A Self-Organizing Wireless Sensor Network for Industrial Monitoring

Zafar Iqbal and Heung-No Lee
School of Electrical Engineering and Computer Science,
Gwangju Institute of Science and Technology
1 Oryong-dong, Buk-gu, Gwangju 61005, South Korea
E-mails: {zafar, heungno}@gist.ac.kr

Abstract: Recently, industrial wireless sensor networks (IWSNs) have been widely used for monitoring the state of heavy machinery and large factories whose condition is critical to the operation of machine as well as the safety of people around them. However, the wireless communication channels, which these sensors must operate in, are not always reliable, and observations of some sensors cannot be reported successfully to the base station. In order to deal with this problem, we propose a cooperative WSN scheme, which organizes itself into groups of cooperation nodes and then start normal operation. The proposed scheme effectively increases the probability of correct decision about the state of the industrial area, and reduces the probability of false alarms at a given signal level. We also propose a novel cooperation protocol that uses the minimum number of transmissions for delivering the cooperative sensing information to the base station, thereby, reducing the overall traffic and energy usage of the network.

Keywords—**self-organizing network, industrial wireless sensor networks, cooperative communication, environment monitoring, fusion, majority rule.**

1. Introduction

Wireless sensors are widely used for machine health monitoring and maintenance, especially the machines which are located in inaccessible areas or are hard to be monitored by human, such as nuclear plants, unmanned underwater vehicles (UUVs), or in large factories. In addition, wireless sensors are also used for environmental monitoring, surveillance, health-care, and security services [1]. The quality of a wireless communication link is very important for transmitting the information collected by the sensors to a central signal processing unit without significant amount of error. A bad communication link results in higher energy consumption because of repeated transmissions by the nodes or by using higher transmit power, and lower overall throughput of the network. Similarly, the amount of data transmitted by the network nodes and the amount of processing at the receiver also contributes towards the energy consumption per bit of the network.

Recently, a number of techniques have been developed to use cooperation in wireless communication which include diversity cooperation and coded cooperation schemes. One of the most widely used techniques is network coding, which uses the idea of cooperation among nodes in the wireless communication network [2]-[4]. Some solutions specifically proposed for cooperative IWSNs include [5], [6].

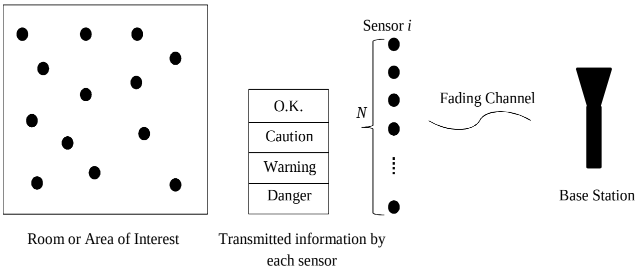


Figure 1. Sensor information and communication to BS.

We propose a new two-phase user cooperation scheme for WSNs in indoor environment that has heavy machinery and harsh wireless characteristics. All the sensors in a cooperation group share their information with each other in the first phase and send the cooperative information to the base station (BS) in the second phase. Our purpose is to achieve highly accurate decision at the base station, for which the network is deployed. The results of cooperative WSN will be compared with those of the non-cooperative network to observe the differences and benefits achieved from cooperation.

2. Network Design

We consider and indoor factory environment which contains office area as well as machinery area. Fig. 1 shows the general scenario where a room or area of interest is covered by N number of nodes. The sensors are used to sens the surrounding area and send the result to the base station. Each node sends four types of information to the base station as shown in Fig. 1. All this information from each sensor is combined at the base station to arrive at a single result on the state of the machine covered by those sensors. Our aim is to achieve a highly accurate decision at the base station to enable correct response mechanism.

In our case of machine health monitoring, the sensors could be deployed according to a pre-planned location map over the entire area of concern. We use the static triangular-grid deployment scheme [7] for the deployment of sensor network and each node maintains a neighbor list of a certain number of sensors [8]. We consider a medium-sized WSN with mostly indoor or line-of-sight configurations; therefore we will use the basic radio propagation model for indoor wireless communication channel [9]. The wireless nodes are clustered into different cooperation groups by their geographic locations. The cooperative transmission is done within each cooperation group, $\mathcal{V} = \{V_i\}_{i=1}^{\mathcal{N}}$, where $\mathcal{N}$ is the maximum number of nodes in a cooperation group.

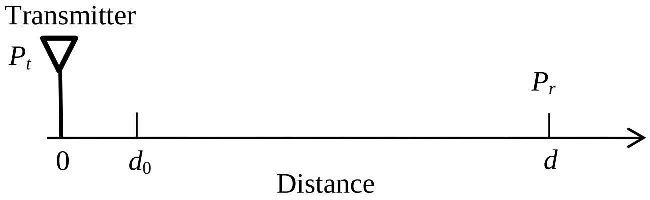


Fig. 2. Calculation of received signal strength

2.1 Received Signal Strength

In order to find the received signal strength at each sensor from all other sensors in the cooperation group, we use the log distance path loss or lognormal shadowing model. This is a generic model used to predict the propagation loss for a wide range of environments including free space and indoor factory environments.

The path loss measured in dB at a distance d from the transmitter is given by,

$$PL_{dB}(d) = PL_{dB}(d_0) + 10\eta \log_{10}\left(\tfrac{d}{d_0}\right) + X_{\sigma,dB} \qquad (1)$$

where PL_{dB} is the path-loss in dB, η is the path-loss exponent indicating the rate of decay of the mean signal with respect to distance, d_0 is a reference distance, and $X_{\sigma,dB}$ is a zero-mean Gaussian random variable with standard deviation σ. In (1), $PL_{dB}(d_0)$ is the path loss in dB at a reference distance d_0, which is calculated using the Friis free-space propagation model. It is used to model the line-of-sight (LOS) path loss incurred in the channel, given as

$$P_r\left(d_0\right) = P_t \frac{G_t G_r \lambda^2}{\left(4\pi d_0\right)^2 L} \qquad (2)$$

where $P_r(d_0)$ is the received signal power in Watts, P_t is the transmitted signal power in Watts, G_t and G_r are the gains of transmitter and receiver, respectively. λ is the wavelength of the carrier in meters, and L is the system losses which are not associated with propagation loss. Generally, it is more convenient to work in log domain because the transmit and receive power are usually available in dBm and the antenna gains in dBi. Therefore, the Friis free-space equation is given in log domain as,

$$\begin{aligned} PL_{dB}\left(d_0\right) &= P_{t,dB} + 10\log_{10}\left(G_t\right) + 10\log_{10}\left(G_r\right) \\ &\quad + 20\log_{10}\left(\lambda\right) - 20\log_{10}\left(4\pi d_0\right) - 10\log_{10}\left(L\right) \end{aligned} \quad .(3)$$

In (3), G_t, G_r, and L are taken equal to 1 as we consider unit gain antennas and the internal system losses are considered as 1, whereas the reference distance d_0 is taken as 1 m. Using (1) and (3), the received signal strength at a sensor is calcualted as,

$$P_{r,dB}(d) = P_{t,dB} - PL_{dB}(d)\,. \qquad (4)$$

We will use (4) to calculate the received signal strength by using the parameters which are suitable for indoor factory non-line-of-sight (NLOS) environments. The details are given in Table 2.

2.2 Cooperative Communication

We use a two-phase cooperative communication to send the sensed information to the BS. In our proposed scheme, the sensors do not transmit the signal to the BS in the first phase but only transmit a cooperative data packet to the BS in the second phase.

In *Phase 1*, after sensing the information from its surrounding area, each sensor in the cooperation group shares this information with the nodes in its neighbor list. The data packet in this phase contains the floor number, sensor ID, time-of-arrival (TOA), and the sensed alarm information.

In *Phase 2*, each node makes a cooperative data packet by combining the information received from the cooperating nodes during the first phase. Upon its turn, every node then transmits the cooperative data packet to the BS in a TDMA manner.

2.3 Organize and Operate Protocol (OOP)

Based on the above described scheme, we propose a MAC protocol for the operation of the WSN. It consists of two main steps, organization of nodes and operation of the network, and therefore referred to as Organize and Operate Protocol (OOP):

1. Organize:
    a. In the Organize stage, the BS sends an Organize message to all the nodes in the network.
    b. Each node turns to Organize mode and update its current list of neighbor nodes by using the received signal strength information from (4). The nodes with higher received signal strength are added as neighbors until the minimum required number of neighbors is satisfied.
    c. After the nodes are organized into cooperation groups, the Operate stage starts.
2. Operate:
    a. In the Operate stage, the sensors start normal operation of sensing the surrounding environment.
    b. Share the sensed data with the nodes in the neighbor list.
    c. This information is then sent to the BS using the cooperation scheme mentioned above.

The information from each cooperation group is received at the base station, decoded, and combined at the fusion center. A majority rule decision is made on the observations after collecting the received information from each sensor in the cooperation group as,

$$R\left(j\right) = \text{mode}\left\{s_1\left(j\right), s_2\left(j\right), s_3\left(j\right), \ldots, s_{\mathcal{N}}\left(j\right)\right\} \qquad (5)$$

Table 1. Fusion at the base station

j \ s_i	s_1	s_2	s_3	s_4	s_5	$R(j)$
1	D	O	C	C	C	*C*
2	C	D	D	D	W	*D*
3	O	O	W	W	W	*W*
4	W	O	O	O	O	*O*
5	D	D	W	D	D	*D*

where $s_i(j)$ is the *j*th cooperative symbol received from a sensor s_i. This helps increase the probability of correct decision at the BS even in bad channel conditions.

We illustrate the fusion mechanism with the help of an example. Let O represent OK, C represent Caution, W represent Warning, and D represent Danger and *j* is the index of the cooperating node whose information is received from the sensor s_i. The fusion mechanism is shown in Table 1, which shows a cooperation group of 5 sensor nodes communicating to the base station in a cooperative manner. *R*(*j*) shows the final result about the sensed information by each sensor, after fusion.

3. Simulation Results

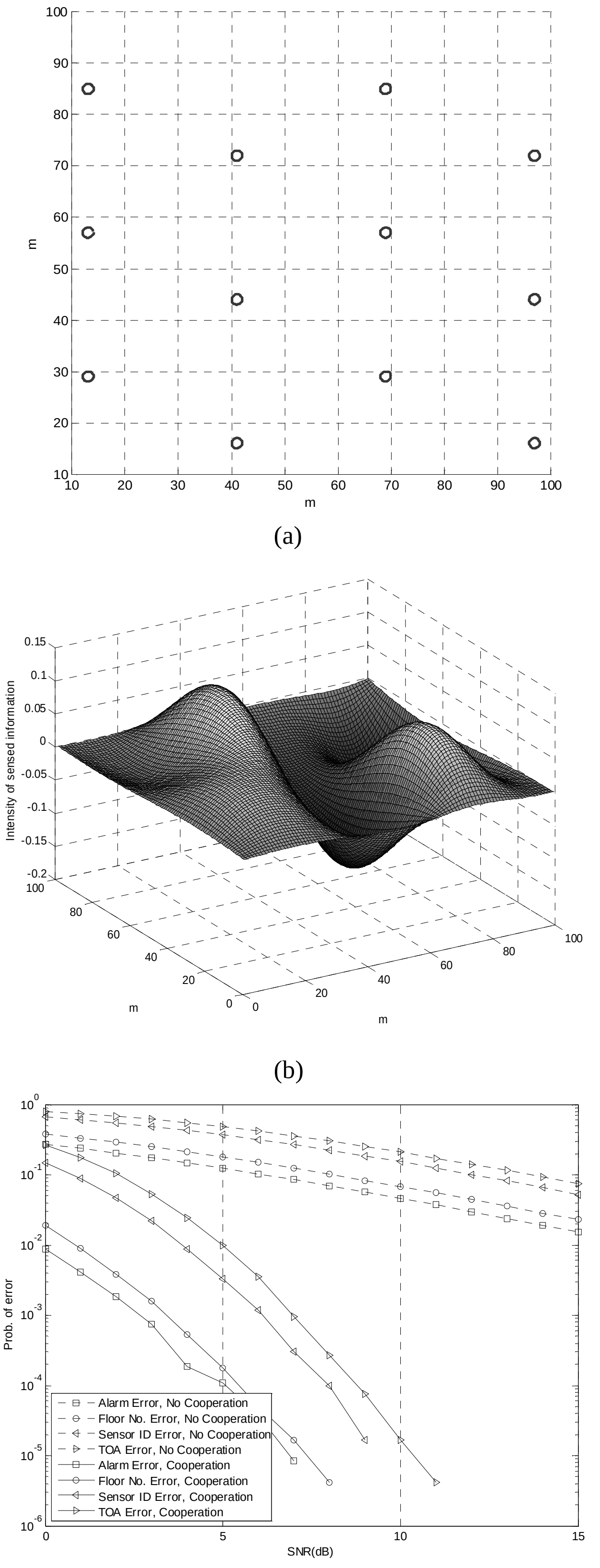
Assume an indoor communication environment of 100×100 m^2. Some machines inside this area generate a kind of radiation information i.e., temperature. The sensor nodes are deployed across this area according to a pre-planned map. The deployment of nodes could be either random or in the form of a fixed triangular grid. In this paper we show the results from a fixed triangular grid deployment as shown in Fig. 3(a). Suppose that a higher temperature at a certain location represents a fault in the operation or state of the machine at that location. We model this information over the entire area as a Gaussian random field, shown in Fig. 3(b). The field varies from high temperature to low, which generates four different kinds of alarms i.e., Danger, Warning, Caution, and OK, respectively.

Rayleigh fading with lognormal shadowing communication channel is assumed for indoor environment. We simulate a cooperation group of 12 nodes and the results are averaged over 20,000 sensing operations by the sensors. Other simulation parameters are shown in Table 2.

Fig. 3(c) shows the probability of error for the alarms generated at the BS, floor number, sensor ID, and TOA for 12-node cooperation. The probability of error is compared for cooperation group with no cooperation among sensors i.e., each sensor transmitting directly to the BS. We can see a clear advantage by using cooperation group of nodes, which achieves, on average, 10^{-3} probability of error at

Table 2. Simulation parameters

Parameter	Value
Total area	100×100 m^2
No. of cooperation nodes, $\mathcal{N}$	12
Carrier frequency	1.5 GHz
Transmit power	1 mW
Standard deviation, σ	7 (Indoor NLOS)
Path-loss exponent, η	3 (Indoor NLOS)
Sensing radius of each sensor	18 m



(a)

(b)

(c)

Figure 3. Simulation results for 12-node cooperation group. (a) Deployment of sensor nodes according to a triangular grid. (b) Simulation field of information. (c) Prob. of error for the received information at the BS.

almost 20 dB lower SNR compared with no cooperation scheme. Looking at the improvement in BER, we can safely say that the extra energy spent by the network in *Phase 1* transmission and in the cooperative packet transmission in *Phase 2* is offset by the huge gain in the BER.

4. Conclusion

In this paper, we have proposed a self-organizing relay based cooperative WSN to monitor the state of machines in an indoor environment. By applying the proposed self-organization mechanism and the cooperation scheme, we obtain a much better performance in terms of BER and achieve a highly accurate decision at the base station. The energy saving provided by the proposed scheme is almost 20 dB, which is very significant for the harsh indoor industrial environment. The proposed cooperation protocol is robust to communication link failures and adapts to changing link conditions in the wireless channel.

5. Acknowledgment

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