On the Improvement of Wireless Sensor Networks Using Modulation Diversity and Fuzzy Clustering

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***Abstract*— In this paper the authors propose an integrated system to increase the lifetime and decrease the packet loss rate in wireless sensor networks. That goals are reached by the use of the normalized fuzzy election and the modulation diversity techniques. The simulation results show the performance improvements of the proposed system, compared with simple fuzzy election and modulation.**

***Index Terms*— Fuzzy clustering, modulation diversity, performance improvement, wireless sensor networks.**

I. Introduction

The technology of wireless sensor networks (WSN) has been used in automatic monitoring of a wide variety of environments [1]. In 2006, the importance of this technology was recognized by the release of the IEEE 802.4.4-2006 standard, which specifies the physical and medium access control layers of personal wireless networks with low data rate transmission (LR-WPANs) and the publication of the ZigBee specification for a set of high level applications using small low-power digital radios based on the IEEE 802.15.4-2003 standard. The rapid progress of research in efficient energy data management and security in sensor networks and the need to compare research results with the solutions adopted in the standards, led to the emergence of several contributions in this area.

Despite the potential applications of wireless sensor networks, there are many problems that need to be treated so that they can operate efficiently in practical applications. An important problem in a sensor network is the control of its topology, since most sensors are equipped with non-rechargeable batteries and density sensors used in practical applications is high. The control of topology is needed to reduce power consumption and extend the lifetime of the network, meeting certain applications requirements [2]. Another relevant aspect of each model is the sensor transmission range of each node, the synchronization in time, fault model and the location information of sensors in the network.

Related to project objectives, some of the main goals are to maximize the network lifetime and balancing of energy consumption, optimization of the coverage of sensors, improve performance tracking and tracing, optimization of network connectivity and maximizing the transmission data rate. The lifetime has been an extensively studied subject and literature has provided various methods that can be used to maximize the lifetime of sensor networks.

Concern over the network lifetime has also encouraged some researchers to look for more long-lasting batteries [3]. In [4], for example, a system is presented for management and storage of energy that contributes to prolong battery lifetime and its miniaturization, making them suitable for use in networks of autonomous wireless sensors. It presents a management strategy to achieve the appropriate power release by using a management unit composed of several converters power capable of operating in bidirectional mode. The power converters, developed from structures of carbon nanotubes, provide the possibility of emergence of power supply fully integrated into the sensor chip, helping to increase the autonomy of future networks.

Cluster-based protocols are successful methods for energy saving, in which the nodes form clusters [5]. In clustered schemes, the cluster head election process is a fundamental issue and impacts significantly in the network energy consumption. Some of the clustering algorithms employ fuzzy logic [6], [7] to handle uncertainties in the wireless sensor networks, which can extend the network lifetime. By considering the fuzzy variables *Energy* and *local distance*, the CHEF protocol [8] defines the variable *chance*, which indicates the probability of a node to elect itself as a cluster head. Therefore, the protocol can elect the optimal cluster heads at that round and extend the network lifetime.

Apart from the limited resources, the fading caused by multipath can significantly degrade the performance of the communication systems in WSNs. Diversity techniques can improve the performance of those systems, since replicas of the transmitted signals are provided to the receiver sink node. However, the application of diversity techniques by the use of multiple antennas, could be impractical in a wireless sensor network, because of the size of the sensor nodes and the energy constraints present in the network [9], [10]. In order to overcome this limitation, the modulation diversity [11] technique can be used to combat the channel fading effects, since it inserts redundancy by the choice of the reference angle of a MPSK constellation, combined with the independent interleaving of the transmitted component symbols. That technique has the advantage of a lower energy dissipation and decreases the bit error rate.

In this paper, the authors propose an integrated system to increase the lifetime and decrease the packet loss rate in wireless sensor networks. That goals are reached by the use of the normalized fuzzy election and the modulation diversity techniques. The performance evaluation deals with the comparison between the proposed system and the original CHEF, at the clustering phase, and simple QPSK modulation at data transmission phase.

II. Fuzzy Clustering with Normalized CHEF

Fuzzy logic is a well suited approach for dealing with uncertainty of measurements performed in communication systems, which are affected by errors in precision and accuracy. In WSN applications, another important advantage in the use of fuzzy logic is that it typically requires few computational resources [12].

In fuzzy logic, decisions are based on *fuzzy inferences*. The fuzzy inference process operates on IF-THEN *propositions* or *production rules*, which are used to determine the value of output variables using approximate reasoning [7]. IF conditions are composed using predicates of the form “X is A”, in which X is a linguistic variable (*e.g.*, SNR, energy, delay) and A is a linguistic term (*e.g.*, high, low, very low), and logical operators (AND, OR and NOT), while THEN statements are commonly basic predicates indicating the fuzzy output attribute.

In the CHEF protocol, the nodes calculate the value of the variable *chance* using fuzzy IF-THEN rules [8] and advertises a message for candidates denoted as *Candidate_Message*, which contains the variable *chance*. It means that the sensor node is a candidate for the cluster head with the value of *chance*. Once a node advertises a *Candidate_Message*, it waits *Candidate_Message* from other nodes. If the *chance* of itself is bigger than every *chance* from other nodes, the sensor node advertises a cluster head message denoted as *CH_Message* which means that the sensor node itself is elected as the cluster head. If a node which is not a cluster head receives the *CH_Message*, the node selects the closest cluster head as its coordinator and sends a message to join that cluster, denoted as *Cluster_Join_Message*.

To calculate the value of *chance*, CHEF uses two fuzzy sets and fuzzy IF-THEN rules. The first fuzzy variable used to determine the *chance* is the energy remaining in the node. The second variable is *local distance*, that is the sum of distances between the candidate node and other nodes which are within a specific range [8].

Energy has more precedence than *local distance*, as shown in the fuzzy IF-THEN rules represented in Table I. The bigger *chance* means that the node has more probability to be a cluster head. For example, in Rule 3 the node has low energy and the sum of distances between the candidate node and other nodes is a low value (the other nodes are close). Then, the chance to be elected as a cluster head is Rather Low. On the other hand, in Rule 7 the node has high energy and *local distance* is a large value (the other nodes are less concentrated). Then, the chance to be elected as a cluster head is Rather High. This is because that *Energy* is more important than the *local distance*. The fuzzy variable *chance* is defuzzified (transformed to a crisp number) by the use of the Center of Area (CoA) method. The mathematical expression for CoA and the membership functions utilized for the fuzzy variables can be found in [8].

TABLE I
Fuzzy IF-THEN Rules [8]

Rule	IF		THEN
	Energy	**Local Distance**	**Chance**
1	Low	Far	Very Low
2	Low	Medium	Low
3	Low	Close	Rather Low
4	Medium	Far	Medium Low
5	Medium	Medium	Medium
6	Medium	Close	Medium High
7	High	Far	Rather High
8	High	Medium	High
9	High	Close	Very High

For the cluster head election, the proposed system improves the CHEF protocol, by the normalization of *local distance*. In original CHEF, if there are few nodes within a specific radius of transmission, the sum of distances between the candidate node and other nodes can be small. In this case, one may infer, erroneously, that the energy consumption of nodes is lower than in the case in which the nodes, in a higher number, are located closer to the candidate node. The proposed scheme overcomes this drawback, with the normalization of that sum by means of division of *local distance* by the number of nodes that are within the specific radius of transmission.

III. Modulation Diversity

Modulation diversity is a technique used to combat the channel fading effects, since it inserts redundancy by the choice of the reference angle of a MPSK constellation, combined with the independent interleaving of the transmitted component symbols. That technique has the advantage of a lower energy dissipation and decreases the bit error rate.

If an original QPSK constellation is rotated by a certain angle, a kind of redundancy between the two quadrature channels is introduced and the system can take advantage of the derived diversity. Then, after the aggregation phase, the elected cluster head of each cluster rotates the constellation by an angle θ:

$$\begin{aligned} s(t) &= A\sum_{n=-\infty}^{+\infty} x_n p(t-nT_s)\cos(2\pi f_c t), \\ &+A\sum_{n=-\infty}^{+\infty} y_n p(t-nT_s)\sin(2\pi f_c t), \end{aligned} \tag{1}$$

in which

$$\begin{aligned} x_n &= a_n\cos\theta - b_n\sin\theta, \\ y_n &= b_n\sin\theta + b_n\cos\theta. \end{aligned}$$

The constant phase θ is selected in such a way that the squared Euclidean distance between QPSK signal constellations is maximized for both components, inphase and quadrature [13].

Quadrature components are generated and each component is independently interleaved. The signal interleavers are chosen such that after deinterleaving, the two components will be independent. The two components are then upconverted to the carrier frequency and added. The transmitted signal from the elected cluster-head is

$$s_s(t) = A \sum_{n=-\infty}^{+\infty} x_n p(t - nT_s) \cos(2\pi f_c t) \quad (2)$$

$$+A \sum_{n=-\infty}^{+\infty} y_{n-k} p(t - nT_s) \sin(2\pi f_c t), \quad (3)$$

in which k is an integer representing the time delay in number of symbols introduced by interleaving between the I and Q components.

Figure 1 presents the bit error rate comparison between transmissions using simple QPSK, and QPSK with modulation diversity, for a rotation angle $\theta = 27°$.

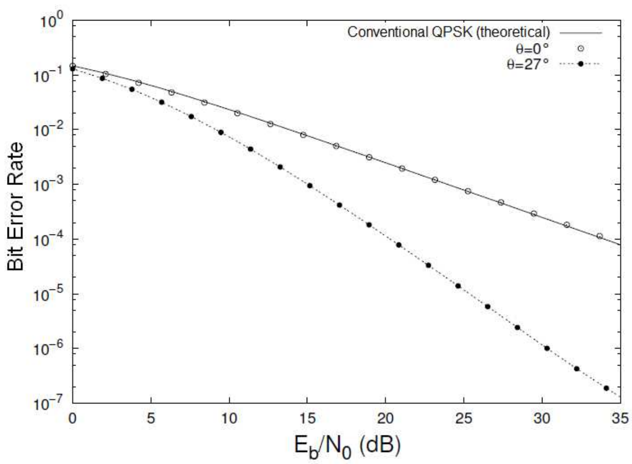

Fig. 1. Bit error rate for the modulation diversity scheme.

A. The Channel Model and the Decoding System

Consider a communication channel with frequency nonselective slowly fading with a multiplicative factor representing the effect of fading and an additive term representing the AWGN channel. The received signal in the sink node is

$$r(t) = \alpha(t)s(t) + n(t), \quad (4)$$

in which $\alpha(t)$ is modeled as zero-mean complex Gaussian process. At the sink node, $r(t)$ is first downconverted to baseband. The obtained signal (equivalent lowpass) in one signaling interval, at the sink node is

$$r_l(t) = \alpha_n e^{-j} \phi_n s_l(t) + z(t), \quad nT_s \leq t \leq (n+1)T_s, \quad (5)$$

in which $z(t)$ represents the complex white Gaussian noise, α_n is the fading amplitude (considered constant over one symbol interval), ϕ_n is the phase shift due to the fading channel, and $s_l(t)$ corresponds to the equivalent low pass of the transmitted signal $s(t)$ [13]. With the phase shift estimation of the received signal and after the demodulation, the received vector is given by

$$\tilde{\mathbf{r}}_n = \alpha_n \mathbf{s}_n + \mathbf{z}_n, \quad (6)$$

in which $\mathbf{s}_n$ is the vector representation of the transmitted signal at time nT_s

$$\mathbf{s}_n = x_n + j y_{n-k} \quad (7)$$

and the elements of the complex vector $\mathbf{z}_n$ are independent identically distributed Gaussian random variables with zero mean and variance $N_0/2$.

The decoded vector at the sink node, after the deinterleaving process, is

$$\mathbf{r}_n = \alpha_n x_n + \text{Re}\{\mathbf{z_n}\} + j[\alpha_{n+k} y_n + \text{Im}\{\mathbf{z_n}\}] \quad (8)$$

which is then processed using symbol-by-symbol detection. The optimum demodulator, at the sink node, computes the squared Euclidean distance between the received vector and each of the four signal vectors of the QPSK scheme and then decides in favor of the one closest to $\mathbf{r}_n$ [11].

IV. Simulation Results

The simulated sensor network is composed of 100 nodes. The nodes are deployed randomly on an area of 50×50 meters. The sink node is located at the coordinates $x = 25$ and $y = 150$ meters. It is assumed that each node has an initial energy of 3 mJ. The dissipation radio model used for the simulations was proposed in [14]. The radio dissipates $\epsilon_{\text{elec}} = 50$ nJ/bit to run the transmitter or receiver circuitry and $\epsilon_{\text{fs}} = 10$ pJ/bit/m^2, or $\epsilon_{\text{mp}} = 0.0013$ pJ/bit/m^4 for the transmitting amplifier to achieve an acceptable $\frac{E_b}{N_0}$. Consider d_0 as a specific threshold distance, given by

$$d_0 = \sqrt{\frac{\epsilon_{\text{fs}}}{\epsilon_{\text{mp}}}}. \quad (9)$$

Thus, to transmit a κ-bit message at a distance d using the radio model, the radio spends

$$E_{Tx}(\kappa, d) = \begin{cases} \kappa \cdot (\epsilon_{\text{elec}} + \epsilon_{\text{fs}} \cdot d^2), & \text{if } d \leq d_0 \\ \kappa \cdot (\epsilon_{\text{elec}} + \epsilon_{\text{mp}} \cdot d^4), & \text{if } d > d_0 \end{cases} \quad (10)$$

and to receive this message, the radio spends:

$$E_{Rx}(\kappa) = \epsilon_{\text{elec}} \cdot \kappa. \quad (11)$$

The proposed protocol integrates the advantages of the normalized CHEF and of the modulation diversity scheme, with the goals of reduce and fairly distribute the overall energy consumption in the network and enhance the quality of transmissions. A comparison between the proposed system and the original CHEF (with simple QPSK) is utilized in the performance evaluation. Both systems use a truncated ARQ scheme and a CRC with $C = 16$ bits is assumed with a cyclic generator polynomial of $\mathsf{G}_{\mathsf{CRC16}}(D) = D^{16} + D^{12} + D^5 + 1$. The maximum number of retransmissions in the simulations is $N_r^{\mathsf{max}} = 4$ and all algorithms were implemented using Matlab 7.

Four different propagation environments were used for the simulations, according to the random SNR distribution range of the propagation paths. After the random choose of the propagation scenario by the network simulation, a random SNR value, within a range that depends on the propagation scenario, is specified to each cluster head. The first scenario comprehends the following SNR range: [4 8 12 16 20] dB. These values are attributed randomly to each path between the respective cluster head and the sink node, in each round. The other SNR range scenarios, are shown in Table II. It is expected that the best performances can be reached as long as the last scenarios become the transmission option adopted for the simulation, because it is more probable the choose of higher SNR values and so, they have better propagation conditions than the first.

TABLE II
SNR RANGE SCENARIOS.

Scenario	SNR range (dB)
One	[4 8 12 16 20]
Two	[5 10 15 20 25]
Three	[6 12 18 24 30]
Four	[7 14 21 28 35]

The simulated sensor network is illustrated in Figure 2. The five cluster heads are represented by circles and aggregate the sensed information of the other sensors, in the respective clusters. That aggregation process is illustrated in Figure 3. The figures show that by the use of normalized CHEF as election technique, the cluster heads are well positioned, which contributes in saving overall energy. The extension of lifetime can be verified in Tables III and IV, in which, for all the propagation scenarios, the proposed scheme overcomes the original CHEF protocol, for the first dead node as much as for the last dead node evaluation. The election of the most prepared nodes to cluster heads and the avoiding of excessive retransmissions, by the efficient use of modulation diversity for correct delivering the packets, are the main reasons of that performance superiority.

TABLE III
AMOUNT OF ROUNDS FOR THE FIRST DEAD NODE.

Scenario	Rounds for the first dead node	
	CHEF	Proposed scheme
One	35	42
Two	48	56
Three	59	71
Four	68	93

Figures 4 and 5 present the performance evaluation related to the energy-balancing, for the round operation of number 50, in scenario four. The proposed scheme shows a distribution of residual energy more uniform than the CHEF protocol. Besides the energy-balancing evaluation, the level of node energy presented in the figures, reinforce the superiority of the proposed scheme in maximizing the network lifetime, since light colors indicate more residual energy.

TABLE IV
AMOUNT OF ROUNDS FOR THE LAST DEAD NODE.

Scenario	Rounds for the last dead node	
	CHEF	Proposed scheme
One	96	111
Two	114	134
Three	128	153
Four	141	172

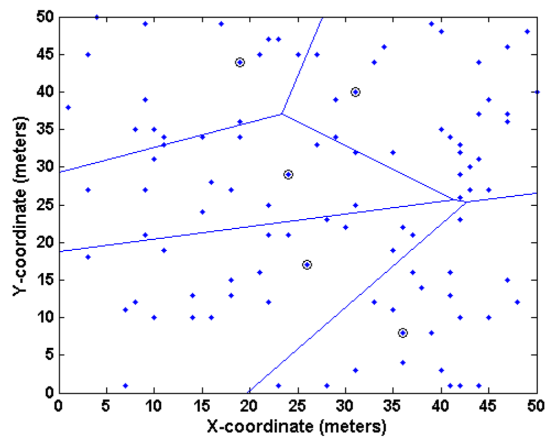

Fig. 2. Five cluster heads (represented in circles) elected by the normalized CHEF algorithm.

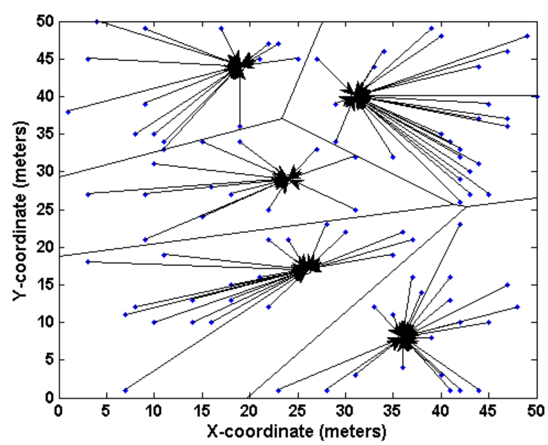

Fig. 3. The aggregation process, which reduces the required amount of information to be transmitted to the sink node.

The overall packet loss rate (PLR) of the sensor network is given by

$$\texttt{PLR} = \frac{\texttt{Number of lost packets}}{\texttt{Number of generated packets}} \tag{12}$$

and it is evaluated in Table V, as a function of the four propagation conditions. As expected, the packet loss rate decreases as the the channel quality becomes better. For all the scenarios, the proposed scheme presents better performance. The average packet loss rate for the former system is equal

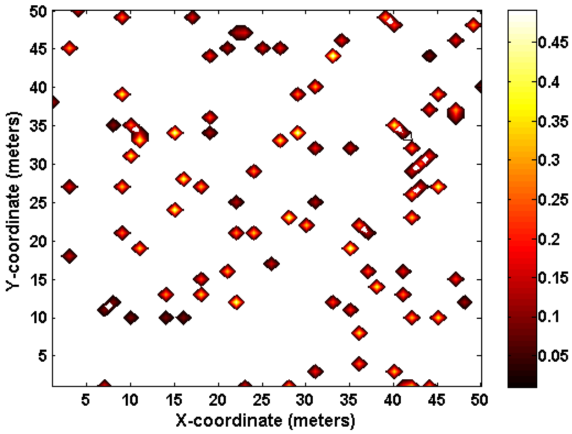

Fig. 4. Residual energy distribution in the sensor network, using the original CHEF protocol, with simple QPSK. An unbalanced distribution of energy can be verified.

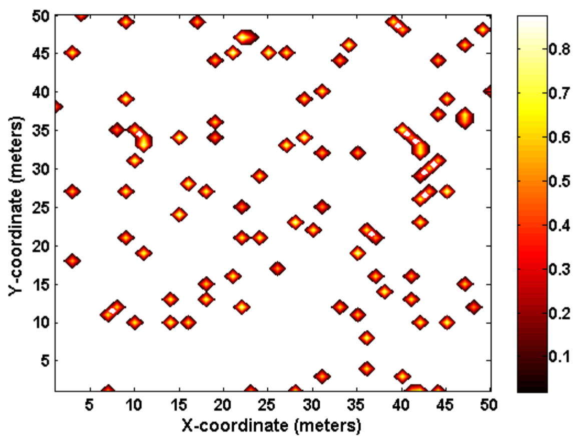

Fig. 5. Residual energy distribution in the sensor network, using the normalized CHEF protocol, with modulation diversity. The proposed scheme presents an energy-balanced performance along the network.

to 0.1329 and for the latter, is equal to 0.4547, that, it is approximately 3.5 times bigger.

TABLE V

OVERALL PACKET LOSS RATE.

Scenario	Packet loss rate	
	CHEF	Proposed scheme
One	0.6033	0.1861
Two	0.5746	0.1415
Three	0.4129	0.1103
Four	0.2281	0.0937

V. CONCLUSION

This paper proposed an integrated system for improving the performance of wireless sensor networks, related to the metrics network lifetime and packet loss rate. The system combines the fuzzy operation of normalized CHEF and modulation diversity technique. The fuzzy clustering elects the most prepared nodes, prolonging the network lifetime and balancing the energy consumption along the network. Furthermore, by the use of the modulation diversity for combating the fading channel effects, the network can decrease the packet loss rate, and thus, reduce the number of retransmissions required to correct deliver the packet, which also increase the network lifetime.

In the future, the authors intend to adapt the proposed system to multi-hop wireless sensor networks. This is specially desired if the sink node is not within the range of all the nodes.

ACKNOWLEDGMENT

The authors would like to thank Iecom, UFCG, CNPq for supporting this research.

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