Throughput and Delay Performance with a Cooperative Retransmission Scheme Using Distributed Beamforming

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Abstract: **In this paper, an efficient retransmission scheme using cooperation from neighboring nodes is investigated. In the cooperative retransmission scheme, an erroneous packet is retransmitted to the destination by cooperative nodes where distributed beamforming is used to accommodate multiple cooperating nodes. A Markov model is used to analyze throughput efficiency and average delay of the proposed retransmission scheme. It is shown that the analytical results are well matched with the simulated results and improved throughput and delay performance can be achieved as compared to the traditional retransmission scheme. The performance of the proposed cooperative retransmission is investigated in the multihop configuration via computer simulation. The transmit power for retransmission packet is also investigated and it can be significantly reduced by using a small feedback channel.**

Index Terms: **Cooperative communications, distributed beamforming, Markov model, packet retransmission.**

I. INTRODUCTION

Cooperative communications has received increased interest recently as a means to overcome fading channels with a limited number of antennas and limited power at a portable device. The basic idea behind cooperative communications is that multiple single antenna devices share their antennas to create a *virtual* multiple antenna system [1]–[3]. One approach to improve system performance using cooperative nodes is distributed beamforming [3], where multiple cooperative nodes transmit the same signal at the same time after proper preprocessing to obtain beamforming gain at the destination.

Erroneous packet reception is inevitable in wireless communication systems. In [4], cooperative diversity was achieved by using an incremental redundancy (INR) scheme. However, this approach can be viewed as a method to obtain temporal diversity not an automatic repeat request (ARQ) method since decoding at the destination is performed after receiving all coded blocks. The idea of the real cooperative ARQ for ad hoc networks was introduced in [5], [6], where the neighboring nodes around the direct link monitor the shared channel to retransmit the packet when errors occur. The authors show that significant performance improvement can be achieved in terms of throughput and average delay by reducing the average number of retransmissions. In [5], however, proper coding and decoding schemes such as the distributed space-time code (STC) are assumed to achieve a full diversity gain, which requires additional information of neighboring nodes. Furthermore, there is loss in data rate for full diversity when the number of cooperating nodes is greater than two. Multiple relay selection and transmission scheme was proposed in [7]. However, full instantaneous channel information including relay nodes need to be available at the source which requires additional overhead for cooperative relay scheme.

In this paper, a more efficient cooperative retransmission scheme is examined which combines packet retransmission and user cooperation. Erroneous data packets are retransmitted to the destination via cooperative nodes only when it is requested by the destination. Cooperating nodes are self-selected by overhearing the packet exchange when the destination receives a data packet and requests retransmission via a feedback message (i.e., a NACK). The proposed approach requires no initial setup and no information sharing between neighboring nodes for cooperation. Furthermore, only those neighboring nodes which have good channels to the destination will be involved in retransmission. Multiple cooperating nodes are involved in retransmission by using distributed beamforming where carrier phase and frequency information for cooperating signals is obtained independently at each cooperating node by observing the retransmission request message from the destination. To improve system performance, all received signals are combined using maximum ratio combining (MRC). A Markov model is used in order to investigate throughput efficiency and average delay of the proposed cooperative retransmission scheme and the analytical results are compared with the simulated results. The analytical and simulated results show that the proposed cooperative retransmission scheme outperforms the traditional retransmission scheme especially when the direct link has low SNR. The performance of the proposed cooperative retransmission scheme is investigated in the multihop network configuration by transmitting multiple packets to the final destination to verify the scenario of the concurrent packet transmission. The average transmit power of the retransmitting packet is also investigated and it can be reduced significantly by using a small bandwidth feedback channel.

The rest of this paper is organized as follows. In Section II, the cooperative retransmission scheme and system model are described. In Section III, throughput efficiency and average delay are analyzed by using a Markov model for both the traditional and the cooperative retransmission schemes. The analytical results are examined and compared with the simulated results in Section IV. The concurrent packet transmission in the multihop configuration is investigated via computer simulation and power control for the retransmitting packet is also examined. Section V concludes this paper.

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II. SYSTEM MODEL

The network configuration as shown in Fig. 1 will be considered to analyze and simulate throughput efficiency and average delay performance. A source delivers packets to a destination and there are M neighboring nodes around the direct link. d_{sd} denotes the distance between the source and the destination. $d_{sr,i}$ and $d_{rd,i}$ denote the distance from the source and the destination to neighboring node i, respectively.

When the received packet is erroneous in delay-tolerant wireless networks, retransmission is typically performed based on a predefined ARQ scheme. In the cooperative retransmission scheme proposed here, the source transmits the packet to the destination in a given time slot. While the destination decodes the first received packet, neighboring nodes around the direct link are also able to decode the overheard packet. If an ACK message is sent by the destination, the next packet is transmitted from the source. Neighboring nodes which decode the data packet correctly discard their overheard packet if the ACK message is received or no correct message is received during a given time interval. When the destination cannot correctly decode the received data packet and requests a retransmission with a NACK message, a subset of the neighboring nodes also overhear this message. Those neighboring nodes which can decode both the information data and the NACK message successfully will be cooperative nodes and will retransmit the data packet to the destination in the next time slot. More details of the cooperative retransmission scheme considered in this paper are shown in [8], where outage probability and packet error rate (PER) were investigated with perfect synchronization and offset estimation of cooperating signals. The quality of the retransmitted packet has a high probability of being acceptable since the selected cooperative nodes have good channels as demonstrated by their ability to decode the NACK message correctly.

Each neighboring node decides independently to retransmit the data packet based on the overheard messages. Therefore, it is possible for multiple nodes to retransmit the data packet at the same time. To achieve the coherent sum of multiple signals at the destination, the carrier phase and frequency from each cooperative node must be synchronized when the data packet is retransmitted. Channel state information (CSI) to the destination from each cooperating node can be obtained from the NACK message and used for phase/frequency compensation. It is assumed that the symbol duration is long enough to ignore the propagation difference (i.e., symbol synchronization errors) from cooperative nodes to the destination.

III. THROUGHPUT AND DELAY ANALYSIS

Throughput efficiency and average packet delay will be analyzed for both the traditional retransmission scheme and the proposed cooperative retransmission scheme in this section.

A. Throughput Analysis

A eight-state Markov process, which state transition table is shown in Table 1, can be used to describe the packet success/failure model for the cooperative retransmission scheme. $O(k)$ represents the state of the cooperative stop-and-wait (SW) ARQ at packet k. $O(k)$ is either in the transmission (T) state or the retransmission (R) state. The transition of $O(k)$ between the T and R states depends on the previous state, $O(k-1)$, the channel state of the direct link, $D(k)$, and the state of the retransmission link, $C(k)$. $D(k)$ and $C(k)$ will be in the good state (G) or in the bad state (B) depending on their channel conditions. There are eight possible steady-states which are denoted as S_i for $i = 0, \cdots, 7$ and p_{s_i} is denoted as the steady-state probability of being in state S_i.

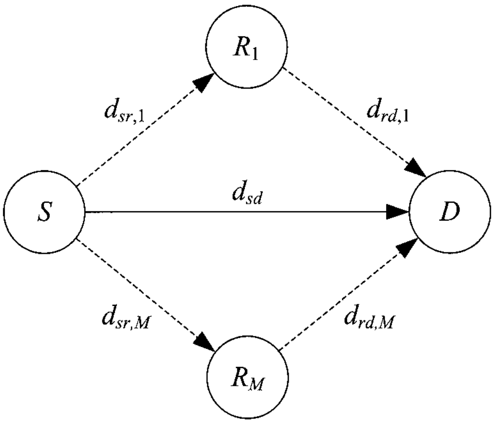

Fig. 1. Network model for the cooperative retransmission scheme.

Table 1. State Transition of SW ARQ scheme.

	$O(k-1)$	$D(k)$	$C(k)$	$O(k)$
S_0	T	G	G	T
S_1	T	G	B	T
S_2	T	B	G	R
S_3	T	B	B	R
S_4	R	G	G	T
S_5	R	G	B	T
S_6	R	B	G	T
S_7	R	B	B	R

In state T, the source delivers a new packet to the destination. In state R, the erroneous packet is retransmitted by cooperating nodes which might be only the source itself in the traditional ARQ scheme and in the cooperative ARQ scheme when there are no possible cooperating nodes.

Fig. 2 shows the state transition diagram based on the logic given in Table 1. In steady-state, the state diagram is satisfied with

$$\begin{aligned} P &= BP \\ p_{s_0} + p_{s_1} + \cdots + p_{s_7} &= 1 \end{aligned} \tag{1}$$

where $P = [p_{s_0}\, p_{s_1} \cdots p_{s_7}]^T$ and

$$B = \begin{bmatrix} \bar{t}\bar{v} & \bar{t}w & 0 & 0 & \bar{t}\bar{v} & \bar{t}w & u\bar{v} & 0 \\ \bar{t}v & \bar{t}\bar{w} & 0 & 0 & \bar{t}v & \bar{t}\bar{w} & uv & 0 \\ t\bar{v} & tw & 0 & 0 & t\bar{v} & tw & \bar{u}\bar{v} & 0 \\ tv & t\bar{w} & 0 & 0 & tv & t\bar{w} & \bar{u}v & 0 \\ 0 & 0 & u\bar{v} & uw & 0 & 0 & 0 & uw \\ 0 & 0 & uv & u\bar{w} & 0 & 0 & 0 & u\bar{w} \\ 0 & 0 & \bar{u}\bar{v} & \bar{u}w & 0 & 0 & 0 & \bar{u}w \\ 0 & 0 & \bar{u}v & \bar{u}\bar{w} & 0 & 0 & 0 & \bar{u}\bar{w} \end{bmatrix} \tag{2}$$

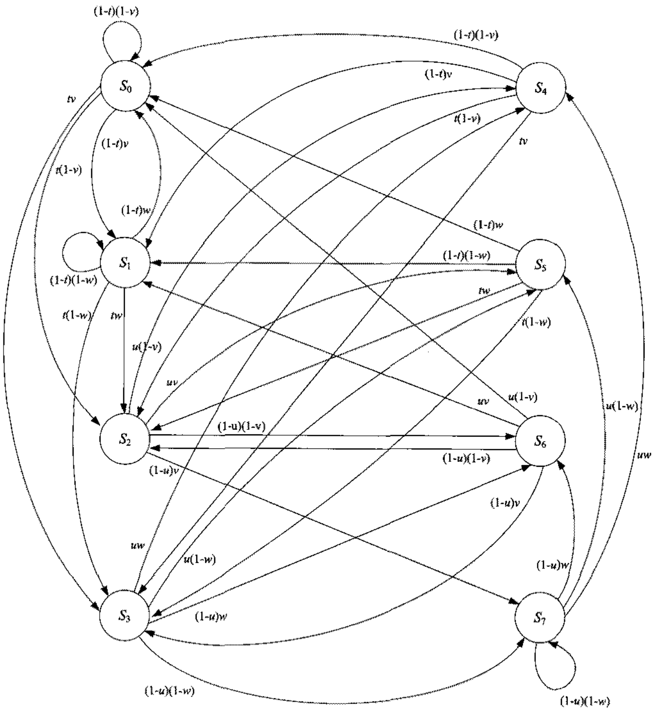

Fig. 2. Markov model for $\{O(k-1), D(k), C(k)\}$.

where $\bar{(\cdot)} = 1 - (\cdot)$. (t, u) is the good and bad reception probability of $D(k)$, and (v, w) is the Markov parameters of $C(k)$, which are defined as

$$\begin{aligned} t &= \Pr\{D(k) = B\} \\ u &= \Pr\{D(k) = G\} \end{aligned} \tag{3}$$

and

$$\begin{aligned} v &= \Pr\{C(k) = B | C(k-1) = G\} \\ w &= \Pr\{C(k) = G | C(k-1) = B\}. \end{aligned} \tag{4}$$

The steady-state probability P can be found by solving (1), which will be expressed with (t, u) and (v, w). The parameters of Markov model used in [5] is adopted to find the throughput efficiency of SW ARQ with the cooperative retransmission scheme, which are defined as

$$\begin{aligned} X &\triangleq \Pr\{O(k) = R | O(k-1) = T\} \\ Y &\triangleq \Pr\{O(k) = T | O(k-1) = R\}. \end{aligned} \tag{5}$$

Using these parameters, the throughput efficiency of SW ARQ with the cooperative retransmission scheme is given by [5], [9]

$$\bar{S} = \frac{Y}{X+Y}. \tag{6}$$

Then, X and Y are given by

$$\begin{aligned} X &= \frac{p_{s_2} + p_{s_3}}{p_{s_0} + p_{s_1} + p_{s_2} + p_{s_3}} \\ Y &= \frac{p_{s_4} + p_{s_5} + p_{s_6}}{p_{s_4} + p_{s_5} + p_{s_6} + p_{s_7}}. \end{aligned} \tag{7}$$

Note that the throughput efficiency of the SW ARQ scheme can be found directly from Fig. 2 with (t, u) and (v, w). However, (5) and (6) give easier tractable formulas compared to the direct approach.

The received signal of $i \to j$ link after matched filtering and sampling can be expressed by

$$\mathbf{r}_{ij} = \sqrt{\alpha_{ij}} h_{ij} \mathbf{s} + \mathbf{n}_{ij}. \tag{8}$$

α_{ij} the large-scale path loss of $i \to j$ link, where $i, j \in \{s, r, d\}$ and s, r, d stand for source, relay, and destination, respectively. h_{ij} is small-scale channel coefficient of $i \to j$ link which is complex Gaussian random variable with zero mean and 0.5 variance per dimension. $\mathbf{s}$ is the transmit signal and $\mathbf{n}_{ij}$ is noise vector of the received signal of $i \to j$ link whose values are complex Gaussian random variable with zero mean and variance σ_n^2. It is assumed that the channel remains constant during a packet transmission time. When the source transmits the packet k to the destination, it cannot be decoded correctly if the received signal-to-noise ratio (SNR) is below a certain threshold SNR, η_{th}, i.e.,

$$D(k) = \begin{cases} B, & \text{if } \eta_{sd}|h_{sd}|^2 \le \eta_{th} \\ G, & \text{if } \eta_{sd}|h_{sd}|^2 > \eta_{th} \end{cases} \tag{9}$$

where $\eta_{sd} = \alpha_{sd}/\sigma_n^2$. Note that η_{th} is the required SNR for the successful reception which depends on the coding and modulation scheme system used. $|h_{sd}|^2$ is an exponentially distributed random variable and its probability density function (PDF) is given by

$$f_Y(y) = \frac{1}{2\sigma^2} e^{-y/2\sigma^2} = e^{-y}. \tag{10}$$

The final equation is obtained by substituting $\sigma^2 = 0.5$, which is channel variance per dimension as mentioned earlier. The probabilities of the success/failure reception for the direct link are given by

$$t = \int_0^{\beta_{sd}} f_Y(y) dy = F_Y(\beta_{sd}) = \gamma(1, \beta_{sd}) \tag{11}$$

$$u = 1 - \gamma(1, \beta_{sd}) \tag{12}$$

where $\beta_{sd} = \eta_{th}/\eta_{sd}$, $F_Y(y)$ is the cumulative density function (CDF) of the received signal, and $\gamma(a, x)$ is the incomplete gamma function given by

$$\gamma(a, x) = \int_0^x t^{a-1} e^{-t} dt. \tag{13}$$

The state of the retransmission link depends on the number of retransmissions since each retransmitted signal is combined with the previously received signals. Fig. 3 shows the Markov model of the retransmission link where RT_k represents the state of kth retransmission and q_k represents the probability of state transition from state k to state $k+1$. It is assumed that all packets are successful after N retransmissions, i.e., $q_N = 0$.

Let p_k^c be the probability that the state of retransmission is in state k. Then, the relation between state probabilities is given by

$$\begin{cases} q_1 p_1^c = \sum_{k=1}^{N} (1 - q_k) p_k^c \\ q_k p_k^c = p_{k+1}^c, \qquad k = 1, 2, \cdots, N-1 \\ p_1^c + p_2^c + \cdots + p_N^c = 1. \end{cases} \tag{14}$$

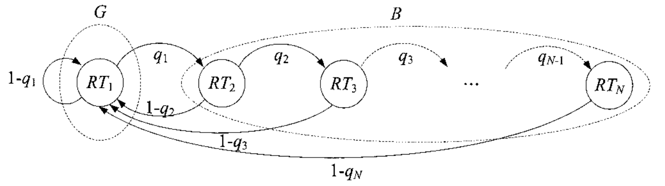

Fig. 3. Markov model for the retransmission link.

After solving (14), probabilities of state transition for the retransmission link are given by

$$\begin{aligned} v &= 1-\frac{1}{A}(1-q_1) \\ w &= \frac{1}{A}\sum_{k=1}^{N-2}\left(\prod_{j=1}^{k} q_j\right)(1-q_{k+1}) \end{aligned} \tag{15}$$

where A is given by

$$A = 1+\sum_{k=1}^{N-1}\prod_{j=1}^{k} q_j. \tag{16}$$

When there are k retransmissions and the channel of each retransmission is independent, the combined signal is the sum of exponential random variables and its pdf and cdf are given by

$$\begin{aligned} f_{U_k}(u) &= \frac{1}{k!}u^k e^{-u} \\ F_{U_k}(u) &= \frac{1}{k!}\gamma(k+1,u). \end{aligned} \tag{17}$$

The probability of state transition from state k to state $k+1$ is given by $q_k = F_{U_k}(\beta_{sd})$ and finally probabilities of state transition for the retransmission link are given by

$$\begin{aligned} v &= 1-\frac{1-\gamma(2,\beta_{sd})}{A} \\ w &= \frac{1}{A}\sum_{k=1}^{N-2}\left(1-\frac{\gamma(k+2,\beta_{sd})}{(k+1)!}\right)\prod_{j=1}^{k}\frac{\gamma(j+1,\beta_{sd})}{j!} \end{aligned} \tag{18}$$

where

$$A = 1+\sum_{k=1}^{N-1}\prod_{j=1}^{k}\frac{\gamma(j+1,\beta_{sd})}{j!}. \tag{19}$$

The state transition diagram in Fig. 3 can be also used for the cooperative retransmission scheme and the state transition probabilities are given by (15). The difference between the traditional retransmission and the cooperative retransmission is the distribution of the received signal at the destination. In the proposed cooperative retransmission scheme, distributed beamforming is used for accommodating multiple cooperating nodes. After assuming perfect synchronization as mentioned earlier, the received signal through cooperating nodes can be approximated as the sum of Rayleigh random variables. Note that the actual distribution of the cooperating signal is not a sum of Rayleigh random variables since the signal strength of each cooperating signal is greater than the threshold for successful NACK reception. In the high SNR regime of $r \to d$ link, however, this approximation is well matched with the actual distribution. It is not easy to obtain the pdf of the sum of Rayleigh random variables for the general case. Without loss of generality, it is assumed that the large-scale path loss of the cooperating links is same, i.e., $d_{sr,j} = d_{sr}$ and $d_{rd,j} = d_{rd}$ for $j = 1, \cdots, M$. Then, the received SNR of the combined signal with the cooperative retransmission scheme at state k can be approximated by

$$\begin{aligned} z_{k,L} &\approx \eta_{sd}\sum_{i=1}^{k_f+1}|h_i|^2 + \eta_{sd}\frac{\delta}{L}\left(\sum_{l=1}^{L}|h_l|\right)^2 \\ &= \eta_{sd}\left[\sum_{i=1}^{k_f+1}|h_i|^2 + \frac{\delta}{L}\left(\sum_{l=1}^{L}|h_l|\right)^2\right] \end{aligned} \tag{20}$$

where the first term represents the received signals from the source and the second term represents the received signals from L cooperating nodes. $k_f = \lfloor k/2 \rfloor$ where $\lfloor z \rfloor$ is the nearest integer of z towards negative infinity. δ is a scale factor based on the relative distance of the cooperating link given by $\delta = (d_{rd}/d_{sd})^{-n}$ with propagation coefficient n. Note that the total transmit power is normalized for the cooperatively retransmitted signal. Let $Z_{k,L} = U_{k_f+1} + (\delta/L)W_L^2$ where U_k is the sum of $k+1$ exponential random variables and its pdf is given in (17). W_L is the sum of L Rayleigh random variables and its approximated pdf is given by [10]

$$f_{W_L}(w) = \frac{w^{2L-1}e^{-w^2/2b(L)}}{2^{L-1}b(L)^L(L-1)!} \tag{21}$$

where $b(L) = \frac{1}{2L}[(2L-1)!!]^{1/L}$ and $(2L-1)!! = (2L-1)\cdot(2L-3)\cdots 3\cdot 1$. The pdf of $Z_{k,L}$ can be evaluated by multiple convolution and its integration which is given by

$$\begin{aligned} f_{Z_{k,L}}(z) = {} & \frac{z^{k_f+L}e^{-z}}{\xi(L)^L(k_f+L)!} \\ & \cdot {}_1F_1\left(L; L+k_f+1; \left(1-\frac{1}{\xi(L)}\right)z\right) \end{aligned} \tag{22}$$

where $\xi(L) = 2\delta b(L)/L$ and ${}_1F_1(a;b;c)$ is the confluent hypergeometric function of the first kind. The cdf of $Z_{k,L}$, $F_{Z_{k,L}}(z)$, cannot be found as the closed form and will be obtained by computer simulation using $f_{Z_{k,L}}(z)$.

The state transition probability of the cooperative link depends on the number of cooperating nodes and their channel conditions. To involve in cooperation, the neighboring node should receive the data packet and the NACK message correctly. Therefore, the probability of cooperation of the neighboring node is given by

$$\begin{aligned} p_{co} &= \Pr\{\eta_{sr}|h_{sr}|^2 > \eta_{th}\}\Pr\{\eta_{rd}|h_{rd}|^2 > \eta_{\mathrm{NACK}}\} \\ &= e^{-\beta_{sr}}e^{-\beta_{rd}} \end{aligned} \tag{23}$$

where $\beta_{sr} = \eta_{th}/\eta_{sr}$, $\beta_{rd} = \eta_{\mathrm{NACK}}/\eta_{rd}$, and η_{NACK} is the required SNR for the successful reception of the NACK message. When there are M neighboring nodes around the direct link, the transition probability from state k to state $k+1$ with the cooperative retransmission scheme is given by

$$q_k = (1 - p_{co})^M F_{U_{k_f}}(\beta_{sd}) + \sum_{m=1}^{k_c M} \binom{k_c M}{m} p_{co}^m (1 - p_{co})^{k_c M - m} F_{Z_{k,m}}(\beta_{sd}). \quad (24)$$

$k_c = \lceil k/2 \rceil$ where $\lceil z \rceil$ is the nearest integer of z towards positive infinity. Probabilities of state transition using the cooperative retransmission scheme can be obtained by substituting (23) into (15) and (16).

B. Delay Analysis

Packet delay is defined as the time required to complete the packet delivery from the source to the destination. Since resource allocation is not considered in this paper, delay analysis does not include the queuing delay such as random backoff time. Then, the average packet delay depends on the packet length and the number of retransmissions. Let T_f be the length of a packet which is assumed to be fixed. When there is no packet error from the source to the destination, the total transmission delay will be T_f. However, the average packet delay is expected to be higher than this value due to possible packet errors. The average packet delay of the cooperative retransmission scheme is given by [5]

$$\bar{D} = \frac{X + Y}{Y} T_f. \quad (25)$$

IV. NUMERICAL RESULTS

A. Single-Hop Configuration

Throughput efficiency and average delay will be compared for the traditional and the cooperative SW ARQ schemes to observe the benefit of the proposed retransmission scheme. The configuration shown in Fig. 1 will be considered where two neighboring nodes are located around the direct link, $M = 2$, with $d_{sr,j} = 0.7d_{sd}$, and $d_{rd,j} = 0.7d_{sd}$ for $j = 1, 2$. It is assumed that path loss coefficient is four, and the required SNR for the successful reception of data and NACK packets are 5 dB and 3 dB, respectively. IEEE 802.11 MAC protocol was implemented with computer simulation and physical layer was simplified with channel condition and the corresponding threshold values. We consider the lowest SNR of the direct link as 0 dB, where three retransmission of the direct link is enough for successful reception with MRC at the destination. Ten retransmission, $N = 10$, is assumed in analysis and simulation to make sure for successful reception after maximum retransmission.

Fig. 4 shows throughput efficiency of both the traditional ARQ and the cooperative ARQ schemes. The throughput efficiency without combining of the previously received packets is also shown in the figure. Throughput efficiency without MRC for both schemes can be analyzed easily by using similar Markov models, which is not included in this paper due to the page limitation. The analytical and the simulated results are well matched for all cases. Significant throughput gain can be achieved by using the cooperative retransmission scheme when erroneous packets are discarded at the destination. When MRC is used for the retransmitted packets, both schemes show relatively good performance even for low SNR ranges. The cooperative ARQ scheme outperforms the traditional ARQ scheme especially when the direct link has low SNR.

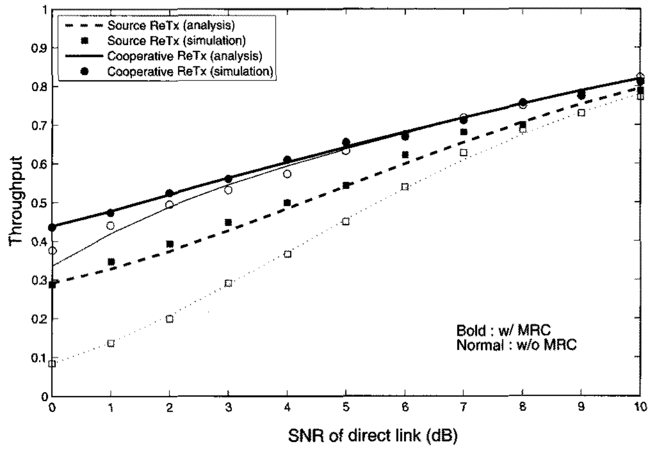

Fig. 4. Throughput efficiency with both retransmission schemes ($M = 2$, $d_{sr} = 0.7d_{sd}$, $d_{rd} = 0.7d_{sd}$).

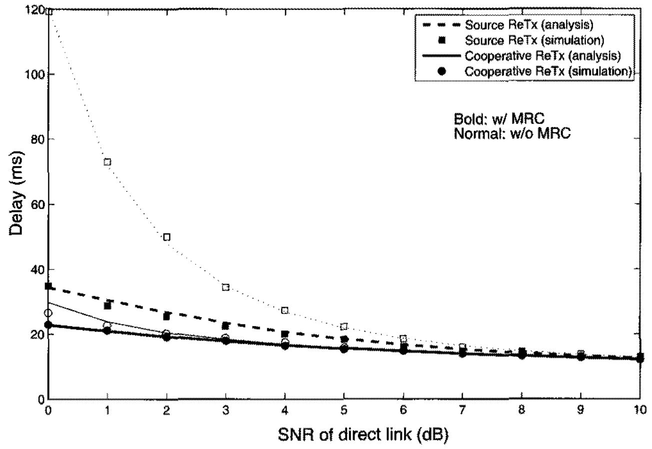

Fig. 5. Average delay with both retransmission schemes ($M = 2, T_f =$ 10 ms, $d_{sr} = 0.7d_{sd}$, $d_{rd} = 0.7d_{sd}$).

Fig. 5 shows the average delay performance with 10 ms packet length. As shown in the figure, the average delay can be significantly improved with the cooperative retransmission scheme even without MRC at the destination. When MRC is used, the proposed cooperative ARQ scheme still outperforms the traditional ARQ scheme and the average delay is reduced by about 30% at low SNR ranges where channel condition of the direct link is poor. The benefits of the cooperative retransmission scheme decrease at high SNR ranges since retransmission through the source is enough to recover the erroneous packet.

B. Multi-Hop Configuration

A single-hop configuration with the same distance of cooperating links was considered in the previous section to verify the analysis of the proposed cooperative retransmission scheme. The performance of the cooperative retransmission scheme will be investigated with the randomly distributed network configuration as shown in Fig. 6. It is assumed that 100 nodes are ran-

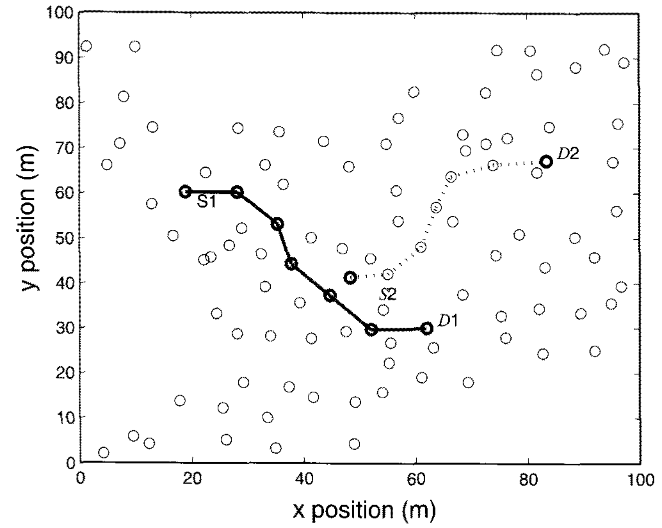

Fig. 6. Random network configuration (# of node = 100).

domly distributed in 100 square meters and there are two transmission links with six hops from the source to the final destination. It is also assumed that each initial source node has ten packets to deliver the final destination and the length of each packet is 10 ms. The dual busy tone multiple access (DBTMA) is assumed to be used with ACK at the end of message delivery [11]. When channel is busy or packet reception is unsuccessful at the receiver, random backoff procedure will be initiated at the transmitter based on IEEE 802.11 standard [12].

Transmit power for the retransmitting packet is also an important issue in terms of battery lifetime and interference to other nodes. In the analysis of the previous section, the transmit power of cooperating signals is assumed to be normalized with the number of cooperating nodes. In the proposed ARQ scheme, however, the cooperative retransmission is decided independently at each neighboring nodes and there is no information exchange among them. When channel is assumed to be constant during the consecutive data packet transmission, each cooperating node can adjust its own transmit power of the retransmitting packet based on the channel condition of the NACK message. It will be referred as power control with *local* information. Due to the limited information, the received signal power for the retransmitted signal might be greater than the required one when there are multiple cooperating nodes. More efficient power control can be achieved if cooperating nodes share their information which will be referred as power control with *global* information. However, it requires the additional overhead for information exchange and the proper coordination among cooperating nodes. In [8], a small feedback channel is used for phase adjustment in the cooperative retransmission scheme, which can be also used for power control of the retransmitting signal. At the start of the retransmitting data packet, power control with *local* information is performed at each cooperating node. After receiving the cooperatively retransmitted packet, the destination observes the received signal power and reassigns the proper transmit power for the cooperating signal through the feedback channel. More details of the feedback approach are shown in [8]. Note that outage probability with channel estimation was compared with the perfect synchronization case in [8] where performance difference is less than 1 dB with three neighboring nodes between the direct link. The single-hop and multi-hop configurations considered here are well covered by that scenario and perfect synchronization can be assumed with a small performance difference.

Fig. 7 shows throughput efficiency of two paths considered in network configuration. Four power control schemes are considered for the cooperative ARQ. For the normalized transmit power and the power control with *global* information, it is assumed that additional information such as the number of cooperating nodes and CSIs of cooperating links is provided at cooperating nodes. Power control methods with *local* information and feedback channel can be performed with the proposed cooperative retransmission scheme. Unit distance for average SNR is assumed to be 10 m. The cooperative ARQ with any power control approach shows better performance than the typical source retransmission. All power control methods considered show almost same performance, which means that the signal quality of cooperating links is good enough to recover the transmitted packet as regardless of power control methods.

Fig. 8 shows the average packet delay from the source to the final destination. There is significant delay performance gain with the cooperative retransmission scheme. For example, about 40% packet delay can be reduced for the first path with the proposed cooperative ARQ when the average SNR of each hop is poor.

The advantage of the cooperative retransmission scheme is diminished in terms of throughput efficiency and packet delay as the average SNR of each hop increases. However, transmit power for retransmission can be reduced with the proper power control method. Fig. 9 shows the average transmit power of the retransmitted signal. As indicated in the figure, the cooperative retransmission scheme with the normalized power uses the same transmit power as the source retransmission scheme. The transmit power of the retransmitting packet can be significantly reduced when all information are shared among cooperating nodes. When each cooperating node knows its own channel information only and adjusts its transmit power based on it, redundant power will be received at high SNR ranges where a large number of neighboring nodes are involved in cooperation. The transmit power with the proposed cooperative retransmission scheme can be reduced significantly by using a small feedback channel without sharing channel information of other cooperating nodes.

V. CONCLUSION

A cooperative retransmission scheme for ad hoc networks has been proposed which accommodates multiple neighboring nodes in cooperation with distributed beamforming. The proposed ARQ scheme requires no *a priori* information about the neighboring nodes. The previously received signals are combined using MRC to improve system performance. A Markov model was used to investigate throughput efficiency and average delay of the proposed cooperative retransmission scheme.

The analytical results were found to be in good agreement with the simulated results. Even with a small number of neigh-

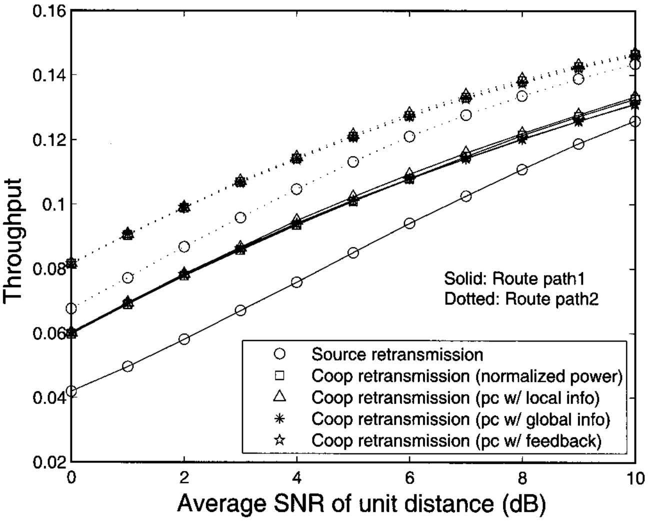

Fig. 7. Average throughput of transmission links with MRC.

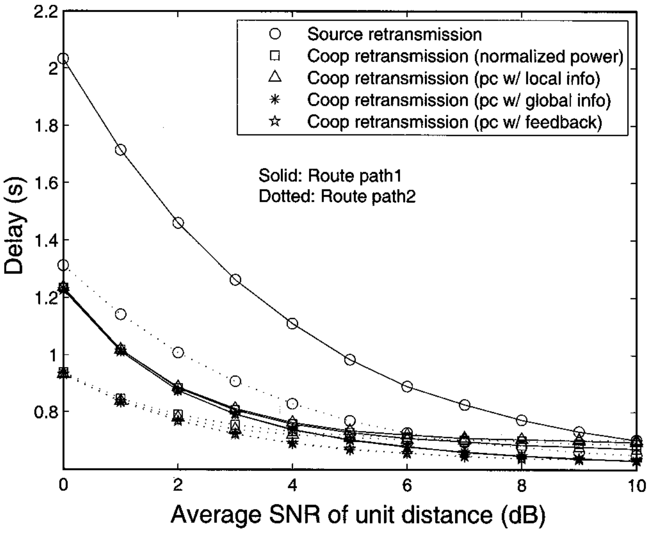

Fig. 8. Average packet delay of transmission links. Average delay of transmission links (with MRC, packet length = 10 ms, 6 hops).

boring nodes, improved throughput efficiency and delay performance can be achieved by using the cooperative retransmission scheme in wireless ad hoc networks. When MRC is used for the erroneous packets, for example, about 30% performance gain can be achieved at low SNR ranges with only two neighboring nodes in the vicinity of the direct link. It is shown that the benefits of the cooperative retransmission scheme increases especially when channel conditions of the direct link is poor.

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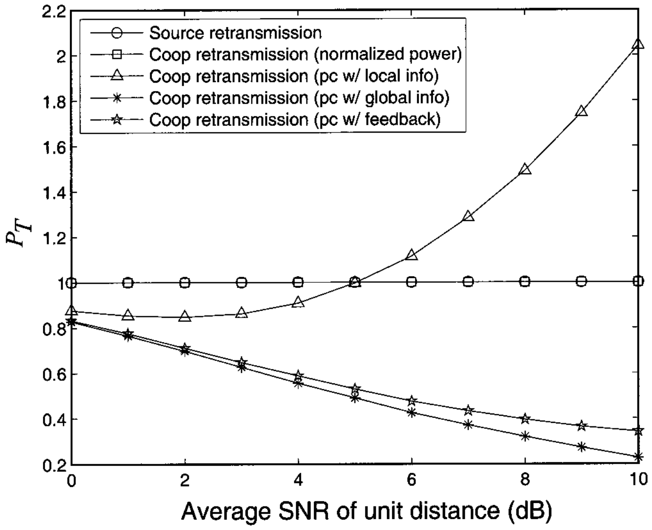

Fig. 9. Average transmit power for retransmission.

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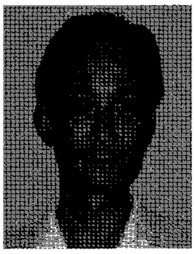

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