Collaborative Signal Reinforcement in Sensor Networks

Tingting Meng and Peter M. Athanas
Department of Electrical and Computer Engineering
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061
Email: {tmeng, athanas}@vt.edu

Abstract

Sensor networks can be used for various application areas such as health, military, and home. Research in collaborative methods and wireless communication has enabled the development of sensor networks. This paper presents a collaborative signal reinforcement scheme for sensor networks in which a cluster of mobile, independent and interchangeable nodes collaborate to send a message to a distant node. The presented scheme offers several advantages over contemporary solutions, including higher fault tolerance, power efficiency, scalability and lower complexity and cost. The primary emphasis of the paper is placed on a novel signal reinforcement modulation method that enables the collaborative scheme. Simulations are presented that validate this collaborative scheme. Furthermore, experimental results obtained from a laboratory hardware prototype are also presented in support of the presented methods.

1. Introduction

Sensor networks are becoming ubiquitous in a multitude of diverse applications, ranging from monitoring temperature and soil moisture levels for crop management, recording seismic activity for earthquake prediction, even monitoring troop movements on a battlefield. In sensor networks, messages are typically conveyed from a remote sensor network to a base station. Despite extensive research, reliable, power efficient communication remains an open problem in networked sensor nodes [1] [2].

The prevalent contemporary solution to this sensor network scheme is to utilize multi-hop ad-hoc techniques [3] [4] [5] to relay the message through the distributed network, ultimately reaching the querying base station. This solution is usually based upon the contemporary store-and-forward model for packet delivery. There are disadvantages to this approach; this strategy is not fair in regards to global energy distribution. The nodal power demands depend upon the network topology. Nodes closer to the base station tend to be burdened as relay nodes and would be subject to higher power drain, while other distant nodes may not participate at all in communications. Another solution is the distributed beamforming models [6] [7] [8], which emulate a centralized antenna array by a cluster of nodes. The disadvantage of this technique is that it presupposes not only accurate knowledge of the channel, but also time and phase synchronization at the transmitter.

The collaborative method presented here is not subject to the synchronization and location constraints of the existing approaches. Here, the energy burden is shared equally among all nodes. The receiver at the base station does not need to be aware of the number of nodes and the exact locations of each node in the network to receive messages properly. All nodes work collaboratively to send a single message from the sensor network to the base station site. The advantages of using this collaborative signal reinforcement method are as follows:

1) Fault Tolerance: All nodes are identical. The failure of any sensor node does not affect the functionality of whole sensor network system. A higher degree of fault tolerance is achieved.

2) Power Efficiency: The signal transport policy distributes energy equally across all participating nodes. Nodes in the cluster can use smaller, simpler, less powerful transmitters, reducing node size, weight, and power consumption.

3) Scalability: The number of sensor nodes and the density can range from few nodes to few hundred nodes in a certain region. The geometrical size of the sensor cluster is related to the range that a single sensor node can reach.

When a node has a message to transmit, a two-step process shown in Figure 1 is followed to convey this data in the form of a packet to the distant base station. In the first step, the message is conveyed to neighboring nodes. The node that is the source of the message is in *transmission* mode and the other nodes that are receiving the message are in *listening* mode. Once the message is present on all of the nodes in the cluster, all of the nodes transition into transmission mode, and the data are conveyed collaboratively in unison to the base station. To do so, all nodes transmit the information in a loosely synchronized manner and the signal waveforms of the individual transmitters are combined in a constructive manner, creating a reinforced waveform that can reach the distant base station.

The energy emanating from individual nodes may be insufficient to reach the distant base station; however, when combined with the energy emitted by the other nodes, the resulting waveform reaches sufficient strength.

There are two ways to make sure that the signals from the nodes reinforce each other instead of weakening or even canceling each other out. One way to accomplish this is to precisely synchronize all of the signals emanating from the sensor nodes. This requires extremely accurate spatial and temporal information of each node, which is in principle possible, but is difficult to achieve. The other way is to utilize a new class of waveforms that do not require precise synchronization. This paper focuses on the second approach.

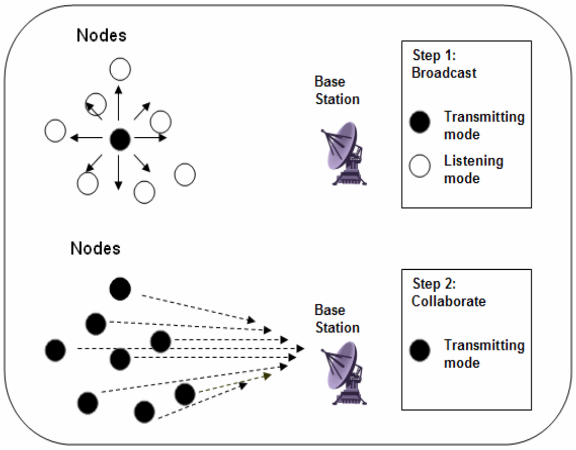

Figure 1. The process of collaborative signal reinforcement. In Step 1, one of the nodes broadcasts a message to others. In Step 2, all nodes transmit the message collaboratively to base station.

The rest of the paper is organized as follows. Section II introduces a new modulation scheme ensuring signal reinforcement for the collaborative scheme in sensor networks. Mathematical verification of the power gain is presented. Section III describes the prototype implementation of this collaborative method. The system design, performance simulation, and performance analysis are presented. The experimental results are described here. Sections IV and V present open issues in this research and concluding remarks, respectively.

2. Random phase shift keying

2.1 Description

Binary Frequency Shift Keying (FSK) is a common form of modulation. In binary FSK, the frequency of a constant-amplitude carrier signal is switched between two values according to the two possible message states, corresponding to a binary *1* or *0*. During each symbol time period, the frequency is fixed and the phase is continuous. However, the binary FSK signal waveform, as well as most signal waveforms, is not practical for collaborative signal reinforcement since the combination of two or more continuous sinusoidal signal waveforms with same frequency and different initial phases would not always constructively reinforce each other.

As shown in Figure 2, a new signal waveform, Random-Phase FSK (RPFSK), is introduced to achieve the combination and reinforcement. Here, each symbol is divided into multiple chips which have random initial phases but the same frequency. Some of these chips may cancel out when combining. However, the others will be enhanced by up to four times in power. As will be shown, the average power of the combined signal is

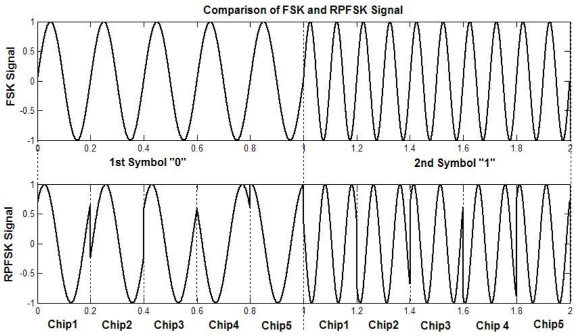

Figure 2. Comparison of FSK with RPFSK. RPFSK signals are divided into chips; each chip has a random initial phase.

N times as strong as a single-node signal, when *N* transmitting nodes work collaboratively. Figure 3 shows two RPFSK signal waveforms in the top two rows, and the combined waveform of the bottom one.

Equation (1) expresses a time domain representation of *M*-ary RPFSK signal waveforms. Mathematically, this can be expressed as

$$s_{RPPSK}(t) = A\cos(2\pi f_i t + \theta_k), \quad i = 1,2,\ldots,M \qquad k = 1,2,\ldots,K \tag{1}$$

where *K* represents the number of chips, *M* denotes the number of symbols, and θ_k denotes the phase offset for *kth* chip. The parameters *k* and *i* vary in chip rate and symbol rate separately. A given symbol duration is divided into multiple chips that each have a random initial phase of θ_k. The θ_k term, which is responsible for inserting random phase offsets, distinguishes RPFSK from FSK.

2.2 Mathematical Analysis

The above section describes how the RPFSK signals work collaboratively and states that the average power of the combined signal is *N* times as strong as a single node signal, when *N* transmitting nodes work collaboratively. In this section , the mathematical proof of the signal combination emphasizes one symbol period, therefore the frequency of signals expressed below is the same. The mathematical proof of the average power gain is shown below.

One single FSK signal with amplitude *A* is expressed as

$$S_{RPFSK}(t) = A\cos(2\pi f t + \theta), \tag{2}$$

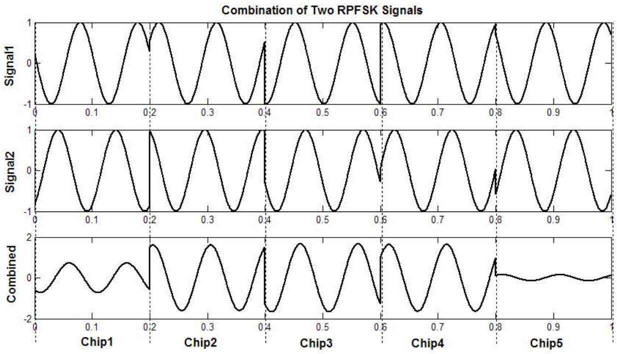

Figure 3. Combination of RPFSK signals from two transmitters. Each transmitter chooses a different initial phase for each chip. After combining, some chips are weakened and some are strengthened; on average, this produces a power gain that is equal to the number of transmitters.

where the initial phase θ is kept constant within a chip. Then the average power of this signal can be expressed as

$$P_{RPFSK} = \frac{1}{T}\int_{-T/2}^{T/2} S^2_{FSK}(t)\,dt = \frac{A^2}{2}. \tag{3}$$

Two signals combined in the wireless collaborative systems occupy different phases usually. When two single FSK signals with different phases add together, the combined signal is given by (4)

$$\begin{aligned} S_{combined}(t) &= A\cos(2\pi f t + \theta_1) + A\cos(2\pi f t + \theta_2) \\ &= 2A\cos\left(\frac{4\pi f t + \theta_1 + \theta_2}{2}\right)\cos\left(\frac{\theta_1 - \theta_2}{2}\right) \end{aligned}, \tag{4}$$

where θ_1 and θ_2 represents the different phases for the two signals and $(\theta_1 - \theta_2)/2$, ranging from *0* to π, is the phase shift between the two. The calculation of average power for this combined signal is as follows,

$$P_{combined} = \frac{1}{T}\int_{-T/2}^{T/2} S^2_{combined}(t)dt = 2A^2\cos^2\left(\frac{\theta_1 - \theta_2}{2}\right). \tag{5}$$

Given that the value of *cos(.)* ranges from *0* to *1*, the reliability of the average power for the combined signals is poor. No detector can make reliable decisions depending on this time-varying power value. However, since the RPFSK signals consists of multiple chips which have different initial phases, the value of phase shifts in one symbol period varies, and the probability of each phase shift value is uniform distributed since the initial phase selection of each chip is totally random. The phase shift $(\theta_1 - \theta_2)$ of two RPFSK signals is uniformly distributed from *0* to 2π and $\delta = (\theta_1 - \theta_2)/2$ is uniformly distributed from *0* to π.

Hence, the average power of two random phase RPFSK signals can be expressed as (5)

$$P_{average} = \int_0^{\pi} P_{average}(\delta)d\delta = A^2\int_0^{\pi}(1 + \cos 2\delta)d\delta = A^2 \tag{6}$$

The average power of two combined random phase RPFSK signals (6) is two times as strong as that of a single signal (3). Similarly, it can be proven that the average power of *N* combined random phase FSK signals is *N* times as strong as a single-node signal.

3. Implementation

3.1 Transmitter/ Receiver Design

Figure 4 shows the design of the transmitter; f_1 and f_2 are two frequencies that map to a binary *1* and *0* respectively. A multiplexer selects the output signal between the two corresponding signals according to the transmitting symbol. For each chip, the initial phase

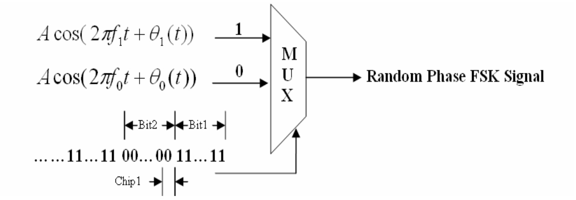

Figure 4. The block diagram of a random phase FSK modulator.

value θ_k is randomly chosen. The RPFSK transmitter is similar to the traditional FSK transmitter. The major difference is that the RPFSK transmitter selects the output signal chip by chip instead of bit by bit.

A block diagram of a non-coherent detection scheme for the receiver of binary RPFSK signals is shown in Figure 5. Due to the random phase scheme, the non-coherent reception is the only choice. There are two reception stages in the non-coherent receiver. First is the chip synchronization which utilizes the hypothesis testing scheme. As shown in Figure 6, one *480*-sample long First in First out (FIFO) queue stores *12* hypothesized chips. All input samples go through this FIFO. In each clock cycle, every *40* samples for each hypothesized chip are summed coherently. Then the chip-sums of total *12* chips are non-coherently added together. The chip synchronization is achieved while the total sum of the *12* chips has the maximum value. The second stage is bit detection. After the chip synchronization is achieved, the decision (*'1'* or *'0'*) of each chip is input to a windowing pipeline to remove the event or short-burst chip errors. Finally, bit decision can be made depending on the majority of the windowed chip decisions.

Here, an important issue in RF modem design must be addressed. A common method for architecting an RF modem is the use of double side band (DSB) amplitude modulation (AM). However, if this is applied to this proposed system, cancellation may occur at the RF level; hence, the single side band (SSB) AM modulation is preferred for avoiding the carrier level cancellation.

3.2 Simulation

The simulations of binary RPFSK signal reinforcement have been studied comprehensively using Matlab. An Additive White Gaussian Noise (AWGN) channel is assumed as the interference environment. A conventional Binary Frequency Shift Keying (BFSK) system with the same transmitting power of a single node is chosen as the baseline for this investigation. Each node accepts 20 chips per symbol.

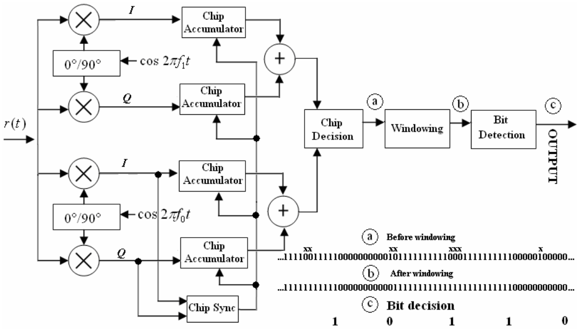

Figure 5. The block diagram of the non-coherent random phase FSK receiver.

Figure 7 shows the Bit Error Rate (BER) performance of RFPSK signal reinforcement with different numbers of collaborative nodes. It is obvious that the system performance improves as the involved nodes increase when ideal synchronization of the symbols is assumed for the transmitters. Although the performance of a single-node RPFSK system is worse than the performance of a single-node BFSK system, the performance of more than two RPFSK nodes exceed that of a single BFSK node, assuming every node has the same power output. Since the RPFSK system processes the received samples chip by chip instead of symbol by symbol, fewer samples are accumulated as a group than BFSK system and the cancellation among the noise portion of the samples are weaken. Hence, the performance of a single-node binary RPFSK is worse than that of the baseline.

The relationship between the performance and the chip-to-symbol ratio has been studied. In Figure 8, the BER performances of binary RPFSK with different chip-to-symbol ratios are observed. The single-node performances with the chip-to-symbol ratios of *10*, *20* and *25* are presented as well as the dual-node performances with the chip-to-symbol ratios of *10*, *20* and *25*. In Figure 8, the single-node system with lower chip-to-symbol ratio achieves better BER performance

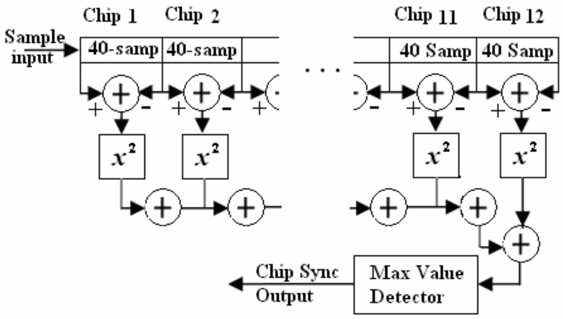

Figure 6. The block diagram of chip synchronizer in receiver.

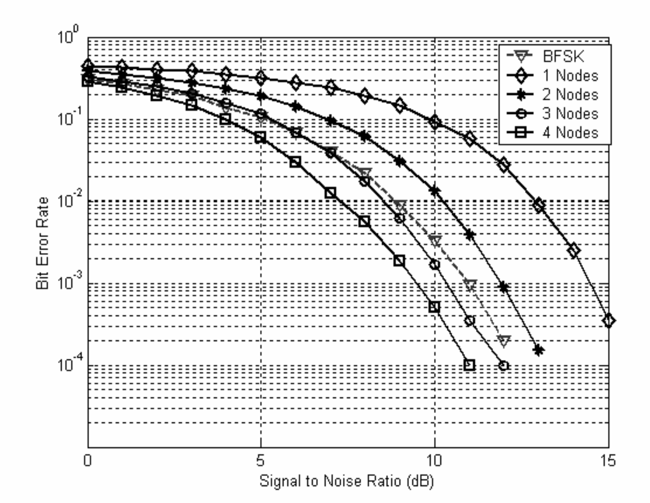

Figure 7. BER performance of RPFSK with different node number. The more nodes work together, the better performance systems can achieve.

since the higher chip-to-symbol ratio causes higher noise power in the chip-by-chip processing scheme. However, in the dual-node cases, the trend of performance curves is a bit complex. In the lower SNR environment, the system with the lower chip-to-symbol ratio has better performance. In the higher SNR environment, the performances trend of the three dual-node case is reversed. This is due to the fact that a higher chip-to-symbol ratio system produces a more stable combined signal power, though it produces less noise power.

Two major factors, SNR and the stability of combining power gain, affect the BER performance of dual-node system. When the SNR is low, the errors caused by noise are much more than the errors cause by the unstable combining power gain. Hence the lower chip-to-symbol ratio case yields better performance. When SNR is high, the errors caused by the unstable combining power gain are the dominant factor of errors. Therefore, the higher chip-to-symbol ratio case has better performance. According to this, the optimization of the system performance is possible.

Since ideal synchronization is impossible, signal delays between each node always exist. Figure 9 investigates how the different delays affect to the system performance. Three different delays are simulated and they are *10%*, *25%*, *50%*, *100%* and *200%* of the chip period, respectively. The *10* chips per symbol setting was chosen in this investigation. Interestingly, more delay between the nodes does not worsen performance. Instead, the worst case is the *50%* chip period delay case. The *100%* and *200%* chip period delay cases have almost the same performance as the zero delay case. Even in the worst case, the performance is still quite acceptable.

3.3 Experimental Results

A hardware prototype has been built to validate these concepts. The laboratory sensor network consists of a base station and two sensor nodes. The functionality of each is implemented in a Xilinx University Program (XUP) board, which includes a Virtex-II Pro 30 FPGA.

The Friis free-space propagation model [10] (7) is introduced here to validate our experiment. P_t is the transmitted power, P_r is the received power, G_t is the transmitter antenna gain, G_r is the receiver antenna gain, d is the transmission distance, the L is the system loss factor not related to propagation, and λ is the wavelength:

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \tag{7}$$

According to (7), when the values of G_t, G_r, λ, and L are fixed, the received power P_r only depends on the transmitted power P_t and transmission distance d. When the two nodes provide two times power of a single node, the transmission distance is increased by 1.41 times ideally; with the receiver maintaining the same received power. In this experiment, when two sensor nodes work collaboratively using the RPFSK modulation method and the proposed scheme, the transmission range is increased by 30% compared to

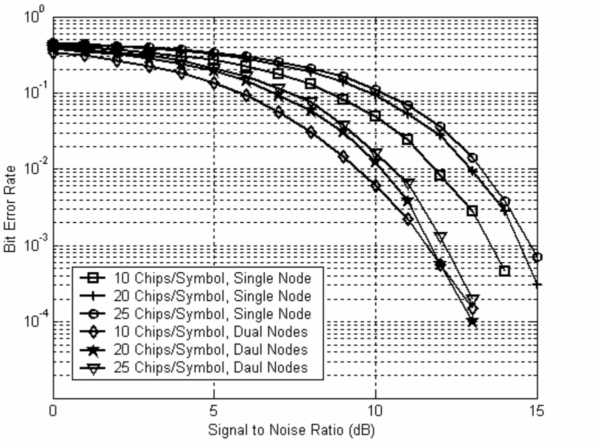

Figure 8. BER performance of RPFSK with different chip-to-symbol ratios. In three single-node cases, the lower chip-to-symbol ratio produces better performance. In the dual-node cases, the three curves cross each other at higher SNRs.

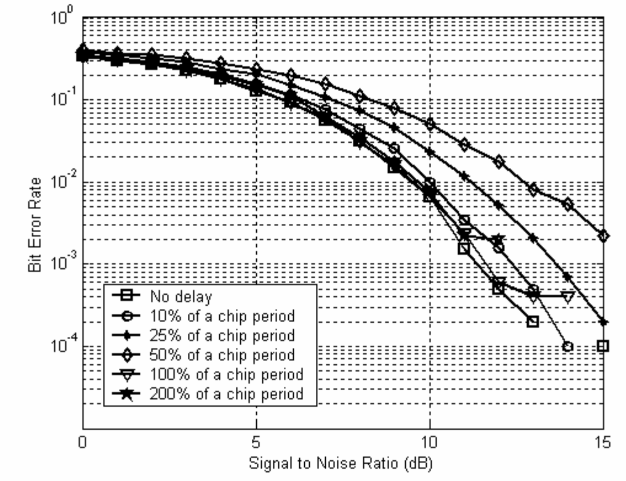

Figure 9. BER performance of RPFSK with different signal delays. The delay will affect the performance. The performance is not getting worse as the delay between nodes increases. The half of a chip period delay case is the worst case. The *100%* and *200%* of a chip period delay cases have almost the same performance as the zero delay case.

the range of a single.

4. Future work

The parameter optimization for some specific cases will continue based on the current work. Optimal cluster size for specific environments will be explored. Hybrid systems based on the RPFSK modulation method will be investigated for the performance improvement. The exploration of more beneficial waveforms for signal reinforcement in sensor network will continue.

5. Conclusion

The flexibility, fault tolerance, and power efficiency characteristics of sensor networks create many exciting application areas for remote sensing. This paper provided a new collaborative signal reinforcement scheme to solve the power efficiency, fault tolerance and scalability issues. The key idea, RPFSK modulation, makes the direct signal waveform reinforcement possible and demonstrates experimentally that collaboration in sensor network can be done using new signal waveforms and modulation methods. The work proposed in this paper also can be combined with existing cooperative methods [11] [12] in wireless sensor networks.

6. Acknowledgement

This work was supported by the Office of Naval Research under contract N00014-05-1-0179.

7. References

[1] G. D. Culler, D. Estrin, and M. Srivastava, “Overview of sensor networks,” *IEEE Computer*, vol.37, no. *8, pp.41-49, Aug.2004.*

[2] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, “ A survey on sensor networks, ” *IEEE Commun. Mag.*, pp. 102 – 114, Aug. 2002.

[3] R. C. Shah and J.M. Rabaey, “Energy aware routing for low energy ad hoc sensor networks,” *IEEE WCNC2002,* vol.1, pp. 350-355, Mar. 2002.

[4] C.G. Cassandras and Wei Li, “Sensor networks and cooperative control,” 44th *IEEE Conference on CDC-ECC '05*, pp. 4237-4238, Dec. 2005

[5] A. Bletsas, A. Khisti, D.P. Reed and A. Lippman, “A simple cooperative diversity method based on network path selection,” *IEEE Journal*, *Communications,* vol. 24, no. 3, pp. 659 - 672, March 2006.

[6] G. Barriac, R. Mudumbai, and U. Madhow, “Distributed beamforming for information transfer in sensor networks,” *Third International Symposium on Information Processing in Sensor Networks*, *2004. IPSN 2004,* pp.81-88, Apr.2004.

[7] M. Tummala, Chan Chee Wai, and P.Vincent, “Distributed beamforming in wireless sensor networks,” *Conference Record of the Thirty-Ninth Asilomar Conference on Signals, Systems and Computers*, *2005*, pp. 793 – 797, Oct. 28 – Nov. 1 2005

[8] S. A. Jafar and A.Goldsmith, “On optimality of beamforming for multiple antenna systems,” *IEEE International Symposium on Information Theory.* Washington, DC, pp. 321, Jun. 2001.

[9] A. Host-Madsen, “Capacity bounds for cooperative diversity,” *IEEE Trans on Information Theory*, vol.5, pp.1522 - 1544, Apr. 2006.

[10] T. S., Rappaport , *Wireless communications, Principles and Practice,* 2nd ed., NJ: Prentice Hall, 1996.

[11] J. N. Laneman , D. N. C. Tse, and G. W. Wornell, “Cooperative diversity in wireless networks: Efficient protocols and outage behavior,” *IEEE Trans on Information Theory*, vol. 50, no. 12, pp. 3062-3080, Dec. 2004.

[12] A. Nosratinia, T.E. Hunter and A. Hedayat, “Cooperative communication in wireless networks,” *IEEE Comm. Mag.*, vol. 42, pp. 74-80, Oct. 2004.