Stimulating Cooperative Diversity in Wireless Ad Hoc Networks through Pricing

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***Abstract*— This paper addresses the issue of stimulating cooperative diversity, using the amplify-and-forward protocol, among selfish nodes in commercial wireless ad hoc networks. For the relay, cooperation represents both a real cost of energy expenditure and an opportunity cost of possible delays for its own data. Since nodes are selfish, we propose a pricing game that stimulates cooperation via reimbursements to the relay. Specifically, given the price per channel use, the source and relay interact through reimbursement prices, transmitter power control and forwarding/protocol preferences such that their utilities are maximized. Our pricing game is shown to converge to a Nash equilibrium where cooperative diversity is induced at intuitively reasonable network geometries.**

I. INTRODUCTION

A wireless ad hoc network consists of a set of nodes that are organized and maintained in a distributed manner. Applications of such a network include battlefield communications, disaster relief, extension of access point (AP) provision, etc. In such networks, node cooperation can significantly increase system performance. "Cooperation" here refers to a node's willingness to sacrifice resources (e.g., energy, bandwidth) for the benefit of other nodes in the network. In applications of ad hoc networks for military and disaster relief, cooperation among nodes can be assumed since the nodes belong to a single authority and thus voluntarily cooperate to achieve a common goal. However, in commercial applications there is no good reason to assume that nodes will cooperate. In fact, given that nodes are independent entities and acts of cooperation expend resources, nodes are *selfish*, i.e., nodes consume their resources solely to maximize their own benefit.

This paper focuses on stimulating nodes in commercial wireless ad hoc networks to cooperate. We consider cooperation by means of packet forwarding in both multi-hop and cooperative diversity transmission. Cooperative diversity has been shown to significantly enhance system performance in comparison to both direct and multi-hop transmission [1], [2]. Typically in ad hoc networks, nodes are battery powered and bandwidth constrained. Thus cooperation incurs both a real and opportunity cost (in lost transmissions). A node therefore needs incentives to cooperate [3]. Researchers have developed reputation-based [4]–[6] or pricing-based [7]–[11] approaches to stimulate packet forwarding in these networks. We focus on the latter approach. To our knowledge, this is the first paper to analyze packet forwarding for cooperative diversity.

In pricing-based systems, a node receives payment (reimbursements) for forwarding packets for others. Buttayan and Hubaux [7] and Zhong *et al.* [8] develop pricing-based protocols where the amount charged per packet is determined exogenously and is the same for each node in the network. Crowcroft *et al.* [9] allow for nodes to dynamically update their price for resources based on available bandwidth and battery level. Marbach and Qiu [10] provide a formal analysis for the above setting, including the existence of equilibrium, the degree of cooperation attained under equilibrium and successful convergence to equilibrium strategies. The drawback with these approaches is the assumption of a simplified channel model - the energy required to forward a packet is assumed to be constant regardless of transmission distance.

Ileri *et al.* were the first to develop a stimulation mechanism that takes into account the fading channel [11]. The authors study the interaction between multiple nodes and a revenue seeking AP. The scheme stimulates cooperation (via forwarding) among nodes by providing reimbursements. A joint maximization approach is taken between the AP and the nodes. Their results show that cooperation is highly dependent on network geometry. This scheme works best in two-hop chains where both nodes are relatively close to each other.

One important drawback in [11] is that, in some network scenarios, a relay node's utility with forwarding is lower than that achieved in a non-forwarding system. This is because the stimulation mechanism is dominated by the revenue maximizing AP. Thus in certain network settings, the pricing mechanism benefits only the AP, not the nodes.

This paper extends the work in [11] to packet forwarding with cooperative diversity. The goal in our mechanism is to not only induce forwarding at reasonable network geometries, but to ensure that *both the AP and users benefit from cooperation*. Specifically, we design a pricing scheme in which the AP charges users for transmitting data packets and users reimburse each other for forwarding. Initially, the AP declares a set of service prices, one for each source-relay pair in the network. These prices are chosen such that the AP's revenue is maximized for the non-forwarding network. Note that the concept of "service" is related to the amount of data transmitted by the user. The effective network therefore reduces to two nodes (one source, one potential relay) and an AP.

We illustrate our pricing scheme in Fig. 1. Given the AP's service price and the source's reimbursement price for

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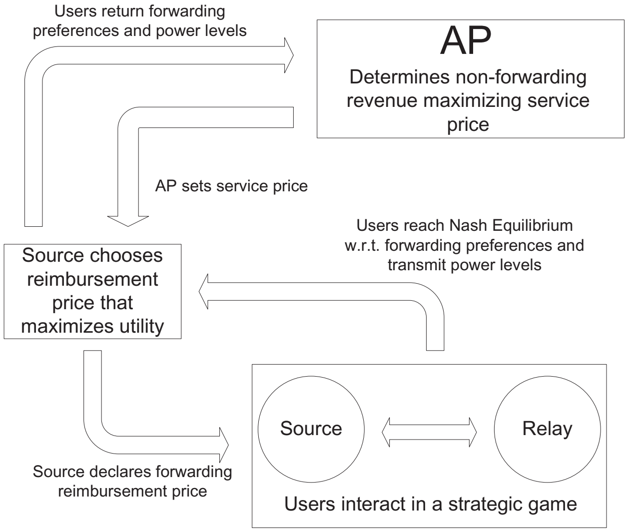

Fig. 1. Illustration of Pricing Scheme for a 2 user one AP network

forwarding, the interaction between users is a strategic game, i.e., a simultaneous move game where players chose actions without knowing the current actions of the other players [12]. Specifically in our case, the users are responsible for choosing their transmit power level and deciding on whether to forward. The game between the users reaches a Nash equilibrium when no user can unilaterally deviate from its strategy and still increase its utility. The source node executes an optimization algorithm to maximize its utility. The pricing mechanism converges at the reimbursement price that maximizes the source node's utility. The advantages of the scheme proposed here are that it is simple, distributed and scalable.

This paper is organized as follows. Section II presents the system model used and defines the utility functions used in this work. Section III analyzes the game set up in Section II. Section IV presents some simulations illustrating the performance of the proposed scheme, with conclusions in Section V.

II. SYSTEM MODEL

The network here comprises a fixed set of users (nodes) communicating with a single AP, the final destination for all user transmissions. Each user is assumed to have data of its own to transmit, organized in a packet of M bits. Each user's transmission is assumed to be interference free. The network is assumed static in the sense that the convergence time of our pricing mechanism is shorter than both the coherence time of the channel and variations in user mobility.

The functionality of our scheme is dependent on the initial routing assignments in the network. We assume simple routes, where users are clustered in groups of two according to their proximity. For each cluster, we assign the "potential relay" role to whichever user is located closer to the AP. The other user in the group is labelled as the "source". Despite our rather simplistic assumptions regarding routing, our model provides significant insight towards the implementation of cooperative diversity transmission in pricing based systems.

A. Communication Satisfaction Metric

The first step in developing the game theoretic framework is to quantify a user's satisfaction in transmitting its own data *independent* of the pricing mechanism described above. Any function that correctly characterizes a user's preferences is an appropriate measure. In an ad hoc network, a user's communication merit depends on two factors: throughput and battery life. A selfish user would want to achieve the greatest throughput possible while expending the least amount of energy. Clearly, a trade off exists between achieving high throughput and low energy consumption. Saraydar *et al.* propose a utility function that quantifies the above trade off:

$$U(p) = \frac{T(p)}{p} \quad \text{bits/joule}, \tag{1}$$

where $T(p)$ and p are the user's throughput and transmit power respectively. The throughput is related to the power via the signal-to-noise ratio (γ) which determines an efficiency function, borrowed from [13], defined below:

$$\begin{aligned} T(p) &= W * f(\gamma), & (2)\\ f(\gamma) &= [1 - 2\mathrm{BER}(\gamma)]^M, \quad \gamma = \frac{hp}{N_o W}, & (3)\end{aligned}$$

where h, N_o and W are the user's channel path gain, noise density and bandwidth respectively. The efficiency function, $f(\gamma)$ *approximates* the true frame success rate (FSR) $[1 - \mathrm{BER}(\gamma)]^M$. Using this function allows for an accurate reflection of the user's preferences. In particular, as $p \to \infty$, $U(p) \to 0$ and as $p \to 0$, $U(p) \to 0$.

B. User and AP Utility Functions

In the proposed pricing mechanism, a user's utility is based on the role it plays in the network. The utility functions used here account for the satisfaction received in transmitting data and the associated AP charges. Depending on the user's role (relay or source), the functions also include the real and opportunity costs with forwarding data along with the respective pricing rewards.

Before developing the utility functions, we first describe the action sets for each user in the game. For the potential relay, its action set is given by $\{p_r, k\}$, where p_r is the transmit power level, bound by a maximum available power $p^{\max}$, and k is the forwarding preference. Therefore, $p_r \in [0, p^{\max}]$ and k is a binary indicator with $k = 0$ the non-forwarding case and $k = 1$ the case where the relay wants to forward the source's packets. The source's action set is specified by $\{p_s, l, \mu\}$, where $p_s \in [0, p^{\max}]$ is its transmit power level, l is a binary indicator describing its choice in transmission protocol and μ is the reimbursement price that the source is willing to pay the relay for forwarding its data. Finally, the parameter λ represents the AP's service charge per unit of data in the network.

Denote the path gains from the source to the AP, the source to the relay, and the relay to the AP as h_{sa}, h_{sr} and h_{ra} respectively. The channel throughputs from the source to the AP, the source to the relay, and the relay to the AP are $T_{sa} = Wf(\gamma_{sa})$, $T_{sr} = Wf(\gamma_{sr})$ and $T_{ra} = Wf(\gamma_{ra})$ with the index indicating the SNR of the corresponding channel. The throughput of the amplify-and-forward protocol is $T_{AF} = Wf(\gamma_{AF})$, where γ_{AF} is the received SNR that the source experiences over the AF channel. To simplify the analysis, we approximate this received SNR to be the upper bound over the AF channel as derived in [2]

$$\gamma_{AF} = \gamma_{sa} + \frac{\gamma_{sr}\gamma_{ra}}{1+\gamma_{sr}+\gamma_{ra}} \simeq \gamma_{sa} + \min\{\gamma_{sr}, \gamma_{ra}\}. \quad (4)$$

The user's utility is dependent on the type of forwarding protocol used in the network. If we consider multi-hop transmission as the forwarding protocol for the network, the source's end-to-end throughput (i.e., effective throughput) is limited by the amount of bandwidth that the relay devotes to forwarding. As a result we express the source's throughput as $\min\{T_{sr}, kT_{ra}\}$. The source's utility function is given by

$$\begin{aligned} U_s^{mh} = W\Bigg[&(1-l)\left(\frac{1}{p_s}-\lambda\right) f(\gamma_{sa}) - \lambda l f(\gamma_{sr}) \\ &+ \left(\frac{1}{p_s}-\mu\right)\min\left\{lf(\gamma_{sr}), kf(\gamma_{ra})\right\}\Bigg]. \end{aligned} \quad (5)$$

The first term in (5) corresponds to the non-forwarding case ($l = 0$) and the other terms to the case where the source transmits cooperatively ($l = 1$). The amount charged by the AP is proportional (via λ) to the amount of data transmitted by the source (i.e., either T_{sa} for direct transmission or T_{sr} for multi-hop transmission). Our pricing mechanism provides forwarding incentives through the reimbursement $\mu \min\{kT_{ra}, T_{sr}\}$. The relay receives a price proportional to the effective throughput received by the source. The relay's utility function is expressed as follows

$$\begin{aligned} U_r^{mh} = W\Bigg[&(1-k)\left(\frac{1}{p_r}-\lambda\right) f(\gamma_{ra}) - \lambda k f(\gamma_{ra}) \\ &+\mu \min\left\{kf(\gamma_{ra}), lf(\gamma_{sr})\right\}\Bigg]. \end{aligned} \quad (6)$$

Note, the relay pays service charges to the AP even when forwarding data for others. This is because the AP provides resources for radio links regardless of traffic characteristics.

Now consider the amplify-and-forward protocol as the forwarding protocol in the network. Since the AF protocol uses repetition coding, the source reimburses the relay by the amount μT_{AF}. Again, this amount is proportional of the effective throughput experienced by the source. The source's utility function is given by:

$$\begin{aligned} U_s^{af} &= W\Bigg[(1-l)\left(\frac{1}{p_s}-\lambda\right) f(\gamma_{sa}) \\ &\qquad + l\left(\frac{1}{p_s}-\lambda-\mu\right) f(\gamma_{AF})\Bigg]. \end{aligned} \quad (7)$$

If the relay prefers to forward data ($k = 1$), the AF protocol requires that the amount of data to be forwarded is T_{AF}. The relay's utility function is therefore expressed as

$$U_r^{af} = W\left[\left(\frac{1}{p_r}-\lambda\right)(1-k)f(\gamma_{ra}) + \mu k f(\gamma_{AF})\right]. \quad (8)$$

Within the pricing framework, the AP's level of satisfaction is determined by the revenue it generates from the network. We allow the AP to charge each user proportionally for the amount data transmitted over the network. The AP's revenue is the sum of the data transmitted by the source and relay of group i multiplied by the price per unit of data λ_i

$$U_{AP} = \sum_i \lambda_i (T_s^i + T_r^i). \quad (9)$$

III. ANALYSIS OF PRICING MECHANISM

We now analyze our scheme to show the existence of Nash equilibria and develop an iterative algorithm to converge to the most desirable equilibrium.

A. User Optimizations

Recall, that given the charge per unit of service, λ, and the reimbursement price for forwarding, μ, the users engage in a strategic game to maximize their utilities unilaterally.

If using multi-hop transmission, the source and relay seek to maximize their utilities in (5) and (6) respectively. We can eliminate the $\min\{\}$ terms from both maximization problems by imposing the same additional constraints as in [11]. The optimization problem of the source and relay are:

$$\begin{aligned} &\max && U_s^{mh}(p_s, l) && (10) \\ &\text{s. t.} && 0 \le p_s \le p^{max} \quad l \in (0,1) \quad lf(\gamma_{sr}) \le kf(\gamma_{ra}), \end{aligned}$$

$$\begin{aligned} &\max && U_r^{mh}(p_r, k) && (11) \\ &\text{s. t.} && 0 \le p_r \le p^{max} \quad k \in (0,1) \quad kf(\gamma_{ra}) \le lf(\gamma_{sr}). \end{aligned}$$

On the other hand, if using the AF diversity protocol, the source's optimization problem corresponds to the maximization of the utility function in (7),

$$\begin{aligned} &\max && U_s^{af}(p_s, l) && (12) \\ &\text{subject to} && 0 \le p_s \le p^{\max} \quad l \in (0,1), \quad l \le k \end{aligned}$$

In the context of the AF protocol, we can simplify the relay's optimization problem by replacing the argument of the $\min\{\}$ term in (8) with γ_{ra}, with the added constraint that $\gamma_{ra} \le \gamma_{sr}$. This is because if $\gamma_{ra} > \gamma_{sr}$, we can reduce γ_{ra} (via slight reduction in p_r) and increase relay utility.

Using the utility function in (8), the optimization problem for the relay is as

$$\begin{aligned} &\max && U_r^{af}(p_r, k) && (13) \\ &\text{subject to} && 0 \le p_r \le p^{max,} \; k\epsilon(0,1), \; k \le l, \; \gamma_{ra} \le \gamma_{sr} \end{aligned}$$

To summarize, we model our strategic game as the simultaneous executions of user problems (12) and (13). This strategic game is a function of both the price per unit of service, λ, and the reimbursement price for forwarding, μ.

B. Nash Equilibria of the Strategic Game

Given λ and μ, if the individual nodes result in an action profile where each user's action is a best response to the other user's action, a Nash equilibrium is reached. In other words, a Nash equilibrium is the action profile (p_s^*, l^*, p_r^*, k^*) where no user has an incentive to deviate by choosing another action given that the other user's action is fixed. The Nash equilibrium action profiles represent steady states in the game. Formally, the Nash equilibria are the following action profiles: For Multi-hop Transmission:

$$\begin{aligned}(p_s^*, l^*) &= \arg\max U_s^{mh}(p_s, l) \;\text{ s. t. } 0 \le p_s \le p^{max}, \\ &\quad l \in (0,1),\; l f(\gamma_{sr}) \le k^* f(\gamma_{ra}^*)\end{aligned}$$

$$\begin{aligned}(p_r^*, k^*) &= \arg\max U_r^{mh}(p_r, k) \;\text{ s. t. } 0 \le p_r \le p^{max}, \\ &\quad k \in (0,1),\; k f(\gamma_{ra}) \le l^* f(\gamma_{sr}^*) \qquad (14)\end{aligned}$$

For AF:

$$\begin{aligned}(p_s^*, l^*) &= \arg\max U_s^{af}(p_s, l) \;\text{ s. t. } 0 \le p_s \le p^{max}, \\ &\quad l \in (0,1), l \le k^*\end{aligned}$$

$$\begin{aligned}(p_r^*, k^*) &= \arg\max U_r^{af}(p_r, k) \;\text{ s. t. } 0 \le p_r \le p^{max}, \\ &\quad k \in (0,1),\; k \le l^*,\; \gamma_{ra} \le \gamma_{sr}^* \qquad (15)\end{aligned}$$

From (15), for multi-hop transmission, it is clear the equilibrium action profile must satisfy the opposing throughput constraints of the users' individual maximization problems. We denote this opposing throughput constraint as $l^* f(\gamma_{sr}^*) = k^* f(\gamma_{ra}^*)$. We can see that the non-forwarding action profile $(p_s^*, 0, p_r^*, 0)$ satisfies the above constraint and always exists in our game. Thus if our game has a unique Nash equilibrium, it corresponds to this non-forwarding equilibrium. We shall see in subsection IV that in certain network settings, a forwarding equilibrium also exists in our game. This equilibrium corresponds to the action profile $(p_s^*, 1, p_r^*, 1)$ that satisfies the throughput constraint $f(\gamma_{sr}^*) = f(\gamma_{ra}^*)$. Thus in situations where both non-forwarding and forwarding equilibriums exist, we design an algorithm that will converge to the forwarding equilibrium. We detail this algorithm later in this section.

For the amplify-and-forward protocol, the opposing constraints $l \le k$ and $k \le l$ imposed on the source and relay respectively result in Nash equilibria with the property $l = k$. It is clear the non-forwarding action profile $(p_s^*, 0, p_r^*, 0)$ is always a Nash equilibrium in our game. As with the multi-hop setting, it is possible for a forwarding equilibrium to exist in our game. This corresponds to the situation where the action profile is $(p_s^*, 1, p_r^*, 1)$ and satisfies the constraint $\gamma_{ra} = \gamma_{sr}$.

In situations here both non-forwarding and forwarding equilibriums exist, the following algorithm converges to the forwarding equilibrium:

The Strategic Game Algorithm:

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1) Maximize $U_s(p_s, l)$ without constraints
2) Maximize $U_r(p_r, k)$ subject to constraints in (15)
3) While(true)
4)     Maximize $U_s(p_s, l)$ subject to constraints in (15)
5)     Perform step 2
6)     If ($(p_s^*, l^*, p_r^*, k^*)$ is the same as last iteration)
7)        break
8)     end
9) end
```

This algorithm converges in exactly two iterations. This is due to the restriction of discrete choices on forwarding/protocol preferences. To summarize, in this section we analyzed the strategic game component of our pricing mechanism. The strategic game is the major component of the pricing mechanism, depicted in Fig. 1.

C. Convergence of the Pricing Mechanism

The pricing mechanism consists of not only the source-relay strategic game, but also the utility maximizing source. Given the price per unit of service, the entire process converges at the reimbursement price that maximizes the utility of the source. We propose an algorithm that iteratively determines this price. Initially, the source sets $\mu = 0$ and the users engage in a strategic game. The algorithm from the previous section determines the users' best responses for this game. The source finds its resulting utility and then sets $\mu = \mu + \Delta\mu$. The process repeats until either the source reaches its maximum value of μ (i.e., the algorithm converges to the non-forwarding case) or to a source utility value that is strictly less than the value of the previous iteration (i.e., the algorithm converges to the cooperative case).

IV. NUMERICAL RESULTS

A. Two User and Single AP Network

Consider a network in which the AP is fixed at the origin and the potential relay is fixed 4 meters north of the AP. We compare the multi-hop and AF forwarding behavior of our pricing algorithm for different locations of the source. The following parameters are used in the simulations [11]: number of bits per frame $M = 80$, bandwidth $W = 10^6$ Hz, noise variance $NoW = 5 \times 10^{-15}$ Watts, BER(γ)=$1/2 \exp(-\gamma/2)$ for non-coherent frequency shift keyed (FSK), and a path gain formula given by $h = 1/d^2$, where d is the distance between the transmitter and receiver in meters.

Figure 2 and 3 show the forwarding regions induced by pricing for multi-hop and AF transmission respectively. The not applicable (NA) region in both figures is a result of the initial routing assignments in the network. The relay node is always the node labelled closest to the AP. Consequently, the source node is never located inside the NA region. We observe from Fig. 2 and Fig. 3 that the pricing algorithm stimulates cooperation at intuitively reasonable network geometries (i.e., geometries where the users are located relatively close to each other). This is because if the inter-user path gain, h_{sr}, is large enough relative to h_{sa}, the source has a strong willingness to pay the relay to forward its data. As a result, the relay has a stronger tendency to forward data. We observe from Fig. 2 and Fig. 3 that the forwarding region is slightly larger for AF transmission, despite reducing its performance through the received SNR approximation $\gamma_{AF} \simeq \gamma_{sa} + \min\{\gamma_{sr}, \gamma_{ra}\}$. This is expected since AF transmission is by far the more energy efficient alternative. Users receive a higher utility using AF since they are able to transmit a larger amount of data for a given energy cost.

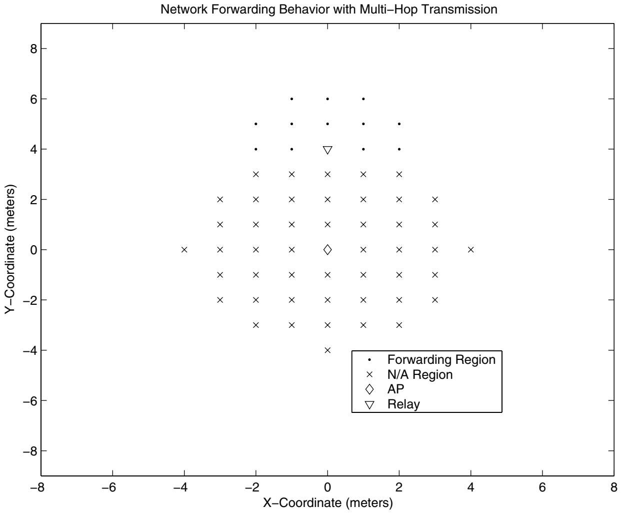

Fig. 2. Network Forwarding Behavior with MH Tx

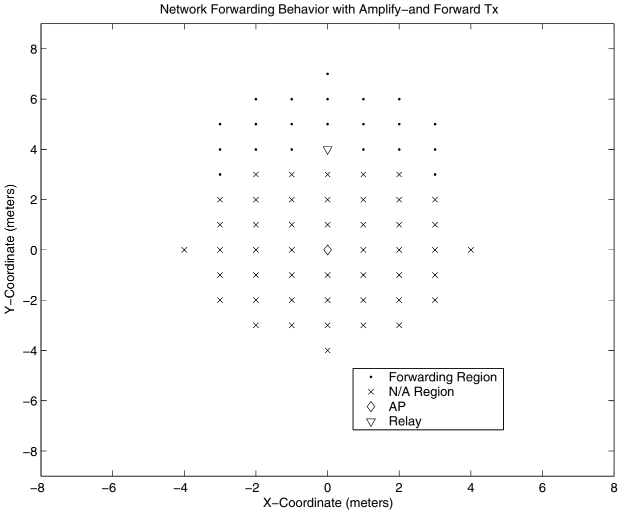

Fig. 3. Network Forwarding Behavior with AF Tx

We also compare the AP revenue, source utility and relay utility of our pricing system to a non-forwarding system. In the non-forwarding system, μ is identically set to zero (i.e., there exists no forwarding incentives for the relay). As a result, the relay and the source choose $k = 0$ and $l = 0$ respectively. The Nash equilibirum of this strategic game has the action profile $(p_s^*, 0, p_r^*, 0)$. The AP chooses the value of λ such that its revenue, $\lambda W[f(\gamma_{sa}^*) + f(\gamma_{ra})^*]$, is maximized. Consider the vertical origin passing line in Fig. 2. Figures [4-6] show the revenue, source utility and relay utility respectively of both systems along this line, north of the relay. The revenue, U_s and U_r are higher in the pricing system than in the non-forwarding system. Thus it is clear all *all parties* (i.e., AP, source and relay) benefit from the use of the pricing mechanism.

From Fig. 5, in the context of our pricing algorithm, we see the source's utility is only slightly improved when using the AF protocol compared to multi-hop transmission. This

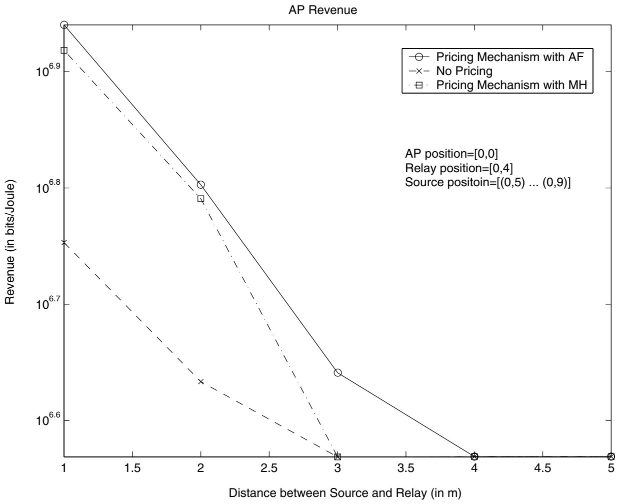

Fig. 4. AP Revenue in a two user network

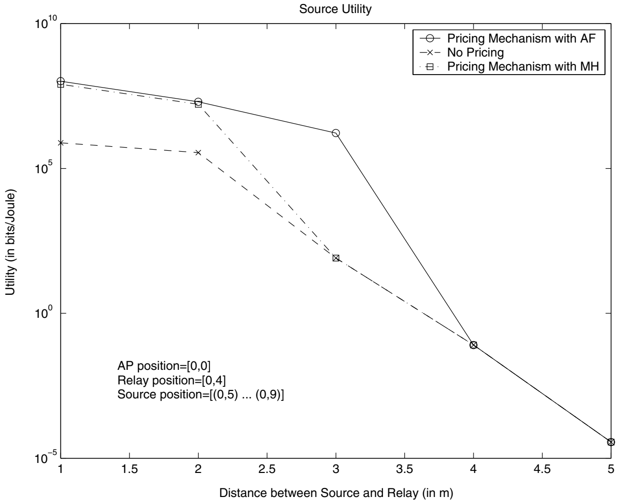

Fig. 5. Source Utility in a two user network

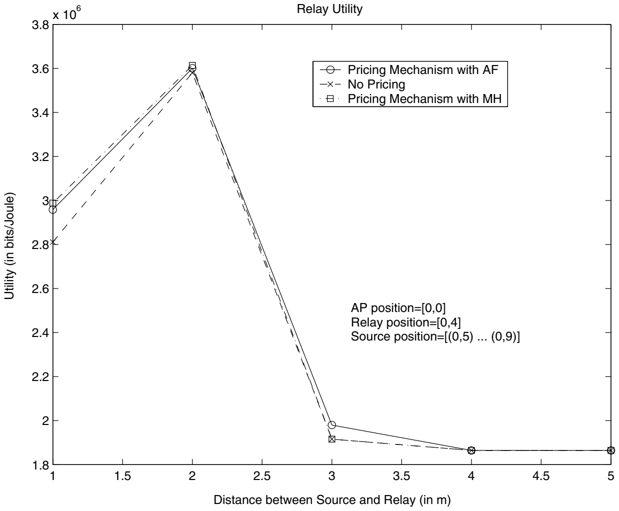

Fig. 6. Relay Utility in a two user network

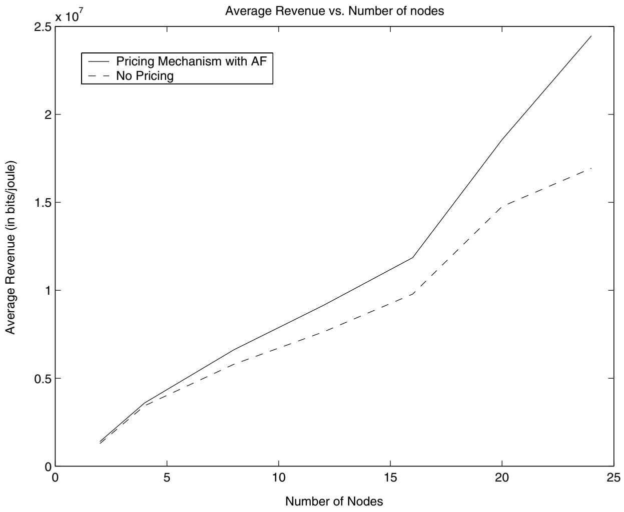

Fig. 7. Access Point's Revenue versus Number of Nodes in the Network

is because when using the AF protocol the received SNR is approximated to equal $\gamma_{AF} = \gamma_{sa} + \min\{\gamma_{sr}, \gamma_{ra}\}$. From this expression, when the source is close to the relay relative to the AP, the term γ_{sr} dominates γ_{sa}. Consequently, the source receives similar levels of satisfaction in using both the AF and multi-hop protocols.

B. Multi-User and Single AP Network

Consider a network in which users are randomly and uniformly distributed in a 10 m × 10 m region with the AP located at its center. We investigate the AP's average revenue, as a function of the number of nodes, using our pricing mechanism and the non-forwarding system. All simulations average over 100 different networks with randomly placed nodes. The parameters used are as in the previous example.

Figure 7 shows that the impact of our pricing scheme on the AP's revenue increases with the number of nodes in the network. Networks consisting of a few randomly distributed nodes do not benefit much. This is because our mechanism requires nodes to be relatively close together in order to provide beneficial results. Thus, on average, in these networks, our mechanism converges to the non-forwarding system. However, with increasing density, the average distance between nodes decreases. Thus the amount of cooperative behavior induced by pricing increases, resulting in increased revenue for the AP.

V. CONCLUSIONS

This paper has presented a pricing mechanism that induces cooperation in commercial wireless ad hoc networks. We have considered cooperation by means of packet forwarding in both multi-hop and cooperative diversity transmission. We have shown that all parties benefit from our pricing mechanism when compared to a non-forwarding system. To our knowledge, we are the first to consider cooperative diversity in such a framework.

The analysis here showed that cooperative Nash equilibria only exist at network geometries where users are located relatively close to each other. Consequently, the impact of our pricing scheme is only beneficial in networks of high densities, or in sparse networks where users are clustered in local groups. By limiting the analysis to binary forwarding decisions, we were able to gain significant insight into the frameworks' equilibrium properties. However, for a more complete analysis, further investigation is required that considers k valued action sets of forwarding decisions, where $k > 2$, including possibly continuous values for cooperation level. This analysis must be coupled with effective cooperation strategies - the cooperation strategies available so far are generally binary in nature, though recent proposals are more flexible [14]. Also, despite degrading the performance of the AF protocol via the received SNR approximation, we have shown that it still outperforms both direct and multi-hop transmission. In the future, we aim to improve this approximation such that our analysis of the AF protocol will be more accurate.

There is another open area of research - the choice of utility functions are an extremely important step in any game theoretic scheme. The choice in (1)-(3) is a fairly ad hoc choice to satisfy $p \to \infty$, $U(p) \to 0$ and as $p \to 0$, $U(p) \to 0$. The practical development of pricing for cooperative diversity must use a more realistic figure of merit, such as mutual information.

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