Low-latency and High-reliability Cooperative WSN for Indoor Industrial Monitoring

Zafar Iqbal, and Heung-No Lee, *Senior Member, IEEE*
School of Electrical Engineering and Computer Science,
Gwangju Institute of Science and Technology, Gwangju, South Korea - 61005.
Emails: {zafar, heungno}@gist.ac.kr

***Abstract*—Sensor networks have been widely used traditionally in 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. Recently, industrial wireless sensor networks (IWSNs) are getting popular for environment monitoring in such conditions to help us make a decision on the state of machines in a certain area of interest. 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 dual-hop cooperative WSN scheme, which uses in-network data aggregation mechanism in order to reduce the overall latency as well as improve the reliability of the received information. We also devise a protocol for the organization and operation of the proposed sensor network. The proposed scheme effectively increases the probability of correct decision about the state of the machines, and reduces the probability of false alarms at a given signal level.**

Keywords—industrial wireless sensor networks, cooperative communication, data aggregation, clustering, low-latency, fusion.

I. 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 required 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], and [6]. These works deal with packet loss issues in wireless traffic, and relay selection mechanism for a networked control system (NCS) for successful cooperative transmission in industrial environments, respectively. Apart from the cooperation among sensor nodes, data aggregation at the intermediate nodes is an important factor of cooperative multi-hop communication system. Since all the packets are addressed to a single destination and the size of data packets is usually small, therefore, a reduction in the size of control packet overhead and the number of transmission packets, can improve the energy efficiency, and throughput, of the system [7]-[9]. In our previous work [10], we have used the concept of in-network data aggregation and cooperation to improve the reliability in the received information at the base station (BS). However, [10] uses repetition of the aggregated data transmission at every node in the cooperation group, which results in some unnecessary redundancy and thus a much more reduced throughput that may be critical to the performance of the network.

In this work, we propose an improvement to our previous work [10] by using cluster heads which helps in reducing the amount of transmissions required to transmit the same information to the BS and also reduces the latency at the expense of some reduction in performance. The proposed system is a 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 unlike [2]-[4] in which the data is received at the BS in the first phase as well. In the second phase, the cooperative information is sent to the BS by a selected number of cluster head (CH) nodes, unlike [10] in which each node in the cooperation group sends the aggregated information to the BS. Also, different from the relay mechanisms in [2]-[4], we use the received data at the relay without regard to it being correctly received or not. The relays only detect the received symbols and do not need to decode the symbols, rather use these symbols in the cooperation phase even if not correctly received. Also, our proposed scheme does not involve the extra overhead of retransmission in order to ensure successful packet delivery, unlike [6] and [11]. This simplifies the hardware and signal processing requirements of the relay node. This work combines the data aggregation and cooperation mechanism to improve the reliability of the received information at the BS as well as

---

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government under Do-Yak research program (NRF-2015R1A2A1A05001826).

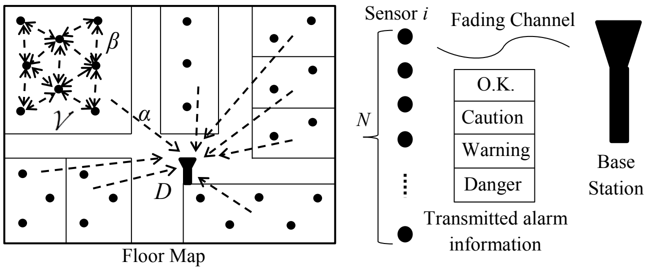

Fig. 1. Sensing the environment and its communication to the BS. The sensors are scattered in an area of interest and convey four different types of alarm information to the BS.

keep the redundancy overhead to a certain limit in order to perform at a low-latency. In this paper, we also propose a protocol for the operation of the cooperative IWSN.

II. NETWORK DESIGN

Fig. 1 shows the general scenario where a floor of a factory building or area of interest is covered by N number of nodes. 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.

A. *Sensor Deployment*

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 [12] for the deployment of sensor network and each node maintains a neighbor list of a certain number of sensors [13]. We use the equation for minimum number of sensors required to cover the area of interest [12], given as,

$$\frac{N\times r^2\pi}{P_{AREA}}=\frac{2\pi}{\sqrt{27}} \tag{1}$$

where N is the minimal number of nodes needed to cover the area of interest, $l \times h = P_{AREA}$ and r is the sensing range of a node. This kind of optimal regular deployment is shown in Fig. 2. Every three nodes, whose sensing ranges intersect, form an equilateral triangle with each side, $d = r\sqrt{3}$.

B. *Organize and Operate Protocol with Cluster Heads (OOP-CH)*

In this paper, we propose a network organization and operation protocol with cluster head selection, named as organize and operate protocol with cluster heads (OOP-CH).

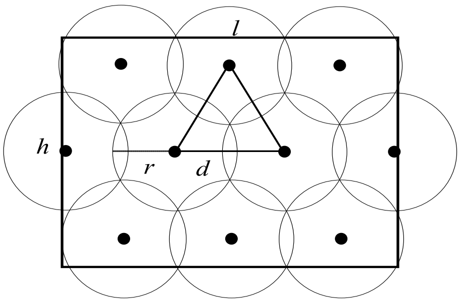

Fig. 2. 2-D triangular grid deployment of sensors in an $l \times h$ area, where d is the inter-node distance and r is the sensing radius of a sensor.

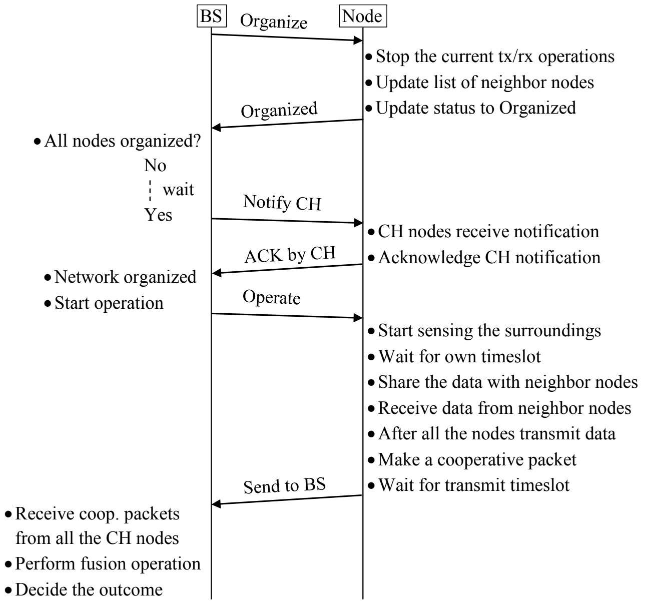

Fig. 3. The proposed organize and operate protocol with cluster heads (OOP-CH) for WSN.

Since the proposed network consists of fixed sensor nodes, therefore mobility issues will not be considered. Also, the network consists of cooperation groups that communicate with the destination in a dual-hop manner. Each node in a cooperation group schedules its communication link in collaboration with other nodes in the group. Every node in a group is assumed to be able to communicate with a minimum number (6 to 20) of neighbor nodes. This neighbor list is maintained by keeping the source address of these nodes which is broadcasted by using a control channel. A node will decode the information received only from the nodes in the neighbor list and discard the rest. The cooperation groups are updated periodically depending on the application and conditions of the sensor nodes. This operation is controlled by the BS by initiating the organization operation of the network. After the organization stage, the usual sensing and reporting operations continue until the next organization process.

In the OOP-CH protocol, described in Fig. 3, the BS sends an "Organize" message to all the nodes in the network, indicating to organize themselves in cooperation groups. Upon receiving this message, the nodes stop tx/rx operations and update their list of neighbor nodes, and update their status to "Organized". After all the nodes are organized in groups, the BS chooses a predefined number of CH nodes based on the received signal strength information (RSSI). Note that, since we use a majority voting-based fusion technique at the BS, therefore, a certain amount of redundancy in the data received at the BS is necessary. The minimum number of CH nodes required to perform majority vote-based fusion at the BS is 3, however, choosing 3 CH nodes does not show significant improvement in the probability of error in the received information at the BS (results not shown here). In this paper, we choose the number of CH nodes to be 5 and we show with the help of simulations that this number may be good enough for cooperation groups of small to medium sizes. After CH nodes are notified, the BS then sends "Operate" message to the nodes indicating to start normal sense and transmit operations. The nodes in a cooperation group then share their sensed information with the neighboring CH nodes. After receiving messages from all the nodes in the cooperation group, each CH node makes a cooperative data packet and transmits it to the BS in its own timeslot. The BS, upon receiving the cooperative packets from all the CH nodes in the cooperation group, performs majority voting-based fusion operation and decides the outcome of the received information from the sensor nodes.

C. *Wireless Link Characteristics*

A medium-sized WSN with a mixed indoor line-of-sight (LOS) and non-line-of-sight (NLOS) configurations is considered; therefore we will use the basic radio propagation model for indoor wireless communication channel [14] given as

$$\begin{aligned} P_{r,dB}(d) &= P_{t,dB} - PL_{dB}(d) \\ PL_{dB}(d) &= PL_{dB}(d_0) + 10\eta \log_{10}\left(\tfrac{d}{d_0}\right) + X_{\sigma,dB} \end{aligned}, \tag{2}$$

where, $P_{r,dB}$ and $P_{t,dB}$ are the received and transmitted powers in dB, PL_{dB} is the path-loss in dB with distance d from the transmitter, η is the path-loss exponent indicating the rate of decay of the mean signal with respect to distance, and $X_{\sigma,dB}$ is a zero-mean Gaussian random variable with standard deviation σ. In (2), $PL_{dB}(d_0)$ 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 LOS path loss incurred in the channel, given as

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

In (3), G_t, G_r, and L are taken equal to 1 because we consider unit gain antennas and the internal system losses as 1, λ is the wavelength of the carrier in meters, and the reference distance d_0 is taken to be 1 m. The value of $PL_{dB}(d_0)$ given in (3) is used to calculate $PL_{dB}(d)$ and eventually $\mathrm{P}_{r,dB}(d)$ in (2). The parameters used in this calculation are chosen according to the indoor factory NLOS environment, given in Table II.

The wireless nodes are clustered into different cooperation groups by their geographic locations, as shown in Fig. 3. 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. The inter-node channels, β, and the node-destination channels, α, are modeled as lognormal distributed Rayleigh fading channels. Keeping the wireless link quality in mind, we have proposed the relayed transmission which uses a two-phase cooperation model. This model helps to improve the BER performance by reducing the errors caused by link failures and channel disruptions.

1) *Phase 1 Communication*

In phase 1, after sensing the information from its surrounding area, each sensor in the cooperation group shares this information with the CH nodes in its neighbor list. This may be a low-energy transmission, sufficient for communication only within the cooperation group. Each node transmits the observed information in the form of BPSK modulated symbols using TDMA. The received signal $r_{j,i}$ at node V_i, from node V_j, in phase 1 is,

$$r_{j,i} = \sqrt{E_{s1}}\, v_j \beta_{j,i} + n_{j,i}, \tag{4}$$

where $E_{\mathrm{s}1}$ is the transmitted symbol power in phase 1, v_j is the binary information sent from node V_j, and $n_{j,i}$ is the additive white Gaussian noise with power spectral density, N_0. The data packet in this phase contains the floor number, sensor ID, time-of-origin (TOO), and the sensed alarm information.

2) *Phase 2 Communication*

In phase 2, each CH node V_i makes a cooperative data packet by combining the information received from the cooperating nodes within its cooperation group, $\mathcal{V}$, during the first phase. We use amplify-and-forward (AF) relaying mechanism at the relays. In the AF protocol, the relay equalizes the channel fades between the source and the relay by amplifying the signal received from the source and forwarding it to the destination. This is achieved by scaling the received signal by a factor that is inversely proportional to the received power. This factor is given as,

$$\zeta_{j,i} = \frac{1}{\sqrt{E_{s1}\left|\beta_{j,i}\right|^2 + N_{0,j,i}}}. \tag{5}$$

Where $\zeta_{j,i}$ is the amplification factor used at relay node V_i with a corresponding source node V_j, $\beta_{j,i}$ is the channel coefficient, and $N_{0j,i}$ is the input noise variance at the relay node i from source node j, respectively.

As mentioned earlier, the size of data packets sent by each sensor is usually small and sending each packet separately to the BS requires a large number of transmissions and therefore increases the energy consumption. This scenario is shown in Fig. 4(a). Aggregation of data at the intermediate nodes to form a cooperative packet reduces the control packet overhead and the number of transmissions needed to send the data to the BS. Therefore, it helps in improving the energy consumption and throughput of the network. The cooperative data packet represented by x_i at a node i, consists of a concatenation of the received and amplified packets ($\zeta_{j,i}\hat{r}_{j,i}$, $j = 1,2,\ldots,\mathcal{N}$ and $j \neq i$) from all the nodes in the cooperation group and its own information v_i. Here, $\hat{r}_{j,i}$ is the detected signal at the relay node V_i from the source node V_j. The cooperative data packet is formed as shown in Fig. 4(b).

Upon its turn, each CH node transmits the cooperative data packet to the BS in a TDMA manner. The received signal at the BS, $y_{i,D}$, can be written as,

$$y_{i,D} = \sqrt{E_{s2}}\, x_i \alpha_{i,D} + n_{i,D} \tag{6}$$

where $\alpha_{i,D}$ is the lognormal fading channel coefficient from node V_i to the BS and $E_{\mathrm{s}2}$ is the transmitted symbol power in phase 2. $n_{i,D}$ is the additive white Gaussian noise at destination

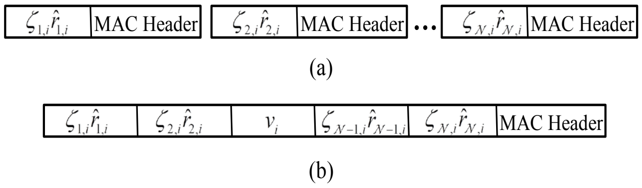

Fig. 4. Concatenation of the received and own information in the cooperative data packet. (a) Each sensor's data with MAC control header. (b) Aggregated data packet with a single MAC control header.

D from node i, with power spectral density, N_0. The signal from the source node j, relayed via the relay node i, and received at the destination D can be written as,

$$y_{i,D} = \frac{\sqrt{E_{s1}E_{s2}}}{\sqrt{E_{s1}\left|\beta_{j,i}\right|^2 + N_{0,j,i}}}\alpha_{i,D}\beta_{j,i}v_j + n'_{i,D}, \tag{7}$$

where

$$n'_{i,D} = \frac{\sqrt{E_{s2}}}{\sqrt{E_{s1}\left|\beta_{j,i}\right|^2 + N_{0,j,i}}}\alpha_{i,D}n_{j,i} + n_{i,D}. \tag{8}$$

Since the noise terms $n_{j,i}$ and $n_{i,D}$ can be assumed independent, then the equivalent noise $n'_{i,D}$ is a zero-mean complex Gaussian random variable with variance given as

$$N'_0 = \left(\frac{E_{s2}\left|\alpha_{i,D}\right|^2}{E_{s1}\left|\beta_{j,i}\right|^2 + N_{0,j,i}} + 1\right)N_0. \tag{9}$$

D. Fusion at the Base Station

The information from each cooperation group is received at the base station, decoded, and combined at the *fusion center*. Each packet contains its sensor ID and cooperation group ID as well as the observed information. Each CH node sends its own observation as well as that from all other sensors in its cooperation group in an aggregated packet to the BS. A *majority rule* decision is made on the observations after collecting the received information from each CH node in the cooperation group. This helps increase the probability of correct decision at the BS even in bad channel conditions. A majority vote decision, which consists of votes from CH nodes in the cooperation group $\mathcal{V}$, can be mathematically represented as follows,

$$R(j) = \arg\max_{X}\sum_{i=1}^{\mathcal{C}} w_i I\left(y_i(j) = X\right) \tag{10}$$

where $y_i(j)$ is the jth cooperative symbol received from a sensor i, w_i is the weight associated with each sensor's information, and $I(.)$ is an indicator function. If the weights are set to $1/\mathcal{C}$, Eq. (10) gives the mode of $y_1, y_2, y_3, \ldots, y_{\mathcal{C}}$. In our experiments, we set the weights w_i to $1/\mathcal{C}$ because the channels are assumed to have equivalent average magnitude and $\mathcal{C} = 5$ as the number of CH nodes is 5.

TABLE I. DATA FUSION AT THE BASE STATION

y_i / j	y_1	y_2	y_3	y_4	y_5	***R*(*j*)**
1	D	O	D	D	C	*D*
2	C	C	W	C	W	*C*
3	O	O	W	W	W	*W*
4	W	O	O	O	D	*O*
5	C	D	C	C	C	*C*
6	W	W	C	W	W	*W*
7	D	D	D	W	D	*D*
8	O	C	O	W	C	*O*

TABLE II. SIMULATION PARAMETERS

Parameter	**Value**
Total area	100×100 m^2
No. of cooperation nodes, $\mathcal{N}$	12
Carrier frequency	2.4 GHz (ISM Band)
Transmit power, E_{s1}, E_{s2}	1 mW
Standard deviation, σ	7 (Indoor NLOS)
Path-loss exponent, η	3 (Indoor NLOS)
Sensing radius of each sensor, r	18 m

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 CH node i. The fusion mechanism is shown in Table I, which shows a cooperation group of 8 sensor nodes with 5 CH 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. When there is a tie in votes, as in row 8 of Table I, the algorithm selects the smallest of the tied values, i.e., O in this case.

III. THROUGHPUT AND ENERGY CONSUMPTION ANALYSIS

In this section, we compare the non-cooperative and cooperative schemes in terms of throughput and energy consumption of the network. For the sake of a fair comparison, we assume a traditional dual-hop communication scheme for the non-cooperative mechanism, in which each node's data is forwarded by a relay node in the second hop towards the BS without any cooperative mechanism. Let B represent the number of bits per symbol, and the symbol duration is given by $T_s = {}^{1}\!/_{f_s}$, where f_s is the symbol rate. Then, the throughput in case of non-cooperative (T_{nc}) and cooperative (T_c) dual-hop communication is given as,

$$\begin{aligned} T_{nc} &= \frac{\mathcal{N}B}{\mathcal{N}T_s + \mathcal{N}T_s}\ \text{bps} \\ T_c &= \frac{\mathcal{N}B}{\mathcal{N}T_s + \mathcal{C}\mathcal{N}T_s}\ \text{bps} \end{aligned}, \tag{11}$$

where the addition in denominator represents the time taken by two hops to transmit the symbol to BS. The additional $\mathcal{C}$ in the denominator for T_c is because each CH node relays the data of $\mathcal{N}$ nodes in the second phase. The time taken by $\mathcal{N}$ nodes to transmit $\mathcal{N}$ packets to the BS in the case of non-cooperative ($\mathcal{D}_{nc}$) and cooperative ($\mathcal{D}_c$) scheme is then computed as,

$$\mathcal{D}_{nc} = \frac{\mathcal{N} \times \text{size of data packet (bits)}}{T_{nc}\ \text{(bps)}}$$
$$\mathcal{D}_{c} = \frac{\mathcal{N} \times \text{size of data packet (bits)}}{T_{c}\ \text{(bps)}} \qquad (12)$$

In order to compute the energy consumption, let E_t, E_i, E_r, and E_f represent the energy consumed by the transmit operation by a sensor, idle listening, reception at a sensor node/BS, and fusion operation at the BS, respectively. In the case of non-cooperative dual-hop communication, each node transmits with energy E_t in phase 1 and the other $\mathcal{N}-1$ nodes receive this information with energy E_r. In phase 2, each relay node transmits with energy E_t to the BS while the other $\mathcal{N}-1$ nodes remain idle, and the BS receives each node's data with energy E_r. Thus the total energy consumed (E_{nc}) is given as,

$$\begin{aligned} E_{nc} &= \mathcal{N}\left(E_t + (\mathcal{N}-1)E_r\right) \\ &\quad + \mathcal{N}\left(E_t + (\mathcal{N}-1)E_i + E_r\right). \end{aligned} \qquad (13)$$

In the case of the proposed cooperative dual-hop communication, the total energy consumed (E_c) is given as,

$$\begin{aligned} E_{c} &= \mathcal{N}\left(E_t + (\mathcal{N}-1)E_r\right) \\ &\quad + \mathcal{C}\left(E_t + (\mathcal{N}-1)E_i + E_r\right) + \mathcal{C}\mathcal{N}E_f \end{aligned} \qquad (14)$$

where E_f is the additional energy spent in fusion at the BS and $\mathcal{C}\mathcal{N}$ represents the number of multiply-and-accumulate operations performed to compute the fusion result for $\mathcal{C}$ cooperative packets each containing $\mathcal{N}$ number of observations as given in (10). Also, in the second term in (14), $\mathcal{N}$ is replaced by $\mathcal{C}$ as there are $\mathcal{C}$ CH nodes transmitting to the BS instead of all the $\mathcal{N}$ relay nodes. Using $T_s = 50\ \mu$s [15], $E_t = 31.6$ mW, $E_i = 2.8$ μW, $E_r = 17.4$ mW [16], and $E_f = 13.3$ mW [17], the results of (12), (13), and (14) are plotted in Fig. 5.

Fig. 5 shows the power consumption and time delay results of our proposed CH cooperation scheme in comparison with the full repetition (F-Rep.) cooperation in which each node transmits a cooperative packet in phase 2 to the BS, as in [10], and the relayed transmission in which each node's data is forwarded by a relay node towards the BS in the second hop without any cooperation mechanism. The results show that the time required transmitting a certain amount of data to the BS increases in the case of F-Rep. cooperation and CH cooperation. However, the increase in energy consumption is reduced from ~2 dB to ~0.5 dB for $\mathcal{N} = 12$ and from ~3 dB to ~0.2 dB when $\mathcal{N} = 30$, in the cases of CH cooperation and F-Rep. cooperation, respectively. Similarly, the time delay has been reduced from ~145 ms to ~53 ms for $\mathcal{N} = 12$ and from ~957 ms to ~132 ms when $\mathcal{N} = 30$, in the cases of F-Rep. cooperation and CH cooperation, respectively. This amount of delay and energy consumption is a further reduction from that reported in [10] and will be helpful in achieving the low-latency design goal of future communication systems. The increase in the energy consumption is easily offset by the gain in SNR, which is achieved by our proposed scheme, shown in Section IV.

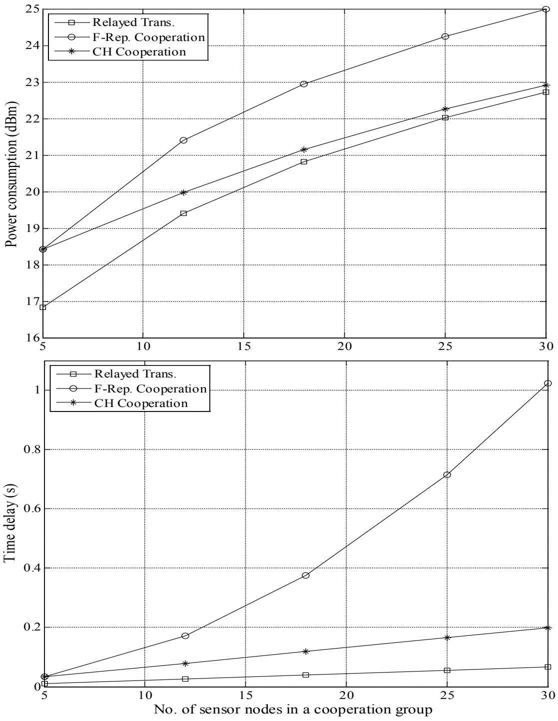

Fig. 5. Comparison of non-cooperative and cooperative schemes in terms of power consumption and time delay.

IV. 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. 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. 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 10,000 sensing operations by the sensors. The channel model parameters used, are according to the indoor factory environment wireless communication channel. The simulation parameters are shown in Table II.

Fig. 6 compares the probability of error for the alarms generated at the BS, floor number, sensor ID, and TOO for non-cooperation and 12-node cooperation schemes. We can see a clear advantage by using cooperation group of nodes. The F-Rep. cooperation and CH cooperation schemes achieve, on average, 10^{-3} probability of error at almost 20 dB and 12 dB lower SNR compared with no cooperation schemes, respectively. Despite the extra energy (~0.5 dB) spent by the network in phase 1 transmission and in the cooperative packet transmission in phase 2, we can still get a saving of ~11 dB by using the proposed CH cooperation scheme. Note that this reduction in energy saving as compared to that in F-Rep. cooperation is a result of the loss in performance due to using fewer nodes to relay the cooperative packet rather than using F-Rep. cooperation, as in [10]. Thus, we are able to reduce the

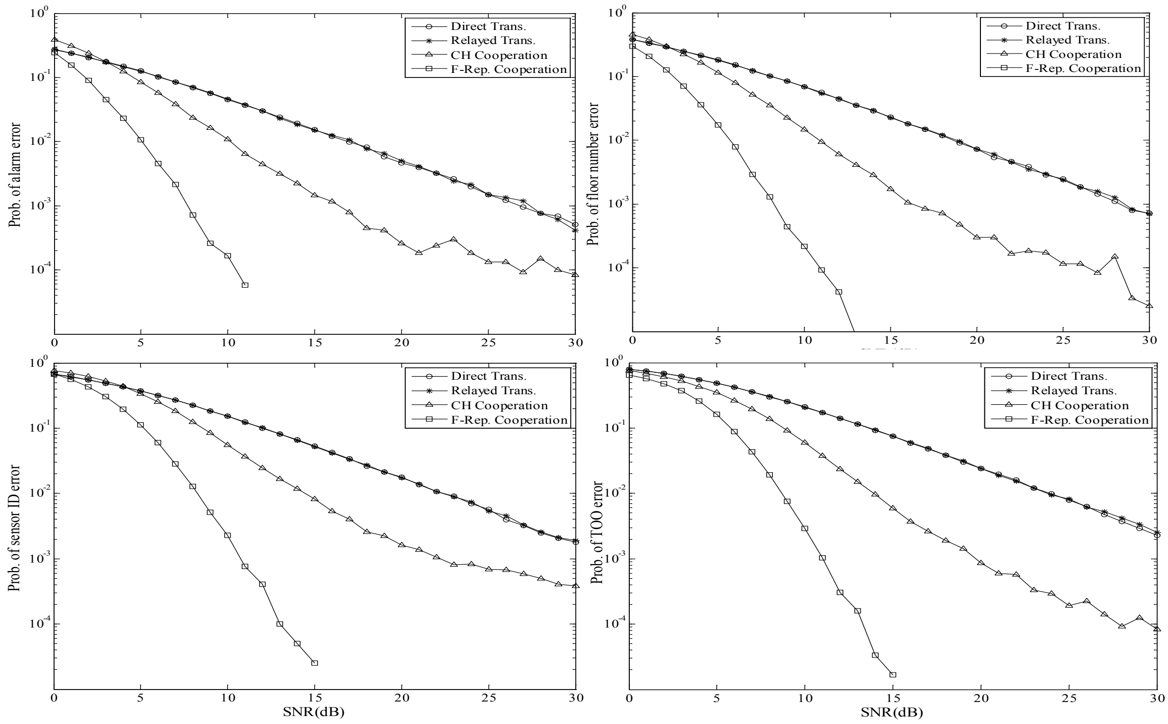

Fig. 6. Comparison of the probability of error in the received information, between direct, relayed, F-Rep., and CH cooperation transmission.

latency and energy consumption of the network at the expense of some performance.

V. CONCLUSION

In this paper, we have proposed a relay based cooperative WSN to monitor the state of machines in an indoor environment. By applying the proposed cooperation scheme, we obtain a much better performance in terms of the probability of error and achieve a highly accurate decision at the base station. The energy saving provided by the proposed scheme is almost 11 dB, which is very significant for the harsh indoor industrial environment. The proposed cooperation scheme is able to reduce the energy consumption and latency in data transmission from that reported in [10] by accepting some loss in performance.

REFERENCES

[1] L. D. Xu, W. He, and S. Li, "Internet of things in industries: a survey," *IEEE Trans. Ind. Inf.*, vol. 10, no. 4, pp. 2233-2243, Nov. 2014.

[2] X. Bao and J. Li, "Adaptive network coded cooperation (ANCC) for wireless relay networks: matching code-on-graph with network-on-graph," *IEEE Trans. Wirel. Comm.*, vol. 7, no. 2, pp. 574-583, Feb. 2008.

[3] J. N. Laneman and G. W. Wornell, "Distributed space-time-coded protocols for exploiting cooperative diversity in wireless networks," *IEEE Trans. Inf. Theory*, vol. 49, no. 10, pp. 2415- 2425, Oct. 2003.

[4] G. Kramer, M. Gastpar, and P. Gupta, "Cooperative strategies and capacity theorems for relay networks," *IEEE Trans. Inf. Theory*, vol. 51, no. 9, pp. 3037- 3063, Sep. 2005.

[5] A. Ulusoy, O. Gurbuz, and A. Onat, "Wireless model-based predictive networked control system over cooperative wireless network," *IEEE Trans. Ind. Inf.*, vol. 7, no. 1, pp. 41-51, Feb. 2011.

[6] N. Marchenko, T. Andre, G. Brandner, W. Masood, and C. Bettstetter, "An experimental study of selective cooperative relaying in industrial wireless sensor networks," *IEEE Trans. Ind. Inf.*, vol. 10, no. 3, pp. 1806-1816, Aug. 2014.

[7] E. Fasolo, M. Rossi, J. Widmer, and M. Zorzi, "In-network aggregation techniques for wireless sensor networks: a survey," *IEEE Wireless Comm.*, vol. 14, no. 2, pp. 70-87, Apr. 2007.

[8] P. Jesus, C. Baquero, and P. S. Almeida, "A survey of distributed data aggregation algorithms" *IEEE Comm. Surv. Tuto.*, vol. 17, no. 1, pp. 381-404, Mar. 2015.

[9] H. Harb, A. Makhoul, R. Tawil, and A. Jaber, "Energy-efficient data aggregation and transfer in periodic sensor networks," IET Wirel. Sensor Syst., vol. 4, no. 4, pp. 149-158, Dec. 2014.

[10] Z. Iqbal, K. Kim, and H.-N. Lee, "A cooperative wireless sensor network for indoor industrial monitoring," *IEEE Trans. Industrial Informatics*, to be published.

[11] J. Niu, L. Cheng, Y. Gu, L. Shu, and S. K. Das, "R3E: Reliable reactive routing enhancement for wireless sensor networks," *IEEE Trans. Ind. Inf.*, vol. 10, no. 1, pp. 784-794, Feb. 2014.

[12] R. Williams, "The geometrical foundation of natural structure: A source book of design," Dover Pub. Inc., New York, pp. 51-52, 1979.

[13] F. Xue and P. R. Kumar, "The number of neighbors needed for connectivity of wireless networks," *Wireless Networks*, vol. 10, no. 2, pp. 169-181, Mar. 2004.

[14] H. Hashemi, "The indoor radio propagation channel," *Proc. of the IEEE,* vol. 81, no. 7, pp. 943-968, Jul. 1993.

[15] IEEE 802.15.4-2011, "Part 15.4: Low-rate wireless personal area networks (LR-WPANs)," IEEE-SA Standards Board, Jun. 2011.

[16] Silicon Labs, *EFR32 Flex Gecko Proprietary Wireless SoC*, www.silabs.com. Accessed, Jun. 2016.

[17] K.-Y. Wu, C.-Y. Liang, K.-K. Yu, and S.-R. Kuang, "Multi-mode floating-point multiply-add fused unit for trading accuracy with power consumption," *IEEE/ACS Int. Conf. Comp. Inf. Sci.*, pp.429-435, Jun. 2013.