

Key Design of Driving Industry 4.0: Joint Energy-Efficient Deployment and Scheduling in Group-based Industrial Wireless Sensor Networks

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ABSTRACT

In the Industry 4.0 framework based on IoT and smart manufacturing, it is essential to support factory automation and flexibility in harsh or dynamic industrial environments. State-of-the-art technology suggests to build a controlled workspace using large-scale deployment of wireless sensors. To overcome the technological challenges in scalability and heterogeneity for large-scale industrial deployment, group-based industrial wireless sensor networks (GIWSNs) is suggested, while wireless sensors are divided into multiple groups for multiple monitoring tasks, and each group of sensors is deployed densely within a subarea in a large plant or along a long production/assembly line, while connectivity between groups is required. As wireless sensors are equipped with batteries with limited power, it has been challenging to plan sleep schedules of sensors, which are influenced significantly by deployment of such a large-scale GIWSN. However, most previous works on wireless sensor networks independently investigated deployment and sleep scheduling problems, both of which have been shown to be NP-hard. Therefore, this work jointly considers deployment and sleep scheduling of sensors in the GIWSN along a production line. Via the theory of symmetries, we alleviate the computational concerns from multiple groups to one group and another medium-size group. Then, we propose a hybrid harmony search and genetic algorithm, which incorporates deployment and the sleep schedules to reduce energy consumption. Simulations verify this jointed methodology to effectively achieve energy-efficiency.

Keywords: Industry 4.0, industrial wireless sensor network, deployment, scheduling, metaheuristic algorithm.

INTRODUCTION

To respond to increasing demand of diversified products and promote competitive advantages, industrial enterprises intend to reply on the fourth industrial revolution to achieve more factory automation and flexibility conforming to green environmental regulations and financial purpose. In conventional factories, it is common to apply

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wired systems to implement industrial monitored and controlled systems, e.g., fieldbus systems and wired HART systems. However, it is costly and difficult to install wired systems in a harsh factory environment, e.g., nuclear power plants and refineries, or to rewire in flexible manufacturing operations, in which especially, a great of variety of complex production operations and processes require frequent adjustments and maintain flexibility in future Industry 4.0 factories. Hence, one promising solution to reduce the deployment cost is to build a controlled workspace installing industrial wireless sensor networks (IWSNs). IWSNs enjoy lots of advantages, e.g., easy and efficient deployment on the required range, and the energy power supported by battery or wireless charging so as to avoid cost of large-scale deployment of wired power in factories. By installing IWSNs on working stations and attaching tags to in-process products, information on production operations can be collected effectively and flexibly, and cyber-physical decisions can be made instantly and precisely, to achieve Industry 4.0.

As compared with wired systems, a further crucial technology is to develop green operations reducing power and energy consumption and to extend the operating lifetime of the whole system under limited battery power of industrial wireless sensors. In a wireless sensor network (WSN), sensors likely operate by own battery power that is hard to be recharged or replaced in harsh industrial environments. Additionally, frequent battery recharging and replacement are apt to cause difficulties of creating and collecting production information, so as not to make instant cyber-physical decisions in Industry 4.0. Previous works on extending lifetime of WSNs are mainly classified into two categories: software/hardware design of sensor devices; and arrangement of using sensors, including deployment of sensors (e.g., [1]) and sleep scheduling of sensors (e.g., [2]). Generally, a good initial deployment of sensors significantly enhances performance of the latter sleep scheduling of sensors to meet green environmental regulations.

For a large-scale deployment of sensors in a harsh and/or dynamic operating environment, limited attention to energy-efficient technology has been paid to investigate green deployment and subsequent sleep scheduling of sensors, until recent emerging group-based industrial wireless sensor networks (GIWSNs) [3], [4], in which a large amount of sensors are divided into multiple groups; and sensors in the same group are deployed within the same geographical region. However, it is still hard to determine precise deployment of each sensor because the number of sensors is huge. Additionally, imbalanced distribution of sensors (especially, those sensors that fall within the intersection region of two groups) plays a critical role to bridge two groups but to consume more energy, such that this critical energy consumption breaks the vital connectivity of multiple groups [3]. Inspired by the theory of symmetries, we propose a new methodology to jointly resolve the challenges on the deployment and the sleep scheduling for multiple groups in GIWSNs along a production/assembly line by reduction to those for one and a “half” groups (e.g., see Fig. 1), in which a group means to deploy sensors within a group in geometry; a “half” group means to deploy sensors within a semicircle in geometry. By such reduction of network size, this work can investigate detail deployment and sleep scheduling of sensors.

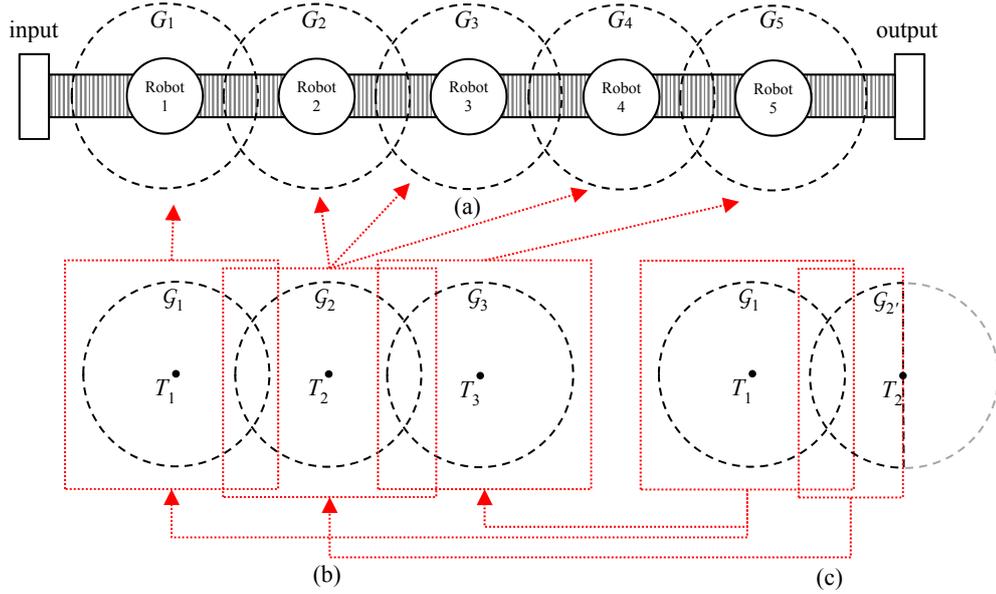


Figure 1. (a) A GIWSN with five groups along a production/assembly line with five robots, in which each group is a circular region centered at a robot; sensors are deployed within this region. (b) Reduction to a GIWSN with three groups. (c) Reduction to a GIWSN with one and a “half” groups.

Most previous works on IWSNs/WSNs (e.g., [5]) separately and independently investigated optimal deployment and sleep scheduling of sensors. However, deployment of sensors influences performance of the latter sleep scheduling of sensors and further the network lifetime. Hence, this work first determines an optimal deployment of sensors in GIWSNs that considers the sleep schedules of sensors for the first several time periods, and then determines sleep schedules of sensors for the later time periods, so that the total lifetime of the network is maximized. Since both deployment and sleep scheduling problems of sensors are NP-hard [6], this work further proposes a metaheuristic algorithm that incorporates geometric selective harmony search algorithm (GSHS) [7], improved harmony search algorithm (IHS) [8], and genetic algorithm (GA) for the two problems, because no metaheuristic algorithm dominates others [9].

RELATED WORK

One of the foundations for Industry 4.0 is to integrate technologies of IoT and smart manufacturing. IoT is used to integrate information on facilities and in-process products within and among factories via the Internet, including integration of internal information and techniques, factories and business partners, and interaction among customers, so that utilization efficiency and flexibility of production resources increase to achieve smart factory settings. To manufacture high-quality diversified products and services, smart manufacturing is to establish a flexible automated production model by collecting and sharing information on facilities and in-process products during production processes. Both of the two technologies are evolved with creating and collecting information, and monitoring and managing some specific targets. Hence, various applications in factories based on the foundation of IWSNs were proposed [10].

Developing IWSNs is necessary for Industry 4.0. IWSNs enjoy merits of low cost, scalability [11], and easy use for flexible adjustment and failure alarm monitoring, to

bring competitive advantages to factory operations. However, some technical challenges still existed during the process of introducing IWSNs, e.g., harsh environment, reliability and latency, packet errors and variable link capacity, and resource constraints. Hence, lots of approaches were proposed for overcoming those challenges in IWSNs from different aspects. The work in [11] investigated some energy-efficient connected coverage strategies, which are evaluated in terms of network lifetime, coverage time, average energy consumption, and ratio of dead nodes. The work [12] proposed an energy-efficient and delay-aware wireless computing system to reduce the latency during the process of collecting data, to satisfy service requirements and reduce the power consumption of the whole IWSN. The work in [13] applied the concept of lightweight packet error discriminator to reduce interference in industrial environments and increase precision of information. The work in [14] combined different types of sensors to implement the concept of data fusion techniques, which not only increases precision of monitoring, but also reduces transmissions of messages, to decrease power consumption. The work in [15] proposed a tree-based data-gathering algorithm for the hotspot problem in local or whole deployment area. The above previous works are compared in Table 1. In previous works on IWSNs, most works focused on issues on transmission (interference, latency, and reliability), but few works jointly focused on power consumption, deployment, and scheduling. Especially, power consumption is concerned with deployment and scheduling, which inspires proposal of this work.

Table 1. Comparison of some major works in IWSNs.

	Interference	Latency	Reliability	Power efficiency	Deployment	Scheduling
[11]			v	v	v	
[12]		v		v		
[13]	v		v			
[14]			v	v		
[15]		v	v	v		
This work				v	v	v

Recently, group-based IWSNs (GIWSNs) [3], [4] received a lot of attention. However, few works on GIWSNs existed. Two main works that are related to this work are reviewed as follows. The work in [4] focused on analyzing connectivity of sensor groups in a GIWSN, in which sensors of each group are deployed according to a normal or uniform distribution. The work in [3] proposed a cross-layer optimization scheme for the network isolation problem in a GIWSN in which the sensors bridging two groups may not have enough time to sleep such that they use out of all power soon.

On extending the WSN lifetime, aside from software/hardware design of sensors, which proposed a reusable WSN platform for flexibly satisfying some requirements, the other line of research is to investigate deployment and sleep scheduling of sensors in WSNs. An ideal deployment of sensors not only are operated effectively, but also maximizes power utilization effectiveness of sensors. Most works on WSN deployment focused on indirectly finding covers of sensors (i.e., the minimal number of sensors to cover all targets [1] or an area [11]) with different criteria, to extend the WSN lifetime.

Multiple sensors within the same region that cover the same target could lead to redundant power consumption, and hence, an appropriate design of sleep schedules of

each sensor at different times can save power. For the sleep scheduling problems in WSNs, each sensor has two modes: active mode and asleep mode. Active sensors work and consume power; while asleep sensors are switched off and are supposed to consume no power. Hence, the sleep scheduling problems of WSNs are concerned with determining the mode of each sensor at different times so that all targets or areas are covered by minimal number of active sensors, load of each sensor is balanced, and the total power consumption is minimized. For example, the work in [2] proposed an energy-efficient sleep scheduling algorithm in WSNs for covering multiple targets in which both the energy for transmitting collected data and overlapped targets is considered. The work in [6] showed that given deployment of sensors, it is NP-complete to determine states of sensors so as to optimize the total lifetime.

Most of the works separately and independently investigated deployment and sleep scheduling problems in WSNs. The work in [5] jointly considered deployment and sleep scheduling of sensors in WSNs. They proposed a two-stage method for the concerned problem, in which Stage 1 applies an artificial bee colony algorithm for deployment of sensors; and then Stage 2 bases on the previously proposed heuristic algorithm to arrange sleep schedules of sensors. However, deployment and sleep scheduling of sensors were still determined separately in [5].

SYSTEM DESCRIPTION

Consider a sequential (i.e., simplified into a straight-line in geometry) production line in a factory where N robots assist in manufacturing or assembling from the input to the output of the production line (e.g., see Fig. 1(a) where $N = 5$). A GIWSN along such a production line is defined as follows. Let each robot along this production line be the central deployment point for a group of sensors. For $i = 1, 2, \dots, N$, each group G_i in the GIWSN is associated with a circle that is centered at the i -th deployment point from the input of the production line and has a uniform radius R_g . To properly cover the production line, every two adjacent groups G_i and G_j have an intersection region denoted by I_{ij} . In general, for conducting multiple monitoring tasks and saving deployment costs, a large-scale number of industrial wireless sensors are deployed within each group to monitor the industrial environment of each corresponding robot, so that information of each robot can be collected efficiently to make instant decisions in the Industry 4.0 framework. To simplify the deployment, this work deploys the same number of uniform sensors (denoted by n) within each group, i.e., the total number of sensors to be deployed in the GIWSN is $N \cdot n$.

Since the total number of sensors in this GIWSN is huge, it is difficult to find an optimal deployment of such a huge network. To simplify this problem, this work supposes that the network deployments of the first group and the last group are the same; and those of intermediate groups are the same. As a result, by the theory of symmetries, all groups of a GIWSN can be reduced to three patterns in Fig. 1(b). That is, the first, each intermediate, and the last groups in Fig. 1(a) are the same with groups G_1 , G_2 , and G_3 , respectively, in Fig. 1(b). Furthermore, if the theory of symmetries holds, Fig. 1(b) has a reflectional symmetry along a vertical axis passing through the deployment point T_2 of group G_2 . Then, the three groups in Fig. 1(b) can further be reduced to one group G_1 and a “half” group G_2' (i.e., the semicircle of G_2 having intersection with G_1) in Fig. 1(c). Hence, the problem concerned in this work is reduced to deployment and sleep scheduling of a GIWSN within one group G_1 and a “half” group G_2' in Fig. 1(c).

Consider to deploy n sensors $s_{11}, s_{12}, \dots, s_{1n}$ within group \mathcal{G}_1 ; and $n/2$ sensors $s_{21}, s_{22}, \dots, s_{2(n/2)}$ within group \mathcal{G}_2' (Fig. 2(a)), in which groups \mathcal{G}_1 and \mathcal{G}_2' are in charge of monitoring the robots at deployment points T_1 and T_2 , respectively. Suppose that sensing and transmission ranges of each sensor are circles with same radius R_s . Each sensor is equipped with a battery with limited power, and has two states: active and asleep modes. Only active sensors consume energy and can communicate; while asleep sensors consume no power.

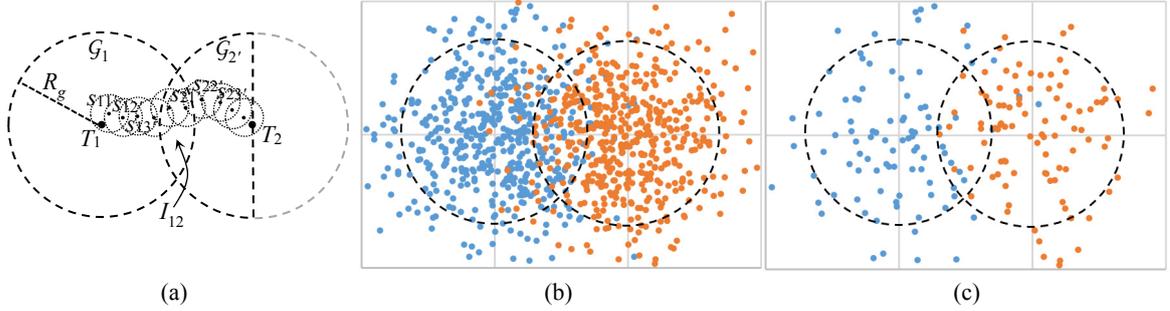


Figure 2. (a) Illustration of a communication path between deployment points T_1 and T_2 via multihop wireless sensors between groups \mathcal{G}_1 and \mathcal{G}_2 . (b) 500 sensors and (c) 100 sensors are deployed in each group according to a normal distribution [4].

Two active sensors are *connected* if their respective transmission range covers each other. An effective *communication path* consists of multiple active connected sensors. The first task is to determine deployment of sensors so that all deployment points of the GIWSN are connected and the energy consumption is as small as possible. Since the problem is reduced to the case of one and a “half” groups, this work aims to find an effective communication path in which the first and the last sensors of this path cover deployment points T_1 and T_2 , respectively, e.g., see the communication path $s_{11}, s_{12}, s_{13}, \dots, s_{21}, s_{22}, s_{23}, \dots$ in Fig. 2(a). Furthermore, when a communication path is active, the other sensors go asleep for saving power.

After deployment of sensors, the second task is to determine the sleep schedule of each sensor, i.e., when to be active or go asleep. Suppose that time is divided into multiple periods with fixed length; and the initial time point (called *key time*) of those time periods are denoted t_0, t_1, t_2, \dots in a sequel. Hence, our task is to determine a sleep schedule δ_i at each key time t_i , to be applied until the next key time t_{i+1} .

Suppose that each sensor has the same initial power b , and the same power consumption rate e . After some sleep schedules, each sensor has a different power level, and hence, it is challenging to determine appropriate sleep scheduling of each sensor at different times. Given one and a “half” groups \mathcal{G}_1 and \mathcal{G}_2' to monitor deployment points T_1 and T_2 in Fig. 2(a), the problem concerned in this work is to deploy n and $n/2$ sensors within \mathcal{G}_1 and \mathcal{G}_2' , respectively, and then to find sleep schedules (i.e., to determine modes of all sensors) at different key times, so that the total energy consumption is minimized, while a communication path between T_1 and T_2 is always active during the whole lifetime of this network.

JOINT DEPLOYMENT AND SLEEP SCHEDULING METHODOLOGY

Most previous research efforts investigated either deployment or sleep scheduling, until a recent work [5] considered the joint maximization of total life time of the WSN. It was facilitated into two stages: Stage 1 determines an initial deployment of sensors; under this fixed deployment, Stage 2 determines sleep schedules of sensors at different times. Performance of the initial deployment significantly influences performance of the sleep schedules at Stage 2. Especially, from Fig. 2(a), the sensors within the intersection region I_{12} are often the intermediate sensors of all communication paths, so that they consume more power and have higher probability to use out of their power early than others. Hence, deployment of sensors in G_1 , G_2 , and their intersection region I_{12} is the key to determine if the network has a long lifetime [3].

However, the previous work on deploying GIWSNs in [4] only applied a simple strategy that deploys a large-scale number of sensors within each group according to a normal or uniform distribution, e.g., 500 and 100 sensors in Fig. 2(b) and Fig. 2(c), respectively. The number of sensors in I_{12} is undeterministic, and is too small when the total number of sensors to be deployed is small (Fig. 2(c)). Hence, instead of deploying sensors with some probability distribution, this work proposes an intelligent method to determine positions of all sensors. Since the total number of sensors to be deployed (which is a huge size) is reduced to that within one and a “half” groups (which is a moderate size) according to the theory of symmetries, it makes it possible to determine precise positions of all sensors.

Although the proposed method is still two-stage, the deployment stage incorporates both deployment of sensors and the sleep schedules at the first several key times, so that the initial deployment of sensors would be better than that without this concern. This work proposes an improved version of the harmony search algorithm (HSA), which is inspired by improvisation behavior of multiple musicians, and has been shown to perform better than GA in many applications. Different from conventional metaheuristic algorithms, the HSA enjoys the merit of being able to improve each parameter of the solution independently, and hence, is suitable for the case with autonomous agents, e.g., the optimal positions of sensors in the concerned problem should be found autonomously. On the other hand, since each solution of the concerned problem has discrete parameters, additional designs should be considered delicately when applying the HSA. Hence, this work proposes a so-called improved geometric selective harmony search algorithm (IGHSA for short) that incorporates GSHS [7], IHS [8], and GA.

Flowchart of the proposed IGHSA is given in Fig. 3(a), which is explained as follows. IGHSA stores a number of harmonies (candidate solutions) and their respective costs (used for evaluating their respective performance) in a matrix HM called harmony memory, and each iteration of the IGHSA generates a new harmony to replace the worst harmony in the HM until a good enough harmony is found or the maximal number of iterations NI is achieved. For each iteration $g \leq NI$, IGHSA generates a new harmony with two options according to whether a random number from $[0, 1]$ is no greater than $HMCR$. At the first option, two harmonies are chosen via two times of tournament selection from HM [7]. Since each harmony encodes deployment and scheduling parts in the proposed method, the two parts of a new harmony at the first option are generated differently. The deployment part of the new harmony is a linear combination of those of the chosen two harmonies. The scheduling

part of the new harmony is the better offspring harmony after a one-point crossover operation and a revision scheme for the scheduling parts of the chosen harmonies, which are motivated from the GA. At the second option, a new harmony is generated as a random harmony within the feasible range. Note that the second option is controlled by two parameters $par(g)$ and $bw(g)$, which are an increasing linear function and an exponential function of g , respectively. Such a dynamic adjustment for $par(g)$ and $bw(g)$ has shown to perform better than setting them as fixed values [8]. Finally, cost of the new harmony is evaluated, and if it is better than the worst harmony in HM , it replaces the worst harmony.

Flowchart of the proposed method is given in Fig. 3(b), which is explained as follows. The proposed method includes two stages. Different from previous works, Stage 1 adopts the proposed IGHSA to jointly determine deployment of sensors and the sleep schedules applied at the first several time periods. Let m denote the number of sleep schedules to be considered at Stage 1. After the m sleep schedules are applied, Stage 2 first checks whether there are available sensors, because some sensors may have used out of their power after m time periods. If true, Stage 2 adopts the proposed IGHSA to determine another m sleep schedules that will be used at the next m time periods. Stage 2 is repeated until no available sensors can constitute a communication path between deployment points T_1 and T_2 . After the two stages, the total lifetime after executing all sleep schedules is evaluated.

The proposed solution encoding schemes at the two stages are different. Stage 1 determines both deployment and sleep schedules of sensors. Let the number of sensors to be inactive be denoted by $\eta = \lceil d_{12}/R_s \rceil + \varepsilon$, where d_{12} is the distance between T_1 and T_2 ; R_s is radius of the transmission range of each sensor; and ε is a given parameter to control the number of active sensors. A solution is encoded as a string of parameters (i.e., a harmony) as follows: $\langle x_{11}, y_{11}, x_{12}, y_{12}, \dots, x_{1n}, y_{1n} \parallel x_{21}, y_{21}, x_{22}, y_{22}, \dots, x_{1(n/2)}, y_{1(n/2)} \parallel a_{11}, a_{12}, \dots, a_{1\eta} \mid a_{21}, a_{22}, \dots, a_{2\eta} \mid \dots \mid a_{m1}, a_{m2}, \dots, a_{m\eta} \rangle$. The harmony has three parts: the first part consists of the (x, y) -coordinate of each sensor s_{1i} (i.e., (x_{1i}, y_{1i})) within the region of group G_1 ; the second part consists of the (x, y) -coordinate of each sensor s_{2i} (i.e., (x_{2i}, y_{2i})) within the region of “half” group G_2 ; the last part consists of m sleep schedules, in which the i -th sleep schedule is $a_{i1}, a_{i2}, \dots, a_{i\eta}$ which are η sensors from $\{s_{11}, s_{12}, \dots, s_{1n}, s_{21}, s_{22}, \dots, s_{2(n/2)}\}$ and represent those active sensors in this sleep schedule. The harmony at Stage 2 only considers sleep schedules, and hence, is represented as only the third part of the harmony at Stage 1, i.e., $\langle a_{11}, a_{12}, \dots, a_{1\eta} \mid a_{21}, a_{22}, \dots, a_{2\eta} \mid \dots \mid a_{m1}, a_{m2}, \dots, a_{m\eta} \rangle$.

Performance of a harmony is evaluated by a cost to be minimized, which is the total power consumed when the m sleep schedules decoded by the harmony are applied. Remind that all sensors have the same power consumption rate e . Let l denote the length of a time period. From the third part of the harmony at Stage 1 or the whole harmony at Stage 2, each active sensor at each of the m sleep schedules consumes its power of $l \cdot e$, if its battery power is enough. However, it is possible that the active sensors during some time period may not form a communication path between deployments T_1 and T_2 , but they can during other time periods. That is, such a harmony is not feasible. Hence, a huge penalty value is added to the cost.

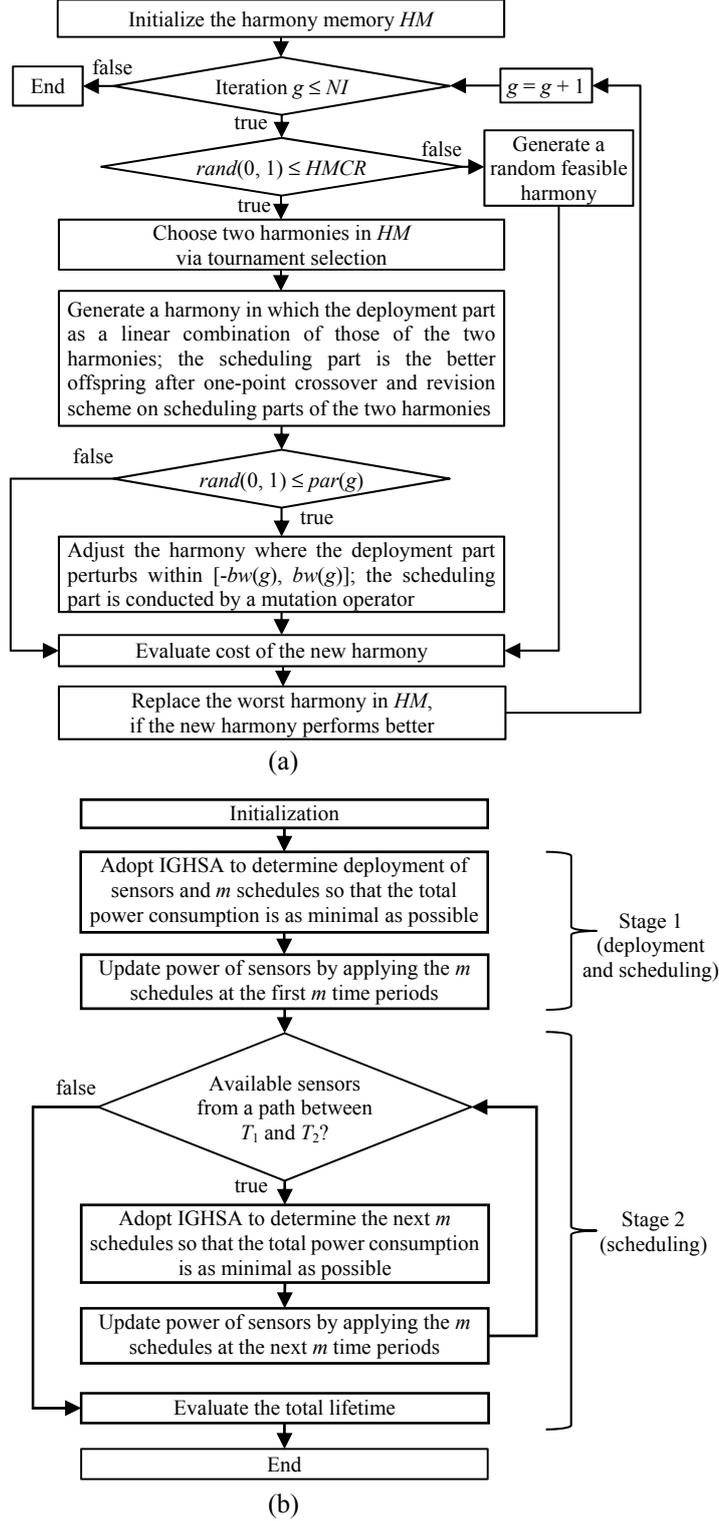


Figure 3. Flowchart of (a) the proposed IGHSA and (b) the proposed method.

IMPLEMENTATION AND EXPERIMENTAL RESULTS

The experimental settings are detailed as follows. Distance between two deployment points: 25 m; range of position of each sensor in the group centered at coordinate (0, 0): $[-25, -25] \times [25, 25]$; number of active sensors η in the same group in a schedule: 6, 8,

or 10; number of schedules m planned in advance: 3; number of sensors within a group: 100, 150, 200, or 250; transmission/sensing range: 3 or 5 m; number of active sensors in a schedule: 10 or 15; initial battery power: 1200 ~ 1800 J. Additionally, to reflect reality, based on the standard for 868 MHz band, the power consumption rate is 1.00, 1.33, or 1.67 Watt. All the simulation is conducted on a laptop with Intel i7-3770 CPU 3.40GHz 3.90GHz and 16-GB RAM.

After a lot of experimental trials, the parameters of the proposed IGHSA are set as follows. Number of iterations NI : 2000; size of the harmony memory HM (hms): 8; $HMCR$: 0.9; par_{min} : 0.2; par_{max} : 0.9; bw_{min} : 3.0; bw_{max} : 6.0; mutation rate: 0.5. Note that par_{min} (resp., bw_{min}) and par_{max} (resp., bw_{max}) denote the maximum and minimum of the linear (resp., exponential) function $par(g)$ (resp., $bw(g)$) [7], respectively.

The key of the proposed method is to incorporate deployment and sleep scheduling at the deployment stage, and then to conduct the scheduling stage. Hence, it is of interest to experimentally analyze the effect with joint consideration of deployment and sleep scheduling under different numbers of sensors, as shown in Fig. 4, in which length of each bar represents an average value of 20 experimental runs. From Fig. 4, the proposed method with joint consideration always has the best performance in all cases; and when number of sensors is greater, the performance difference becomes greater.

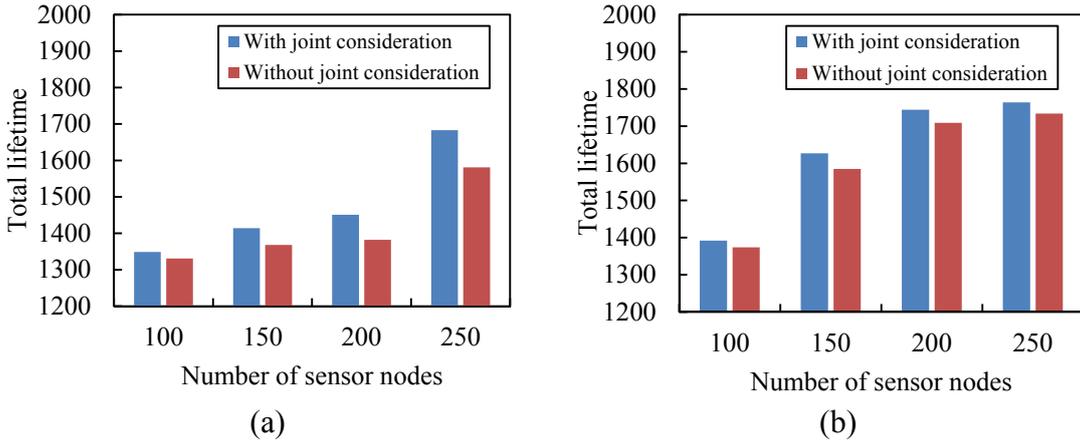


Figure 4. Comparison of the lifetime for the proposed method with and without joint considerations of deployment and sleep scheduling under different number of sensor nodes using sensing range of (a) 3 m and (b) 5m.

The nonparametric statistics for number of sensors is conducted for testing whether there is significant difference between performances of the proposed method with and without joint considerations. Each case for number of sensors is conducted by 20 times, and the statistical results are given in Table 2. From Table 2, except for the cases with 100 and 150 sensors, the other cases have significant differences. Hence, it is concluded that more sensors make the performance effect with joint consideration become more obvious. The performance gap with and without joint considerations becomes smaller while setting sensing range from 3m to 5m, which are reasonable because it is easy to make connectivity when using a larger sensing range.

Table 2.
Nonparametric statistics of the proposed method

Sensing range of 3m		Sensing range of 5m	
Number of sensors	p-value	Number of sensors	p-value
100	0.631	100	0.912
150	0.971	150	0.796
200	0.029	200	0.035
250	0.023	250	0.015

CONCLUSION

In light of the trend of flexible manufacturing for Industry 4.0, a key foundation is to install industrial wireless sensor networks (IWSNs) in factories so that information on in-process products and machine stations is collected continuously and efficiently and instant decisions can be made. This article introduces the way to incorporate deployment and sleep scheduling of the group-based IWSNs (GIWSNs) along a production/assembly line to achieve the purpose of green. Since number of sensors in GIWSNs is large-scale in general, the theory of symmetries is employed to transform multiple groups into one group and another medium-size group. Then, to increase diversify of the solution population, we propose a hybrid metaheuristic algorithm based on GSHS, IHS, and GA in which the deployment stage jointly considers deployment and sleep schedules of sensors for the first several time periods. Simulation results show that the proposed method with joint consideration performs better, and performance of the case with more sensor nodes is more obvious. Aside from extending the network lifetime and achieving effective communications of monitoring industrial conditions, energy-efficient deployment and sleep scheduling in GIWSNs by the proposed method can decrease frequency of replacing failed sensors and further decrease environmental pollution due to discarded sensors and facilities, achieving the purpose of sustainability.

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