High Reliability, Low Latency and Cost Effective Network Planning for Industrial Wireless Mesh Networks

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***Abstract*—In this paper, we study high reliability, low latency and cost effective network planning for industrial wireless mesh networks. Based on the requirements of routing reliability, minimum end-to-end delay and reduced deployment cost in wireless mesh networks, such as WirelessHART network, we propose three network planning approaches following the principles of the shortest hops, the least routers and balance of the shortest hops and the least routers, respectively. We then implement the proposed algorithms respectively to generate the network deployment for a given factory layout. Simulation results show that there exists a performance trade-off between these three algorithms. The proposed algorithms have also been implemented and validated in an NS-2 WirelessHART network simulator.**

***Index Terms*—Network planning, wireless mesh networks, WirelessHART, high reliability, low latency, cost effective.**

I. Introduction

RECENTLY, wireless technologies have attracted great interests to deploy industrial networks [1]. Compared with wireless community networks, the industrial control environment is harsher and noisier and thus has more stringent requirements on reliable and real-time communication. Missing or delaying the process data may severely degrade the quality of control. Traditional wireless standards such as ZigBee and Bluetooth were not designed to meet the stringent timing and security requirements of industry control. Thus, the HART Communication Foundation proposed the WirelessHART standard [2], which uses a time-synchronized, self-organizing and self-healing mesh architecture, to provide a complete solution for real-time process control applications. The self-organizing and self-healing mesh technologies in WirelessHART network enable wireless field devices to self-route through the process environment and re-route when the environment changes, and thus guarantee long-term reliability and predictability, even under changing environmental conditions.

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Network coverage and connectivity are two of the most fundamental issues in wireless mesh networks. Coverage is usually defined as a measure of how well and for how long the sensors are able to observe the physical space. Connectivity is usually defined as a measure of how well the network remains connected so that information collected by sensor nodes can be relayed back to data sinks or controllers. In wireless mesh networks, network deployment is a key technology, which has great impact on network coverage, connectivity, lifetime and the cost of the network [3]–[12]. It is extremely difficult to find an optimal node deployment strategy that can minimize deployment cost, preserve network connectivity while maximizing coverage by using the limited number of energy constrained nodes.

In order to deal with the harsh and noisy industrial environment, we take into account both reliability and connectivity requirements of WirelessHART networks and develop high reliability, low latency and cost effective network planning approaches for industrial wireless mesh network in this paper. The proposed network planning algorithms can also be extended to other wireless mesh networks with similar requirements. The main contributions of this paper are listed as follows:

- Besides the routing reliability and connectivity requirements in order to address the harsh industrial environment, we also consider minimizing end-to-end delay and reducing deployment cost, and propose three network planning approaches based on the principles of the shortest hops, the least routers and balance of the shortest hops and the least routers;
- Implement these three network planning approaches in Matlab, respectively, and study the performance trade-off among them;
- Verify the effectiveness of proposed algorithms by using an NS-2 based network simulator in [13].

Note that network planning is different from network routing protocol design. Network routing protocol design is to search the most appropriate routers subset among all routers deployed in the current network to connect access points and field devices. However, the network planning is an opposite process, which is to determine the necessary routers first and then deploy them accordingly. Network routing protocol design is usually performed on-line after the network has been initialized and stabilized and re-routing will be triggered if any node is down. Network planning is one step before network routing protocol design and performed during network set up stage. It is usually offline. The input parameters will be the layout of the industry factory and positions of field devices, which are attached to machines on the predefined positions. The output will be the positions of gateway, access points and routers. Only if the factory layout changes or the positions of field devices change, we need to perform network planning again. We highlight that our algorithms are more advantageous than manual planning, because manual planning does not guarantee efficiency (e.g., the number of nodes may not be minimum guaranteeing the coverage and redundancy requirements), and cannot address real-time need in the dynamically changing environment.

Note that partial of this work has been presented on IEEE GLOBECOM 2018 [14]. The major difference between this journal paper and the conference paper is that we propose one more new network planning approach, in addition to the two network planning approaches presented in the conference paper. Different from the previous two approaches, which either consider end-to-end delay or deployment cost, this new approach takes both end-to-end delay and deployment cost into account and therefore is more practical. We also introduce one more performance metric, number of usage of routers, and present extensive simulation results to compare the performance of these three approaches.

The rest of this paper is organized as follows: Section II reviews previous works relating to network deployment. Section III introduces the WirelessHART network topology and routing reliability requirements. In Section IV, we propose three high reliability, low latency and cost effective network planning approaches. The related performance evaluation is shown in Section V. Finally, Section VI concludes this paper.

II. Related Works

In literature, there are two kinds of deployment: random deployment and deterministic deployment. For random deployment, sensor/actuator nodes are randomly deployed across the working area. On the contrary, the deterministic deployment requires to well plan the locations of sensor/actuator nodes to deploy a wireless mesh network. In [15], the network planning problem was addressed by considering the constraints of coverage, target localization and network connectivity. In [16], Chen et al. presented an approach to integrate the network planning with QoS estimation for industrial applications. The design of heterogeneous networks with the objectives of minimizing costs and maximizing network lifetime was proposed in [17]. An efficient triangular grid based sensor deployment planning for coverage was studied in [18]. The authors in [19] described two self-configuration mechanisms to establish mesh topologies in IEEE 802.11s multiradio WMNs: a distributed mechanism based on the portal announcement protocol specified in the IEEE 802.11s standard to determine the initial channel assignment of the mesh points forming a backhaul network and a centralized mechanism to optimize the topology initially created once the network is stable. In [20], Savazzi et al. proposed algorithms to optimize the network connectivity and provided practical deployment rules for WirelessHART and ISA standards. The authors in [21] predicted the wireless link quality by using a site-specific channel model and optimized the wireless node connectivity for WirelessHART and ISA SP100 industrial networks. Shamsi in [22] applied simple design rules to ensure optimum connectivity of field devices back to the WirelessHART gateway.

Most of the previous works only solve the network connectivity problem. However, compared with wireless community networks, the industrial control environment presents more design challenge for industrial wireless networks. Industrial facilities usually have dense infrastructure with metals that interferes with wireless transmission. There are frequent movement of large equipment and changing conditions. Numerous sources of radio-frequency and electromagnetic interference may cause communication challenges [23]. Therefore, the industrial wireless network needs to be planned and optimized to meet the stringent reliability and low-latency requirement in this harsh and noisy environment. The WirelessHART mesh network is also different from most previous works, which only consider the network with one AP and take into account of connectivity. It is a redundant, self-healing mesh network with multiple access points. Different from [19] etc., each intermediate node on the WirelessHART routing graph must have at least two neighbours to help forward the traffic [24]. In addition, it monitors the paths for degradation and repairs itself by finding alternative paths around obstructions and hopping in different frequency channels. In this way, messages can be routed around interferences and obstacles and the network performance is greatly improved. This is especially important in the noisy and harsh industrial environments. For this reason, the previous works cannot be directly applied in WirelessHART networks, and new network planning algorithms have to be designed. To the best of our knowledge, this paper is the first work to take into account both reliability and connectivity requirements of WirelessHART networks to develop high reliability, low latency and cost effective network planning approaches for industrial wireless mesh network.

III. WirelessHART Networks

A. WirelessHART Network Topology

The WirelessHART mesh network supports several basic node types which include network manager, gateway, security manager, access point, router, field device, handheld, adapter, etc. Without loss of generality, a typical topology of WirelessHART mesh network is illustrated in Fig. 1. The gateway connects host applications with field devices. The network manager is responsible for network management such as network configuration, resource scheduling, routing path configuration, etc. The security manager is responsible for the management and distribution of security keys. Normally, the network manager and security manger reside in gateway. The access point connects the wireless network and the gateway, and the router provides the routing capability to improve the network connectivity and coverage. The field device

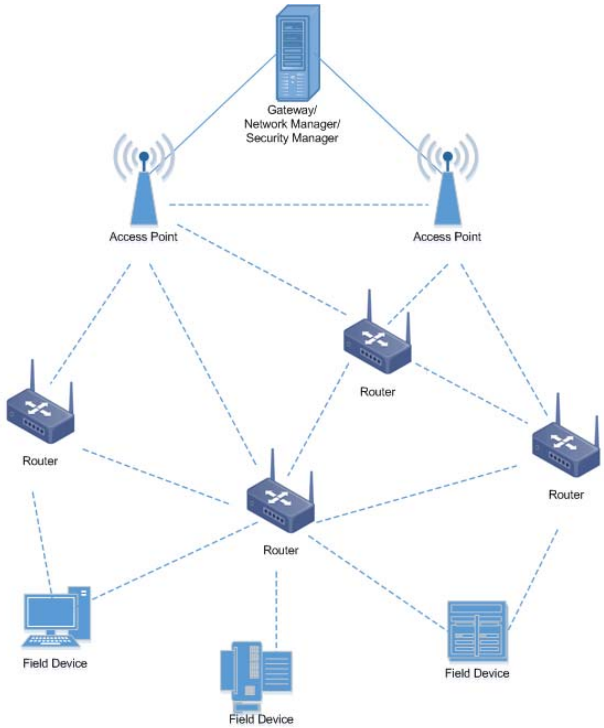


Fig. 1. A typical topology of WirelessHART mesh network.

collects the data and performs the sensing and/or actuation functions. All the WirelessHART nodes should support the basic mesh node functionalities including routing. However, in this paper, to simplify the network structure, we assume that only the router plays a role of forwarding packets from one node to another node, while the field device is responsible for collecting data from its attached machines and transmitting/receiving its own packets to/from the neighbouring nodes. For reliable transmission, the number of access points should be two or more, and the connection between access points and the gateway are supposed to be wired.

B. Routing Reliability in WirelessHART

Two primary routing protocols are defined in WirelessHART Standard: *Source Routing* and *Graph Routing*. In source routing, the complete routing path from source to destination is explicitly written in the ongoing packet. Thus, only the specified intermediate node can forward the current packet to the next following node. Due to the deterministic routing path, the source routing is usually used for network diagnostics. Unlike the source routing, the graph routing specifies only a graph ID in the packet. The graph information corresponding to this graph ID is pre-configured by the network manager prior to its use and route. Thus, when an arbitrary node receives this packet, it will check the corresponding graph routing table to determine whether or not to forward the current packet.

For different transmission purposes, the WirelessHART standard defines three types of routing graphs: *broadcast*, *uplink* and *downlink*. Here, a broadcast graph is used for broadcasting common messages from the gateway to every node in the network. An uplink graph is used for uploading data from every field device to the gateway. Last, a downlink graph is used for the gateway to send unicast messages to a specific field device. All these routing graphs are generated and updated by the network manager and eventually downloaded to every node.

TABLE I

NOTATIONS OF VARIABLES/SYMBOLS

G	Routing graph
V	Nodes set
E	Edges set
$G(V, E)$	Network topology
δ_i^+	Outgoing degrees of an arbitrary node i
δ_i^-	Incoming degrees of an arbitrary node i
G_B, V_B	Broadcast graph, nodes set of broadcast graph
G_U, V_U	Uplink graph, nodes set of uplink graph
G_v, V_v	Downlink graph and the relating nodes set for node v
GW	Gateway
A_1,A_2	Access Points
AP	(A_1, A_2)
T	Edge length of each triangular cell
$\mathbb{N}_R$	Routers subset
RANK	Number of usage of a vertex
(X_i, Y_i)	Position of field device
$H(a, b)$	Shortest number of hops between nodes a and b
N_F	Number of field devices
N_R	Number of planned routers
$\overline{H}$	Average hops per route
$\overline{R}$	Average ranks of routers

To counter against the harsh and noisy industrial environment, the WirelessHART mesh network defines higher requirements of routing reliability, as introduced in [24]. In this paper, we use $G(V, E)$ to represent the WirelessHART network topology, where G refers to an specific routing graph, V refers to the set of nodes required for this kind of routing, and E refers to the set of edges, i.e., the required transmission links among the node set V. Let δ_i^+ and δ_i^- denote the outgoing and incoming degrees of an arbitrary node i, respectively. Thus, we can summarize the reliability requirements for each kind of routing graph as follows:

- Broadcast graph (denoted by G_B): Each node should have at least two parent nodes from which it can receive the broadcasting messages, i.e., for $\forall i \in V_B$, $\delta_i^- \geq 2$.
- Uplink graph (denoted by G_U): Each node should have at least two child nodes to forward its packets to the gateway, i.e., for $\forall i \in V_U$, $\delta_i^+ \geq 2$.
- Downlink graph for node v (denoted by G_v): Each intermediate node should have at least two child nodes to forward packets, i.e., for $\forall i \in V_v$, $\delta_i^+ \geq 2$.

Obviously, the broadcast graph and uplink graph are global graphs shared by all nodes, but the downlink graph is unique for each node. Therefore, V_B and V_U refer to all the nodes of the entire network, and V_v refers to only the necessary nodes for unicasting from gateway to node v. Furthermore, to avoid any cyclic transmission and reduce delay, the reliability of downlink graph have two more restricting conditions [24] which are given below:

1) Node v is the only sink and the gateway is the only source in V_v;
2) There is only one cycle of length 2 in G_V, and each node on this cycle has a direct edge to the sink node v.

For better illustration, we summarize all the notations of variables/symbols used in this paper in Table I.

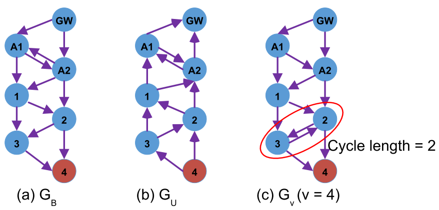


Fig. 2. An example of G_B, G_U and G_v.

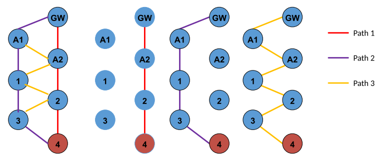


Fig. 3. Network structure of deployment: triangle.

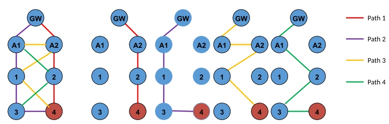


Fig. 4. Network structure of deployment: square.

Based on the aforementioned reliability conditions of *broadcast* graph, *uplink* graph and *downlink* graph, we draw Fig. 2 as an example to illustrate the routing graphs of G_B, G_U and G_v for a WirelessHART mesh network, which consists of one gateway "GW", two access points "A_1" and "A_2", and four nodes denoted from 1 to 4. In Fig. 2, each arrow represents one hop in the routing path, following which the message will be forwarded from source to destination.

IV. Computer-Aided Network Planning Approaches

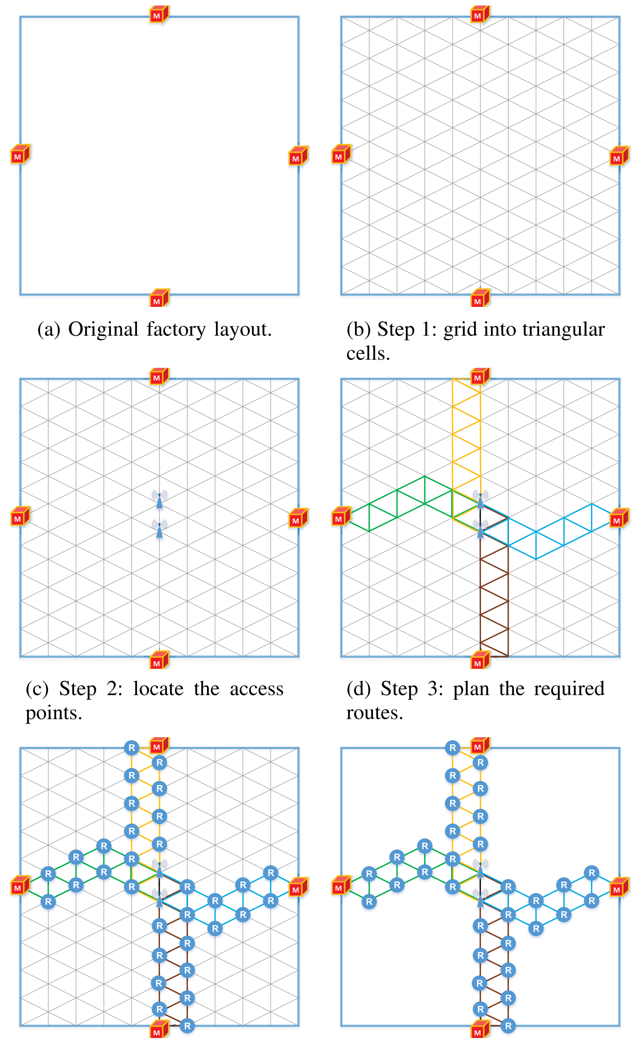
In this section, we will describe in detail the procedures of network planning for reliable transmission in WirelessHART mesh networks.

A. Network Deployment Structures

To satisfy the routing reliability requirements, the key method is to find out suitable structures to deploy the WirelessHART mesh network.

We use the network in Fig. 2 as an example again. If we overlap three different routing graphs and ignore the link directions, we can easily obtain a network structure for reliable transmission, which is shown in Fig. 3. It is obvious that three neighbouring nodes form a triangular cell, and adjacent cells expand to the entire network. Furthermore, we also observe that this triangle-based network structure ensures that each node has two degrees of both outgoing and incoming. Thus, there exist at least three different routes between gateway and every node. For example, if considering the downlink routes from gateway to Node 4, we have three redundancy routes: (GW $\rightarrow$ A2 $\rightarrow$ 2 $\rightarrow$ 4), (GW $\rightarrow$ A1 $\rightarrow$ 1 $\rightarrow$ 3 $\rightarrow$ 4) and (GW $\rightarrow$ A1 $\rightarrow$ A2 $\rightarrow$ 1 $\rightarrow$ 2 $\rightarrow$ 3 $\rightarrow$ 4).

Of course, the triangle structure is not the only way to construct the WirelessHART mesh network. As shown in Fig. 4, a square structure also can achieve the purpose of reliable transmission. In this square structure, each node has three degrees of outgoing and incoming, respectively. Therefore, there exist four different routes between gateway and every node. Due to the page limit, we only use the triangle structure to demonstrate how to construct the reliable mesh network in the remaining part of this paper. However, we must emphasize that the proposed approaches can straightforwardly extend to other structures.



(a) Original factory layout.

(b) Step 1: grid into triangular cells.

(c) Step 2: locate the access points.

(d) Step 3: plan the required routes.

(e) Step 4: place the routers.

(f) Step 5: finalize network layout.

Fig. 5. The network planning procedures. M indicates machine and R indicates router.

B. Network Planning Procedures

Given the layout of an industrial factory and the predefined positions of machines, the positions of field devices are considered as fixed since they are attached to these machines as mentioned in Section III-A. Thus, we only consider how to appropriately deploy the positions of gateway, access points and routers, in order to reliably connect all field devices.

Without loss of generality, we suppose that the layout of an industrial factory is a square or rectangular with the size of L meters $\times$ W meters, and the machines are amounted inside the factory, which is shown in Fig. 5(a).

To do the network planning, the first step is to grid the factory layout into triangular cells as mentioned in Section IV-A. In Fig. 5(b), each vertex can be potentially deployed by a router if necessary. To ensure the connectivity, the edge length of each triangular cell (denoted by T) should not be greater than the WirelessHART standard defined transmission range, i.e., one edge can be regarded as one hop of transmission link.

The second step is to locate the access points. Here, we consider an example of two access points. By using Dijkstra's algorithm [25], we calculate the shortest hops between any vertex and any field device. Based on that, we can easily find out the best vertex for placing the first access point, which has the least number of total hops between this vertex and every field device. Furthermore, considering the connectivity between two access points, the second access point should be selected only from the neighbouring vertices of the first one and meanwhile maintaining the least hops principle. In such way, the positions of the two access points can be determined, which are shown in Fig. 5(c). Since the gateway connects two access points through wire, its location is less constrained.

In the third step, we plan routes between access points and every field device. We know that the routing protocol design is to search the most appropriate routers subset among all routers deployed in the current network to connect access points and field devices. The network planning is an opposite process, which is to determine the necessary routers first and then deploy them accordingly. In addition to the reliability requirements given in Section III-B, network planning can also take into account other design criteria and rules. In this paper, we consider the principles of the shortest hops and the least routers, and balance of the shortest hops and the least routers to develop three network planning algorithms as shown by Algorithm of the Shortest Hops (Algorithm-SH), Algorithm of the Least Routers (Algorithm-LR) and Algorithm of Balance of the Shortest hops and the Least Routers (Algorithm-BSHLR), respectively. Here, we use a greedy approach to search the appropriate vertices subset $\mathbb{N}_R$ for deploying routers, which begins from each field device and ends at two access points. In Algorithm-SH, each intermediate vertex must satisfy the conditions **C1**, **C2** and **C3**, where **C3** ensures the shortest hops from the current vertex to both access points. In Algorithm-LR, the difference is that the condition **C4** is used prior to **C3** in order to search for the next intermediate vertex. Here, **C4** refers to the criteria that if the current vertex has already been selected by the routing path of any other field device, it should also be shared by the current field device in order to reduce the total number of planned routers. This algorithm leads to the least routers. In Algorithm-BSHLR, condition **C5** is used prior to **C3** to search for the next intermediate vertex. Here, **C5** refers to the criteria that the vertex with higher rank has higher priority to be chosen as next intermediate vertex. Here rank indicates the number of usage of a vertex. In this way, we can control the usage of vertices by adjusting the value of RANK. For example, if RANK $= 1$, Algorithm-BSHLR will have the same output as Algorithm-LR, which implies the least routers and the longest hops. If RANK increases, we will have increased routers and decreased hop numbers. If RANK is equal to infinity, Algorithm-BSHLR will have the same output as Algorithm-SH. Using these three algorithms, we can plan routes as shown in Fig. 5(d).

The fourth step is to place a router at the position of every vertex in $\mathbb{N}_R$, as shown in Fig. 5(e). In the last step, we remove all the unnecessary vertices and edges and generate the finalized layout of network deployment as shown in Fig. 5(f).

It should be noted that although we only show an example of convex factory layout, our algorithms can also work for concave factory layout or the situation that there are some areas with very bad physical channel conditions. In these scenarios, all the steps are the same, except that we need to block the specific areas out in the initial factory layout gridding step, where no routers can be placed or the physical channels conditions are very bad.

Note that the complexity of all these algorithms is moderate, which is equals to $\mathcal{O}(N^2)$, where $N = |\mathbb{N}_D| + |\mathbb{N}_V|$ is the total number of vertices and field devices in the factory layout. The highest complexity occurs in the step where we calculate the shortest number of hops $H(a, b)$ between any pair of nodes. In other steps, we only need at most N iterations to find a vertex to satisfy the specific requirements.

V. Performance Evaluation

In this section, we develop programs in Matlab to implement Algorithms-SH, Algorithm-LR and Algorithm-BSHLR given in Section IV and compare their performance. In addition, we make use of an existing WirelessHART network simulator [13] to validate the effectiveness of the developed algorithms.

A. Network Planning Implementation

In our simulation, we consider an industrial factory with size 100m $\times$ 100m, and the edge length T of triangular cell is set to 10m. For the convenience of demonstration, we assume that the machines attached with field devices are all mounted along the boundaries of this factory.

To show the planning results of our implemented algorithms, we vary the number of field devices (denoted by N_F) from small to large and assume that all these field devices are uniformly distributed along the boundaries. In Section IV-A, we mentioned that there exist three different routes from the gateway to an arbitrary field device. Thus, we can define the average hops per route as the average hops of these three routes among all the field devices, which is denoted by $\overline{H}$. We also consider the required number of planned routers, denoted by N_R, as another performance metric. The average rank of routers is denoted by $\overline{R}$, which indicates the number of usage of routers. The performance comparison between the proposed algorithms will be based on these three performance metrics.

We depict the planned WirelessHART network layout for different number of field devices in Fig. 6. From Figs. 6(a), 6(b) and 6(c), we can see that if $N_F = 4$, the planned router numbers N_R under all these three algorithms are the same, and the values of average hops per route $\overline{H}$ and average rank $\overline{R}$ have slight difference. This is

Algorithm 1 Algorithm of the Shortest Hops (Algorithm-SH)

Input: Factory size: L meters $\times$ W meters;
Position (X_i, Y_i) of each field devices, $i \in \mathbb{N}_D$;
Predefined edge length T of triangle cells.

Output: Planned routers set $\mathbb{N}_R$ with their locations (X_j, Y_j), $j \in \mathbb{N}_R$.

1: Grid the factory into triangle cells with edge length T, and get the locations (X_v, Y_v) of every vertex v, $v \in \mathbb{N}_V$.
2: Calculate the shortest number of hops $H(a, b)$ between any pair of nodes, $a, b \in \mathbb{N}_V \cup \mathbb{N}_D$.
3: Find out the vertex satisfying $\underset{j \in \mathbb{N}_V}{\operatorname{argmin}} \sum_{i=1}^{\mathbb{N}_D} H(i, j)$ as the position of the first access point A_1.
4: Find out another vertex satisfying $\underset{j \in \mathbb{N}_V \text{ and } H(j, A_1)=1}{\operatorname{argmin}} \sum_{i=1}^{\mathbb{N}_D} H(i, j)$ as the position of the second access point A_2.
5: Set edge $\text{AP} = (A_1, A_2)$ and $\mathbb{N}_R = \{\varnothing\}$.
6: **foreach** field device $i \in \mathbb{N}_D$ **do**
7: Find out the nearest two neighbouring vertices R_1 and R_2, $R_1, R_2 \in \mathbb{N}_V$. In initial step, set $\text{Edge}_1 = (R_1, R_2)$, $\text{Edge}_2 = (\varnothing, \varnothing)$, and the planned routers subset $\mathbb{N}_R^{(i)} = \{\varnothing\}$ for current field device i.
8: **while** $\text{Edge}_1 \neq \text{AP}$ and $\text{Edge}_2 \neq \text{AP}$ **do**
9: Set $P_1 = P_2 = \infty$.
10: **foreach** Non-empty Edge_k, $k \in \{1, 2\}$ **do**
11: Find out another vertex of $R_{3,k}$ from the vertices set $\mathbb{N}_V$ that satisfies the following conditions:
12: **C1**: $H(R_{3,k}, \text{Edge}_k(1)) = 1$;
13: **C2**: $H(R_{3,k}, \text{Edge}_k(2)) = 1$;
14: **C3**: $R_{3,k} = \underset{j \in \mathbb{N}_V \text{ and } j \notin \mathbb{N}_R^{(i)}}{\operatorname{argmin}} H(j, A_1) + H(j, A_2)$.
15: Then, calculate the number of routing hops from $R_{3,k}$ to both A_1 and A_2, i.e., $P_k = H(R_{3,k}, A_1) + H(R_{3,k}, A_2)$.
16: **end**
17: **if** $P_1 \leq P_2$ **then**
18: $R_3 = R_{3,1}$, $R_1 = \text{Edge}_1(1)$, and $R_2 = \text{Edge}_1(2)$;
19: **else**
20: $R_3 = R_{3,2}$, $R_1 = \text{Edge}_2(1)$, and $R_2 = \text{Edge}_2(2)$.
21: **end if**
22: $\mathbb{N}_R^{(i)} = \mathbb{N}_R^{(i)} \cup \{R_3\}$
23: $\text{Edge}_1 = (R_1, R_3)$ and $\text{Edge}_2 = (R_2, R_3)$
24: **end while**
25: $\mathbb{N}_R = \mathbb{N}_R \cup \mathbb{N}_R^{(i)}$
26: **end**
27: **return** $\mathbb{N}_R$ with locations (X_j, Y_j), $j \in \mathbb{N}_R$.

Algorithm 2 Algorithm of the Least Routers (Algorithm-LR)

Input: Same as Algorithm-SH.

Output: Same as Algorithm-SH.

1: Steps 1 to 5 are the same as Algorithm-SH.
2: **foreach** field device $i \in \mathbb{N}_D$ **do**
3: Find out the nearest two neighbouring vertices R_1 and R_2, $R_1, R_2 \in \mathbb{N}_V$. Set $\text{Edge}_1 = (R_1, R_2)$, $\text{Edge}_2 = (\varnothing, \varnothing)$, and the planned routers subset $\mathbb{N}_R^{(i)} = \{\varnothing\}$ for current field device i.
4: **while** $\text{Edge}_1 \neq \text{AP}$ and $\text{Edge}_2 \neq \text{AP}$ **do**
5: Set $P'_1 = P_1 = P'_2 = P_2 = \infty$.
6: **foreach** Non-empty Edge_k, $k \in \{1, 2\}$ **do**
7: **if** There exists a vertex of $R'_{3,k}$ that satisfies the conditions: **C1**, **C2** (in Algorithm-SH) and **C4**: $R'_{3,k} = \underset{j \in \mathbb{N}_R \text{ and } j \notin \mathbb{N}_R^{(i)}}{\operatorname{argmin}} H(j, A_1) + H(j, A_2)$, **then**
8: $P'_k = H(R'_{3,k}, A_1) + H(R'_{3,k}, A_2)$.
9: **else if** There exists a vertex of $R_{3,k}$ that satisfies the conditions: **C1**, **C2** and **C3**, **then**
10: $P_k = H(R_{3,k}, A_1) + H(R_{3,k}, A_2)$
11: **end if**
12: **end**
13: **if** $P'_1 \leq P'_2$ and $P'_1 \neq \infty$ **then**
14: $R_3 = R'_{3,1}$, $R_1 = \text{Edge}_1(1)$, and $R_2 = \text{Edge}_1(2)$;
15: **else if** $P'_1 > P'_2$ **then**
16: $R_3 = R'_{3,2}$, $R_1 = \text{Edge}_2(1)$, and $R_2 = \text{Edge}_2(2)$;
17: **else if** $P_1 \leq P_2$ and $P_1 \neq \infty$ **then**
18: $R_3 = R_{3,1}$, $R_1 = \text{Edge}_1(1)$, and $R_2 = \text{Edge}_1(2)$;
19: **else**
20: $R_3 = R_{3,2}$, $R_1 = \text{Edge}_2(1)$, and $R_2 = \text{Edge}_2(2)$;
21: **end if**
22: $\mathbb{N}_R^{(i)} = \mathbb{N}_R^{(i)} \cup \{R_3\}$
23: $\text{Edge}_1 = (R_1, R_3)$ and $\text{Edge}_2 = (R_2, R_3)$
24: **end while**
25: $\mathbb{N}_R = \mathbb{N}_R \cup \mathbb{N}_R^{(i)}$
26: **end**
27: **return** $\mathbb{N}_R$ with locations (X_j, Y_j), $j \in \mathbb{N}_R$.

because that the generated positions of four field devices are far away from each other in the current case. Thus, it is hard for them to share too many common routing paths to reduce the number of required routers by using Algorithm-LR or Algorithm-BSHLR. However, if N_F increases to 10, as shown in Figs. 6(d), 6(e) and 6(f), we observe that $\overline{H}$ increases from 12.8 to 13, but N_R dramatically decreases from 65 to 57, if Algorithm-SH and Algorithm-LR are compared. Algorithm-BSHLR leads to a compromised output between Algorithm-SH and Algorithm-LR. Furthermore, we consider much dense scenario with $N_F = 100$. With Algorithm-SH, we can see that besides two access points, every vertex should be placed with a router in Fig. 6(g), and the related N_R is equal to 126 and $\overline{H}$ is equal to 14.14. On the contrary, with Algorithms-LR, N_R decreases to 108 and $\overline{H}$ increases to 16.1 as shown in Fig. 6(h). It is obvious that there exists a trade-off between $\overline{H}$ and N_R under these two algorithms: Algorithm-SH achieves better performance in hop number, but Algorithm-LR works better in router number. Algorithm-BSHLR with $N_R = 116$ and $\overline{H} = 15.29$ as shown in Fig. 6(i) works between these two algorithms and leads to a balance between number of hops and number of routers.

B. Performance Comparisons

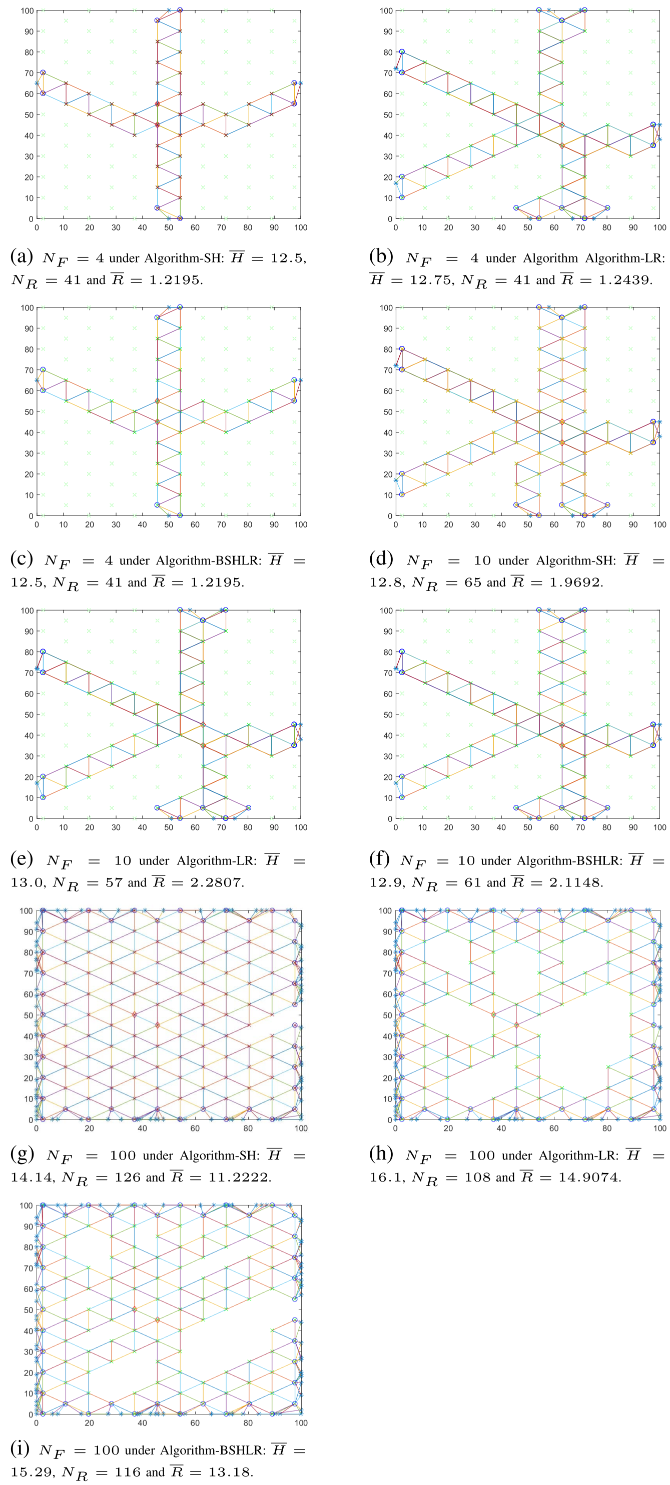
To further investigate the performance of $\overline{H}$, N_R and $\overline{R}$ achieved by Algorithms-SH, Algorithm-LR and Algorithm-BSHLR, we vary N_F from 4 to 100, choose $\text{RANK} = 2$,

Algorithm 3 Algorithm of Balance of the Shortest Hops and the Least Routers (Algorithm-BSHLR)

Input: Same as Algorithm-SH.
Output: Same as Algorithm-SH.

```
Steps 1 to 5 are the same as Algorithm-SH.
rank(j) = 0, ∀j ∈ N_V.
foreach field device i ∈ N_D do
  Find out the nearest two neighbouring vertices R_1 and R_2, R_1, R_2 ∈ N_V. Set Edge_1 = (R_1, R_2), Edge_2 = (∅, ∅), and the planned routers subset N_R^(i) = {∅} for current field device i.
  while Edge_1 ≠ AP and Edge_2 ≠ AP do
    Set P'_1 = P_1 = P'_2 = P_2 = ∞.
    foreach Non-empty Edge_k, k ∈ {1, 2} do
      if There exists a vertex of R'_{3,k} that satisfies the conditions: C1, C2 (in Algorithm-SH) and C5: R'_{3,k} = argmin_{j∈N_V and rank(j)>RANK} H(j, A_1) + H(j, A_2), then
        P'_k = H(R'_{3,k}, A_1) + H(R'_{3,k}, A_2).
      else if There exists a vertex of R_{3,k} that satisfies the conditions: C1, C2 and C3, then
        P_k = H(R_{3,k}, A_1) + H(R_{3,k}, A_2)
      end if
    end
    if P'_1 ≤ P'_2 and P'_1 ≠ ∞ then
      R_3 = R'_{3,1}, R_1 = Edge_1(1), and R_2 = Edge_1(2);
    else if P'_1 > P'_2 then
      R_3 = R'_{3,2}, R_1 = Edge_2(1), and R_2 = Edge_2(2);
    else if P_1 ≤ P_2 and P_1 ≠ ∞ then
      R_3 = R_{3,1}, R_1 = Edge_1(1), and R_2 = Edge_1(2);
    else
      R_3 = R_{3,2}, R_1 = Edge_2(1), and R_2 = Edge_2(2);
    end if
    N_R^(i) = N_R^(i) ∪ {R_3}
    Edge_1 = (R_1, R_3) and Edge_2 = (R_2, R_3)
    rank(R_3) = rank(R_3) + 1
  end while
  N_R = N_R ∪ N_R^(i)
end
return N_R with locations (X_j, Y_j), j ∈ N_R.
```

RANK $= 4$ or RANK $= 6$ and run 1000 times of simulations for each entry of N_F. Eventually, we obtain the average values of $\overline{H}$, $\overline{N}_R$ and $\overline{R}$ in Figs. 7, 8 and 9, respectively. It is obvious that Algorithm-SH, Algorithm-LR and Algorithm-BSHLR achieve almost the same performance when N_F is a small number. As N_F increases, Algorithm-SH outperforms Algorithm-LR in $\overline{H}$, but Algorithm-LR outperforms Algorithm-SH in $\overline{N}_R$ and $\overline{R}$. Algorithm-BSHLR has in-between performance between Algorithm-SH and Algorithm-LR. We also observe that Algorithm-LR reduces 20% of routers, but increases the routing hops by less than two hops compared to Algorithm-SH. Algorithm-BSHLR with RANK $= 2$ has close performance to Algorithm-LR, while Algorithm-BSHLR with RANK $= 6$ has close



(a) $N_F = 4$ under Algorithm-SH: $\overline{H} = 12.5$, $N_R = 41$ and $\overline{R} = 1.2195$.
(b) $N_F = 4$ under Algorithm Algorithm-LR: $\overline{H} = 12.75$, $N_R = 41$ and $\overline{R} = 1.2439$.
(c) $N_F = 4$ under Algorithm-BSHLR: $\overline{H} = 12.5$, $N_R = 41$ and $\overline{R} = 1.2195$.
(d) $N_F = 10$ under Algorithm-SH: $\overline{H} = 12.8$, $N_R = 65$ and $\overline{R} = 1.9692$.
(e) $N_F = 10$ under Algorithm-LR: $\overline{H} = 13.0$, $N_R = 57$ and $\overline{R} = 2.2807$.
(f) $N_F = 10$ under Algorithm-BSHLR: $\overline{H} = 12.9$, $N_R = 61$ and $\overline{R} = 2.1148$.
(g) $N_F = 100$ under Algorithm-SH: $\overline{H} = 14.14$, $N_R = 126$ and $\overline{R} = 11.2222$.
(h) $N_F = 100$ under Algorithm-LR: $\overline{H} = 16.1$, $N_R = 108$ and $\overline{R} = 14.9074$.
(i) $N_F = 100$ under Algorithm-BSHLR: $\overline{H} = 15.29$, $N_R = 116$ and $\overline{R} = 13.18$.

Fig. 6. Planned WirelessHART network layouts for different numbers of field devices.

performance to Algorithm-SH. In fact, as we increase RANK to infinity, Algorithm-BSHLR will work almost the same as Algorithm-SH, while it will work almost the same as Algorithm-LR when we reduce RANK to one. By adjusting the value of RANK, we can get a compromised performance between Algorithm-LR and Algorithm-SH.

Therefore, we conclude that for delay sensitive application, we suggest using Algorithm-SH for network planning,

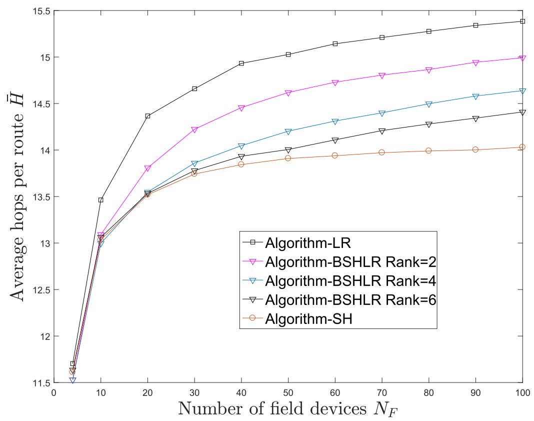


Fig. 7. The performance of $\overline{N}_R$ achieved by Algorithm-SH, Algorithm-LR and Algorithm-BSHLR.

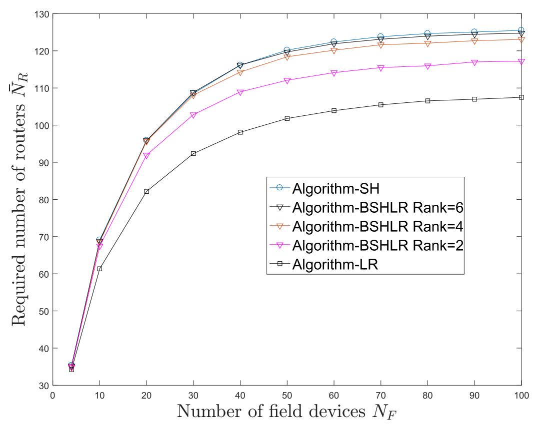


Fig. 8. The performance of $\overline{N}_R$ achieved by Algorithm-SH, Algorithm-LR and Algorithm-BSHLR.

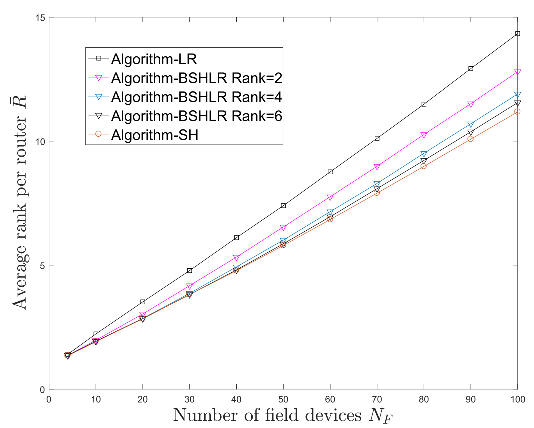


Fig. 9. The performance of $\overline{R}$ achieved by Algorithm-SH, Algorithm-LR and Algorithm-BSHLR.

while for cost sensitive scenario, we suggest choosing Algorithm-LR instead. If we have requirements for both delay and deployment cost, we suggest choosing Algorithm-BSHLR. The less number of routers, the higher usage of each router. If we also have load requirements for routers, we can adjust and select a proper value of RANK in Algorithm-BSHLR.

C. Algorithm Effectiveness Validation

To validate the effectiveness of our proposed network planning algorithms, we make use of an existing NS2-based WirelessHART network simulator given by [13]. The procedures are given below:

First, for a given factory layout and the intended locations of machines, we choose Algorithm-SH, Algorithm-LR, or Algorithm-BSHLR and run our network planning program to obtain the corresponding network deployment, i.e., the locations of access points and routers planned for this network.

Next, we use this information as an input to initialize the network and run the program in [13] to check whether the deployed network can satisfy the reliability requirements of broadcast graph, uplink graph and downlink graphs.

Last, to validate the robustness of these three algorithms, we randomly generate 100 factory layouts for each entry of N_F. We observe that the proposed network planning algorithms work perfectly and the success rates, defined as the ratio that a planned network can successfully satisfy the reliability requirements of all three kinds of routing graphs, achieve at 100% for Algorithm-SH, Algorithm-LR and Algorithm-BSHLR.

VI. Conclusions

In this paper, we have studied high reliability, low latency and cost effective network planning for industrial wireless mesh networks. Based on the reliability requirements for three kinds of routing graphs in WirelessHART networks, we have proposed three different network planning approaches following different principles: the shortest hops, the least routers, and balance of the shortest hops and the least routers. We have validated that the proposed approaches work perfectly for network planning purpose and also showed that there exist a performance trade-off between them.

Our future research includes new algorithm design with the consideration of other requirements, such as energy balance, noise/interference, link traffic rate constraints, etc.

References

[1] V. C. Gungor and G. P. Hancke, *Industrial Wireless Sensor Networks: Applications, Protocols, and Standards*. Boca Raton, FL, USA: CRC Press, 2013.

[2] *Industrial Communication Networks—Wireless Communication Network and Communication Profiles—WirelessHART*, IEC Standard 62591, 2016.

[3] G. D. González, H. Hakula, A. Rasila, and J. Hämäläinen, "Spatial mappings for planning and optimization of cellular networks," *IEEE/ACM Trans. Netw.*, vol. 26, no. 1, pp. 175–188, Feb. 2018.

[4] S. Sarkar, H. H. Yen, S. Dixit, and B. Mukherjee, "Hybrid wireless-optical broadband access network (WOBAN): Network planning using Lagrangean relaxation," *IEEE/ACM Trans. Netw.*, vol. 17, no. 4, pp. 1094–1105, 2009.

[5] S. Bosio, A. Capone, and M. Cesana, "Radio planning of wireless local area networks," *IEEE/ACM Trans. Netw.*, vol. 15, no. 6, pp. 1414–1427, Dec. 2007.

[6] C. Zhao, M. Dong, K. Ota, J. Li, and J. Wu, "Edge-MapReduce-based intelligent information-centric IoV: Cognitive route planning," *IEEE Access*, vol. 7, pp. 50549–50560, 2019.

[7] H. Li, K. Ota, M. Dong, and H.-H. Chen, "Efficient energy transport in 60 Ghz for wireless industrial sensor networks," *IEEE Wireless Commun.*, vol. 24, no. 5, pp. 143–149, Oct. 2017.

[8] W. El-Hajj, A. Al-Fuqaha, M. Guizani, and H.-H. Chen, "On efficient network planning and routing in large-scale MANETs," *IEEE Trans. Veh. Technol.* vol. 58, no. 7, pp. 3796–3801, Sep. 2009.

[9] T.-Y. Lin, K.-C. Hsieh, and H.-C. Huang, "Applying genetic algorithms for Multiradio wireless mesh network planning," *IEEE Trans. Veh. Technol.*, vol. 61, no. 5, pp. 2256–2270, Jun. 2012.

[10] J.-H. Huang, L.-C. Wang, and C.-J. Chang, “QoS provisioning in a scalable wireless mesh network for intelligent transportation systems,” *IEEE Trans. Veh. Technol.*, vol. 57, no. 5, pp. 3121–3135, Sep. 2008.

[11] P.-J. Wan and C.-W. Yi, “Coverage by randomly deployed wireless sensor networks,” *IEEE Trans. Inf. Theory*, vol. 52, no. 6, pp. 2658–2669, Jun. 2006.

[12] S. Toumpis and L. Tassiulas, “Optimal deployment of large wireless sensor networks,” *IEEE Trans. Inf. Theory*, vol. 52, no. 7, pp. 2935–2953, Jul. 2006.

[13] P. Zand, A. Dilo, and P. Havinga, “Implementation of WirelessHART in NS-2 simulator,” in *Proc. IEEE ETFA*, Sep. 2012, pp. 1–8.

[14] Q. Chen, X. Zhang, W. L. Lim, Y. S. Kwok, and S. Sun, “Automated network planning for industrial wireless mesh networks,” in *Proc. IEEE Globecom*, Dec. 2018, pp. 1–6.

[15] S. Chamberland, L. Cobo, F. Mourchid, and A. Quintero, “A wireless sensor network deployment model with target localization constraints,” in *Proc. NETWORKS*, Oct. 2012, pp. 1–4.

[16] F. Chen, R. German, and F. Dressle, “QoS-oriented integrated network planning for industrial wireless sensor networks,” in *Proc. IEEE 6th Annu. Commun. Soc. Conf. Sensor Mesh Ad Hoc Commun. Netw. Workshops*, Jun. 2009, pp. 1–3.

[17] R. Machado, W. Zhang, and G. Wang, “Network planning for heterogeneous wireless sensor networks in environmental survivability,” in *Proc. IEEE ICTAI*, Nov. 2009, pp. 814–821.

[18] G. Takahara, K. Xu, and H. Hassanein, “Efficient coverage planning for grid-based wireless sensor networks,” in *Proc. IEEE ICC*, Jun. 2007, pp. 3522–3526.

[19] J.-C. Gregoire, C. Roy, and Z. Dziong, “A study of topology formation in 802.11s multiradio wireless mesh networks,” in *Proc. IEEE 36th Conf. Local Comput. Netw.*, Oct. 2011, pp. 890–896.

[20] S. Savazzi, R. H. de Souza, and L. B. Becker, “Wireless network planning and optimization in oil and gas refineries,” in *Proc. SBESC*, Dec. 2013, pp. 29–34.

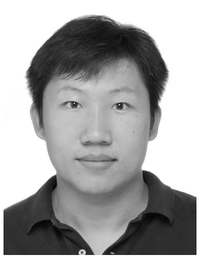
[21] M. Kostadinović, Z. Bundalo, and D. Bundalo, “Planning and management of WirelessHart network,” in *Proc. MIPRO*, May 2010, pp. 567–571.

[22] M. Shamsi, *Wireless Device Network Planning and Design*. St. Louis, MI, USA: Emerson Process Management, 2016.

[23] C. Deji, *WirelessHART: Real-Time Mesh Network for Industrial Automation*, 1st ed. New York, NY, USA: Springer, 2010.

[24] S. Han, X. Zhu, A. K. Mok, D. Chen, and M. Nixon, “Reliable and real-time communication in industrial wireless mesh networks,” in *Proc. IEEE RTAS*, Chicago, IL, USA, Apr. 2011, pp. 3–12.

[25] E. W. Djikstra, “A note on two problems in connection with graphs,” *Numer. Math.*, vol. 1, pp. 269–271, 1959.



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