A Cooperative Wireless Sensor Network for Indoor Industrial Monitoring

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***Abstract*—Industrial wireless sensor networks (IWSNs) are getting popular for indoor monitoring of heavy machinery and large factories to make a reliable decision on the state of machines in a certain area of interest. However, the indoor wireless communication channel is 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 by introducing a novel cooperation mechanism and a medium access control (MAC) protocol. The proposed scheme effectively increases the probability of correct decision about the state of the machine, reduces the probability of false alarms at a given signal level, and reduces the overall energy consumption as compared to non-cooperative schemes. We also present a closed-form expression for the symbol-error rate analysis of the proposed scheme, which shows that our proposed scheme achieves full diversity order offered by the cooperation scheme.**

***Index Terms*—machine condition monitoring, industrial wireless sensor networks, cooperative communication, medium access control, indoor industrial monitoring.**

I. Introduction

WIRELESS sensors are widely used for machine condition monitoring (MCM) 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, healthcare, and security services [1]. But these sensors are prone to failure and the wireless communication channel may also fail sometimes due to severe conditions. Therefore, it is a good idea to use cooperation among the sensor nodes that communicate with a central base station to ensure the accuracy and timeliness of information gathered from the nodes [2].

The wireless communication channel in indoor industrial environment suffers from severe conditions such as propagation loss, time variation, and multipath fading etc. 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. There has been a lot of research on multipath fading in wireless networks and channel characterization for industrial environments, such as [3], and a work that deals with the underground link quality characteristics [4]. However, a recent work and the references therein, provides a suitable channel model for indoor industrial environments [5].

A bad communication link results in higher energy consumption because of repeated transmissions or use of higher transmit power by the nodes, and reduces the 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. Various techniques have been proposed to deal with these issues in wireless networks, such as user cooperation in communication [6]-[8] for improved spatial diversity, time-slot reassignment [9], and sleep scheduling [10] strategies used to improve the energy efficiency of the WSN. In the case of cooperation among sensor nodes, data aggregation at the intermediate nodes is an important factor of multi-hop communication. Since the size of data packets is usually small and are addressed to a single destination, therefore, reducing the number of transmissions and the size of control packet overhead, improves the energy efficiency and throughput of the system [11].

In this paper, we propose a cooperation scheme for IWSNs, in which the network consists of small cooperation groups of sensors. Each node in the cooperation group shares its information with all others in the first phase. In the second phase each node forms a cooperative data packet and sends it to the base station (BS). In this way, the nodes help relay information for its neighbor nodes with a significant reduction in energy consumption at the cost of an acceptable reduced throughput.

A. Related Works and Contributions of this Paper

Recently, network coding has become one of the most widely used techniques for cooperation among nodes in a wireless communication network. Some works that deal with improving the energy efficiency and packet delivery ratio include, a Reliable Reactive Routing Enhancement (R3E) algorithm for IWSN, which finds a guide path towards the sink and provides a reliable and energy-efficient packet delivery against the unreliable wireless links [2]. A physical-layer cooperative transceiver, which can use either amplify-and-

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forward (AF) or decode-and-forward (DF) relaying to improve the packet error rate, was proposed in [6]. The work in [7] presents an adaptive-gain *M*-relay AF cooperative system with conventional relay (CR) and best relay (BR) selection schemes and shows that the BR scheme provides higher asymptotic error limits than that of the CR scheme. A generalized dynamic-network code (GDNC) for a network of *M* users sending independent information to a common base station using independent block fading channels was proposed in [8]. The proposed scheme offers a much better tradeoff between rate and diversity as compared to the DNC. Similarly, [12] presents a selective cooperative relaying protocol with periodic, adaptive, and reactive relay selection mechanism. The scheme improves packet delivery ratio and reduces the number of retransmissions for successful delivery.

An adaptive and energy-efficient TDMA-based MAC protocol called receiver-driven MAC (RMAC), which uses a timeslot stealing and timeslot reassignment mechanism, was proposed in [9]. RMAC performs better in terms of average packet delay and average power consumption per packet as compared to S-MAC. An energy-aware sleep scheduling mechanism for wireless sensor networks was presented in [10], which significantly reduces the variation in energy level among sensors and extends the lifetime of the network by around 18%. A practical wireless model-based predictive networked control system (W-MBPNCS) was proposed in [13], in order to achieve a decent control under severe impairments, such as unbounded delay, burst of packet loss, and ambient wireless traffic.

Another solution, used for MCM in large factories, distributes the signal processing operations among the central unit and the sensor nodes to reduce the energy consumption in data transmission and improve the network throughput, was proposed in [14]. Similarly, [15] presents an IWSN-based MCM system which overcomes false alarms caused by loss of data, interference, or invalid data. An improvement in the SNR and false alarm detection rate, after Dempster-Shafer Theory (DST)-based fusion method, was observed.

Most of the above-mentioned works use cooperative and selective relaying to improve packet delivery and energy consumption of the network. However, relay selection comes with an extra overhead of reduced network throughput and the problem becomes more evident in the case of multi-hop and multiple cluster sensor networks. We propose a method in which the cooperation groups are fixed in the organization stage of the network. A source node acts as a relay node in the cooperative phase of transmission. A relay node uses data aggregation and AF relaying to send the cooperative packet to the BS. The contributions of this paper are as follows,

- We propose a novel two-phase cooperation scheme that works in a dual-hop manner.
- Our proposed scheme does not involve the extra overhead of relay selection and retransmission to ensure successful packet delivery, unlike [2], [7], and [12].
- The relay does not need to check whether the data was correctly received. It forwards the detected binary symbols without regard to the error induced in it in the first hop.
- We also propose a TDMA-based MAC protocol for the organization and operation of the sensor network.
- A closed-form expression has been derived for the symbol error rate analysis and it is shown that the proposed method achieves full diversity order.
- We have carried out the throughput and energy consumption analysis to show the effectiveness of the proposed scheme.

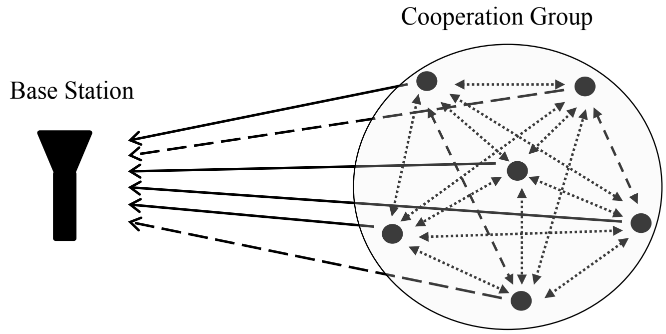


Fig. 1. Cooperative wireless sensor network

The rest of the paper is organized as follows. Section II describes the network design. Section III explains the MAC and cross-layer design. Section IV explains the fusion mechanism. Section V presents performance analysis. Section VI presents the simulation results, and Section VII concludes the paper.

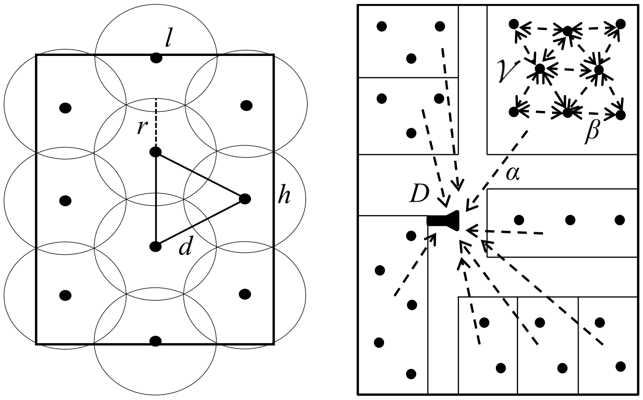
II. Network Design

Fig. 1 shows a cooperative WSN where the sensor nodes share their information with each other in the first phase and send the cooperative information to the base station in the second phase. Inter-sensor channels are shown by dotted lines while the channels from sensor to base station are shown by solid lines. We assume that some of the communication links between the sensors and from a sensor to the base station might be broken at a particular time instance, shown by long-dashed lines.

A. Sensor Deployment

Sensor deployment deals with the problem of coverage and connectivity of the sensor network while minimizing the power consumption for prolonged network lifetime and to transmit the sensed data timely and efficiently to the BS. In our case of indoor industrial area monitoring, the sensors could be deployed according to a pre-planned location map around huge machines in the factories. Considering these scenarios, our coverage problem becomes a static coverage problem, where the nodes do not change their positions. Assume that the sensing range of a sensor is *r*, the minimum number of sensors required to cover the area of interest [16], is given as,

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



(a) (b)

Fig. 2. Sensor nodes deployed in a rectangular area. (a) Triangular-grid, ensuring the coverage of the whole area with minimal overlap. (b) Indoor communication scenario showing a floor layout.

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

In order to ensure connectivity, we use the argument in [17] for minimum number of neighbor nodes, which says that for a network to be connected, $\Theta(\log N)$ (0.074log$N$ to 5.1774log$N$) neighbors are necessary and sufficient. Therefore, we choose the minimum number of neighbors for a sensor to be equal to 6, with which it can communicate in a single-hop manner. This is used to enable cooperative transmission to the base station for a combined decision on the sensed data.

B. *Sensor Localization*

Sensor localization is used to locate the sensor positions and time of the observed information in the network. We consider a medium-sized fixed sensor network. Each sensor contains its local coordinate information, which is sent to the base station along with its observation. The local coordinate system (LCS) field in the transmitted packet contains geographic coordinates and floor number in case of multi-story buildings. The received signal strength (RSS) and angle-of-arrival (AOA) information could be used to find the sensors' distance and angular position, respectively, but the LCS field in the transmitted packet already contains the position information. Therefore, the only information that needs to be determined is the time of the event. Thus, along with the LCS, we use the time-of-arrival (TOA) information in order to locate the time of the event. This will help us localize the received information in both time and geographical location of the observation.

The transmitted packet structure and alarm information by each sensor is shown in Fig. 3. This information will be decoded at the base station by the fusion center to find out the nature of the observations at a particular location in the network and activate response mechanisms on time.

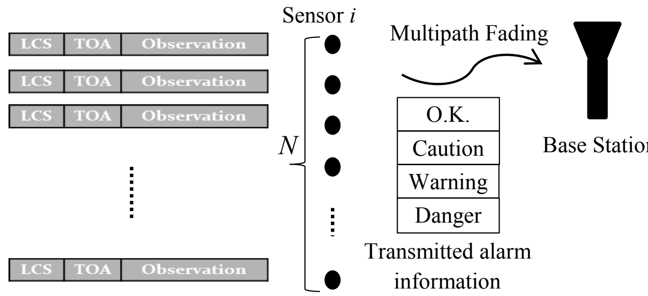


Fig. 3. Information transmission to the base station.

C. *Time Synchronization*

In our problem of a medium-sized network, most of the computations are done by the base station and the sensors are supposed to be in harsh environmental conditions which make it difficult for fine-grained synchronization algorithms to be used. Therefore, we adapt the Wisden system [18] of coarse-grained synchronization. In our synchronization technique, each sensor records the delay from the time of generation/reception of a sample to the time it is transmitted to the next hop or BS. Also, the cooperating node will record its own time delay for the packet that it processes before sending it to the base station. The TOA field in the transmitted packet contains this time delay information of all the nodes that the packet has traversed before reaching the base station.

Assume that the time spent by each packet k at the sensor node i is λ_i^k . Let the number of hops the packet traverses be n, and the time of arrival of the packet k, at the base station D, be T_D^k . Then, the start time of the packet at the origin node s, can be calculated as,

$$T_s^k = T_D^k - \sum_{i=1}^{n} \lambda_i^k \ . \tag{2}$$

The second term in (2) represents the time spent by the packet in the network. Thus, we can get the time of origination of the observation at the base station by subtracting the total time spent in the network from the current time at the BS. The BS is assumed to have an accurate reference clock periodically synchronized with the GPS time reference while each sensor node has its own local clock. This method of achieving time synchronization is simple, cost-effective, and robust to many sources of latency that contribute to error but is vulnerable to varying clock drifts in the intermediate nodes. But we assume a well-maintained medium-sized network of nodes and a moderate accuracy requirement; therefore, clock drift is not a very critical issue and can be traded off with the simplicity of the approach.

D. *Wireless Link Characteristics*

We consider a medium-sized indoor industrial WSN with mixed line-of-sight (LOS) and non-line-of-sight (NLOS) configurations, therefore we will use the statistical one-slope radio propagation model for path-loss [5], given as

$$\begin{aligned} P_{r,dB}(d) &= P_{t,dB} - PL_{dB}(d) \\ PL_{dB}(d) &= PL_{dB}(d_0) + 10\eta \log_{10}\left(\tfrac{d}{d_0}\right) + X_{\sigma,dB} \end{aligned}, \quad (3)$$

where, $P_{r,dB}$ and $P_{t,dB}$ are the received and transmitted powers in dB, PL_{dB} is the Friis free-space 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, d_0 is a reference distance, and $X_{\sigma,dB}$ is a zero-mean Gaussian random variable with standard deviation σ. The model in (3) provides a very good approximation for the indoor industrial wireless channel by considering the multipath and shadowing effects present in the environment. However, the values of η and σ need to be carefully chosen according to the environment, as described in [5] and the references therein.

Fig. 2(b) shows a floor map of a building with sensors scattered all over the floor that communicate to a common BS. Each link in the network is modeled by using (3) and incorporating η and σ with respect to indoor communication scenario. The inter-node channels, β_i, and the node-destination channels, α_i, are modeled as lognormal distributed Rayleigh fading channels.

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. The wireless nodes V_i's in a cooperation group are physically close to each other and the destination node is relatively far away from the group. Further assumptions are that the channels from each node V_i to the destination D is modeled as a lognormal fading channel with fading coefficient α_i, which is assumed to be fixed for a sufficiently longer period of time. As the group of wireless nodes is collocated and the destination is relatively far away, the fading coefficients α_i's are assumed to have the same average magnitude determined by the path loss from V_i to D. Also, the fading channels from V_i to D, are independent, thus, the fading coefficients α_i's, from V_i to D, are i.i.d. lognormal random variables. The channel from a transmitting node V_i to a node V_j within a group are also modeled as lognormal fading channels with fading coefficients $\beta_{i,j}$. To further simplify the analysis, it is assumed that the relative distance among these nodes is almost the same. Under this assumption, $\beta_{i,j}$'s are also i.i.d. lognormal random variables with the same average magnitude determined by the path loss among them.

III. MAC and Cross-Layer Design

Some of the major sources of energy wastage in WSNs are packet collisions, overhearing, packet overhead, and idle listening [19]. In order to reduce the energy loss to collisions and overhearing, we will use a TDMA-based MAC scheme in a two-phase communication model. Scheduling reduces packet collisions over the air, while the overheard information by

(a)

10-bit	10-bit	2-bit
LCS	TOA	Observation

(b)

10-bit	10-bit	2-bit	5-bit	32-bit
SourceAddr	DestAddr	Timeout	Width	Bitmap

(c)

$\mathcal{N}$ ×10-bit	$\mathcal{N}$ ×10-bit	10-bit	$\mathcal{N}$ ×2-bit
LCS (1… $\mathcal{N}$)	TOA (1… $\mathcal{N}$)	T_d	Observation (1… $\mathcal{N}$)

Fig. 4. (a) Data packet structure of each node in *Phase 1*. (b) Schedule packet structure used for organization of the network. (c) Data packet structure of each node in *Phase 2* for cooperative data transmission. (d) Cooperation group of 12 nodes in the sensor network.

each sensor is used to reduce the error rate and improve data transfer to the base station, which helps reduce the energy wastage in the network. For a medium-sized network of fixed sensors, we propose this protocol to meet our needs of scheduling, to reduce the header length and computation time.

A. Design of the Data Packet

As mentioned earlier, the data packet contains LCS, TOA, and Observation fields. The LCS contains the location information of the sensor which is embedded in it during the network deployment stage. It contains the following information fields:

- *Floor Number:* Although this parameter may vary according to the design under consideration, we choose this value to be 3 bit in order to cover up to 8-story buildings with our design.
- *Sensor ID:* Each sensor on a floor is assigned a unique identification number. We assign 7 bits to this field to allow up to 128 sensors on each floor of the building.
- *TOA:* This field is of 10 bits and contains the time duration between the time-of-arrival/observation of information on the current sensor and the time it was transmitted.
- *Observation:* The 2-bit observation field contains the alarm information, i.e., OK, Caution, Warning, and Danger.

The resulting data packet is a 22-bit packet as shown in Fig. 4(a). If Δ is the total time taken by the network to transmit one sensing event to the base station in a TDMA manner, then in the worst-case scenario, each sensor may have to wait for Δ seconds before it can send its data to the base station.

B. Design of the Schedule Packet

In our proposed scheme, each sensor transmits a schedule packet to select the winner of a given time slot, which is called Schedule, as shown in Fig. 4(b).

The source and destination node addresses of the current schedule packet are called SourceAddr and DestAddr, respectively. These fields contain the LCS information of the corresponding nodes and are therefore 10 bits each.

Timeout is used to resend the scheduling information to the next node in case it did not respond at the first time. The number of retries is limited to 4, after which the node is considered dead, its bitmap is set to 1, and the DestAddr is changed to next node in the schedule.

Width defines the number of nodes in a cooperation group and in turn the size of the data packet each node has to send to the BS. This value is set to 5 bit in our design for a maximum of 32 nodes in the cooperation group.

Bitmap contains a bitmap of all the sensors in the network. A '0' in the bitmap means the node is not organized and a '1' means the node is organized in the network. A node ID corresponding to the bitmap is saved at each node in the network, so that it knows which bit represents which node in the network.

C. Network Organization

Our proposed network consists of fixed nodes and therefore mobility issues are not considered. Further, the network is assumed to have local groups of nodes that communicate cooperatively with the destination in a dual-hop manner. There are no cluster-heads formed because all the nodes in a group will schedule their communication links independently and in collaboration with other nodes in their vicinity. As mentioned earlier, a node is able to communicate with a minimum number of neighboring nodes in the network. Each node keeps a list of 6 to 20 neighboring nodes by saving the source address of these nodes which will be broadcasted using a low-frequency control channel. A node will decode the received information only from the nodes within its neighbor list. The rest of the received information will be discarded. The cooperation group will be updated periodically depending upon the application and conditions of the sensor nodes.

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

1. *Organize*
   - (i) *BS sends Organize message to all the nodes in the network, using the Schedule packet described earlier.*
     - *The Bitmap is set to all* 0*'s, i.e., none of the nodes is organized as yet.*
     - *It also contains the address of the first node to start the Organize process from. This address will be generated randomly on each Organize message.*
   - (ii) *Upon receiving the Organize message, each node turns to Organize mode, i.e.,*
     - *Stop all the current transmit/receive operations.*
     - *Update its current list of neighbor nodes.*
     - *Listen to the received Schedule packet from neighbor node.*
     - *After receiving a Schedule packet, each node updates its information in the Schedule packet, sets its corresponding bit in the Bitmap field to* '1' *and passes the Schedule packet to the next node.*
   - (iii) *When the bitmap becomes all* 1*'s,*
     - *The current node transmits this information to the BS, by setting the DestAddr to that of the BS.*
     - *The BS, upon receiving this packet, sends a global message to all the nodes indicating to start normal sense and transmit operations mode, called Operate.*

2. *Operate*

   Upon receiving the Operate message from BS, each sensor then,
   - (i) *Senses the surrounding environment and wait for its turn to transmit.*
   - (ii) *Shares the data with the nodes in its neighbor list.*
     - *Each node in the neighbor list receives this data and stores it in its local memory.*
   - (iii) *Upon receiving the data from all the nodes in its neighbor list,*
     - IF *this was the first node in Organize stage*,*
       Transmit the cooperative data packet to the BS,
       ELSE
       Wait for its turn to transmit.
   - (iv) *Go to* (i)

**Each node stores the bitmap and next node DestAddr information during the Organize stage, which is also used in the operation scheduling.*

D. Cooperative Communication

Assume that the network is organized in sub groups of nodes that cooperate with each other, called cooperation group. We use the AF relaying protocol at the relays. The communication is done in two phases, as follows,

1) 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 in a TDMA manner. Every node in the neighbor list that receives this data, stores it in its local memory. The received signal $r_{i,j}$ at the relay node V_i, from the source node V_j, in phase 1 is,

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

where E_{s1} is the transmitted symbol power in phase 1, v_j is the BSPK-modulated symbol sent from node V_j, and $n_{i,j}$ is the additive white Gaussian noise at node i from node j, with variance, N_0. The data packet sent by each node in this phase is shown in Fig. 4(a).

2) Phase 2

The size of the data packets sent by a sensor is usually small and sending each packet separately to the BS requires a large number of transmissions, which increases the energy consumption. Therefore, aggregation of data is used at the intermediate nodes to reduce the control packet overhead and the number of transmissions required to send the same amount of data to the BS. The aggregated data is forwarded to the BS by using the AF protocol, in which, the relay equalizes the channel fades between the source and the relay by amplifying the received signal by a factor that is inversely proportional to the received power.

Each node V_i, combines the received information from the nodes within its cooperation group, $\mathcal{V}$, to form a cooperative data packet. The cooperative data packet represented by x_i at a node i, consists of a concatenation of the received and amplified packets from all the nodes in the cooperation group ($\zeta_{i,j}\hat{u}_{i,j}$, $j = 1,2,...,\mathcal{N}$ and $j \neq i$) and its own information v_i. $\hat{u}_{i,j}$ is the detected signal and $\zeta_{i,j}$ is the amplification factor at the relay node V_i with a corresponding source node V_j. The cooperative data packet is formed as,

$$x_i = \begin{cases} \zeta_{i,j}\hat{u}_{i,j} & j \neq i \\ v_i & j = i \end{cases}, \tag{5}$$

where

$$\zeta_{i,j} = \frac{1}{\sqrt{E_{s1}\left|\beta_{i,j}\right|^2 + N_{0,i,j}}}, \tag{6}$$

and $N_{0,i,j}$ is the input noise variance at the relay i from node j. The cooperative data packet sent by each node in this phase is shown in Fig. 4(c). In the cooperative packet, all the LCS and TOA information of the cooperation group including self-information is concatenated in sequential order. T_d contains the time spent at the relay node and Observation contains the observed alarm information by each node in the cooperation group, $\mathcal{V}$.

Upon its turn, every node transmits the cooperative data packet to the BS. The received signal at the BS, $y_{i,D}$, can be written as,

$$y_{i,D} = \sqrt{E_{s2}}x_i\alpha_{i,D} + n_{i,D} \tag{7}$$

where $\alpha_{i,D}$ is the lognormal fading channel coefficient from node V_i to the destination D and E_{s2} is the transmitted symbol power in phase 2. $n_{i,D}$ is the additive white Gaussian noise at destination D from node i, with power spectral density, N_0. More specifically, the received signal at the destination D can be written as,

$$y_{i,D} = \frac{\sqrt{E_{s1}E_{s2}}}{\sqrt{E_{s1}\left|\beta_{i,j}\right|^2 + N_0}}\alpha_{i,D}\beta_{i,j}v_i + n'_{i,D}, \tag{8}$$

where

$$n'_{i,D} = \frac{\sqrt{E_{s2}}}{\sqrt{E_{s1}\left|\beta_{i,j}\right|^2 + N_0}}\alpha_{i,D}n_{i,j} + n_{i,D}. \tag{9}$$

Since the noise terms $n_{i,j}$ 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

$$N'_0 = \left(\frac{E_{s2}\left|\alpha_{i,D}\right|^2}{E_{s1}\left|\beta_{i,j}\right|^2 + N_0} + 1\right)N_0. \tag{10}$$

IV. 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 node sends its own as well as the observation from all other sensors in its cooperation group to the BS in a combined packet. A *majority rule* decision is made on the observations after collecting the received information from each sensor in the cooperation group. This helps increase the probability of correct decision at the BS even in bad channel conditions. This is illustrated in Table I, where j is the index of the cooperating node whose information is received from the sensor s_i. Here, O, C, W, and D represent OK, Caution, Warning, and Danger, respectively. A final result $R(j)$ is obtained based on majority rule as shown in Table I. A majority vote decision, which consists of votes from sensors in the cooperation group $\mathcal{V}$, can be mathematically represented as follows,

TABLE I. Data Fusion at the Base Station

j \ s_i	s_1	s_2	s_3	s_4	s_5	s_6	s_7	$R(j)$
1	D	O	O	O	C	C	W	*O*
2	C	C	W	W	W	W	D	*W*
3	O	O	C	C	C	C	C	*C*
4	W	W	D	D	D	D	D	*D*
5	D	D	W	C	W	C	C	*C*
6	O	C	W	W	W	W	W	*W*
7	W	C	C	O	O	O	O	*O*

$$R(j) = \arg\max_X \sum_{i=1}^{\mathcal{N}} w_i I\left(s_i(j) = X\right) \tag{11}$$

where $s_i(j)$ is the jth cooperative symbol received from a sensor s_i with the information X. $I(.)$ is an indicator function given as, $I(x) = \begin{cases} 1 & x \text{ is true} \\ 0 & x \text{ is false} \end{cases}$. For example, in the case of alarm information, $X = \{\text{O,C,W,D}\}$. Therefore, $I(x)$ will be true if the received information $s_i(j)$ is equal to one of O, C, W, or D, otherwise it will be false. w_i is the weight associated with each sensor's information. In this work, the channels are assumed to have equivalent average magnitude, therefore the weights are set to $1/\mathcal{N}$. Note that, if the weights w_i are set to $1/\mathcal{N}$, (11) results in the mode of $s_1, s_2, s_3, ..., s_{\mathcal{N}}$.

V. Performance Analysis

Fig. 5 shows the proposed dual-hop multiple-branch communication system where each relay has multiple branch inputs and a single branch output, each working in an orthogonal manner based on TDMA. AF scheme is used at the relays in order to repeat the symbols for the neighbor nodes. The resulting symbol-error rate (SER) can be approximated as stated in the following theorem.

Theorem 1: If all of the channel links of the proposed multi-hop multi-branch cooperative system are known, the SER of a sensor node i at the destination D in the proposed system, can be tightly approximated as,

$$P_s\left(\gamma_{eq,i,D}\right)=F\left(1+\frac{g_{PSK}}{N_0'\sin^2\theta}\left(\frac{\sigma_{i,D}^2\prod_{j=1}^{\mathcal{N}-1}\sigma_{i,j}^2}{\prod_{j=1}^{\mathcal{N}-1}\sigma_{i,j}^2+\sigma_{i,D}^2+1}\right)\right) \quad (12)$$

where $F\left(x(\theta)\right)=\frac{1}{\pi}\int_0^{(M-1)\pi/M}\frac{1}{x(\theta)}d\theta$, *M is the modulation symbol size,* $g_{PSK}=\sin^2\left(\pi/M\right)$, $\gamma_{eq,i,D}$ *represents the instantaneous SNR per relay node at the destination, and* $\sigma_{i,j}^2$, $\sigma_{i,D}^2$ *are the variances of the Rayleigh fading channel coefficients* $\beta_{i,j}$ *and* $\alpha_{i,D}$*, respectively.*

Proof: See Appendix A.

Since, we use the majority voting rule in the fusion process, to decide a final outcome. Therefore, the probability of error, in the result after fusion, can be computed by using the Binomial theorem. Let, P_s, be the probability that the information sent by a sensor has error, and $l=\left\lceil\frac{\mathcal{N}+1}{2}\right\rceil$ be the minimum number of votes needed for majority, then the probability of error in the consensus is given as,

$$P_e(\mathcal{N})=\sum_{m=l}^{\mathcal{N}}\binom{\mathcal{N}}{m}P_s^m\left(1-P_s\right)^{\mathcal{N}-m}. \quad (13)$$

With (13), we expect to obtain a diversity order of l in the final SER of the proposed system.

A. Throughput and Energy Consumption of the Network

In this subsection, we aim to 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,

$$\begin{aligned}T_{nc}&=\frac{\mathcal{N}B}{\mathcal{N}T_s+\mathcal{N}T_s}\text{ bps}\\T_c&=\frac{\mathcal{N}B}{\mathcal{N}T_s+\mathcal{N}\mathcal{N}T_s}\text{ bps}\end{aligned}, \quad (14)$$

where the addition in denominator represents the time taken by two hops to transmit the symbol to BS. The additional $\mathcal{N}$ in the denominator for T_c comes from the fact that each 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,

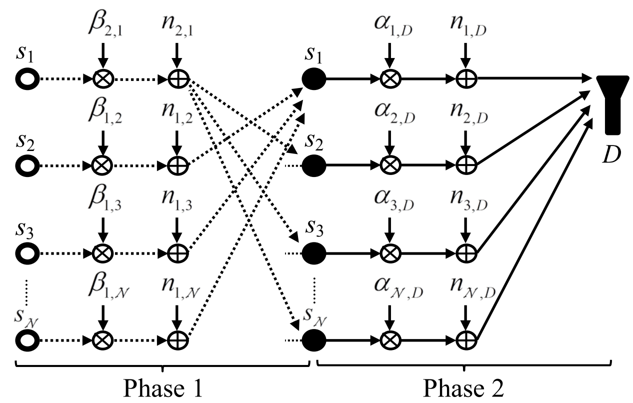


Fig. 5. The proposed two-phase communication system. In Phase 1, sensor s_1 in the cooperation group sends its information to all other sensors during its time slot. Similarly, all the other sensors send their information to s_1 during their allocated time slots. In Phase 2, the sensors then make a cooperative packet and send it to the destination, D.

$$\begin{aligned}\mathcal{D}_{nc}&=\frac{\mathcal{N}\times\text{size of data packet (bits)}}{T_{nc}\text{ (bps)}}\\\mathcal{D}_c&=\frac{\mathcal{N}\times\text{size of data packet (bits)}}{T_c\text{ (bps)}}\end{aligned}. \quad (15)$$

Using T_s = 15 μs, the time delay given by (15) is plotted in Fig. 6(a).

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, 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. This process is repeated $\mathcal{N}$ times. In phase 2, each 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,

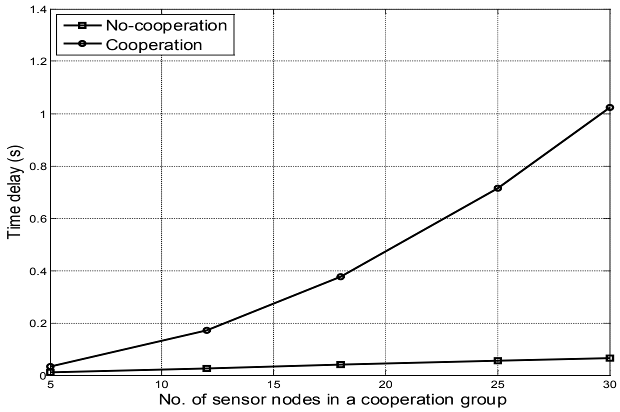
$$\begin{aligned}E_{nc}&=\mathcal{N}\left(E_t+\left(\mathcal{N}-1\right)E_r\right)\\&+\mathcal{N}\left(E_t+\left(\mathcal{N}-1\right)E_i+E_r\right)\end{aligned}. \quad (16)$$

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

$$\begin{aligned}E_c&=\mathcal{N}\left(E_t+\left(\mathcal{N}-1\right)E_r\right)\\&+\mathcal{N}\left(E_t+\left(\mathcal{N}-1\right)E_i+E_r\right)+\mathcal{N}^2E_f\end{aligned}, \quad (17)$$

where E_f is the additional energy spent in fusion at the BS and $\mathcal{N}^2$ represent the number of multiply-and-accumulate operations performed to compute the fusion result for $\mathcal{N}$ cooperative packets each containing $\mathcal{N}$ number of observations given in (11). Using E_t = 31.6 mW, E_i = 2.8 µW, E_r = 17.4 mW [20], and E_f = 13.3 mW [21], the results of (16) and (17) are plotted in Fig. 6(b).

Fig. 6(a) shows that the time required transmitting a certain amount of data to the BS increases in the case of our proposed cooperation scheme. But the given delay is still acceptable as it is 336 ms for $\mathcal{N}=18$ and can go up to 957 ms for $\mathcal{N}=30$. This amount of delay is not very critical and can be accepted



(a)

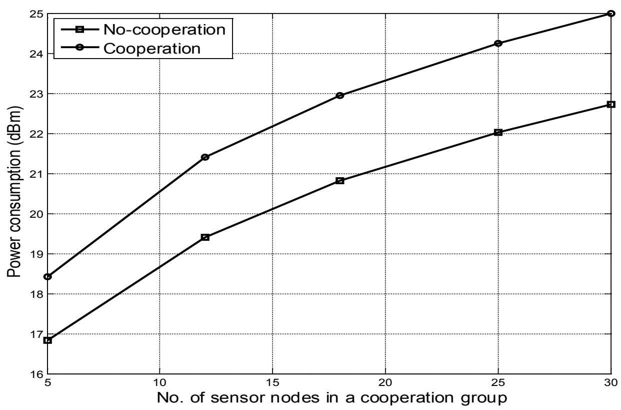


Fig. 6. Results of (15), (16), and (17). (a) Time delay for packet delivery. (b) Energy consumption of the network.

in return for improved robustness and reliability. Fig. 6(b) shows that the cooperation mechanism increases the amount of energy consumption by about 2 dB for $\mathcal{N} = 12$ and remains below 3 dB for $\mathcal{N} = 30$. This increase in the energy consumption is easily offset by the gain in SNR which is achieved by our proposed scheme, given in Section VI.

B. Comparative Analysis

The false alarm rate (FAR) and packet delivery rate (PDR) metrics are used to compare our results with some of the previous works mentioned in Section 1-*A*. The FAR and PDR for our work was calculated and averaged over a range of SNR (0 to 30 dB) and a total of 12,000 packets. In order to make a fair comparison, we use the PDR reported by [2] for IWSN and the PDR reported by [12], when no relay selection mechanism is used. As shown in Table II, our work shows a significant improvement in the FAR as compared to [14] and [15]. The PDR of our scheme is higher than that of [13] and is significantly higher than [2] and [12]. For improving the PDR, these works involve a significant overhead of retransmission, guide-path discovery, and relay selection mechanism, respectively. In contrast, our work does not involve guide-path discovery, relay selection, and retransmission overhead but still gives a higher PDR and very low FAR.

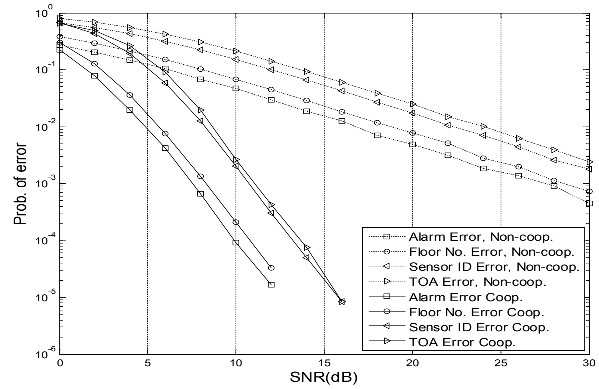


Fig. 7. Simulation results for 12-node cooperation group. (a) Simulation field of information. (b) Prob. of error for the received information at the BS.

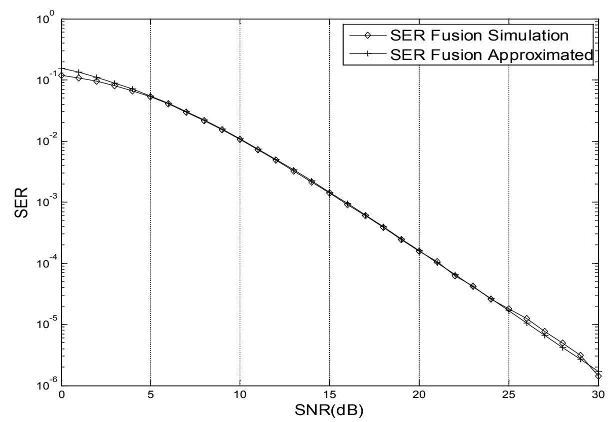


Fig. 8. Comparison of simulation result after fusion at the BS and the approximated SER given in (13).

TABLE II. COMPARISON WITH RELATED WORKS

Performance Metrics	[2]	[12]	[13]	[14]	[15]	Our Work
FAR	–	–	–	3.8%	10.5%	1.8%
PDR	~70%	~73%	~84%	–	–	~86%

VI. SIMULATION RESULTS

Assume an indoor communication environment of 100×100 m^2 with hard-partitioned rooms. Some machines are scattered inside this area that generate some 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. The inter-sensor channels and the channels from sensor to BS are modeled as Rayleigh faded with lognormal shadowing for indoor environments with $\sigma = 7$ and $\eta = 3$. Each sensor has a sensing range of 18 m and 2.4 GHz ISM band carrier frequency is used. We assume the destination location at the edge of the area under consideration, and the nodes deployed according to the scheme discussed in Section II-*A*. The results are averaged over 20,000 sensing operations and compare our proposed scheme with that of a non-cooperative dual-hop communication.

Fig. 7 shows the probability of error for the alarms generated at the BS, floor number, sensor ID, and TOA for 12-node cooperation. We can see a clear advantage by using the proposed cooperation schemes, which achieves, on average, 10^{-3} probability of error at almost 20 dB lower SNR compared with the non-cooperative scheme. By taking into account the 2 dB increase in the cooperative transmission to the BS for $\mathcal{N}=12$, we can still get ~18 dB savings in the SNR as compared to the traditional dual-hop transmission without cooperation.

Fig. 8 shows the numerical result obtained in (13) for the SER of a cooperation group of 3 nodes, using majority vote fusion scheme at the BS compared with the simulated result. We can see that the approximated result matches that of simulation, especially at high SNR. The result also verifies that our proposed cooperation and fusion scheme is able to achieve the full diversity order of l=2 here.

VII. Conclusion

In this paper, we have proposed a relay based dual-hop cooperative WSN to monitor the state of an indoor industrial environment. By applying the proposed cooperation scheme, we obtain a much better performance in terms of SER and achieve a highly accurate decision at the base station. The packet overhead and energy consumption is reduced by combining a limited number of sensors' data into one packet for transmission. The energy saving provided by the proposed scheme is almost 18 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. We also derived a closed-form solution for the SER of the proposed scheme, which verifies the diversity benefit of the scheme.

As a future work, this scheme can be extended to multi-hop and mobile sensor networks. Furthermore, the MAC design proposed in this paper can be further developed in future.

Appendix A
Proof of Theorem 1

In order to find the SNR at the destination D, we need to calculate the signal power and noise power components at the destination. The signal power for a single link is $\left(\beta_{1,j}^2\zeta_{1,j}^2\right)\left(\alpha_{1,D}^2\right)$. Since, each node sends independent information, we take average to approximate the received signal power for each node at the destination. The signal power received from ith relay node is given as,

$$\begin{aligned}\mathrm{SP}_i&=\begin{bmatrix}\left(\beta_{i,1}^2\zeta_{i,1}^2\right)\times\left(\beta_{i,2}^2\zeta_{i,2}^2\right)\times\left(\beta_{i,3}^2\zeta_{i,3}^2\right)\times\ldots\\ \times\left(\beta_{i,\mathcal{N}-1}^2\zeta_{i,\mathcal{N}-1}^2\right)\end{bmatrix}\left(\alpha_{i,D}^2\right)\\&=\alpha_{i,D}^2\prod_{j=1}^{\mathcal{N}-1}\beta_{i,j}^2\zeta_{i,j}^2\end{aligned}. \quad (18)$$

Similarly, the noise power for a single link is $\left(N_{0,1,j}\zeta_{1,j}^2\right)\left(\alpha_{1,D}^2\right)+N_{0,1,D}$. The total noise power at the destination can be calculated as follows,

$$\begin{aligned}\mathrm{NP}_i&=\begin{bmatrix}\left(N_{0,i,1}\zeta_{i,1}^2\right)\times\left(N_{0,i,2}\zeta_{i,2}^2\right)\times\\ \left(N_{0,i,3}\zeta_{i,3}^2\right)\times\ldots\times\left(N_{0,i,\mathcal{N}-1}\zeta_{i,\mathcal{N}-1}^2\right)\end{bmatrix}\left(\alpha_{i,D}^2\right)+N_{0,i,D}\\&=N_{0,i,D}+\alpha_{i,D}^2\prod_{j=1}^{\mathcal{N}-1}N_{0,i,j}\zeta_{i,j}^2\end{aligned}. \quad (19)$$

The equivalent SNR at the destination, $\gamma_{eq,i,D}$ with respect to the relay node i can then be calculated by dividing the signal power with noise power as follows,

$$\gamma_{eq,i,D}=\frac{\alpha_{i,D}^2\prod_{j=1}^{\mathcal{N}-1}\beta_{i,j}^2\zeta_{i,j}^2}{N_{0,i,D}+\alpha_{i,D}^2\prod_{j=1}^{\mathcal{N}-1}N_{0,i,j}\zeta_{i,j}^2}. \quad (20)$$

Dividing the numerator and the denominator by $N_{0,i,D}\prod_{j=1}^{\mathcal{N}-1}N_{0,i,j}\zeta_{i,j}^2$, (20) is simplified as follows,

$$\text{Numerator}=\gamma_{i,D}\prod_{j=1}^{\mathcal{N}-1}\gamma_{i,j}, \quad (21)$$

$$\text{Denominator}=\frac{1}{\prod_{j=1}^{\mathcal{N}-1}N_{0,i,j}\zeta_{i,j}^2}+\frac{\alpha_{i,D}^2}{N_{0,i,D}}. \quad (22)$$

Putting $\zeta_{i,j}=\dfrac{1}{\sqrt{E_{s1}\left|\beta_{i,j}\right|^2+N_{0,i,j}}}$ in (22), we get the following,

$$\text{Denominator}=\prod_{j=1}^{\mathcal{N}-1}\gamma_{i,j}+\gamma_{i,D}+1. \quad (23)$$

Therefore, the equivalent SNR at the destination D with respect to a sensor node i, is given as,

$$\gamma_{eq,i,D}=\frac{\gamma_{i,D}\prod_{j=1}^{\mathcal{N}-1}\gamma_{i,j}}{\prod_{j=1}^{\mathcal{N}-1}\gamma_{i,j}+\gamma_{i,D}+1}. \quad (24)$$

The SER formulation for the proposed system with M-PSK modulation, and conditioned upon known channel coefficients is given as,

$$\begin{aligned}P_s\left(\gamma_{eq,i,D}\right)&=\frac{1}{\pi}\int_0^{(M-1)\pi/M}e^{\left(-\frac{g_{PSK}\gamma_{eq,i,D}}{\sin^2\theta}\right)}d\theta\\&=\frac{1}{\pi}\int_0^{(M-1)\pi/M}e^{\left(-\frac{g_{PSK}}{\sin^2\theta}\left(\frac{\gamma_{i,D}\prod_{j=1}^{\mathcal{N}-1}\gamma_{i,j}}{\prod_{j=1}^{\mathcal{N}-1}\gamma_{i,j}+\gamma_{i,D}+1}\right)\right)}d\theta\end{aligned}. \quad (25)$$

Since, each hop in the multi-hop multi-branch communication experiences independent fading and,

$$\int_0^\infty e^{\left(-\frac{g_{PSK}E_s z}{N_0\sin^2\theta}\right)} p_{|h|^2}\left(z\right)dz = \frac{1}{1+\frac{g_{PSK}E_s\sigma_h^2}{N_0\sin^2\theta}} \qquad (26)$$

where h is the corresponding fading channel coefficient. Therefore, we can write $P_s\left(\gamma_{eq,i,D}\right)$ as

$$P_s\left(\gamma_{eq,i,D}\right) = F\left(1+\frac{g_{PSK}}{N_0'\sin^2\theta}\left(\frac{\sigma_{i,D}^2\prod_{j=1}^{N-1}\sigma_{i,j}^2}{\prod_{j=1}^{N-1}\sigma_{i,j}^2+\sigma_{i,D}^2+1}\right)\right) \qquad (27)$$

where $F\left(x\left(\theta\right)\right) = \frac{1}{\pi}\int_0^{(M-1)\pi/M}\frac{1}{x\left(\theta\right)}d\theta$.

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