Research Article

Time Slots Allocating and Multicycle Scheduling in IWSN for Narrow Process Automation

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Industrial wireless sensor networks (IWSNs) have become a viable solution for diverse application. However, commercial products and real-world deployments of IWSNs are faced with harsh reliability, real time, and predictability issues. The problem is more challenging in the narrow process industry. A novel two-tier wireless network consisting of subnetworks (FNs) and a backbone (BN) in the field is proposed in this paper. Along exploring time and frequency diversity, we present an optional polling slots allocation method in the FN to maximize communication reliability and integrity. Since time slots are scarce in the communication network for narrow process, we design a slot-reuse strategy with time slots consumption of $2N$ to construct a $N$-hop multipath BN without violating industrial standard. Furthermore, a multicycle scheduling strategy for polling and convergecast is presented to reduce the workload over the BN. Performance analysis and simulations show that our solution outperforms traditional ones in terms of communication reliability and integrity.

1. Introduction

Employing wireless communication technologies, we can quickly and easily deploy field instruments to temporarily or permanently monitor the status of equipment, process trends, locate assets, and then control the process [1]. Wireless technologies have been identified as an attractive option for industrial and factory automation. As the application and real-world deployments, IWSNs have become a viable solution for diverse application areas, including factory automation, building automation, and energy distribution system. The process automation has experienced generation of technology advancement. Wireless technology is regarded as a paradigm shifter in the process industry.

IWSNs have several advantages over traditional wired systems, including self-organization, rapid deployment, flexibility, and their inherent intelligent-processing capability. However, to realize the envisioned industrial applications and hence taking the advantages of the potential gains of WSNs, the effective wireless communication link, which can address the unique challenges posed by IWSNs, is required [2]. Effective communication in industry is characterized by concurrent demands on reliability, real time, and predictability, which is more challenging in process automation. Reliability is of importance in industrial large-scale production process, and communication errors can cause significant production outages [3]. At the same time, the data transmitted in field networks is only valid in a short time due to the nature of automation. If the data is delivered too late, it is of limited use even harming on process. On the other hand, the transmissions of data over wireless communication links are severely subject to a number of disturbances, in terms of the interference level perceived at destination, and dynamics of wireless links over time and space due to obstructive and noisy industrial environment.

Over the years, along with a considerable improvement of wireless communication technologies (e.g., the IEEE 802.11 wireless LAN and the IEEE 802.15.x wireless PAN), solutions specifically designed for the process automation have been put forward by commercial products and IEC (International
Electrotechnical Commission). The most remarkable example is wireless HART (WH), which is the first wireless field bus based on an open standard (IEEE 802.15.4) designed for process measurement and control applications [4]. WH was officially released in September 2007, including several features to provide availability of wireless communication and networks in industrial process. Figure 1 shows the architecture of WH. The basic elements of a typical WH network include field devices (FDs), access point (AP), gateways (GW), and network manager (NM). FDs attach to the plant process and act as sensor, controller, or actor. GW and AP connect host applications with FDs. NM is responsible for configuring the network and scheduling and managing communication among WH devices.

Drawing upon the key insights and lessons learned from real-world industrial applications, the WH standard specifies the following salient features designed to meet the stringent reliability, real time, and predictability requirements of process automation: multipath communication, redundant routes, multichannel frequency hopping, TDMA (time division multiple access) transmission, and centralized network management architecture. The network manager disseminates a global transmission schedule based on TDMA strategy to field devices, and then communication is conducted slot by slot to ensure communication predictability and real time. Employing mesh network topology and reserved slots, WH has the redundancy communication, in which a communication route is composed of at least two radio signal transmission links between adjacent nodes [5]. The networks using the channel hopping communication method can resend the message in other frequency channels to recover errors of communication even. Another well-known solution, ISA100.11, includes similar technical features to WH.

Integrating communication technology into the real-world industrial process environment, WH and ISA SP100.11 have been applied in many process automation systems. However, above solutions cannot run efficiently for narrow process industries. Figure 2 shows a narrow process system of 2050 mm hot strip mill production line in Baosteel in China. The whole hot strip mill process contains sequent process sections from the functional and physical point of view, such as reversing rougher R1, reversing rougher R2, finishing mill, and laminar cooling. In the typical solution, as wireless HART and ISA100.11, all FDs form a mesh network, and process data is forwarded to the control center slot by slot by employing TDMA scheduling. In this kind of narrow process industries, for example, a packet delivering over N hop mesh network in WH needs at least $2^N$ slots, which acts as unbearable time consumption case, and more packets delivering may lead to network congestion. Furthermore, field instruments are often installed manually in groups more than random deploying assumed in most research work. The number of communication devices along the process may be not enough for mesh to take into play. The design of IWSNs must be based on the characteristics of the target process. The diversity of industrial process motivates the design of different metrics to capture different aspects of requirements.

Our observation is that industrial large-scale production is usually divided into several process zones for control separately, and data transfers requirement between FDs takes place more in the same zone other than in different ones. Bounding relevant FDs in the same FNs will reduce convergecast over BN and improve real time effectively. More important, relevant FDs exchanging data within the same subnetwork is a path to provide single loop integrity, process integrity, and truly distributed control [6, 7]. Starting from such observation, we propose a novel IWSN for narrow process industry, in which a two-tier network is employed in the field. The FDs are divided into clusters according to process zones, and a series of clusters constitute a network chain. The cluster head polls the FDs periodically. The cluster
head and the rest FDs formulate a star topology network in each cluster. A multihop multichannel BN network is constructed with cluster heads and APs, over which the polled packets are forwarded to the GW. In this paper, we design slots allocating strategies and multicycle scheduling scheme to improve communication reliability in the two-tier IWSN.

Communication reliability is an important issue in IWSNs. With mesh topology being absent, retransmission is a key knob to improve communication reliability in FNs. Time slots are important communication resources and must be employed efficiently. In the traditional wired and wireless process automation systems, slots are allocated to FDs averagely [8]. From the system viewpoint, average allocating transmission trials may not be efficient. For example, time slots may be used luxuriously over high quality links, while low quality links suffer from data delivering failure for using up attempt trials. In the FN for a zone, the reliability will refer to system performance. A process variable is updated when a slave is polled successfully before its deadline. Only when all variables in a zone are available can the process be reconstituted well and truly [7]. We say the communication in a FN is reliable and integrated when all variables are updated. Different from traditional average allocating slots strategy, an optional slots allocating scheme is presented to maximize system communication reliability and integrity in this paper.

It is more challenging to forward the process data to the GW reliability over a multihop BN. In a multihop network, it is considered reliable if and only if, for each FD except the AP, it has two children to forward its packet to the GW [5]. According to WH standard, at least \(2^N\) slots must be available for data delivering over a \(N\)-hop network, which is unbearable case in a narrow process. To address this problem, we design a slots-reuse scheme based on the characteristics of the proposed system. The scheduling with slots-reuse strategy can achieve the same end-to-end reliability of WH, while the number of time slots consumed is \(2 \times N\). To reduce the workload over the BN, a multicycle scheduling scheme following above strategies is presented. Section 6 gives a further discussion on FNs based industrial wireless system. Finally, we conclude the paper.

2. System Model and Motivation

Adopting WH for narrow process, we propose a two-tier IWSN. We consider that a network consists of \(\{\text{FN}_j\}^M_{j=0}\), two APs, and one GW. The system architecture is shown in Figure 3(a). We name a cluster in the field as FN. A master and redundancy ones are available in a FN. Masters, APs, and the GW constitute a multihop multichannel BN for convergecast.

Let \(\Omega_i = \{n_i^1\}_{j=0}^M\) denote the FDs in the FN\(_i\), and \(n_0^i, n_M^i\) denote primary master and the redundancy ones. Based on this architecture, we focus on efficiency of wireless communication in the field, which aims to improve the communication reliability of polling and convergecast. Assuming that \(D_i^{\max}\) slots are available for FN\(_i\), let \(A_i = \{a_i^j\}_{j=0}^M\) denote the slots allocation, where \(a_i^j\) is the number of slots for slave \(n_i^j\). A set of periodic communication transactions must be supported in the system, which are interrelated and compete for the shared system resources. Let \(\Gamma = \{\tau_i^p, \tau_i^c\}_{i=1}^N\) denote the set of transactions with period = \([h_i^N]_{i=1}^N\), where \(\tau_i^p, \tau_i^c\) refer to polling transactions in the FN\(_i\) according to convergecast transactions over the BN. We try to address the following problems:

(i) finding an optional polling slots sequence \(A_i = \{a_i^j\}_{j=0}^M\) in FN\(_i\) to maximize communication reliability and integrity constrained with the given \(D_i^{\max}\);
(ii) constructing convergecast routing graph and a slots-reuse strategy to achieve the same communication reliability of WH in the BN;
(iii) finding a multicycle schedule scheme for polling and convergecast to reduce the workload over the BN.

We assume the following:

(i) Time is synchronized and slotted based on TDMA strategy. Each time slot allows the transmission of a single packet and the associated link level acknowledgement, which is named as a transaction.
(ii) The system can use a maximum of 16 parallel channels. Strategy based on adaptive frequency hopping runs in the BN and FNs.
3. Optional Polling Slots Allocation

We consider monocycle polling strategy in FN, with the given $D^\text{max}_i$ slots. Master $n^i_j$ uses a single cycle to poll all the slaves. We will refer to this cycle as the polling cycle. It is obvious that $D^\text{max}_i \geq M$, and some slaves can be polled more than once. We try to find $A_i = \{a^i_j\}_{j=1}^M$ for FN, to maximize communication reliability and integrity in this section.

3.1. Communication Link and Reliability.

Without loss of generality, we consider that a FN consists of $\Omega_i = \{n^i_j\}_{j=0}^M$ within a geographical area. We get $M$ communication links for polling in FN. Let $Y^i_j$ denote available channels for $j$th link, and $Y_i$ present the ones for FN. There are $|Y^i_j|$ sublinks between $n^i_0$ and $n^i_j$. Assuming that available channels of different link are heterogeneous, we get sublink set $\Theta_i = \{[p^i_1, q^i_1], \ldots, [p^i_{N^i_1}, q^i_{N^i_1}], \ldots, [p^i_{N^i_M}, q^i_{N^i_M}]\} = \{L_{i,1}, L_{i,2}, \ldots, L_{i,M}\}$. In the FN, there are up to $|Y_i| \sum_{i=1}^M |Y^i_j|$ possible switches for polling, which can be applied for retransmission strategies against cochannel interference (CCI). Multipolling architecture for FN is shown in Figure 3(b).

We assume that links are unreliable with independent erasure events following Bernoulli model. The presence of a sublink $p^i_j$, means that $n^i_j$ is able to finish polling slave $n^i_0$ with probability $p^i_j$, over it, where $\pi \in \{1, 2, \ldots, |Y_i|\}$. Assuming $a^i_j$ slots for link $L_{i,j}$, we can denote reliability over link $L_{i,j}$ as follows:

$$ p^i_j = 1 - \prod_{j \in q^i_j} (1 - p^i_{\pi,j}), \quad (1) $$

where $q^i_j \subseteq Y^i_j$ denotes the channel set selected for link $L_{i,j}$, $|q^i_j| = a^i_j$.

3.2. The Metric of Communication Reliability and Integrity.

Let $R_i = \prod_{j=0}^M p^i_j$. In this section, we show that $R_i$ can be the metric of communication reliability and formulate integrity and formulate the problem of the optional polling slots allocation.

Communication reliability and integrity are an important issue for process automation [7]. As mentioned previously, bounding FDs of a zone in the same FN is a path to provide loop integrity and process integrity. We try to poll all slaves successfully other than only one to improve system integrity. Just as the compensation of temperature and pressure on the flow measure, only when all variables are available can the accurate result be calculated. The slaves should be polled fairly in a FN. We adopt proportional fair scheduling (PFS) to address this problem. A scheduling policy is proportionally fair, if and only if the sum of the logarithmic average user throughput is maximized after the scheduling decision [9]:

$$ Q = \arg \max_S \sum_{i=1}^M \log Q^i_{\text{avg}}, \quad (2) $$

where $Q^i_{\text{avg}}$ is the average throughput of all slaves under scheduling policy $S$. As assumed in Section I, the polling command and the ACK information form a transaction in a time slot. The average throughout over link $L_{i,j}$ in a polling cycle can be represented with $p^i_j$; formula (2) can be rewritten as:

$$ Q = \arg \max_{A_i, Y_i} \sum_{j=1}^M \log p^i_j. \quad (3) $$

Formula (3) can be equivalently expressed as:

$$ Q = \arg \max_{R_i} R_i. \quad (4) $$

By maximizing $R_i$ with joint slot-channel selecting, we can schedule slaves fairly to improve communication reliability and integrity. Technically, opportunistic scheduling can exploit the multiuser diversity gain to improve system efficiency in wireless networks. PFS is an improved opportunistic scheduling. Comparing with average polling scheduling, the scheduling gain that PFS can achieve is up to $E[\max_{i=1,2, \ldots, N^i} X^i_j]$, where $X^i_j$ denotes unit independent and identically distributed random variables [10]. Employing PFS scheme, the maximal gain of joint slot-channel selecting will be achieved. In this case, polling slaves following $A_i$ will maximize communication reliability and integrity.

3.3. Optional Polling Slots Allocation for Application.

In formula (4), the PFS is degenerated to joint select slot-channel policy. The problem is a nonlinear integer programming problem. Theoretically, we can get globally optimal solution, for example, through integer programming box in MATLAB, which is computationally time-consuming to solve practical problem, and it is difficult to apply this solution to the engineering practice.

We study the scheduling strategy of allocating $D^\text{max}_i$ slots to $\Theta_i$ to maximize $R_i$. Let $C_i$ denote the channel set allocated to FN, and the cardinality $U = |C_i|$; then we can denote allocation of slots and channels as follows:

$$ C = \begin{bmatrix} c^{i,1}_{1,1} & c^{i,1}_{1,2} & \cdots & c^{i,1}_{1,L_1} \\ c^{i,1}_{2,1} & c^{i,1}_{2,2} & \cdots & c^{i,1}_{2,L_1} \\ \vdots & \vdots & \ddots & \vdots \\ c^{i,1}_M & c^{i,1}_{2M} & \cdots & c^{i,1}_{LM} \\ c^{i,2}_{1,1} & c^{i,2}_{1,2} & \cdots & c^{i,2}_{1,L_1} \\ c^{i,2}_{2,1} & c^{i,2}_{2,2} & \cdots & c^{i,2}_{2,L_1} \\ \vdots & \vdots & \ddots & \vdots \\ c^{i,2}_M & c^{i,2}_{2M} & \cdots & c^{i,2}_{LM} \\ \vdots & \vdots & \ddots & \vdots \\ c^{i,M}_{1,1} & c^{i,M}_{1,2} & \cdots & c^{i,M}_{1,L_1} \\ c^{i,M}_{2,1} & c^{i,M}_{2,2} & \cdots & c^{i,M}_{2,L_1} \\ \vdots & \vdots & \ddots & \vdots \\ c^{i,M}_M & c^{i,M}_{2M} & \cdots & c^{i,M}_{LM} \end{bmatrix}, \quad (5) $$

where $c^{i,\pi}_{\pi,j}$ is defined as a 0-1 binary variable:

$$ c^{i,\pi}_{\pi,j} = \begin{cases} 1, & \text{if } c^{i,\pi}_{i,j} \text{ attached to a slot in link } L_{i,j}, \\ 0, & \text{if } c^{i,\pi}_{i,j} \text{ is not selected in link } L_{i,j}. \end{cases} \quad (6) $$

We consider that $a^i_j$ slot is allocated to $L_{i,j}$, then we can denote constrained condition $D_{i}^\text{max}$ as follows:

$$ \sum_{\pi=1}^U c^{i}_{\pi,j} = a^i_j, \quad \sum_{j=1}^M a^i_j = D^\text{max}_i. \quad (7) $$
We introduce an ordering \( \{k_1, k_2, \ldots, k_{|\phi_j|}\} \) of the next-slot channel in terms of decreasing reliability, where \( k_j \in (1, 2, \ldots, |\phi_j|) \). We have

\[
p_j^i(a_j^i) = 1 - \prod_{j=1}^{a_j^i} \left(1 - p_j^{k_j}ight).
\]

(8)

The problem (4) can be rewritten as

\[
\max_j R_i(A_j) = \prod_{j=1}^M p_j^i(a_j^i)
\]

subject to (7).

Now, the problem (4) is converted into a conventional resource allocation problem. The optimal resource allocation can be solved by defining a marginal returns utility:

\[
\Delta \log p_j^i(a_j^i) = \log p_j^i(a_j^i) - \log p_j^i(a_j^i - 1),
\]

\( j = 1, 2, \ldots, M. \)

(10)

\( \Delta \log p_j^i(a_j^i) \) describes the increase in utility when one polling attempt is added to \( L_{i,j} \). We can get

\[
\Delta \log p_j^i(1) \geq \Delta \log p_j^i(2) \geq \cdots \geq \Delta \log p_j^i(D - N).
\]

(11)

Since the link utilities are strictly concave, the optional allocation consists of the \( D_{i}^{\text{max}} \) largest elements in the set of all possible \( \Delta \log p_j^i(a_j^i) \) [11]. We can find the largest elements in a greedy fashion to address the slots allocation problem. The solution for optional slots allocating is shown as Algorithm 1.

We consider that two slots are available for each slave averagely. Channels failing successively for two polling cycles will be removed from the channel sequence (white list) in practical implementations and communication loss probability is less than 1/4. A simulation is shown in Figure 4. Let communication loss probabilities behave as Rayleigh distribution on [1%~75%]. We compare the polling schedule based on the optional slots allocating scheme with the traditional ones using average allocating slots scheme. We also simulate the case in which interferences take place in some links. We calculate the communication reliability and integrity for four cases: average allocating slots, optional allocating slots, average allocating slots with interference presented, and optional allocating slots with interference presented. The number of time slots consumed is the same \( 2 \cdot N \). Figure 4 shows the integrity curves. Our solution outperforms traditional scheme in terms of communication reliability and integrity.

### 4. Convergecast over the BN

We focus our attention on convergecast from a set of FNs to the GW over the BN. Reliability is specially challenging for packets delivering over long and narrow process hop by hop. As mentioned early, retransmission is a major control knob against communication failure. Since slots are scarce
(1) Input $M$ slaves and corresponding prima reliability $P$, maximal slots $D_j^{\text{max}}$ for FN$_i$

(2) Output slots allocated sequence $\{a^i_j\}_{j=1}^M$

(3) $a^i_j = 1, r^i_j = p^i_{j,p}, j \in \{1, 2, \ldots, M\}$, $R = \prod_{j=1}^M p^i_{j,p}$

(4) For $j = 1$ to $D_j^{\text{max}} - N$ do

(5) \{calculate $\Delta \log p^j(a^i_j)$

(6) $n^* = \arg \max_{i=1,2,\ldots,M} \Delta \log p^j(a^i_j)$

(7) $a^{n^*} = a^{n^*} + 1$

(8) $r^i_j = r^i_j + \Delta p^i_{j,p}(d_j)$

(9) \}

(10) Calculate $D = \sum_{j=1}^M a^i_j$

(11) Return $A_i = \{a^i_j\}_{j=1}^M$

**Algorithm 1: Optional slots allocating algorithm.**

Of course, the inherent unreliability of wireless links makes radio network planning a fundamental step that must be carried out prior to actual deployment for process automation. Virtual radio planning is based on the prediction of wireless link quality. Prediction can be supported by independent radio measurement campaigns over typical environments. Since the traditional use of sensors in industrial environments was in monitoring industrial equipment, a group of sensors are placed manually and then clustered for the purpose. For narrow process automation, FDs in a long assembly line are composed of FNs, which may cover each assembly. It is necessary to deploy FNs properly and deliberately to achieve high connectivity. New wireless repeaters will be added to improve the coverage according to requirement. In a general way, most FDs in a FN can cover adjacent zones unit.

4.2. Reusing Slots to Improve Routing. Consider a multihop multipath communication shown in Figure 5(a). The node $n_1$ does not communicate directly with node $n_3$, and added communication slot is used to relay data to $n_2$. Node $n_1$ employed another path for delivering data when no acknowledgement is received from $n_2$, and added two slots in the superframe are reserved. Obviously, some slots are used luxuriously. If the delivering in primary path is successful, slots of redundant path are wasted, and the slot3 has no chance to exert. Improvement is possible if we reallocate the slots. In Figure 5(b), added retransmission time slot is reserved in primary path. After two failed transmissions to $n_2$, $n_1$ will deliver data to $r_1$ in slot3. Following that, $r_1$ has chance to relay the data to $n_3$ in slot4.

4.3. Master Sets Selection and Convergecast Reliability Factor Calculation. FDs in a FN being able to cover adjacent zones unit, we get a strongly connected weighted directed graph $G(V, E)$ for convergecast, where the vertices $V = [\Omega]_i \cup (AP_1, AP_2) \cup GW$ represent network devices and the edges $E$ denote the device pairs that can sustain communication. Let $K = \{k^i\}_{i=1}^{N}$ denote the outdegree. We want to select masters...
for each FN, including primary masters and redundancy ones. Following that, the weighted graph for convergecast is constructed according to the reliability factor.

We want to maximize the convergecast reliability as well as polling reliability when we construct convergecast routing graph $G^*$. We sort FDs according to $R_i$, in terms of decreasing reliability in $\Omega_i$, and the first two are selected to constitute master set $\Lambda_j = \{n_i\}$, where $j \in \{0, 1, \ldots, M\}$, $|A| = 2$. Accordingly, $\Lambda_{i+1}$ and $\Lambda_{i-1}$ denote master sets in the adjacent zones. Let $R^i_j = \{r_{i,j}^0, r_{i,j}^1, r_{i,j}^2, r_{i,j}^{-1}\}$, where $r_{i,j}^0$ presents polling reliability of $\Lambda_i$ in FN$_j$, $r_{i,j}^1$, and $r_{i,j}^2$ present corresponding convergecast reliability to $\Lambda_{i+1}$ and from $\Lambda_{i-1}$. Let $r_{i,j}^- = r_{i,j}^0 * (r_{i,j}^0 + r_{i,j}^{-2})/2 * (r_{i,j}^1 + r_{i,j}^2)/2$ present the metric for primary master selecting in $\Lambda_i$. Refreshing $\Lambda_i$ according to $r_{i,j}^-$ in a descending order, then we get master set $\Lambda = \{\Lambda_i\}_{i=1}^N$. According to metrics for primary master selecting, a convergecast routing graph is constructed as shown in Algorithm 2.

We define the convergecast reliability factor for a master as the reliability for delivering from the master to GW, which represents convergecast force. The factors for BN are calculated as shown in Algorithm 3. We construct a reversed graph $G^R(V^R, E^R)$ and calculate the reliability factors for the last two masters to AP. The calculation results are used for the next two masters. Rolling calculations present all the factors.

$$F^C = \{f_{i,j}\}_{i,j=1}^N$$

We can get a directed graph $G^C(V^C, E^C)$.

Let communication reliability probabilities behave as Rayleigh distribution on [1%−75%]; set the number of FNs from 2 to 19. We calculate the convergecast reliability and compare the result with the case with two disconnected paths. The number of time slots consumed is the same 2 + $N$. We also simulate the case in which interferences take place in some links. We calculate the end-to-end reliability for four cases: two paths for each hop with slots reuse, two disconnected paths, two paths with interferences presented, and two disconnected paths with interferences presented. Figure 6 shows the reliability curves. Our solution is reliable obviously. WH can achieve the same performance in reliability with a time slots consumption of $2^N$.

### 5. Multicycle Scheduling

We consider scheduling a set of transactions in FNs and the BN. In the proposed system, bandwidth is limited in BN. The master runs convergecast and polling schedule. We hope to reduce the load of the BN network to improve feasibility in scheduling and alleviate the burden of masters.

#### 5.1. Problem Formulation

As described above, we denote the set of transactions $\Gamma = \{r^p_i, r^M_i\}_{i=1}^M$ with validity period $H = \{h_i\}_{i=1}^M$. Let $B = \{b_i\}_{i=1}^M$, $E = \{e_i\}_{i=1}^M$ denote the valid period and relative deadline. $C = \{c_i\}_{i=1}^M$ presents slots consumed by masters to deliver a packet to the GW [13]. The problem can be formulated as follows:

$$\min \quad Z = \sum_{i=1}^N \frac{Q_i}{b_i} \quad (12)$$

subject to $H$.

In order to guarantee the freshness of temporal data, $b_i + e_i \leq h_i$ must be met. Since $e_i$ is constant for FN$_j$, we try to increase $h_i$ without violating $b_i$ to reduce the load of the BN. An equivalent scheme is to decrease $e_i$. We get

$$Z = \sum_{i=1}^N \frac{Q_i}{h_i - e_i} \quad (13)$$

This is a nonlinear programming problem. We adjust the scheduling sequence and develop a heuristic algorithm to address the problem [14].
5.2. Interference Avoiding and Channel Sets Allocation. Interference and collision must be avoided when the Γ is scheduled. Interference may come not only from nodes transmitting on the same channel that are not far enough from the receiver but also from nodes transmitting on the adjacent channel if they are very close. In fact, even though channels are not overlapped, recent research shows that some cross-channel interference actually takes place between adjacent channels due to spurious emissions.

In general, diversity, such as channel diversity, time diversity, and space diversity, can help to avoid interference mentioned above. According to the spatial characteristics of narrow process, we propose a simple approach shown in Figure 7 to address the problem. Firstly, available channels are parted into two groups, named odd channel set and even channel set; then adjacent FNs in different zones select different sets. Each follows sequence rules with order or reverse. All channels are available for the BN in order not to violate WH standard. Forwarding to the GW within four hops is forbidden in the BN and interference avoiding is natural when convergecast runs correctly.

5.3. Shortest-Validity-First (SVF) Schedule and Adjustment. SVF produces an approximate solution for multicycle schedule. It is proved that deadline monotonic scheduling acts as an optimal strategy constrained with $e_i < h_i$. We sort the sets $\{r^p_j, r^e_j\}_{j=1}^m$ using SVF policy at the first step. The transaction with a smaller validity interval is assigned with a higher priority, and an assignment $(r^p_j, r^e_j) \rightarrow (r^p_1, r^e_1) \cdots \rightarrow r^p_N, r^e_N$ can be available. We assume that the transactions occurred before $\{r^p_j, r^e_j\}$ can be complete. We get

$$e_i \geq \sum_{j=1}^{i} \left[\frac{e_j}{h_j}\right] \left(c_j + a_j\right).$$

The low limit is selected to reduce the load of BN. Furthermore, we try to rearrange $\Gamma$ to decrease the factor $c_j + a_j$. The following strategy, called adjust function, is adopted when reordering runs.

(a) For all $j < i$; if $3r^e_j \geq r^p_j$, let $r^p_j$ share slots for $r^p_j$, $a_i = 0$. Otherwise, choose the largest one and $a_i = |a_i - a_j|$.
(1) Input $H = \{h_i\}_{i=1}^N$, $C = \{c_i\}_{i=1}^N$, $A = \{a_i\}_{i=1}^N$, ordered $\tilde{\Gamma} = \{\tilde{\tau}_i, \tilde{\tau}'_i\}_{i=1}^N$ according to SVF

(2) Output $B, E$

(3) for $i=2$ to $N$ do

(4) adjust($a_i, c_i$);

(5) $R_{ii} = c_i$

(6) Do $e_i = R_{ii}$, $R_{ii} = c_i + a_i$;

(7) for $j=1$ to $i-1$ do

(8) $R_{ii} = R_{ii} + \left\lfloor \frac{e_i}{b_j} \right\rfloor \cdot (c_i + a_i)$;

(9) while ($R_{ii} \neq e_i$)

(10) $b_i = h_i - e_i$

(11) }

Algorithm 4: Multicycle scheduling algorithm.

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**Figure 6:** Reliability over the BN.

**Figure 7:** Channel sets allocation.

(b) For all $\tau'_j, j < i$; if $\exists |j-i| > 3$, let $\tau'_j$ share slots for $\tau'_j$, $c_i = 0$.

Algorithm 4 presents the framework of multicycle schedule in the system. In WH, the supported update rates should be defined as $2^i$, where $i$ is positive or negative integer values, for example, update rate selections of $(1/4)$ 250 msec, $(1/2)$ 500 msec, 1 sec, 2 sec, 4 sec, 8 sec, 16 sec, 32 sec, and 64 sec (or more). We present the case with the heaviest workload; for example, $|\Gamma| = 19$. Let all update rates equal 250 msec, and polling time equals 100 ms. In the BN, four convergecast transactions can run at the same slot when the FNs are located at four hops away from each other. We can calculate the $c_i = 8N - 4$ [15], and each transaction can be finished within 148 slots. This is commonly satisfied in industrial process automation.

6. Further Discussion on FNs Based Industrial Wireless System

To cover the narrow process efficiently with FDs, we propose a FNs based IWSN. In this section, we present the further discussion on the system architecture.

6.1. Performance Benefits in Reliability and Availability. Comparing to traditional DCS systems, polling and control loops can be deployed in the same FN, which provides fewer points of failure. Polling and control in FNs will keep the process running even with the absence of the BN network and HMI. The increased MTBF (mean time between failures) combined with the reduction in data transfers required substantially increases reliability and availability. The overall reduction in network traffic also increases network availability.

6.2. Performance Benefits in Real Time. Generally, wireless sensors, actuators, and controllers for a loop are in the same subnet FN, and they communicate with each other directly without forwarding. The time of message processing, sending, and receiving is very small; we have the loop latency as $T_L = T$, where $T$ is communication cycle of FNs. In traditional IWSNs, all devices are in the same wireless network; the transmitted information must be forwarded by routing devices. Similarly, we have the latency over the upper network as $T_{LU} = T + T_F$, where $T_F$ is the communication cycle of upper network. The ISA (the instrumentation, systems, and automation society) defined the reliability and latency for process control application. Generally speaking, latency
in loop is tens of milliseconds, while the latency in upper network is hundreds of milliseconds. Polling and control in FNs can improve real time obviously. Taking account of the reduction in data delivering in upper network for controlling in FNs, more improvement can be anticipated.

6.3. Performance Benefits in Flexibility and Reconfiguration. Polling and control in FNs mean not only increased reliability, availability, and real time but also increased flexibility. In FNs, control function blocks may be performed in FNs which are not attached to upper network. Remodeling function can be deployed with an appropriate configuration of field devices and data transfer in FNs. These are considerations that must be undertaken by the designer of the system. Since function block can be executed in different devices in a FN, even in different FNs, which can be configured to take advantage of parallel computations, FNs can also be integrated into process automation with tropism to ubiquitous computing or ubiquitous automation [16, 17].

7. Conclusion

We have studied the IWNS for the process automation in this paper. To meet the requirement in narrow process industry, we present an IWSN based on FNs and BN. Aiming to improve reliability and integrity in the FN, an optional slots allocation solution constrained with available slots is presented. We construct a $N$-hop BN in which each master has two paths for convergecast with time slots consumption of $2 \times N$. We construct convergecast routing graph and calculate the reliability factor. Since the bandwidth of a multihop BN is limited, a multicycle schedule strategy for polling and convergecast is presented to reduce the workload in BN. Further discussion on FNs based industrial wireless system is presented. Automation, including process automation, is making ways to the scenario combined with network, distributing, and intelligence. We hope to design a distributed IWSN based on FNs for field bus making its way to field net.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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