A Fair Multiuser Cooperation Protocol for Increasing the Throughput in Energy-Constrained Ad-hoc Networks ♣

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***Abstract*—In ad-hoc networks, cooperative diversity is especially desired where the use of multiple antennas may be impractical due to the size of nodes. There has been a lot of work on improving the peer-to-peer link quality by using advanced coding or power and rate allocation between a single source node and its relays. However, how to efficiently and fairly allocate resources among multiple users and their relays is still unknown. In this paper, a novel multiuser cooperation protocol is proposed, where multiuser diversity scheme is adopted to schedule different source/destination pairs and each pair computes its required rate based on a *power reward*. Power reward is adopted by each node to evaluate the power contributed to and by others so as to guarantee fairness. It will be shown that in energy-constrained cooperative ad-hoc networks, fairness can actually bring significant throughput gains. Simulation results will validate our analysis and show that compared to direct transmission and full cooperation protocols, much higher aggregate throughput can be achieved by the proposed Fair Cooperation Protocol thanks to improved fairness.**

Keywords- *Cooperative diversity, Multiuser diversity, Energy-constrained, Fairness, Spectral efficiency, Resource allocation.*

I. INTRODUCTION

The use of multiple antennas at both the transmitter and receiver can bring significant capacity gains. Unfortunately, this could be impractical in ad-hoc wireless networks, due to the size of the node or the mobile unit. In order to overcome this limitation, a new form of spatial diversity, whereby diversity gains are achieved via the cooperation of nodes, has been proposed. The main idea behind this approach, which is called *cooperative diversity*, is to use orthogonal relay transmission to achieve diversity gain. A virtual antenna array is then obtained through the use of the relays' antennas without complicated signal design or adding more antennas at the nodes.

Sendonaris *et al* firstly proposed the idea of cooperative diversity and applied it into CDMA cellular systems [1-2]. Laneman and Wornell further extended this work and presented several cooperative protocols, including amplify-and-forward, decode-and-forward, selection relaying and space-time-coded cooperation [3-4]. Coding is further introduced into the cooperation [5-6]. Other important work includes cooperative regions analysis for coded cooperative protocol [7], space-time code design criteria for amplify-and-forward relay channels [8], information-theoretic achievable rate regions and bounds [9], and symbol error rate analysis for Rayleigh-fading channels with K amplifying relays [10].

Most of the existing work focuses on improving the peer-to-peer link quality in the single-user scenario by using coding or power and rate allocation. In ad-hoc networks, how to efficiently and fairly allocate resources among multiple users and their relays is still unknown. Several cooperation protocols for medium-access control were proposed in [4], which are symmetric and fixed. That is, a group of users act as relays for each other. By carefully grouping the users (with similar channel gains, for example), fairness and efficiency can be achieved simultaneously in cellular networks where all the users transmit to the same destination, namely, the base station. However, in ad-hoc networks, nodes may transmit to different destinations. Each node should have its own relay set so as to improve the spectral efficiency. As a result, there will probably, if not surely, be some nodes that have more chances to be relays. As such, their power will be used up quickly. Unfairness will then occur.

There has been a lot of work on multiuser resource allocation with time-varying channels. For example, in opportunistic transmission [11], the time slot is allocated to the user with the best instantaneous channel gain to maximize the throughput. In cooperative ad-hoc networks, it may become much more complex since both the channel state between the source node and the destination node and the channel states of the relay nodes should be considered when contesting the access slot. Besides, as stated before, fairness should be guaranteed so that the resources required by each node (i.e., the power contributed by its relays) are no more than what it contributes to other nodes. In this paper, we propose a novel multiuser cooperation protocol for ad-hoc networks, where opportunistic transmission is adopted to schedule different source/destination pairs and each pair computes its required rate based on the *power reward*. Here power reward is adopted by each node to evaluate the power contributed to and by others. The power reward will increase if the node acts as a relay and decrease if the node employs the other nodes as relays. The node can use cooperation only if its power reward is large enough to cover the power required by its relays. It can be seen that by the use of the power reward, no nodes will over-contribute to others or over-utilize others as relays. As a result, fairness can be improved significantly.

Fairness and efficiency are two crucial issues. Spectral efficiency is evaluated in terms of the aggregate throughput,

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which is sometimes unfair to those users with bad channel conditions. On the other hand, absolute fairness may lead to low bandwidth efficiency. Therefore, there is usually a tradeoff between efficiency and fairness. In this paper, we will show that in energy-constrained cooperative ad-hoc networks, fairness will actually bring significant throughput gains. In particular, we assume that each node has an energy constraint *E*. With unfair protocols the nodes will run out of energy successively and the number of nodes will decrease fast. This implies that the number of available relay nodes will also decrease fast, which will lead to lower throughput and higher transmission power for each node. Besides, since opportunistic transmission is adopted, the throughput is dependent on multiuser diversity gain which will decrease with the number of nodes. Therefore, it can be expected that higher throughput can be achieved if all nodes run out of energy simultaneously. We will show that compared to direct transmission and full cooperation protocols, our proposed Fair Cooperation Protocol can achieve significant throughput gains thanks to its fairness and beamforming gain.

This paper is organized as follows. In Section II, we provide our system model. The new Fair Cooperation Protocol is proposed in Section III. Section IV presents the lifetime and throughput analysis of direct transmission, Full Cooperation Protocol and the proposed Fair Cooperation Protocol. Simulation results are given in Section V. Finally, Section VI summarizes and concludes this paper.

II. System Model and Multiuser Cooperation Protocol

We consider an ad-hoc network with *K* nodes and assume that each node is equipped with only one antenna. All nodes are associated with an energy constraint, denoted by *E*. A node uses its energy in transmitting, receiving and processing traffic. Here we assume that the energy consumed in the transmit mode is the dominant source of energy consumption. Therefore, this paper will only consider the energy consumption on transmission. The system operates in discrete time slots and TDMA is assumed. That is, in each time slot, only one source/destination pair is selected for transmission. Besides, it is assumed that the channel is time-invariant in one time slot but may change over different time slots. Let *t* denote the length of one time slot. Assume a flat fading channel between any node *i* and node *j* with the channel gain g_{ij}, where g_{ij} is assumed to be a complex Gaussian random variable with zero-mean and variance σ_{ij}^2. Here, σ_{ij}^2 accounts for the effect of large-scale path loss and shadowing [3]. In this paper, we neglect the effect of shadowing and so $\sigma_{ij}^2 = d_{ij}^{-\alpha}$, where d_{ij} is the distance between node *i* and node *j*. We assume that power control is available at the source node so that the effect of path loss can be overcome by letting the transmission power $P = P_0 d_{ij}^{\alpha}$, where P_0 is the required average receive power at the destination node in each time slot. Let h_{ij} and z_{ij} denote the small scale fading and the additive white Gaussian noise, respectively. h_{ij} and z_{ij} are complex Gaussian random variables with zero-mean and variance 1 and N_0, respectively.

Decode-and-forward relays are assumed to be used. In particular, the source node transmits the data packet to the relays in the first time slot and the relays decode and forward the packet with the source node to the destination node in the second time slot. Therefore, the source-relay (s-r) channels should be good enough compared to the source-destination (s-d) channel so as to avoid severe error propagation [9]. In ad-hoc networks, any node *k* may have different relay sets when it transmits to different destinations. Therefore, fixed multiuser cooperative protocols proposed in [4] cannot work here. In this paper, we define a *relay region* $\mathcal{R}_i$ for any source/destination pair *i*. The nodes located inside the relay region $\mathcal{R}_i$ can be regarded as the relays of the source/destination pair *i*. In particular, assume that the distance of the source/destination pair *i* is d_i and the radius of the relay region $\mathcal{R}_i$ is R_i. Then, the ratio of R_i and d_i should satisfy

$$\xi = \frac{R_i}{d_i} = (\eta / \beta)^{1/\alpha} \quad (1)$$

where $\eta = P_{sr} / P_{sd}$ is the transmission power ratio of the first time slot to the second time slot, and we have $(P_{sr} + P_{sd})/2 = P$. α is the path loss factor and β is the required average error probability ratio of the s-d channel to s-r channel. For a large β (β=100 for instance), the s-r channels will have a much lower error probability than the s-d channel so that they can be approximately regarded as error-free relative to the s-d channel. Therefore, the relay region $\mathcal{R}_i$ of the source/destination pair *i* should be a round area with a radius $R_i = d_i (\eta / \beta)^{1/\alpha}$. It can be seen that for a source/destination pair with a large distance d_i, its relay region will be large so that more relays can contribute to the transmission. The number of relays will decrease with the distance of the source/destination pair.

In this paper, we adopt a multiuser diversity scheme to schedule different source/destination pairs [11].[1] In particular, for each time slot, we compute the corresponding throughput of each source/destination pair and select the one with the maximum throughput.[2] Obviously higher throughput can be achieved with more source/destination pairs, which is called multiuser diversity gain. In order to maximize the throughput of each source/destination pair, beamforming is assumed to be adopted by the source node and the relay nodes.[3]

III. Fair Multiuser Cooperation Protocol

The fairness issue is not addressed in the above multiuser cooperative protocol. As stated before, fairness is very important especially in energy-constrained networks. With opportunistic transmission, the aggregate throughput is dependent on the multiuser diversity gain: higher throughput can be achieved with more nodes in the network. Besides, the number of available relays is also dependent on the number of

[1] Here we assume that an access point is available for scheduling, which is feasible in wireless mesh networks, for example.

[2] Note that here we do not use the fairness constraint in [11].

[3] Other multiple antennas transmission algorithms, such as space-time coding, can be also used. Beamforming is adopted here since the throughput can be optimized with the use of beamforming.

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nodes in the network. Therefore, it is desired that the number of nodes should be as large as possible, which implies that the energy of all the nodes should decrease at a similar rate. Unfortunately, the above cooperation protocol (which is referred to as Full Cooperation Protocol in the following) is an unfair one: the nodes with more relays will always occupy the time slots and so run out of energy very fast. Besides, since the cooperation mode is not fixed, there are always some nodes who have larger chances to act as relays (those who are located in the central area of the network, for instance). These nodes are treated unfairly as their power is mainly consumed in relaying while their throughput is actually decreased. With a certain energy constraint, their power will be used up much faster than the other nodes.

In this section, a novel fair multiuser cooperative protocol will be proposed. In particular, we define a *Power Reward* W_k for any node k, k=1,…, K. W_k will increase if node k acts as relays and we have

$$W_k = W_k + P_k^R \tag{2}$$

where P_k^R is the transmission power of node k. W_k will decrease if node k employs the other nodes as relays and we have

$$W_k = W_k - RP_k \tag{3}$$

where $RP_k = \sum_{j=1}^{N_k} P_j^R$, P_j^R is the transmission power of the j-th relay of node k, j=1,…, N_k.

For each source/destination pair $k(S_k, D_k)$, source node S_k will compute the possible throughput according to W_{S_k} before competing for the time slot. W_{S_k} indicates whether node S_k should use cooperation or not. If W_{S_k} is larger than the total required power of S_k's relays, cooperation should be adopted. Otherwise, node S_k cannot afford the cooperation. The corresponding possible throughput can be computed then. It can be seen that with the use of W_k, no nodes can keep employing relays. Since the time slot is allocated to the one with the highest possible throughput, by using power reward it is very unlikely that one node will continuously occupy the time slot. On the other hand, if some node always contributes to other nodes' transmission, it will have a larger W_k so that it can have more chances to transmit with relays. Therefore, it can be seen that with this new protocol, fairness can be guaranteed in two aspects: no node can keep accessing the channel and no node will always act as relays. The energy of all the nodes would decrease at a similar rate and so the throughput can be improved.

This cooperation protocol shall be referred to as *Fair Cooperation Protocol* and is described below.

FAIR COOPERATION PROTOCOL

1. *For each pair $k(S_k, D_k)$, compare W_{S_k} and the total required power of relays RP_k.*
   If $W_{S_k} \geq RP_k$, compute the possible throughput with cooperation.
   Else, compute the possible throughput with direct transmission (without cooperation).
2. *Compare the throughput of all the pairs and select the maximal one $k^*\left(S_k^*, D_k^*\right)$.*
3. *Update the power reward of S_k^* and its relays $R_j^{S_k^*}$, $j = 1,..., N_k$, using (2) and (3).*

IV. Throughput and Lifetime Analysis

In this section, we will evaluate the performance of the Full Cooperation Protocol and Fair Cooperation Protocol in terms of the aggregate throughput and lifetime. For comparison, the related analysis of direct transmission will be also presented.

A. Direct Transmission

Assume no cooperation among the nodes. For each time slot, the corresponding throughput of the i-th source/destination pair, i=1,…, $\mathcal{M}_d(t)$, is computed and the one with the maximum throughput is selected. Let us define the *network lifetime* as the maximum lifetime over all nodes, i.e., $T = \max\{T_1, T_2, ..., T_K\}$, where T_i is the lifetime of node i, i=1,…, K. Then, with direct transmission the network lifetime, T_d, can be given by

$$T_d \approx \left\lceil P_t / (P_0 \overline{D_d}^{\alpha}) \right\rceil \cdot K \tag{4}$$

where $P_t = E/T$ and $\overline{D_d}$ is the average distance of the selected source/destination pair.

The aggregate throughput of the network C_d can then be given by

$$C_d = \int_0^{T_d} \max_{i=1,...,\mathcal{M}_d(t)} \log_2\left(1+\rho\|h_i\|^2\right) dt \tag{5}$$

where $\rho = P_0 / N_0$ is the average received SNR in each transmission. Due to the Rayleigh fading assumption, $\|h_i\|^2$ is exponentially distributed. Then, from [12], (5) can be further written as

$$C_d = \int_0^{T_d} \int_0^{\infty} \mathcal{M}_d(t) e^{-\gamma} \log_2\left(1+\rho\gamma\right)\left(1-e^{-\gamma}\right)^{\mathcal{M}_d(t)-1} d\gamma dt \tag{6}$$

Assume that all the nodes always have packets to transmit in each time slot. Then, $\mathcal{M}_d(t) = \mathcal{K}_d(t)$, where $\mathcal{K}_d(t)$ is the number of nodes in time slot t and is a monotonously decreasing function of t. Notice that here we do not use the fairness constraint [11]. In each time slot, we only select the pair with the maximal throughput. Therefore, some pairs with good channel conditions will always access the channel. Their corresponding source nodes will run out of energy very rapidly (which implies that the minimum lifetime of the nodes is much smaller than T_d so that it can be neglected). In that case, the number of nodes $\mathcal{K}_d(t)$ can be shown to be

$$\mathcal{K}_d(t) \approx K(1 - t/T_d) \tag{7}$$

By substituting (7) into (6), the aggregate throughput can be computed. Obviously the increasing rate of C_d will go down with time due to the decreasing multiuser diversity gain. The curves of $\mathcal{K}_d(t)$ and C_d will be presented in Section V.

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B. Full Cooperation Protocol

Here node cooperation is always adopted. In particular, for any source/destination pair *i*, N_i relay nodes located in the relay region $\mathcal{R}_i$ will assist the communication. With node cooperation, one time slot in direct transmission protocol is split into two sub time slots. In the first sub time slot, the source node transmits to the relays and the relays decode and forward the packet with the source node using beamforming to the destination node in the second sub time slot. With decode-and-forward protocol, the throughput of each transmission is given by [3]

$$c_b = \min\{c_1, c_2\}/2 \tag{8}$$

where c_1 and c_2 are the throughput of the first sub time slot and the second sub time slot, respectively. Assume the same transmission power in two sub time slots, i.e., η=1. Then, the radius of the relay region $\mathcal{R}_i$ can be computed by (1). For a large β, the average receive SNR of s-r channels is much higher than the s-d channel (and the r-d channels). Therefore, we have $c_1 \ge c_2$ and so c_{b_i} is given by

$$c_{b_i} = \frac{1}{2}\log_2\left(1+\rho\sum_{j=0}^{N_i}\| h_j \|^2\right) \tag{9}$$

Multiuser diversity scheme is adopted to schedule different source/destination pairs. In each time slot, the corresponding throughput c_{b_i} of the *i*-th source/destination pair, *i*=1,…, $\mathcal{M}_b(t)$, is computed and the one with the maximum throughput is selected. Then, the aggregate throughput is given by

$$C_b = \int_0^{T_b} \max_{i=1,\ldots,\mathcal{M}_b(t)} \frac{1}{2}\log_2\left(1+\rho\lambda_i\right)dt \tag{10}$$

where $\lambda_i = \sum_{j=0}^{N_i}\| h_j \|^2$ is chi-square distributed with dimension $2(N_i+1)$, and we have $N_i \propto d_i^2\mathcal{M}_b(t)$.

Again, it can be shown that

$$T_b \approx \left\lceil P_t/(P_0\overline{D_b}^{\alpha})\right\rceil \cdot K \tag{11}$$

and

$$\mathcal{K}_b(t) \approx K(1-t/T_b) \tag{12}$$

where $\overline{D_b}$ is the average distance of the selected source/destination pair with Full Cooperation Protocol. From (1), we know that the radius R_i of the relay region $\mathcal{R}_i$ will increase with the distance of source/destination pair. More relays can be used with a larger R_i so that higher throughput can be achieved. As multiuser diversity scheduling is adopted here, the source/destination pair with a larger distance will have more chances to access the channel. Therefore, it can be proved that $\overline{D_b} > \overline{D_d}$. This implies that compared to direct transmission, Full Cooperation Protocol will lead to a smaller lifetime T_b and at any time slot *t*, $\mathcal{K}_b(t) < \mathcal{K}_d(t)$. Although the lifetime of Full Cooperation Protocol is less than that of direct transmission, the throughput of each transmission will increase thanks to the beamforming gain. It can be expected that Full Cooperation Protocol will bring significant capacity gains over direct transmission in the first several time slots. However, this gain will gradually fall down due to the decrease of $\mathcal{K}_b(t)$. Besides, the Full Cooperation Protocol is also an unfair protocol where the minimum lifetime of nodes is very small compared to T_b. That is why $\mathcal{K}_b(t)$ again linearly decreases with *t*. These will be clearly shown in Section V.

C. Fair Cooperation Protocol

It has been shown that Full Cooperation Protocol will lead to unfairness in two aspects: some nodes may always access the channel and some nodes over contribute to relaying. In our proposed Fair Cooperation Protocol, whether to cooperate or not is dependent on the *power reward*. The node can use cooperation only if its power reward is large enough to cover the power required by its relays. Here power reward is adopted by each node to evaluate the power contributed to and by others. The power reward will increase if the node acts as a relay and decrease if the node employs the other nodes as relays. It can be seen that by the use of power reward, no nodes will over-contribute to others or over-utilize others as relays. As a result, fairness can be improved significantly.

The aggregate throughput of Fair Cooperation Protocol is given by

$$C_f = \int_0^{T_f} \max\Big(\max_{\substack{W_i > \sum_{j=1}^{N_i} P_j^R \\ i=1,\ldots,\mathcal{M}_f(t)}} \frac{1}{2}\log_2\left(1+\rho_2\lambda_i\right), \max_{\substack{W_i < \sum_{j=1}^{N_i} P_j^R \\ i=1,\ldots,\mathcal{M}_f(t)}} \log_2(1+\rho\|h_i\|^2)\Big)dt \tag{13}$$

and the lifetime of Fair Cooperation Protocol is given by

$$T_f \approx \left\lceil P_t/(P_0\overline{D_f}^{\alpha})\right\rceil \cdot K \tag{14}$$

where $\overline{D_f}$ is the average distance of the selected source/destination pair with Fair Cooperation Protocol. In contrast to the full cooperation case, the source/destination pair with a small distance is more likely to use relays for cooperation since the required power cost is low. Therefore, with the use of power reward, $\overline{D_f}$ will decrease and so the lifetime increases.

In (13), ρ_2 is the average received SNR of the second time slot. (1) provides the relationship between the power ratio η and distance ratio ξ. Usually we assume the same transmission power (η=1) in two sub time slots (as we did in Section IV.B). However, there should be an optimum η^* (or ξ^* equivalently) with which the aggregate throughput can be maximized. Intuitively, with a larger ξ (or η), more relays can contribute to the transmission but less power P_{sd} is allocated to the second time slot. An appropriate ξ (or η) can be found to maximize the throughput of each transmission. On the other hand, for any node *i*, a larger ξ implies a higher P_{sr} and a lower $P_{sd}/(N_i+1)$. ξ can be optimized to minimize the transmission power P_i of node i. It is found that to maximize the aggregate throughput, the optimal ξ^* should satisfy

$$\xi^* = \max_{\xi}\left\{\left[\frac{\xi^2}{1+\xi^{\alpha}\beta}\right] \Big/ \left[\frac{1}{1+\xi^{\alpha}\beta}\left(\xi^{\alpha}\beta + \frac{R^2}{\xi^2\overline{D_f}^2 K}\right)\right]\right\} \tag{15}$$

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where R is the radius of the network. This will be verified in Section V. It is not easy to obtain the analytical expression of $\mathcal{K}_f(t)$. The simulation results will be presented in Section V and we will show that with this new cooperation protocol can improve the fairness significantly.

V. Simulation Results

In this section, we present simulation results that validate the previous analysis. We assume that the source nodes and destination nodes are uniformly distributed in two round areas with unit radius and the distance between two centers is denoted by R_0. There are totally K=250 source nodes, each of which has a total power constraint $P_t = E/t$. Assume that all the nodes always have packets to transmit in each time slot and in each transmission, the average received SNR ρ is 0dB. The required average error probability ratio β is 100 and path loss factor α is 4. The initial power reward of each node is given by W_0. With a small W_0, no nodes can afford cooperation and the throughput will be the same as direct transmission. However, a large W_0 will lead to full cooperation and so the fairness cannot be guaranteed. Therefore, W_0 should be carefully selected. In our simulations, we let $W_0 = \rho \cdot R_0^{\alpha} / 2$.

As shown in Section IV.B and C, the aggregate throughput with cooperation is dependent on the transmit power ratio η of two sub time slots (or distance ratio ξ). With Full Cooperation Protocol, the transmission power in the first time slot is equal to that in the second time slot and so from (1) we know that the distance ratio $\xi = 0.316$. With Fair Cooperation Protocol, the optimal ξ^* can be calculated via (15). We obtain the aggregate throughput with Fair Cooperation Protocol via simulation under different values of ξ when R_0=3 and P_t =20dB. As shown in Fig. 1, the analytical optimal ξ^* is marked by diamond, which perfectly matches the simulation results. Besides, the throughput may vary a lot with ξ, which implies that ξ should be carefully selected to maximize the aggregate throughput.

Fig. 2 presents the aggregate throughput curves with direct transmission, Full Cooperation Protocol and Fair Cooperation Protocol when R_0=3 and P_t=20dB. It can be seen that the increasing rate of throughput with direct transmission, Full Cooperation Protocol and Fair Cooperation Protocol will go down with time due to a decreasing multiuser diversity gain. A closer observation indicates that during the first 150 time slots, Full Cooperation Protocol can achieve the highest throughput thanks to beamforming gain. However, as stated in Section IV.B, it always chooses the source/destination pair with a larger distance and some nodes may always act as relays. Such nodes will run out of energy very quickly. As shown in Fig. 2, the throughput with Full Cooperation Protocol will keep constant after 160 time slots, which implies that all the nodes have run out of energy. Direct transmission can achieve a higher aggregate throughput than Full Cooperation Protocol, while its throughput is always lower than that with the Fair Cooperation Protocol. Our proposed Fair Cooperation Protocol can achieve the highest aggregate throughput thanks to both fairness and beamforming gain. For instance, the aggregate throughput of direct transmission, Full Cooperation Protocol and Fair Cooperation Protocol is 1650 bit/s/Hz, 1250 bit/s/Hz and 550 bit/s/Hz, respectively. At least 30% and 200% gain can be obtained by Fair Cooperation Protocol over direct transmission and Full Cooperation Protocol, respectively.

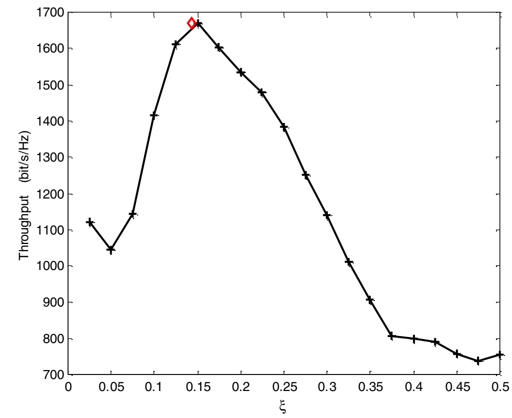

Fig. 1: Throughput vs. ξ with Fair Cooperation Protocol when R_0=3 and P_t =20dB

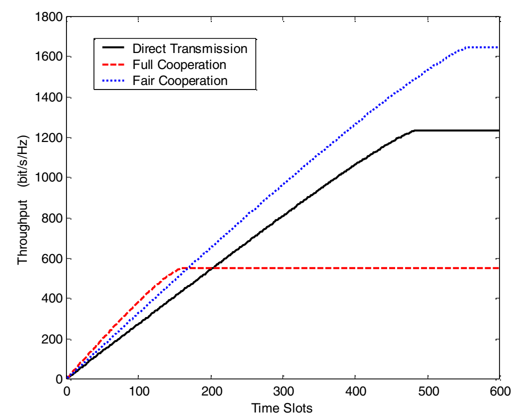

Fig. 2: Throughput curves of direct transmission, Full Cooperation Protocol and Fair Cooperation Protocol when R_0=3 and P_t=20dB

The lifetime comparison is shown in Fig. 3. As stated in Section IV.A and B, both direct transmission and Full Cooperation Protocol are unfair protocols. Some nodes may run out of energy quickly. Therefore, the number of nodes will decrease linearly with time. Our proposed Fair Cooperation Protocol can improve the fairness significantly. As shown in Fig. 3, in the first 150 time slots, nearly no nodes run out of energy. Actually this stage is expected to be as long as possible.[4] After that, the number of nodes will decrease very fast, partially because the residual power of nodes is very low, and partially because in each transmission totally N_i+1 nodes will contribute to the transmission and so more than one node may run out of energy in one time slot (Notice that with direct transmission, at most one node may run out of energy).

If we increase the power constraint P_t to be 30dB, Fair Cooperation Protocol will approach the ideal fair case. As shown in Fig. 4, the number of nodes will not decrease until

[4] The ideal case is that all nodes run out of energy simultaneously.

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the 2500th time slot. It turns out that this fairness will bring significant throughput gains. The simulation results show that in this case, 60% and 200% gain of aggregate throughput can be obtained by Fair Cooperation Protocol over direct transmission and Full Cooperation Protocol, respectively. We do not present the curves here due to limited space.

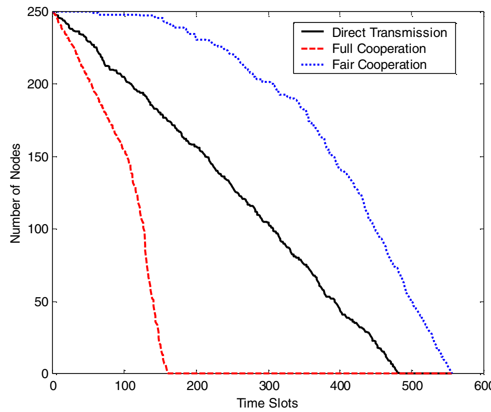

Fig. 3: Number of nodes vs. Time slots with direct transmission, Full Cooperation Protocol and Fair Cooperation Protocol when when R_0=3 and P_t =20dB

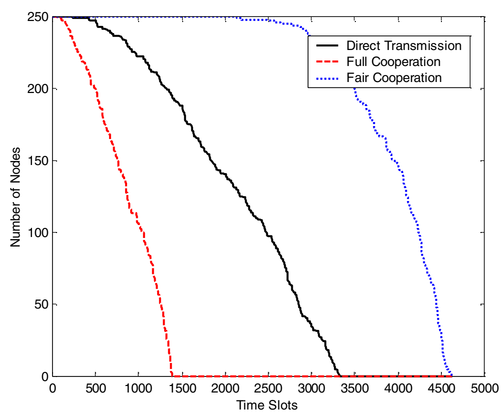

Fig. 4: Number of nodes vs. Time slots with direct transmission, Full Cooperation Protocol and Fair Cooperation Protocol when R_0=3 and P_t =30dB.

It has been shown that Fair Cooperation Protocol can provide substantial throughput gains over the direct transmission. However, this gain is dependent on the average distance of source/destination pairs. In particular, the pair with a large distance can have more relays and so the throughput would increase. Therefore, if the network has a large average distance of source/destination pairs, cooperation can bring significant throughput gains. On the other hand, for a small average distance, the gain is quite slight. Fig. 5 presents the throughput gain of Fair Cooperation Protocol over direct transmission under different values of R_0. We evaluate here such gain as $\left(C_d - C_f\right)/C_d \times 100\%$. It can be seen that the throughput gain will increase dramatically with the increase of R_0. For instance, with a R_0 of 4, Fair Cooperation Protocol can bring over 80% gains over direct transmission. However, this gain will diminish when R_0 is less than 0.5. Therefore, we conclude that cooperation is more suitable for the network with long-distance transmissions.

VI. CONCLUSIONS

In this paper, we proposed a novel multiuser cooperation protocol for energy-constrained ad-hoc networks, where power reward is used to improve the fairness and optimal power allocation is adopted to maximize the throughput. We compared this Fair Cooperation Protocol to the direct transmission and full cooperation protocols and showed that our proposed protocol can significantly improve the fairness performance and increase the lifetime. Substantial throughput gains can therefore be obtained. The numerical results validated our analysis and demonstrated that our proposed Fair Cooperation Protocol can achieve 60% and 200% gain over direct transmission and Full Cooperation Protocol, for instance. This gain will be even larger for a network with long-distance transmissions.

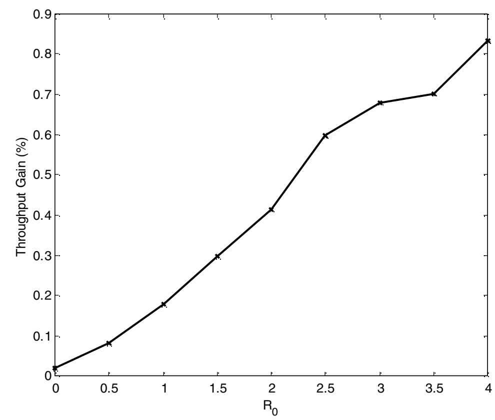

Fig. 5: Throughput gain of Fair Cooperation Protocol over direct transmission vs. R_0 when P_t =30dB.

REFERENCES

[1] A. Sendonaris, E. Erkip and B. Aazhang, "User cooperation diversity – Part I: system description," *IEEE Trans. Commun.*, vol. 51, no. 11, pp. 1927-1938, Nov. 2003.

[2] A. Sendonaris, E. Erkip and B. Aazhang, "User cooperation diversity – Part II: implementation aspects and performance analysis," *IEEE Trans. Commun.*, vol. 51, no. 11, pp. 1939-1948, Nov. 2003.

[3] J. N. Laneman, G. W. Wornell, and D. N. C. Tse, "Cooperative diversity in wireless networks: efficient protocols and outage behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062-3080, Dec. 2004.

[4] J. N. Laneman and G. W. Wornell, "Distributed space-time-coded protocols for exploiting cooperative diversity in wireless networks," *IEEE Trans. Inf. Theory*, vol. 49, pp. 2415-2425, Oct. 2003.

[5] M. Janani, A. Hedayat, T. E. Hunter and A. Nostratinia, "Coded cooperation in wireless communications: space-time transmission and iterative decoding," *IEEE Trans. Signal Processing*, vol. 52, no. 2, pp. 362-371, Feb. 2004.

[6] A. Stefanov and E. Erkip, "Cooperative coding for wireless networks," *IEEE Trans. Commun.*, vol. 52, no. 9, pp. 1470-1476, Sep. 2004.

[7] Z. Lin, E. Erkip, and A. Stefanov, "Cooperative regions for coded cooperative systems," in *Proc. Globecom'04*, pp. 21-25, Dallas, TX, Nov. - Dec. 2004.

[8] R. U. Nabar and H. Bölcskei, "Space-time signal design for fading relay channels," in *Proc. Globecom'03*, pp. 1952-1956, San Francisco, Nov. 2003.

[9] A. Host-Madsen and J. Zhang, "Capacity bounds and power allocation for wireless relay channels," *IEEE Trans. Inf. Theory*, vol. 51, no. 6, pp. 2020-2040, June 2005.

[10] P. A. Anghel and M. Kaveh, "Exact symbol error probability of a cooperative network in a Rayleigh-fading environment," *IEEE Trans. Wireless Commun.*, vol. 3, no. 5, pp. 1416-1421, Sep. 2004.

[11] P. Viswanath, D. N. C. Tse and R. Laroia, "Opportunistic beamforming using dumb antennas," IEEE Trans. Inf. Theory, vol. 48, no. 6, pp. 1277-1294, June 2002.

[12] N. Balakrishnan and A. C. Cohen, *Order Statistics and Inference: Estimation Methods*, San Diego: Academic Press, 1991.

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