

Improved Fairness in Energy-Constrained Cooperative Ad-Hoc Networks

Lin Dai and Leonard J. Cimini, Jr.

Electrical and Computer Engineering Department
University of Delaware, Newark, DE19711

dai@udel.edu; cimini@ece.udel.edu

Abstract—In ad-hoc networks, cooperative diversity is especially useful where the use of multiple antennas may be impractical. 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 [1] a novel multiuser cooperation protocol was proposed, where a *power reward* is adopted by each node to evaluate the power contributed to and by others so as to guarantee fairness. It was shown that in energy-constrained cooperative ad-hoc networks, fairness can actually bring significant throughput gains. In order to further improve the fairness, in this paper, we propose a price-aware cooperation protocol, where the residual energy information of each node is exploited to shape the relay set. Simulation results show that by using this price lever, fairness can be significantly improved compared to the Fair Cooperation Protocol [1]. This benefit turns out to bring much higher throughput than the traditional direct transmission (without cooperation) and full cooperation schemes.

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, in particular because of limitations on 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 first proposed the idea of cooperative diversity and applied it to CDMA cellular systems [2-3]. 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 [4-5]. Coding is further introduced into the cooperation in [6-7]. Other important work includes a cooperative regions analysis for the coded cooperative protocol [8], space-time code design criteria for amplify-and-forward relay channels [9], information-theoretic achievable rate regions and bounds [10], and a symbol error rate analysis for Rayleigh-fading channels with K amplifying relays [11].

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. Fairness is an important issue in resource allocation. Traditionally, a user may regard itself as unfairly treated if its throughput is much lower than

others. In cooperative ad-hoc networks, the issue is more complex since unfairness would exist even if all the users achieve similar throughput. For instance, if some node always acts as a relay but its own throughput is not improved accordingly, it may simply refuse to cooperate. In sensor networks, this means some nodes may consume their power very fast, which will lead to a routing failure and a decrease in the network throughput. Therefore, fairness issue needs to be addressed carefully in cooperative ad-hoc networks.

Several cooperative protocols for medium-access control have been proposed. In [5], these 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 be some nodes that have more opportunities to act as relays. As such, their power will be used up quickly and an unfair situation will then occur.

Fairness and efficiency are two crucial issues in resource allocation. Spectral efficiency is evaluated in terms of the aggregate throughput, 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. Somewhat surprisingly, however, in previous work [1], we showed that in energy-constrained cooperative ad-hoc networks, fairness will actually bring significant throughput gains. As we know, with unfair protocols the nodes will run out of energy successively and the number of nodes will decrease rapidly. 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. Therefore, it can be expected that higher throughput can be achieved if all nodes run out of energy simultaneously.

To address the fairness issue in energy-constrained cooperative ad-hoc networks, in [1], a novel multiuser cooperative protocol for ad-hoc networks was proposed. In this scheme, a *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 using of a power reward, no nodes will over-contribute to others or over-utilize others as relays so that fairness can be greatly improved.

In this paper, we provide the analytical framework for this issue. Fairness is evaluated by the ratio of the minimum and maximum lifetimes of the nodes, which should be one in the

ideal case. Towards this goal, we further propose a price-aware cooperation protocol, where the residual energy information of each node is exploited to shape the relay set. In particular, as [1] shows cooperation is always encouraged in the proposed Fair Cooperation Protocol since more power reward can be gained via helping others. Therefore, for those “popular” nodes (which have a large relay set so that they would have more chances to act as relays), their energy will still drop faster than others.

To improve their lifetime, one natural solution is to restrain the power contributed to other nodes when their residual power is significantly lower than others'. In this paper, we propose that each node should charge a different *price* for acting as a relay, and this price should be related to the status of its residual power: a node with less residual power would charge a higher price for being a relay. The relay set of each node only includes the ones with an affordable price. By doing so, the nodes will always look for the ones with better energy for relaying so that the minimum lifetime of nodes can be greatly extended. Simulation results show that by using this price lever, fairness can be significantly improved compared to the Fair Cooperation Protocol [1]. This benefit turns out to bring much higher throughput than the traditional direct transmission (without cooperation) and full cooperation schemes.

II. SYSTEM MODEL AND COOPERATION PROTOCOLS

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 . The system operates in discrete time slots and TDMA is assumed. Let T denote the length of one time slot. Then the total power of each node is $P_t = E/T$. 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 [4]. 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.

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 [10].

As claimed in [1], in ad-hoc networks any node k may have different relay sets when it transmits to different destinations. Therefore, the fixed multiuser protocols proposed in [5] will not work here; instead, we adopt the *relay region* proposed in [1]. In particular, the nodes located inside the relay region \mathcal{R}_i can be regarded as the relays of the source/destination pair i and \mathcal{R}_i should satisfy $R_i = d_i (1/\beta)^{1/\alpha}$, where d_i is the distance of the source/destination pair i , α is the path loss exponent, and β is the required average error probability ratio of the s-d channel to s-r channel. 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 focus on the case that all the source/destination pairs have the same distance D_0 . 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.¹ A multiuser diversity scheme is adopted to schedule different source/destination pairs [11].²

In [1], a novel Fair Cooperative Protocol was proposed where a *power reward* is adopted by each node to evaluate the power contributed to and by others. In particular, a *Power Reward* W_k is defined for any node k , $k=1, \dots, K$, and will increase if node k acts as a relay, that is

$$W_k = W_k + P_k^R \quad (1)$$

where P_k^R is the transmission power of node k . On the other hand, W_k will decrease if node k employs the other nodes as relays, that is

$$W_k = W_k - RP_k \quad (2)$$

where $RP_k = \sum_{j=1}^{N_k} P_j^R$ and P_j^R is the transmission power of the

j -th relay of node k , $j=1, \dots, N_k$. Node k can use cooperation only if its power reward W_k is large enough to cover the power required by its relays. Compared to Direct Transmission (where no cooperation is adopted among the nodes) and the Full Cooperation Protocol (where node cooperation is always assumed), here fairness can be guaranteed in two ways: no node can continue to access the channel and no node will always act as a relay. Simulation results in [1] show that substantial aggregate throughput gain can be achieved by the proposed Fair Cooperative Protocol compared to Direct Transmission and Full Cooperation Protocols.

III. FAIRNESS AND LIFETIME

Let T_i represent the lifetime of node i , $i=1, \dots, K$. That means, node i runs out of energy at the T_i th time slot. We define

$$T_{\max} = \max \{T_1, T_2, \dots, T_K\} \text{ and } T_{\min} = \min \{T_1, T_2, \dots, T_K\}. \quad (3)$$

Here T_{\max} is the lifetime of the overall network. T_{\min} is desired to be as large as possible. In an ideal case, all the nodes run out of energy at the same time so that $T_{\min} = T_{\max}$. Therefore, define

$$\xi = T_{\min} / T_{\max}. \quad (4)$$

Obviously ξ reflects the fairness (the absolute fairness is achieved when $\xi=1$). In the following, we will review the previous protocols and show that both Direct Transmission and the Full Cooperation Protocol suffer from a small ξ which indicates severe unfairness.

A. Direct Transmission

In direct transmission, the power for each transmission is $P_d = P_0 D_0^\alpha$. Therefore, the total time slots that node i can actively transmit are given by

¹ 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.

² Here we assume that an access point is available for scheduling, which is feasible in wireless mesh networks, for example.

$$N_d = \lceil P_t / P_d \rceil = \lceil P_t / (P_0 D_0^\alpha) \rceil^3 \quad (5)$$

Obviously we have $T_{\max}^d = KN_d \cdot T_{\min}^d$ is given in the following.

Theorem 1. The minimum lifetime of Direct Transmission is given by

$$T_{\min}^d = \sum_{x=N_d}^{K(N_d-1)+1} x \cdot P(T_{\min}^d = x) \quad (6)$$

where

$$P(T_{\min}^d = x) = K \binom{x-1}{N_d-1} \left[\frac{1}{K} \right]^x \prod_{l=1}^L \prod_{i=1}^{z_l} \left[K - 1 - \sum_{j=1}^{i-1} k_j^l \right] \binom{x-N_d-\sum_{j=1}^{i-1} b_j^l}{b_j^l} / k_i^l!$$

$\{k_j^l\}$ and $\{b_j^l\}$ are all possible positive integers which satisfy

$$\sum_{j=1}^{z_l} k_j^l b_j^l = x - N_d.$$

Proof: Due to the limited space, here we only provide a sketch rather than the detailed proof. As we know, T_{\min}^d is the number of time slots it takes for any node to run out of energy. With opportunistic transmission, the time slots are allocated to each node with an equiprobable probability. Therefore, here the solution of T_{\min}^d turns out to be a ball drawing problem: A bag contains K balls. Each time one ball is drawn with replacement. How many drawings are needed when any ball is drawn N_d times?

With a given small N_d , T_{\min}^d is a concave function of K , with an increasing rate of $K^{1/2}$. Therefore, for a small N_d , the lifetime ratio of Direct Transmission, ξ_d , is scaled by $1/K^{1/2}$, which will be quite small with a large number of nodes in the network. Nevertheless, ξ_d can be improved by an increase in N_d .

B. Full Cooperative Protocol

In this approach node cooperation is always adopted. In particular, for any source/destination pair i , M_i relay nodes located in the relay region \mathcal{R}_i will assist the communication. The total transmission power in each time slot is still $P_d = P_0 D_0^\alpha$. Therefore, T_{\max}^b is given by

$$T_{\max}^b = \lceil KP_t / P_d \rceil. \quad (7)$$

To obtain T_{\min}^b , we first focus on the symmetrical case where all the nodes have the same number of relays, i.e., $M_k = M$, $k=1, \dots, K$. Rewrite T_{\min}^d as a function of K and N_d : $g(K, N_d)$. The upper and lower bounds of T_{\min}^b are then given by Theorem 2.

Theorem 2. The minimum lifetime of the Full Cooperation Protocol is bounded by

$$g(K, MN_d) / M \leq T_{\min}^b \leq g(K, 2N_d) \quad (8)$$

Stretch of proof: The solution of T_{\min}^b is still a ball drawing problem. However, instead of drawing one ball each time, M balls need to be drawn with replacement. This is not a trivial combinatorics problem. Therefore, we resort to upper and lower bounds. As for the lower bound, notice that the event that M balls are drawn with replacement each time is equivalent to that one ball is drawn without replacement each

time and the total counts are divided by M . The upper bound can be obtained if we neglect the power transmitted by the relays.

It is found that T_{\min}^d is a convex function of N_d when K is given. Therefore, it is clear that for any K , $g(K, MN_d) / M \geq g(K, N_d) = T_{\min}^d$. In other words, T_{\min}^b is always larger than T_{\min}^d . So we can conclude that compared to Direct Transmission, the Full Cooperative Protocol can always achieve a higher ξ_b which indicates better fairness. Nevertheless, ξ_b is upper bounded by $g(K, 2N_d) / KN_d$, which is still quite low for a small N_d and a large K .

Notice that the above statement holds true only under the assumption that the number of relays for each node is equal, which usually cannot be satisfied. For the general cases where different nodes have different numbers of relays, the one with the largest number of relays has the largest probability to access the channel due to the fact that the more relays it has, the higher throughput it can get. Under a severely unsymmetrical network topology, T_{\min}^b approaches $2N_d$, where the node with a significantly large number of relays will always access the channel so that it will run out of energy rapidly. Therefore, the performance of T_{\min}^b is highly dependent on the network topology. In Table 1, we list the values ξ_d and ξ_b for five different kinds of random network topologies ($P_t=150$, $D_0=3$).

TABLE I. FAIRNESS COMPARISON OF DIRECT TRANSMISSION AND THE FULL COOPERATION PROTOCOL

	$K=20$	$K=50$	$K=100$	$K=150$	$K=200$
ξ_d	0.2	0.11	0.08	0.06	0.05
ξ_b	0.16	0.14	0.07	0.04	0.03

It can be seen that both Direct Transmission and the Full Cooperation Protocol have a small ξ which indicates severe unfairness. This unfairness will lead to significant throughput loss, as we will show later.

C. Fair Cooperative Protocol

When node cooperation is adopted, unfairness occurs in two ways: 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 a better chance of acting 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 an energy constraint, their power will be used up much faster than the other nodes.

In [1] we have proposed a Fair Cooperative Protocol where a *power reward* is adopted to guarantee that the power contributed by one's relays will not exceed the power one contributes to other nodes. A node cannot transmit unless its power reward is large enough to cover the required power of its relays. As a result, no nodes can keep employing relays. For the nodes who always contribute to other nodes' transmission, they will have a larger W_k so that they can have more chances to transmit with relays. Since the time slot is allocated to the one with the highest possible throughput, by using a power reward it is very unlikely that one node will continuously occupy the time slot. It can be proved that on the symmetrical assumption the minimum lifetime of the Fair Cooperation Protocol is bounded by

³ Here P_0 is the required receive power at the destination node. When the residual power is lower than $P_0 D_0^\alpha$, an outage event occurs. The throughput in this time slot will not be counted accordingly.

$$MN_d \leq T_{\min}^f \leq KN_d \quad (9)$$

Due to space limitation, we have omitted the proof here. From (9) it can be seen that with the increase of M , ξ_f , which is lower bounded by M/K , will be improved significantly. For the unsymmetrical case, ξ_f still suffers from the fact that the nodes with more relays will have a greater chance to access the channel. Nevertheless, as we have shown in [1], substantial benefits can be observed by the use of power reward.

IV. USE PRICE TO IMPROVE FAIRNESS

By the use of the power reward, no nodes will over-contribute to others or over-utilize others as relays so that fairness can be greatly improved. However, some “popular” nodes (which have a large relay set so that they would have more chances to act as relays) still suffer from a shorter lifetime compared to others. As we know, power reward can help to prevent these nodes from continuing to occupy the time slot. However, compared to the other nodes, it is easier for them to earn enough power reward (by acting as relays for other nodes) for transmission. As a result, they still have more chances to transmit, which leads to a faster power consumption.

To further improve the fairness, which is limited by the lifetime of those popular nodes, we propose to use *price* to reshape the relay set. In particular, each node k charges a price for acting as a relay, \mathcal{P}_k , which is a monotonically decreasing function of its residual power \tilde{P}_k : $\mathcal{P}_k = f(\tilde{P}_k)$. For each relay, instead of using the whole relay set (which are located inside the relay region \mathcal{R}_k), only the ones with an affordable price are selected. Therefore, let $r_k(i) \subseteq \{j: d_{jk} \leq R_k\}$. The relay selection issue can be then formulated by:

$$\begin{aligned} \max_{r_k(i)} c_{r_k(i)} &= \frac{1}{2} \log_2 \left(1 + \rho \sum_{j=0}^{M_i} \|h_j\|^2 \right) \\ \text{subject to } \sum_{j=1}^{M_i} \mathcal{P}_j &\leq \mathbb{P}_k \end{aligned} \quad (10)$$

where $M_i = |r_k(i)|$ and h_j is the channel gain between the j -th node in relay set $r_k(i)$ and node k 's destination (h_0 is the channel gain between node k and its destination). \mathcal{P}_j is the price of the j -th node in relay set $r_k(i)$ and \mathbb{P}_k is the total price affordable by node k .

There are numerous options to decide \mathbb{P}_k and the price function $f(\cdot)$. In this paper, we simply let $\mathcal{P}_k = -\tilde{P}_k$ and require that for any j -th node in relay set r_k , $\mathcal{P}_j \leq \bar{\mathcal{P}}/l$.⁴ Here, $\bar{\mathcal{P}}$ is the mean price of the whole network. Parameter l should be carefully adjusted to achieve a good ξ_f . With a small l , the variance of nodes' residual power will decrease; however, the transmission power of each node will increase due to a smaller number of relays. A large l , on the other hand, can help to increase the size of the relay set while incurring a larger variance of the nodes' residual power which indicates a lopsided power consumption. Later, we will show that an appropriate l can significantly increase ξ_f .

The *Improved Fair Cooperation Protocol* then becomes

IMPROVED FAIR COOPERATION PROTOCOL

1. For each source node S_k , decide the relay set r_{S_k} according to (10).
2. Compare W_{S_k} and the total required power of the relays RP_k .
If $W_{S_k} \geq RP_k$, compute the possible throughput with cooperation.
Else, compute the possible throughput with direct transmission
3. Compare the throughput of all the pairs and select the maximal one (S_k^*, D_k^*) .
4. Update the power reward of S_k^* and its relays, $j \in r_{S_k^*}$.
5. Update the price of S_k^* and its relays, $j \in r_{S_k^*}$, and broadcast the mean price of the whole network.

V. SIMULATION RESULTS

Assume that the source nodes are uniformly distributed in a circular area with unit radius. Let the distance between any source node and its destination node be fixed to $D_0=3$. There are a total of $K=250$ source nodes, each of which has a total power constraint $P_t=150$.⁵ Assume that all the nodes always have packets to transmit in each time slot, and for each transmission, the average received SNR ρ is 0 dB. Assume unit noise power. The required average error probability ratio of the s-d channel to s-r channel, β , is 100 and the path loss exponent 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 for 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 $W_0 = \rho \cdot D_0^\alpha / 2$. 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.

Table II shows the value of ξ_f achieved by the Improved Full Cooperation Protocol (FCP) and the one proposed in [1]. Substantial gains can be observed. For instance, when $l=8$, ξ_f increases to 0.6379 compared to 0.4640 with FCP. Nearly 40% gain is brought by Improved FCP.

TABLE II. IMPROVEMENT ON ξ_f BY THE USE OF PRICE

	$l=2$	$l=5$	$l=8$	$l=12$	$l=15$
Improved FCP	0.4843	0.4953	0.6379	0.5857	0.5711
FCP in [1]	0.4640				

Fig. 1 shows the curves for the number of nodes vs. time slots with $l=2, 8$ and 15 . After obtaining T_{\max}^f and T_{\min}^f , the number of nodes at time slot t , $\mathcal{K}(t)$, is approximately given by:

$$\mathcal{K}(t) = \begin{cases} K & t < T_{\min} \\ K(T_{\max} - t)/(T_{\max} - T_{\min}) & T_{\min} \leq t \leq T_{\max} \end{cases}$$

Clearly by the use of price, the lifetime performance of the network is improved significantly. It is also noticed that further improvement can be obtained by optimizing l . With a large l the unbalanced power consumption cannot be

⁴ Notice that this is a stronger condition than the one given by (10).

⁵ We omit the unit here since we only care about the signal-to-noise ratio.

improved a lot due to a loose constraint on the selection of relay set. While a small l , on the other hand, will lead to a shrinking size of the relay set so that the source node and each relay have to share more transmission power.

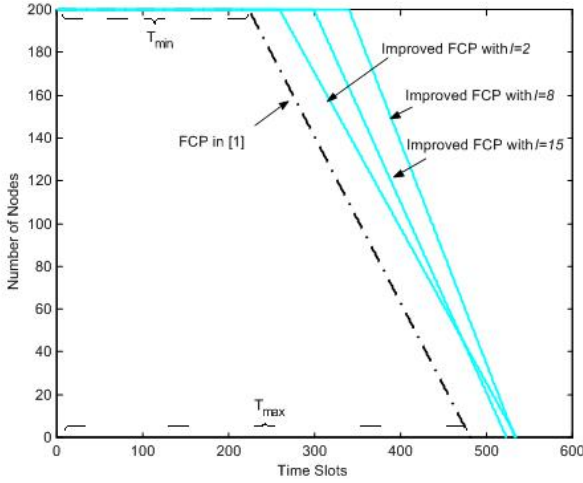


Fig. 1: Lifetime comparison when price function is adopted ($l=2, 8$ and 15)

Figs. 2 and 3 present the performance comparison of Improved FCP and the unfair schemes including Direct Transmission and the Full Cooperation Protocol. As Fig. 2 shows, both Direct Transmission and Cooperation Protocol suffer from a small ξ . Some nodes run out of energy very rapidly and the number of nodes nearly decrease linearly with time. In contrast, with Improved FCP, in the first 350 time slots no nodes run out of energy. This implies that more relays are available than the Full Cooperation Protocol so that higher throughput can be achieved.

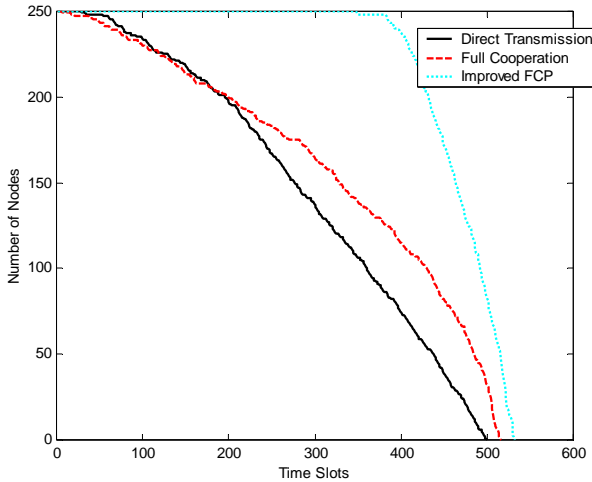


Fig. 2: Lifetime comparison of Direct Transmission, Full Cooperation Protocol and Improved FCP with $l=8$.

Fig. 3 clearly shows how fairness provides gains in throughput. During the first 50 time slots, the Full Cooperation Protocol can achieve nearly the same throughput as Improved FCP. However, since some popular nodes run out of energy rapidly, the number of available relays keeps decreasing. That is why the increase rate of throughput falls down. The aggregate throughput with the Full Cooperation Protocol will remain constant after 516 time slots, which implies that all the nodes have run out of energy. In contrast, the Improved FCP can better schedule the node transmissions so that the number of relays remains nearly unchanged for a rather long time period (say, 380 time slots). The throughput

gain over Full Cooperation Protocol keeps increasing with time. Finally 30% gain can be achieved. Both the Full Cooperation Protocol and the Improved FCP can achieve a significant throughput gain over Direct Transmission thanks to the beamforming gain.

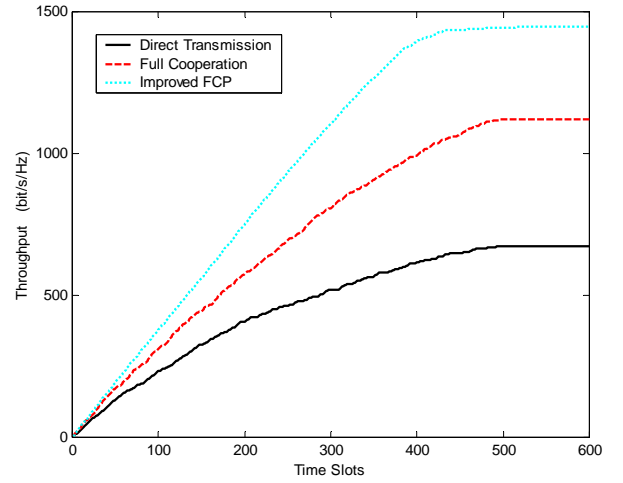


Fig. 3: Throughput comparison of Direct Transmission, Full Cooperation Protocol and Improved FCP with $l=8$.

VI. CONCLUSIONS

In this paper, we proposed a fair multiuser cooperation protocol for energy-constrained ad-hoc networks, where a price function is used to reshape the relay set. Based on the work in [1], we further take the residual power information into consideration and better balance the power consumption of nodes using a pricing mechanism. Simulation results show that the proposed Improved FCP can significantly improve the fairness performance compared to the protocol in [1]. This gain is obtained at the cost of requiring more information on network status.

REFERENCES

- [1] L. Dai, W. Chen, K. B. Letaief and Z. Cao, "A fair multiuser cooperation protocol for increasing the throughput in energy-constrained ad-hoc networks," to appear in *Proc. ICC'06*, Istanbul, Turkey, 2006.
- [2] 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.
- [3] 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.
- [4] 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.
- [5] 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.
- [6] 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.
- [7] A. Stefanov and E. Erkip, "Cooperative coding for wireless networks," *IEEE Trans. Commun.*, vol. 52, no. 9, pp. 1470-1476, Sep. 2004.
- [8] 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.
- [9] 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.
- [10] 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.
- [11] 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.
- [12] 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.