Power Efficient Link for Multi-Hop Wireless Networks*

Alejandra Mercado† and Babak Azimi-Sadjadi†‡

† Department of ECSE, Rensselaer Polytechnic Institute, Troy, NY 12180

‡ Institute for Systems Research, University of Maryland, College Park, MD 20742

Abstract

In this paper we propose a method in CDMA wireless multi-hop networks which groups transmission nodes into cooperative clusters coupled with RAKE receivers at each receiving node to reduce the total power expenditure of transmitting nodes. With this method cooperative nodes in each cluster act as a distributed nonlinear antenna array which, with an implementable synchronization technique, can achieve the diversity gain of a single transmitter with multiple antennas.

1 Introduction

In wireless multi-hop networks it is desirable to keep transmission powers low, both to preserve the battery life for the transmitting nodes, as well as to limit multi-user interference. A reduction in the effective radiated power from each transmitter has the added benefit of requiring cheaper smaller linear amplifiers at each node. Methods to minimize the power expenditure in wireless systems have been studied extensively [1, 2, 3, 4], however these techniques address only the routing, scheduling algorithm, multicast tree generation, and other network layer subjects without focusing on the link layer. In [5], Stark et al provide a high level description of energy efficient system design with some detail about amplifier performance. These methods may be viewed as complementary to the work presented in this paper, since we focus primarily on transmission diversity techniques with multicast in ad hoc and sensor networks.

Diversity is a popular multipath fading reduction technique, which can be used alternatively to increase the transmission rate or to reduce power without sacrificing the bit error rate. The preferable method to implement diversity depends on the particular application. In many systems it may be impractical to have antenna arrays at each node to provide space diversity for the receiver. In wireless telephony, where it is feasible to install antenna arrays at the base station but not so at the mobile station, transmit diversity can be used. Here several antennas at the base station each transmit a filtered version of the signal, with the intent of inducing a frequency selective channel, which can be handled with an equalizer at the receiver. Though, in practical terms, transmit diversity may not yield the same diversity gain as receiver diversity, Winters showed in [6] that transmit diversity yields comparable gain to receive diversity with low probabilities of large digressions.

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In recent publications, to fully take advantage of the available bandwidth, several diversity techniques are commonly studied and used (e.g. transmit diversity, RAKE receivers, and MIMO systems). The two powerful techniques with effective rates that approach the capacity of MIMO systems are BLAST [7, 8, 9] and Space-Time coding [10, 11]. In both of these methods the transmitter and the receiver use multiple antennas for diversity, which we do not.

In this paper we propose a scheme for a wide-band CDMA system in which all network nodes have single omnidirectional antennas. Except for the originating node's link, each link will be comprised of a group of adjacent transmitting nodes to another group of adjacent receiving nodes. The intermediate nodes form a cooperative cluster which synchronizes their transmission and transmits the information to another group of nodes (cluster). The information is relayed in this cooperative fashion until it is delivered to the destination. The intent is to induce diversity gain by guaranteeing independent paths for each transmission antenna while avoiding antenna arrays at any nodes.

The distinct benefit of the proposed method with respect to current cooperative diversity techniques [12, 13, 14, 15, 16] is that multiple cooperating transmitter nodes transmit to multiple receiver nodes. Thus, the system potentially achieves a MIMO-type diversity gain with the cooperation of multiple receivers. This is possible because this method does not require a tight transmission synchronization. The synchronization of the received diversity signals will be finalized at each individual RAKE receiver. This is a novel synchronization technique that distributes the task of synchronization between transmitters and receivers.

We consider both non-frequency selective and frequency selective channels. In the former case, we assume that the cooperating member nodes of a cluster are roughly synchronized such that their messages arrive to the destination within a range of a few chips from each other. Each receiving node has a RAKE receiver to profit from the diversity. We argue that the synchronization is a practicable task since there is a tolerance level of several chips.

The same technique can be applied to frequency selective Rician channels where the Rician parameter is large. Depending on the number of spreading codes available, each node in a cluster may have a distinct spreading code, which would require several RAKE receivers at each receiving node, one for each transmitting cluster node. Alternatively, all nodes in a transmitting cluster may use the same spreading code, which is better suited for the case where there are few distinguishable multipaths per transmitting cluster node. Here, each receiving node has a single high order RAKE receiver.

We simulate a Rayleigh fading channel to test the results of this method. Our simulations show that this method provides a significant reduction in the total power expenditure among nodes. For example, if the target bit error rate (BER) is 10^{-3}, then the average simulated reduction of total expended power for diversity orders between two and six is over 13 dB. For the same experiment, the average power for each individual transmitting node decreases by over 19 dB.

This paper is organized as follows: Section 2 presents the model we use. Section 3 describes the effect of diversity in ad hoc networks and sensor networks, it addresses the issue of synchronization for space-time diversity, and it describes the reduction in power we expect with this method. Section 4 shows our simulation results and Section 5 are our concluding remarks and future work.

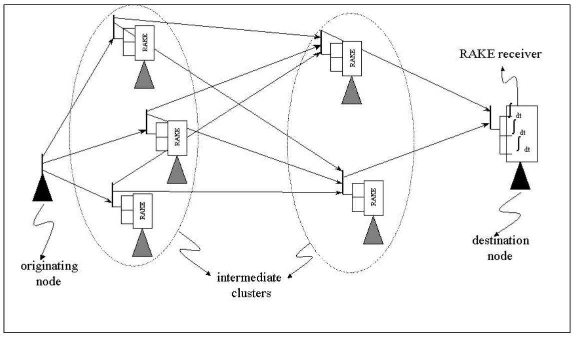

Figure 1: Each node in the network has a RAKE receiver so intermediate nodes also use diversity.

2 System Model

Consider an ad hoc network, where each receiving node is equipped with a single omni-directional antenna and a RAKE receiver. In this model, routing tables between nodes would not be composed of single link-by-link hops, but rather would list group-by-group hops. The groups of nodes would work together providing space-time diversity for the receiver, as shown in Figure 1. With this method the transmitting powers for all nodes can be reduced and advantages of this are twofold: both saving battery life as well as reducing interference for bystander nodes.

We assume that all nodes must transmit at a power sufficient to result in an adequate signal to interference and noise ratio (SINR) at the receiver, say γ_0. Power control techniques are in effect to guarantee that transmitters transmit at the minimum possible power which guarantees an SINR of γ_0 at the receivers. As an example, consider the link portrayed in Figure 2. A single hop between the packet source and its destination would be comprised of several intermediate nodes. In this example, Figure 2(b) shows that the single hop uses three nodes to pass on the information from the source to the destination. Rather than silencing the three intermediate cluster nodes and transmitting to a single intermediate node, as shown in Figure2(a), the system uses the diversity of the three cluster nodes to increase the SINR at the receiver to γ_0. In this way, the originator node must only transmit with quality γ_0 to a radius of $r_1 < R_1$. The cluster nodes must each transmit with quality γ_0 to an approximate radius $r_2 < R_2$. The diversity gain at the destination node receiver compensates for the low SINR it perceives from each individual intermediate cluster member. Note that r_2 need not be the same for all cluster nodes, and we make no distinction among them here for simplicity.

Consider a spread spectrum system, where node k sends in information sequence $d_k(\cdot)$. The transmitted signal is

$$s_k(t) = \sqrt{P_k} d_k(t) f_k(t) \ , \tag{1}$$

where P_k is the transmitted power for user k and $f_k(\cdot)$ is the spreading code used by k.

The signal is relayed to a first cluster of nodes. In Figure 1 this cluster has three nodes. Each node is capable of diversity combining any multipath signal from the originating node. Each node in this intermediate cluster then relays the signal to the next cluster. In Figure 1 the next cluster has two nodes. This continues until the packet has reached its destination, which also has a RAKE receiver.

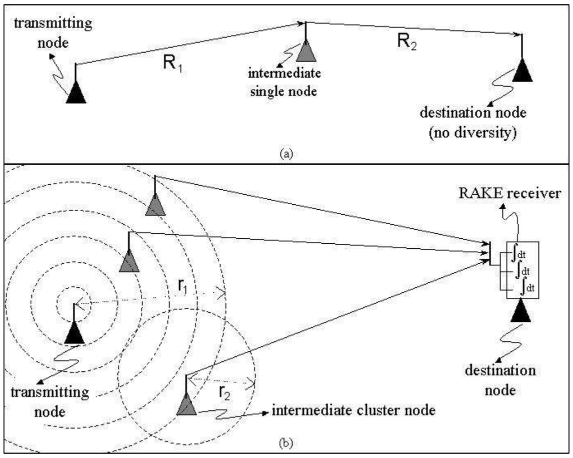

Figure 2: (a) Conventional network where a single node is used to relay the message from the source to the destination. (b) The transmitter uses a cluster of several nodes to relay the signal benefiting from diversity.

We consider the received signal at any receiver, be it intermediate or destination. The signal is

$$x(t) = \sum_{n=1}^{N} \sum_{l=1}^{L_n} \beta_{n,l} \sqrt{P_n G_{n,l}} s_k(t - \tau_{n,l}) e^{-j\omega\tau_{n,l}} + i(t) + n(t) \ , \tag{2}$$

where N is the number of nodes in the previous cluster (in the case of the originating node, $N = 1$), P_n is the transmitting power of node n, L_n is the number of discernable multipaths for node n, $\beta_{n,l}$ is a complex random number that models the fading effect of the $(n,l)^{th}$ path whose amplitude is Rayleigh distributed, $G_{n,l}$ and $\tau_{n,l}$ are respectively the pathloss and delay experienced by multipath l of node n. We assume that all nodes have a similar height and that they all have omnidirectional antennas with unity gain, therefore, $G_{n,l}$ reduces to $1/d_n^{\alpha}$, where d_n is the distance between node n and the receiver and $\alpha \geq 2$. $i(\cdot)$ represents the interference due to other clusters transmitting signals from unrelated originating nodes towards other destinations, and $n(\cdot)$ is additive white Gaussian noise at the receiver.

After carrier synchronization, the RAKE receiver either uses a bank of decorrelators or a sliding decorrelator to detect the highest quality multipath signals from all those originating from the N intermediate nodes from the transmitting cluster.

3 Transmission Diversity in Multi-Hop Wireless Networks

In this section we describe the effect of diversity in ad hoc and multi-hop sensor networks. We first consider the case of frequency non-selective channels where we describe the diversity gain achieved by synchronized transmission and a RAKE receiver. We go on to expand the idea of transmit diversity to frequency selective channels. Henceforth, we use the term *multipath spread* to describe the arrival time span for the collection of all multipath signals with relevant power from all nodes in a transmitting cluster. We denote this induced multipath spread as T_m.

3.1 Frequency Non-Selective Channels

In frequency non-selective channels the multipath spread is small enough so that there are no discernible multipaths. Using a cluster of transmitters, as in Figure 1, we artificially introduce a multipath spread of length T_m. We will assume that the symbol duration, T_s, is larger than the multipath spread, so we may neglect any inter-symbol interference. For this we assume that all the nodes in the cluster have access to the same information stream, and that they use a communication link among themselves to determine the transmission starting time for each cluster node. We will refer to this process as *cluster synchronization*. The objective of cluster synchronization is that the delays among the discernable multipaths from a given cluster of nodes all stay within a symbol period, therefore, the cluster nodes do not need to synchronize their transmission to the chip level. The only requirement is that the cluster should be synchronized so as to provide enough discernable multipaths so that the receiver gains adequate diversity. This method would therefore allow a RAKE receiver to perform well in an indoor environment, where traditionally RAKE receiver performance is inadequate [17].

Let L be the number of fingers in the RAKE receiver. L should be greater than the number of nodes in the cluster, N, to be able to take full advantage of the transmit diversity procured by the transmitting cluster. The RAKE receiver may use a bank of L decorrelators, or it may use a sliding decorrelator with resolution of a chip, T_c.

Without loss of generality, we study the k^{th} receiver at the destination cluster. We assume that the receiver has the estimates of β_n then the output of the decorrelator for signal $s_k(\cdot)$ relayed by node n is

$$\begin{aligned} z_n &= \frac{1}{T_s}\int_{iT_b-\tau_n}^{(i+1)T_b-\tau_n} x(t) f_k(t-\tau_n)dt \\ &= \beta_n\sqrt{P_nG_n}d_k(iT_b) + I_n + n_n \ , \end{aligned} \tag{3}$$

where I_n denotes the decorrelator output for all other multipath signals, and n_n is the decorrelator output of the noise. In equation (3) we have dropped the index l since $L = 1$. By construction of the spreading codes, we assert that

$$\frac{1}{T_s}\int_{iT_b}^{(i+1)T_b} f_m(t-\tau) f_k(t-\tau_k)dt \ll 1 \tag{4}$$

if $\tau \neq \tau_k$ or $k \neq m$. Then the decision variable Z for the k^{th} receiver node in the cluster can be expressed as

$$\begin{aligned} Z &= \sum_{n=1}^{N} \bar{\beta}_n\sqrt{P_nG_n}z_n \\ &= \sum_{n=1}^{N} |\beta_n|^2 P_nG_nd_k(iT_b) + \sum_{n=1}^{N} \bar{\beta}_n\sqrt{P_nG_n}(I_n+n_n) \ , \end{aligned} \tag{5}$$

Where $\bar{\beta}_n$ is the complex conjugate of β_n. The instantaneous signal to noise ratio is [18]

$$\begin{aligned} \gamma &= \sum_{n=1}^{N} \gamma_n \\ &= \frac{\sum_{n=1}^{N} |\beta_n|^2 P_nG_n}{\Phi_I+\Phi_n} \ , \end{aligned} \tag{6}$$

where Φ_I and Φ_n are the powers of the interference, I_n and the noise, n_n, respectively. For comparison convenience, we assume that $G_n = 1$ for $n = 1, \cdots, N$, furthermore we also assume that the transmitted power for each node in the cluster is the same, i.e., $P_n = P/N$ where P is collective transmitted power from all N nodes in the cluster. Therefore the SINR in this case is

$$\begin{aligned} \gamma &= \frac{\sum_{n=1}^{N} |\beta_n|^2 P_n G_n}{\Phi_I + \Phi_n} , \\ &= \frac{P/N}{\Phi_I + \Phi_n} \sum_{n=1}^{N} |\beta_n|^2 . \end{aligned} \tag{7}$$

We compare the expectation of (7) with the average SINR for a single transmitter with power P, $\frac{P}{\Phi_I + \Phi_n} |\beta_1|^2$, and we observe that if the expectation of β_n is a constant for all n, then both average SINR levels are equal. However, the variance of the (7) is smaller. This is equivalent to saying that as the number of transmitters grows for a constant transmit power the channel converges to a Gaussian channel.

As an example, consider a BPSK modulator, where the probability of error is $Q(\sqrt{2\gamma})$, which is a strictly convex function with respect to γ, therefore, for i.i.d. β_n

$$E\left[Q\left(\sqrt{\frac{2P/N}{\Phi_I + \Phi_n} \sum_{n=1}^{N} |\beta_n|^2} \right) \right] < E\left[Q\left(\sqrt{\frac{2P}{\Phi_I + \Phi_n} |\beta_1|^2} \right) \right] . \tag{8}$$

This shows that for the same bit error rate the synchronized cluster transmission requires lower total power, P. Furthermore, each individual node transmits with a power approximately equal to P/N, requiring smaller transmitters.

3.2 Frequency Selective Channels

In frequency selective channels, as seen in Figure 3, the delay spread for each individual link is larger than the chip length, T_c. Here we consider the case where the number of multipaths for each transmitting node is either limited or, alternatively, the non-dominant multipaths have considerably lower power with respect to the dominant multipath, in other words, a Rician channel with a relatively high Rician parameter. We argue that for this case, as in the case of the frequency non-selective channel, synchronized cluster transmission provides lower bit error rates for the same overall transmission power. We consider two possible scenarios for this setup. First we assume that the number of spreading codes available allow each node in the cluster to use their own distinct code. Later, we assume that all nodes of a cluster use a single spreading code that is assigned to the cluster.

In the former case, where each node has a distinct code, the receiver can have several parallel RAKE receivers for each transmitting node. Using the same methodology as in the previous section, we can show that the SINR of the k^{th} receiver is given as follows

$$\begin{aligned} \gamma &= \sum_{n=1}^{N} \sum_{l}^{L} \gamma_{n,l} \\ &= \frac{\sum_{n=1}^{N} \sum_{l=1}^{L} |\beta_{n,l}|^2 P_n G_{n,l}}{\Phi_I + \Phi_n} , \end{aligned} \tag{9}$$

where L is the number of fingers in each parallel RAKE combiner. Therefore, with assumptions similar to the previous section, the maximum diversity gain is $\sum_{n}^{N} \sum_{l=1}^{L} |\beta_{n,l}|^2$.

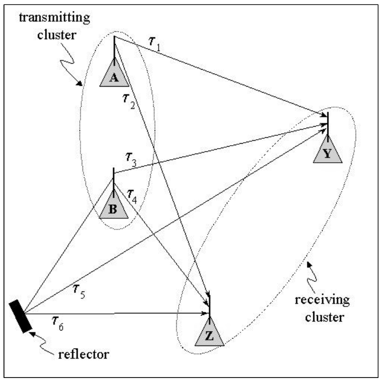

Figure 3: The relative distances between nodes of two clusters place further constraints on the synchronization requirements.

The more interesting case is where the number of available spreading codes only allows one code per cluster. In this case the k^{th} receiver only uses a single RAKE receiver with a larger number of fingers. In this setup the RAKE receiver only uses the L strongest multipaths. We define the set Λ as the group of indexes of the L strongest multipath for all N cluster nodes. The decision variable is

$$\begin{aligned} Z &= \sum_{l\in\Lambda} \bar{\beta}_l \sqrt{P_l G_l} z_l \\ &= \sum_{l\in\Lambda} |\beta_l|^2 P_l G_l d_k(nT_b) + \sum_{l\in\Lambda} \bar{\beta}_l \sqrt{P_l G_l} (I_l + n_l) \ . \end{aligned} \tag{10}$$

The signal to noise ratio is [18]

$$\begin{aligned} \gamma = & \sum_{l\in\Lambda} \gamma_l \\ & \frac{\sum_{l\in\Lambda} |\beta_l|^2 P_l G_l}{\Phi_I + \Phi_n} \ . \end{aligned} \tag{11}$$

By the same assumptions and reasoning of the previous section, the resulting instantaneous SINR is

$$\gamma = \frac{P/N}{\Phi_I + \Phi_n} \sum_{l\in\Lambda} |\beta_l|^2 \ . \tag{12}$$

Note here that the order of the RAKE receiver, L, may be larger than N. Therefore, when $L > N$, this yields better performance than in the frequency non-selective case.

3.3 Synchronization for Space-Time Diversity

We distinguish between two types of transmission synchronization: the synchronization among nodes of a cluster transmitting to another intermediate cluster in the route, and the synchronization from the last cluster to the destination node.

The former problem is more challenging than the latter since the two objectives, namely that the diversity signals all arrive within the span of one symbol, and that at least several of the multipath should be discernable, depend on the relative distance of the transmitting nodes to several receiving nodes.

As an example, in Figure 3 $\tau_i,\ i = 1, 2, \cdots, 6$ are the transmission delays between each of the transmitting nodes, A and B, to the receiving nodes, Y and Z. These delays

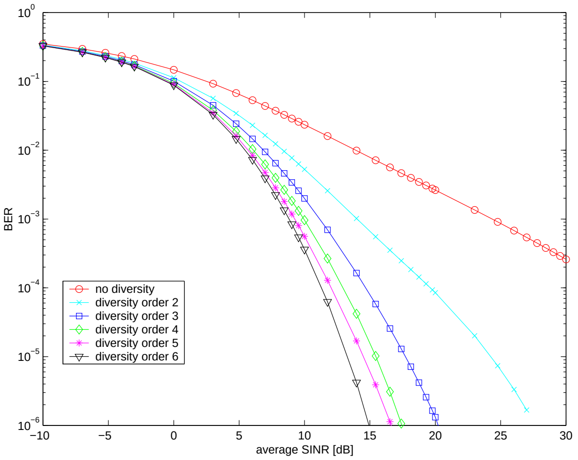

Figure 4: This plots the probability of a bit error (BER) with respect to the signal to noise ratio at the receiver averaged over the fading. Each curve corresponds to a different order of diversity.

are associated to the multipaths with high enough reception power to construe diversity paths. We denote the moment that each transmitter, A and B, begins to transmit its message as T_A and T_B, respectively. With ideal synchronization we have

$$\max(T_A + \max_{i=1,2} \tau_i, T_B + \max_{j=3,4,5,6} \tau_j) - \min(T_A + \min_{i=1,2} \tau_i, T_B + \min_{j=3,4,5,6} \tau_j) < T_m \ , \qquad (13)$$

in order to avoid inter-symbol interference and we also have for L_c paths

$$T_i + \tau_k - (T_j + \tau_l) > T_c, \quad i, j \in \{A, B\} \text{ and } k, l \in \{1, \cdots 6\} \ , \qquad (14)$$

in order to get enough diversity gain, where L_c is preferably equal to L, though it may be smaller. In practice the nodes in the cluster may not have access to the estimate of the delay for the paths to the receiver. In this case these delays should be estimated from the hand shakes between the cluster nodes. The distributed synchronization of the nodes in the cluster is a subject that is under investigation by the authors.

4 Simulations

Given a target signal to interference and noise level at any receiver node, the bit error rate will depend on the order of the transmitting diversity. For a range of average signal to interference and noise levels ranging from $-10\ dB$ to $30\ dB$ we simulate a Rayleigh fading channel where the center transmission cluster node has an average distance of 200 meters from the receiver. We calculate the effective bit error rate for different orders of diversity. Figure 4 shows the resulting plot where each point is the resulting average of 10000 experiments. As expected, the plot shows a marked decrease in the bit error rate between having no diversity and diversity of any order for signal to interference and noise levels above $5\ dB$. The incremental drop in bit error rate decreases as the order increases.

If we fix the bit error rate to some level deemed acceptable for a given system, we can reduce the transmitting power of each node. We assume that the *average received* power level from all transmitting nodes to any receiving node is roughly equal. That

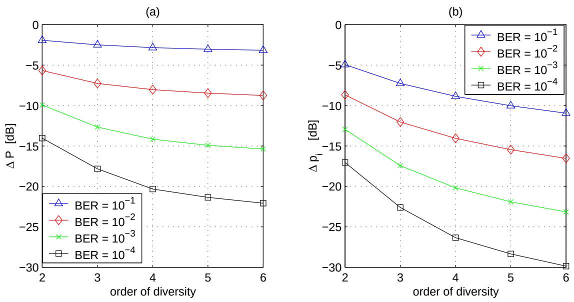

Figure 5: These plots describe the ratio of the power expended when transmitting the signal from several nodes (the case of diversity) to the power expended when transmitting from a single node (the case of no diversity). Each curve corresponds to a certain BER at the receiver. (a) This plot reflects the ratio of the total power expenditure. (b) This plot shows the average ratio per node in power expenditure.

is, we assume that distance among the nodes in the transmitting cluster is small when compared to the distance of the transmitting cluster to the receiving cluster. We compare the transmitted power from a single node in order to achieve the target bit error rate to the transmitted power of each node in a cooperative cluster which achieves the same bit error rate. Figure 5 shows the reduction in transmitted power attained by the transmitting cluster for different orders of diversity. Again, each point is the average of 10000 experiments.

Figure 5(a) shows that the added power among all transmitting nodes in a cluster is significantly less than the transmitting power of a single node. Each experiment to arrive to ΔP represents the ratio $\sum_i p_i/P$, where p_i are the transmitting powers of the cluster nodes and P is the power of the single non-diversity node. The change in total power is more pronouncedly affected by the order of diversity as the target bit error rate goes down. This graph shows an overall reduction of total expended power among all nodes, reducing the interference levels for other links and saving battery life.

In Figure 5(b), each experiment to arrive to Δp_i represents the average $\frac{1}{N}\sum_i p_i/P$. In other words, each point, Δp_i, is the comparison of the transmitting power of each cooperative node to the case where there is a single transmitting node. The significant reduction shown in this graph tells us that the dynamic range of the transmitted power for each node is much smaller with diversity. This translates to smaller cheaper power amplifiers for each node.

5 Conclusions and Future Work

We have presented a way of providing space-time diversity in a wide-band CDMA ad hoc system without the use of linear antenna arrays at any node. This method is shown to reduce the collective power expenditure among all nodes and greatly reduce the transmitted power of each individual node, thus reducing interference in the system, extending battery life, and requiring smaller less expensive power amplifiers at each node.

In this paper we have not addressed many problems associated to the method presented. Some of the issues that the authors are currently investigating are

- It is plausible that if all member nodes of a cluster have access to the decision variables of all other member nodes, then they can achieve a diversity gain similar to that of space-time coding. The cost here is the extra bandwidth and power used for intra-cluster communication between member nodes. However, since the nodes in the cluster are geographically close, the transmission power is expected to be small and therefore the bandwidth spent can be reused for other clusters.

- Clustering and routing techniques for group transmission should take into account the delay spread for the nodes in the cluster.
- After applying the proper diversity gain, each node in the cluster decodes the data. If error free transmission is not guaranteed by the upper network layers, it is possible that the nodes may have erroneous copies of the same information. It remains to be seen to what extent this will affect the performance of the system.
- What kind of diversity gain can be achieved if the data in the cooperating cluster nodes are not identical, but merely highly correlated to each other?

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