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# Joint Real-Time Scheduling Methods for Deterministic Industrial Field/Backhaul Networks
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## Abstract

In industrial field/backhaul networks, the joint real-time scheduling method is important to keep end-to-end data streams meeting the deadline. This document proposes four joint scheduling methods, and the four methods consider time slotting the industrial backhaul network, regarding industrial backhaul network as a black box system, ignoring delay of industrial backhaul and establishing latency model of an industrial backhaul network.

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## 1. Introduction

Industrial field network is a network that can be deployed in industrial process and monitor industrial field equipment and systems to achieve the target of control and management. It can improve production efficiency, reduce human intervention to industrial production process and decrease the cost of production. It has significant importance for industrial modernization.

Industrial field bus and industrial ethernet are two kinds of common solutions to industrial automation with the development of industrial field network, however they are both wired network. If they can combine the technology of wireless sensor network, a new network, industrial wireless network, can free from being bonded to wires and cables, and is more easy and flexible to deployment. Industrial wireless network is a communication network which is oriented toward building automation, and process automation, and industrial automation. There are three major international standards (ISA100.11a[IEC62734], WirelessHART[IEC62591], WIA-PA[IEC62601]) in the area of industrial wireless network currently.

Industrial backhaul network is a transition network, which combines industrial field network with higher level network to achieve the goal of interconnection. It mainly solves the problem of access of industrial field network data to higher level network. Industrial field network is generally limited to a specific region, such as a plant. Through this network, transaction data of industrial field network can be transferred to internet or other industrial field networks. Industrial backhaul network is a medium-sized network, which can cover from a few kilometers to tens of kilometers. The major technology of industrial wireless backhaul network consists of Wi-Fi, WiMAX or LET.

In order to adapt the presentation and development of industry 4.0, which is aimed to elevate the level of manufacturing, industrial field network should not be confined to a plant network only. Therefore, it is necessary to introduce the technology of industrial backhaul network to break the restrictions of interconnection between different networks, and to form a mixed network of industrial field network and backhaul network. Figure 1 indicates a typical network architecture of the mixed network. It is a type of deterministic network, and had been illustrated about use cases and architecture in the drafts proposed by DetNet Workgroup of IETF of draft-bas-usecase-detnet-02 and draft-finn-detnet-architecture-04.

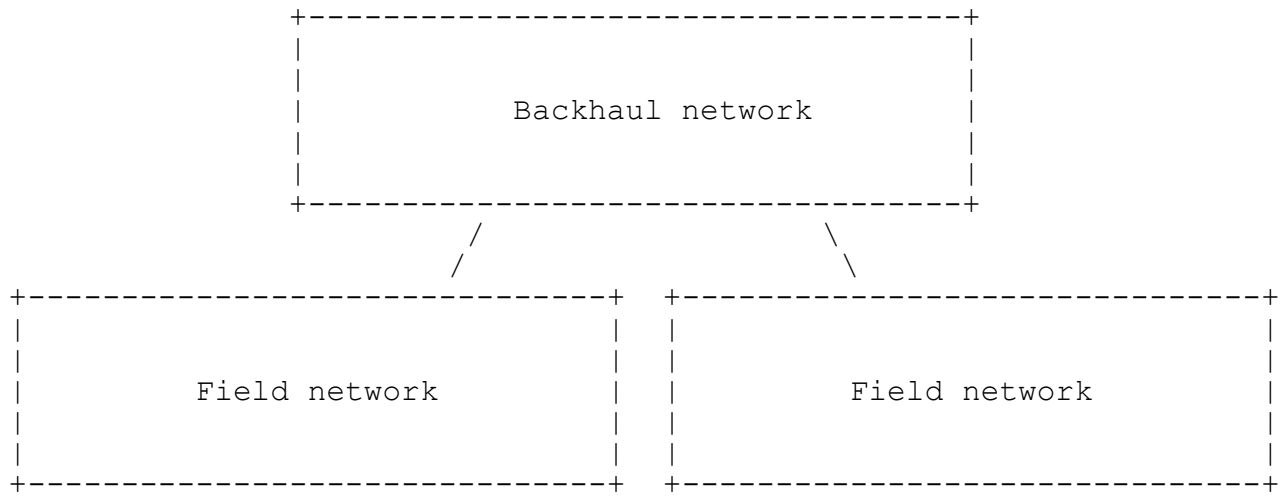


Figure 1. Typical industrial field-backhaul network

In this mixed network architecture of industrial field network and backhaul network, field network is made up of ISA100.11a, which is industrial wireless sensor network protocol. In the former network, a node deployed in a plant can communicate with a node deployed in another plant through a backhaul network.

## 2. Deterministic Industrial Field-Backhaul Network Requirement

The draft of draft-finn-detnet-problem-statement put forward by DetNet Workgroup of IETF had described the requirement of deterministic network and deterministic scheduling partially. Because industrial field network directly faces the monitoring of industrial process, it is a difference between industrial field network data and general network data. Industrial field network has high demands about the deterministic delay bounds. It will affect the productivity, and even generate industrial accidents, when there are high packet loss and latency in a field network. For instance, real-time monitoring of level measurement and control are required to avoid overfilling of oil tanks that may lead to serious economic loss and environmental threats.

So, it is needed that a deterministic joint scheduling method can guarantee the determination of network data in such a new network architecture.

# 3. Deterministic Industrial Field-Backhaul Network Joint Scheduling Key Technology

## 3.1. End-to-end Network Data Stream

In an industrial field network, end-to-end network data stream indicates a complete transmission path that a source device node transfers to a destination device node (common node or gateway). While in an industrial field-backhaul network, it indicates a complete transmission path that a field network source device node transfers through an industrial backhaul to another field network destination device node.

Industrial field-backhaul network data stream have following features:

- Period. Every data stream in network generates period data.
- Deterministic. Every data stream in network has a deadline, network scheduling should ensure every data stream arrive at destination node before its deadline.
- Sequential. A path of an end-to-end network data stream are made up of every two sequential node transmission link. In the process of scheduling, it must be scheduled by the order of sequence of links in the path.
- Priority. Every end-to-end network data stream has a priority, when the data streams with different priorities occur collisions, the data stream with lower priority should be delayed.

## 3.2. Network Communication Resource

In the deterministic industrial field networks with backhaul network architecture, schedulable network communication resources are time slot, channel and link. If the backhaul network is based on the SDN architecture, then the SDN controller could schedule the bandwidth and cache of switch. Therefore, bandwidth and cache resources can be included in schedulable network communication resources.

- Time slot. Time slot is the basic unit in the TDMA based network communications. The length of time slots is settled and is same in the entire network. Only one packet and its ACK can be transmitted in one time slot.

- Channel. In order to increase network throughput, industrial field network standards provide a number of channels of different frequencies. If the links do not interfere with each other, then we can use different channels to transmit simultaneously.

- Link. Link refers to a direct communication link between one node and another and no intermediate switching nodes. The network data stream is composed of a lot of links. The devices in the industrial field network devices are half-duplex, so the links in the industrial field network are unidirectional.

### 3.3. Network Time Slot Scheduling

In TDMA-based industrial field network, time is divided into time slots of the same length. One transmission can be conducted in each time slot and the links using different channels to transmit if they do not interfere each other.

In the time slot scheduling process, it will cause link collision when a node arranged to transmit and receive simultaneously, and it will cause channel collision when the same channel is used within a certain range. AS shown in figure 2, the network time slot scheduling process should avoid such collisions.

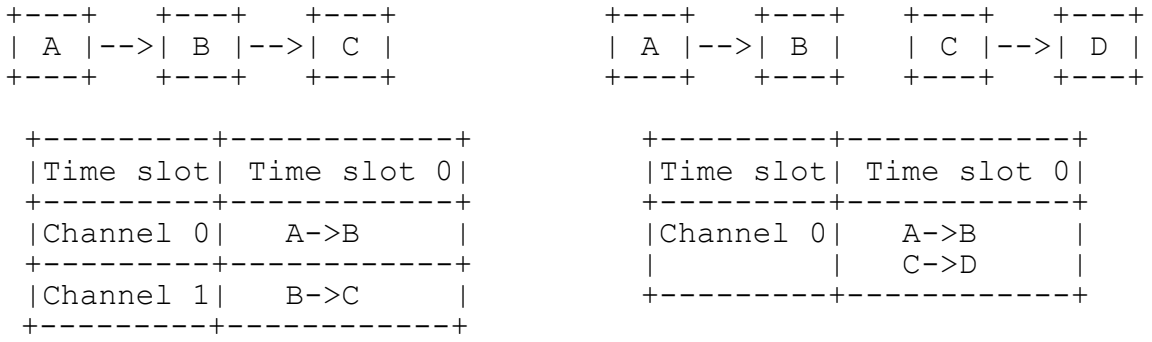


Figure 2. Link Collision & Channel Collision

## 4. Joint Real-Time Scheduling Methods for Deterministic Industrial Field-Backhaul Network

Joint real-time scheduling methods for deterministic industrial field/backhaul networks, which cross networks, are intend to solve the deterministic problem of industrial field /backhaul networks. Since the current network infrastructure imports backhaul network, the deterministic scheduling algorithm need to collaborate with backhaul network to conduct joint scheduling to ensure data certainty. The proposal put forward the following solutions.

### 4.1. Time-Slotted Industrial Backhaul Networks

In order to ensure determinism, industrial field networks utilize TDMA to make the network time-slotted. If the industrial backhaul network can also be time-slotted, then the deterministic scheduling algorithm can jointly schedule with minor alterations. Industrial backhaul network can be built with a variety of network standards such as Wi-Fi, WiMAX, LTE and so on. But in consideration of the high cost and poor feasibility of time-slotted WiMAX and LTE, we assume that the IEEE802.11 can be time-slotted. Wi-Fi network has various networking modes, such as peer to peer networking mode, point to multi-point networking mode and the relay network mode. Here we consider the hierarchical network constructed in point to multi-point networking mode, as shown in Figure 3.

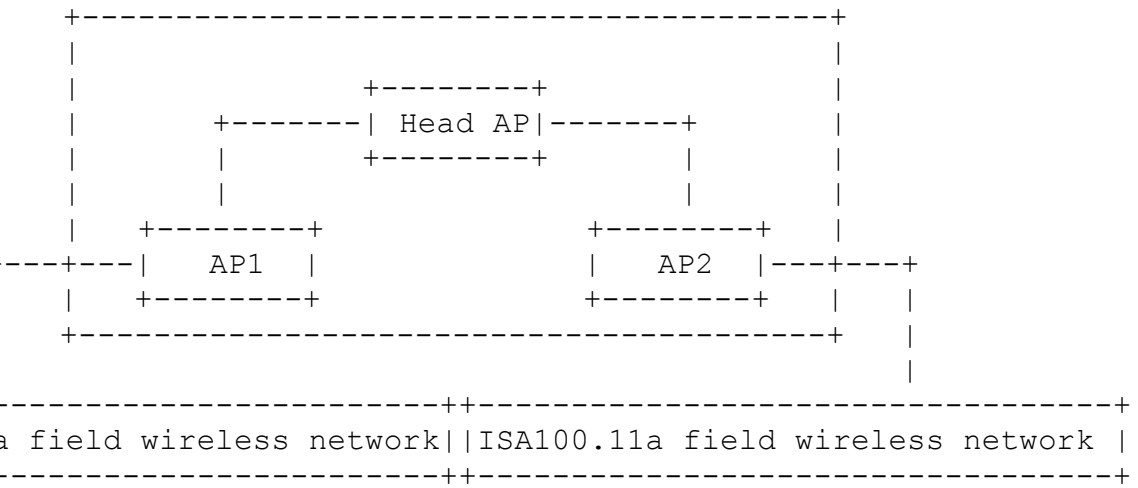


Figure 3. Industrial Backhaul Network consisting of WIFI

Although IEEE802.11 also supports 13 channels, but the AP was not free to switch channels, which means that the AP cannot use a channel in the current time slot and use another channel the next time slot. However, we assume that the network architecture, the following points AP under head AP, which are AP1 and AP2 in FIG 1, can transmit packets simultaneously as long as their transmission task do not contain the same AP, i.e. head AP. For example, when a data stream of field network is transmitting packets to AP1 in a time slot, AP2 is able to receive packets from head AP, or send packets to field network in the same time slot. Therefore, the backhaul network constructed with wireless APs can be considered as a single-channel linear network, which is shown in Figure 4.

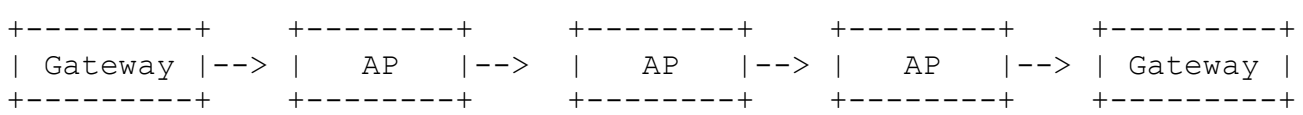


Figure 4. A single-channel linear network

Therefore, the data stream in industrial field/ backhaul network can be deemed to be equivalent to the data stream in field network, only that every piece of data streams need to go through the linear network consisting of wireless APs. So the scheduling process is proposed as follows:

1. Abstract end to end data stream in the entire network, and initialize a different priority for each stream.

2. Establish the delay model of network data stream. If collisions happened between different priority data stream, the low-priority data stream will be delayed by high-priority data stream, so a model can be built under the worst circumstances that the low-priority data streams impacted by higher priority data streams.

3. Estimate the network schedulability. A data stream is schedulable if the minimum time for the data stream to complete transmission, plus the worst delay time caused by higher priority data streams, is less than or equal to deadline, In the current priority allocation scheme, if each data stream is schedulable, the network can be considered as schedulable. If the data stream cannot be scheduled, then change the priority allocation scheme and estimate again until a corresponding scheme is found.

4. Allocate time slot and channel for every data stream. Traverse data streams according to their priorities, and each data stream should allocate the next link that is about to be released in each time slot to the greatest extent. According to the rule that low-priority data streams should give way to high-priority data streams, the spare channels can be utilized if there is no collision. However, if collisions happened between data streams of different priority, then the lower-priority data stream should be placed in the next time slot until there are no unallocated higher priority data streams. Follow these rules until the whole network scheduling is completed.

The scheduling process is shown in Figure 5:

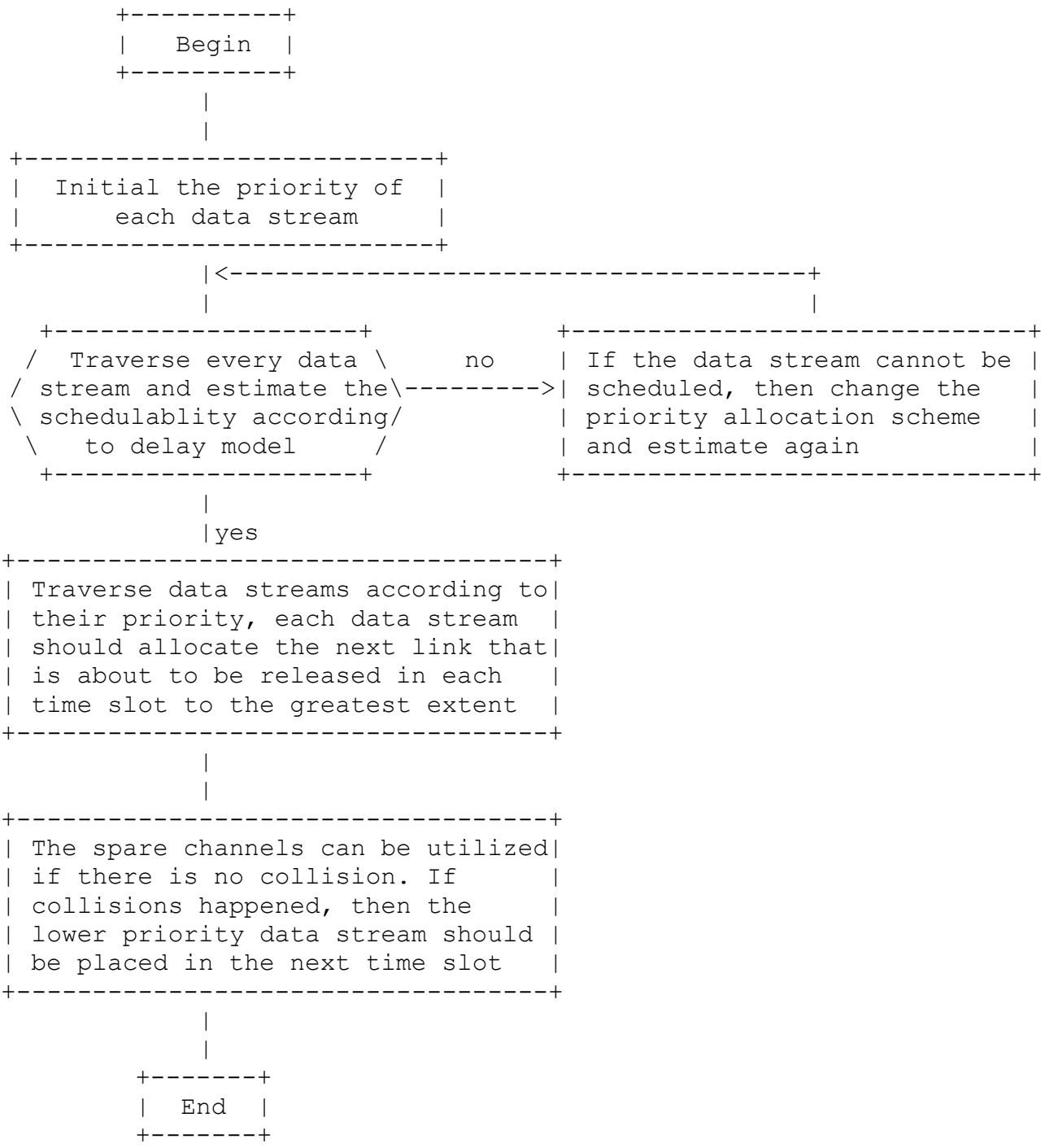


Figure 5. Scheduling of times-slotted industrial backhaul network

Further, if the backhaul network can support TDMA mechanism like the industrial field network completely, the deterministic scheduling methods in field network can be applied in industrial field/backhaul networks.

## 4.2. Consider Industrial Backhaul Network as a Black Box

In order to solve the deterministic problem of industrial backhaul network, industrial backhaul can be deemed as white box to conduct fine controls through inner mechanism. While it can also be regarded as a black box so that we can only consider its delay impacts and ignore its internal details.

When the packet goes through the industrial backhaul network, we can give it a timestamp at the application layer and read it after the transmission completed. Then delay caused by the backhaul network can be figured out and a fitting curve of delay can be worked out by collecting large amount of data. It has been verified experimentally that the delay is concentrated in a numerical range despite its randomness. Therefore, we can get the approximate delay of packets caused by the industrial backhaul network.

After that, a few of scheduling paths of different priority can be implemented in the industrial field network. A main scheduling path can be configured according to the average delay of the backhaul network. And some redundant paths should be pre-configured in case the delay of the main path is too high.

The scheduling process of industrial field/backhaul network can be divided into three periods, as shown in Figure 6:

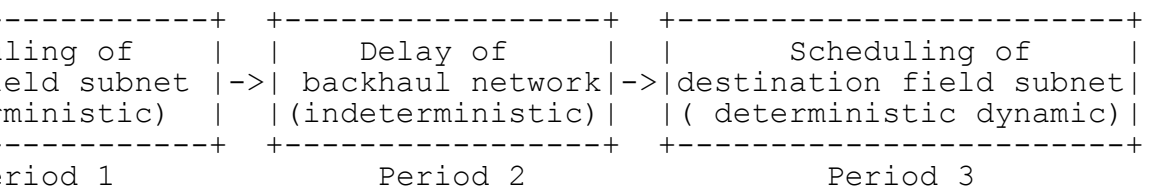


Figure 6. Three periods of scheduling

In source field subnet we can apply the deterministic scheduling algorithm of field network to conduct deterministic polymerization and get the time spent by each data stream to go through the source subnet. Then the data stream goes through the backhaul network, which is a black box and it will cause indeterministic delay which is in a numerical range. When the data stream comes out the backhaul network, the timestamp should be parsed. If the deadline is missed,

it indicates that the packet has gone through poor network and need to be retransmitted. If there is time left, scheduling path can be dynamically selected at downward gateway to get the schedulability of the end to end data stream.

### 4.3. Ignore the Delay of Industrial Backhaul Network

Since the field network is slow-speed (250 KB/s), while industrial backhaul network is a high-speed, if the industrial backhaul networks adopt IEEE802.11, gigabit wireless routers supporting IEEE802.11 ac can make the delay of industrial backhaul network quite small. As a result, the joint deterministic scheduling of the entire network only needs to cover the field network that is located at the ends of the backhaul network.

### 4.4. Build Delay Model of Industrial Backhaul Network

If industrial backhaul network is built with IEEE802.11, the network access delay test model under IEEE802.11 DCF mode can be established by using Markov chain or queuing theory. At the same time, the model under IEEE802.11 PCF mode can be established based on queuing theory.

Therefore, the field network only need to build the delay model of backhaul network that follows one delay model, then the total transmission scheduling delay will follow certain regularity. The total transmission delay will meet delay requirements with specified probability by scheduling, in other words, the unsuccessfulness of scheduling is acceptable, but the scheduling success rate should be in a range of 90% ~ 95%.

## 5. Security Considerations

## 6. IANA Considerations

This memo includes no request to IANA.

## 7. References

### 7.1. Normative References

### 7.2. Informative References

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