Cohesion of Wireless Sensor Networks with MIMO Communications

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Abstract

Wireless sensor networks are an enabling technology for many future surveillance-oriented applications. Before a practical wireless sensor network is realized, however, significant challenges must be overcome. Chief among the obstacles to netted sensors is providing low power, robust communications between sensor nodes. Multiple Input, Multiple Output (MIMO) communication promises performance enhancements over conventional single input, single output (SISO) technology for the same radiated power. If leveraged in a sensor network, MIMO may be able to provide significant network performance improvements in power consumption, latency, and network robustness. However, improvements in the physical layer are not always realized in the higher layers. This paper investigates the benefit of MIMO implementations in multihop wireless sensor networks in terms of network cohesion—that is, the ability of the sensor nodes to form a completely connected network

1. Introduction

Despite extensive research, reliable, power efficient communication remains an open problem in networked sensors [1]. However, MIMO technology has promising characteristics that make it a candidate for netted sensors communication technology. MIMO communication has been shown to provide performance gains over traditional SISO communication without increasing the bandwidth consumed by the system or the total power radiated from a transmitter [2], [3]. Capacity gains have been shown to be achievable, under certain conditions, when MIMO is used in a spatial multiplexing fashion [2], [4], [5], [6]. Signal processing techniques that use multiple transmit and receive antennas, such as space-time coding (STC), have been shown to increase transmission reliability [3], [7]. Because of these features, MIMO has been proposed and incorporated into several standards [5].

In this paper, we analyze the network performance benefits resulting from a MIMO physical layer, paying particular attention to the network's ability to form a completely connected network. In a surveillance application, the ability of sensor nodes to relay data is critical to the utility and effectiveness of the sensor network. Thus, MIMO's promise of low power, high reliability communications, if fulfilled, is a key argument in favor of implementing MIMO in wireless sensor networks. To determine whether MIMO delivers on its promise of improved reliability, we simulate multihop MIMO and SISO networks and compare their respective performances in terms of probability of cohesion and the sizes of clusters they form.

2. Link Model

In a multipath environment, the received signal x resulting from a transmitted symbol s is given in (1), in which H is the complex normal channel ($\alpha e^{j\theta}$), s is the transmitted symbol, and n is the noise. The channel given by H is $\mathcal{CN}(0,1)$, thus modeling a rich scattering environment.

$$x = Hs + n \tag{1}$$

In the SISO case, H, s, and n reduce to single elements. A representation of the received symbol can be derived as in (2) in the SISO case.

$$\begin{aligned} \tilde{s} &= H^* x \\ &= \alpha^2 s + H^* n \end{aligned} \tag{2}$$

In the MIMO case, Alamouti coding for two transmitters and two receivers is used [7]. Alamouti coding exploits space and time diversity to improve communications performance between the transmitter and receiver. In Alamouti coding, two symbols are transmitted over two symbol periods. In an initial symbol period, each transmitter broadcasts one of the symbols. In the subsequent symbol period, each transmitter sends the complex conjugate of the symbol transmitted by the other

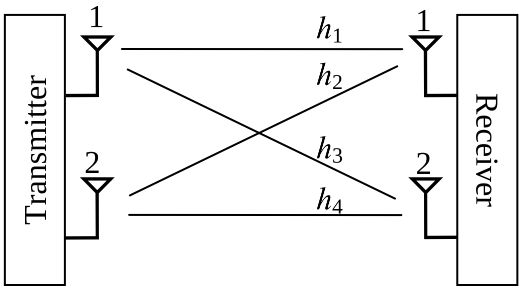

Figure 1: MIMO channels

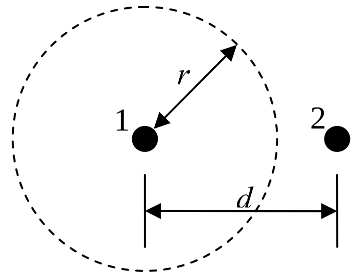

Figure 2: Two nodes a distance *d* apart

in the previous symbol period; one of the two transmitters additionally inverts the symbol before transmission. Table I illustrates the transmission sequence.

Table I: Transmitter behavior in 2x2 Alamouti Coding

	Transmitter 1	Transmitter 2
Symbol Period 1	s_1	s_2
Symbol Period 2	$-s_2^*$	s_1^*

In each symbol period, each receiver receives a symbol altered by the channel and corrupted by noise on two diversity channels, as shown in Figure 1. (3) gives the received symbols, $x_{n,t}$, where n indicates the receive antenna and t indicates the symbol period.

$$\begin{aligned} x_{1,1} &= h_1 s_1 + h_2 s_2 + n_1 \\ x_{2,1} &= h_3 s_1 + h_4 s_2 + n_2 \\ x_{1,2} &= -h_1 s_2^* + h_2 s_1^* + n_3 \\ x_{2,2} &= -h_3 s_2^* + h_4 s_1^* + n_4 \end{aligned} \tag{3}$$

The receiver maximal ratio combines the four received symbols in the standard way, producing representations for each of the two information symbols. The representations are given in (4).

$$\begin{aligned} \tilde{s}_1 &= h_1^* x_{1,1} + h_2 x_{1,2}^* + h_3^* x_{2,1} + h_4 x_{2,2}^* \\ &= \left(\alpha_1^2 + \alpha_2^2 + \alpha_3^2 + \alpha_4^2\right) s_1 + h_1^* n_1 + h_2 n_2^* \\ &\qquad + h_3^* n_3 + h_4 n_4^* \\ \tilde{s}_2 &= h_2^* x_{1,1} - h_1 x_{1,2}^* + h_4^* x_{2,1} - h_3 x_{2,2}^* \\ &= \left(\alpha_1^2 + \alpha_2^2 + \alpha_3^2 + \alpha_4^2\right) s_2 - h_1 n_3^* + h_2^* n_1 \\ &\qquad - h_3 n_4^* + h_4^* n_2 \end{aligned} \tag{4}$$

We model multihop wireless sensor networks as a set of N nodes. Each node has an identical transmission radius, r, such that the channel mean for successful SISO communication is located at the radius.

We model a lossy communications channel between every pair of nodes in the set. The channel model is based on a d^{-4} large scale fading model combined with a complex normal fading channel to model a rich scattering environment. We assume the transmit and receive antenna gain are unity. To simplify calculations, we fix the SISO transmit power to 1.

In our simulations, we determine the received E_b/N_0 for transmissions between the nodes. In the MIMO simulations E_b/N_0 is measured after maximal ratio receive combining [3], [7].

Available links are identified using received E_b/N_0. As noted above, the received E_b/N_0 is determined based on a channel model that accounts for rich scattering and free space path loss. The received E_b/N_0 is normalized by the effective radius of the nodes, which we chose. The normalization is such that beyond the effective radius the received E_b/N_0 is attenuated; the E_b/N_0 is amplified closer to the nodes.

Consider two nodes separated by a distance d, as shown in Figure 2. In the SISO simulations, a complex normal channel h exists between the nodes. The E_b/N_0 at node 2 due to a transmission from node 1, including the normalization factor, is given by (5).

$$\gamma = |h|^2 \times \frac{r^4}{d^4} \tag{5}$$

In the MIMO case the power per antenna is one half that of the SISO case, to provide an equal transmitted power comparison. In addition, four separate channels, h_1, h_2, h_3, and h_4—the diversity channels between the two transmit antennas and the two receive antennas—are modeled between nodes 1 and 2. Thus, the equivalent channel h between the two nodes is given by (6), and the E_b/N_0 at node 2 due to a transmission from node 1, including the normalization factor, is given by (5). A link is considered to be present when γ is greater than or equal to 1 for both the SISO and MIMO cases.

$$h = \sqrt{\frac{|h_1|^2 + |h_2|^2 + |h_3|^2 + |h_4|^2}{2}} \tag{6}$$

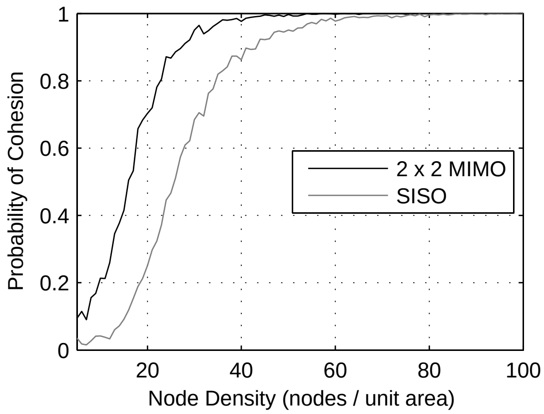

Figure 3: Probability of cohesion for randomly distributed SISO and MIMO networks

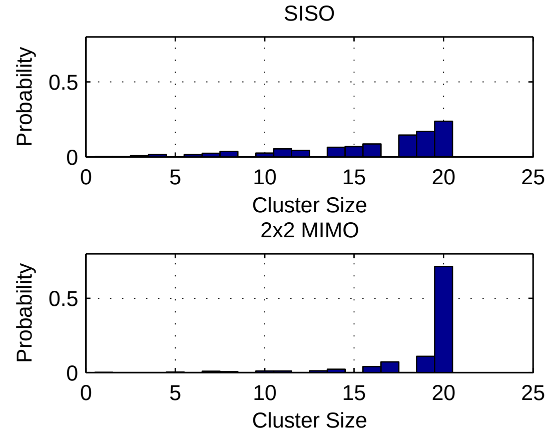

Figure 4: Largest cluster size of SISO and MIMO randomly distributed networks

Thus randomly available links between the nodes in a set are provided. A set of nodes is said to constitute a *cohesive network* if communication between any pair of nodes is possible over 1 or more intermediate hops. That is, any node in the set can communicate with any other node in the set via one or more intermediate wireless links, using intervening nodes as routers. We assume an optimal routing protocol such that nodes forward packets toward their destinations along the shortest path.

The nodes may be fragmented into unconnected clusters. A *cluster* is defined as a group of nodes within a set that are able to communicate through one or more intermediate hops. In a cohesive set, there is exactly one cluster—the cluster containing all N nodes in the set. In a noncohesive set, there are several clusters; communication between nodes in different clusters is impossible. A cluster may contain only one node (an isolated node). The largest cluster in a set is the one that contains the greatest number of nodes. As can be deduced from the above remarks, the largest cluster in a cohesive set is the network containing all the nodes in the set.

3. Adjacency Matrices

Network connectivity is described in the standard way using adjacency matrices. In [8] Li explores different characteristics of wireless networks, including node degree, diameter, and connectivity, with adjacency matrices. In [9] Zhang and Seah formulate algorithms that use adjacency matrices to calculate the maximum number of simultaneous sessions in an ad hoc network, as well as the average hop count and lengths of shortest paths between pairs of nodes in the network.

Adjacency matrices provide insight into the richness of connectivity of the network simply by their sparseness or denseness. Furthermore, raising the adjacency matrix to the n^{th} power yields information about the ability of network nodes to communicate over n intermediate hops. By exploring the adjacency matrices for both MIMO and SISO networks, both network cohesion and path lengths between pairs of nodes can be analyzed.

4. Results

Monte Carlo simulations were performed on sets of 5–100 nodes randomly located in the unit square. For each set of N nodes, the N nodes were randomly placed (uniform in x and y) 200 times. The channels between the nodes were calculated 10 times for each of the node placements or topologies. Each calculation produced a set of links between the nodes. If the set of links was such that a path consisting of one or more hops existed between every pair of nodes in the set of nodes, the instance of the topology and link calculations was counted as a cohesive network for that particular N. The probability of cohesion for N nodes is defined as the number of cohesive instances divided by the total number of trials for that N (2000 for each N). In each of the experiments, each node had an effective transmission radius of 0.3 units.

The simulations reveal that MIMO improves network cohesion. Because MIMO provides a range extension, some nodes that are beyond the range of SISO communications can communicate with MIMO. Consequently, using MIMO results in a higher probability of cohesion for less-dense networks.

The probability densities shown in Figure 3 illustrate the improvements provided by MIMO. Figure 3 shows the probability of cohesion with respect to node density for the random SISO and MIMO node distribution cases.

Random MIMO networks show greater probability of cohesion for less dense networks. To achieve 0.9 probability of cohesion, for example, requires a density of roughly 27 MIMO nodes per unit area. A node density of approximately 43 nodes per unit area is required to reach the same performance level with SISO-equipped nodes.

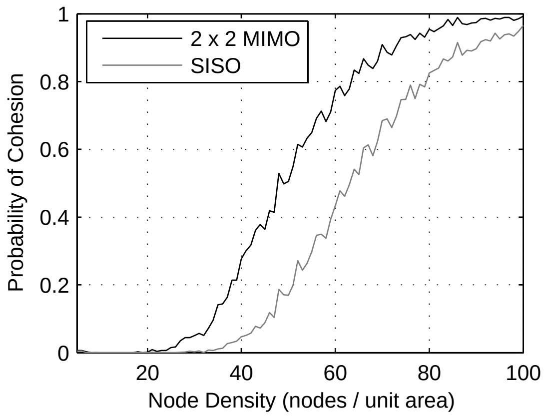

Figure 5: Probability of cohesion for road surveillance scenario

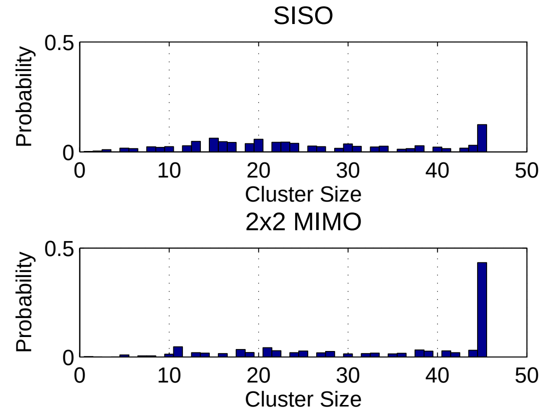

Figure 6: Largest cluster size of SISO and MIMO networks for road surveillance scenario

Thus MIMO provides a 16 nodes/unit area improvement over SISO. In a scenario in which node availability is limited, the communications technology employed in the nodes could mean the difference between the success or failure of a given application. While MIMO nodes can realize 0.9 probability of cohesion with a node density of 27 nodes per unit area, SISO nodes can attain only a 0.57 probability of cohesion with the same node density.

MIMO also shows performance improvements in terms of achievable cluster sizes. To determine the cluster size distribution for a fixed *N*, 200 topologies were constructed, and the channels between the nodes in each topology were calculated 10 times. The size of the largest cluster (the largest group of nodes that are able to communicate with each other through one or more intermediate hop) was recorded, and a histogram of cluster sizes was plotted.

Figure 4 shows a histogram of maximum cluster sizes for networks of 20 randomly distributed SISO and MIMO nodes. Despite the sparseness of the node layout, the MIMO network tends to form large clusters and has a high probability of cohesion. The SISO network, while also tending to form large clusters, has a much lower probability of forming large clusters or a cohesive network. Additionally, it is more likely to form small networks than the MIMO network. Therefore, MIMO can provide substantial benefit to sparse, randomly distributed networks.

While random distributions of nodes are interesting, they are just one possible node deployment—one that is not very likely in actual applications of sensor networks. A more likely deployment is one in which the nodes are arranged around an object or area of interest, for example, a road or building. To model this type of network we maintain the uniform random variable to determine the node locations, but scale the *x* coordinate by a factor of 4 and constrict the *y* coordinate by the same factor to elongate the target area (as in the case of a road) but retain the unit size of the area.

As might be expected, achieving network cohesion is more difficult in this setting. For a given node density, nodes are more likely to be out of range in the *x* direction, thus inhibiting communication. In a situation such as this, the extended range of MIMO is of greater importance because it enables cohesion, which guarantees the success of an application.

Figure 5 shows the probability of convergence of SISO and MIMO networks distributed to observe an elongated area, such as a section of a road. As can be seen from the figure, MIMO provides superior performance for a given node density, and can achieve the same level of performance at lower node density. A MIMO-equipped network reaches 0.9 probability of cohesion at a node density of roughly 73 nodes per unit area. A SISO-equipped network attains 0.9 probability of cohesion at about 90 nodes per unit area. The probability of cohesion for a SISO node network with node density of 73 nodes per area is approximately 0.7.

In this more challenging communications environment, both MIMO and SISO networks also suffer in terms of cluster sizes. MIMO, however, outperforms SISO. While both SISO and MIMO tend to form cohesive networks, MIMO networks have a greater probability of cohesion. The probability of various clusters sizes for networks of 45 nodes, shown in Figure 6, is indicative of this.

As can be seen in Figure 6, the probability of forming a SISO cluster of a given size is nearly uniformly distributed over all possible cluster sizes. The MIMO network, conversely, is more likely to form a cohesive network than to form disjoint clusters.

2x2 MIMO provides appreciable gain in terms of network cohesion and cluster sizes over SISO for nodes randomly distributed in a unit square and an elongated region in a multipath environment when Alamouti coding is used. This is due to the fact that MIMO exploits transmitted and receiver diversity as well as multipath diversity. Thus, MIMO is less susceptible to fading and can, in a sense, provide greater reliability and longer transmission range. Therefore, in certain situations, MIMO can provide a richer set of connections for a given topology, including connections between nodes that were previously unable to communicate because of distance. Ergo, in many cases MIMO provides a higher probability of cohesion and larger cluster sizes for a given node density than SISO.

5. Conclusions

MIMO provides noticeably improved performance over SISO in sensor networks. The improvement can be seen in random deployments and in more practical settings.

In this paper we explored the relative performance of SISO and MIMO in random deployments and in a scenario that simulated the surveillance of a road, path, or other elongated area. In both cases the MIMO-equipped networks were more likely than the SISO-equipped networks to form cohesive networks and large clusters. Of course a MIMO network requires higher implementation costs. Future work includes investigating performance in scenarios that simulate intrusion detection around the perimeter of a building or other facility and the impact of link costs on the magnitude of the improvement provided by MIMO.

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