit power is P_T, the power received at distance d from the transmitter is

$$P_R = C\frac{P_T}{d^\alpha}, \tag{1}$$

where α depends on the propagation characteristics of the area (urban, suburban, rural, etc.). Typically, α takes values in the range $2 \leq \alpha \leq 4$.

We divide the time scale in time slots of equal duration and assume that the users are active in one time slot (have message to send) with probability a. We take the symmetric scenario where each user is equally likely to send data to any of the other users. Under these assumptions, we will be essentially interested in the total power consumed by the network over time.

Let us say that at one time slot user A needs to transmit to user B and that the power it uses for direct transmission is P_D. As result of the propagation effects, the received power at user B is $P_R = C\frac{P_D}{d_{AB}^\alpha}$. We define the signal-to-noise ratio at the receiver as $SNR = P_R/\sigma^2$, where where σ^2 is the noise variance. We say that the transmission is *successful* if the signal-to-noise ratio at the receiver defined exceeds a certain threshold, $SNR \geq SNR_0 = P_{R_0}/\sigma^2$, which is required for reliable reception. In other words, in order to have a successful transmission, the node A should transmit with power $P_D \geq d_{AB}^\alpha P_{R_0}$. In the first instant, for simplicity, we assume perfect power adaptation (which should be justified in general) and assume that the node A adjusts the transmit power to the distance d_{AB}, such that it meets the receive SNR requirement exactly. This is, of course, a simplification, since for this adaptation to work, A should know the network topology (the distance to B, d_{AB}) or, at least, to have a feedback from B about the receive SNR such that it can adjust the transmit power P_D.

We say that a node C is in *range* of or *connected* to A if it can "hear" A' transmission to B. Under the assumed power adaptation, a node C is in the range of A if $d_{AR} \leq d_{AB}$. We also call this node an *intermediate* node. In the time period that node A transmits data to node B, there is a certain number of nodes which may be in the range of A. The connections are represented as edges in the graph. We note that this means that each transmission from A to B is associated with one directed network graph. Since in real networks there exist simultaneous transmissions between different pairs of users, at each time slot the networks is actually described by a **set** of different directed graphs, rather then a single graph. Depending on the users activity, the set of graphs also changes over time.

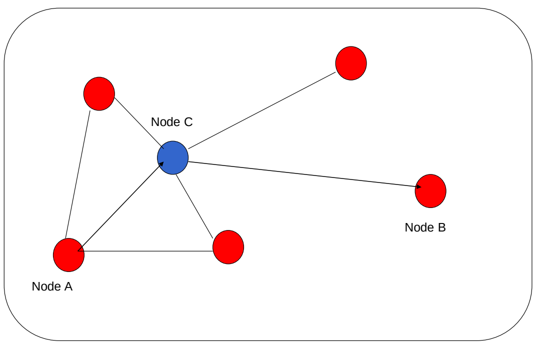

Fig. 1. An intermediate node C helps the transmission from A to B.

Now, if the intermediate node C decides to help A in the transmission, i.e to cooperate, it will retransmit the signal received from A and retransmit it to B, with power P_C. Again, this power is chosen such that the power received at B is exactly the minimal one required for successful transmission, P_{R_0}. Thus, the cost of the cooperation is the retransmission power, $c = P_C$. The benefit that the node A obtains from the cooperative act of C is that, in the presence of the cooperator C, A can decrease the transmit power to a value lower then the power required for direct transmission, $P_I \leq P_D$, where the subscript I stands for indirect transmission (transmission when cooperators are involved). In this context, we can define the benefit of the cooperative act as $b = P_D - P_I$.

Now, let us say that A is connected to k nodes, out of which $i \leq k$ help A in the transmission, i.e. cooperate. Having more then one cooperator, $i \geq 1$, produces the effect of *cooperative diversity*, well known in cooperative relaying [1], [2]. Namely, when i different cooperators retransmit the signal received from A, B receives i copies of the signal at the same time yielding an average receive power of iP_R. If we look the other way around, the cooperators can now share the retransmission power P_C and still yield the same SNR at user B, as a single cooperator would do by using a retransmission power P_C. Obviously, having more cooperators helping the transmission decreases the cost of cooperation for a single cooperator.

Let us now change the perspective and look at the network at time slot n from the viewpoint of a single node (user), let us say node C for example. For the node C we distinguish between *incoming* and *outgoing* edges. The outgoing edges are associated with the nodes which are in the range of C, when C transmits its' own packets (to user D for example).

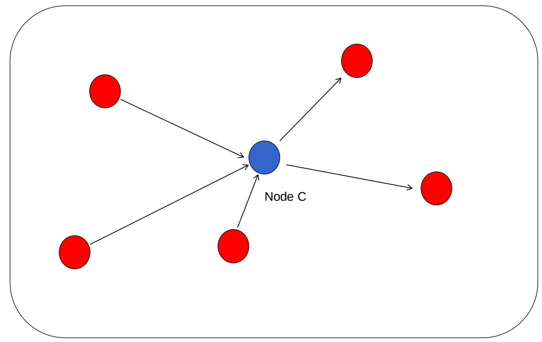

Fig. 2. Ingoing and outgoing edges for node C.

On the other hand, if the node C is in the range of one node, let us say A for example, then there is an incoming edge to C, outgoing from A. We note that by adapting this model, we allow that at one time slot the node C can be in the range of several other nodes and also help several of them in the transmission. In reality this can be done by performing a kind of multiplexing at the nodes, for example by using spread-spectrum sequences to distinguish between the different users.

Now, we can define a fitness function for the node C which is associated with the power it spends over time. Let us take that the number of incoming edges is l, out of which $j \leq l$ are active (associated with ongoing transmissions). Also, let us take that the number of outgoing edges is k, out of which $i \leq k$ are active (associated with cooperators). According to this model, the total power that C spends for cooperation, P_C, is a function of j, $P_I = P_I(j)$. On the other hand, the power that C spends for its own transmission is either P_I or P_D.

We can now define the change of the fitness of the network node C at time slot n as

$$\Delta f(n) = -\alpha \left[\beta P_I + (1-\beta) P_D\right] - \gamma \delta P_C(j) \qquad (2)$$

where $\alpha, \beta, \gamma, \delta \in 0, 1$ are parameters which indicate packet transmission and presence of cooperators and defectors. In particular, $\alpha = 1$ when C has a packet to transmit; $\beta = 1$ when C has at least one cooperator as a neighbor; $\gamma = 1$ when C is connected to at least one active node at that time instant; and $\delta = 1$ corresponds to C being a cooperator.

At first sight, the benefit of cooperation is not obvious. However, one can see that, according to this model, when cooperators are present in the networks, both P_I and P_C decrease.

Since a certain user has data to transmit with a certain probability, we need to work over more time slots when calculating the change in the fitness. We therefore update the strategy at the end of a session of length N_s time slots. The change in the fitness of C at the end of the session is:

$$\Delta F = \sum_{n=1}^{N_s} \Delta f(n) \tag{3}$$

B. Simulations

Since the model is complex to be analyzed analytically, we perform simulations in order the track the cooperative behavior over time. We take initially a 300m x 300m square grid, with 30 nodes distributed randomly in the grid area.

The fitness of the individual nodes is averaged over time blocks of length 20 (one iteration). At the end of the iteration the individual nodes update their strategy based on their individual fitness, in the following way. If the fitness has not changed in the previous block (for example if the node has not been active), the strategy remains unchanged. If the fitness of the individual node has increased compared to the previous iteration, the node becomes cooperator (if previously was defector) or remains cooperator otherwise. Similarly, a cooperator becomes/remains defector when the fitness decreases.

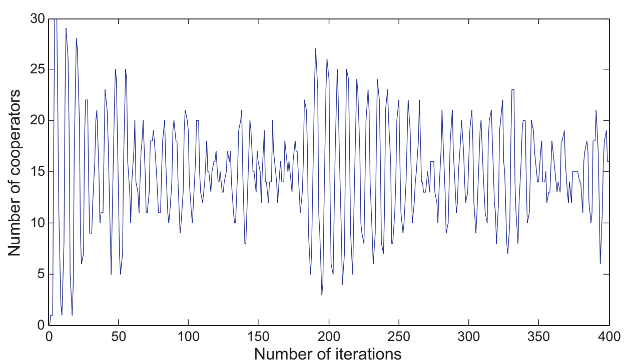

Fig. 3. Number of cooperators in the network over time.

The initial observations show an oscillatory behavior in the network, as shown in Fig. 3, where a single cooperator introduced in the network by chance (mutation), leads to clusters of cooperators which develop and diminish over time. The conclusion from the experiment is that, once introduced by chance, cooperative behavior can persist over time with high probability.

Fig. 4 illustrates the average fitness in the network. We observe an increasing trend of the average fitness in the network, as the users update their strategy. We should note that the instantaneous fitness is related to the power spent for transmission at the moment in time, and is affected by the randomness of the users'transmissions. Additionally, the strategy adaptation is simple and is performed based only on the comparison with the previous session (time block), and not over longer periods of time. These are the main reasons for the oscillatory behavior of the fitness function over time. Fig. 5 shows the average network power, which is directly related to the average fitness (absolute value). As expected, as the individual users update their strategies over time based on

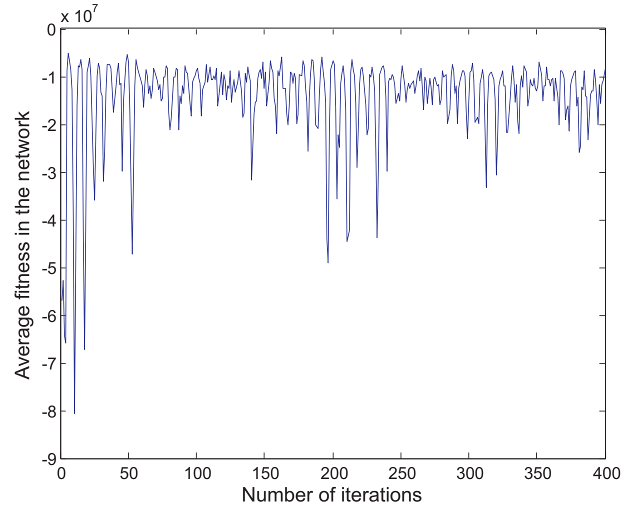

Fig. 4. Average fitness in the network over time.

the fitness, the total network consumption shows a decreasing trend.

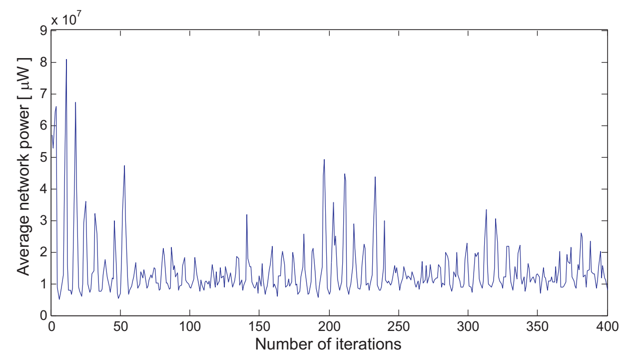

Fig. 5. Average network power.

IV. Conclusions

We investigate the mechanisms for promotion of cooperation in decentralized wireless networks. The approach is motivated by recent results in evolutionary biology which suggest that cooperation can be favored by natural selection, if a certain mechanism is at work. The wireless network is modelled as a graph, where benefits and costs are associated with the strategy that the network users follow at a certain time instant (cooperation or defection). We define a fitness function for the individual modes which is based on the amount of power each node has to transmit. The simulation results demonstrate that in the particular network model, cooperative behavior, once introduced by chance, can persist over time with high probability. As a future work, the results will be extended to different network models and under different traffic loads.

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