**Joint Real-Time Scheduling Methods for Deterministic Industrial
Field/Backhaul Networks
draft-wang-detnet-joint-scheduling-03**

Abstract

   In industrial field/backhaul networks, joint real-time scheduling
   method is important to make end-to-end flows meet their deadline.
   This document proposes four joint scheduling methods, and they
   involve four scenarios: time-slotted industrial backhaul network,
   regarding industrial backhaul network as a black box system,
   ignoring delay of industrial backhaul and establishing latency model
   of industrial backhaul network.

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1. Introduction

   Industrial field networks are often deployed to process control
   industry to monitor industrial field equipment. Industrial field
   network can improve production efficiency, reduce human intervention
   and decrease cost, which are significant for industrial
   modernization.

Industrial field bus and industrial Ethernet are two kinds of common networks deployed in industrial automation, while they are wired networks. With the development of industrial wireless technology, Wireless Sensor Networks (WSN), a typical industrial wireless network, has been applied to industrial network. WSN can free traditional field devices from the limits of abundant cables, and it is flexible to deploy in industrial environment. WSN can be applied to building automation, process automation, and industrial automation. Currently, There are three major industrial wireless networks international standards: ISA100.11a[IEC62734], WirelessHART[IEC62591], WIA-PA[IEC62601].

Industrial backhaul network is used as transition network, which combines industrial field network with high-level network to achieve the goal of interconnection. It mainly solves the problem that makes the sensor or control data from industrial field network transmit to high-level network. Generally, industrial field network is deployed to a specific region. Through industrial backhaul network, 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 and LTE.

To apply well in the burgeoning industry 4.0, which aims 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 construct a hybrid industrial network. Figure 1 indicates a typical network architecture of the hybrid industrial network. It is a type of architecture of industrial deterministic network that was illustrated with use cases in the drafts proposed by DetNet Workgroup of IETF of [I-D.bas-usecase-detnet] and [I-D.finn-detnet-architecture].

```
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        |                                  |
        |                                  |
        |          Backhaul network        |
        |                                  |
        |                                  |
        +----------------------------------+
              /                      \
             /                        \
  +------------------------------+  +------------------------------+
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  |                            | |  |                              |
  |        Field network       | |  |         Field network        |
  |                            | |  |                              |
  |                            | |  |                              |
  +------------------------------+  +------------------------------+
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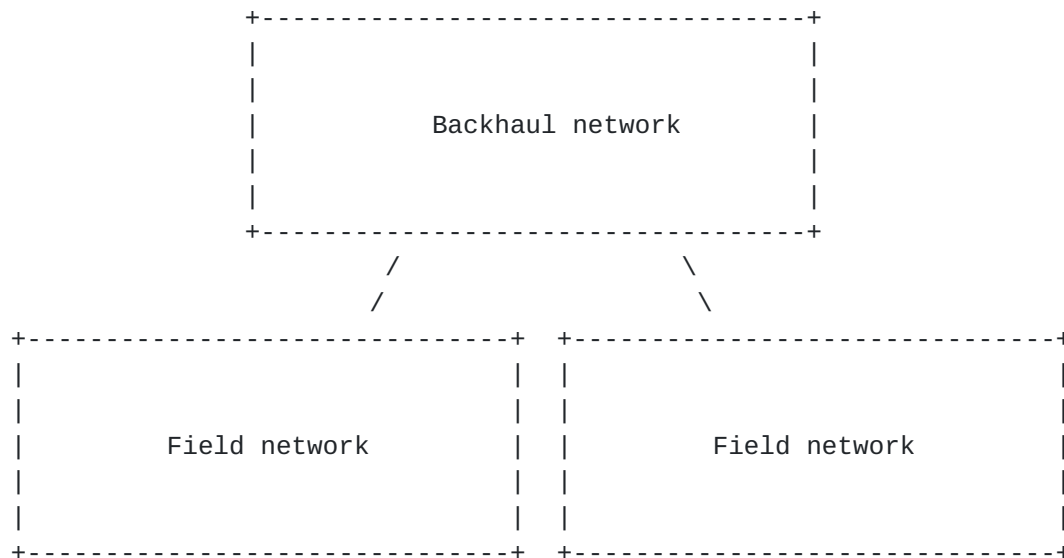
Figure 1. Typical industrial field/backhaul network

In the hybrid network architecture, field network may be an
ISA100.11a. In Figure 1, a node deployed in a plant can communicate
with a node in another plant through backhaul network.

2. Deterministic Industrial Field/Backhaul Network Requirement

The draft of [I-D.finn-detnet-problem-statement], proposed by DetNet
Workgroup of IETF, has described the requirements of deterministic
network and deterministic scheduling partially. Due to industrial
field network directly monitor the industrial process, a difference
between industrial field network and general network exists.
Industrial field network has high demands on the deterministic delay
bounds. In a field network, the delay of data flows will affect
productivity, and even cause industrial accidents when happening
high packet loss ratio and transmission latency. For example, real-
time measure and control of liquid level is required to avoid
overfilling of oil tanks, because overflow may lead to serious
economic loss and environmental threats. Therefore, it requires a
deterministic joint scheduling method to guarantee the deterministic
transmission of data stream in the new network architecture.

3. Deterministic Industrial Field/Backhaul Network Joint Scheduling Key Technology

3.1. End-to-end Network Data Stream

In industrial field/backhaul network, end-to-end data stream indicates a complete transmission path that a source node of field network transfers to destination node located in another field network through an industrial backhaul network.

Industrial field/backhaul network data stream has following features:

o Period. Every data stream generates data with periodicity.

o Deterministic. Every data stream has a deadline, and scheduling methods should ensure each data stream arrives at destination node before its deadline.

o Sequential. A path of an end-to-end data stream contains some transmission links. In the process of scheduling, it must be scheduled in the order of sequence of links on the path.

o Priority. End-to-end data stream has a priority. When data streams with different priorities occur collisions, the data streams with lower priority should be delayed by higher priority data streams.

3.2. Network Communication Resource

In deterministic industrial field/backhaul network architecture, network communication resources include time slot, channel and link. If backhaul network adopts Software Defined Network (SDN) architecture, then the SDN controller can schedule the bandwidth and cache of switch. Therefore, bandwidth and cache resources can be included in schedulable communication resources.

o Time slot. Time slot is the basic transmission unit in the network communications based on Time Division Multiple Access (TDMA). In the entire network, the length of time slots is fixed and stays the same. Only one sending packet and its corresponding ACK can be accommodated in one time slot.

o Channel. In order to increase network throughput, industrial field network provides a number of channels with different frequencies.

o Link. Link refers to a direct packet transmission between two
   nodes that located in a communication radius of each other. A
   data stream comprises many links.

3.3. Network Time Slot Scheduling

In TDMA-based industrial field network, time is divided into time
slots with the same length. In the time-slot scheduling process, it
will cause link collisions when a node transmits and receives
simultaneously, and it will cause channel collisions when the same
channel is used within a certain range. As shown in Figure 2, the
time-slot scheduling process should avoid such collisions.
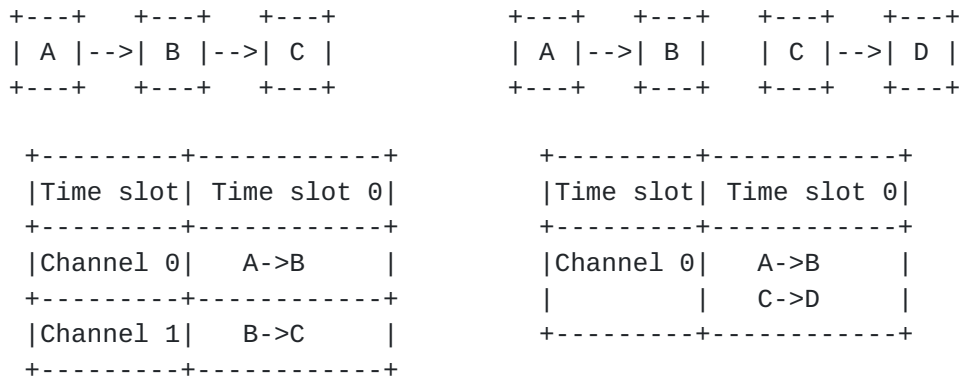
```
   +---+   +---+   +---+           +---+   +---+   +---+   +---+
   | A |-->| B |-->| C |           | A |-->| B |   | C |-->| D |
   +---+   +---+   +---+           +---+   +---+   +---+   +---+


    +---------+------------+        +---------+------------+
    |Time slot| Time slot 0|        |Time slot| Time slot 0|
    +---------+------------+        +---------+------------+
    |Channel 0|   A->B     |        |Channel 0|   A->B     |
    +---------+------------+        |         |   C->D     |
    |Channel 1|   B->C     |        +---------+------------+
    +---------+------------+
```
            Figure 2. Link Collision & Channel Collision

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

Joint real-time scheduling methods of industrial field/backhaul
networks intend to solve the deterministic problem of industrial
field/backhaul networks. Due to the investigative architecture
includes backhaul network, the deterministic scheduling algorithm
needs to collaborate with backhaul network to conduct joint
scheduling to ensure data deterministic transmission. The proposed
joint scheduling methods are described as follows.

4.1. Time-Slotted Industrial Backhaul Networks

In order to ensure determinism, industrial field networks adopts
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 small modification. Industrial
backhaul network contains various of network standards such as WIFI,
WiMAX, and LTE. WiMAX and LTE are high cost and poor feasibility,
thus we assume the IEEE 802.11 as backhaul network. Wi-Fi network
has various operating modes, such as peer-to-peer mode, point to

multi-point networking mode and the relay network mode. Here we
consider the hierarchical network architecture in a way of point to
multi-point networking mode, as shown in Figure 3.

```
      +----------------------------------------+
      |                                        |
      |              +--------+                |
      |      +-------| Head AP|-------+         |
      |      |       +--------+       |         |
      |      |                        |         |
      |   +--------+            +--------+      |
   +---+---|  AP1   |           |  AP2   |---+---+
   |   |   +--------+           +--------+   |   |
   |   +------------------------------------+   |
   |                                            |
+-----------------------------++---------------------------------+
|ISA100.11a field wireless network||ISA100.11a field wireless network |
+-----------------------------++---------------------------------+
```
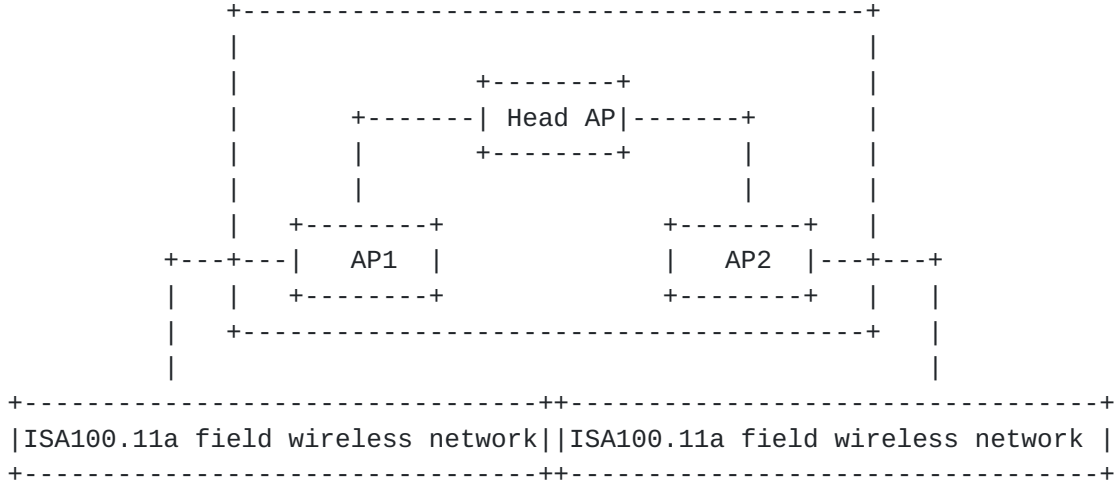
         Figure 3. Industrial Backhaul Network consisting of WIFI

   Although IEEE 802.11 supports multiple channels, but AP is not able
   to perform channel hopping between transmission timeslots, which
   means that the AP cannot use a channel in the current time slot and
   use another channel the next time slot. We assume that AP1 and AP2
   in Figure 3 can transmit packets simultaneously as long as their
   transmission tasks 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 framework with wireless APs can be considered
   as a single-channel linear network, which is shown in Figure 4.


```
+---------+    +--------+    +--------+    +--------+    +---------+
| Gateway |--> |   AP   |--> |   AP   |--> |   AP   |--> | Gateway |
+---------+    +--------+    +--------+    +--------+    +---------+
```

            Figure 4. A single-channel linear network

   Therefore, the data stream in industrial field/backhaul network can
   be seen as equivalent to the data stream in field network, except
   that each data stream needs to flow through the WIFI. The scheduling
   process is illustrated as follows:

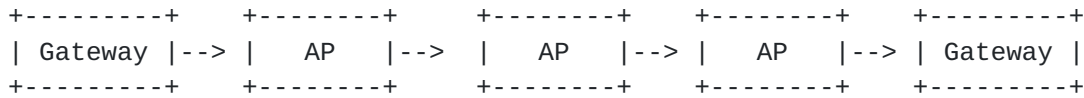1. Abstract end-to-end data stream in the entire network, and allocate a priority for each stream.

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, so a model can be built under the worst circumstances that the low-priority data streams impacted by all higher priority data streams.

3. Estimate the network schedulability. A data stream is schedulable when the minimum time for the data stream to complete its once transmission task plus the worst delay time caused by higher priority data streams is less than or equal to its 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 try to change the priority allocation scheme and estimate again until a corresponding scheme is found or return no schedulable results.

4. Allocate time slot and channel for each data stream. Traverse data streams according to their priorities, and each data stream should allocate link that is about to be released in a time slot. According to the rule that low priority data streams should give way to high priority data streams, the channels can be utilized if it is not unoccupied. 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. Repeat these steps until the whole network scheduling is completed.

The scheduling process is described in Figure 5:

```
                +----------+
                |  Begin   |
                +----------+
                     |
                     |
        +--------------------------+
        |  Initial the priority of |
        |     each data stream     |
        +--------------------------+
                     |<--------------------------------------+
                     |                                       |
          +-------------------+        +------------------------------+
          /  Traverse every data \    no  | If the data stream cannot be |
         / stream and estimate the\------->| scheduled, then change the   |
         \ schedulablity according/        | priority allocation scheme   |
          \   to delay model    /          | and estimate again           |
          +-------------------+            +------------------------------+
                     |
                     |yes
        +----------------------------------+
        | Traverse data streams according to|
        | their priority, each data stream  |
        | should allocate the next link that|
        | is about to be released in each   |
        | time slot to the greatest extent  |
        +----------------------------------+
                     |
                     |
        +----------------------------------+
        | The spare channels can be utilized|
        | if there is no collision. If      |
        | collisions happened, then the     |
        | lower priority data stream should |
        | be placed in the next time slot   |
        +----------------------------------+
                     |
                     |
                +-------+
                | End   |
                +-------+
```
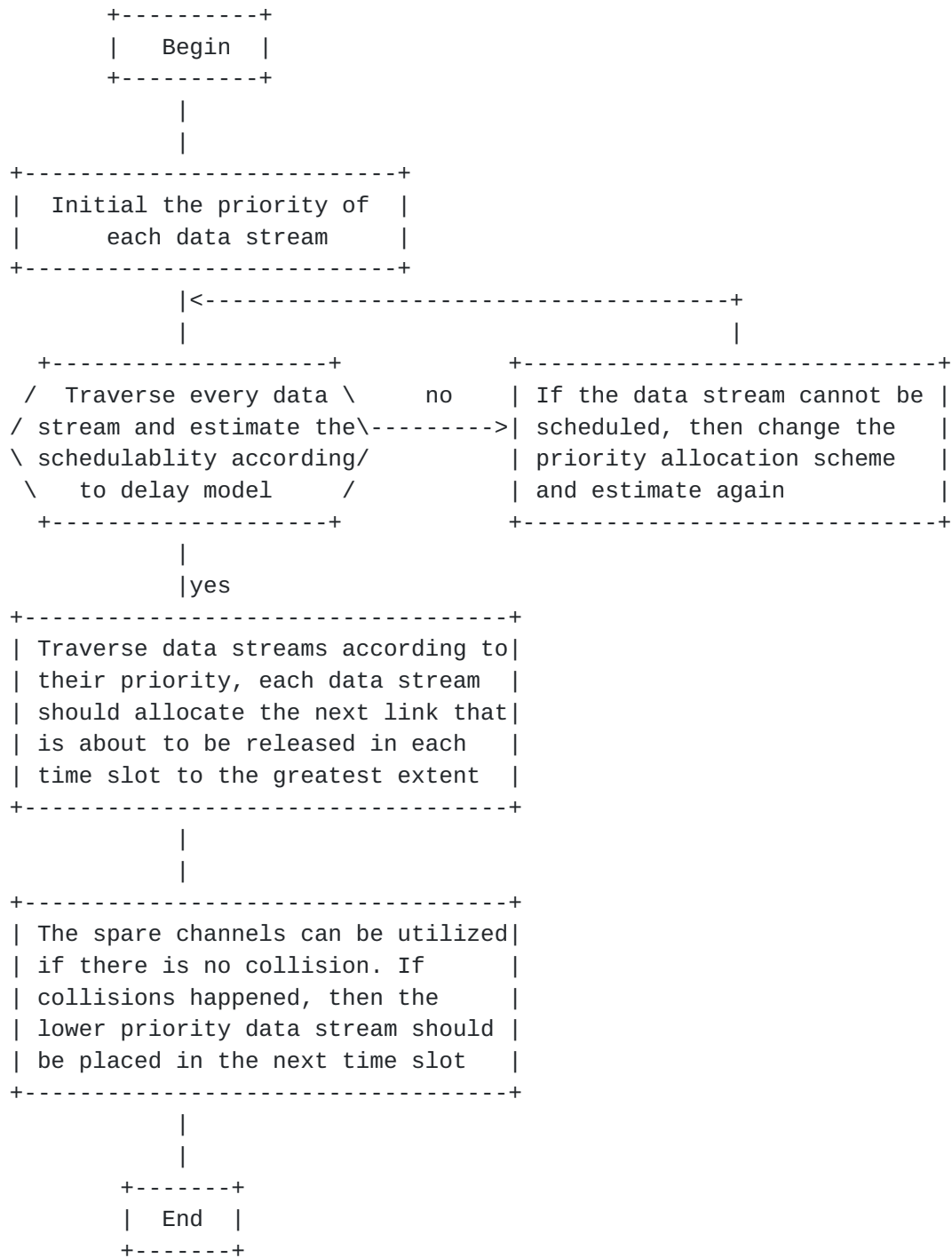
Figure 5. Scheduling of times-slotted industrial backhaul network

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.

For backhaul network using wired technology, time-sensitive network
based on Ethernet is preferred for industrial scenarios. Time-
sensitive network can provide dedicated slots for scheduled traffic,
so above scheduling method can be used in this kind of backhaul
network to guarantee the deterministic performance for data flows
across field and backhaul networks.

4.2. Consider Industrial Backhaul Network as a Black Box

In order to solve the deterministic problem of industrial network,
backhaul network can be regarded as a black box so that we can only
consider its delay impacts and ignore its internal details.

When the packet passes through the industrial backhaul network, we
can give it a timestamp at the application layer and read it after
the transmission is ready to leave the backhaul network. Delay
caused in backhaul network can be calculated, and a fitting curve of
delay can be obtained 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 estimate
the approximate delay time caused by industrial backhaul network.

A main scheduling path can be configured according to the average
delay of the backhaul network. 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 sections, as shown in Figure 6:

```
+--------------------+  +----------------+  +------------------------+
|   Scheduling of    |  |    Delay of    |  |     Scheduling of      |
|source field subnet |->| backhaul network|->|destination field subnet|
|   (deterministic)  |  |(indeterministic)|  |( deterministic dynamic)|
+--------------------+  +----------------+  +------------------------+
       Period 1              Period 2                Period 3
```
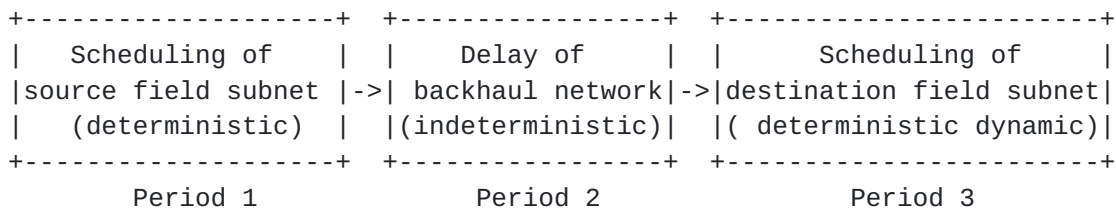
Figure 6. Three periods of scheduling

In source field subnet we can apply the deterministic scheduling
algorithm of field network to get the time spent by each data stream
before entering the source subnet. Then the data stream enters the
backhaul network, which will cause indeterministic delay in a
numerical range. When the data stream leaves the backhaul network,

the timestamp should be parsed. If the deadline is missed, it
indicates that the packet has gone through poor network and needs to
be retransmitted. If there is free time after leaving the backhaul
network, 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 high-speed, if the industrial backhaul networks
adopt IEEE 802.11 protocol, gigabit wireless routers supporting IEEE
802.11 ac can make the delay of industrial backhaul network quite
low. As a result, the joint deterministic scheduling of the entire
network only needs to consider the field networks.

4.4. Build Delay Model of Industrial Backhaul Network

If industrial backhaul network is constructed with IEEE 802.11, the
network access delay test model in IEEE 802.11 Distributed
Coordination Function (DCF) mode can be established by using Markov
chain or queue theory. While the model in IEEE 802.11 Point
Coordination Function (PCF) mode can be established based on queue
theory.

Therefore, the field network needs to build a delay model, while
backhaul network follows another delay model, then the total
transmission scheduling delay will have certain regularity. The
total transmission delay will meet delay requirements with specified
probability by scheduling, in other words, the unsuccessful
scheduling is acceptable.

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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Authors' Addresses

    Heng Wang
    Chongqing University of Posts and Telecommunications
    2 Chongwen Road
    Chongqing, 400065
    China

    Phone: (86)-23-6248-7845
    Email: wangheng@cqupt.edu.cn

    Ping Wang
    Chongqing University of Posts and Telecommunications
    2 Chongwen Road
    Chongqing, 400065
    China

    Phone: (86)-23-6246-1061
    Email: wangping@cqupt.edu.cn

    Hang Yang
    Chongqing University of Posts and Telecommunications
    2 Chongwen Road
    Chongqing, 400065
    China

    Phone: (86)-23-6246-1061
    Email: 18716322620@163.com