A Technique to Exploit Cooperation for Packet Retransmission in Wireless Ad Hoc Networks

Haesoo Kim and R. Michael Buehrer

Abstract: **In wireless data communication systems, retransmission of an erroneous packet is inevitable due to the harsh communication environment. In this paper, an efficient retransmission scheme using cooperation from neighboring nodes is investigated. In the cooperative retransmission scheme, an erroneous packet is transmitted to the destination by cooperative nodes which have favorable channels. This cooperative retransmission scheme requires no *a priori* information of neighboring nodes and has no limitation on the number of cooperating nodes. Distributed beamforming is used to accommodate multiple cooperating nodes. Phase and frequency offsets of cooperating signals are extracted from the NACK message and used to co-phase retransmitted data packets. The outage probability of the cooperative retransmission scheme is analyzed for the case of perfect synchronization and when the offsets are estimated. To reduce the impact of the residual phase and frequency offsets in cooperating signals, a low-rate feedback scheme is also investigated. It is shown that improved outage probability and reduced packet error rate (PER) performance can be achieved even for long data packets. The proposed cooperative retransmission scheme is found to outperform simple retransmission by the source as well as decode-and-forward cooperation.**

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

I. INTRODUCTION

Cooperative communications have received increased interest as a means to overcome fading channels with a limited number of antennas at a portable device. The basic idea of cooperative communications is that multiple single antenna devices share their antennas to create a *virtual* multiple antenna system. It has the potential to provide distributed spatial diversity and beamforming gains especially when the number of nodes in the networks is moderate to large. Cooperative diversity was first proposed in [1], where it was shown that the capacity and robustness of wireless systems were increased via user cooperation. The performance of several cooperative protocols have recently been investigated in [2]–[6]. Another approach to improve system performance using cooperative nodes is distributed beamforming [7], where multiple cooperative nodes transmit the same signal at the same time after proper preprocessing to obtain beamforming gain at the destination.

In cooperative diversity methods, orthogonal signaling dimensions are required for each cooperating signal (e.g., different time slots, frequency bands, or spreading codes), which results in poor spectral efficiency. Even for cooperative space-time block codes (STBC) where all corresponding code blocks are transmitted via the same signaling dimension, an initial stage is still needed to identify cooperating nodes and generate the corresponding code blocks [4], [8]. Also, proper synchronization of cooperating signals is required to achieve cooperative diversity [9]. In [4], the authors proposed a coded cooperation technique by combining user cooperation with channel coding to utilize the given resources more efficiently where two nodes form a group and transmit the partner's or their own information depending on the decoding result of the partner's received code block. Another example of coded cooperation was investigated in [10], where the total encoded data is divided into blocks and each block is transmitted by a different cooperative user in order to introduce temporal diversity even in slow fading. However, the quality of cooperating signals cannot be guaranteed since those methods do not account for channel conditions from the various transmitters to the destination. Those facts result in some inefficiencies in cooperative diversity schemes since nodes may cooperate even when their transmission is not useful.

Distributed beamforming is more efficient than cooperative diversity in terms of system bandwidth usage since it accommodates multiple cooperating signals in the same signaling dimension. However, it requires strict synchronization to achieve distributed beamforming gain. There are three synchronization issues in distributed beamforming: Symbol timing, carrier phase, and carrier frequency. Symbol timing offset occurs due to propagation delay differences and can be ignored when the symbol duration is sufficiently long as compared to propagation delay differences. In [11], for example, it is shown that a 10% timing jitter does not have much effect on the performance of the cooperative transmission. Carrier phase information for cooperating signals can be obtained from a reference signal which is broadcasted by the destination [7]. For carrier frequency synchronization, a master-slave architecture was considered in [7] where the master node broadcasts the reference signal periodically to cooperating nodes. However, this approach requires a master node for carrier frequency synchronization as well as additional reference signals from the destination for carrier phase synchronization. Even though better spectral efficiency can be achieved by distributed beamforming as compared to cooperative diversity, it still requires an initial stage to form the cooperating cluster as well as additional overhead to achieve synchronization of the cooperating signals. Again, the quality of cooperating signals is not considered in the current distributed beamforming approach.

A number of protocols have been proposed to use opportunistic relay channels in wireless ad hoc networks [12], [13]. In those protocols, however, only one relay will be selected to forward the data packet to the destination and additional information is required for the node selection procedure such as internode loss rates and geographic distance. Furthermore, those approaches limit the potential performance gain by restricting the

---

Manuscript received December 15, 2007.

The authors are with the Mobile and Portable Radio Research Group (MPRG), Virginia Tech, Blacksburg, VA 24061. email: {hakim,buehrer}@vt.edu.

1229-2370/08/$10.00 © 2008 KICS

number of the forwarding nodes to one even when multiple neighboring nodes can be involved in cooperation.

Erroneous packet reception is inevitable in wireless communication systems. In [10], cooperative diversity was achieved by using an incremental redundancy (INR) scheme. However, it can be viewed as a method to obtain block fading channels, i.e., temporal diversity, not an automatic repeat request (ARQ) method since decoding at the destination is performed after receiving all coded blocks. The idea of cooperative ARQ for ad hoc networks was introduced in [14] and [15], where the neighboring nodes around the direct link monitor the packet exchange and retransmit the packet if an error occurs. The authors show that significant performance improvement can be achieved in terms of throughput and average delay by reducing the average duration of retransmission trials. However, this work is focused on the upper layer performance (i.e., the throughput and the average delay of the ARQ protocol scheme) and does not consider the important issues in the physical layer such as node selection or their coordination when there are multiple possible cooperating nodes around the direct link. Retransmission by the neighboring nodes is also proposed to increase throughput in multihop networks [12]. However, it can be considered as a dynamic routing protocol rather than an ARQ method since the closest node to the final destination will be the receiving node of the current transmission.

In this paper, an efficient cooperative retransmission scheme is examined which combines packet retransmission and user cooperation. When the received packet can be decoded successfully with only the direct link, the overhead to form cooperative transmission and cooperating signals to the destination will be wasteful. Therefore, user cooperation without considering the quality of the direct link decreases network efficiency. In the proposed cooperative retransmission scheme, the erroneous data packet is 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. The outage probability of cooperative retransmission is analyzed first with perfect synchronization and latter with offset estimation. The residual phase and frequency offsets of cooperating signals can diminish the benefits of cooperative retransmission especially for long data packets. Thus, phase adjustment via a low-rate feedback channel is examined to reduce the effect of the residual offsets. It is shown that outage probability and packet error rate (PER) performance is substantially improved at the cost of a small feedback bandwidth.

The rest of this paper is organized as follows. In Section II, the cooperative retransmission scheme and system model are described. In Section III, the outage probability of the cooperative retransmission scheme is analyzed for the case of perfect synchronization as well as with offset estimation and compensation using the NACK message. The effect of the residual offset is examined in Section IV. Phase adjustment method via a feedback channel is investigated and the numerical results for outage probability and PER performance are also shown. Section V concludes this paper.

II. SYSTEM MODEL

The network configuration shown in Fig. 1(a) will be considered in this paper. There are multiple neighboring nodes which are assumed to be uniformly distributed around a source and a destination. The neighboring nodes have no *a priori* knowledge of the channel to the source or the destination. The source transmits a data packet to the destination at a given time. It is assumed that nodes in the networks use the same frequency band to transmit and receive the packets (i.e., time-division duplexing). The channel is assumed to be reciprocal between nodes and constant during the time interval of NACK and data retransmission. It is also assumed that each node is operating with a decentralized manner based on its need.

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 developed here, the source transmits the packet to the destination at 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 if no NACK is heard during a given time interval. When the destination cannot correctly decode the received data 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. 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 which are exchanged between the source and the destination. 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. This assumption is reasonable for short-range sensor networks. Table 1 shows the procedure of the proposed cooperative retransmission scheme.

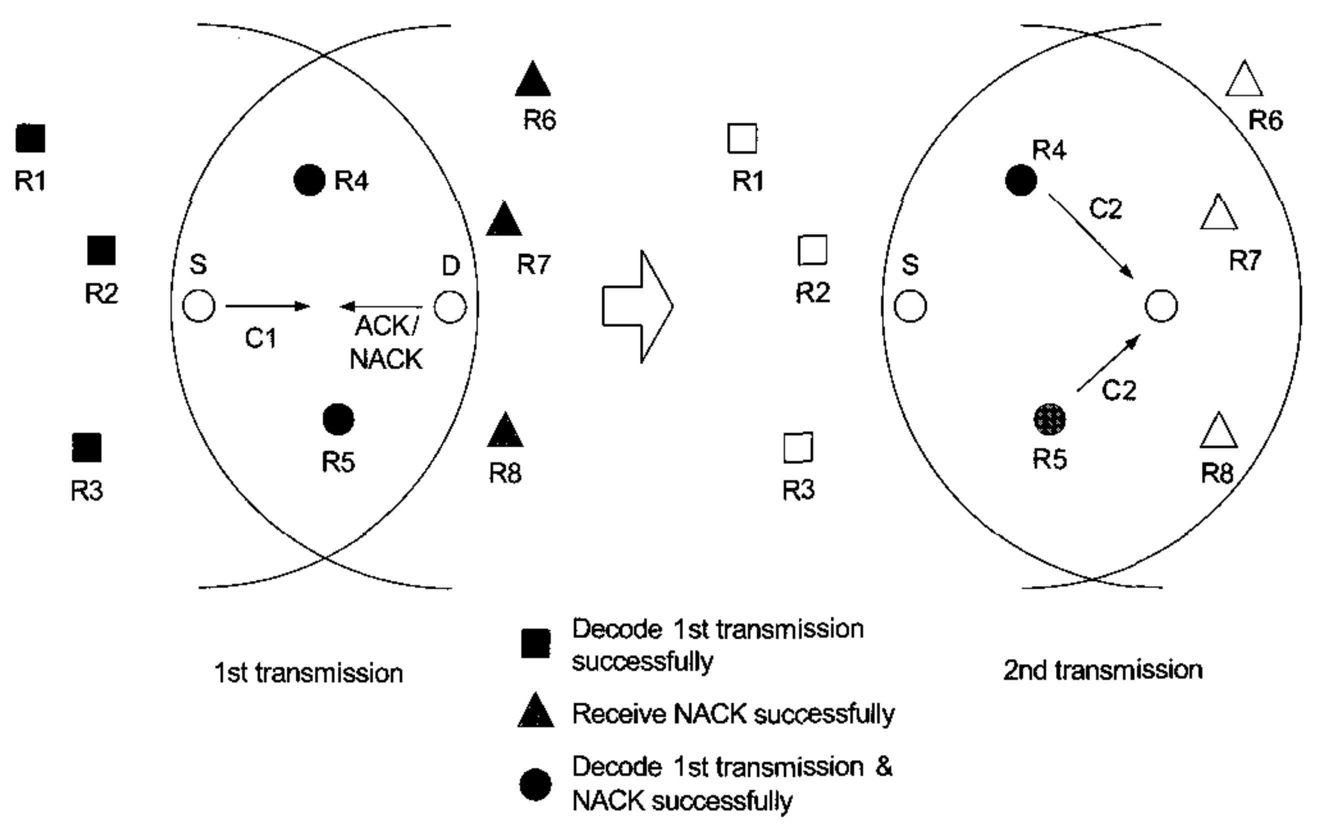


Fig. 1. Example of the cooperative retransmission scheme in distributed networks.

Table 1. Cooperative retransmission scheme in ad hoc networks.

```
Transmit data packet $C_1$ to destination
    Decode $C_1$ at destination and neighboring nodes
    Send ACK or NACK to source
If ACK is received, go to next packet
If NACK is received at neighboring nodes which receive $C_1$ correctly
    Extract phase and frequency offset information from NACK message
    Transmit $C_2$, which could be $C_1$, after compensating offsets
If no relays can send $C_2$, retransmit $C_2$ at source after random backoff
```

Fig. 1 shows an example of the proposed retransmission scheme for an ad hoc network. During the first exchange of data and ACK/NACK packets, R_4 and R_5 can decode both packets correctly and will be cooperating nodes. When packet retransmission is requested by the destination, these nodes retransmit the data packet to the destination using distributed beamforming as shown in Fig. 1(b). Note that the retransmitted data packet $\mathbf{C}_2$ can be same as $\mathbf{C}_1$ or different depending on the ARQ method. While cooperating nodes retransmit the data packet, the source performs the random backoff procedure. If the source receives the ACK message during the backoff interval, retransmission procedure will be stopped and the next packet will be transmitted following the normal step. If the NACK message is received during the backoff interval, it will be ignored and the normal retransmission procedure will be performed. The proposed cooperative retransmission scheme will be continued for the next retrial packet with the same procedure. In this paper, we will focus on the performance of the cooperative retransmission scheme with only a single retrial.

There are several advantages of the proposed cooperative retransmission method. First, this method does not require any *a priori* information concerning the neighboring nodes or an initial setup stage to form the cooperative cluster, which reduces the required overhead. Second, cooperative nodes are selected based on channel conditions from the source to the nodes as well as from the nodes to the destination, which results in good signal quality for the retransmitted data packet. Finally, distributed beamforming gain is exploited when multiple relays are involved in the cooperation.

III. ANALYSIS OF OUTAGE PROBABILITY

A. Retransmission via Source

The outage probability of the proposed cooperative retransmission scheme will be examined in this section. It is assumed that the same data packet is retransmitted if necessary and both received signals are combined with maximum ratio combining (MRC).

First, let's consider the outage probability when the source retransmits the erroneous data packet. The received signals during two time slots are given by

$$\begin{aligned} \mathbf{r}_1 &= \sqrt{\alpha_{sd}}h_{sd,1}\mathbf{s} + \mathbf{n}_1 \\ \mathbf{r}_2 &= \sqrt{\alpha_{sd}}h_{sd,2}\mathbf{s} + \mathbf{n}_2 \end{aligned} \tag{1}$$

where α_{sd} is the large scale path loss of the direct link and $h_{sd,i}$ is channel coefficient of the ith transmission of the direct link which is complex Gaussian random variable with zero mean and 0.5 variance per dimension. It is assumed that channel coefficients of the first and the second transmission are independent by considering random backoff time before retransmission. $\mathbf{s}$ is the transmit signal and $\mathbf{n}_i$ is noise vector of the received signal i which entities are complex Gaussian random variables with zero mean and variance σ_n^2. The mutual information of the first received signal and the combined signal with the second received signal are given by

$$\begin{aligned} I_{sd}^1 &= \log_2\left(1+\eta|h_{sd,1}|^2\right) \\ I_{sd}^2 &= \frac{1}{2}\log_2\left(1+\eta[|h_{sd,1}|^2+|h_{sd,2}|^2]\right) \end{aligned} \tag{2}$$

where $\eta = \alpha_{sd}/\sigma_n^2$ is the average SNR of direct link. $|h_{sd,1}|^2$ is an exponentially distributed random variable, U_1, and $|h_{sd,1}|^2 + |h_{sd,2}|^2$ is the sum of exponentially distributed random variables, U_2. The probability density function (pdf) and cumulative density function (cdf) of the sum of k exponential random variables can be easily evaluated by multiple convolution and its integration which are given by

$$\begin{aligned} f_{U_k}(u) &= \frac{1}{(k-1)!}u^{k-1}e^{-u} \\ F_{U_k}(u) &= \frac{1}{(k-1)!}\gamma(k,u) \end{aligned} \tag{3}$$

where $\gamma(a,x)$ is incomplete gamma function given by

$$\gamma(a,x) = \int_0^x t^{a-1}e^{-t}dt. \tag{4}$$

After k times retransmission from the source, the outage probability of the combined signal can be obtained by

$$\begin{aligned} P_{o,k}^{sd} &= \Pr\{I_{sd}^k < R\} = F_{U_k}\left(\frac{2^{kR}-1}{\eta}\right) \\ &= \frac{1}{(k-1)!}\gamma\left(k,\frac{2^{kR}-1}{\eta}\right) \end{aligned} \tag{5}$$

where R is transmission data rate.

B. Cooperative Retransmission with Perfect Synchronization

When L cooperating nodes are involved in cooperation, the received signal during the second time slot is given by

$$\mathbf{r}_2 = \frac{1}{\sqrt{L}} \sum_{l=1}^{L} \sqrt{\alpha_{rd,l}} h_{rd,l} \mathbf{s} + \mathbf{n}_2 \tag{6}$$

where $\alpha_{rd,l}$ and $h_{rd,l}$ represent the large scale path loss and channel coefficient of the cooperating link l, respectively. The total transmit power of the retransmitted signal is normalized with the number of cooperating nodes. When perfect synchronization is assumed in cooperating signals, the mutual information of the combined signal is given by

$$I_{co}^{L} = \frac{1}{2}\log_2\left(1 + \eta|h_{sd,1}|^2 + \frac{1}{L\sigma_n^2}\left[\sum_{l=1}^{L} \sqrt{\alpha_{rd,l}}|h_{rd,l}|\right]^2\right). \tag{7}$$

The distribution of the combined signal is not easy to obtain for general case. For simplicity, consider the case when the long term path loss of all cooperating nodes is same, $\alpha_{sr,l} = \kappa\alpha_{sd}$ and $\alpha_{rd,l} = \delta\alpha_{sd}$ for $l = 1, 2, \cdots, L$. The scale factor κ and δ depend on the relative distance between the cooperating link and the direct link, which is given by $\kappa = (d_{sr}/d_{sd})^{-n}$ and $\delta = (d_{rd}/d_{sd})^{-n}$ with propagation coefficient n. d_{ij} is the distance between node i and node j, where $i, j \in \{s, r, d\}$ and s, r, d stand for source, relay (i.e., cooperating node), and destination, respectively. Then, (7) can be rewritten as

$$I_{co}^{L} = \frac{1}{2}\log_2\left(1 + \eta\left[|h_{sd,1}|^2 + \frac{\delta}{L}W_L^2\right]\right) \tag{8}$$

where $W_L = \sum_{l=1}^{L} |h_{rd,l}|$. W_L is not a sum of typical Rayleigh random variables but a sum of partial Rayleigh random variables since only good channels are involved in cooperation. The distribution of W_L depends on the average SNR of cooperative links and hard to find as a closed form. Instead of finding the distribution of the sum of partial Rayleigh random variables, W_L is assumed to be a sum of Rayleigh random variables and its minimum values will be included at the final distribution. With this assumption, the approximated pdf of W_L is given by [16]

$$f_{W_L}(w) = \frac{w^{2L-1}e^{-w^2/2b(L)}}{2^{L-1}b(L)^L(L-1)!} \tag{9}$$

where $b(L) = \frac{1}{2L}[(2L-1)!!]^{1/L}$ and $(2L-1)!! = (2L-1)\cdot(2L-3)\cdot\cdots\cdot 3\cdot 1$. The pdf of $X_L = W_L^2$ is given by

$$f_{X_L}(x) = \frac{x^{L-1}e^{-x/2b(L)}}{2^L b(L)^L (L-1)!}. \tag{10}$$

The distribution of the combined signal is the sum of the exponential random variable and the weighted X_L, $Y_L = U_1 + \frac{\delta}{L}X_L$. The pdf and cdf of Y_L can be obtained by

$$\begin{aligned} f_{Y_L}(y) =& \frac{e^{-y}}{(1-\xi(L))^L(L-1)!}\gamma\left(L, \frac{1-\xi(L)}{\xi(L)}y\right) \\ F_{Y_L}(y) =& \frac{1-e^{-y}}{(1-\xi(L))^L} - \frac{\xi(L)}{(1-\xi(L))^L} \\ & \cdot\sum_{l=0}^{L-1}\frac{(1-\xi(L))^l}{l!}\gamma\left(l+1, \frac{y}{\xi(L)}\right) \end{aligned} \tag{11}$$

where $\xi(L) = 2\delta b(L)/L$. Since the received SNR of cooperating signals is greater than the required SNR for the successful reception of the NACK message, random variable y should be greater than the normalized value $y_c = \eta_{NACK}/\eta_{rd}$, where η_{rd} is the average SNR of $r \rightarrow d$ link and η_{NACK} is the required SNR to receive the NACK message correctly. Then, the outage probability with L cooperating signals can be approximated as

$$P_{o,L}^{perf} = \Pr\left\{I_{co}^{L} < R\right\} \approx \frac{F_{Y_L}\left(\frac{2^{2R-1}}{\eta}\right) - F_{Y_L}(y_c)}{1 - F_{Y_L}(y_c)}. \tag{12}$$

The outage probability of the proposed cooperative retransmission scheme depends on the probability that the neighboring node is involved in cooperation. To be involved in retransmission, 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

$$\begin{aligned} p_{co} =& \Pr\{I_{sr} > R\}\Pr\{\eta_{rd}|h_{rd}|^2 > \eta_{NACK}\} \\ =& \exp\left(-\frac{2^R-1}{\eta_{sr}}\right)\exp\left(-\frac{\eta_{NACK}}{\eta_{rd}}\right) \end{aligned} \tag{13}$$

where η_{sr} is the average SNR of $s \rightarrow r$ link.

The outage probability of the cooperative retransmission scheme with M neighboring nodes is given by

$$\begin{aligned} P_{o,M}^{co} =& (1-p_{co})^M P_{o,2}^{sd} \\ & + \sum_{m=1}^{M}\binom{M}{m} p_{co}^m (1-p_{co})^{M-m} P_{o,m}^{perf}. \end{aligned} \tag{14}$$

The first term represents the outage probability when there is no cooperating node out of M neighboring nodes and the second term represents the outage probability when there are m cooperating nodes out of M neighboring nodes.

C. Cooperative Retransmission with Offset Estimation

In the proposed retransmission scheme, the preamble part of the NACK message will be used to obtain carrier phase and frequency offsets between the cooperating node and the destination. It is assumed that the preamble signal is divided into N_p subgroups with the length of L_p. The received preamble part of the NACK message at the cooperating node m is given by

$$\mathbf{r}_{p,m}(t) = \sqrt{\alpha_{rd,m}} h_{rd,m} e^{j2\pi f_m t}\mathbf{c} + \mathbf{n}_m \tag{15}$$

where $\mathbf{c}$ is the preamble signal and f_m is carrier frequency offset between the destination and the cooperating node m. The matched filter output for each subgroup is given by

$$r_m(i) = \sqrt{\alpha_{rd,m}}|h_{rd,m}|L_p e^{j\theta_m(i)} + v_m(i), \quad i = 1, \cdots, N_p \tag{16}$$

where $\theta_m(i)$ is phase value of ith sample at the cooperating node m, and $v_m(i) = \sum_{l=(i-1)L_p+1}^{iL_p} c(l)n_m(l)$. The estimate of phase offset at the cooperating node m can be obtained by $\hat{\theta}_m(i) = \angle r_m(i)$ for $i = 1, \cdots, N_p$. Using two samples of phase estimates, frequency offset between the destination and the cooperating node m can be estimated as

$$\hat{f}_m = \frac{\hat{\theta}_m(k) - \hat{\theta}_m(j)}{2\pi(k-j)T_p} \tag{17}$$

where T_p is time duration of a subgroup.

The distribution of the mimimum mean square error (MMSE) phase estimation error at the cooperating node m is given by [17]

$$\begin{aligned} p_{\theta_e}(\theta, \eta_m) =& \frac{1}{2\pi} e^{-\eta_m} \Big[1 + \sqrt{4\pi\eta_m} \cos\theta e^{\eta_m \cos^2\theta} \\ & \cdot Q\left(-\sqrt{2\eta_m}\cos\theta\right)\Big], \qquad -\pi \le \theta \le \pi \end{aligned} \tag{18}$$

where $\eta_m = \alpha_{rd,m}|h_{rd,m}|^2 L_p/\sigma_n^2$ and $Q(\cdot)$ is the Q-function. The average phase estimation error for a given channel is

$$\bar{\theta}_e(\eta_m) = \int_{-\pi}^{\pi} |\theta| p_{\theta_e}(\theta, \eta_m) d\theta. \tag{19}$$

The frequency offset estimation is obtained by the amount of phase shift between two estimated phase estimators. The estimation error of phase shift, ϕ_e, is the sum of i.i.d. random variable θ_e. The distribution of phase shift estimation error can be evaluated by convolution and given by

$$\begin{aligned} p_{\phi_e}(\phi, \eta_m) =& \int_{-\infty}^{\infty} p_{\theta_e}(\phi - \theta, \eta_m) p_{\theta_e}(\theta, \eta_m) d\theta \\ =& \frac{e^{-2\eta_m}}{4\pi^2} \int_{-\pi}^{\phi} \Big[1 + \sqrt{4\pi\eta_m} \cos(\phi - \theta) \\ & \cdot e^{\eta_m \cos^2(\phi-\theta)} Q\left(-\sqrt{2\eta_m}\cos(\phi - \theta)\right)\Big] \cdot \\ & \Big[1 + \sqrt{4\pi\eta_m}\cos\theta e^{\eta_m\cos^2\theta} Q\left(-\sqrt{2\eta_m}\cos\theta\right)\Big] d\theta. \end{aligned} \tag{20}$$

The average estimation error of phase shift for a given channel can be obtained by

$$\bar{\phi}_e(\eta_m) = \int_{-\pi}^{\pi} |\phi| p_{\phi_e}(\phi, \eta_m) d\phi. \tag{21}$$

The average frequency estimation error is directly related with $\bar{\phi}_e(\eta_m)$ and given by

$$\bar{f}_e(\eta_m) = \frac{\bar{\phi}_e(\eta_m)}{2\pi T_o} \tag{22}$$

where T_o is time duration between two phase samples.

Figs. 2 and 3 show the average estimation errors of phase and frequency offsets at five cooperating nodes which have the same average received SNR. For the preamble signal, $L_p = 32$ and $N_p = 6$ are assumed. It is shown that the analytical and numerical results are well matched.

When cooperating nodes adjust their phase and frequency offsets with the estimated values, the received signal of the cooperatively retransmitted packet can be expressed by

$$\mathbf{r}_2 = \frac{1}{\sqrt{L}} \sum_{m=1}^{L} w_m \sqrt{\alpha_{rd,m}} |h_{rd,m}| \mathbf{s} + \mathbf{n}_2 \tag{23}$$

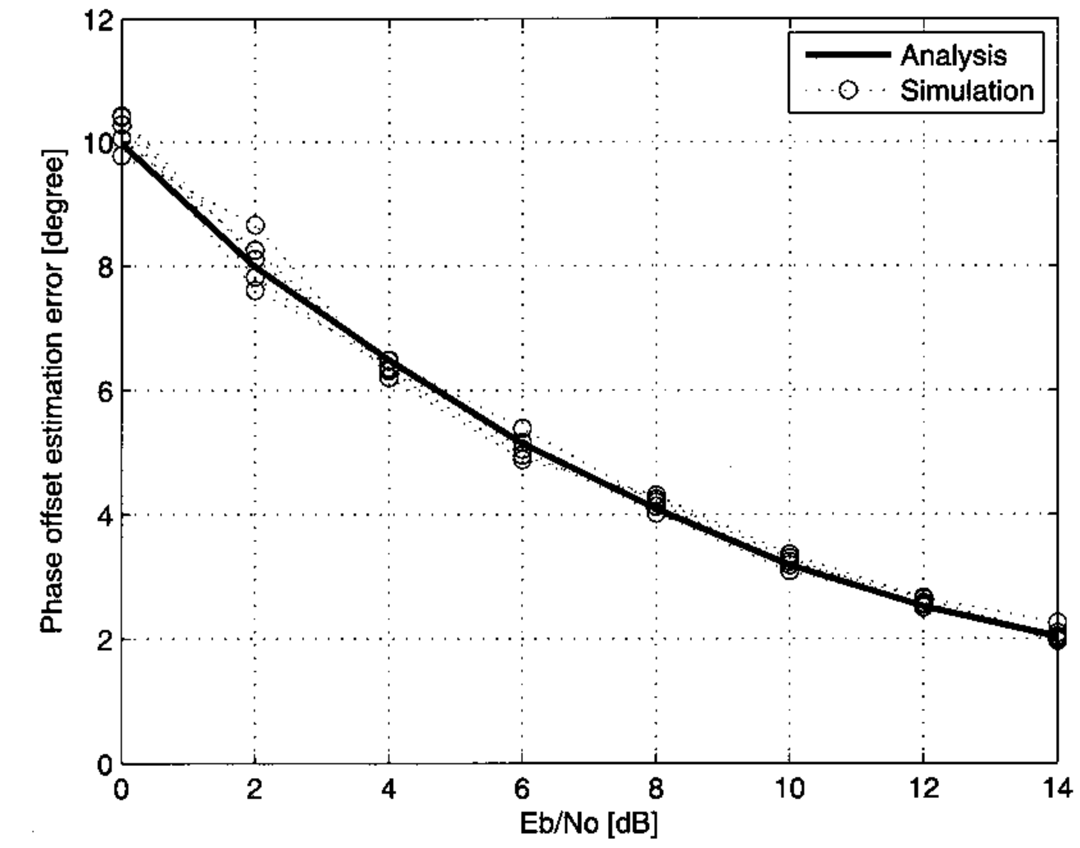


Fig. 2. Phase offset estimation error with NACK message (5 cooperating nodes, $L_p = 32$, $N_p = 6$, maximum frequency offset = 2 kHz).

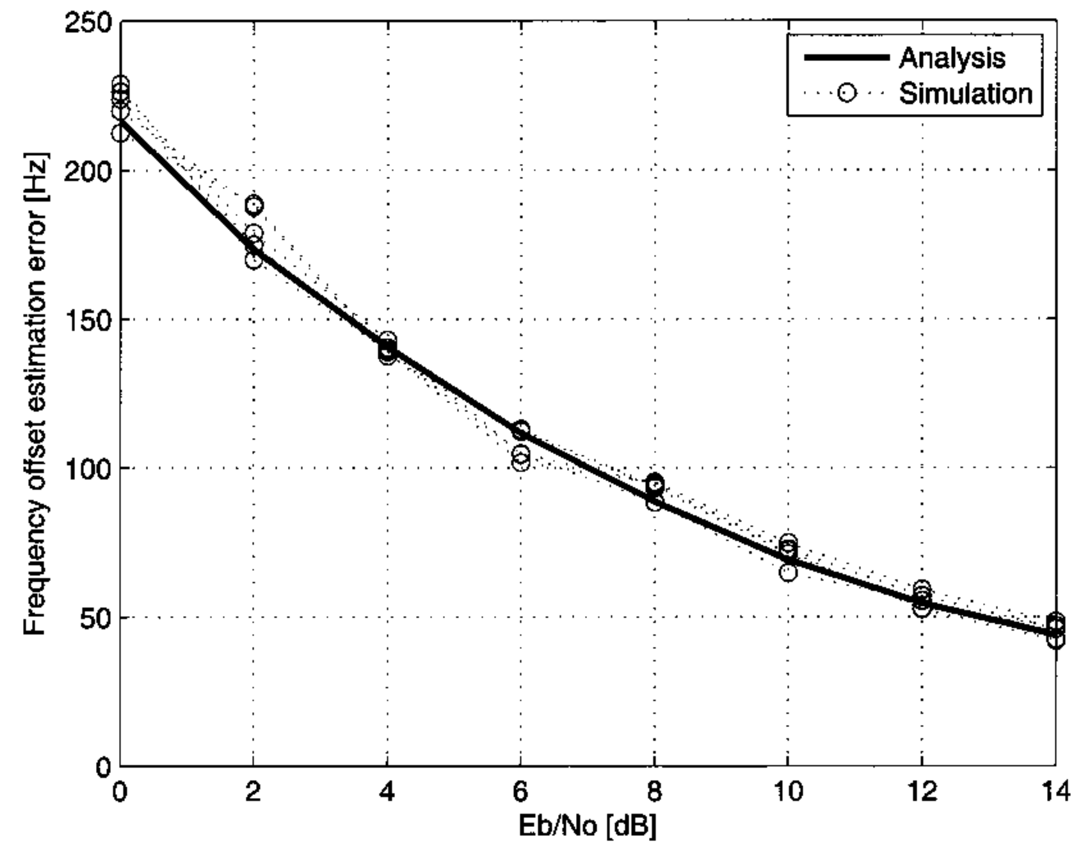


Fig. 3. Frequency offset estimation error with NACK message (5 cooperating nodes, $L_p = 32$, $N_p = 6$, maximum frequency offset = 2 kHz).

where w_m is the loss factor of the cooperating signal m due to the offset estimation errors which is given by $w_m = \bar{\theta}_e(\eta_m)\bar{f}_e(\eta_m)$. Let $X_w = \sum_{m=1}^{L} w_m \sqrt{\alpha_{rd,m}}|h_{rd,m}|$, then the outage probability with the offset estimation scheme is given by

$$P_{o,L}^{esti} = \Pr\left\{\frac{1}{2}\log_2\left(1 + \eta|h_{sd}|^2 + \frac{|X_w|^2}{L\sigma_n^2}\right) < R\right\}. \tag{24}$$

When there are M neighboring nodes around the direct link, the outage probability of the proposed cooperative retransmission scheme is given by

$$\begin{aligned} P_{o,M}^{co} =& (1 - p_{co})^M P_{o,2}^{sd} \\ & + \sum_{m=1}^{M} \binom{M}{m} p_{co}^m (1 - p_{co})^{M-m} P_{o,m}^{esti}. \end{aligned} \tag{25}$$

Fig. 4 shows the outage probability of the cooperative retransmission scheme with perfect synchronization and offset estimation. It is assumed that η_{NACK} = 5 dB, transmission bandwidth is 1 MHz, and the length of data packet is 2 ms. It is also as-

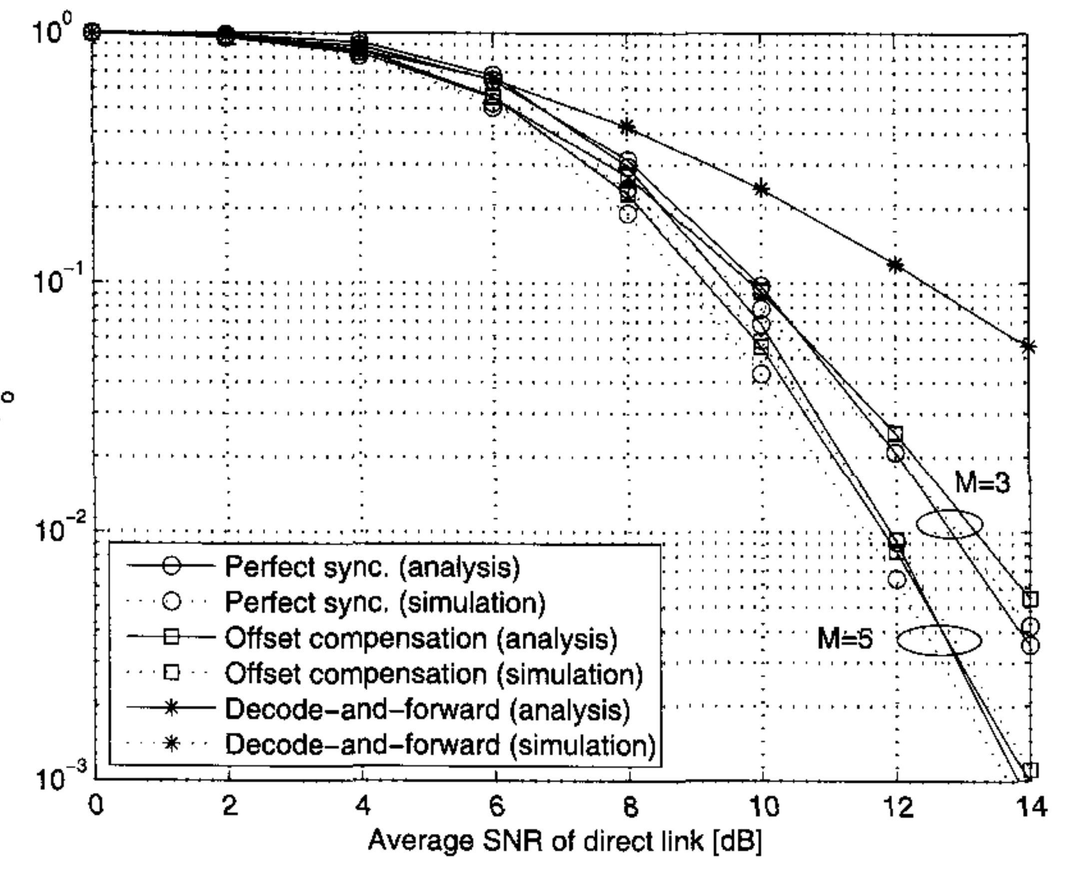


Fig. 4. Outage performance with cooperative retransmission scheme using phase and frequency offset compensation ($M = \{3, 5\}$, packet length = 2 ms, maximum frequency offset = 2 kHz, $d_{rd} = 0.8d_{sd}$).

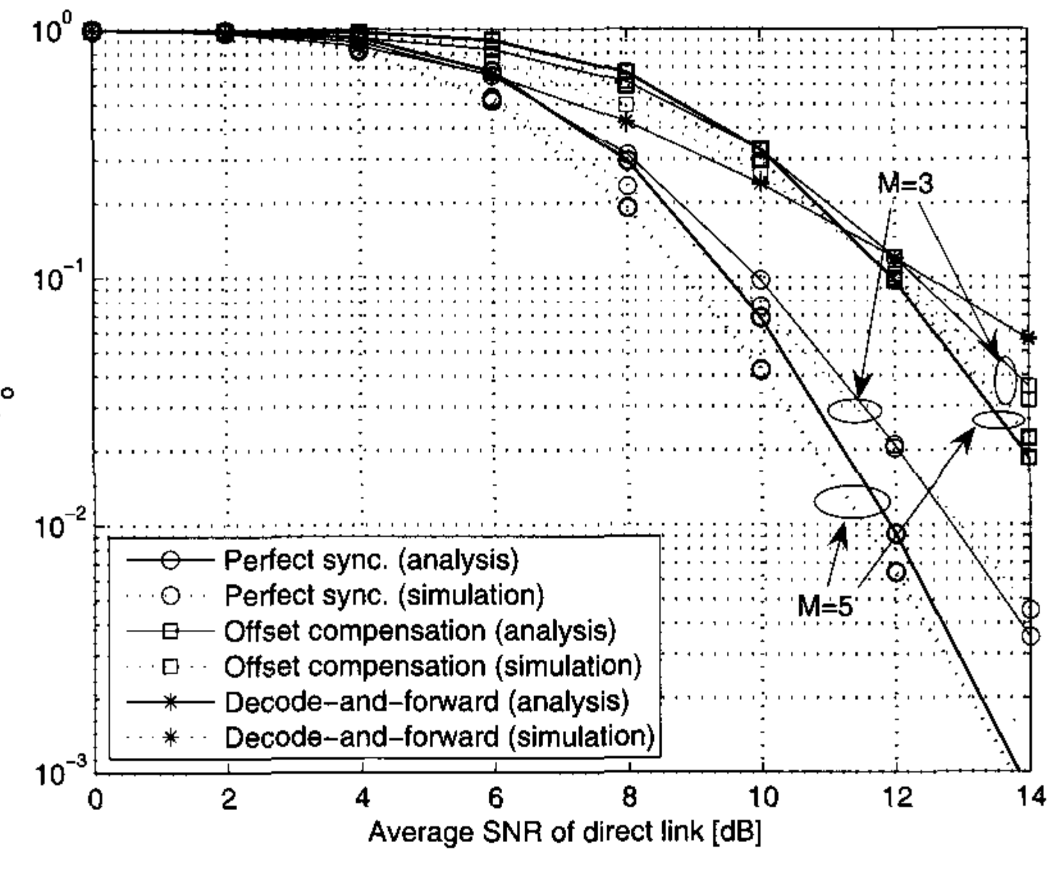


Fig. 5. Outage performance with cooperative retransmission scheme using phase and frequency offset compensation ($M = \{3, 5\}$, packet length = 10 ms, maximum frequency offset = 2 kHz, Doppler frequency = 20 Hz, $d_{rd} = 0.8d_{sd}$).

sumed that all neighboring nodes are located at the same position as $d_{sr} = 0.2d_{sd}$ and $d_{rd} = 0.8d_{sd}$. The analytical results are well matched with the numerical results even though there are some performance differences for the perfect synchronization case due to approximation. The proposed cooperative retransmission scheme works well and its outage performance is close to the case of perfect synchronization. As the number of neighboring nodes increases, better outage performance is shown as expected. The proposed cooperative retransmission scheme shows better performance than decode-and-forward cooperation by exploiting good cooperating signals with distributed beamforming. Note that again the transmit power of the cooperatively retransmitted signal was normalized with the number of cooperating nodes.

IV. COOPERATIVE RETRANSMISSION FOR LONG DATA PACKETS

A. Effect of the Residual Phase and Frequency Offsets

The cooperative retransmission scheme with offset estimation using the NACK message performs very well for short data packets as shown in Fig. 4. When the length of the retransmitted packet increases, cooperating channel coefficients for the retransmitted packet could not be assumed as constant anymore. Furthermore, the latter part of the retransmitted packet will be more out of phase due to the residual frequency offset. Fig. 5 shows the outage probability for long retransmitted packets. It is assumed that the packet length is 10 ms and cooperating channels are also varying with doppler frequency of 20 Hz. As shown in Fig. 5, the proposed cooperative retransmission scheme does not work well anymore due to channel variation and phase rotation caused by the residual frequency offset. The effect of the residual offsets is more clear from the fact that there is no performance gain even with the large number of neighboring nodes.

B. Phase Adjustment with Feedback Channel

A low-rate feedback channel will be considered to adjust phase variation due to time-varying channel and the residual offsets. To track the phase variation of each cooperating signal, a small phase offset will be induced intentionally at the retransmitted signals. Since no information of other cooperating nodes is available, each cooperation node adds the randomly generated phase offset during a feedback interval and updates its phase offset according to feedback information.

Let $\mathbf{\Theta}_m$ be an induced phase subset in the cooperating node m, which is independently generated at each cooperating node as $\mathbf{\Theta}_m = \Delta\theta \mathbf{A}_m$. $\Delta\theta$ is the amount of the intentional phase offset and $\mathbf{A}_m$ is a set of the randomly generated binary bits at the cooperating node m. $\mathbf{\Theta}_m$ has the length of N_g and is repeated N_s times to form a final set of the induced phase offset, $\mathbf{B}_m = \{\mathbf{\Theta}_m, \mathbf{\Theta}_m, \cdots, \mathbf{\Theta}_m\}$. For example, with N_g = 4, N_s = 2, and $\mathbf{A}_m = \{1, 1, -1, 1\}$, the final induced phase offset is given by $\mathbf{B}_m = \{\Delta\theta, \Delta\theta, -\Delta\theta, \Delta\theta, \Delta\theta, \Delta\theta, -\Delta\theta, \Delta\theta\}$ during eight transmit symbols. The number of feedback message, N_f, is decided by $N_f = \lfloor T_d/T_f \rfloor$ where T_d is the retransmitted packet duration, T_f is a feedback interval, and $\lfloor z \rfloor$ is the nearest integer of z towards negative infinity.

The received signal of the cooperatively retransmitted packet during a feedback interval can be expressed by

$$\mathbf{r}_f(t) = \frac{1}{\sqrt{L}} \sum_{m=1}^{L} \sqrt{\alpha_{rd,m}} |h_{rd,m}| \mathbf{E}_{rd,m} \mathbf{s}_f + \mathbf{n}_f \tag{26}$$

where $\mathbf{E}_{rd,m}$ is the term of the phase mismatch by both offset estimation errors and the induced phase offset, which is given by $\mathbf{E}_{rd,m} = e^{j\theta_{e,m}} e^{j2\pi f_{e,m} t} e^{j\mathbf{B}_m}$. $\theta_{e,m}$ and $f_{e,m}$ are the residual phase and frequency offsets of the cooperating signal m, respectively. $\mathbf{s}_f$ and $\mathbf{n}_f$ are the transmit signal and noise vectors during a feedback interval.

After receiving cooperating signals during a feedback interval, the destination averages the magnitude of N_s subsets of the received signal and searches the index k in the subset $\mathbf{\Theta}_m$ which has the maximum average magnitude. The index k is delivered

Table 2. Phase adjustment procedure with feedback channel.

```
When NACK is received at cooperating node $m$
  Extract phase and frequency offsets from the preamble of NACK
  Compensate phase and frequency offsets of the cooperating data
      packet with the estimated values
  Set initial reference phase offset as zero, $\theta_{m,ref} = 0$
  Generate the induced phase offset, $\mathbf{B}_m(\Theta_m)$
  for p = 1 to $N_f$
    Retransmit data packet after inducing phase offset $\mathbf{B}_m$
    At the destination
      Find the index k of $\Theta_m$ which has maximum average
          received magnitude
      Deliver k to cooperating nodes via feedback channel
    At the cooperating node m
      Update reference phase offset as $\theta_{m,ref} \leftarrow \theta_{m,ref} + \Theta_m(k)$
      Regenerate the induced phase offset, $\mathbf{B}_m$
      Add reference phase offset to $\mathbf{B}_m$, $\mathbf{B}_m \leftarrow \mathbf{B}_m + \theta_{m,ref}$
```

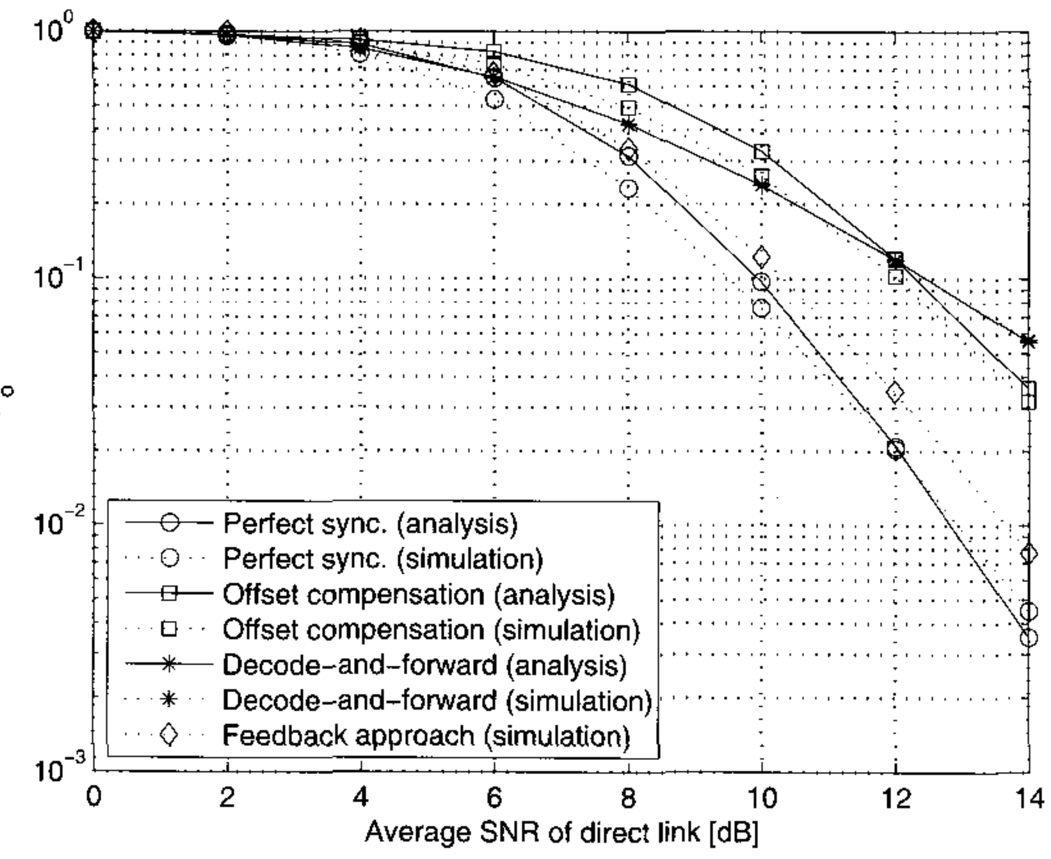


Fig. 6. Outage probability with cooperative retransmission scheme using phase and frequency offset compensation ($M = 3$, packet length = 10 ms, Doppler frequency = 20 Hz, maximum frequency offset = 2 kHz, $d_{rd} = 0.8d_{sd}$).

to cooperating nodes via a feedback channel. Note that the modulated signal is assumed to be a constant envelope such as M-ary phase shift keying. After receiving the index of the induced phase set, each cooperating node updates its reference phase offset as $\theta_{m,ref} \leftarrow \theta_{m,ref} + \Theta_m(k)$. The update of phase offset for cooperating signals continues to the end of the retransmitted data packet. The phase adjustment method using a feedback channel is summarized in Table 2.

Figs. 6 and 7 show the outage probabilities of the cooperative retransmission scheme using a feedback channel with M = 3 and 5, respectively. The same parameters used for Fig. 5 are assumed for the transmission channel. For the feedback channel, 10 kHz bandwidth, $N_p = 16$, $N_s = 25$, and $\Delta\theta = 30°$ are used. As shown in both figures, outage probability is substantially improved by using a small feedback channel where bandwidth usage of a feedback channel is included in the numerical results. As compared to the performance without a feedback channel, the performance gain is also achieved as the number of neighboring nodes increases.

The proposed cooperative retransmission scheme can be easily used in INR ARQ scheme by transmitting the redundant code block via cooperating nodes. INR ARQ scheme is suitable for the proposed cooperative retransmission scheme since the length of the retransmitted data packet is shorter than that of the full retransmission scheme. To examine the PER performance of INR ARQ with the cooperative retransmission scheme, a $R_c = 1/3$ convolutional code with $K = 4$ is considered. The polynomial generators are $g_1 = 15_{(8)}$, $g_2 = 17_{(8)}$, and $g_3 = 13_{(8)}$. The first code block, $\mathbf{C}_1$, is a $R_c = 1/2$ convolutional code which is obtained by puncturing the whole code block. The punctured bits will be the redundant code block, $\mathbf{C}_2$, which will be delivered to the destination if necessary. The length of information data is assumed to be 10ms, which will be 1250 bytes of the retransmitted data packet. The transmission bandwidth is assumed to be 1 MHz and BPSK modulation is used.

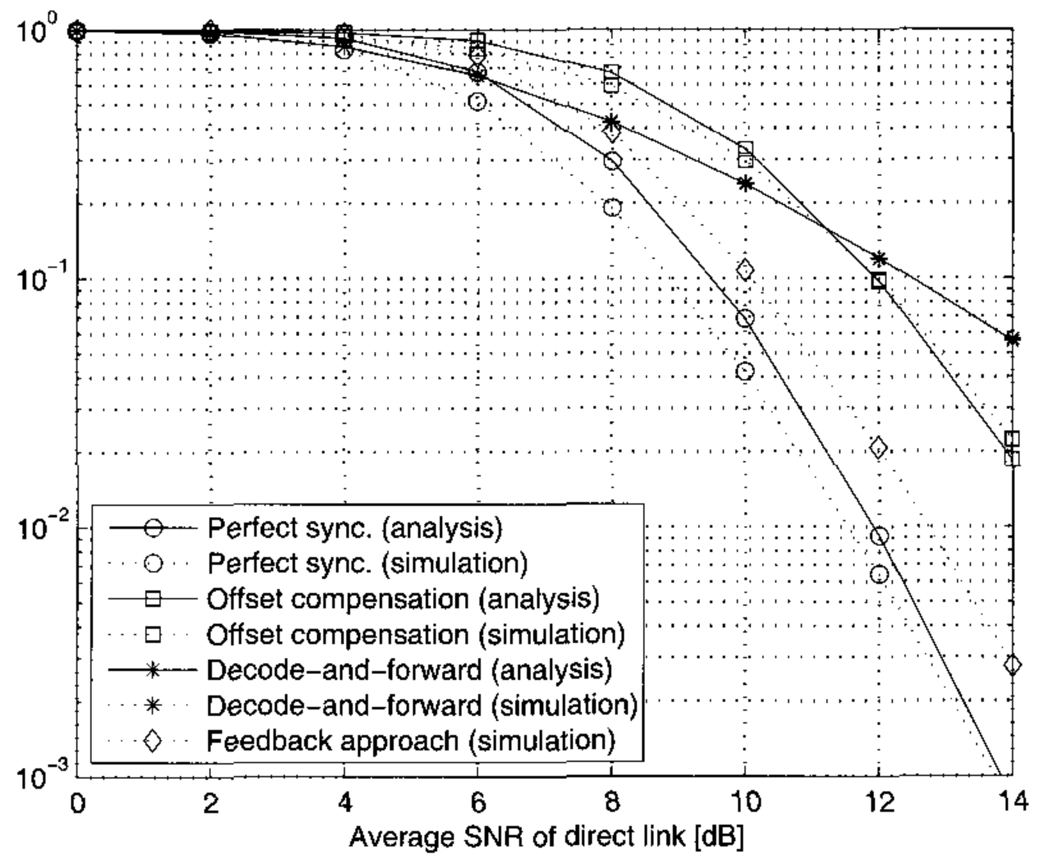


Fig. 7. Outage probability with cooperative retransmission scheme using phase and frequency offset compensation ($M = 5$, packet length = 10 ms, Doppler frequency = 20 Hz, maximum frequency offset = 2 kHz, $d_{rd} = 0.8d_{sd}$).

High PER performance gain can be achieved even for long data packets with a low-rate feedback channel as shown in Fig. 8. The retransmission by the source can be considered as decode-and-forward cooperation in this numerical result since it is assumed that cooperating nodes are located at the same position as the source. When the feedback channel is not used, there is no benefit with a large number of neighboring nodes using the proposed method. By using a small feedback channel, however, the proposed cooperative retransmission scheme can efficiently utilize a large number of neighboring nodes and outperforms the retransmission scheme by the source.

V. CONCLUSION

A cooperative retransmission scheme for ad hoc networks is proposed and analyzed which accommodates multiple neighboring nodes in the cooperation. The proposed cooperative transmission scheme uses system resource more efficiently than previously proposed approaches by initiating user cooperation only when it is requested. Specifically, when the destination requests retransmission of an erroneous packet, multiple cooperative nodes retransmit data packet after adjusting their phase and frequency offsets, which are estimated from the NACK message, to

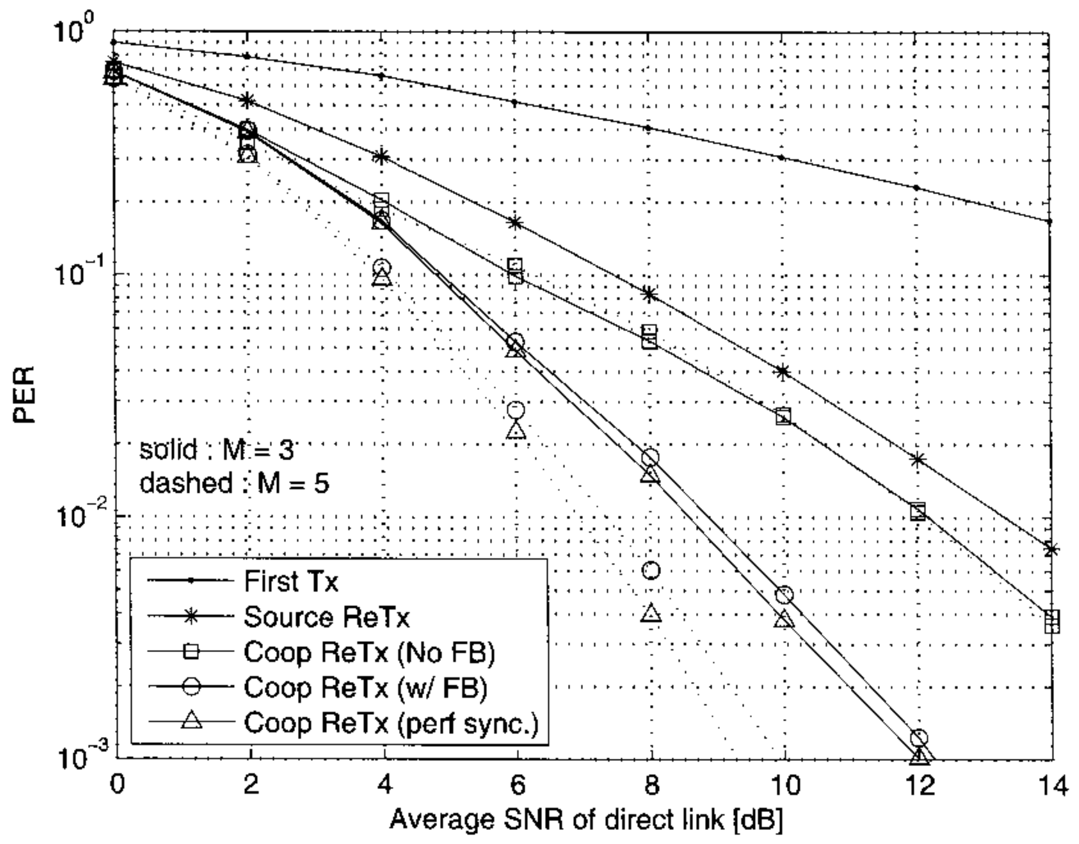


Fig. 8. PER performance of INR ARQ scheme with cooperative retransmission ($M = \{3, 5\}$, retransmit packet length = 10 ms, doppler frequency = 20 Hz, maximum frequency offset = 2 kHz, $d_{rd} = d_{sd}$).

obtain distributed beamforming gain. The proposed cooperative retransmission scheme does not require any *a priori* knowledge concerning the neighboring nodes or initial setup to form the cooperative transmission. Since channel conditions from cooperating nodes to the destination are included during the node selection, good signal quality for the retransmitted data packet can be achieved.

The outage probability of the proposed cooperative retransmission scheme is analyzed with perfect synchronization and offset estimation using the NACK message. The analytical results of the proposed retransmission scheme are well matched with the numerical results and it performs well for short data packets. The residual offsets of cooperating signals can diminish the benefits of the cooperative retransmission scheme especially for long data packets. A low-rate feedback scheme is investigated to reduce the impact of the residual offsets. It is shown that outage probability and PER performance are substantially improved at the cost of a small feedback bandwidth in the proposed cooperative retransmission scheme.

REFERENCES

[1] A. Sendonaris, E. Erkip, and B. Aazhang, "Increasing uplink capacity via user cooperation diversity," in *Proc. IEEE ISIT*, Aug. 1998, p. 156.

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

[3] 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, no.10, pp. 2415–2425, Oct. 2003.

[4] T. E. Hunter and A. Nosratinia, "Diversity through coded cooperation," *IEEE Trans. Wireless Commun.*, vol. 5, no. 2, pp.283–289, Feb. 2006.

[5] T. E. Hunter, S. Sanayei, and A. Nosratinia, "Outage analysis of coded cooperation," *IEEE Trans. Inf. Theory*, vol. 52, no. 2, pp. 375–391, Feb. 2006.

[6] H. Kim and R. M. Buehrer, "Power allocation strategies in cooperative MIMO networks," in *Proc. IEEE WCNC*, 2006, pp. 1675–1680.

[7] R. Mudumbai, G. Barriac, and U. Madhow, "On the feasibility of distributed beamforming in wireless networks," *IEEE Trans. Wireless Commun.*, vol. 6, no. 5, pp. 1754–1763, May 2007.

[8] G. Scutari and S. Barbarossa, "Distributed space-time coding for regenerative relay networks," *IEEE Trans. Wireless Commun.*, vol. 4, no. 5, pp. 2387–2399, Sept. 2005.

[9] J. Mietzner, J. Eick, and P. A. Hoeher, "On distribued space-time coding techniques for cooperative wireless networks and their sensitivity to frequency offsets," in *Proc. IEEE ITG Workshop on Smart Antennas*, 2004, pp. 114–121.

[10] R. Liu, P. Spasojević, and E. Soljanin, "Cooperative diversity with incremental redundancy turbo coding for quasi-staic wireless netowrks," in *Proc. IEEE 6th Workshop on Signal Processing Advances in Wireless Communications*, 2005, pp. 791–795.

[11] S. Jagannathan, H. Aghajan, and A. J. Goldsmith, "The effect of time synchronization errors on the performance of cooperative MISO systems," in *Proc. IEEE GLOBECOM*, 2004, pp. 102–107.

[12] S. Biswas and R. Morris, "ExOR: Opportunistic multi-hop routing for wireless networs," *ACM SIGCOMM*, vol. 35, no. 4, pp. 133–144, Oct. 2005.

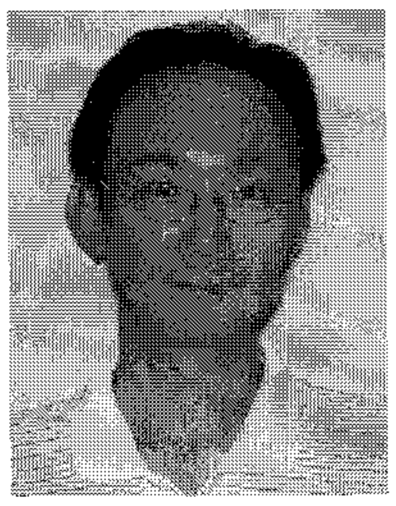
[13] M. Zorzi and R. Rao, "Geographic random forwarding (GeRaF) for Ad Hoc and sensor networks: Multihop performance," *IEEE Trans. Mobile Computing*, vol. 2, no. 4, pp. 337–348, 2003.

[14] M. Dianati, X. Ling, K. Naik, Member, and X. Shen, "A node-cooperative ARQ scheme for wireless Ad Hoc networks," *IEEE Trans. Veh. Technol.*, vol. 55, no. 3, pp. 1032–1044, May 2006.

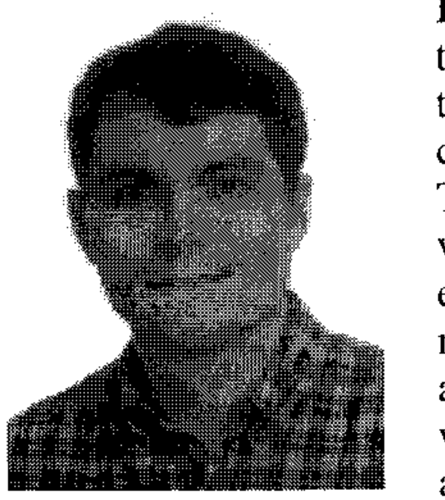
[15] V. Mahinthan, H. Rutagemwa, J. W. Mark, and X. Shen, "Performance of adaptive relaying schemes in cooperative diversity systems with ARQ," in *Proc. IEEE GLOBECOM*, 2007, pp. 4402–4406.

[16] N. C. Beaulieu, "An infinite series for the computation of the complementary probability distribution function of a sum of independent random variables and its application to the sum of Rayleigh random variables," *IEEE Trans. Commun.*, vol. 38, no. 9, pp. 1463–1474, Sept. 1990.

[17] R. Reggiannini, "A fundamental lower bound to the performance of phase estimators over Rician-fading channels," *IEEE Trans. Commun.*, vol. 45, no. 7, pp. 775–778, July 1997.



Haesoo Kim received the B.S. and M.S. degrees from Korea University, Seoul, Korea, in 1993 and 1995, respectively, all in electronics engineering. He is currently pursuing the Ph.D. degree with the Bradley Department of Electrical and Computer Engineering, Virginia Tech, Blacksburg, VA. From March 1995 to June 2000, he was with Samsung Electronics in Seoul and Bundang, Korea as a system/software engineer on Samsung CDMA Cellular Basestation System. His current research interests include cooperative communications, multiple-input multiple-output (MIMO) communications, OFDM, and medium access control (MAC) protocol design.



R. Michael Buehrer joined Virginia Tech as an assistant professor with the Bradley Department of Electrical Engineering in 2001. He is currently an associate professor and is part of Wireless at Virginia Tech, a comprehensive research group focusing on wireless communications. His current research interests include dynamic spectrum sharing, multiple-input multiple-output (MIMO) communications, intelligent antenna techniques, position location networks, ultra wideband, spread spectrum, interference avoidance, and propagation modeling. In 2003, he was named Outstanding New Assistant Professor by the Virginia Tech College of Engineering.

From 1996 to 2001, he was with Bell Laboratories in Murray Hill, NJ and Whippany, NJ. While at Bell Labs his research focused on CDMA systems, intelligent antenna systems, and multiuser detection. He was named a Distinguished Member of Technical Staff in 2000 and was a co-winner of the Bell Labs President's Silver Award for research into intelligent antenna systems. He received the BSEE and MSEE degrees from the University of Toledo in 1991 and 1993 respectively. He received a Ph.D. from Virginia Tech in 1996 where he studied under the Bradley Fellowship.

He has co-authored 30 journal and approximately 75 conference papers and holds 11 patents in the area of wireless communications. He is currently a senior member of IEEE, and an associate editor for IEEE Transactions on Wireless Communications, IEEE Transactions on Vehicular Technologies and IEEE Transactions on Signal Processing.