Analysis of Energy-Efficient Connected Target Coverage Algorithms for Industrial Wireless Sensor Networks

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***Abstract*—Recent breakthroughs in wireless technologies have greatly spurred the emergence of industrial wireless sensor networks (IWSNs). To facilitate the adaptation of IWSNs to industrial applications, concerns about networks' full coverage and connectivity must be addressed to fulfill reliability and real-time requirements. Although connected target coverage (CTC) algorithms in general sensor networks have been extensively studied, little attention has been paid to reveal both the applicability and limitations of different coverage strategies from an industrial viewpoint. In this paper, we analyze characteristics of four recent energy-efficient coverage strategies by carefully choosing four representative connected coverage algorithms: 1) communication weighted greedy cover; 2) optimized connected coverage heuristic; 3) overlapped target and connected coverage; and 4) adjustable range set covers. Through a detailed comparison in terms of network lifetime, coverage time, average energy consumption, ratio of dead nodes, etc., characteristics of basic design ideas used to optimize coverage and network connectivity of IWSNs are embodied. Various network parameters are simulated in a noisy environment to obtain the optimal network coverage. The most appropriate industrial field for each algorithm is also described based on coverage properties. Our study aims to provide IWSNs designers with useful insights to choose an appropriate coverage strategy and achieve expected performance indicators in different industrial applications.**

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I. Introduction

RECENTLY, industrial wireless sensor networks (IWSNs), which consist of many sensor nodes, have evolved as a powerful tool for an industrial automation system (IAS). Different from traditional IAS realized through wired communications, sensors of an IWSN can be installed on industrial equipment and monitor critical parameters to ensure normal operations [1]. Also, each sensor has wireless communication capability to provide data delivery service. Due to the absence of cables, the use of inexpensive and tiny sensor nodes contributes to the flexibility and energy efficiency of IAS [2].

Industrial applications require a high measure of reliability, so any sensing of essential equipment or processes must be prioritized and free of interruption. As a leading application of IAS, supervisory control and data acquisition require a high level of reliability in terms of data integrity and timely reporting [3]. Therefore, an IWSN should guarantee uninterrupted target coverage and connectivity among all sensor nodes and a sink node [4]. This is often referred to as the connected target coverage (CTC) problem, where each discrete target in the network must be within the sensing range of at least one sensor node, and where at least one routing path must be found to connect any source node to the sink node [5]. However, in industrial environments, the coverage area of a sensor node, as well as the link connectivity, may suffer from noise, cochannel interferences, and multipath propagation. In addition, energy is arguably the main constraint of wireless sensor nodes [6]–[8]. Therefore, the energy-efficient CTC problem has become an important issue that urgently needs to be addressed.

Energy-efficient CTC approaches ensure that selected nodes are prioritized and remain connected to the control sink even if other nodes die out, while also working toward extending the energy lifetime of the essential nodes and the network as a whole. These approaches could be used to monitor essential equipment with dedicated target sensor nodes. These nodes could be in hard-to-maintain areas, e.g., inside motors, pipes, or furnaces, which places a premium on longer lifetime in addition to connection reliability. IWSNs also need to be resistant to noisy environments [2], a requirement not commonly considered in consumer network design. This paper evaluates prominent approaches to CTC in terms of reliability of covering essential nodes in noisy environments.

A. Contributions

In this paper, both the applicability and limitations of four typical CTC algorithms, namely communication weighted greedy cover (CWGC) [9], optimized connected coverage heuristic (OCCH) [10], overlapped target and connected coverage (OTTC) [11], and adjustable range set covers (AR-SC) [12], are first surveyed and carefully analyzed from an industrial viewpoint. Then, through a detailed comparison in terms of network lifetime, coverage time, average energy consumption, ratio of dead nodes, etc., characteristics of basic design ideas used to optimize coverage and network connectivity of IWSNs are presented. Different network parameters are simulated to obtain the optimal network coverage in a noisy environment. Finally, the most appropriate industrial field for each algorithm is presented according to its own coverage properties.

B. Paper Organization

This paper is organized as follows. In Section II, we review related work and conduct an analysis of existing coverage algorithms. In Section III, the four typical algorithms, named CWGC, OCCH, OTTC, and AR-SC, are carefully analyzed. Section IV provides a performance comparison of the four algorithms. Finally, conclusion is drawn in Section V.

II. Related Work

In the literature, there are numerous papers on optimizing routing and connectivity of networks in a number of different ways. For example, there are proposals that prioritize geographic area coverage [13] as well as barrier coverage [14], rather than the coverage of discrete targets, and allow for network nodes to move after deployment [15]. Due to energy constraint in IWSNs, the scope of our study is confined to CTC protocols with claims to energy efficiency. In this section, we briefly review some of the prominent existing CTC algorithms, which adopt different energy conservation technologies. Related research attempted to schedule sensor nodes to alternate between active and sleep mode by organizing nodes in sets. In [16], a maximum covers algorithm using mixed integer programming (MC-MIP) was proposed. Based on the output of MC-MIP, nodes are organized into disjoint set covers (DSC) which are activated successively. In [17], a greedy algorithm designed for maximum set covers (MSC-Greedy) was proposed. Cover sets generated from MSC-Greedy are not required to be disjoint and are allowed to operate in different time intervals. Compared with MC-MIP, MSC-Greedy produces better results in terms of network lifetime, since the solution space of DSC problem is included in the solution space of the maximum set cover (MSC) problem. Another power-saving method is to adjust transmission or sensing range of sensor nodes by making use of power control technology. In [18], a virtual backbone-based (VBB) algorithm was proposed to solve adjustable sensing range connected sensor cover (ASR-CSC) problem. By determining the transmission range of each node, both target coverage and network connectivity can be guaranteed. In [19], Dhawan *et al.* proposed adjustable range load balancing protocol (ALBP). Combining sleep-sense scheduling technique with adjustable range model, further improvement in network lifetime can be derived by ALBP.

In the above-mentioned related work, special features for industrial environments are not taken into consideration. Also, we observe that basic design ideas behind them determine their performances while a fair and reasonable comparison helps to reveal their characteristics.

III. Energy-Efficient CTC Algorithms

In this section, we show the rationality of our comparison, including why CWGC, OCCH, OTCC, and AR-SC are representative and appropriate to be chosen and why properties of each design idea behind these four algorithms can be embodied through our comparison. The main idea of each algorithm is also introduced by highlighting the energy conserving mechanism they applied.

A. Preliminaries

Since wireless sensor networks (WSN) are application-oriented, algorithms applied in different target applications are based on different design assumptions and objectives. It is unfair and misleading to compare algorithms without considering their assumptions and objectives. In addition, a general survey of literature ignores the characteristics of the algorithm itself. Therefore, a comparison analysis based on a set of sample algorithms which share the same design assumptions and objectives is considered as a better method to understand the algorithms. In this paper, the selected four CTC algorithms, CWGC, OCCH, OTCC, and AR-SC, have a common design objective: to maximize network lifetime while maintaining sensing coverage and network connectivity. Furthermore, they share identical design assumptions including detection model, sensing area, transmission range, failure model, time synchronization, location information, and distance information.

The main difference of the four algorithms is the design ideas they adopted to save energy and prolong network lifetime. These four protocols represent the four typical approaches which fulfill CTC and are, therefore, chosen in this paper as the most representative for the purpose of comparison. The four typical design ideas behind them can be, respectively, summarized as follows: 1) scheduling sensor node activity to allow redundant nodes to enter the sleep mode (CWGC); 2) protecting nodes which monitor critical targets from forwarding data (OCCH); 3) eliminating the redundancy caused by overlapped targets (OTCC); and 4) reducing power consumption to minimize the sensing range while the sensing coverage objective is met (AR-SC). Scientific studies allow the clear identification of cause and effect because only one factor is different at a time, so that the effect of that single factor can be determined. In our study, the same design assumptions and objectives are recognized as constant factors while the idea used to conserve energy is the only variable factor whose effect need to be determined. Therefore, it is fair to embody the properties of each power-saving idea by a detailed comparison. In the following sections, the four typical CTC algorithms are presented in detail.

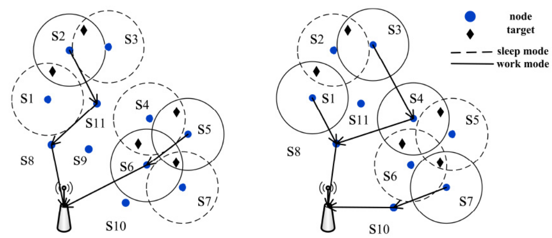

Fig. 1. Example of an MCT.

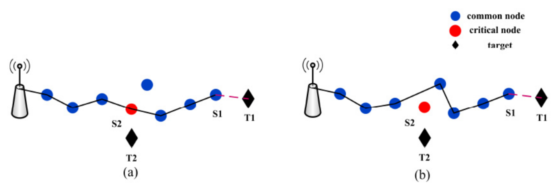

Fig. 2. Avoid traversing a node that covers a critical target.

B. Communication Weighted Greedy Cover

In [9], Zhao *et al.* modeled the CTC problem as a maximum cover tree (MCT) problem. A fast heuristic algorithm called CWGC was proposed to solve the MCT problem. As shown in Fig. 1, a complete cover tree is a logical topology which has the following properties.

1) The root of the tree is a sink node.
2) Each leaf of the tree is a source node.
3) Each target can directly connect to at least one source in the tree.

CWGC consists of three steps.

1) Select sources in a greedy manner that can cover all the targets.
2) Calculate the communication overhead of each edge in the graph to generate the shortest routing path to the sink.
3) Update the communication overhead to avoid selecting nodes with low residual energy.

C. Optimized Connected Coverage Heuristic

It can be observed that a target, which is covered by the minimum number of sensors, is the bottleneck in terms of the network lifetime. This kind of target is known as a critical target. The sensor nodes that monitor the critical targets are defined as critical nodes. Zorbas and Douligeris [10] proposed an efficient algorithm called OCCH to protect the critical nodes from forwarding data. By manually increasing the communication weight of critical nodes, the possibility that a critical node is selected to relay data can be decreased. As shown in Fig. 2, red dots are used to represent critical nodes, while blue dots are used to represent common nodes. Targets are denoted by black rhombuses. It can be observed that, once a critical node appears in the optimal route, a common node in the vicinity of the critical node will replace it and establish a suboptimal route. Although using other nodes may increase the transmission cost, it makes sense to prolong the whole network lifetime.

D. Overlapped Target and Connected Coverage

The energy a node consumes to sense and transmit is proportional to the number of targets within its sensing area. However, multiple transmissions of the same data are redundant and the energy used to process the redundant data is meaningless if we do not take data reliability into consideration. In Fig. 3, adjacent nodes may gather overlapped data from targets and deliver them to the sink node. This is referred to as the overlapped target issue [20].

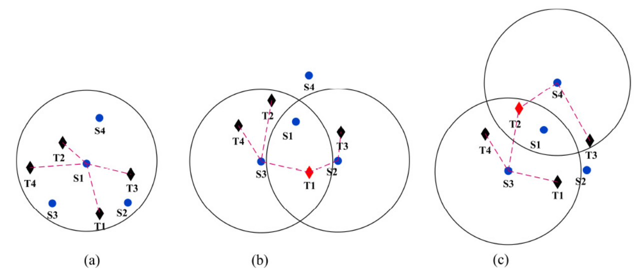

Fig. 3. Overlapped target and corresponding overlapping sensors in joint sets. (a) Set1 = {S1}, no overlapped target. (b) Set2 = {S2, S3}; overlapped target: T1; overlapping sensors: S2,S3. (c) Set3 = {S3,S4}; overlapped target: T2; overlapping sensors: S3,S4.

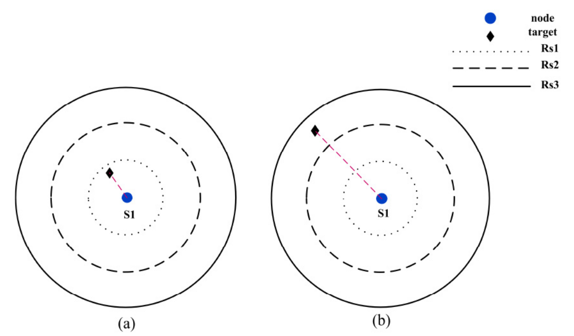

Fig. 4. Example with one node, one target, and three power levels.

To prevent redundant coverage and transmission, it is acceptable that data generated from an overlapped target are transmitted only once. OTCC, proposed by Kim *et al.* [11], was such an algorithm designed to eliminate the redundancy caused by the overlapped target. OTCC constructs a directed acyclic graph named cover and transmission (CT)-graph to find a unique routing path from each target to the sink.

E. Adjustable Range Set Covers

In [12], Cardei *et al.* addressed the target coverage problem with adjustable sensing radius. As shown in Fig. 4, the sensing radius of each node can be adjusted by working on different power levels. A dotted line represents the sensing radius when a node works on a low power level. A dash line represents the sensing radius when a node works on a medium power level, while a solid line represents the sensing radius when a node works on a high power level. Since energy resources are conserved, working on a low power level allows the sensor to be operational longer [Fig. 4(a)]. In addition, the ability to adjust the sensing radius helps the network to be more flexible. When a node with enough residual energy cannot monitor any target in the current state, it has the possibility to join the sensing task by increasing its power level [Fig. 4(b)].

A quadratic model is given to describe the relationship between the energy consumption and sensing radius as it fits

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Physical layer	IEEE 802.15.4
Channel model	AWGN
Shadowing mode	Constant
Multipath effect	Rayleigh
Path loss factor a	2
Transmit amplifier b	100 pJ/bit/m^2
Sensing energy e_s	150 nJ/bit
Receiving energy e_r	150 nJ/bit
Transmission energy e_t	50 nJ/bit
Packet	500 bytes
Data rate	1 kbps
Initial power	20 J

well with the characteristics of energy consumption in wireless communication. The mathematical expression is given as

$$e_p = c_2 \times {r_p}^2 \tag{1}$$

$$c = E/2\left(\sum_{r=1}^{P} {r_P}^2\right) \tag{2}$$

where e_p denotes the energy consumed for sensing a bit of data corresponding to the current sensing radius r_P. c is a constant defined in (2). E is the initial energy and P is the number of different power levels (e.g., P is equal to 3 in Fig. 4). This quadratic model implies that expanding the sensing radius is at the cost of consuming more energy. The goal of AR-SC is to determine appropriate sensing radii for active sensor nodes while satisfying the coverage requirements.

IV. SIMULATION

A. Simulation Environment

We conduct simulations in MATLAB to compare the four coverage algorithms. Although there are several network simulators available, our major focus is on the effects of industrial noise in harsh environments on the physical layer communication and how it affects these protocols. We take the advantage of MATLAB's built-in ability to model and visualize channels with various realistic noise models, although this requires us to implement our own model for other network operations. Both shadowing and pass loss effect are considered in our simulation to describe signal attenuation. Due to reflections of walls and machines in industrial environments, multipath effects (Rayleigh fading in our simulation) that severely affect the signal strength are also taken into account. As it is a common physical layer for industrial control and monitoring networks, a sensor network communicating with IEEE 802.15.4 [1] is simulated that encounters various noise environments. Both sensor nodes and targets are randomly deployed in a square area. We envisage that the targets, such as motors, pumps, or furnace, are essential industrial equipment within which sensor nodes are located. Since the targets are hard to maintain and require long service life, critical parameters such as temperature, pressure, vibrations, or power usage need to be continuously monitored. The rest of nodes will function as relay nodes to upload data to a sink node, while ensuring that the target always remains connected to the network. The communication radius of each node is 30 m. The maximum sensing radius is 10 m and can be adjusted by the power level. The position of the sink is fixed at the center of the square area to notify any potential problem caused by failures or malfunctions in machinery. Simulation parameters are listed in Table I.

B. Energy Consumption Model

We use e_{ij}^t to denote the energy consumed by a sender node s_i for transmitting one bit of packet to a receiver node s_j

$$e_{ij}^t = e_t + b \times d_{ij}^a \tag{3}$$

where e_t is the energy/bit consumed by the transmitter electronics, b is the energy dissipated in the transmit amplifier, d_{ij} is the Euclidean distance between two nodes, and a is the path loss factor. For simplicity, we omit the IDs of sender nodes and receiver nodes and use e_{trans} instead of e_{ij}^t.

Let $S_s(\tau)$ and $S_r(\tau)$ denote the sets of active sensing nodes and relay nodes in an operational time interval τ, respectively. Node s might have different functions at different moments, the energy consumption model of the node is given by

$$E(s) = \begin{cases} (e_s + e_{\text{trans}}) B(\tau)\, \theta_s, & \text{if } s \in S_s(\tau),\ s \notin S_r(\tau) \\ (e_r + e_{\text{trans}})\, B(\tau)\, \Phi_s(\tau), & \text{if } s \notin S_s(\tau),\ s \in S_r(\tau) \\ (e_s + e_{\text{trans}} + e_r)\, B(\tau)\, \Phi_s(\tau), & \text{if } s \in S_s(\tau),\ s \in S_r(\tau) \\ 0, & \text{if } s \notin S_s(\tau),\ s \notin S_r(\tau) \end{cases} \tag{4}$$

where $B(\tau)$ is a fixed amount of bits generated by each target in the time interval τ, θ_s denotes the number of targets within the sensing area of node s, $\Phi_s(\tau)$ denotes the data relayed by node s, and e_s and e_r are the energy consumed for sensing and receiving one bit of packet.

C. Evaluation Metrics

In order to evaluate the algorithms comprehensively, we investigate their properties through the following five metrics.

1) *Network lifetime:* Network lifetime is defined as the duration until there exists one target that can no longer be monitored by any node or the sensed data cannot be forwarded to the sink any longer by multihop.
2) *Coverage time:* Coverage time, which is used to reflect the convergence speed of the algorithm, is defined as the running time of the coverage algorithm.
3) *Average energy consumption:* Average energy consumption is defined as the overall energy consumption in the network divided by the number of deployed sensor nodes.
4) *Ratio of dead nodes:* The ratio of the number of nodes that run out of energy to the number of deployed nodes.
5) *Balancing characteristic in energy consumption:* The topology of remaining energy distribution is used to describe the characteristic of energy balance.

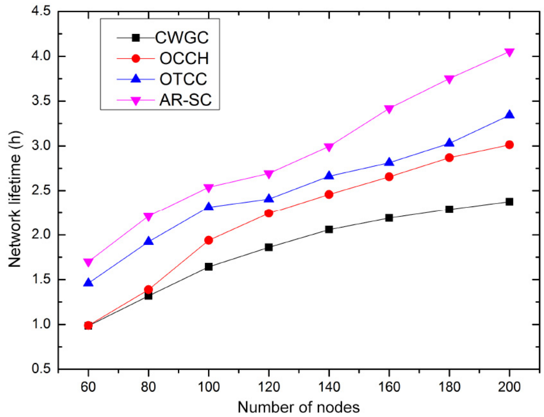

Fig. 5. Network lifetime versus the number of nodes.

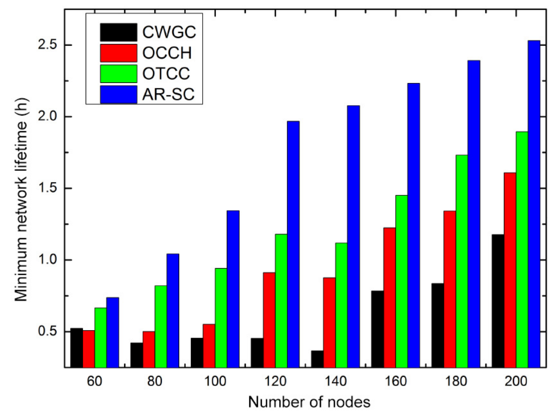

Fig. 6. Minimum network lifetime versus the number of nodes.

D. Performance Analysis

Since sensor nodes are typically battery equipped, an important issue of CTC algorithms is how to optimize energy consumption for data sensing, relaying, and transmission. We mainly focus on comparing network lifetime under different network conditions, i.e., the number of sensor nodes, the number of targets, the network size, the communication radius, etc.

1) Network Lifetime: Fig. 5 highlights the effect of node density on the network lifetime. In such simulation scenario, 20 targets are deployed in a 100 m $\times$ 100 m square area. We change the number of sensor nodes from 60 to 200 with an increment of 20. When the number of nodes increases, the four algorithms prolong the network lifetime to different degrees. It is observed that AR-SC always performs better than the other three algorithms and the corresponding curve rises rapidly. This phenomenon can be explained in the following way: first, with the increasing number of nodes, more cover sets can be generated so that the network lifetime can be prolonged by adding more working rounds. It also explains why the other three algorithms have better performance with more sensor nodes. Second, AR-SC uses nodes more efficiently. In AR-SC, the sensor nodes can expand or narrow their sensing radii when necessary, so that the cover sets generated in AR-SC balance QoS of coverage and energy consumption in the network. The property that each node can expand their sensing range implies AR-SC has much more potential sensing nodes to fulfill the requirement of coverage. From this point of view, AR-SC is quite sensitive to the number of nodes and the curve illustrates this characteristic.

OTCC is designed to extend network lifetime by eliminating redundant coverage and transmission. It is observed that, when the number of nodes is lower than 100, the advantage of AR-SC is not apparent compared to that of OTCC. However, the performance gap between them becomes significant when the number of nodes is larger than 100. This means that when sensor nodes are sparsely deployed, the improvement of network lifetime caused by eliminating redundancy is similar to that caused by selecting appropriate sensing radii. However, when the sensor nodes are densely deployed, the redundancy caused by overlapping targets does not play a leading role in affecting network lifetime. This is because the number of targets is unchanged, so the amount of overlapping data remains the same. Moreover, dense deployment implies that more nodes can be scheduled, as relay nodes weaken the influence of redundancy. However, in the case that one target can no longer be monitored by any node, AR-SC can expand the sensing radii of certain nodes to maintain the coverage requirement while OTCC cannot do this.

It is interesting to note that when sensor nodes are deployed sparsely (e.g., the number of nodes is 60), the network lifetime of CWGC is almost equal to that of OCCH. The mechanism that OCCH uses to protect critical nodes contributes to this result. OCCH aims to schedule common nodes instead of critical nodes to relay data by manually increasing the communication weights of the critical nodes. This mechanism only works well when there exist neighbor nodes around critical nodes. In a sparsely deployed network, critical nodes have few or even no neighbor nodes so that the protection mechanism for critical nodes loses its potency. However, when the number of sensor nodes is larger than 100, both CWGC and OCCH show improvement, especially OCCH. Besides, the more sensor nodes are added to generate the cover set, the more alternative neighbor nodes are offered to OCCH for protecting critical nodes.

Under the same simulation scenario as mentioned in Fig. 5, Fig. 6 shows the minimum network lifetime versus the number of nodes over the 20 simulation runs. We can see that the minimum lifetime not always increases as the number of nodes becomes larger, except for AR-SC. So, if we only take the number of nodes into consideration, the scalability of CWGC, OCCH, and OTCC is relatively worse than that of AR-SC. The key point is that the performance of those three algorithms has much to do with the network topology, though increasing the number of nodes can weaken this effect.

Fig. 7 depicts the relationship between network lifetime and the number of targets. In this case, 100 nodes are randomly deployed in a 100 m $\times$ 100 m square area to monitor various number of targets. The network lifetime achieved by the four algorithms decreases with an increase in the number of targets. As more targets are deployed in the network, more sensor nodes are needed to be active in a cover set. Also, the increasing amount of data generated from the targets aggravates the traffic load. We observe that when the density of targets is up to a certain degree, OTCC outperforms AR-SC and becomes the best

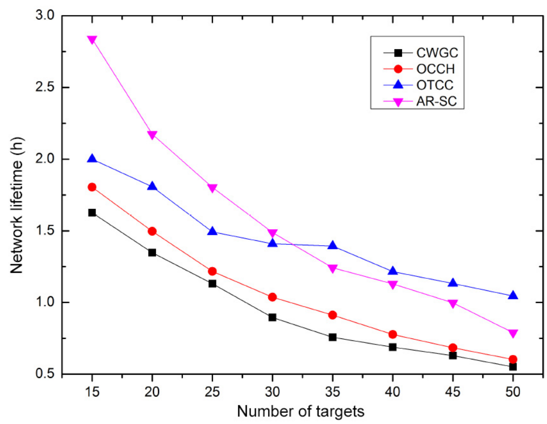

Fig. 7. Network lifetime versus the number of targets.

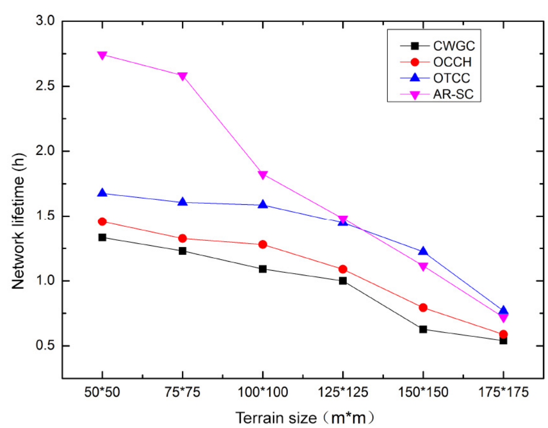

Fig. 8. Network lifetime versus the terrain size.

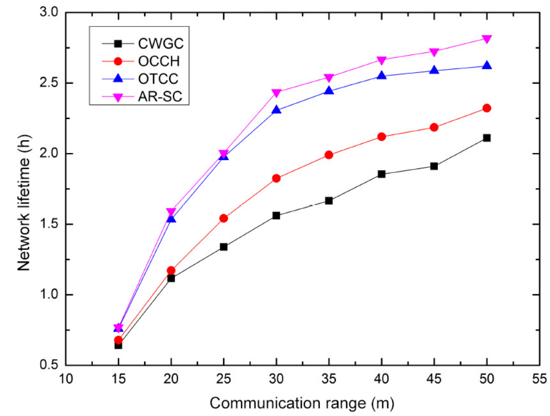

Fig. 9. Network lifetime versus the communication range.

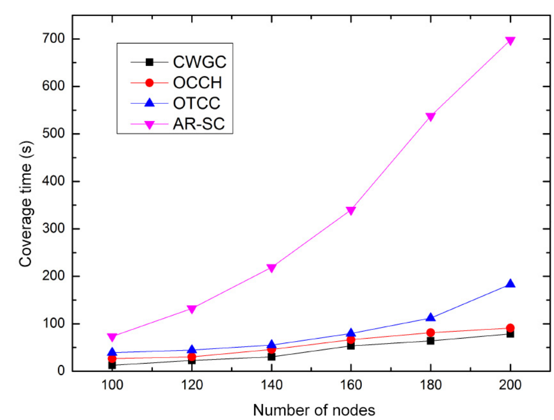

Fig. 10. Coverage time versus the number of nodes.

one among the four CTC algorithms. In this case, the redundant coverage caused by overlapping targets becomes the most important factor for energy consumption. Many redundant data transmissions consume a large amount of energy. OTCC aims to reduce the redundancy and save communication overhead and, therefore, it outperforms the other three algorithms.

Fig. 8 presents the performance of the four algorithms when the terrain size increases. The network consists of 100 sensors and 20 targets while the length of the network area changes from 50 to 175 m. Increasing terrain size decreases the density of sensor nodes and increases the communication distance. Besides the negative effect introduced by a decreasing density of nodes, long-distance communication is also unexpected, since it weakens the quality of the communication links, reduces network stability and reliability, incurs a drop in the throughput and increases the communication overhead. Considering these negative impacts, the four algorithms are sensitive to the change of terrain size, as shown in Fig. 8.

Fig. 9 analyzes the impact of the communication range on network lifetime. In this case, we establish a 100 m × 100 m network which consists of 100 nodes to monitor 20 targets. With the increase of communication range, each node is able to communicate with more neighbors. The increase of communication range affects the four algorithms in different ways. As for CWGC, enlarging communication range means that previously disconnected links can be constructed for transmission or reception. Similarly, OTCC can find more energy-efficient routes from each target to the sink. In terms of OCCH, enlarging the communication range means more alternative neighbor nodes are offered to protect the critical nodes. AR-SC also performs better with increasing communication range of sensor nodes.

2) Coverage Time: Fig. 10 depicts the relationship between coverage time and the number of sensor nodes. In this case, the number of targets remains the same at 20 and the network size is still 100 m × 100 m. It can be observed that the gap between CWGC and OCCH is small due to their similar framework. OTCC needs to find a unique routing path for each target in the weighted graph so that it spends more time in searching routes. AR-SC performs the worst because AR-SC needs to calculate the contribution of each node under different power levels and choose the node with the highest contribution until all the targets are covered. The same operation is performed repeatedly until the remaining nodes cannot fulfill the coverage requirement under their maximum power levels. This procedure consumes a large amount of time, especially when the network is densely deployed.

3) Average Energy Consumption: In Fig. 11, it can be observed that, under the condition that 20 targets randomly deployed in a 100 m × 100 m square area, when sensor nodes are sparsely deployed in the network, the average energy consumption is large because most of the nodes need to be

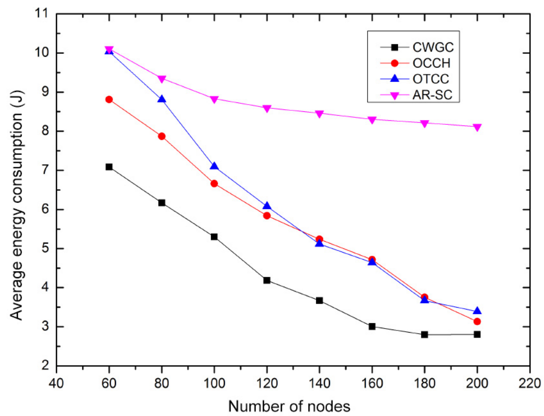

Fig. 11. Average energy consumption versus the number of nodes.

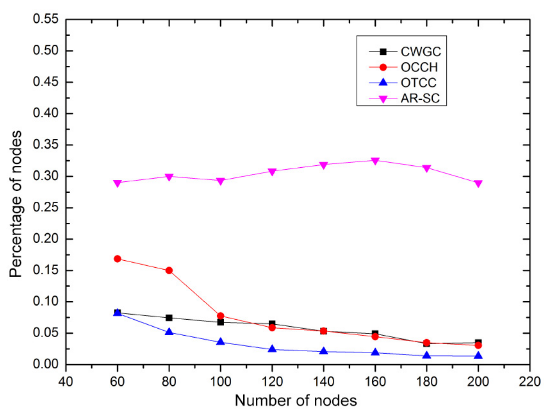

Fig. 12. Dead nodes ratio versus the number of nodes.

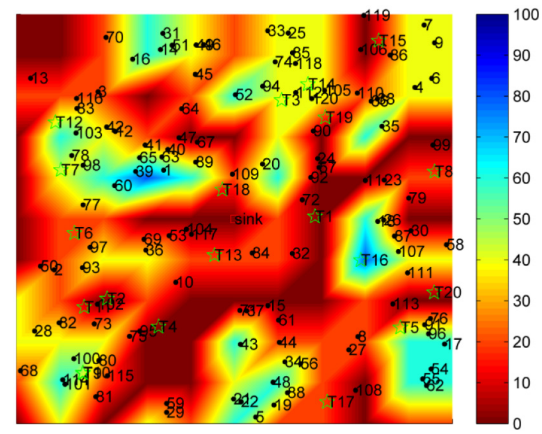

Fig. 13. Initial spatial energy distribution of the network.

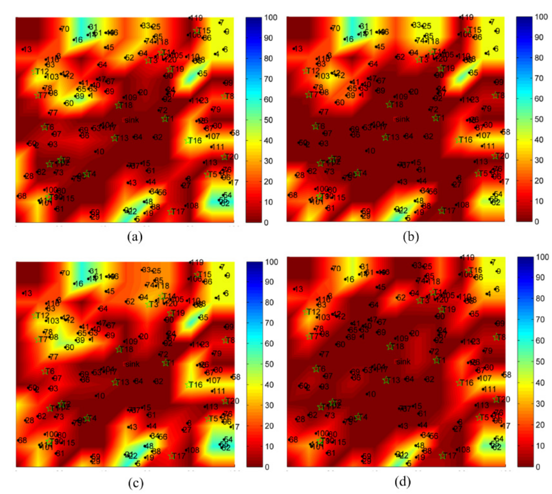

Fig. 14. Spatial energy distribution of each protocol. Energy topology of: (a) CWGC, (b) OCCH, (c) OTCC, and (d) AR-SC.

awakened for sensing or transmission. Moreover, multihop transmission is hard to realize when the network consists of only a few nodes. The average energy consumption decreases with more sensor nodes in the network. In addition, it should be pointed out that the increasing number of sensor nodes does not mean that all of them are scheduled to consume energy for complying with the requirement of coverage and connectivity. In terms of CTC, only some of the nodes have energy consumption for data sensing and relaying. Fig. 11 also shows that AR-SC drops slowly compared with the other three algorithms. It is reasonable that AR-SC outperforms the other three algorithms in terms of the usage of sensor nodes as analyzed above.

4) Ratio of Dead Nodes: Fig. 12 presents the percentage of dead nodes with the increasing number of sensor nodes when 20 targets deployed in a 100 m × 100 m network. When network lifetime is over, the number of dead nodes helps to reflect the overuse of certain nodes, which is a direct cause of ending network lifetime. It can be observed that OTCC sacrifices only a small part of nodes by the time that the connected coverage cannot be provided. This is because OTCC schedules a large number of nodes to establish an unique route for each target so that the energy consumption of each node is moderate. AR-SC sacrifices most of the sensor nodes in favor of high performance of network lifetime. The ability to expand sensing ranges makes it possible to prolong network lifetime at the cost of consuming much more energy.

5) Characteristic of Energy Balance: Fig. 13 represents the initial energy distribution of the network. Dark spots represent 120 nodes (marked by ID 1–120) while green stars represent 20 targets (marked by T1–T20). The darker the red color of the area, the lower energy the nodes have in this area. In contrast, we use blue to color the area in which nodes have sufficient energy reserves. Before running the four CTC algorithms, each node has the same initial energy, so the area where sensor nodes are densely deployed is labeled with a high energy level.

Fig. 14 provides snapshots of the remaining energy distribution of sensor nodes in the last round of CWGC, OCCH, OTTC, and AR-SC, respectively. Among the subfigures, the area around the sink always shows the worst energy distribution because of the heavy traffic load. Compared with CWGC, the sensor nodes in OCCH have a lower energy level because many more common nodes need to be awakened to protect critical nodes. The power level of OTCC is optimistic because the waste of energy caused by redundancy is weakened. In AR-SC, the area displays a dangerously low level of energy, which means most of the sensor nodes in the network are dead or dying. It can

TABLE II
COMPARISON SUMMARY

CTC algorithm	Advantage	Disadvantage	Appropriate industrial field	Probable industrial application
CWGC	Low computational complexity, fast convergence speed, low dead nodes ratio, low average energy consumption	Low utilization of working nodes, minor improvement in network lifetime, low scalability (spatial node distribution determines network lifetime)	Limited network construction cost, limited industrial plant area, few industrial equipment need to be monitored, quick initiation is required	Industrial self-calibration system or self-diagnosis system
OCCH	Improved sensing quality of poorly covered targets, enhanced upper bound of overall network lifetime, medium convergence speed, medium average energy consumption	High dead nodes ratio, low scalability (strategy of critical node protection only works in a densely deployed network)	A large-scale industrial area is available, relay nodes are densely deployed, part of the equipment might be only monitored by a small number of nodes	Equipment status monitoring in large manufacturing sector
OTTC	Eliminated redundancy of overlapped targets, medium convergence speed, medium average energy consumption	Medium convergence speed, low scalability (the number of adjacent targets determines network lifetime)	Large number of equipment needs to be monitored, small number of relay nodes is offered, redundant data make no sense	Flow-line equipment monitoring in wood machining or plastic extrusion
AR-SC	Maximum utilization of working nodes, high scalability, major improvement in network lifetime	High ratio of dead nodes, high average energy consumption, low convergence speed	A long-time stable working condition is asked, latency in initialization can be endured, the industrial environment is unfriendly (node recycling can be ignored)	Leakage monitoring of oil pipeline or natural gas pipeline

be observed that the tradeoff between energy consumption and network lifetime is different among the four CTC algorithms. CWGC and OCCH aim to achieve a balance of energy consumption and network lifetime, while OTCC aims to minimize the average energy consumption. AR-SC is a typical algorithm that tends to place too much emphasis on the performance of network lifetime.

E. Comparison Summary

Based on the previous discussion, both advantages and shortcomings of each algorithm are summarized in Table II. We also list useful insights that can be obtained from this paper's comparison and the industrial application scenarios they fit best.

V. Conclusion and Future Work

In this paper, we have analyzed different energy-efficient coverage strategies designed for industrial environments. Through comparing four representative CTC algorithms, properties of each strategy are embodied under different conditions. Since coverage performance is difficult to obtain uniformly, the selection of coverage algorithms should consider which factor (convergence speed, maximum lifetime, etc.) is the focus in a specific practical application. Attention should be paid to improve the performance determined by the main focus. Efforts can then be made to achieve the relative performance of other parameters. Based on our analysis, useful insights are given for IWSN designers to choose an appropriate coverage strategy.

In the future, additional work is required to bridge the gap between ideal simulations and real-world coverage systems. For instance, mobility should be introduced to an IWSN. Static sensor nodes may be disturbed by the vibration of industrial equipment, which could cause a change in network topology. Therefore, simulation results achieved by energy-efficient CTC algorithms should be extended to include possible influences of real industrial applications.

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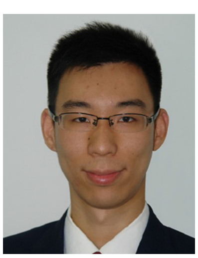

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