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Sleep Scheduling in Industrial Wireless Sensor Networks for Toxic Gas Monitoring

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Abstract

Toxic gas leakage that leads to equipment damage, environmental effects, and injuries to humans is the key concern in large-scale industries, particularly in petrochemical plants. Industrial wireless sensor networks (IWSNs) are specially designed for industrial applications with improved efficiency, and remote sensing for toxic gas leakage. Sleep scheduling is a common approach in IWSNs to overcome the network lifetime problem due to energy constrained nodes. In this article, we propose a sleep scheduling scheme that ensures a coverage degree requirement based on the dangerous levels of the toxic gas leakage area, while maintaining global network connectivity with minimal awake nodes. Unlike the previous sleep scheduling algorithm, for example, the connected k-neighborhood (CKN)-based approach that wakes up the sleep nodes over the entire sensing field by increasing the k-value, our proposed scheme dynamically wakes up the sleep nodes only in the particular toxic gas leakage area. Simulation results show that our proposed scheme outperforms the CKN-based sleep scheduling scheme with the same required coverage degree for the toxic gas leakage area. In addition, the proposed scheme considers multiple hazardous zones with various coverage degree requirements. We show that at the expense of a slight extra message overhead, energy consumption in terms of totally awake nodes over the entire sensing field is reduced compared to the other approaches, while maintaining network connectivity.

Introduction

Toxic gas monitoring is a critical issue in large-scale petrochemical plants, alerting personnel of potential exposure and preventing explosions. Industrial wireless sensor networks (IWSNs), with the advantages of easy deployment, small size, energy efficiency, and mobility of sensor nodes, becomes a promising approach for both petrochemical plant designers and manufacturers to solve the critical issue of toxic gas monitoring.

Moreover, detecting the boundary of a toxic gas leakage area is very difficult due to the invisibility, fast movement, and changing shape with time. In most gas leakage accidents, different types of chemical gases tend to leak at the same time, which causes the phenomenon of gas-mixture. Thus, we need more than one type of gas sensor to detect the gas mixture during a leakage in large-scale petrochemical facilities [1]. Figure 1 illustrates an example with different gas sensors that are used for toxic gas monitoring at the SINOPEC Maoming Petrochemical Company, Maoming, Guangdong, China, which became an integrated refining and leading chemical enterprise in the petrochemical sector.

Apart from these, different types of toxic gases have various levels of influence on humans as well as industries. For example, some manufacturers set the low alarm level at 0.5 parts-per-million (PPM)[1], with at least 30 s concentration monitoring for chlorine, while the low alarm level is set at 2 PPM with at least 30 s concentration monitoring for hydrogen sulphide [2]. Therefore, we have the following observation during toxic gas leakage in large-scale petrochemical plants:

- Several gas leakage zones are identified over the entire industrial sensing field based on the type of toxic gas and the probability of occurrence at a given instant.
- The alarm levels are adjusted based on the sensor detection characteristics and various safe-zone requirements due to the various purposes, e.g., worker safety, equipment damage, process control, and environmental safety.

The IWSN, however, inherits the drawbacks of traditional wireless sensor networks (WSNs), i.e., limited lifetime due to the power-constrained wireless nodes. Sleep scheduling is one effective approach to prolong network lifetime. Since it allows a subset of the deployed sensor nodes to be awakened, other nodes sleeping conserves energy.

Therefore, it is required to keep a minimum number of awake nodes to meet the coverage degree[2] in various gas leakage zones. Figure 2 shows an example of a few gas leakage zones. We observe that it is not an effective approach to wake up the sleep nodes by the same amount over the entire network. This motivates us to design a varying coverage requirement-based sleep scheduling scheme for toxic gas monitoring in large-scale industrial plants.

The main contributions of this article are summarized as follows:

- This article mainly considers various coverage requirements in several toxic gas leakage areas in the sleep scheduling scheme.
- It is an important issue to prolong the network lifetime as well as to ensure safety requirements during toxic gas leakage. This article proposes an approach that wakes up the minimum number of nodes to provide the coverage requirement compared to other schemes that increase the number of awake nodes over the entire network.

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[1] PPM is the most common unit of measurement for toxic gases. A 10,000 PPM concentration level equals a 1 percent by volume exposure.

[2] Coverage degree for a certain point is defined as the number of awake sensor nodes that cover the point.

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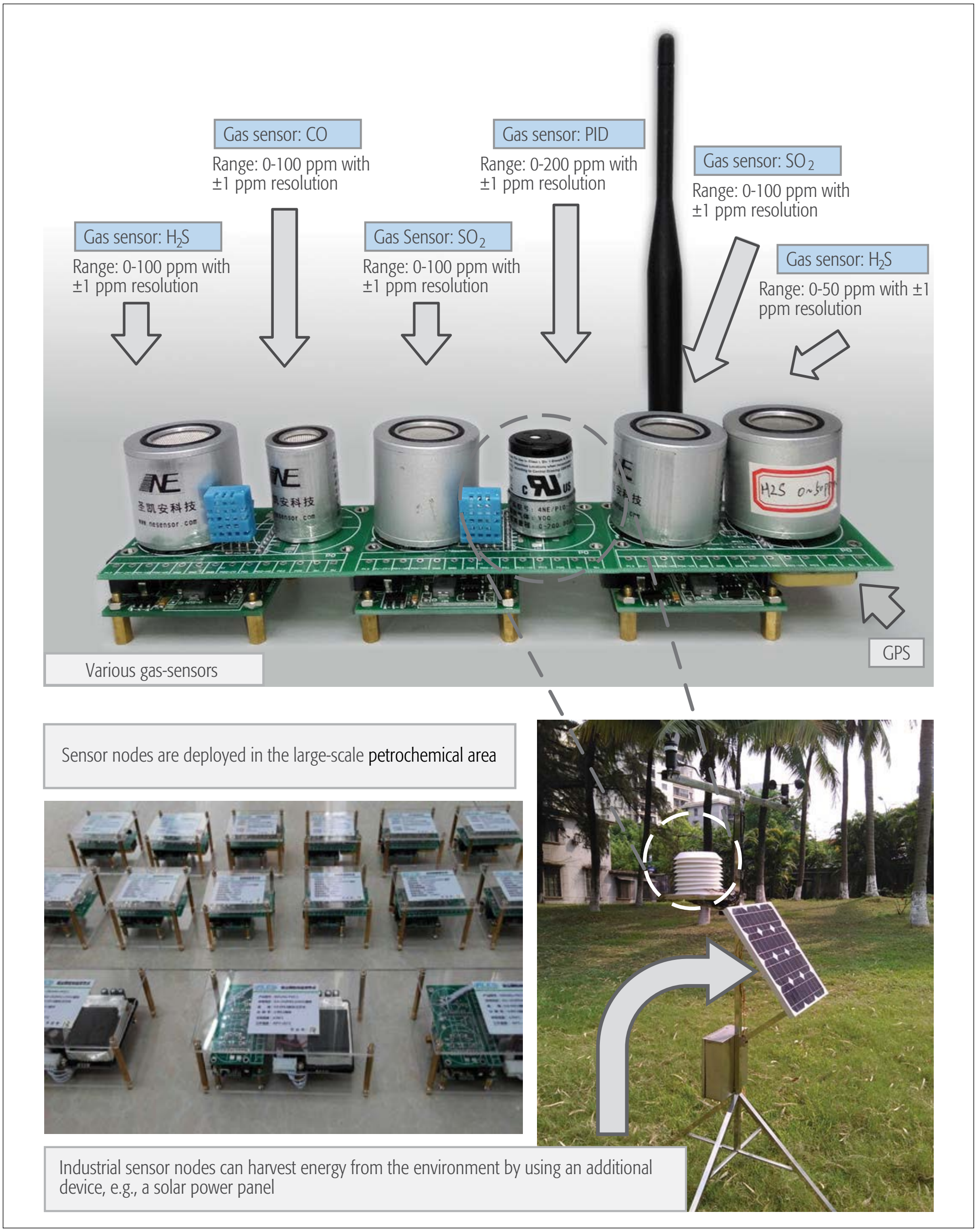

FIGURE 1. These gas sensors are made available for various experimental purposes. We use six types of toxic gas sensors (e.g., two hydrogen sulfide (H_2S) sensors with different sensing ranges, sulphur dioxide (SO_2), carbon monoxide (CO), volatile organic compounds (VOCs) with photoionisation detection (PID) sensor technology, and nitrogen dioxide (NO_2) to detect different types of explosive gases.

The energy in a wireless sensor node is not always renewable due to the cost, harsh industrial environment, and hard-to-reach areas in a petrochemical plant. One approach to minimize energy consumption is to allow some sensor nodes to be in sleep-state. The sensor node in a sleep-state turns off its either sensory or radio device.

SLEEP SCHEDULING SCHEMES IN DUTY-CYCLED IWSNS

The energy in a wireless sensor node is not always renewable due to the cost, harsh industrial environment, and hard-to-reach areas in a petrochemical plant. One approach to minimize energy consumption is to allow some sensor nodes to be in sleep state. The sensor node in sleep state turns off either its sensory or radio device. Turning off the sensory device results in undetected events, whereas turning off the radio device disrupts the communication capability. Recently, Spenza *et al.* [3] discussed ultra-low-power transceivers with features such as high sensitivity (up to –55 dBm), short wake-up latency, and nano ampere current consumption (560 nA at 3 V) in idle listening state. Without loss of generality, we assume that a state-of-the-art ultra-low-power wake-up radio is always on to save energy compared to the main transceiver in idle listening state.

Since network *coverage* and *connectivity* are the main issues in duty-cycled WSNs, we discuss the most relevant research studies as follows. Existing works on sleep-scheduling mainly focus on point coverage (also known as *spatial coverage*), and node coverage to maintain global connectivity.[3] Kumar *et al.* [4] studied a randomized independent scheduling mechanism to

[3] In a globally connected network, each sleep node has at least one 1-hop awake node.

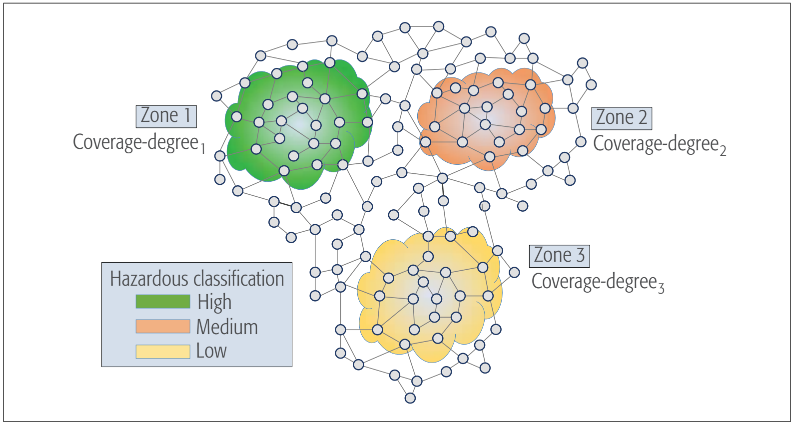

FIGURE 2. A few gas leakage zones are identified in the entire region, e.g., Zone 1, Zone 2, and Zone 3, based on the type of gases and danger levels in the large-scale IWSN. Different coverage requirements should be applied to these zones.

prolong network lifetime while achieving asymptotic K-coverage. In addition, a centralized as well as distributed sleep-scheduling algorithm that maintains K-coverage has been discussed in [5]. Tian and Georganas proposed a distributed sleep scheduling scheme [6] that allows a sensor node to turn off only if its sensing area is completely covered by its neighbors' sensing areas. Since this method [6] only considers those neighbors within a node's sensing area, it is not able to determine the optimal number of awake nodes. The coverage-aware sleep scheduling scheme is proposed in [7], where each sensor computes the total overlap area between itself and its active neighbors during each scheduling cycle. Then, the sleep-node goes to sleep in the next cycle with a probability that is proportional to the size of the overlapping area.

Connected k-Neighborhood (CKN)-Based Sleep Scheduling Algorithm: A sleep scheduling algorithm is proposed in [8] to solve the CKN problem.[4] Figure 3 illustrates the examples of the unconnected, 1-, 2-, and 3-connected graphs along with the CKN algorithm with different k-values in a 600 × 600 m^2 area with 400 sensor nodes. The focus of the CKN is to save energy consumption while the global network is still connected by the awake nodes. Recently, we proposed several CKN-based sleep scheduling schemes such as geographic routing-oriented sleep scheduling (GSS), energy-consumption-based CKN (EC-CKN) [9], geographic-distance-based connected k-Neighborhood for first path (GCKNF), geographic-distance-based connected k-neighborhood for all paths (GCKNA), collaborative location-based sleep scheduling scheme (CLSS) [10], and priority-based sleep scheduling (PSS). The CKN-based GSS scheme awakes the potential nearest neighbor nodes to the sink. In addition, the EC-CKN [9] considers the nodes' residual energy information as the parameter to decide whether a node is active or asleep. However, another sleep-scheduling scheme, data contain oriented sleep scheduling (DSS), is based on the fact that the sensor node with more data scope should be awakened so more important data related to environmental changes can be transmitted.

Coverage Issues for Toxic Gas Monitoring

It is required to monitor highly dangerous gas leakage areas with a significant number of awake sensor nodes. The increased coverage degree leads to an improvement in detection and accuracy. Hence, it helps to ensure accurate and fast detection of the toxic-gas area that is potentially harmful to humans as well as industrial applications. From the discussion above, we observe that the focus of [5–7] is to minimize the overlapping area. In contrast, our aim is to increase the overlapping area, which helps guarantee the coverage requirement for a high dangerous leakage zone. In addition, most approaches did not consider the various danger levels in the sensing area.

The coverage area is enhanced by either increasing the transmission radius or increasing the number of awake nodes. Recently, we proposed a cross-layer optimization scheme, called adjusting the transmission radius (ATR) [11], that is based on the EC-CKN sleep scheduling algorithm. This scheme increases the transmission radius of the other neighbor nodes to get a sleep opportunity. In contrast, to increase the number of awake nodes, we may increase the value of k in the CKN algorithm over the entire sensing area. It is worth noting that we need to wake up sleep nodes in high danger gas leakage areas rather than the entire field. Therefore, increasing the k-value in the CKN algorithm unnecessarily increases the number of awake nodes over the entire area. As a result, the network lifetime will decrease due to higher energy consumption in a large number of awake nodes. Hence, there is a trade-off between the number of sleep nodes to prolong the network lifetime and varying coverage degree to ensure accurate detection of toxic gas. Our research interests fall within the following scope: we propose a scheme that wakes up the minimum number of sleep nodes to balance the coverage requirement and network lifetime in a large-scale plant with IWSNs.

System Model

Network Model

We consider a multihop WSN with uniformly and randomly deployed sensor nodes in a large-scale 2-dimensional industrial sensing field with N sensor nodes. The transmission range r is assumed to be the same for all the sensor nodes. For simplicity, but without losing too much generality, the transmission range is equal to the sensing range of the sensor nodes. We assume the CKN-based sleep scheduling model for the initial phase of our scheme. This allows us to maintain global connectivity with a maximum number of sleep nodes. The nodes u and v are 1-hop neighbors to each other if they are within the transmission range. The location of any sensor node along with its 1-hop and 2-hop neighbors can be obtained by using the Global Positioning System (GPS) or other techniques such as triangulation or localization. The sink node knows the location and IDs of all nodes. We use the well known request-to-send (RTS)/clear-to-send (CTS)-based link scheduling approach [12] to prevent message collision of more than one node.[5] We do not consider noise and interference in the industrial network model since we only focus on the theoretical aspect of this research problem. Since strong wind changes the shape and the concentration of toxic gas with time,

[4] Given a constant k and an undirected graph $G = (U, L)$, where U and L are the set of nodes and edges, respectively, a connected-k neighborhood is a subsect $C \subseteq U$ with the following two characteristics: each node $u \in U$ has at least $m = \min(k, d_u)$ neighbors from C, where d_u is the degree of u in G; the nodes in C are connected.

[5] RTS/CTS is managed by the local zone head.

it has a strong impact on the gas leakage area [13]. However, without increasing the complexity of the system model, we do not consider the scenario with a strong wind nor wind direction. For the theoretical study and analysis, we model the toxic gas as a circle with an increasing radius. It is also assumed that each node has the same functionality and capability. With a very large number of sensor nodes, we ensure a well connected WSN in the deployed area.

Hazardous Classification

The hazardous-zone that is used for the proposed sleep scheduling scheme is characterized by the type of gas and the probability of occurrence. Let $\{A_i, i = 1, 2 \ldots, N\}$ be the gas leakage area that is identified by the above classification. We denote the number of awake nodes in the A_ith zone by N_i^a. Thus, the *zone coverage degree D* is approximated as $(N_i^a \times \pi r^2)/A_i$. However, this approximation is valid if we assume a uniform deployment and infinite points to be covered in the A_ith sensing area. Without loss of generality, we calculate D as follows [14]. The entire sensing area is divided into small square grids. We assume that the center point of this square grid is the point to be covered by a sensor node. Then, we average the number of awake sensor nodes over all points in that area to obtain D. Afterward, we set a threshold zone coverage degree D_{Th} (sometimes known as the alarm level in an industrial application) to ensure safety in the A_ith hazardous zone. These threshold values are adjusted based on a statistical analysis of the previous stored data related to toxic gas leakage.

Proposed Scheme

In this section, we describe the scheme that ensures D_{Th} while maintaining global connectivity in the network with a minimum number of awake nodes. Figure 4 presents a workflow of our proposed scheme. An explanation of the detailed operation follows.

Step 1–Hazardous Classification and Zone-Head Selection: As discussed earlier, we assume that all the deployed nodes are aware of the geographic field and their own locations. The area of the A_ith gas leakage zone is determined by a boundary detection algorithm [15] with the boundary nodes. Thus, any awake node decides itself whether it is either inside or outside the gas leakage area. In addition, every A_ith zone has its own head node. A sensor node inside the gas leakage area is selected as the *zone head* based on the largest residual energy by restricted flooding of the *head selection* message within the A_ith zone.

Step 2–Apply the CKN Algorithm with k = 1: Each sensor node applies the CKN algorithm over the entire network to ensure global connectivity. In addition, the CKN algorithm with $k = 1$ allows the maximum number of sleep nodes to prolong the network lifetime.

Step 3–Determine the Zone Coverage Degree: Each awake node reports the sensing status and the grid centers covered by itself to the zone head. In this way, the zone head estimates D and sends this status to the sink. After comparing it with the D_{Th}, the sink returns a message either to increase the zone coverage degree or not. Then, the zone head estimates the location that has $D < D_{Th}$.

Step 4–Self-Scheduling Phase: Each awake sensor node that covers the grid centers with $D < D_{Th}$ sends a *wake-up* message that contains its position, node ID, and the co-ordinates of the grid-points covered by itself, to its 1-hop sleep-neighbor. After receiving the wake-up message, the sleep node waits for any broadcast message from its other 1-hop awake neighbors. The sleep node then estimates the D of the area under its sensing range. Since the message exchange between the awake node and the sleep node is limited within the localized A_ith area rather than the entire sensing field, the data-traffic overhead is significantly reduced compared to the centralized scheme.

Step 5–Awake the Sleep Nodes: The sleep node wakes up based on the following criteria. The sleep node compares D with its 1-hop and 2-hop sleep-neighbor. Then, the sleep nodes *collaboratively* identify the node that has more impact on the increase of D. Once the sleep node wakes up, it sends the no-wake-up message to its 1-hop and 2-hop sleep nodes. Since we use the RTS/CTS model [12] for link scheduling, the collision of the no-wake-up messages due to simultaneous wake-up nodes is prevented. Furthermore, the wake-up node sends an *update coverage degree* request to its 1-hop or 2-hop nodes that cover the same sensing area.

If a sleep node receives a *no-wake-up* message from its 1-hop or 2-hop neighbors, then it extends its sleeping time, consequently prolonging the network lifetime.

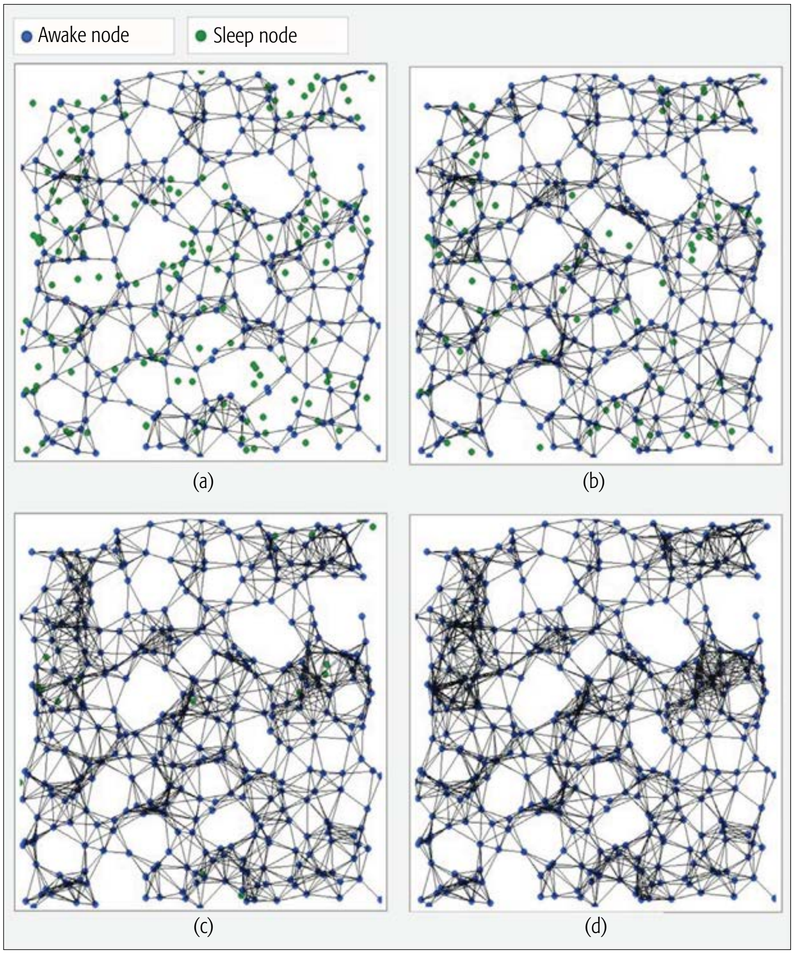

Figure 3. Some basic examples the CKN algorithm with different k-values in a 600×600 m^2 area with 400 sensor nodes. a) A large number of sleep nodes is observed for $k = 1$. However, the number of sleep node declines at higher k-values, for example: b) $k = 2$; c) $k = 4$; d) almost all sensor nodes are awake with $k = 8$.

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For the theoretical study and analysis, we model the toxic gas as a circle with an increasing radius. It is also assumed that each node has the same functionality and capability. With a very large number of sensor nodes, we ensure a well-connected WSN in the deployed area.

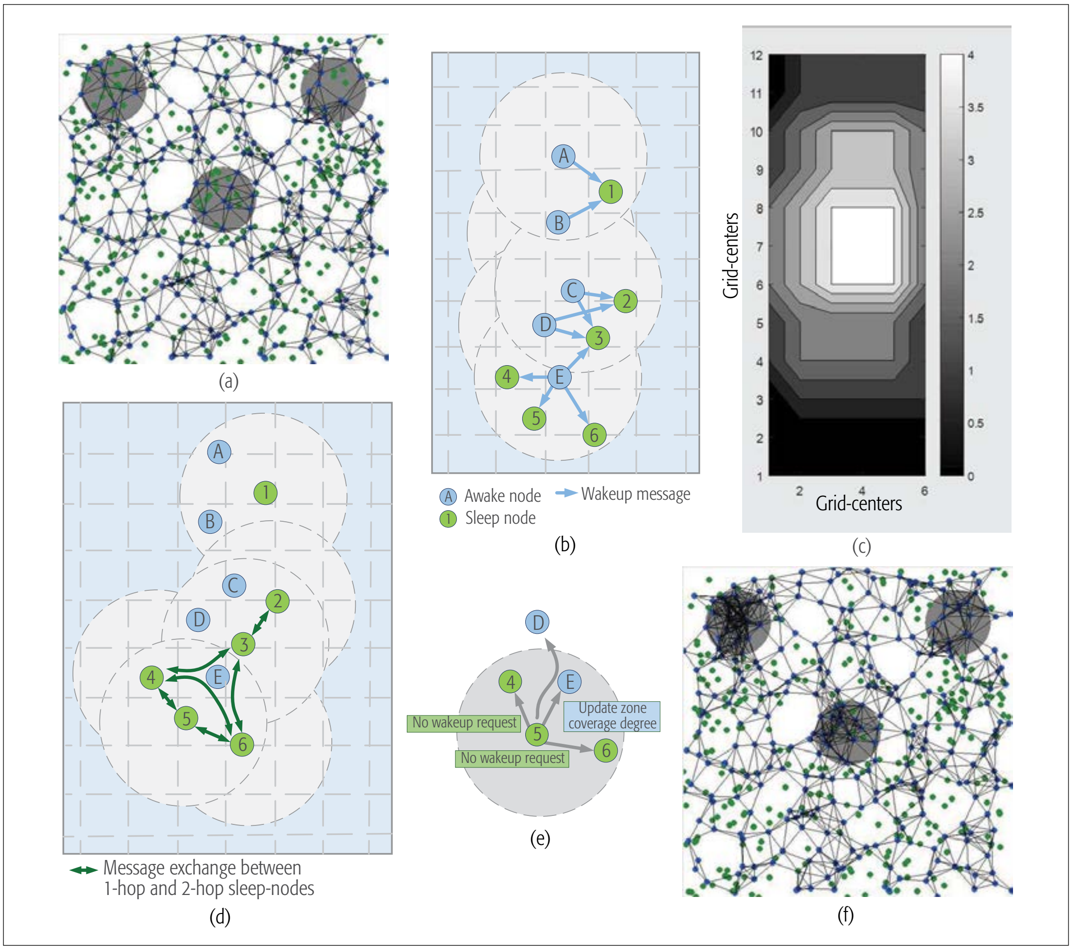

FIGURE 4. Illustration of the proposed scheme. a) Each sensor node applies the CKN algorithm with $k = 1$ to ensure global connectivity with a large number of sleep nodes. Green and light black colored nodes represent sleep nodes and awake nodes, respectively. A few gas leakage areas are identified in the sensing field. b) The gas leakage area is divided into small grids. The zone head estimates D and sends the status to the sink. c) A contour plot of D at the grid centers. After comparing with the $D < D_{Th}$, the sink returns a message to increase the coverage degree or not. In this way, the zone header estimates the location that has $D < D_{Th}$. Each awake sensor node that covers the grid center points with $D < D_{Th}$, sends a *wake-up* message to a 1-hop sleep neighbor. d) The sleep node then compares the zone coverage degree with any 1-hop or 2-hop sleep neighbors. Then, the sleep nodes collaboratively select the node that has more impact on increasing the coverage degree. e) When a sleep-node (e.g., node 5) wakes up, it sends the *no wake-up* message to its 1-hop and 2-hop sleep nodes. Moreover, it sends the *update zone coverage degree* request to 1-hop or 2-hop nodes within the same grid centers covered by the recently awakened node (e.g., node 5). f) The sleep nodes and awake nodes in the gas leakage areas with the proposed scheme.

Energy Consumption: Assuming the r^2-energy-loss model in channel transmission, the energy consumption to transmit and receive a bit packet over a distance d are expressed as $E_{Tx}(d) = E_{elec} + E_{amp}d^2$ and $E_{Rx} = E_{elec}$, respectively, where E_{amp} is the energy consumed in the amplifier of the transmitter to send a packet at unit distance, and a node consumes E_{elec} to run the transceiver circuitry. When a node u executes the CKN algorithm, its energy consumption is given by $E_{CKN} = E_{c,CKN} + 2(E_{Tx} + |N_u|E_{Rx})$, where $E_{c,CKN}$ is the constant additional energy consumed during the CKN algorithm execution and $|N_u|$ is the number of 1-hop neighbors of the uth node. Further, the energy consumption during each epoch is expressed as $E_{Epoch} = E_{c,Epoch} + T(\gamma E_{Tx} + \lambda E_{Rx})$, where λ and γ are the input and output packet rate of the uth node, respectively, T is the transmit time duration of a packet, and $E_{c,Epoch}$ is the constant energy consumed due to battery power leakage in each epoch.

Since we assume the always-on ultra-low power wake-up transceiver that consumes energy $E_w \ll E_{Tx}, E_{Rx}$ to transmit as well as receive a wake-up message within its 1-hop neighbor, the self-scheduling phase discussed in *Step 4* requires an additional $|N_u|E_w$ amount of energy. In this way, each *no-wake-up* and *update coverage degree* message consume an additional $(|N_u| + 2|N'_u|)E_w$ amount of energy in each epoch, where $|N'_u|$ is the number of 2-hop neighbors of the uth node.

PERFORMANCE EVALUATION

In this section, we evaluate the zone coverage degree performance of the CKN-based sleep scheduling approach, and compare the performance of the proposed scheme with the CKN-based schemes.

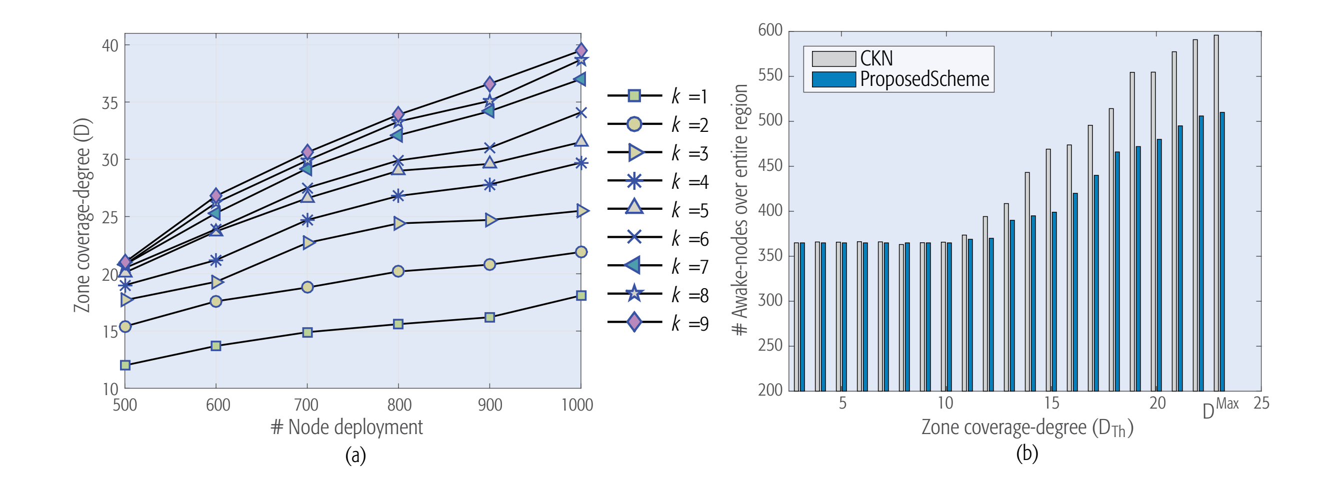

FIGURE 5. a) Zone coverage degree performance for different *k*-values in the CKN-based scheme with different node deployments; b) performance comparison in terms of number of awake nodes to meet different D_{Th} with a 600 node deployment.

Simulation Setup

We conduct the simulation using a WSN simulator known as NetTopo.[6] The sensor nodes are distributed over an area of 600 m × 600m. For each number of deployed sensor nodes, we average the results over 100 different network topologies. The number of sensor nodes ranges from 500 to 1000 (each time incremented by 100). The transmission radius of each node is 60 m. We use a grid-size of 0.5 m × 0.5 m over the entire area to calculate *D*.

Performance of Zone Coverage Degree in the CKN-based Scheme

Figure 5a shows the zone coverage degree performance of the CKN-based sleep scheduling scheme with a different node deployment in the entire sensing field. It is clear that *D* increases either by increasing the *k*-value in the CKN algorithm or with larger node deployments. For example, $D \approx 30$ is obtained with $k = 9$ with 700 deployed nodes; $k = 6$ with 800 deployed nodes; $k = 5$ with 900 deployed nodes; and $k = 4$ with 1000 deployed nodes. However, it is interesting to note that although we increase the *k*-value in the CKN algorithm, *D* cannot be increased further. Thus, the maximum zone coverage degree (D^{Max}) is reached when almost all nodes are awakened after a certain *k*-value in the CKN algorithm with a particular node deployment. We also observed that D^{Max} increases at a larger node deployment. Thus, with a deployment cost, *D* range is larger at higher node density.

Performance Comparison between the Proposed Scheme and the CKN-based Sleep Scheduling

We model the toxic gas leakage as a circle with a radius of 60 m at location (300, 300). The value of D_{Th} for the gas leakage area is increased by 1 each time. From Fig. 5b, we observe that the number of awake nodes with $k = 1$ in the CKN algorithm is the same as the proposed scheme up to $D = 11$ for 600 nodes. The reason is that in our scheme, each sensor node applies the CKN algorithm with $k = 1$ over the entire network to ensure global connectivity. Hence, a certain *D* is obtained with the same number of awake nodes as $k = 1$ in the CKN-based scheme. We observe that the CKN-based scheme with $k = 1$ satisfies $D^{Th} \leq 11$ in the case of the deployment of 600 nodes. As expected, the value of *k* is increased to meet D^{Th} in the CKN-based scheme. However, for $D^{Th} > 11$, the proposed scheme outperforms the CKN-based scheme in terms of awake nodes over the entire region. As the number of deployed nodes is same in the gas leakage area for both scenarios, $D^{Max} = 23$ for both the CKN-based scheme and proposed scheme with a node deployment of 600. An improvement of about 11 percent and 14 percent in terms of awake nodes over the entire network is observed in the proposed scheme to meet the D^{Th} of about 15 and 23 in a deployment of 400 and 600 nodes, respectively.

Two Hazardous Zones with Different D_{Th}

To evaluate the performance of the proposed scheme with more than one hazardous zone with different D_{Th}, we identify two gas leakage areas at locations (400, 300) and (300, 400), respectively. The threshold zone coverage degrees $D_{Th}^{Gas\,1}$ and $D_{Th}^{Gas\,2}$ are summarized in Table 1. It is important to note that the CKN-based schemes change the *k*-value over the entire region to consider max-$\{D_{Th}^{Gas\,1}, D_{Th}^{Gas\,2}\}$. However, our proposed scheme wakes the sleep nodes to satisfy D_{Th} per gas leakage area. Hence, a significant advantage in terms awake nodes is observed in the proposed scheme, as shown in Table 1. It is worthwhile to observe that the proposed scheme satisfies more than one gas leakage area with various D_{Th} with a minimum number of awake nodes over the entire sensing area.

Conclusion

In this article, we proposed a sleep scheduling scheme based on the hazardous classification of a gas leakage area in a petrochemical plant. The proposed scheme wakes up a minimum number of sleep nodes in a gas leakage area compared to the well known CKN algorithm that considers the entire region to meet the threshold zone coverage degree. By exhaustive simulation, we observed that the proposed scheme performs significantly better than the CKN-based schemes in terms of awake nodes over the entire sensing area. In addition, from the

[6] NetTopo (online at http://sourceforge.net/projects/nettopo/) is open source software for simulating and visualizing WSNs.

A future research avenue would be to validate the scheme in a testbed since such a scheme is well suited for the large-scale industrial area, particularly petrochemical plants to prolong the network lifetime while satisfying the threshold zone-coverage degree and global connectivity.

D^{Th}		# Awake nodes		Advantage (%)
$D^{Gas\ 1}_{Th}$	$D^{Gas\ 2}_{Th}$	CKN	Proposed scheme	
4	15	450	363	19.33
6	24	597	367	38.52
14	15	447	386	13.64
23	24	598	405	32.27

Table 1. Number of awake nodes over the entire region with two hazardous zones (Gas 1 and Gas2), node deployment = 600.

simulation results, it is observed that the proposed scheme results in an improvement of about 11 percent and 14 percent in terms of awake nodes over the entire network to meet the threshold zone coverage degree of about 15 and 23 in deployments of 400 and 600 nodes, respectively. Furthermore, the proposed scheme considers more than one threshold zone coverage degree for different gas leakage areas. A future research avenue would be to validate the scheme in a testbed since such a scheme is well suited for a large-scale industrial area, particularly petrochemical plants, to prolong the network lifetime while satisfying the threshold zone coverage degree and global connectivity.

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Biographies

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