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THE NODE PLACEMENT OF LARGE-SCALE INDUSTRIAL WIRELESS SENSOR NETWORKS BASED ON BINARY DIFFERENTIAL EVOLUTION HARMONY SEARCH ALGORITHM

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Abstract. *This paper discusses the optimal node placement problem of Industrial Wireless Sensor Networks (IWSNs). Compared with the non-industrial Wireless Sensor Networks (WSNs), IWSNs have a critical requirement on the reliability of networks. Thus, a new model of the IWSNs node placement is formulated in which the reliability, cost, load constraint and scalability are taken into account. Considering its NP-hard characteristic, a novel hybrid Binary Differential Evolution Harmony Search Algorithm (HBDEHS) is presented to tackle the optimal sensor deployment problem. Four large-scale node deployment problems are generated as the benchmarks to verify the proposed model and the optimization algorithm. Furthermore, the other five binary optimization algorithms, i.e., Global Harmony Search Algorithm (NGHS), Modified Binary Differential Evolution Algorithm (MBDE), Discrete Binary Harmony Search Algorithm (DBHS), Discrete Binary PSO algorithm (DBPSO) and Simple Genetic Algorithm (SGA) are also adopted to solve the problems for a comparison. The experimental results indicate that all algorithms can find out the feasible solutions, which demonstrates that the proposed model is valid and can be effectively used to tackle the optimal node placement problem. Moreover, the comparison results also illustrate that HBDEHS has the best global search ability and outperforms DBHS, NGHS, MBDE, DBPSO and SGA in terms of search accuracy and convergence speed.*

Keywords: Industrial wireless sensors networks, Node placement, Binary harmony search, Binary differential evolution, Meta-heuristic

1. **Introduction.** Nowadays, industrial companies face growing demands to improve process efficiencies, comply with environmental regulations and meet corporate financial objectives. Therefore, industrial automation systems are applied to improving the productivity and efficiency of industrial systems. During the last decades, wired industrial communications, such as fieldbus systems and wired HART, have been widely installed in the field of factory automation and process automation. However, it is still difficult and quite expensive to install wiring in the harsh industrial environments. It costs roughly $200 per meter to install wires in an ordinary process plant and approximately $1000 per meter in offshore installations [1]. The high cost on the installation as well as regular

maintenance is an obstacle to the applications of wired automation system in industrial plants, and therefore a large number of secondary process variables have long gone unmeasured and expensive pieces of critical rotating equipment remain non-instrumented [2]. Thus, using wireless technologies, such as wireless Industrial Ethernet and wireless HART, in industrial and factory automation is very attractive [3,4] as the wireless way of communicating makes plant setup and modification easier, cheaper and more flexible. The industrial wireless technology also provides a natural approach towards communication with mobile equipment where wires are in constant danger of breaking and enables new applications where wireless transmission is the only option, e.g., measurements and control of rotating or highly mobile devices. Furthermore, tasks like machine diagnosis and maintenance can be greatly simplified by equipping the maintenance personnel with wireless terminals without installation of additional wires [5].

With the advent of Industrial Wireless Sensor Networks (IWSNs), the fusion of wireless communication and distributed sensing technologies, now engineers are able to unlock stranded information in instruments and gather information from where it previously has been economically unfeasible such that the process can be enhanced with respect to quality and quantity [1]. By offering an extended range and lower costs of plant and process network communications, significant improvements in the overall efficiency of the plant can be realized [6]. Due to its huge market potential, IWSNs have drawn more and more attention from companies and research institutes [7]. In academia, researchers developed various IWSNs for industrial applications. Tan et al. designed and applied an IWSN system to fault detection in metal cutting processes [8]; Evans discussed the IWSN application in the electrical manufacturing system [9]; Bayindir and Cetinceviz designed a small-scale control system based on IWSN and programmable logic controller to control a water pumping system designed for production plants [10]; Salvadori et al. proposed a digital system based on IWSN for energy usage evaluation, condition monitoring, diagnosis and supervisory control for electric systems [11]; our research group is developing an IWSN maintenance monitoring system based on IEEE 802.15.4 and IEEE 802.15.4a [12] for a steel company. In the industry community, Honeywell, an international automation and control company, presents its IWSN solution named OneWireless [13] and series wireless productions to realize the application of IWSN in industrial fields. Other companies including Emerson [14], Siemens [15], ABB [16], Rockwell [17] and YOKOGAWA all provide their IWSN solutions and the related wireless productions based on wireless HART or ISA100.11a. Now, these IWSNs have been successfully applied to the food industry, beverages industry, pharmaceuticals industry, oil industry, gas industry, chemical industry, mining industry, refining industry, power plants, pulp industry, etc. The industrial applications of IWSNs show that wireless installation typically costs as much as 50 percent less than the wired alternative. Furthermore, IWSNs can improve the efficiency, reduce manual workload and can be applied to the fields where the wired system cannot be installed [13]. It is no doubt that IWSNs have been one of the hottest trends in industry automation and control.

However, the current applications of IWSNs are still on a small scale because of the technical obstacles. To make up for it and realize the large-scale applications of IWSNs, the researches on scheduling algorithms [18,19], MAC Protocols [20], routing protocols [21-23], UWB technology [24], intrusion detection [25] and advanced control algorithms in IWSNs framework [26] have been performed to improve the performance of IWSNs. Among the challenges of large-scale IWSNs applications, how to achieve reliable communication in the harsh industrial radio environment is the foremost barrier to conquer. IWSNs play a vital role in monitoring and controlling that directly affect the performance of the control system such as Distributed Control System (DCS) and Programmable Logic

Control (PLC) System. In industrial environments wireless sensors may be subject to RF interference, highly caustic or corrosive environments, high humidity levels, vibrations and dust, which may cause sensor nodes to malfunction and break the link of network. Most industrial applications require absolute reliability in systems control to avoid serious consequences such as injury, explosions, and material losses. Moreover, the previous studies have shown that wireless channels exhibit transient errors at often much higher rates than observed on wires or fiber cables [27]. To meet the requirement, researchers attempt to enhance the reliability of IWSNs by modifying the encoding strategy [28], MAC protocol [29] and routing algorithm [30]. However, for large-scale IWSNs consisting of thousands even ten thousands of nodes, only improving coding, MAC or routing is insufficient. The challenges from the harsh industrial fields are more complicated. For instance, moving people or equipment may block the communication link for a period of time and it is unavoidable that some node is out of work by accident. Obviously the network architecture of IWSNs has a significant influence on the reliability of data transmission. In cluster-based IWSNs, the placement of sensor nodes and cluster-head nodes determine the communication reliability and efficiency. It is essential to design IWSNs topology carefully to guarantee the expected reliability as well as other application requirements such as the balance of network loads and reducing cost of system.

Actually, the same situation exists in the non-industrial applications of Wireless Sensor Networks (WSNs) in which the reliability of system is also a vital issue. At first, the works mainly focus on the MAC and routing protocols to improve the basic performance of WSNs. Then people realize the importance of the network topology and show great interest in optimizing the node placement problem of WSNs. Various deployment strategies and algorithms have been proposed to construct the WSNs to improve the reliability as well as energy efficiency, network coverage and connectivity [31,32]. The previous works have proven that the optimal node deployment of WSNs is an NP-hard problem [33,34]. During the last few decades, meta-heuristic optimization algorithms have shown outstanding performances in solving the NP-hard problems like traveling salesman problem (TSP) and job-shop schedule applications. Thus, meta-heuristic optimization algorithms including Genetic Algorithm (GA) [35-38], Particle Swarm Optimization (PSO) [39-42], Ant Colony Optimization (ACO) [43] and Memetic Algorithm (MA) [44] have been researched and applied to solve node placement in WSNs. However, due to the complexity of large scale WSNs, the optimizing performances are not ideal and the global search ability of algorithms need to be improved further. Furthermore, contrary to generic WSNs, the node placement in IWSN is deterministic to meet the desired monitoring tasks. Unlike in WSNs, each IWSN sensor measurement is unique and cannot be replaced by data from another sensor [45]. Thus, the deployment strategies of WSNs cannot be directly adopted for IWSNs as the requirements and work conditions are not the same.

Recently, Harmony Search (HS) [46], a novel meta-heuristic algorithm inspired by the improvising process, raises comprehensive interests because of its characteristics such as ease of implement and robust search ability. Now HS has been successfully applied to a wide range of problems in the scientific and engineering fields. However, most of the previous work on HS focused on the continuous or discrete optimization problems, and so far just several researches are concerned with the binary-coded problems. Geem [47] firstly used HS to solve the water pump switching problem and later applied HS to tackling the ecological conservation problem [48] of which the candidate solution is binary. Then Greblicki and Kotowski [49] analyzed the properties of HS on the one dimensional binary knapsack problem and the results illustrate that the optimization performance is unsatisfactory. Afterwards, Wang et al. [50] pointed out that the pitch adjustment rule of HS could not perform its function on the binary space, which spoiled the performance of HS for binary optimization problems. Therefore, he proposed a modified discrete binary HS (DBHS) algorithm in which a new pitch adjustment operator was developed to ameliorate the optimization ability. Afterwards, Wang et al. [51] extended the DBHS to solve Pareto-based multi-objective problems. Recently, Zou et al. [52] used a novel global harmony search algorithm to solve binary optimization problems, which replaces the real number with the nearest integer to generate the binary-coded solution. In summary, the research on binary HS has just begun, and to the best of our knowledge, HS has not been applied to solve node placement of IWSNs or WSNs. In this paper, we investigate characteristics of IWSNs and build an optimal node placement model considering the reliability of IWSNs as well as the cost, energy balance and scalability. A novel hybrid binary Differential Evolution Harmony Search (HBDEHS) algorithm is proposed to solve the optimal node placement problem of IWSNs. Different from the previous works [28-30], this paper studies and improves the reliability of IWSNs from the system point of view. As the proposed method does not depend on the specific coding, protocol or routing, it can be easily applied to various IWSNs applications. Thus, our work can be regarded as an extension and development research. Furthermore, the presented sensor placement scheme is a multi-objective optimization method, which can guarantee the other application requirements like minimizing the cost and ensuring the scalability of system.

The rest of the paper is organized as follows. Section 2 introduces the developed node placement model of IWSNs, where the solution representation and the objective function are addressed in detail. Then the proposed HBDEHS algorithm is described in Section 3. Section 4 presents the implementation of solving the optimal node placement problem with HBDEHS. In Section 5, the designed model and optimization method are validated on solving various large-scale optimal node placement problems of IWSNs. Finally, the conclusions are drawn in Section 6.

2. Node Placement of IWSNs.

2.1. **Cluster-based communication model of IWSNs.** In this work, IWSNs based on the two-tiered clustering architecture are researched. The lower-layer is the single-hop communication between the sensor node and its cluster-head node. The upper-layer is the multi-hop routing among cluster-head node to the base station or sink node. The sensor node and cluster-head node have a maximal communication radius denoted as R_s and R_{ch}, respectively. Generally, the data-handling and communication capacities of cluster-head nodes are more powerful than those of regular sensor nodes. For instance, Figure 1 depicts an IWSN with three sensor nodes (S1, S2 and S3) and three cluster-head nodes (H1, H2 and H3). The distance between the sensor node S1 and the cluster-head node H1 or H2 is within R_s, that is, H1 and H2 can be covered by the communication circle of S1. Thus, the sensing data of S1 can be reliably transmitted to H1 or H2. However, the data transmitted from S2 will not be received by H1, H2 and H3 as the real transmitting distance is beyond the maximal communication range R_s of S2.

2.2. **Node placement for reliability.** In Figure 1, the control system will lose the monitored information from S3 if H3 fails, which is dangerous as the whole system may be out of control. Compared with S3, the communication of S1 is more reliable as the data can be transmitted by H1 or H2. IWSNs have a critical requirement on the reliability of network. Thus, the network should be designed to ensure that each sensor node and cluster-head node can communicate with at least two cluster-head nodes, of which one is used as the regular communication head and the rest is retained for a backup.

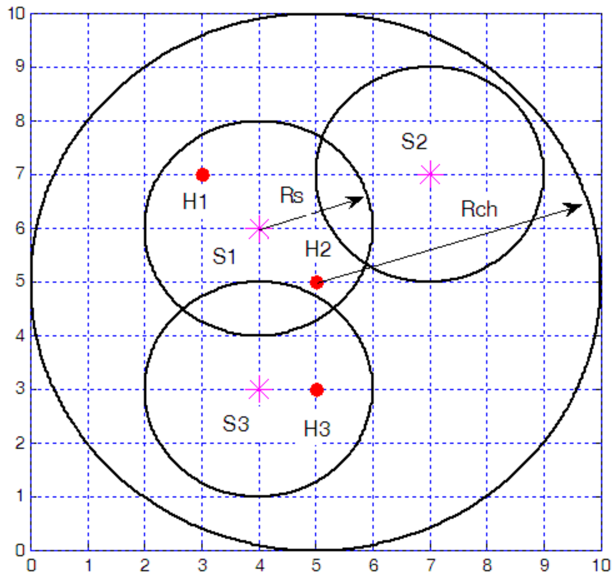

FIGURE 1. A sample of the model of IWSNs (sensor node *, cluster-head node •)

In the applications of IWSNs, sensor nodes are installed on the machines or other facilities that need to be monitored according to the pre-designed scheme, which means that these nodes cannot be deployed randomly and freely. Thus, the optimal placement of IWSNs focuses on the location optimization of cluster-head nodes. To meet the reliability requirement, we have two schemes:

1) deploy the additional cluster-head node;
2) upgrade the current sensor node to serve as a cluster-head node.

2.3. **Optimal node placement model of IWSNs.** The objective of designing the architecture of IWSNs is to guarantee the reliability of data communication, minimize the setup cost and improve the uniformity of the communication load to reduce the maintenance cost. Moreover, the maximal communication loads and the scalability of system also need to be considered in industrial applications. Therefore, the optimal node placement problem of IWSNs is a complicated constrained multi-objective optimization problem which can be formulated as Equations (1) and (2).

$$f = w_1 \times C + w_2 \times SD_{CL} \tag{1}$$

$$\text{s.t.} \quad \begin{aligned} & MIN_{CH}^{CH} \geq L_{RN} \\ & MIN_{CH}^{S} \geq L_{RN} \\ & LCH_i \leq MCL - Nr \end{aligned} \tag{2}$$

where C is the setup cost of IWSNs; SD_{CL} is the standard deviation of cluster-head node communication load which is an important metric related with the maintenance cost; and are the corresponding weight factors with $w_1 + w_2 = 1.0$. $MIN_{CH}^{CH} \geq L_{RN}$ and $MIN_{CH}^{S} \geq L_{RN}$ represent the reliability constraint of the cluster-head node and the sensor node, respectively. MIN_{CH}^{CH} is the minimum number of the connections between one cluster-head node and the other cluster-head nodes while MIN_{CH}^{S} is the minimum connection number between each sensor node and all the cluster-head nodes in the IWSN; L_{RN} is the pre-defined least number of connected cluster-head nodes. LCH_i is the real load number of each cluster-head node, MCL is the maximum connection number of the cluster-head nodes and Nr is the connection number preserved for the expansibility of IWSN.

2.3.1. *Setup cost.* Although IWSNs can greatly reduce the setup cost compared with the traditional wired system, its constructing expense still should be considered, especially for the large-scale applications. As the number of sensor nodes is determined by the requirements of industrial systems, the main objective of optimizing the setup cost of IWSNs is to decrease the investment of cluster-head nodes, which is comprised of two parts, i.e., the cost of the additional cluster-head nodes and the upgrading fee of the existing sensor nodes as Equation (3)

$$C = \alpha \times Nch + \beta \times Nchu \tag{3}$$

where Nch and $Nchu$ are the number of the additional cluster-head nodes and the cluster-head nodes upgraded from the sensor nodes, respectively; α and β are the corresponding unit cost of these two kinds of the cluster-head nodes.

2.3.2. *Maintenance cost.* In IWSNs, sensor nodes transmit the scheduled data to the cluster-head node, and thus energy consumption of sensor nodes are almost same. However, the number of sensor nodes connected with each cluster-head node is different, and therefore the energy consumption of cluster-head nodes is un-balanced. The communication load equilibration of cluster-head nodes has to be taken into account as the non-uniformity loads mean that engineers need replace the battery of the cluster-head node frequently to ensure IWSN working normally. To tackle it, the standard deviation of communication load of cluster-head nodes (SD_{CL}) are adopted as the metric denoting the maintenance cost to be optimized in this work, which can be calculated as Equations (4) and (5).

$$SD_{CL} = \sqrt{\frac{\sum_{i=1}^{Nch+Nchu} (LCH_i - ML_{CH})^2}{Nch + Nchu - 1}} \tag{4}$$

$$ML_{CH} = \frac{\sum_{i=1}^{Nch+Nchu} LCH_i}{Nch + Nchu} \tag{5}$$

2.3.3. *Reliability constraint.* To guarantee the reliability of IWSN, each sensor node or cluster-head node must have at least L_{RN} heads for data-transmitting, which can be described as as Equations (6)-(8)

$$\begin{cases} MIN_{CH}^{S} \geq L_{RN} \\ MIN_{CH}^{CH} \geq L_{RN} \end{cases} \tag{6}$$

$$MIN_{CH}^{S} = \min\{N_i | i = 1, 2, \ldots, N_S\} \tag{7}$$

$$MIN_{CH}^{CH} = \min\{M_i | i = 1, 2, \ldots, N_{cht}\} \tag{8}$$

where Ns is the number of sensor nodes, $N_{cht} = Nch + Nchu$ is the total number of cluster-head nodes, and usually $L_{RN} = 2$.

2.3.4. *Maximal load constraint.* Although the energy and communication capacity of cluster-head nodes is more powerful than the regular sensor nodes, the loads of each cluster-head node still should be limited to ensure the real-time of data processing and extend the working period. Therefore, the maximal communication load number MCL

is introduced in the proposed model, and the loads of each cluster-head node cannot be more than MCL, i.e.,

$$LCH_i \leq MCL \tag{9}$$

where LCH_i is the real load number of cluster-head i.

2.3.5. *Scalability.* The industry system may be upgraded or maintained and therefore the additional nodes will be introduced into the current IWSN permanently or temporarily. Considering these situations, cluster-head nodes need to reserve certain number of loads for the expansibility of IWSNs, that is,

$$LCH_i \leq MCL - Nr \tag{10}$$

where Nr is the preserved load number.

3. Hybrid Binary Differential Evolution Harmony Search Algorithm.

3.1. Harmony search algorithm.

Harmony Search (HS) is inspired by the improvising process of musicians. In HS, the best solution vectors found are stored in the Harmony Memory (HM), and the number of vectors in the HM is called the Harmony Memory Size (HMS). HS algorithm performs the search through three operators, i.e., harmony memory considering operator (HMCO), pitch adjusting operator (PAO) and random selection operator (RSO), based on the harmony memory considering rate (HMCR) and the pitch adjusting rate (PAR). The procedure of HS can be briefly described as following steps:

Step 1: Initialize the algorithm. The parameters of HS are set and the HM is randomly initialized with the feasible solutions.

Step 2: Improvise the new harmony. After initialization, the new harmony vector is improvised by using the harmony memory consideration rule, the pitch adjustment rule and randomization, which is determined by the pre-defined HMCR and PAR. The HMCR is the probability of choosing one value from the HM while PAR determines whether the value from the HM should be pitch-adjusted.

Step 3: Update the HM. If the new harmony vector performs better than the worst harmony vector in the HM, the new one is included in the HM instead of the worst harmony memory vector.

Step 4: Check the terminal criterion. If the stopping criterion is satisfied, the search process is terminated and the optimal solution is output. Otherwise, Step 2 and Step 3 are repeated.

More details on HS can be found in [53].

3.2. Hybrid binary differential evolution harmony search algorithm.

The standard HS can directly use binary encoding to tackle the binary optimization problems. However, the performance of binary-coding HS (BHS) is not satisfactory due to the degeneration of the pitch adjustment operator. To make up for it, a hybrid binary differential evolution harmony search algorithm (HBDEHS) is proposed in this paper to solve binary optimization problems more efficiently and effectively.

3.2.1. *Initialization of the harmony memory.* HBDEHS adopts binary encoding, and the HM of HBDEHS is randomly initialized over the binary space as Equation (11).

$$HM = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1j} & \cdots & x_{1M} \\ x_{21} & x_{22} & \cdots & x_{2j} & \cdots & x_{2M} \\ \cdots \\ x_{i1} & x_{i2} & \cdots & x_{ij} & \cdots & x_{iM} \\ \cdots \\ x_{HMS,1} & x_{HMS,2} & \cdots & x_{HMS,j} & \cdots & x_{HMS,M} \end{bmatrix}$$
$$x_{i,j} = \begin{cases} 1, & \text{if } r_0 < 0.5 \\ 0, & \text{otherwise} \end{cases} \quad i \in \{1, 2, \ldots, HMS\}, \quad j \in \{1, 2, \ldots, M\} \tag{11}$$

where r_0 is a uniform distributed random number within $[0, 1)$; HMS is the size of HM; x_{ij} is the element of the harmony vector and M is the length of the harmony vector, i.e., the dimension of the solution.

3.2.2. *Improvising of the new harmony vector.* Similar with standard HS, HBDEHS improvises the new harmony vector by executing harmony memory consideration operator, random selection operator and pitch adjustment operator. In addition, to remedy the drawback of the standard BHS, an improved harmony memory considering operator and pitch adjusting operator are developed to enhance the performance by fusing the search mechanism of differential evolution (DE) algorithm in HBDEHS.

The mutation operator is the main search operating of DE, and the most popular mutation scheme in DE called "*DE/rand/1*" can be described as Equation (12)

$$u_{ij}^{t+1} = x_{r1,j}^t + F * \left(x_{r2,j}^t - x_{r3,j}^t\right) \tag{12}$$

where u_{ij} is the element of the new mutant individual u_i; $x_{r1,j}$, $x_{r2,j}$ and $x_{r3,j}$ are three bits of the randomly chosen individuals with index $r_1 \neq r_2 \neq r_3 \neq i$; t is the index of generation; F is the scaling factor which determines the effect of $(x_{r2,j}^t - x_{r3,j}^t)$ for the new solution.

Inspired by the mutation operator of DE, the three independent individuals and their differential information are used to search for the new solution. HBDEHS firstly performs a global search using HMCO as Equations (13) and (14) with the probability HMCR

$$v_{i,j}^{G+1} = \begin{cases} x_{r1,j}^G, & rand1 \leq HMCR \\ RSO, & \text{otherwise} \end{cases} \tag{13}$$

$$RSO = \begin{cases} 1, & rand2 \leq 0.5 \\ 0, & \text{otherwise} \end{cases} \tag{14}$$

where $v_{i,j}^{G+1}$ is the j-th bit of the new harmony individual v_i; x_{r1}^G is a random harmony vector chosen from the HM and $x_{r1,j}^G$ is the j-th bit of x_{r1}^G; $rand1$ and $rand2$ are two independent random number between 0 and 1.

If $v_{i,j}^{G+1}$ comes from HM, it needs be judged whether to be pitch adjusted by PAO with the probability PAR as Equations (15) and (16).

$$v_{i,j}^{G+1} = \begin{cases} \text{PAO}, & rand3 \leq PAR \\ v_{i,j}^{G+1}, & \text{otherwise} \end{cases} \tag{15}$$

$$PAO = \begin{cases} x_{r2,j}^G, & \text{if } (x_{r2,j}^G - x_{r3,j}^G) = 0 \text{ or } (x_{r2,j}^G - x_{r3,j}^G \neq 0 \text{ and } rand4 < 0.5) \\ x_{r3,j}^G, & \text{otherwise} \end{cases} \tag{16}$$

where *rand3* and *rand4* are two random number uniformly distributed in the range $[0, 1]$; x_{r2}^G and x_{r3}^G are another two harmony vector in HM with index $r_1 \neq r_2 \neq r_3 \neq i$.

Compared with the mutation operator of DE, HMCO is analog to the first term on the right of Equation (12). Meanwhile, HBDEHS executes RSO with the rate of (1-HMCR) which can ensure that the feasible value not included in HM can be obtained by the algorithm. PAO of HBDEHS is similar to the second term on the right of Equation (12) and performs a local search based on the differential information between $x^G_{r2,j}$ and $x^G_{r3,j}$, which helps HBDEHS find the global optima effectively and efficiently.

3.2.3. *Updating of the HM.* To keep the diversity of HM and avoid premature of the algorithm, the parallel updating mechanism of DE is utilized in HBDEHS for updating the HM which is formulated as Equation (17)

$$x_i^{G+1} = \begin{cases} v_i^{G+1}, & \text{if } f(v_i^{G+1}) < f(x_i^G) \\ x_i^G, & \text{otherwise} \end{cases} \tag{17}$$

HBDEHS repeats HMCO, RSO, PAO and the updating of the HM to search for the global optimal solution until the terminated condition is satisfied. In summary, the whole procedure of the proposed HBDEHS can be described as Figure 2.

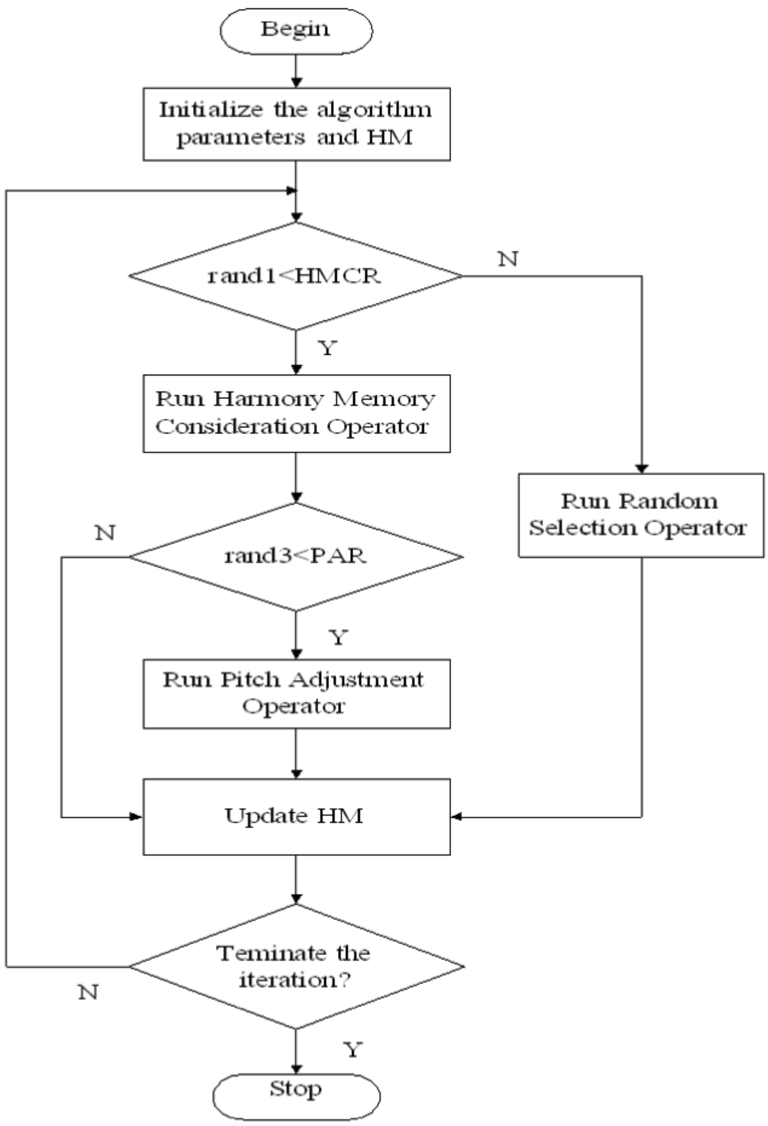

Figure 2. Flowchart of the HBDEHS algorithm

4. **The Optimal Node Placement of IWSNs Based on HBDEHS.**

4.1. **Encoding.** For the node placement problem, the deployed area of IWSNs can be mapped as a $W \times L$ grid. Then the solution of problem can be represented as a binary string with length $M = W \times L$ where the bit value of "1" represents that a cluster-head node is deployed or the original sensor node is upgraded into the cluster-head node at the corresponding intersection of grid and vice versa. And therefore, the dimension of the harmony vector is M, and each individual represents a deployment scheme. A simple example of encoding with $4 * 4$ gird is given in Figure 3.

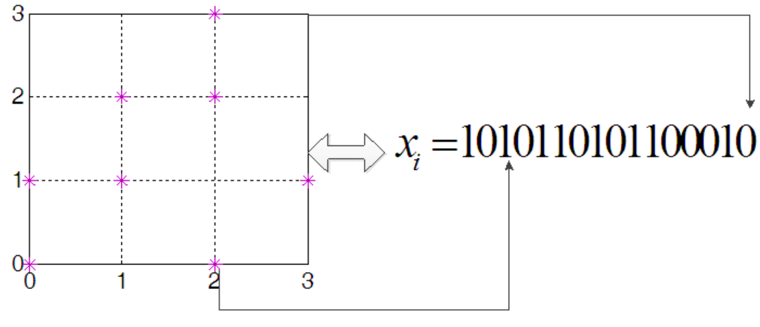

FIGURE 3. Binary representation of the IWSN node deployment problem

4.2. **Constraint handling.** As mentioned above, the optimal node placement of IWSN is a complicated constrained problem and the infeasible solutions are generated during the search process. Therefore, the penalty function is introduced to fix the fitness of the infeasible solution and lead the algorithm to search the feasible area effectively as Equations (18)-(21):

$$F = f + p_1 + p_2 + p_3 \tag{18}$$

$$p_1 = \sum_{i=1}^{Nvs} \max\{0,\ c_p \times (L_{RN} - N_i)\} \tag{19}$$

$$p_2 = \sum_{i=1}^{Nvch} \max\{0,\ c_p \times (L_{RN} - M_i)\} \tag{20}$$

$$p_3 = \sum_{i=1}^{Nvc} \max\{0,\ c_p \times (MCL - LCH_i)\} \tag{21}$$

where f is the original fitness value defined as Equation (1); p_1 and p_2 are the penalty function for the reliability constraints; p_3 is the penalty function of violating the constraint of the maximal communication load number and scalability; c_p is the penalty coefficient; Nvs is the number of sensor nodes violating the reliability constraint; $Nvch$ is the number of cluster-head nodes violating the reliability constraint and Nvc is the number of cluster-head nodes beyond the upper bound of the communication load and expansibility.

4.3. **Procedure of optimal IWSNs node placement based on HBDEHS.** Based on the given node placement model of IWSNs, the whole procedure of HBDEHS solving the node deployment problem can be described as follows:

Step 1: Map the deployed area into grid according to the accuracy requirements, mark the positions of the sensor nodes and set the parameters of HBDEHS and IWSN model such as R_S, R_{CH}, MCL, HMS, HMCR and PAR.

Step 2: Initialize the HM of HBDEHS and calculate the fitness value of each harmony individual in the HM according to the fitness function Equations (18)-(21).

Step 3: Improvise the new trial harmony individuals by using harmony memory consideration operator, random selection operator and pitch adjustment operator as Equations (13)-(16).

Step 4: Calculate the fitness of the trial harmony individuals and update HM according to Equation (17).

Step 5: Terminate the search procedure and output the best individual in the HM if the maximal iterative number is met; otherwise, go to Step 3.

5. **Experiments and Analysis.** The presented HBDEHS-based node placement scheme is not subject to the specific hardware or protocols, and thus it can be used as a general tool for various applications of IWNSs. However, the position of node in IWSNs is determined by the monitoring and control of industrial systems, so it changes in the different industrial applications. Without loss of generality, four node placement problems are generated and studied as benchmarks in which the sensor nodes spread randomly in $300\text{m} \times 300\text{m}$ and $600\text{m} \times 600\text{m}$ area with the node density $\delta = 0.2$ and $\delta = 0.5$, respectively. The parameters of model are given in Table 1.

Table 1. The model parameters of the node placement of IWSNs

Parameter	Accuracy of the grid	α	β	MCL	Nr	R_s	R_{ch}
Value	10m	1	0.8	8	1	50m	100m

To verify the proposed node placement model of IWSNs and HBDEHS algorithm, the other five binary-coding optimization algorithms, i.e., Novel Global Harmony Search Algorithm (NGHS) [52], Discrete Harmony Search Algorithm (DBHS) [50], Discrete Binary Particle Swarm Optimization (DBPSO) [54], simple Genetic Algorithm (SGA) [55] and Modified Binary Differential Evolution Algorithm (MBDE) [56] are also adopted to tackle the optimal node placement of IWSNs for a comparison. The recommended parameters of NGHS, DBHS, DBPSO, SGA and MBDE are used which are listed in Table 2 as well as those of HBDEHS. The population size and the maximal generation are set as $NP = 100$ and $G_{\max} = 100$, respectively. All the algorithms run on each case with 10 times independently. The simulator is implemented in Java using Eclipse and run on Intel Core 4 Duo Processor running Window 7 at 2.5 GHz with 2×2 GB RAMs. The results are given in Tables 3-6 and the convergence curves are drawn in Figures 4 and 5.

Tables 3-6 show that HBDEHS, NSGH, MBDE, DBHS, DBPSO and SGA all found the feasible solutions for each node placement problem, which demonstrates that the proposed model of optimal IWSNs node deployment is valid and can be used to solve the problems efficiently. Based on the formulated fitness functions, the optimization

Table 2. Control parameters of HBDEHS, NGHS, MBDE, DBHS, DBPSO and SGA

Algorithms	Control parameters
MBDE	$F = 0.8$, $CR = 0.2$
DBHS	$HMCR = 0.7$, $PAR = 0.1$
DBPSO	$w = 0.8$, $c_1 = c_2 = 2.0$, $v_{\max} = 6.0$
SGA	$p_s = 1.0$, $p_c = 0.8$, $p_m = 0.005$
HBDEHS	$HMCR = 1 - 6/individual - length$, $PAR = 0.4$
NGHS	$p_m = 2/individual - length$

algorithms can tackle this NP hard problem to reduce the cost of IWSNs and guarantee the reliability and scalability. Compared with the previous works, our work can greatly improve the reliability and robustness of IWSNs through supplying the redundant link as the communication of system is still guaranteed even if one or more nodes malfunction.

Among six optimization algorithms, the comparison results display that proposed HBDEHS outperforms NSGH, MBDE, DBHS, DBPSO and SGA in terms of search accuracy and convergence speed. The convergence curves in Figures 4 and 5 clearly illustrate that HBDEHS achieved the better solutions than those of NSGH, MBDE, DBHS, DBPSO and SGA. NGHS has a fast convergence speed at the beginning of searching, but it is easy to stick in the local optima and its final solutions are poorer than those of HBDEHS and MBDE. Compared with other algorithms, the convergence speed of MBDE is not fast, but it can escape from the local optima and perform the global search effectively. Obviously, the proposed HBDEHS has the advantages of both DE and HS. The convergence speed of HBDEHS is only slower than that of NGHS on 300m $\times$ 300m at the beginning. However, on the 600m $\times$ 600m examples, HBDEHS performed a similar convergence speed as

Table 3. Results of 300m $\times$ 300m IWSNs node deployment problem with $\delta = 0.2$

Algorithm	HBDEHS	MBDE	DBHS	DBPSO	SGA	NGHS
Best value	**50.5**	225.9	281.9	257.5	263.5	235.6
Feasible	YES	YES	YES	YES	YES	YES
Mean value	**56.4**	234.3	287.6	261.8	270.9	248.6
Variance	**3.2**	4.7	3.4	3.6	4.4	9.4

Table 4. Results of 300m $\times$ 300m IWSNs node deployment problem with $\delta = 0.5$

Algorithm	HBDEHS	MBDE	DBHS	DBPSO	SGA	NGHS
Best value	**56.6**	212.9	262.2	239.4	250.2	228.9
Feasible	YES	YES	YES	YES	YES	YES
Mean value	**59.8**	220.3	268.6	245.3	256.8	237.9
Variance	**2.4**	3.8	3.9	2.6	3.9	6.4

Table 5. Results of 600m $\times$600m IWSNs node deployment problem with $\delta = 0.2$

Algorithm	HBDEHS	MBDE	DBHS	DBPSO	SGA	NGHS
Best value	**613.2**	1152.4	1248.7	1191.4	1207.1	1179.4
Feasible	YES	YES	YES	YES	YES	YES
Mean value	**642.4**	1163.1	1267.0	1210.3	1226.7	1199.4
Variance	**13.7**	6.1	10.1	8.6	12.5	16.5

Table 6. Results of 600m $\times$600m IWSNs node deployment problem with $\delta = 0.5$

Algorithm	HBDEHS	MBDE	DBHS	DBPSO	SGA	NGHS
Best value	**590.0**	1075.1	1177.1	1126.0	1141.2	1095.9
Feasible	YES	YES	YES	YES	YES	YES
Mean value	**606.3**	1090.6	1188.2	1137.9	1174.4	1129.8
Variance	**10.9**	8.2	6.6	6.3	17.7	23.3

NGHS at the early search iteration and outperformed MBDE, DBHS, DBPSO and SGA. Thus, it is fair to claim that HBDEHS has the best global search ability and can design the node deployment of large-scale IWSN applications efficiently and effectively.

6. **Conclusions.** This paper discusses the optimal node placement problem of large-scale IWSNs. Compared with the non-industrial WSNs, IWSNs have a critical requirement on the reliability of network as well as the cost, the maximal loads and the scalability. Thus, a new model of IWSNs node placement is proposed and formulated, in which the reliability as well as the other requirements are taken into account. Considering its NP-hard characteristic, the hybrid Binary Differential Evolution Harmony Search Algorithm is developed to tackle the optimal sensor deployment problem to achieve the better results. Four large-scale node deployment problems with two node densities are generated as the benchmarks. The proposed HBDEHS and the other five optimization algorithms, i.e., NGHS, MBDE, DBHS, DBPSO and SGA, are adopted to solve the problems for a comparison. The experimental results show that all algorithms can find out the feasible solutions, which demonstrates that the proposed model is valid and can guide the optimization algorithm to tackle the optimal node placement of IWSNs efficiently and effectively. The compared results also indicate that the developed HBDEHS has the best global search ability and

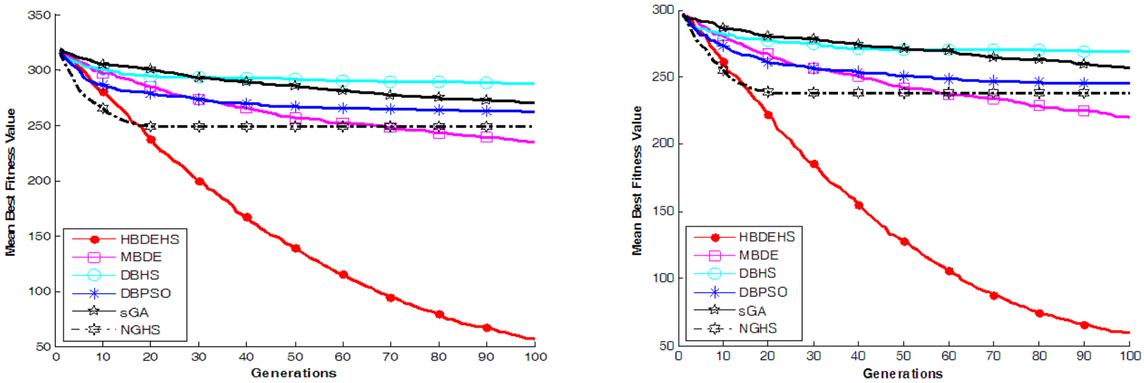

FIGURE 4. 300m $\times$ 300m sensor node deployment problem with node density $\delta = 0.2$ (left) and $\delta = 0.5$ (right)

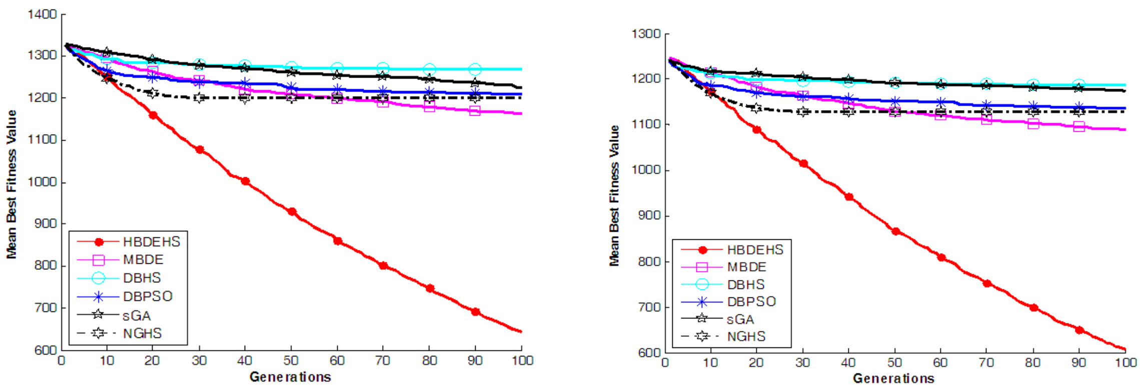

FIGURE 5. 600m $\times$ 600m sensor node deployment problem with node density $\delta = 0.2$ (left) and $\delta = 0.5$ (right)

outperforms DBHS, NGHS, MBDE, DBPSO and SGA in terms of search accuracy and convergence speed.

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