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# Deterministic Networking Use Cases
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Abstract

This draft documents requirements in several diverse industries to establish multi-hop paths for characterized flows with deterministic properties. In this context deterministic implies that streams can be established which provide guaranteed bandwidth and latency which can be established from either a Layer 2 or Layer 3 (IP) interface, and which can co-exist on an IP network with best-effort traffic.

Additional requirements include optional redundant paths, very high reliability paths, time synchronization, and clock distribution. Industries considered include wireless for industrial applications, professional audio, electrical utilities, building automation systems, radio/mobile access networks, automotive, and gaming.

For each case, this document will identify the application, identify representative solutions used today, and what new uses an IETF DetNet solution may enable.

Status of This Memo



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## 1. Introduction

This draft presents use cases from diverse industries which have in common a need for deterministic streams, but which also differ notably in their network topologies and specific desired behavior. Together, they provide broad industry context for DetNet and a yardstick against which proposed DetNet designs can be measured (to what extent does a proposed design satisfy these various use cases?)

For DetNet, use cases explicitly do not define requirements; The DetNet WG will consider the use cases, decide which elements are in scope for DetNet, and the results will be incorporated into future drafts. Similarly, the DetNet use case draft explicitly does not suggest any specific design, architecture or protocols, which will be topics of future drafts.

We present for each use case the answers to the following questions:

- What is the use case?
- How is it addressed today?
- How would you like it to be addressed in the future?
- What do you want the IETF to deliver?

The level of detail in each use case should be sufficient to express the relevant elements of the use case, but not more.

At the end we consider the use cases collectively, and examine the most significant goals they have in common.

## 2. Pro Audio Use Cases

### 2.1. Introduction

The professional audio and video industry includes music and film content creation, broadcast, cinema, and live exposition as well as public address, media and emergency systems at large venues (airports, stadiums, churches, theme parks). These industries have already gone through the transition of audio and video signals from analog to digital, however the interconnect systems remain primarily

point-to-point with a single (or small number of) signals per link, interconnected with purpose-built hardware.

These industries are now attempting to transition to packet based infrastructure for distributing audio and video in order to reduce cost, increase routing flexibility, and integrate with existing IT infrastructure.

However, there are several requirements for making a network the primary infrastructure for audio and video which are not met by todays networks and these are our concern in this draft.

The principal requirement is that pro audio and video applications become able to establish streams that provide guaranteed (bounded) bandwidth and latency from the Layer 3 (IP) interface. Such streams can be created today within standards-based layer 2 islands however these are not sufficient to enable effective distribution over wider areas (for example broadcast events that span wide geographical areas).

Some proprietary systems have been created which enable deterministic streams at layer 3 however they are engineered networks in that they require careful configuration to operate, often require that the system be over designed, and it is implied that all devices on the network voluntarily play by the rules of that network. To enable these industries to successfully transition to an interoperable multi-vendor packet-based infrastructure requires effective open standards, and we believe that establishing relevant IETF standards is a crucial factor.

It would be highly desirable if such streams could be routed over the open Internet, however even intermediate solutions with more limited scope (such as enterprise networks) can provide a substantial improvement over todays networks, and a solution that only provides for the enterprise network scenario is an acceptable first step.

We also present more fine grained requirements of the audio and video industries such as safety and security, redundant paths, devices with limited computing resources on the network, and that reserved stream bandwidth is available for use by other best-effort traffic when that stream is not currently in use.

## 2.2. Fundamental Stream Requirements

The fundamental stream properties are guaranteed bandwidth and deterministic latency as described in this section. Additional stream requirements are described in a subsequent section.

### 2.2.1. Guaranteed Bandwidth

Transmitting audio and video streams is unlike common file transfer activities because guaranteed delivery cannot be achieved by re-trying the transmission; by the time the missing or corrupt packet has been identified it is too late to execute a re-try operation and stream playback is interrupted, which is unacceptable in for example a live concert. In some contexts large amounts of buffering can be used to provide enough delay to allow time for one or more retries, however this is not an effective solution when live interaction is involved, and is not considered an acceptable general solution for pro audio and video. (Have you ever tried speaking into a microphone through a sound system that has an echo coming back at you? It makes it almost impossible to speak clearly).

Providing a way to reserve a specific amount of bandwidth for a given stream is a key requirement.

### 2.2.2. Bounded and Consistent Latency

Latency in this context means the amount of time that passes between when a signal is sent over a stream and when it is received, for example the amount of time delay between when you speak into a microphone and when your voice emerges from the speaker. Any delay longer than about 10-15 milliseconds is noticeable by most live performers, and greater latency makes the system unusable because it prevents them from playing in time with the other players (see slide 6 of [SRP_LATENCY]).

The 15ms latency bound is made even more challenging because it is often the case in network based music production with live electric instruments that multiple stages of signal processing are used, connected in series (i.e. from one to the other for example from guitar through a series of digital effects processors) in which case the latencies add, so the latencies of each individual stage must all together remain less than 15ms.

In some situations it is acceptable at the local location for content from the live remote site to be delayed to allow for a statistically acceptable amount of latency in order to reduce jitter. However, once the content begins playing in the local location any audio artifacts caused by the local network are unacceptable, especially in those situations where a live local performer is mixed into the feed from the remote location.

In addition to being bounded to within some predictable and acceptable amount of time (which may be 15 milliseconds or more or less depending on the application) the latency also has to be

consistent. For example when playing a film consisting of a video stream and audio stream over a network, those two streams must be synchronized so that the voice and the picture match up. A common tolerance for audio/video sync is one NTSC video frame (about 33ms) and to maintain the audience perception of correct lip sync the latency needs to be consistent within some reasonable tolerance, for example 10%.

A common architecture for synchronizing multiple streams that have different paths through the network (and thus potentially different latencies) is to enable measurement of the latency of each path, and have the data sinks (for example speakers) buffer (delay) all packets on all but the slowest path. Each packet of each stream is assigned a presentation time which is based on the longest required delay. This implies that all sinks must maintain a common time reference of sufficient accuracy, which can be achieved by any of various techniques.

This type of architecture is commonly implemented using a central controller that determines path delays and arbitrates buffering delays.

#### 2.2.2.1. Optimizations

The controller might also perform optimizations based on the individual path delays, for example sinks that are closer to the source can inform the controller that they can accept greater latency since they will be buffering packets to match presentation times of farther away sinks. The controller might then move a stream reservation on a short path to a longer path in order to free up bandwidth for other critical streams on that short path. See slides 3-5 of [SRP_LATENCY].

Additional optimization can be achieved in cases where sinks have differing latency requirements, for example in a live outdoor concert the speaker sinks have stricter latency requirements than the recording hardware sinks. See slide 7 of [SRP_LATENCY].

Device cost can be reduced in a system with guaranteed reservations with a small bounded latency due to the reduced requirements for buffering (i.e. memory) on sink devices. For example, a theme park might broadcast a live event across the globe via a layer 3 protocol; in such cases the size of the buffers required is proportional to the latency bounds and jitter caused by delivery, which depends on the worst case segment of the end-to-end network path. For example on todays open internet the latency is typically unacceptable for audio and video streaming without many seconds of buffering. In such scenarios a single gateway device at the local network that receives

the feed from the remote site would provide the expensive buffering required to mask the latency and jitter issues associated with long distance delivery. Sink devices in the local location would have no additional buffering requirements, and thus no additional costs, beyond those required for delivery of local content. The sink device would be receiving the identical packets as those sent by the source and would be unaware that there were any latency or jitter issues along the path.

## 2.3. Additional Stream Requirements

The requirements in this section are more specific yet are common to multiple audio and video industry applications.

### 2.3.1. Deterministic Time to Establish Streaming

Some audio systems installed in public environments (airports, hospitals) have unique requirements with regards to health, safety and fire concerns. One such requirement is a maximum of 3 seconds for a system to respond to an emergency detection and begin sending appropriate warning signals and alarms without human intervention. For this requirement to be met, the system must support a bounded and acceptable time from a notification signal to specific stream establishment. For further details see [ISO7240-16].

Similar requirements apply when the system is restarted after a power cycle, cable re-connection, or system reconfiguration.

In many cases such re-establishment of streaming state must be achieved by the peer devices themselves, i.e. without a central controller (since such a controller may only be present during initial network configuration).

Video systems introduce related requirements, for example when transitioning from one camera feed to another. Such systems currently use purpose-built hardware to switch feeds smoothly, however there is a current initiative in the broadcast industry to switch to a packet-based infrastructure (see [STUDIO_IP] and the ESPN DC2 use case described below).

### 2.3.2. Use of Unused Reservations by Best-Effort Traffic

In cases where stream bandwidth is reserved but not currently used (or is under-utilized) that bandwidth must be available to best-effort (i.e. non-time-sensitive) traffic. For example a single stream may be nailed up (reserved) for specific media content that needs to be presented at different times of the day, ensuring timely delivery of that content, yet in between those times the full

bandwidth of the network can be utilized for best-effort tasks such as file transfers.

This also addresses a concern of IT network administrators that are considering adding reserved bandwidth traffic to their networks that users will just reserve a ton of bandwidth and then never un-reserve it even though they are not using it, and soon they will have no bandwidth left.

### 2.3.3. Layer 3 Interconnecting Layer 2 Islands

As an intermediate step (short of providing guaranteed bandwidth across the open internet) it would be valuable to provide a way to connect multiple Layer 2 networks. For example layer 2 techniques could be used to create a LAN for a single broadcast studio, and several such studios could be interconnected via layer 3 links.

### 2.3.4. Secure Transmission

Digital Rights Management (DRM) is very important to the audio and video industries. Any time protected content is introduced into a network there are DRM concerns that must be maintained (see [CONTENT_PROTECTION]). Many aspects of DRM are outside the scope of network technology, however there are cases when a secure link supporting authentication and encryption is required by content owners to carry their audio or video content when it is outside their own secure environment (for example see [DCI]).

As an example, two techniques are Digital Transmission Content Protection (DTCP) and High-Bandwidth Digital Content Protection (HDCP). HDCP content is not approved for retransmission within any other type of DRM, while DTCP may be retransmitted under HDCP. Therefore if the source of a stream is outside of the network and it uses HDCP protection it is only allowed to be placed on the network with that same HDCP protection.

### 2.3.5. Redundant Paths

On-air and other live media streams must be backed up with redundant links that seamlessly act to deliver the content when the primary link fails for any reason. In point-to-point systems this is provided by an additional point-to-point link; the analogous requirement in a packet-based system is to provide an alternate path through the network such that no individual link can bring down the system.

### 2.3.6. Link Aggregation

For transmitting streams that require more bandwidth than a single link in the target network can support, link aggregation is a technique for combining (aggregating) the bandwidth available on multiple physical links to create a single logical link of the required bandwidth. However, if aggregation is to be used, the network controller (or equivalent) must be able to determine the maximum latency of any path through the aggregate link (see Bounded and Consistent Latency section above).

### 2.3.7. Traffic Segregation

Sink devices may be low cost devices with limited processing power. In order to not overwhelm the CPUs in these devices it is important to limit the amount of traffic that these devices must process.

As an example, consider the use of individual seat speakers in a cinema. These speakers are typically required to be cost reduced since the quantities in a single theater can reach hundreds of seats. Discovery protocols alone in a one thousand seat theater can generate enough broadcast traffic to overwhelm a low powered CPU. Thus an installation like this will benefit greatly from some type of traffic segregation that can define groups of seats to reduce traffic within each group. All seats in the theater must still be able to communicate with a central controller.

There are many techniques that can be used to support this requirement including (but not limited to) the following examples.

#### 2.3.7.1. Packet Forwarding Rules, VLANs and Subnets

Packet forwarding rules can be used to eliminate some extraneous streaming traffic from reaching potentially low powered sink devices, however there may be other types of broadcast traffic that should be eliminated using other means for example VLANs or IP subnets.

#### 2.3.7.2. Multicast Addressing (IPv4 and IPv6)

Multicast addressing is commonly used to keep bandwidth utilization of shared links to a minimum.

Because of the MAC Address forwarding nature of Layer 2 bridges it is important that a multicast MAC address is only associated with one stream. This will prevent reservations from forwarding packets from one stream down a path that has no interested sinks simply because there is another stream on that same path that shares the same multicast MAC address.

Since each multicast MAC Address can represent 32 different IPv4 multicast addresses there must be a process put in place to make sure this does not occur. Requiring use of IPv6 address can achieve this, however due to their continued prevalence, solutions that are effective for IPv4 installations are also required.

## 2.4. Integration of Reserved Streams into IT Networks

A commonly cited goal of moving to a packet based media infrastructure is that costs can be reduced by using off the shelf, commodity network hardware. In addition, economy of scale can be realized by combining media infrastructure with IT infrastructure. In keeping with these goals, stream reservation technology should be compatible with existing protocols, and not compromise use of the network for best effort (non-time-sensitive) traffic.

## 2.5. Security Considerations

Many industries that are moving from the point-to-point world to the digital network world have little understanding of the pitfalls that they can create for themselves with improperly implemented network infrastructure. DetNet should consider ways to provide security against DoS attacks in solutions directed at these markets. Some considerations are given here as examples of ways that we can help new users avoid common pitfalls.

### 2.5.1. Denial of Service

One security pitfall that this author is aware of involves the use of technology that allows a presenter to throw the content from their tablet or smart phone onto the A/V system that is then viewed by all those in attendance. The facility introducing this technology was quite excited to allow such modern flexibility to those who came to speak. One thing they hadn't realized was that since no security was put in place around this technology it left a hole in the system that allowed other attendees to "throw" their own content onto the A/V system.

### 2.5.2. Control Protocols

Professional audio systems can include amplifiers that are capable of generating hundreds or thousands of watts of audio power which if used incorrectly can cause hearing damage to those in the vicinity. Apart from the usual care required by the systems operators to prevent such incidents, the network traffic that controls these devices must be secured (as with any sensitive application traffic). In addition, it would be desirable if the configuration protocols that are used to create the network paths used by the professional

audio traffic could be designed to protect devices that are not meant to receive high-amplitude content from having such potentially damaging signals routed to them.

### 2.6. A State-of-the-Art Broadcast Installation Hits Technology Limits

ESPN recently constructed a state-of-the-art 194,000 sq ft, $125 million broadcast studio called DC2. The DC2 network is capable of handling 46 Tbps of throughput with 60,000 simultaneous signals. Inside the facility are 1,100 miles of fiber feeding four audio control rooms. (See details at [ESPN_DC2] ).

In designing DC2 they replaced as much point-to-point technology as they possibly could with packet-based technology. They constructed seven individual studios using layer 2 LANS (using IEEE 802.1 AVB) that were entirely effective at routing audio within the LANs, and they were very happy with the results, however to interconnect these layer 2 LAN islands together they ended up using dedicated links because there is no standards-based routing solution available.

This is the kind of motivation we have to develop these standards because customers are ready and able to use them.

## 3. Utility Telecom Use Cases

### 3.1. Overview

[I-D.finn-detnet-problem-statement] defines the characteristics of a deterministic flow as a data communication flow with a bounded latency, extraordinarily low frame loss, and a very narrow jitter. This document intends to define the utility requirements for deterministic networking.

Utility Telecom Networks

The business and technology trends that are sweeping the utility industry will drastically transform the utility business from the way it has been for many decades. At the core of many of these changes is a drive to modernize the electrical grid with an integrated telecommunications infrastructure. However, interoperability, concerns, legacy networks, disparate tools, and stringent security requirements all add complexity to the grid transformation. Given the range and diversity of the requirements that should be addressed by the next generation telecommunications infrastructure, utilities need to adopt a holistic architectural approach to integrate the electrical grid with digital telecommunications across the entire power delivery chain.

Many utilities still rely on complex environments formed of multiple application-specific, proprietary networks. Information is siloed between operational areas. This prevents utility operations from realizing the operational efficiency benefits, visibility, and functional integration of operational information across grid applications and data networks. The key to modernizing grid telecommunications is to provide a common, adaptable, multi-service network infrastructure for the entire utility organization. Such a network serves as the platform for current capabilities while enabling future expansion of the network to accommodate new applications and services.

To meet this diverse set of requirements, both today and in the future, the next generation utility telecommunnications network will be based on open-standards-based IP architecture. An end-to-end IP architecture takes advantage of nearly three decades of IP technology development, facilitating interoperability across disparate networks and devices, as it has been already demonstrated in many mission-critical and highly secure networks.

IEC (International Electrotechnical Commission) and different National Committees have mandated a specific adhoc group (AHG8) to define the migration strategy to IPv6 for all the IEC TC57 power automation standards. IPv6 is seen as the obvious future telecommunications technology for the Smart Grid. The Adhoc Group has disclosed, to the IEC coordination group, their conclusions at the end of 2014.

It is imperative that utilities participate in standards development bodies to influence the development of future solutions and to benefit from shared experiences of other utilities and vendors.

## 3.2. Telecommunications Trends and General telecommunications Requirements

These general telecommunications requirements are over and above the specific requirements of the use cases that have been addressed so far. These include both current and future telecommunications related requirements that should be factored into the network architecture and design.

### 3.2.1. General Telecommunications Requirements

- IP Connectivity everywhere
- Monitoring services everywhere and from different remote centers
- Move services to a virtual data center

- Unify access to applications / information from the corporate network
- Unify services
- Unified Communications Solutions
- Mix of fiber and microwave technologies - obsolescence of SONET/ SDH or TDM
- Standardize grid telecommunications protocol to opened standard to ensure interoperability
- Reliable Telecommunications for Transmission and Distribution Substations
- IEEE 1588 time synchronization Client / Server Capabilities
- Integration of Multicast Design
- QoS Requirements Mapping
- Enable Future Network Expansion
- Substation Network Resilience
- Fast Convergence Design
- Scalable Headend Design
- Define Service Level Agreements (SLA) and Enable SLA Monitoring
- Integration of 3G/4G Technologies and future technologies
- Ethernet Connectivity for Station Bus Architecture
- Ethernet Connectivity for Process Bus Architecture
- Protection, teleprotection and PMU (Phaser Measurement Unit) on IP

#### 3.2.1.1. Migration to Packet-Switched Network

Throughout the world, utilities are increasingly planning for a future based on smart grid applications requiring advanced telecommunications systems. Many of these applications utilize packet connectivity for communicating information and control signals across the utility's Wide Area Network (WAN), made possible by

technologies such as multiprotocol label switching (MPLS). The data that traverses the utility WAN includes:

- Grid monitoring, control, and protection data
- Non-control grid data (e.g. asset data for condition-based monitoring)
- Physical safety and security data (e.g. voice and video)
- Remote worker access to corporate applications (voice, maps, schematics, etc.)
- Field area network backhaul for smart metering, and distribution grid management
- Enterprise traffic (email, collaboration tools, business applications)

WANs support this wide variety of traffic to and from substations, the transmission and distribution grid, generation sites, between control centers, and between work locations and data centers. To maintain this rapidly expanding set of applications, many utilities are taking steps to evolve present time-division multiplexing (TDM) based and frame relay infrastructures to packet systems. Packet-based networks are designed to provide greater functionalities and higher levels of service for applications, while continuing to deliver reliability and deterministic (real-time) traffic support.

### 3.2.2. Applications, Use cases and traffic patterns

Among the numerous applications and use cases that a utility deploys today, many rely on high availability and deterministic behaviour of the telecommunications networks. Protection use cases and generation control are the most demanding and can't rely on a best effort approach.

#### 3.2.2.1. Transmission use cases

Protection means not only the protection of the human operator but also the protection of the electric equipments and the preservation of the stability and frequency of the grid. If a default occurs on the transmission or the distribution of the electricity, important damages could occured to the human operator but also to very costly electrical equipments and perturb the grid leading to blackouts. The time and reliability requirements are very strong to avoid dramatic impacts to the electrical infrastructure.

#### 3.2.2.1.1. Tele Protection

The key criteria for measuring Teleprotection performance are command transmission time, dependability and security. These criteria are defined by the IEC standard 60834 as follows:

- Transmission time (Speed): The time between the moment where state changes at the transmitter input and the moment of the corresponding change at the receiver output, including propagation delay. Overall operating time for a Teleprotection system includes the time for initiating the command at the transmitting end, the propagation delay over the network (including equipments) and the selection and decision time at the receiving end, including any additional delay due to a noisy environment.

- Dependability: The ability to issue and receive valid commands in the presence of interference and/or noise, by minimizing the probability of missing command (PMC). Dependability targets are typically set for a specific bit error rate (BER) level.

- Security: The ability to prevent false tripping due to a noisy environment, by minimizing the probability of unwanted commands (PUC). Security targets are also set for a specific bit error rate (BER) level.

Additional key elements that may impact Teleprotection performance include bandwidth rate of the Teleprotection system and its resiliency or failure recovery capacity. Transmission time, bandwidth utilization and resiliency are directly linked to the telecommunications equipments and the connections that are used to transfer the commands between relays.

##### 3.2.2.1.1.1. Latency Budget Consideration

Delay requirements for utility networks may vary depending upon a number of parameters, such as the specific protection equipments used. Most power line equipment can tolerate short circuits or faults for up to approximately five power cycles before sustaining irreversible damage or affecting other segments in the network. This translates to total fault clearance time of 100ms. As a safety precaution, however, actual operation time of protection systems is limited to 70- 80 percent of this period, including fault recognition time, command transmission time and line breaker switching time. Some system components, such as large electromechanical switches, require particularly long time to operate and take up the majority of the total clearance time, leaving only a 10ms window for the telecommunications part of the protection scheme, independent of the distance to travel. Given the sensitivity of the issue, new networks

impose requirements that are even more stringent: IEC standard 61850 limits the transfer time for protection messages to 1/4 - 1/2 cycle or 4 - 8ms (for 60Hz lines) for the most critical messages.

#### 3.2.2.1.1.2. Asymetric delay

In addition to minimal transmission delay, a differential protection telecommunications channel must be synchronous, i.e., experiencing symmetrical channel delay in transmit and receive paths. This requires special attention in jitter-prone packet networks. While optimally Teleprotection systems should support zero asymmetric delay, typical legacy relays can tolerate discrepancies of up to 750us.

The main tools available for lowering delay variation below this threshold are:

- A jitter buffer at the multiplexers on each end of the line can be used to offset delay variation by queuing sent and received packets. The length of the queues must balance the need to regulate the rate of transmission with the need to limit overall delay, as larger buffers result in increased latency. This is the old TDM traditional way to fulfill this requirement.

- Traffic management tools ensure that the Teleprotection signals receive the highest transmission priority and minimize the number of jitter addition during the path. This is one way to meet the requirement in IP networks.

- Standard Packet-Based synchronization technologies, such as 1588-2008 Precision Time Protocol (PTP) and Synchronous Ethernet (Sync-E), can help maintain stable networks by keeping a highly accurate clock source on the different network devices involved.

##### 3.2.2.1.1.2.1. Other traffic characteristics

- Redundancy: The existence in a system of more than one means of accomplishing a given function.

- Recovery time : The duration of time within which a business process must be restored after any type of disruption in order to avoid unacceptable consequences associated with a break in business continuity.

- performance management : In networking, a management function defined for controlling and analyzing different parameters/metrics such as the throughput, error rate.

- packet loss : One or more packets of data travelling across network fail to reach their destination.

#### 3.2.2.1.1.2.2. Teleprotection network requirements

The following table captures the main network requirements (this is based on IEC 61850 standard)

| Teleprotection Requirement | Attribute |
|---|---|
| One way maximum delay | 4-10 ms |
| Asymetric delay required | Yes |
| Maximum jitter | less than 250 us (750 us for legacy IED) |
| Topology | Point to point, point to Multi-point |
| Availability | 99.9999 |
| precise timing required | Yes |
| Recovery time on node failure | less than 50ms - hitless |
| performance management | Yes, Mandatory |
| Redundancy | Yes |
| Packet loss | 0.1% to 1% |

Table 1: Teleprotection network requirements

#### 3.2.2.1.2. Inter-Trip Protection scheme

Inter-tripping is the controlled tripping of a circuit breaker to complete the isolation of a circuit or piece of apparatus in concert with the tripping of other circuit breakers. The main use of such schemes is to ensure that protection at both ends of a faulted circuit will operate to isolate the equipment concerned. Inter-tripping schemes use signaling to convey a trip command to remote circuit breakers to isolate circuits.

| Inter-Trip protection Requirement | Attribute |
|---|---|
| One way maximum delay | 5 ms |
| Asymetric delay required | No |
| Maximum jitter | Not critical |
| Topology | Point to point, point to Multi-point |
| Bandwidth | 64 Kbps |
| Availability | 99.9999 |
| precise timing required | Yes |
| Recovery time on node failure | less than 50ms - hitless |
| performance management | Yes, Mandatory |
| Redundancy | Yes |
| Packet loss | 0.1% |

Table 2: Inter-Trip protection network requirements

#### 3.2.2.1.3. Current Differential Protection Scheme

Current differential protection is commonly used for line protection, and is typical for protecting parallel circuits. A main advantage for differential protection is that, compared to overcurrent protection, it allows only the faulted circuit to be de-energized in case of a fault. At both end of the lines, the current is measured by the differential relays, and based on Kirchhoff's law, both relays will trip the circuit breaker if the current going into the line does not equal the current going out of the line. This type of protection scheme assumes some form of communications being present between the relays at both end of the line, to allow both relays to compare measured current values. A fault in line 1 will cause overcurrent to be flowing in both lines, but because the current in line 2 is a through following current, this current is measured equal at both ends of the line, therefore the differential relays on line 2 will not trip line 2. Line 1 will be tripped, as the relays will not measure the same currents at both ends of the line. Line differential protection schemes assume a very low telecommunications delay between both relays, often as low as 5ms. Moreover, as those systems are often not time-synchronized, they also assume symmetric telecommunications paths with constant delay, which allows comparing current measurement values taken at the exact same time.

| Current Differential protection Requirement | Attribute |
|---|---|
| One way maximum delay | 5 ms |
| Asymetric delay Required | Yes |
| Maximum jitter | less than 250 us (750us for legacy IED) |
| Topology | Point to point, point to Multi-point |
| Bandwidth | 64 Kbps |
| Availability | 99.9999 |
| precise timing required | Yes |
| Recovery time on node failure | less than 50ms - hitless |
| performance management | Yes, Mandatory |
| Redundancy | Yes |
| Packet loss | 0.1% |

Table 3: Current Differential Protection requirements

#### 3.2.2.1.4. Distance Protection Scheme

Distance (Impedance Relay) protection scheme is based on voltage and current measurements. A fault on a circuit will generally create a sag in the voltage level. If the ratio of voltage to current measured at the protection relay terminals, which equates to an impedance element, falls within a set threshold the circuit breaker will operate. The operating characteristics of this protection are based on the line characteristics. This means that when a fault appears on the line, the impedance setting in the relay is compared to the apparent impedance of the line from the relay terminals to the fault. If the relay setting is determined to be below the apparent impedance it is determined that the fault is within the zone of protection. When the transmission line length is under a minimum length, distance protection becomes more difficult to coordinate. In these instances the best choice of protection is current differential protection.

| Distance protection Requirement | Attribute |
|---|---|
| One way maximum delay | 5 ms |
| Asymetric delay Required | No |
| Maximum jitter | Not critical |
| Topology | Point to point, point to Multi-point |
| Bandwidth | 64 Kbps |
| Availability | 99.9999 |
| precise timing required | Yes |
| Recovery time on node failure | less than 50ms - hitless |
| performance management | Yes, Mandatory |
| Redundancy | Yes |
| Packet loss | 0.1% |

Table 4: Distance Protection requirements

#### 3.2.2.1.5. Inter-Substation Protection Signaling

This use case describes the exchange of Sampled Value and/or GOOSE (Generic Object Oriented Substation Events) message between Intelligent Electronic Devices (IED) in two substations for protection and tripping coordination. The two IEDs are in a master-slave mode.

The Current Transformer or Voltage Transformer (CT/VT) in one substation sends the sampled analog voltage or current value to the Merging Unit (MU) over hard wire. The merging unit sends the time-synchronized 61850-9-2 sampled values to the slave IED. The slave IED forwards the information to the Master IED in the other substation. The master IED makes the determination (for example based on sampled value differentials) to send a trip command to the originating IED. Once the slave IED/Relay receives the GOOSE trip for breaker tripping, it opens the breaker. It then sends a confirmation message back to the master. All data exchanges between IEDs are either through Sampled Value and/or GOOSE messages.

| Inter-Substation protection Requirement | Attribute |
|---|---|
| One way maximum delay | 5 ms |
| Asymetric delay Required | No |
| Maximum jitter | Not critical |
| Topology | Point to point, point to Multi-point |
| Bandwidth | 64 Kbps |
| Availability | 99.9999 |
| precise timing required | Yes |
| Recovery time on node failure | less than 50ms - hitless |
| performance management | Yes, Mandatory |
| Redundancy | Yes |
| Packet loss | 1% |

Table 5: Inter-Substation Protection requirements

#### 3.2.2.1.6. Intra-Substation Process Bus Communications

This use case describes the data flow from the CT/VT to the IEDs in the substation via the merging unit (MU). The CT/VT in the substation send the sampled value (analog voltage or current) to the Merging Unit (MU) over hard wire. The merging unit sends the time-synchronized 61850-9-2 sampled values to the IEDs in the substation in GOOSE message format. The GPS Master Clock can send 1PPS or IRIG-B format to MU through serial port, or IEEE 1588 protocol via network. Process bus communication using 61850 simplifies connectivity within the substation and removes the requirement for multiple serial connections and removes the slow serial bus architectures that are typically used. This also ensures increased flexibility and increased speed with the use of multicast messaging between multiple devices.

| Intra-Substation protection Requirement | Attribute |
|---|---|
| One way maximum delay | 5 ms |
| Asymetric delay Required | No |
| Maximum jitter | Not critical |
| Topology | Point to point, point to Multi-point |
| Bandwidth | 64 Kbps |
| Availability | 99.9999 |
| precise timing required | Yes |
| Recovery time on Node failure | less than 50ms - hitless |
| performance management | Yes, Mandatory |
| Redundancy | Yes - No |
| Packet loss | 0.1% |

Table 6: Intra-Substation Protection requirements

#### 3.2.2.1.7. Wide Area Monitoring and Control Systems

The application of synchrophasor measurement data from Phasor Measurement Units (PMU) to Wide Area Monitoring and Control Systems promises to provide important new capabilities for improving system stability. Access to PMU data enables more timely situational awareness over larger portions of the grid than what has been possible historically with normal SCADA (Supervisory Control and Data Acquisition) data. Handling the volume and real-time nature of synchrophasor data presents unique challenges for existing application architectures. Wide Area management System (WAMS) makes it possible for the condition of the bulk power system to be observed and understood in real-time so that protective, preventative, or corrective action can be taken. Because of the very high sampling rate of measurements and the strict requirement for time synchronization of the samples, WAMS has stringent telecommunications requirements in an IP network that are captured in the following table:

| WAMS Requirement | Attribute |
|---|---|
| One way maximum delay | 50 ms |
| Asymetric delay Required | No |
| Maximum jitter | Not critical |
| Topology | Point to point, point to Multi-point, Multi-point to Multi-point |
| Bandwidth | 100 Kbps |
| Availability | 99.9999 |
| precise timing required | Yes |
| Recovery time on Node failure | less than 50ms - hitless |
| performance management | Yes, Mandatory |
| Redundancy | Yes |
| Packet loss | 1% |

Table 7: WAMS Special Communication Requirements

#### 3.2.2.1.8. IEC 61850 WAN engineering guidelines requirement classification

The IEC (International Electrotechnical Commission) has recently published a Technical Report which offers guidelines on how to define and deploy Wide Area Networks for the interconnections of electric substations, generation plants and SCADA operation centers. The IEC 61850-90-12 is providing a classification of WAN communication requirements into 4 classes. You will find herafter the table summarizing these requirements:

| WAN Requirement | Class WA | Class WB | Class WC | Class WD |
|---|---|---|---|---|
| Application field | EHV (Extra High Voltage) | HV (High Voltage) | MV (Medium Voltage) | General purpose |
| Latency | 5 ms | 10 ms | 100 ms | > 100 ms |
| Jitter | 10 us | 100 us | 1 ms | 10 ms |
| Latency Asymetry | 100 us | 1 ms | 10 ms | 100 ms |
| Time Accuracy | 1 us | 10 us | 100 us | 10 to 100 ms |
| Bit Error rate | 10-7 to 10-6 | 10-5 to 10-4 | 10-3 | |
| Unavailability | 10-7 to 10-6 | 10-5 to 10-4 | 10-3 | |
| Recovery delay | Zero | 50 ms | 5 s | 50 s |
| Cyber security | extremely high | High | Medium | Medium |

Table 8: 61850-90-12 Communication Requirements; Courtesy of IEC

### 3.2.2.2. Distribution use case

#### 3.2.2.2.1. Fault Location Isolation and Service Restoration (FLISR)

As the name implies, Fault Location, Isolation, and Service Restoration (FLISR) refers to the ability to automatically locate the fault, isolate the fault, and restore service in the distribution network. It is a self-healing feature whose purpose is to minimize the impact of faults by serving portions of the loads on the affected circuit by switching to other circuits. It reduces the number of customers that experience a sustained power outage by reconfiguring distribution circuits. This will likely be the first wide spread application of distributed intelligence in the grid. Secondary substations can be connected to multiple primary substations. Normally, static power switch statuses (open/closed) in the network dictate the power flow to secondary substations. Reconfiguring the network in the event of a fault is typically done manually on site to operate switchgear to energize/de-energize alternate paths. Automating the operation of substation switchgear allows the utility to have a more dynamic network where the flow of power can be altered under fault conditions but also during times of peak load. It allows the utility to shift peak loads around the network. Or, to be more precise, alters the configuration of the network to move loads

between different primary substations. The FLISR capability can be enabled in two modes:

- Managed centrally from DMS (Distribution Management System), or
- Executed locally through distributed control via intelligent switches and fault sensors.

There are 3 distinct sub-functions that are performed:

1. Fault Location Identification

This sub-function is initiated by SCADA inputs, such as lockouts, fault indications/location, and, also, by input from the Outage Management System (OMS), and in the future by inputs from fault-predicting devices. It determines the specific protective device, which has cleared the sustained fault, identifies the de-energized sections, and estimates the probable location of the actual or the expected fault. It distinguishes faults cleared by controllable protective devices from those cleared by fuses, and identifies momentary outages and inrush/cold load pick-up currents. This step is also referred to as Fault Detection Classification and Location (FDCL). This step helps to expedite the restoration of faulted sections through fast fault location identification and improved diagnostic information available for crew dispatch. Also provides visualization of fault information to design and implement a switching plan to isolate the fault.

2. Fault Type Determination

I. Indicates faults cleared by controllable protective devices by distinguishing between:

a. Faults cleared by fuses

b. Momentary outages

c. Inrush/cold load current

II. Determines the faulted sections based on SCADA fault indications and protection lockout signals

III. Increases the accuracy of the fault location estimation based on SCADA fault current measurements and real-time fault analysis

3. Fault Isolation and Service Restoration

Once the location and type of the fault has been pinpointed, the systems will attempt to isolate the fault and restore the non-faulted section of the network. This can have three modes of operation:

I. Closed-loop mode : This is initiated by the Fault location sub-function. It generates a switching order (i.e., sequence of switching) for the remotely controlled switching devices to isolate the faulted section, and restore service to the non-faulted sections. The switching order is automatically executed via SCADA.

II. Advisory mode : This is initiated by the Fault location sub-function. It generates a switching order for remotely and manually controlled switching devices to isolate the faulted section, and restore service to the non-faulted sections. The switching order is presented to operator for approval and execution.

III. Study mode : the operator initiates this function. It analyzes a saved case modified by the operator, and generates a switching order under the operating conditions specified by the operator.

With the increasing volume of data that are collected through fault sensors, utilities will use Big Data query and analysis tools to study outage information to anticipate and prevent outages by detecting failure patterns and their correlation with asset age, type, load profiles, time of day, weather conditions, and other conditions to discover conditions that lead to faults and take the necessary preventive and corrective measures.

| FLISR Requirement | Attribute |
|---|---|
| One way maximum delay | 80 ms |
| Asymetric delay Required | No |
| Maximum jitter | 40 ms |
| Topology | Point to point, point to Multi-point, Multi-point to Multi-point |
| Bandwidth | 64 Kbps |
| Availability | 99.9999 |
| precise timing required | Yes |
| Recovery time on Node failure performance management | Depends on customer impact |
| Redundancy | Yes, Mandatory |
| Packet loss | Yes |
| | 0.1% |

Table 9: FLISR Communication Requirements

### 3.2.2.3. Generation use case

#### 3.2.2.3.1. Frequency Control / Automatic Generation Control (AGC)

The system frequency should be maintained within a very narrow band. Deviations from the acceptable frequency range are detected and forwarded to the Load Frequency Control (LFC) system so that required up or down generation increase / decrease pulses can be sent to the power plants for frequency regulation. The trend in system frequency is a measure of mismatch between demand and generation, and is a necessary parameter for load control in interconnected systems.

Automatic generation control (AGC) is a system for adjusting the power output of generators at different power plants, in response to changes in the load. Since a power grid requires that generation and load closely balance moment by moment, frequent adjustments to the output of generators are necessary. The balance can be judged by measuring the system frequency; if it is increasing, more power is being generated than used, and all machines in the system are accelerating. If the system frequency is decreasing, more demand is on the system than the instantaneous generation can provide, and all generators are slowing down.

Where the grid has tie lines to adjacent control areas, automatic generation control helps maintain the power interchanges over the tie lines at the scheduled levels. The AGC takes into account various parameters including the most economical units to adjust, the coordination of thermal, hydroelectric, and other generation types, and even constraints related to the stability of the system and capacity of interconnections to other power grids.

For the purpose of AGC we use static frequency measurements and averaging methods are used to get a more precise measure of system frequency in steady-state conditions.

During disturbances, more real-time dynamic measurements of system frequency are taken using PMUs, especially when different areas of the system exhibit different frequencies. But that is outside the scope of this use case.

| FCAG (Frequency Control Automatic Generation) Requirement | Attribute |
|---|---|
| One way maximum delay | 500 ms |
| Asymetric delay Required | No |
| Maximum jitter | Not critical |
| Topology | Point to point |
| Bandwidth | 20 Kbps |
| Availability | 99.999 |
| precise timing required | Yes |
| Recovery time on Node failure | N/A |
| performance management | Yes, Mandatory |
| Redundancy | Yes |
| Packet loss | 1% |

Table 10: FCAG Communication Requirements

### 3.2.3. Specific Network topologies of Smart Grid Applications

Utilities often have very large private telecommunications networks. It covers an entire territory / country. The main purpose of the network, until now, has been to support transmission network monitoring, control, and automation, remote control of generation sites, and providing FCAPS (Fault. Configuration. Accounting. Performance. Security) services from centralized network operation centers.

Going forward, one network will support operation and maintenance of electrical networks (generation, transmission, and distribution), voice and data services for ten of thousands of employees and for exchange with neighboring interconnections, and administrative services. To meet those requirements, utility may deploy several physical networks leveraging different technologies across the country: an optical network and a microwave network for instance. Each protection and automatism system between two points has two telecommunications circuits, one on each network. Path diversity between two substations is key. Regardless of the event type (hurricane, ice storm, etc.), one path shall stay available so the SPS can still operate.

In the optical network, signals are transmitted over more than tens of thousands of circuits using fiber optic links, microwave and telephone cables. This network is the nervous system of the utility's power transmission operations. The optical network represents ten of thousands of km of cable deployed along the power lines.

Due to vast distances between transmission substations (for example as far as 280km apart), the fiber signal can be amplified to reach a distance of 280 km without attenuation.

### 3.2.4. Precision Time Protocol

Some utilities do not use GPS clocks in generation substations. One of the main reasons is that some of the generation plants are 30 to 50 meters deep under ground and the GPS signal can be weak and unreliable. Instead, atomic clocks are used. Clocks are synchronized amongst each other. Rubidium clocks provide clock and 1ms timestamps for IRIG-B. Some companies plan to transition to the Precision Time Protocol (IEEE 1588), distributing the synchronization signal over the IP/MPLS network.

The Precision Time Protocol (PTP) is defined in IEEE standard 1588. PTP is applicable to distributed systems consisting of one or more nodes, communicating over a network. Nodes are modeled as containing a real-time clock that may be used by applications within the node for various purposes such as generating time-stamps for data or ordering events managed by the node. The protocol provides a mechanism for synchronizing the clocks of participating nodes to a high degree of accuracy and precision.

PTP operates based on the following assumptions :

It is assumed that the network eliminates cyclic forwarding of PTP messages within each communication path (e.g., by using a spanning

tree protocol). PTP eliminates cyclic forwarding of PTP messages between communication paths.

PTP is tolerant of an occasional missed message, duplicated message, or message that arrived out of order. However, PTP assumes that such impairments are relatively rare.

PTP was designed assuming a multicast communication model. PTP also supports a unicast communication model as long as the behavior of the protocol is preserved.

Like all message-based time transfer protocols, PTP time accuracy is degraded by asymmetry in the paths taken by event messages. Asymmetry is not detectable by PTP, however, if known, PTP corrects for asymmetry.

A time-stamp event is generated at the time of transmission and reception of any event message. The time-stamp event occurs when the message's timestamp point crosses the boundary between the node and the network.

IEC 61850 will recommend the use of the IEEE PTP 1588 Utility Profile (as defined in IEC 62439-3 Annex B) which offers the support of redundant attachment of clocks to Paralell Redundancy Protcol (PRP) and High-availability Seamless Redundancy (HSR) networks.

## 3.3. IANA Considerations

This memo includes no request to IANA.

## 3.4. Security Considerations

### 3.4.1. Current Practices and Their Limitations

Grid monitoring and control devices are already targets for cyber attacks and legacy telecommunications protocols have many intrinsic network related vulnerabilities. DNP3, Modbus, PROFIBUS/PROFINET, and other protocols are designed around a common paradigm of request and respond. Each protocol is designed for a master device such as an HMI (Human Machine Interface) system to send commands to subordinate slave devices to retrieve data (reading inputs) or control (writing to outputs). Because many of these protocols lack authentication, encryption, or other basic security measures, they are prone to network-based attacks, allowing a malicious actor or attacker to utilize the request-and-respond system as a mechanism for command-and-control like functionality. Specific security concerns common to most industrial control, including utility telecommunication protocols include the following:

- Network or transport errors (e.g. malformed packets or excessive latency) can cause protocol failure.

- Protocol commands may be available that are capable of forcing slave devices into inoperable states, including powering-off devices, forcing them into a listen-only state, disabling alarming.

- Protocol commands may be available that are capable of restarting communications and otherwise interrupting processes.

- Protocol commands may be available that are capable of clearing, erasing, or resetting diagnostic information such as counters and diagnostic registers.

- Protocol commands may be available that are capable of requesting sensitive information about the controllers, their configurations, or other need-to-know information.

- Most protocols are application layer protocols transported over TCP; therefore it is easy to transport commands over non-standard ports or inject commands into authorized traffic flows.

- Protocol commands may be available that are capable of broadcasting messages to many devices at once (i.e. a potential DoS).

- Protocol commands may be available to query the device network to obtain defined points and their values (i.e. a configuration scan).

- Protocol commands may be available that will list all available function codes (i.e. a function scan).

- Bump in the wire (BITW) solutions : A hardware device is added to provide IPSec services between two routers that are not capable of IPSec functions. This special IPsec device will intercept then intercept outgoing datagrams, add IPSec protection to them, and strip it off incoming datagrams. BITW can all IPSec to legacy hosts and can retrofit non-IPSec routers to provide security benefits. The disadvantages are complexity and cost.

These inherent vulnerabilities, along with increasing connectivity between IT an OT networks, make network-based attacks very feasible. Simple injection of malicious protocol commands provides control over the target process. Altering legitimate protocol traffic can also alter information about a process and disrupt the legitimate controls that are in place over that process. A man- in-the-middle attack

could provide both control over a process and misrepresentation of data back to operator consoles.

### 3.4.2. Security Trends in Utility Networks

Although advanced telecommunications networks can assist in transforming the energy industry, playing a critical role in maintaining high levels of reliability, performance, and manageability, they also introduce the need for an integrated security infrastructure. Many of the technologies being deployed to support smart grid projects such as smart meters and sensors can increase the vulnerability of the grid to attack. Top security concerns for utilities migrating to an intelligent smart grid telecommunications platform center on the following trends:

- Integration of distributed energy resources
- Proliferation of digital devices to enable management, automation, protection, and control
- Regulatory mandates to comply with standards for critical infrastructure protection
- Migration to new systems for outage management, distribution automation, condition-based maintenance, load forecasting, and smart metering
- Demand for new levels of customer service and energy management

This development of a diverse set of networks to support the integration of microgrids, open-access energy competition, and the use of network-controlled devices is driving the need for a converged security infrastructure for all participants in the smart grid, including utilities, energy service providers, large commercial and industrial, as well as residential customers. Securing the assets of electric power delivery systems, from the control center to the substation, to the feeders and down to customer meters, requires an end-to-end security infrastructure that protects the myriad of telecommunications assets used to operate, monitor, and control power flow and measurement. Cyber security refers to all the security issues in automation and telecommunications that affect any functions related to the operation of the electric power systems. Specifically, it involves the concepts of:

- Integrity : data cannot be altered undetectably
- Authenticity : the telecommunications parties involved must be validated as genuine

- Authorization : only requests and commands from the authorized users can be accepted by the system

- Confidentiality : data must not be accessible to any unauthenticated users

When designing and deploying new smart grid devices and telecommunications systems, it's imperative to understand the various impacts of these new components under a variety of attack situations on the power grid. Consequences of a cyber attack on the grid telecommunications network can be catastrophic. This is why security for smart grid is not just an ad hoc feature or product, it's a complete framework integrating both physical and Cyber security requirements and covering the entire smart grid networks from generation to distribution. Security has therefore become one of the main foundations of the utility telecom network architecture and must be considered at every layer with a defense-in-depth approach. Migrating to IP based protocols is key to address these challenges for two reasons:

1. IP enables a rich set of features and capabilities to enhance the security posture

2. IP is based on open standards, which allows interoperability between different vendors and products, driving down the costs associated with implementing security solutions in OT networks.

Securing OT (Operation technology) telecommunications over packet-switched IP networks follow the same principles that are foundational for securing the IT infrastructure, i.e., consideration must be given to enforcing electronic access control for both person-to-machine and machine-to-machine communications, and providing the appropriate levels of data privacy, device and platform integrity, and threat detection and mitigation.

## 4. Building Automation Systems

### 4.1. Use Case Description

A Building Automation System (BAS) manages equipment and sensors in a building for improving residents' comfort, reducing energy consumption, and responding to failures and emergencies. For example, the BAS measures the temperature of a room using sensors and then controls the HVAC (heating, ventilating, and air conditioning) to maintain a set temperature and minimize energy consumption.

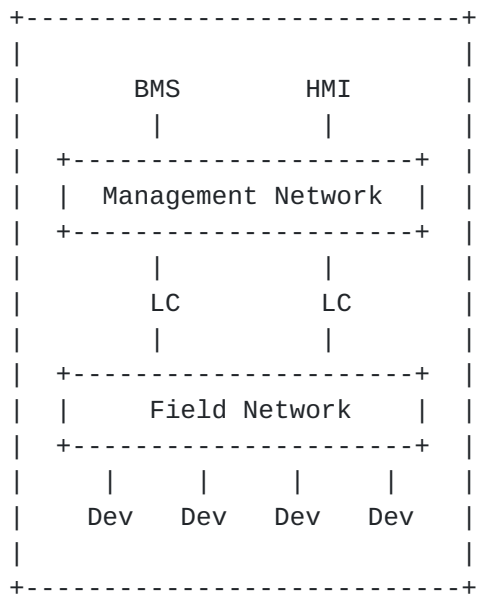
A BAS primarily performs the following functions:

- Periodically measures states of devices, for example humidity and illuminance of rooms, open/close state of doors, FAN speed, etc.
- Stores the measured data.
- Provides the measured data to BAS systems and operators.
- Generates alarms for abnormal state of devices.
- Controls devices (e.g. turn off room lights at 10:00 PM).

## 4.2. Building Automation Systems Today

### 4.2.1. BAS Architecture

A typical BAS architecture of today is shown in Figure 1.




BMS := Building Management Server
HMI := Human Machine Interface
LC := Local Controller

Figure 1: BAS architecture

There are typically two layers of network in a BAS. The upper one is called the Management Network and the lower one is called the Field Network. In management networks an IP-based communication protocol is used, while in field networks non-IP based communication protocols ("field protocols") are mainly used. Field networks have specific timing requirements, whereas management networks can be best-effort.

A Human Machine Interface (HMI) is typically a desktop PC used by operators to monitor and display device states, send device control commands to Local Controllers (LCs), and configure building schedules (for example "turn off all room lights in the building at 10:00 PM").

A Building Management Server (BMS) performs the following operations.

- Collect and store device states from LCs at regular intervals.
- Send control values to LCs according to a building schedule.
- Send an alarm signal to operators if it detects abnormal devices states.

The BMS and HMI communicate with LCs via IP-based "management protocols" (see standards [bacnetip], [knx]).

A LC is typically a Programmable Logic Controller (PLC) which is connected to several tens or hundreds of devices using "field protocols". An LC performs the following kinds of operations:

- Measure device states and provide the information to BMS or HMI.
- Send control values to devices, unilaterally or as part of a feedback control loop.

There are many field protocols used today; some are standards-based and others are proprietary (see standards [lontalk], [modbus], [profibus] and [flnet]). The result is that BASs have multiple MAC/PHY modules and interfaces. This makes BASs more expensive, slower to develop, and can result in "vendor lock-in" with multiple types of management applications.

### 4.2.2. BAS Deployment Model

An example BAS for medium or large buildings is shown in Figure 2. The physical layout spans multiple floors, and there is a monitoring room where the BAS management entities are located. Each floor will have one or more LCs depending upon the number of devices connected to the field network.

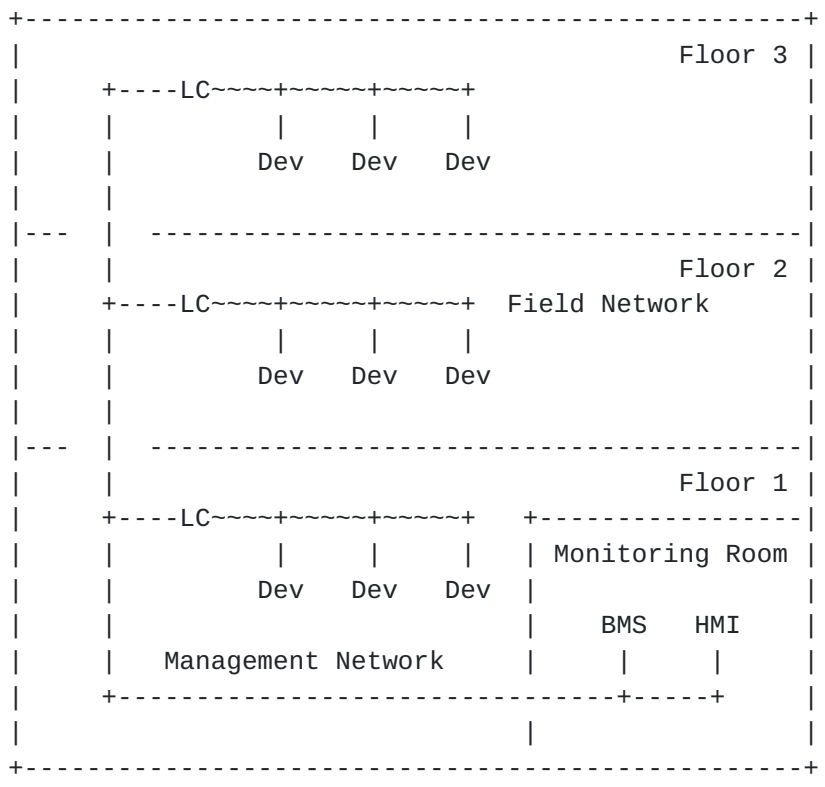



Figure 2: BAS Deployment model for Medium/Large Buildings

Each LC is connected to the monitoring room via the Management network, and the management functions are performed within the building. In most cases, fast Ethernet (e.g. 100BASE-T) is used for the management network. Since the management network is non-realtime, use of Ethernet without quality of service is sufficient for today's deployment.

In the field network a variety of physical interfaces such as RS232C and RS485 are used, which have specific timing requirements. Thus if a field network is to be replaced with an Ethernet or wireless network, such networks must support time-critical deterministic flows.

In Figure 3, another deployment model is presented in which the management system is hosted remotely. This is becoming popular for small office and residential buildings in which a standalone monitoring system is not cost-effective.

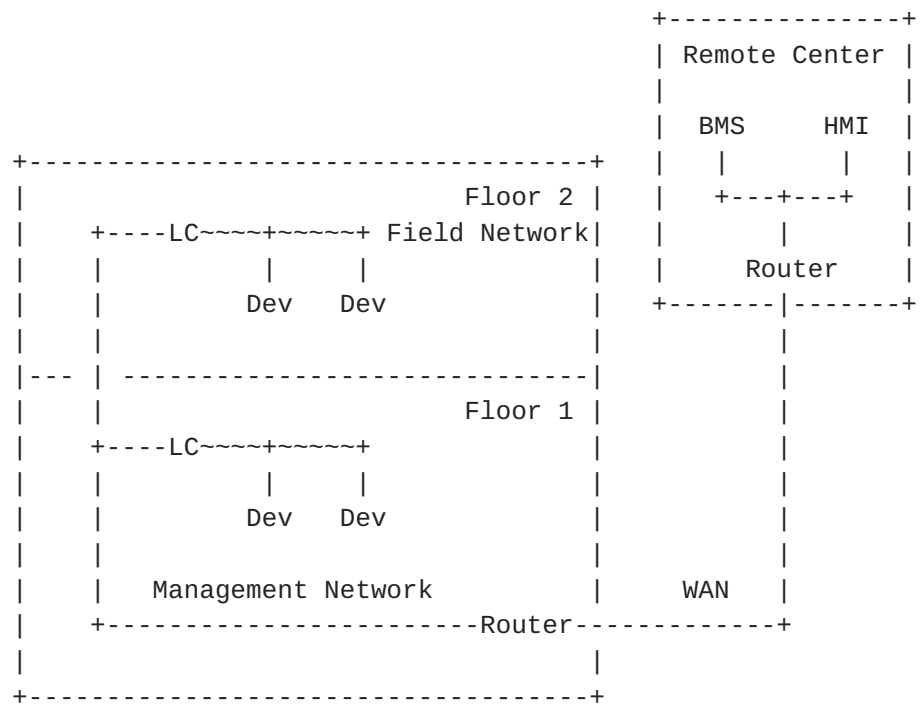



Figure 3: Deployment model for Small Buildings

Some interoperability is possible today in the Management Network, but not in today's field networks due to their non-IP-based design.

### 4.2.3. Use Cases for Field Networks

Below are use cases for Environmental Monitoring, Fire Detection, and Feedback Control, and their implications for field network performance.

#### 4.2.3.1. Environmental Monitoring

The BMS polls each LC at a maximum measurement interval of 100ms (for example to draw a historical chart of 1 second granularity with a 10x sampling interval) and then performs the operations as specified by the operator. Each LC needs to measure each of its several hundred sensors once per measurement interval. Latency is not critical in this scenario as long as all sensor values are completed in the measurement interval. Availability is expected to be 99.999 %.

#### 4.2.3.2. Fire Detection

On detection of a fire, the BMS must stop the HVAC, close the fire shutters, turn on the fire sprinklers, send an alarm, etc. There are typically ~10s of sensors per LC that BMS needs to manage. In this

scenario the measurement interval is 10-50ms, the communication delay is 10ms, and the availability must be 99.9999 %.

#### 4.2.3.3. Feedback Control

BAS systems utilize feedback control in various ways; the most time-critial is control of DC motors, which require a short feedback interval (1-5ms) with low communication delay (10ms) and jitter (1ms). The feedback interval depends on the characteristics of the device and a target quality of control value. There are typically ~10s of such devices per LC.

Communication delay is expected to be less than 10 ms, jitter less than 1 sec while the availability must be 99.9999% .

### 4.2.4. Security Considerations

When BAS field networks were developed it was assumed that the field networks would always be physically isolated from external networks and therefore security was not a concern. In today's world many BASs are managed remotely and are thus connected to shared IP networks and so security is definitely a concern, yet security features are not available in the majority of BAS field network deployments .

The management network, being an IP-based network, has the protocols available to enable network security, but in practice many BAS systems do not implement even the available security features such as device authentication or encryption for data in transit.

## 4.3. BAS Future

In the future we expect more fine-grained environmental monitoring and lower energy consumption, which will require more sensors and devices, thus requiring larger and more complex building networks.

We expect building networks to be connected to or converged with other networks (Enterprise network, Home network, and Internet).

Therefore better facilities for network management, control, reliability and security are critical in order to improve resident and operator convenience and comfort. For example the ability to monitor and control building devices via the internet would enable (for example) control of room lights or HVAC from a resident's desktop PC or phone application.

### 4.4. BAS Asks

The community would like to see an interoperable protocol specification that can satisfy the timing, security, availability and QoS constraints described above, such that the resulting converged network can replace the disparate field networks. Ideally this connectivity could extend to the open Internet.

This would imply an architecture that can guarantee

- Low communication delays (from <10ms to 100ms in a network of several hundred devices)
- Low jitter (< 1 ms)
- Tight feedback intervals (1ms - 10ms)
- High network availability (up to 99.9999% )
- Availability of network data in disaster scenario
- Authentication between management and field devices (both local and remote)
- Integrity and data origin authentication of communication data between field and management devices
- Confidentiality of data when communicated to a remote device

## 5. Wireless for Industrial Use Cases

(This section was derived from draft-thubert-6tisch-4detnet-01)

### 5.1. Introduction

The emergence of wireless technology has enabled a variety of new devices to get interconnected, at a very low marginal cost per device, at any distance ranging from Near Field to interplanetary, and in circumstances where wiring may not be practical, for instance on fast-moving or rotating devices.

At the same time, a new breed of Time Sensitive Networks is being developed to enable traffic that is highly sensitive to jitter, quite sensitive to latency, and with a high degree of operational criticality so that loss should be minimized at all times. Such traffic is not limited to professional Audio/ Video networks, but is also found in command and control operations such as industrial automation and vehicular sensors and actuators.

At IEEE802.1, the Audio/Video Task Group [IEEE802.1TSNTG] Time Sensitive Networking (TSN) to address Deterministic Ethernet. The Medium access Control (MAC) of IEEE802.15.4 [IEEE802154] has evolved with the new TimeSlotted Channel Hopping (TSCH) [RFC7554] mode for deterministic industrial-type applications. TSCH was introduced with the IEEE802.15.4e [IEEE802154e] amendment and will be wrapped up in the next revision of the IEEE802.15.4 standard. For all practical purpose, this document is expected to be insensitive to the future versions of the IEEE802.15.4 standard, which is thus referenced undated.

Though at a different time scale, both TSN and TSCH standards provide Deterministic capabilities to the point that a packet that pertains to a certain flow crosses the network from node to node following a very precise schedule, as a train that leaves intermediate stations at precise times along its path. With TSCH, time is formatted into timeSlots, and an individual cell is allocated to unicast or broadcast communication at the MAC level. The time-slotted operation reduces collisions, saves energy, and enables to more closely engineer the network for deterministic properties. The channel hopping aspect is a simple and efficient technique to combat multi-path fading and co-channel interferences (for example by Wi-Fi emitters).

The 6TiSCH Architecture [I-D.ietf-6tisch-architecture] defines a remote monitoring and scheduling management of a TSCH network by a Path Computation Element (PCE), which cooperates with an abstract Network Management Entity (NME) to manage timeSlots and device resources in a manner that minimizes the interaction with and the load placed on the constrained devices.

This Architecture applies the concepts of Deterministic Networking on a TSCH network to enable the switching of timeSlots in a G-MPLS manner. This document details the dependencies that 6TiSCH has on PCE [PCE] and DetNet [I-D.finn-detnet-architecture] to provide the necessary capabilities that may be specific to such networks. In turn, DetNet is expected to integrate and maintain consistency with the work that has taken place and is continuing at IEEE802.1TSN and AVnu.

## 5.2. Terminology

Readers are expected to be familiar with all the terms and concepts that are discussed in "Multi-link Subnet Support in IPv6" [I-D.ietf-ipv6-multilink-subnets].

The draft uses terminology defined or referenced in [I-D.ietf-6tisch-terminology] and [I-D.ietf-roll-rpl-industrial-applicability].

The draft also conforms to the terms and models described in [RFC3444] and uses the vocabulary and the concepts defined in [RFC4291] for the IPv6 Architecture.

### 5.3. 6TiSCH Overview

The scope of the present work is a subnet that, in its basic configuration, is made of a TSCH [RFC7554] MAC Low Power Lossy Network (LLN).

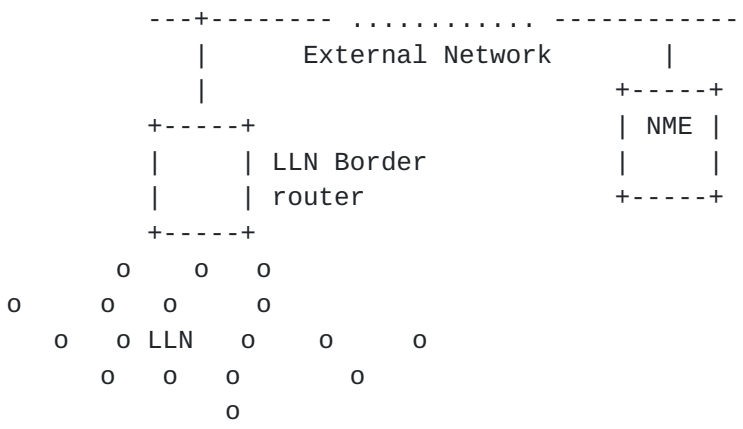



Figure 4: Basic Configuration of a 6TiSCH Network

In the extended configuration, a Backbone Router (6BBR) federates multiple 6TiSCH in a single subnet over a backbone. 6TiSCH 6BBRs synchronize with one another over the backbone, so as to ensure that the multiple LLNs that form the IPv6 subnet stay tightly synchronized.

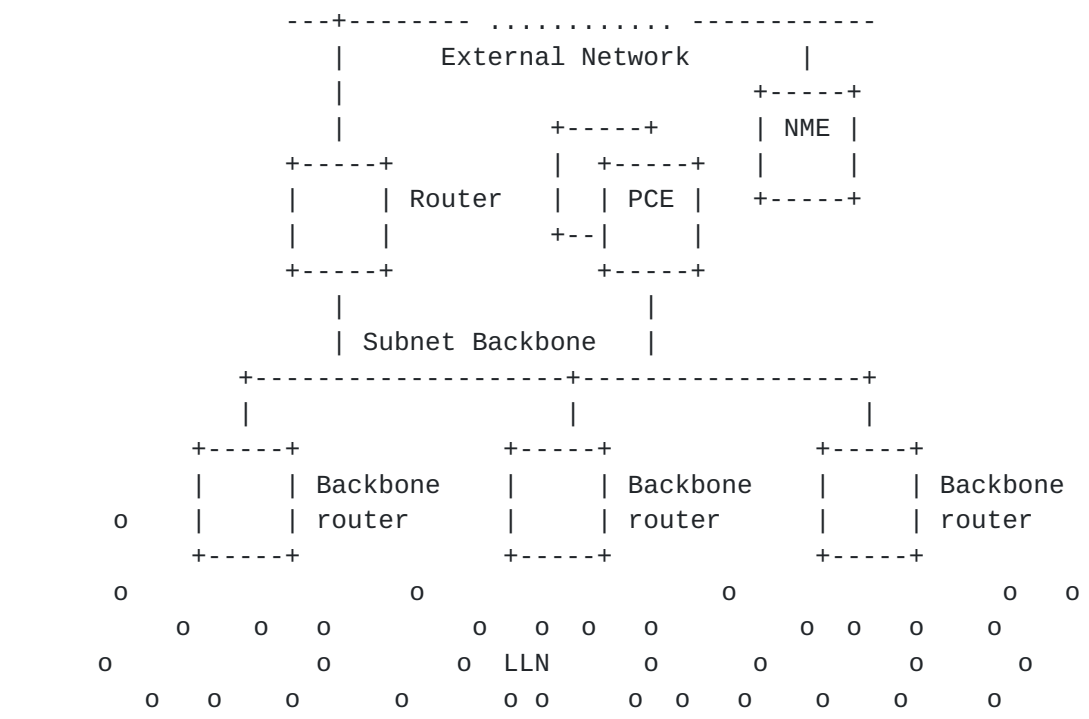



Figure 5: Extended Configuration of a 6TiSCH Network

If the Backbone is Deterministic, then the Backbone Router ensures that the end-to-end deterministic behavior is maintained between the LLN and the backbone. This SHOULD be done in conformance to the DetNet Architecture [I-D.finn-detnet-architecture] which studies Layer-3 aspects of Deterministic Networks, and covers networks that span multiple Layer-2 domains. One particular requirement is that the PCE MUST be able to compute a deterministic path and to end across the TSCH network and an IEEE802.1 TSN Ethernet backbone, and DetNet MUST enable end-to-end deterministic forwarding.

6TiSCH defines the concept of a Track, which is a complex form of a uni-directional Circuit ([I-D.ietf-6tisch-terminology]). As opposed to a simple circuit that is a sequence of nodes and links, a Track is shaped as a directed acyclic graph towards a destination to support multi-path forwarding and route around failures. A Track may also branch off and rejoin, for the purpose of the so-called Packet Replication and Elimination (PRE), over non congruent branches. PRE may be used to complement layer-2 Automatic Repeat reQuest (ARQ) to meet industrial expectations in Packet Delivery Ratio (PDR), in particular when the Track extends beyond the 6TiSCH network.

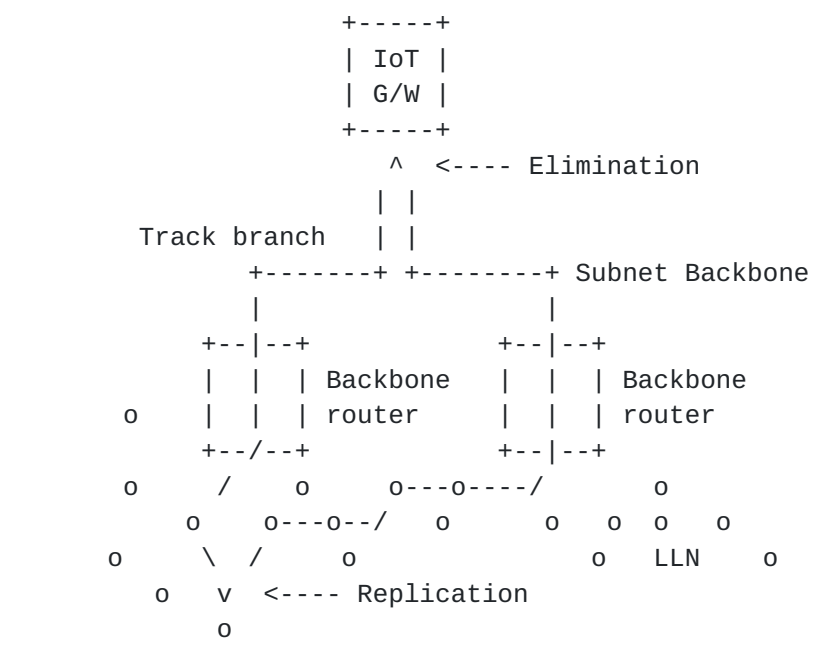



Figure 6: End-to-End deterministic Track

In the example above, a Track is laid out from a field device in a 6TiSCH network to an IoT gateway that is located on a IEEE802.1 TSN backbone.

The Replication function in the field device sends a copy of each packet over two different branches, and the PCE schedules each hop of both branches so that the two copies arrive in due time at the gateway. In case of a loss on one branch, hopefully the other copy of the packet still makes it in due time. If two copies make it to the IoT gateway, the Elimination function in the gateway ignores the extra packet and presents only one copy to upper layers.

At each 6TiSCH hop along the Track, the PCE may schedule more than one timeSlot for a packet, so as to support Layer-2 retries (ARQ). It is also possible that the field device only uses the second branch if sending over the first branch fails.

In current deployments, a TSCH Track does not necessarily support PRE but is systematically multi-path. This means that a Track is scheduled so as to ensure that each hop has at least two forwarding solutions, and the forwarding decision is to try the preferred one and use the other in case of Layer-2 transmission failure as detected by ARQ.

### 5.3.1. TSCH and 6top

6top is a logical link control sitting between the IP layer and the TSCH MAC layer, which provides the link abstraction that is required for IP operations. The 6top operations are specified in [I-D.wang-6tisch-6top-sublayer].

The 6top data model and management interfaces are further discussed in [I-D.ietf-6tisch-6top-interface] and [I-D.ietf-6tisch-coap].

The architecture defines "soft" cells and "hard" cells. "Hard" cells are owned and managed by an separate scheduling entity (e.g. a PCE) that specifies the slotOffset/channelOffset of the cells to be added/moved/deleted, in which case 6top can only act as instructed, and may not move hard cells in the TSCH schedule on its own.

### 5.3.2. SlotFrames and Priorities

A slotFrame is the base object that the PCE needs to manipulate to program a schedule into an LLN node. Elaboration on that concept can be found in section "SlotFrames and Priorities" of the 6TiSCH architecture [I-D.ietf-6tisch-architecture]. The architecture also details how the schedule is constructed and how transmission resources called cells can be allocated to particular transmissions so as to avoid collisions.

### 5.3.3. Schedule Management by a PCE

6TiSCH supports a mixed model of centralized routes and distributed routes. Centralized routes can for example be computed by a entity such as a PCE. Distributed routes are computed by RPL.

Both methods may inject routes in the Routing Tables of the 6TiSCH routers. In either case, each route is associated with a 6TiSCH topology that can be a RPL Instance topology or a track. The 6TiSCH topology is indexed by a Instance ID, in a format that reuses the RPLInstanceID as defined in RPL [RFC6550].

Both RPL and PCE rely on shared sources such as policies to define Global and Local RPLInstanceIDs that can be used by either method. It is possible for centralized and distributed routing to share a same topology. Generally they will operate in different slotFrames, and centralized routes will be used for scheduled traffic and will have precedence over distributed routes in case of conflict between the slotFrames.

Section "Schedule Management Mechanisms" of the 6TiSCH architecture describes 4 paradigms to manage the TSCH schedule of the LLN nodes:

Static Scheduling, neighbor-to-neighbor Scheduling, remote monitoring and scheduling management, and Hop-by-hop scheduling. The Track operation for DetNet corresponds to a remote monitoring and scheduling management by a PCE.

The 6top interface document [I-D.ietf-6tisch-6top-interface] specifies the generic data model that can be used to monitor and manage resources of the 6top sublayer. Abstract methods are suggested for use by a management entity in the device. The data model also enables remote control operations on the 6top sublayer.

[I-D.ietf-6tisch-coap] defines an mapping of the 6top set of commands, which is described in [I-D.ietf-6tisch-6top-interface], to CoAP resources. This allows an entity to interact with the 6top layer of a node that is multiple hops away in a RESTful fashion.

[I-D.ietf-6tisch-coap] also defines a basic set CoAP resources and associated RESTful access methods (GET/PUT/POST/DELETE). The payload (body) of the CoAP messages is encoded using the CBOR format. The PCE commands are expected to be issued directly as CoAP requests or to be mapped back and forth into CoAP by a gateway function at the edge of the 6TiSCH network. For instance, it is possible that a mapping entity on the backbone transforms a non-CoAP protocol such as PCEP into the RESTful interfaces that the 6TiSCH devices support. This architecture will be refined to comply with DetNet [I-D.finn-detnet-architecture] when the work is formalized.

### 5.3.4. Track Forwarding

By forwarding, this specification means the per-packet operation that allows to deliver a packet to a next hop or an upper layer in this node. Forwarding is based on pre-existing state that was installed as a result of the routing computation of a Track by a PCE. The 6TiSCH architecture supports three different forwarding model, G-MPLS Track Forwarding (TF), 6LoWPAN Fragment Forwarding (FF) and IPv6 Forwarding (6F) which is the classical IP operation. The DetNet case relates to the Track Forwarding operation under the control of a PCE.

A Track is a unidirectional path between a source and a destination. In a Track cell, the normal operation of IEEE802.15.4 Automatic Repeat-reQuest (ARQ) usually happens, though the acknowledgment may be omitted in some cases, for instance if there is no scheduled cell for a retry.

Track Forwarding is the simplest and fastest. A bundle of cells set to receive (RX-cells) is uniquely paired to a bundle of cells that are set to transmit (TX-cells), representing a layer-2 forwarding state that can be used regardless of the network layer protocol.

This model can effectively be seen as a Generalized Multi-protocol Label Switching (G-MPLS) operation in that the information used to switch a frame is not an explicit label, but rather related to other properties of the way the packet was received, a particular cell in the case of 6TiSCH. As a result, as long as the TSCH MAC (and Layer-2 security) accepts a frame, that frame can be switched regardless of the protocol, whether this is an IPv6 packet, a 6LoWPAN fragment, or a frame from an alternate protocol such as WirelessHART or ISA100.11a.

A data frame that is forwarded along a Track normally has a destination MAC address that is set to broadcast - or a multicast address depending on MAC support. This way, the MAC layer in the intermediate nodes accepts the incoming frame and 6top switches it without incurring a change in the MAC header. In the case of IEEE802.15.4, this means effectively broadcast, so that along the Track the short address for the destination of the frame is set to 0xFFFF.

A Track is thus formed end-to-end as a succession of paired bundles, a receive bundle from the previous hop and a transmit bundle to the next hop along the Track, and a cell in such a bundle belongs to at most one Track. For a given iteration of the device schedule, the effective channel of the cell is obtained by adding a pseudo-random number to the channelOffset of the cell, which results in a rotation of the frequency that used for transmission. The bundles may be computed so as to accommodate both variable rates and retransmissions, so they might not be fully used at a given iteration of the schedule. The 6TiSCH architecture provides additional means to avoid waste of cells as well as overflows in the transmit bundle, as follows:

In one hand, a TX-cell that is not needed for the current iteration may be reused opportunistically on a per-hop basis for routed packets. When all of the frame that were received for a given Track are effectively transmitted, any available TX-cell for that Track can be reused for upper layer traffic for which the next-hop router matches the next hop along the Track. In that case, the cell that is being used is effectively a TX-cell from the Track, but the short address for the destination is that of the next-hop router. It results that a frame that is received in a RX-cell of a Track with a destination MAC address set to this node as opposed to broadcast must be extracted from the Track and delivered to the upper layer (a frame with an unrecognized MAC address is dropped at the lower MAC layer and thus is not received at the 6top sublayer).

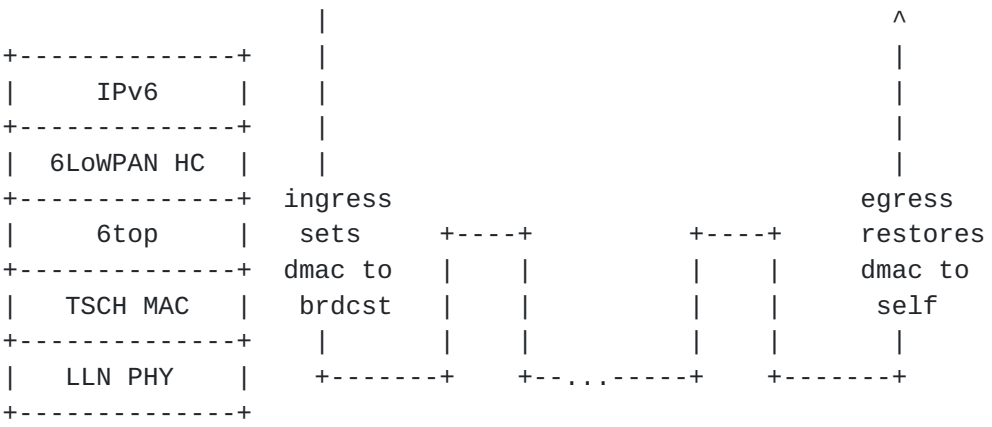
On the other hand, it might happen that there are not enough TX-cells in the transmit bundle to accommodate the Track traffic, for instance

if more retransmissions are needed than provisioned. In that case, the frame can be placed for transmission in the bundle that is used for layer-3 traffic towards the next hop along the track as long as it can be routed by the upper layer, that is, typically, if the frame transports an IPv6 packet. The MAC address should be set to the next-hop MAC address to avoid confusion. It results that a frame that is received over a layer-3 bundle may be in fact associated to a Track. In a classical IP link such as an Ethernet, off-track traffic is typically in excess over reservation to be routed along the non-reserved path based on its QoS setting. But with 6TiSCH, since the use of the layer-3 bundle may be due to transmission failures, it makes sense for the receiver to recognize a frame that should be re-tracked, and to place it back on the appropriate bundle if possible. A frame should be re-tracked if the Per-Hop-Behavior group indicated in the Differentiated Services Field in the IPv6 header is set to Deterministic Forwarding, as discussed in Section 5.4.1. A frame is re-tracked by scheduling it for transmission over the transmit bundle associated to the Track, with the destination MAC address set to broadcast.

There are 2 modes for a Track, transport mode and tunnel mode.

#### 5.3.4.1. Transport Mode

In transport mode, the Protocol Data Unit (PDU) is associated with flow-dependant meta-data that refers uniquely to the Track, so the 6top sublayer can place the frame in the appropriate cell without ambiguity. In the case of IPv6 traffic, this flow identification is transported in the Flow Label of the IPv6 header. Associated with the source IPv6 address, the Flow Label forms a globally unique identifier for that particular Track that is validated at egress before restoring the destination MAC address (DMAC) and punting to the upper layer.




Track Forwarding, Transport Mode

#### 5.3.4.2. Tunnel Mode

In tunnel mode, the frames originate from an arbitrary protocol over a compatible MAC that may or may not be synchronized with the 6TiSCH network. An example of this would be a router with a dual radio that is capable of receiving and sending WirelessHART or ISA100.11a frames with the second radio, by presenting itself as an access Point or a Backbone Router, respectively.

In that mode, some entity (e.g. PCE) can coordinate with a WirelessHART Network Manager or an ISA100.11a System Manager to specify the flows that are to be transported transparently over the Track.

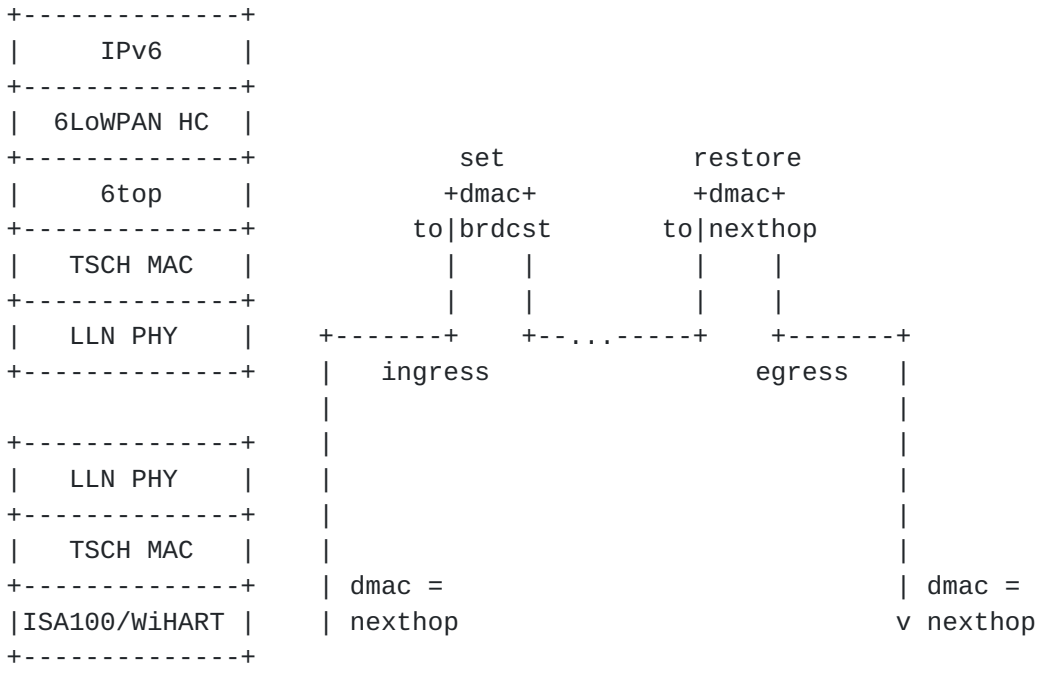



Figure 7: Track Forwarding, Tunnel Mode

In that case, the flow information that identifies the Track at the ingress 6TiSCH router is derived from the RX-cell. The dmac is set to this node but the flow information indicates that the frame must be tunneled over a particular Track so the frame is not passed to the upper layer. Instead, the dmac is forced to broadcast and the frame is passed to the 6top sublayer for switching.

At the egress 6TiSCH router, the reverse operation occurs. Based on metadata associated to the Track, the frame is passed to the appropriate link layer with the destination MAC restored.

#### 5.3.4.3. Tunnel Metadata

Metadata coming with the Track configuration is expected to provide the destination MAC address of the egress endpoint as well as the tunnel mode and specific data depending on the mode, for instance a service access point for frame delivery at egress. If the tunnel egress point does not have a MAC address that matches the configuration, the Track installation fails.

In transport mode, if the final layer-3 destination is the tunnel termination, then it is possible that the IPv6 address of the destination is compressed at the 6LoWPAN sublayer based on the MAC address. It is thus mandatory at the ingress point to validate that the MAC address that was used at the 6LoWPAN sublayer for compression matches that of the tunnel egress point. For that reason, the node that injects a packet on a Track checks that the destination is effectively that of the tunnel egress point before it overwrites it to broadcast. The 6top sublayer at the tunnel egress point reverts that operation to the MAC address obtained from the tunnel metadata.

### 5.4. Operations of Interest for DetNet and PCE

In a classical system, the 6TiSCH device does not place the request for bandwidth between self and another device in the network. Rather, an Operation Control System invoked through an Human/Machine Interface (HMI) indicates the Traffic Specification, in particular in terms of latency and reliability, and the end nodes. With this, the PCE must compute a Track between the end nodes and provision the network with per-flow state that describes the per-hop operation for a given packet, the corresponding timeSlots, and the flow identification that enables to recognize when a certain packet belongs to a certain Track, sort out duplicates, etc...

For a static configuration that serves a certain purpose for a long period of time, it is expected that a node will be provisioned in one shot with a full schedule, which incorporates the aggregation of its behavior for multiple Tracks. 6TiSCH expects that the programing of the schedule will be done over COAP as discussed in 6TiSCH Resource Management and Interaction using CoAP [I-D.ietf-6tisch-coap].

But an Hybrid mode may be required as well whereby a single Track is added, modified, or removed, for instance if it appears that a Track does not perform as expected for, say, PDR. For that case, the expectation is that a protocol that flows along a Track (to be), in a fashion similar to classical Traffic Engineering (TE) [CCAMP], may be used to update the state in the devices. 6TiSCH provides means for a device to negotiate a timeSlot with a neighbor, but in general that flow was not designed and no protocol was selected and it is expected

that DetNet will determine the appropriate end-to-end protocols to be used in that case.

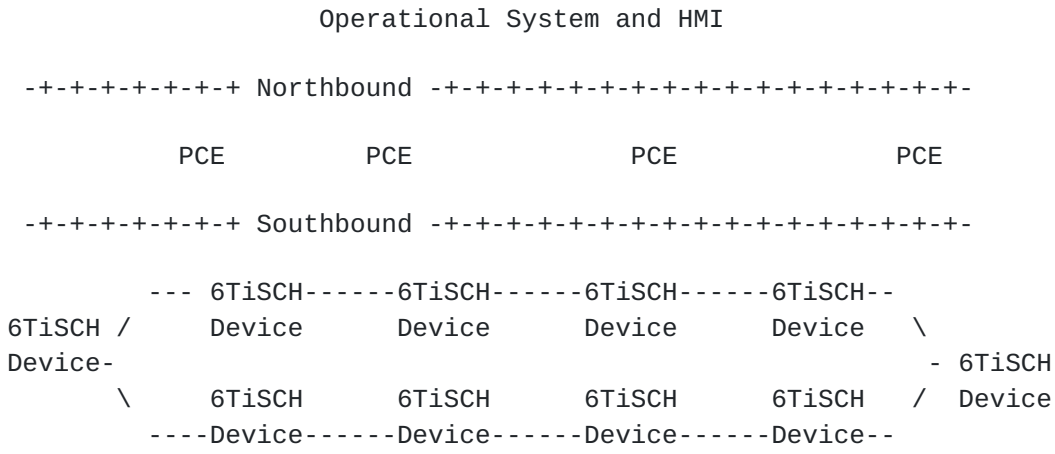



Figure 8: Stream Management Entity

### 5.4.1. Packet Marking and Handling

Section "Packet Marking and Handling" of [I-D.ietf-6tisch-architecture] describes the packet tagging and marking that is expected in 6TiSCH networks.

#### 5.4.1.1. Tagging Packets for Flow Identification

For packets that are routed by a PCE along a Track, the tuple formed by the IPv6 source address and a local RPLInstanceID is tagged in the packets to identify uniquely the Track and associated transmit bundle of timeSlots.

It results that the tagging that is used for a DetNet flow outside the 6TiSCH LLN MUST be swapped into 6TiSCH formats and back as the packet enters and then leaves the 6TiSCH network.

Note: The method and format used for encoding the RPLInstanceID at 6lo is generalized to all 6TiSCH topological Instances, which includes Tracks.

#### 5.4.1.2. Replication, Retries and Elimination

6TiSCH expects elimination and replication of packets along a complex Track, but has no position about how the sequence numbers would be tagged in the packet.

As it goes, 6TiSCH expects that timeSlots corresponding to copies of a same packet along a Track are correlated by configuration, and does not need to process the sequence numbers.

The semantics of the configuration MUST enable correlated timeSlots to be grouped for transmit (and respectively receive) with a 'OR' relations, and then a 'AND' relation MUST be configurable between groups. The semantics is that if the transmit (and respectively receive) operation succeeded in one timeSlot in a 'OR' group, then all the other timeSLots in the group are ignored. Now, if there are at least two groups, the 'AND' relation between the groups indicates that one operation must succeed in each of the groups.

On the transmit side, timeSlots provisioned for retries along a same branch of a Track are placed a same 'OR' group. The 'OR' relation indicates that if a transmission is acknowledged, then further transmissions SHOULD NOT be attempted for timeSlots in that group. There are as many 'OR' groups as there are branches of the Track departing from this node. Different 'OR' groups are programmed for the purpose of replication, each group corresponding to one branch of the Track. The 'AND' relation between the groups indicates that transmission over any of branches MUST be attempted regardless of whether a transmission succeeded in another branch. It is also possible to place cells to different next-hop routers in a same 'OR' group. This allows to route along multi-path tracks, trying one next-hop and then another only if sending to the first fails.

On the receive side, all timeSlots are programmed in a same 'OR' group. Retries of a same copy as well as converging branches for elimination are converged, meaning that the first successful reception is enough and that all the other timeSlots can be ignored.

#### 5.4.1.3. Differentiated Services Per-Hop-Behavior

Additionally, an IP packet that is sent along a Track uses the Differentiated Services Per-Hop-Behavior Group called Deterministic Forwarding, as described in [I-D.svshah-tsvwg-deterministic-forwarding].

### 5.4.2. Topology and capabilities

6TiSCH nodes are usually IoT devices, characterized by very limited amount of memory, just enough buffers to store one or a few IPv6 packets, and limited bandwidth between peers. It results that a node will maintain only a small number of peering information, and will not be able to store many packets waiting to be forwarded. Peers can be identified through MAC or IPv6 addresses, but a Cryptographically Generated Address [RFC3972] (CGA) may also be used.

Neighbors can be discovered over the radio using mechanism such as beacons, but, though the neighbor information is available in the 6TiSCH interface data model, 6TiSCH does not describe a protocol to pro-actively push the neighborhood information to a PCE. This protocol should be described and should operate over CoAP. The protocol should be able to carry multiple metrics, in particular the same metrics as used for RPL operations [RFC6551]

The energy that the device consumes in sleep, transmit and receive modes can be evaluated and reported. So can the amount of energy that is stored in the device and the power that it can be scavenged from the environment. The PCE SHOULD be able to compute Tracks that will implement policies on how the energy is consumed, for instance balance between nodes, ensure that the spent energy does not exceeded the scavenged energy over a period of time, etc...

### 5.5. Security Considerations

On top of the classical protection of control signaling that can be expected to support DetNet, it must be noted that 6TiSCH networks operate on limited resources that can be depleted rapidly if an attacker manages to operate a DoS attack on the system, for instance by placing a rogue device in the network, or by obtaining management control and to setup extra paths.

## 6. Cellular Radio Use Cases

### 6.1. Use Case Description

This use case describes the application of deterministic networking in the context of cellular telecom transport networks. Important elements include time synchronization, clock distribution, and ways of establishing time-sensitive streams for both Layer-2 and Layer-3 user plane traffic.

#### 6.1.1. Network Architecture

Figure 9 illustrates a typical 3GPP-defined cellular network architecture, which includes "Fronthaul" and "Midhaul" network segments. The "Fronthaul" is the network connecting base stations (baseband processing units) to the remote radio heads (antennas). The "Midhaul" is the network inter-connecting base stations (or small cell sites).

In Figure 9 "eNB" ("E-UTRAN Node B") is the hardware that is connected to the mobile phone network which communicates directly with mobile handsets ([TS36300]).

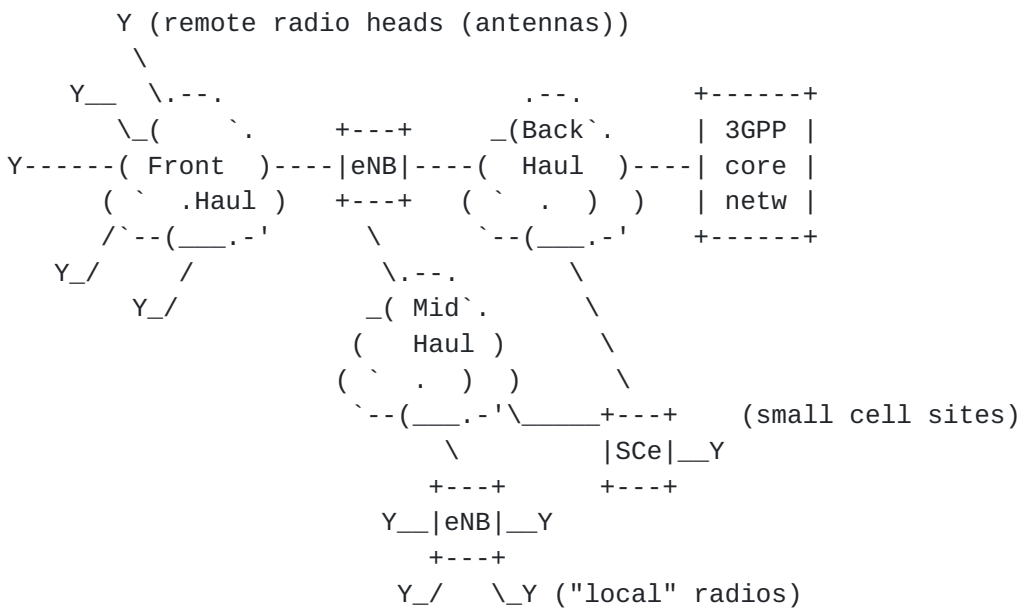



Figure 9: Generic 3GPP-based Cellular Network Architecture

The available processing time for Fronthaul networking overhead is limited to the available time after the baseband processing of the radio frame has completed. For example in Long Term Evolution (LTE) radio, processing of a radio frame is allocated 3ms, but typically the processing completes much earlier (<400us) allowing the remaining time to be used by the Fronthaul network. This ultimately determines the distance the remote radio heads can be located from the base stations (200us equals roughly 40 km of optical fiber-based transport, thus round trip time is 2*200us = 400us).

The remainder of the "maximum delay budget" is consumed by all nodes and buffering between the remote radio head and the baseband processing, plus the distance-incurred delay.

The baseband processing time and the available "delay budget" for the fronthaul is likely to change in the forthcoming "5G" due to reduced radio round trip times and other architectural and service requirements [NGMN].

### 6.1.2. Time Synchronization Requirements

Fronthaul time synchronization requirements are given by [TS25104], [TS36104], [TS36211], and [TS36133]. These can be summarized for the current 3GPP LTE-based networks as:

Delay Accuracy:
+-8ns (i.e. +-1/32 Tc, where Tc is the UMTS Chip time of 1/3.84 MHz) resulting in a round trip accuracy of +-16ns. The value is

this low to meet the 3GPP Timing Alignment Error (TAE) measurement requirements.

Packet Delay Variation:
Packet Delay Variation (PDV aka Jitter aka Timing Alignment Error) is problematic to Fronthaul networks and must be minimized. If the transport network cannot guarantee low enough PDV then additional buffering has to be introduced at the edges of the network to buffer out the jitter. Buffering is not desirable as it reduces the total available delay budget.

* For multiple input multiple output (MIMO) or TX diversity transmissions, at each carrier frequency, TAE shall not exceed 65 ns (i.e. 1/4 Tc).

* For intra-band contiguous carrier aggregation, with or without MIMO or TX diversity, TAE shall not exceed 130 ns (i.e. 1/2 Tc).

* For intra-band non-contiguous carrier aggregation, with or without MIMO or TX diversity, TAE shall not exceed 260 ns (i.e. one Tc).

* For inter-band carrier aggregation, with or without MIMO or TX diversity, TAE shall not exceed 260 ns.

Transport link contribution to radio frequency error:
+-2 PPB. This value is considered to be "available" for the Fronthaul link out of the total 50 PPB budget reserved for the radio interface. Note: the reason that the transport link contributes to radio frequency error is as follows. The current way of doing Fronthaul is from the radio unit to remote radio head directly. The remote radio head is essentially a passive device (without buffering etc.) The transport drives the antenna directly by feeding it with samples and everything the transport adds will be introduced to radio as-is. So if the transport causes additional frequence error that shows immediately on the radio as well.

The above listed time synchronization requirements are difficult to meet with point-to-point connected networks, and more difficult when the network includes multiple hops. It is expected that networks must include buffering at the ends of the connections as imposed by the jitter requirements, since trying to meet the jitter requirements in every intermediate node is likely to be too costly. However,

every measure to reduce jitter and delay on the path makes it easier to meet the end-to-end requirements.

In order to meet the timing requirements both senders and receivers must remain time synchronized, demanding very accurate clock distribution, for example support for IEEE 1588 transparent clocks in every intermediate node.

In cellular networks from the LTE radio era onward, phase synchronization is needed in addition to frequency synchronization ([TS36300], [TS23401]).

### 6.1.3. Time-Sensitive Stream Requirements

In addition to the time synchronization requirements listed in Section Section 6.1.2 the Fronthaul networks assume practically error-free transport. The maximum bit error rate (BER) has been defined to be 10^-12. When packetized that would imply a packet error rate (PER) of 2.4*10^-9 (assuming ~300 bytes packets). Retransmitting lost packets and/or using forward error correction (FEC) to circumvent bit errors is practically impossible due to the additional delay incurred. Using redundant streams for better guarantees for delivery is also practically impossible in many cases due to high bandwidth requirements of Fronthaul networks. For instance, current uncompressed CPRI bandwidth expansion ratio is roughly 20:1 compared to the IP layer user payload it carries. Protection switching is also a candidate but current technologies for the path switch are too slow. We do not currently know of a better solution for this issue.

Fronthaul links are assumed to be symmetric, and all Fronthaul streams (i.e. those carrying radio data) have equal priority and cannot delay or pre-empt each other. This implies that the network must guarantee that each time-sensitive flow meets their schedule.

### 6.1.4. Security Considerations

Establishing time-sensitive streams in the network entails reserving networking resources for long periods of time. It is important that these reservation requests be authenticated to prevent malicious reservation attempts from hostile nodes (or accidental misconfiguration). This is particularly important in the case where the reservation requests span administrative domains. Furthermore, the reservation information itself should be digitally signed to reduce the risk of a legitimate node pushing a stale or hostile configuration into another networking node.

### 6.2. Cellular Radio Networks Today

Today's Fronthaul networks typically consist of:

- Dedicated point-to-point fiber connection is common
- Proprietary protocols and framings
- Custom equipment and no real networking

Today's Midhaul and Backhaul networks typically consist of:

- Mostly normal IP networks, MPLS-TP, etc.
- Clock distribution and sync using 1588 and SyncE

Telecommunication networks in the cellular domain are already heading towards transport networks where precise time synchronization support is one of the basic building blocks. While the transport networks themselves have practically transitioned to all-IP packet based networks to meet the bandwidth and cost requirements, highly accurate clock distribution has become a challenge.

Transport networks in the cellular domain are typically based on Time Division Multiplexing (TDM-based) and provide frequency synchronization capabilities as a part of the transport media. Alternatively other technologies such as Global Positioning System (GPS) or Synchronous Ethernet (SyncE) are used [SyncE].

Both Ethernet and IP/MPLS [RFC3031] (and PseudoWires (PWE) [RFC3985] for legacy transport support) have become popular tools to build and manage new all-IP Radio Access Networks (RAN) [I-D.kh-spring-ip-ran-use-case]. Although various timing and synchronization optimizations have already been proposed and implemented including 1588 PTP enhancements [I-D.ietf-tictoc-1588overmpls][I-D.mirsky-mpls-residence-time], these solution are not necessarily sufficient for the forthcoming RAN architectures or guarantee the higher time-synchronization requirements [CPRI]. There are also existing solutions for the TDM over IP [RFC5087] [RFC4553] or Ethernet transports [RFC5086].

### 6.3. Cellular Radio Networks Future

We would like to see the following in future Cellular Radio networks:

- Unified standards-based transport protocols and standard networking equipment that can make use of underlying deterministic link-layer services

- Unified and standards-based network management systems and protocols in all parts of the network (including Fronthaul)

New radio access network deployment models and architectures may require time sensitive networking services with strict requirements on other parts of the network that previously were not considered to be packetized at all. The time and synchronization support are already topical for Backhaul and Midhaul packet networks [MEF], and becoming a real issue for Fronthaul networks. Specifically in the Fronthaul networks the timing and synchronization requirements can be extreme for packet based technologies, for example, on the order of sub +-20 ns packet delay variation (PDV) and frequency accuracy of +0.002 PPM [Fronthaul].

The actual transport protocols and/or solutions to establish required transport "circuits" (pinned-down paths) for Fronthaul traffic are still undefined. Those are likely to include (but are not limited to) solutions directly over Ethernet, over IP, and MPLS/PseudoWire transport.

Even the current time-sensitive networking features may not be sufficient for Fronthaul traffic. Therefore, having specific profiles that take the requirements of Fronthaul into account is desirable [IEEE8021CM].

The really interesting and important existing work for time sensitive networking has been done for Ethernet [TSNTG], which specifies the use of IEEE 1588 time precision protocol (PTP) [IEEE1588] in the context of IEEE 802.1D and IEEE 802.1Q. While IEEE 802.1AS [IEEE8021AS] specifies a Layer-2 time synchronizing service other specification, such as IEEE 1722 [IEEE1722] specify Ethernet-based Layer-2 transport for time-sensitive streams. New promising work seeks to enable the transport of time-sensitive fronthaul streams in Ethernet bridged networks [IEEE8021CM]. Similarly to IEEE 1722 there is an ongoing standardization effort to define Layer-2 transport encapsulation format for transporting radio over Ethernet (RoE) in IEEE 1904.3 Task Force [IEEE19043].

All-IP RANs and various "haul" networks would benefit from time synchronization and time-sensitive transport services. Although Ethernet appears to be the unifying technology for the transport there is still a disconnect providing Layer-3 services. The protocol stack typically has a number of layers below the Ethernet Layer-2 that shows up to the Layer-3 IP transport. It is not uncommon that on top of the lowest layer (optical) transport there is the first layer of Ethernet followed one or more layers of MPLS, PseudoWires and/or other tunneling protocols finally carrying the Ethernet layer visible to the user plane IP traffic. While there are existing

technologies, especially in MPLS/PWE space, to establish circuits through the routed and switched networks, there is a lack of signaling the time synchronization and time-sensitive stream requirements/reservations for Layer-3 flows in a way that the entire transport stack is addressed and the Ethernet layers that needs to be configured are addressed.

Furthermore, not all "user plane" traffic will be IP. Therefore, the same solution also must address the use cases where the user plane traffic is again another layer or Ethernet frames. There is existing work describing the problem statement [I-D.finn-detnet-problem-statement] and the architecture [I-D.finn-detnet-architecture] for deterministic networking (DetNet) that targets solutions for time-sensitive (IP/transport) streams with deterministic properties over Ethernet-based switched networks.

### 6.4. Cellular Radio Networks Asks

A standard for data plane transport specification which is:

- Unified among all *hauls
- Deployed in a highly deterministic network environment

A standard for data flow information models that are:

- Aware of the time sensitivity and constraints of the target networking environment
- Aware of underlying deterministic networking services (e.g. on the Ethernet layer)

Mapping the Fronthaul requirements to IETF DetNet [I-D.finn-detnet-architecture] Section 3 "Providing the DetNet Quality of Service", the relevant features are:

- Zero congestion loss.
- Pinned-down paths.

## 7. Cellular Coordinated Multipoint Processing (CoMP)

### 7.1. Use Case Description

In cellular wireless communication systems, Inter-Site Coordinated Multipoint Processing (CoMP, see [CoMP]) is a technique implemented within a cell site which improves system efficiency and user quality experience by significantly improving throughput in the cell-edge

region (i.e. at the edges of that cell site's radio coverage area). CoMP techniques depend on deterministic high-reliability communication between cell sites, however such connections today are IP-based which in current mobile networks can not meet the QoS requirements, so CoMP is an emerging technology which can benefit from DetNet.

Here we consider the JT (Joint Transmit) application for CoMP, which provides the highest performance gain (compared to other applications).

### 7.1.1. CoMP Architecture

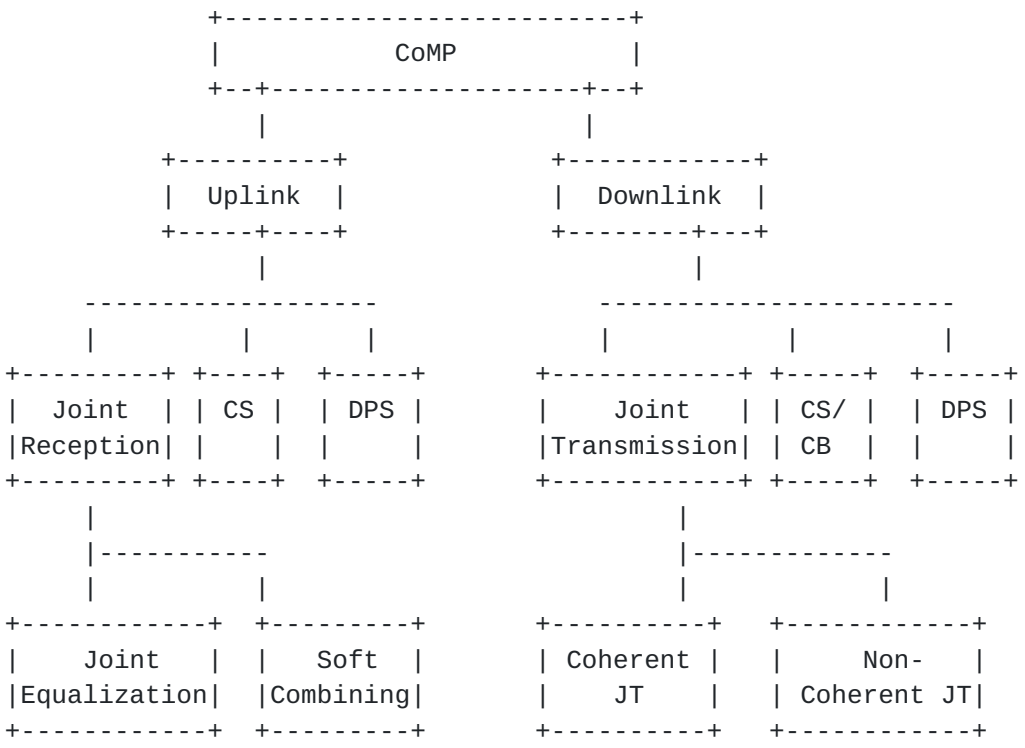



Figure 10: Framework of CoMP Technology

As shown in Figure 10, CoMP reception and transmission is a framework in which multiple geographically distributed antenna nodes cooperate to improve the performance of the users served in the common cooperation area. The design principal of CoMP is to extend the current single-cell to multi-UE (User Equipment) transmission to a multi-cell- to-multi-UEs transmission by base station cooperation.

### 7.1.2. Delay Sensitivity in CoMP

In contrast to the single-cell scenario, CoMP has delay-sensitive performance parameters, which are "backhaul latency" and "CSI (Channel State Information) reporting and accuracy". The essential feature of CoMP is signaling between eNBs, so the backhaul latency is the dominating limitation of the CoMP performance. Generally, JT can benefit from coordinated scheduling (either distributed or centralized) of different cells if the signaling delay between eNBs is within 4-10ms. This delay requirement is both rigid and absolute because any uncertainty in delay will degrade the performance significantly.

## 7.2. CoMP Today

Due to the strict sensitivity to latency and synchronization, CoMP between eNB has not been deployed yet. This is because the current interface path between eNBs cannot meet the delay bound because it is usually IP-based and passing through multiple network hops (this interface is called "X2" or "eX2" for "enhanced X2"). Today lack of absolute delay guarantee on X2/eX2 traffic is the main obstacle to JT and multi-eNB coordination.

There is still lack of Layer-3 (IP) transport protocol and signaling that is capable of low latency services; current techniques such as MPLS and PWE focus on establishing circuits using pre-routed paths but there is no such signaling for reservation of time-sensitive stream.

## 7.3. CoMP Future

### 7.3.1. Mobile Industry Overall Goals

[METIS] documents the fundamental challenges as well as overall technical goals of the 5G mobile and wireless system as the starting point. These future systems should support (at similar cost and energy consumption levels as today's system):

- 1000 times higher mobile data volume per area
- 10 times to 100 times higher typical user data rate
- 10 times to 100 times higher number of connected devices
- 10 times longer battery life for low power devices
- 5 times reduced End-to-End (E2E) latency

The current LTE networking system has E2E latency less than 20ms [LTE-Latency] which leads to around 5ms E2E latency for 5G networks. To fulfill these latency demands at similar cost will be challenging because as the system also requires 100x bandwidth and 100x connected devices, simply adding redundant bandwidth provisioning can no longer be an efficient solution.

In addition to bandwidth provisioning, reserved critical flows should not be affected by other flows no matter the pressure of the network. Deterministic networking techniques in both layer-2 and layer-3 using IETF protocol solutions can be promising to serve these scenarios.

### 7.3.2. CoMP Infrastructure Goals

Inter-site CoMP is one of the key requirements for 5G and is also a near-term goal for the current 4.5G network architecture. Assuming network architecture remains unchanged (i.e. no Fronthaul network and data flow between eNB is via X2/eX2) we would like to see the following in the near future:

- Unified protocols and delay-guaranteed forwarding network equipment that is capable of delivering deterministic latency services.

- Unified management and protocols which take delay and timing into account.

- Unified deterministic latency data model and signaling for resource reservation.

## 7.4. CoMP Asks

To fully utilize the power of CoMP, it requires:

- Very tight absolute delay bound (100-500us) within 7-10 hops.

- Standardized data plane with highly deterministic networking capability.

- Standardized control plane to unify backhaul network elements with time-sensitive stream reservation signaling.

In addition, a standardized deterministic latency data flow model that includes:

- Network-aware constraints on the networking environment

- Time-aware description of flow characteristics and network resources, which may not need to be bandwidth based

- Application-aware description of deterministic latency services.

## 8. Industrial M2M

### 8.1. Use Case Description

Industrial Automation in general refers to automation of manufacturing, quality control and material processing. In this "machine to machine" (M2M) use case we consider machine units in a plant floor which periodically exchange data with upstream or downstream machine modules and/or a supervisory controller within a local area network.

The actors of M2M communication are Programmable Logic Controllers (PLCs). Communication between PLCs and between PLCs and the supervisory PLC (S-PLC) is achieved via critical control/data streams Figure 11.

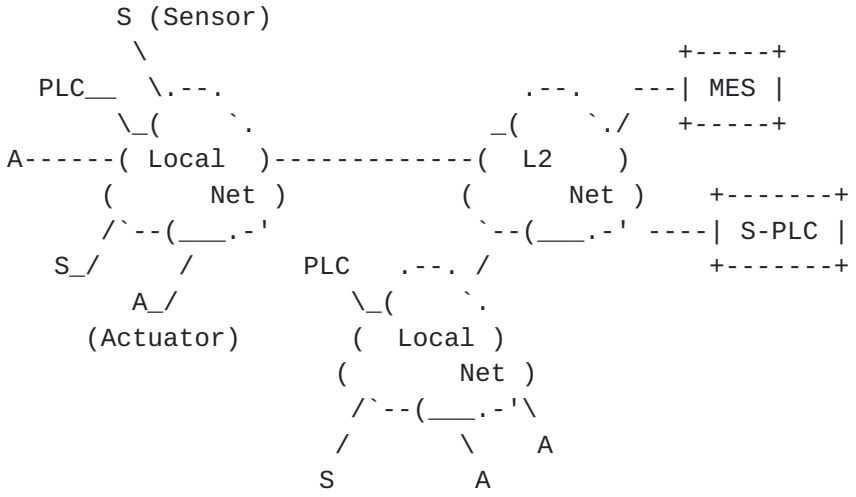



Figure 11: Current Generic Industrial M2M Network Architecture

This use case focuses on PLC-related communications; communication to Manufacturing-Execution-Systems (MESs) are not addressed.

This use case covers only critical control/data streams; non-critical traffic between industrial automation applications (such as communication of state, configuration, set-up, and database communication) are adequately served by currently available prioritizing techniques. Such traffic can use up to 80% of the total

bandwidth required. There is also a subset of non-time-critical traffic that must be reliable even though it is not time sensitive.

In this use case the primary need for deterministic networking is to provide end-to-end delivery of M2M messages within specific timing constraints, for example in closed loop automation control. Today this level of determinism is provided by proprietary networking technologies. In addition, standard networking technologies are used to connect the local network to remote industrial automation sites, e.g. over an enterprise or metro network which also carries other types of traffic. Therefore, flows that should be forwarded with deterministic guarantees need to be sustained regardless of the amount of other flows in those networks.

## 8.2. Industrial M2M Communication Today

Today, proprietary networks fulfill the needed timing and availability for M2M networks.

The network topologies used today by industrial automation are similar to those used by telecom networks: Daisy Chain, Ring, Hub and Spoke, and Comb (a subset of Daisy Chain).

PLC-related control/data streams are transmitted periodically and carry either a pre-configured payload or a payload configured during runtime.

Some industrial applications require time synchronization at the end nodes. For such time-coordinated PLCs, accuracy of 1 microsecond is required. Even in the case of "non-time-coordinated" PLCs time sync may be needed e.g. for timestamping of sensor data.

Industrial network scenarios require advanced security solutions. Many of the current industrial production networks are physically separated. Preventing critical flows from be leaked outside a domain is handled today by filtering policies that are typically enforced in firewalls.

### 8.2.1. Transport Parameters

The Cycle Time defines the frequency of message(s) between industrial actors. The Cycle Time is application dependent, in the range of 1ms - 100ms for critical control/data streams.

Because industrial applications assume deterministic transport for critical Control-Data-Stream parameters (instead of defining latency and delay variation parameters) it is sufficient to fulfill the upper bound of latency (maximum latency). The underlying networking

infrastructure must ensure a maximum end-to-end delivery time of messages in the range of 100 microseconds to 50 milliseconds depending on the control loop application.

The bandwidth requirements of control/data streams are usually calculated directly from the bytes-per-cycle parameter of the control loop. For PLC-to-PLC communication one can expect 2 - 32 streams with packet size in the range of 100 - 700 bytes. For S-PLC to PLCs the number of streams is higher - up to 256 streams. Usually no more than 20% of available bandwidth is used for critical control/data streams. In today's networks 1Gbps links are commonly used.

Most PLC control loops are rather tolerant of packet loss, however critical control/data streams accept no more than 1 packet loss per consecutive communication cycle (i.e. if a packet gets lost in cycle "n", then the next cycle ("n+1") must be lossless). After two or more consecutive packet losses the network may be considered to be "down" by the Application.

As network downtime may impact the whole production system the required network availability is rather high (99,999%).

Based on the above parameters we expect that some form of redundancy will be required for M2M communications, however any individual solution depends on several parameters including cycle time, delivery time, etc.

### 8.2.2. Stream Creation and Destruction

In an industrial environment, critical control/data streams are created rather infrequently, on the order of ~10 times per day / week / month. Most of these critical control/data streams get created at machine startup, however flexibility is also needed during runtime, for example when adding or removing a machine. Going forward as production systems become more flexible, we expect a significant increase in the rate at which streams are created, changed and destroyed.

## 8.3. Industrial M2M Future

We would like to see the various proprietary networks replaced with a converged IP-standards-based network with deterministic properties that can satisfy the timing, security and reliability constraints described above.

### 8.4. Industrial M2M Asks

- Converged IP-based network
- Deterministic behavior (bounded latency and jitter )
- High availability (presumably through redundancy) (99.999 %)
- Low message delivery time (100us - 50ms)
- Low packet loss (burstless, 0.1-1 %)
- Precise time synchronization accuracy (1us)
- Security (e.g. prevent critical flows from being leaked between physically separated networks)

## 9. Internet-based Applications

### 9.1. Use Case Description

There are many applications that communicate across the open Internet that could benefit from guaranteed delivery and bounded latency. The following are some representative examples.

#### 9.1.1. Media Content Delivery

Media content delivery continues to be an important use of the Internet, yet users often experience poor quality audio and video due to the delay and jitter inherent in today's Internet.

#### 9.1.2. Online Gaming

Online gaming is a significant part of the gaming market, however latency can degrade the end user experience. For example "First Person Shooter" (FPS) games are highly delay-sensitive.

#### 9.1.3. Virtual Reality

Virtual reality (VR) has many commercial applications including real estate presentations, remote medical procedures, and so on. Low latency is critical to interacting with the virtual world because perceptual delays can cause motion sickness.

### 9.2. Internet-Based Applications Today

Internet service today is by definition "best effort", with no guarantees on delivery or bandwidth.

### 9.3. Internet-Based Applications Future

We imagine an Internet from which we will be able to play a video without glitches and play games without lag.

For online gaming, the maximum round-trip delay can be 100ms and stricter for FPS gaming which can be 10-50ms. Transport delay is the dominate part with a 5-20ms budget.

For VR, 1-10ms maximum delay is needed and total network budget is 1-5ms if doing remote VR.

Flow identification can be used for gaming and VR, i.e. it can recognize a critical flow and provide appropriate latency bounds.

### 9.4. Internet-Based Applications Asks

- Unified control and management protocols to handle time-critical data flow
- Application-aware flow filtering mechanism to recognize the timing critical flow without doing 5-tuple matching
- Unified control plane to provide low latency service on Layer-3 without changing the data plane
- OAM system and protocols which can help to provide E2E-delay sensitive service provisioning

## 10. Use Case Common Elements

Looking at the use cases collectively, the following common desires for the DetNet-based networks of the future emerge:

- Open standards-based network (replace various proprietary networks, reduce cost, create multi-vendor market)
- Centrally administered (though such administration may be distributed for scale and resiliency)
- Integrates L2 (bridged) and L3 (routed) environments (independent of the Link layer, e.g. can be used with Ethernet, 6TiSCH, etc.)

- Carries both deterministic and best-effort traffic (guaranteed end-to-end delivery of deterministic flows, deterministic flows isolated from each other and from best-effort traffic congestion, unused deterministic BW available to best-effort traffic)

- Ability to add or remove systems from the network with minimal, bounded service interruption (applications include replacement of failed devices as well as plug and play)

- Uses standardized data flow information models capable of expressing deterministic properties (models express device capabilities, flow properties. Protocols for pushing models from controller to devices, devices to controller)

- Scalable size (long distances (many km) and short distances (within a single machine), many hops (radio repeaters, microwave links, fiber links...) and short hops (single machine))

- Scalable timing parameters and accuracy (bounded latency, guaranteed worst case maximum, minimum. Low latency, e.g. control loops may be less than 1ms, but larger for wide area networks)

- High availability (99.9999 percent up time requested, but may be up to twelve 9s)

- Reliability, redundancy (lives at stake)

- Security (from failures, attackers, misbehaving devices - sensitive to both packet content and arrival time)

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## 12. Informative References

[ACE] IETF, "Authentication and Authorization for Constrained Environments", <https://datatracker.ietf.org/doc/charter-ietf-ace/>.

[bacnetip] ASHRAE, "Annex J to ANSI/ASHRAE 135-1995 - BACnet/IP", January 1999.

[CCAMP] IETF, "Common Control and Measurement Plane", <https://datatracker.ietf.org/doc/charter-ietf-ccamp/>.

[CoMP] NGMN Alliance, "RAN EVOLUTION PROJECT COMP EVALUATION AND ENHANCEMENT", NGMN Alliance NGMN_RANEV_D3_CoMP_Evaluation_and_Enhancement_v2.0, March 2015, <https://www.ngmn.org/uploads/media/NGMN_RANEV_D3_CoMP_Evaluation_and_Enhancement_v2.0.pdf>.

[CONTENT_PROTECTION] Olsen, D., "1722a Content Protection", 2012, <http://grouper.ieee.org/groups/1722/contributions/2012/avtp_dolsen_1722a_content_protection.pdf>.

[CPRI] CPRI Cooperation, "Common Public Radio Interface (CPRI); Interface Specification", CPRI Specification V6.1, July 2014, <http://www.cpri.info/downloads/CPRI_v_6_1_2014-07-01.pdf>.

[DCI] Digital Cinema Initiatives, LLC, "DCI Specification, Version 1.2", 2012, <http://www.dcimovies.com/>.

[DICE] IETF, "DTLS In Constrained Environments", <https://datatracker.ietf.org/doc/charter-ietf-dice/>.

[EA12] Evans, P. and M. Annunziata, "Industrial Internet: Pushing the Boundaries of Minds and Machines", November 2012.

[ESPN_DC2] Daley, D., "ESPN's DC2 Scales AVB Large", 2014, <http://sportsvideo.org/main/blog/2014/06/espns-dc2-scales-avb-large>.

[flnet] Japan Electrical Manufacturers' Association, "JEMA 1479 - English Edition", September 2012.

[Fronthaul]
Chen, D. and T. Mustala, "Ethernet Fronthaul Considerations", IEEE 1904.3, February 2015, <http://www.ieee1904.org/3/meeting_archive/2015/02/tf3_1502_che n_1a.pdf>.

[HART] www.hartcomm.org, "Highway Addressable remote Transducer, a group of specifications for industrial process and control devices administered by the HART Foundation".

[I-D.finn-detnet-architecture]
Finn, N., Thubert, P., and M. Teener, "Deterministic Networking Architecture", draft-finn-detnet-architecture-02 (work in progress), November 2015.

[I-D.finn-detnet-problem-statement]
Finn, N. and P. Thubert, "Deterministic Networking Problem Statement", draft-finn-detnet-problem-statement-04 (work in progress), October 2015.

[I-D.ietf-6tisch-6top-interface]
Wang, Q. and X. Vilajosana, "6TiSCH Operation Sublayer (6top) Interface", draft-ietf-6tisch-6top-interface-04 (work in progress), July 2015.

[I-D.ietf-6tisch-architecture]
Thubert, P., "An Architecture for IPv6 over the TSCH mode of IEEE 802.15.4", draft-ietf-6tisch-architecture-09 (work in progress), November 2015.

[I-D.ietf-6tisch-coap]
Sudhaakar, R. and P. Zand, "6TiSCH Resource Management and Interaction using CoAP", draft-ietf-6tisch-coap-03 (work in progress), March 2015.

[I-D.ietf-6tisch-terminology]
Palattella, M., Thubert, P., Watteyne, T., and Q. Wang, "Terminology in IPv6 over the TSCH mode of IEEE 802.15.4e", draft-ietf-6tisch-terminology-06 (work in progress), November 2015.

[I-D.ietf-ipv6-multilink-subnets]
Thaler, D. and C. Huitema, "Multi-link Subnet Support in IPv6", draft-ietf-ipv6-multilink-subnets-00 (work in progress), July 2002.

[I-D.ietf-roll-rpl-industrial-applicability]
Phinney, T., Thubert, P., and R. Assimiti, "RPL applicability in industrial networks", draft-ietf-roll-rpl-industrial-applicability-02 (work in progress), October 2013.

[I-D.ietf-tictoc-1588overmpls]
Davari, S., Oren, A., Bhatia, M., Roberts, P., and L. Montini, "Transporting Timing messages over MPLS Networks", draft-ietf-tictoc-1588overmpls-07 (work in progress), October 2015.

[I-D.kh-spring-ip-ran-use-case]
Khasnabish, B., hu, f., and L. Contreras, "Segment Routing in IP RAN use case", draft-kh-spring-ip-ran-use-case-02 (work in progress), November 2014.

[I-D.mirsky-mpls-residence-time]
Mirsky, G., Ruffini, S., Gray, E., Drake, J., Bryant, S., and S. Vainshtein, "Residence Time Measurement in MPLS network", draft-mirsky-mpls-residence-time-07 (work in progress), July 2015.

[I-D.svshah-tsvwg-deterministic-forwarding]
Shah, S. and P. Thubert, "Deterministic Forwarding PHB", draft-svshah-tsvwg-deterministic-forwarding-04 (work in progress), August 2015.

[I-D.thubert-6lowpan-backbone-router]
Thubert, P., "6LoWPAN Backbone Router", draft-thubert-6lowpan-backbone-router-03 (work in progress), February 2013.

[I-D.wang-6tisch-6top-sublayer]
Wang, Q. and X. Vilajosana, "6TiSCH Operation Sublayer (6top)", draft-wang-6tisch-6top-sublayer-04 (work in progress), November 2015.

[IEC61850-90-12]
TC57 WG10, IEC., "IEC 61850-90-12 TR: Communication networks and systems for power utility automation - Part 90-12: Wide area network engineering guidelines", 2015.

[IEC62439-3:2012]
TC65, IEC., "IEC 62439-3: Industrial communication networks - High availability automation networks - Part 3: Parallel Redundancy Protocol (PRP) and High-availability Seamless Redundancy (HSR)", 2012.

[IEEE1588]
IEEE, "IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems", IEEE Std 1588-2008, 2008, <http://standards.ieee.org/findstds/standard/1588-2008.html>.

[IEEE1722]
IEEE, "1722-2011 - IEEE Standard for Layer 2 Transport Protocol for Time Sensitive Applications in a Bridged Local Area Network", IEEE Std 1722-2011, 2011, <http://standards.ieee.org/findstds/standard/1722-2011.html>.

[IEEE19043]
IEEE Standards Association, "IEEE 1904.3 TF", IEEE 1904.3, 2015, <http://www.ieee1904.org/3/tf3_home.shtml>.

[IEEE802.1TSNTG]
IEEE Standards Association, "IEEE 802.1 Time-Sensitive Networks Task Group", March 2013, <http://www.ieee802.org/1/pages/avbridges.html>.

[IEEE802154]
IEEE standard for Information Technology, "IEEE std. 802.15.4, Part. 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks".

[IEEE802154e]
IEEE standard for Information Technology, "IEEE standard for Information Technology, IEEE std. 802.15.4, Part. 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks, June 2011 as amended by IEEE std. 802.15.4e, Part. 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs) Amendment 1: MAC sublayer", April 2012.

[IEEE8021AS]
IEEE, "Timing and Synchronizations (IEEE 802.1AS-2011)", IEEE 802.1AS-2001, 2011, <http://standards.ieee.org/getIEEE802/download/802.1AS-2011.pdf>.

[IEEE8021CM]
Farkas, J., "Time-Sensitive Networking for Fronthaul", Unapproved PAR, PAR for a New IEEE Standard; IEEE P802.1CM, April 2015, <http://www.ieee802.org/1/files/public/docs2015/new-P802-1CM-dr aft-PAR-0515-v02.pdf>.

[IEEE8021TSN]
IEEE 802.1, "The charter of the TG is to provide the specifications that will allow time-synchronized low latency streaming services through 802 networks.", 2016, <http://www.ieee802.org/1/pages/tsn.html>.

[IETFDetNet]
IETF, "Charter for IETF DetNet Working Group", 2015, <https://datatracker.ietf.org/wg/detnet/charter/>.

[ISA100] ISA/ANSI, "ISA100, Wireless Systems for Automation", <https://www.isa.org/isa100/>.

[ISA100.11a]
ISA/ANSI, "Wireless Systems for Industrial Automation: Process Control and Related Applications - ISA100.11a-2011 - IEC 62734", 2011, <http://www.isa.org/Community/SP100WirelessSystemsforAutomation>.

[ISO7240-16]
ISO, "ISO 7240-16:2007 Fire detection and alarm systems -- Part 16: Sound system control and indicating equipment", 2007, <http://www.iso.org/iso/catalogue_detail.htm?csnumber=42978>.

[knx] KNX Association, "ISO/IEC 14543-3 - KNX", November 2006.

[lontalk] ECHELON, "LonTalk(R) Protocol Specification Version 3.0", 1994.

[LTE-Latency]
Johnston, S., "LTE Latency: How does it compare to other technologies", March 2014, <http://opensignal.com/blog/2014/03/10/lte-latency-how-does-it-compare-to-other-technologies>.

[MEF] MEF, "Mobile Backhaul Phase 2 Amendment 1 -- Small Cells", MEF 22.1.1, July 2014, <http://www.mef.net/Assets/Technical_Specifications/PDF/MEF_22.1.1.pdf>.

[METIS] METIS, "Scenarios, requirements and KPIs for 5G mobile and wireless system", ICT-317669-METIS/D1.1 ICT-317669-METIS/D1.1, April 2013, <https://www.metis2020.com/wp-content/uploads/deliverables/METIS_D1.1_v1.pdf>.

[modbus] Modbus Organization, "MODBUS APPLICATION PROTOCOL SPECIFICATION V1.1b", December 2006.

[net5G] Ericsson, "5G Radio Access, Challenges for 2020 and Beyond", Ericsson white paper wp-5g, June 2013, <http://www.ericsson.com/res/docs/whitepapers/wp-5g.pdf>.

[NGMN] NGMN Alliance, "5G White Paper", NGMN 5G White Paper v1.0, February 2015, <https://www.ngmn.org/uploads/media/NGMN_5G_White_Paper_V1_0.pdf>.

[PCE] IETF, "Path Computation Element", <https://datatracker.ietf.org/doc/charter-ietf-pce/>.

[profibus] IEC, "IEC 61158 Type 3 - Profibus DP", January 2001.

[RFC2119] Bradner, S., "Key words for use in RFCs to Indicate Requirement Levels", BCP 14, RFC 2119, DOI 10.17487/RFC2119, March 1997, <http://www.rfc-editor.org/info/rfc2119>.

[RFC2460] Deering, S. and R. Hinden, "Internet Protocol, Version 6 (IPv6) Specification", RFC 2460, DOI 10.17487/RFC2460, December 1998, <http://www.rfc-editor.org/info/rfc2460>.

[RFC2474] Nichols, K., Blake, S., Baker, F., and D. Black, "Definition of the Differentiated Services Field (DS Field) in the IPv4 and IPv6 Headers", RFC 2474, DOI 10.17487/RFC2474, December 1998, <http://www.rfc-editor.org/info/rfc2474>.

[RFC3031] Rosen, E., Viswanathan, A., and R. Callon, "Multiprotocol Label Switching Architecture", RFC 3031, DOI 10.17487/RFC3031, January 2001, <http://www.rfc-editor.org/info/rfc3031>.

[RFC3209] Awduche, D., Berger, L., Gan, D., Li, T., Srinivasan, V., and G. Swallow, "RSVP-TE: Extensions to RSVP for LSP Tunnels", RFC 3209, DOI 10.17487/RFC3209, December 2001, <http://www.rfc-editor.org/info/rfc3209>.

[RFC3393] Demichelis, C. and P. Chimento, "IP Packet Delay Variation Metric for IP Performance Metrics (IPPM)", RFC 3393, DOI 10.17487/RFC3393, November 2002, <http://www.rfc-editor.org/info/rfc3393>.

[RFC3444] Pras, A. and J. Schoenwaelder, "On the Difference between Information Models and Data Models", RFC 3444, DOI 10.17487/RFC3444, January 2003, <http://www.rfc-editor.org/info/rfc3444>.

[RFC3972] Aura, T., "Cryptographically Generated Addresses (CGA)", RFC 3972, DOI 10.17487/RFC3972, March 2005, <http://www.rfc-editor.org/info/rfc3972>.

[RFC3985] Bryant, S., Ed. and P. Pate, Ed., "Pseudo Wire Emulation Edge-to-Edge (PWE3) Architecture", RFC 3985, DOI 10.17487/RFC3985, March 2005, <http://www.rfc-editor.org/info/rfc3985>.

[RFC4291] Hinden, R. and S. Deering, "IP Version 6 Addressing Architecture", RFC 4291, DOI 10.17487/RFC4291, February 2006, <http://www.rfc-editor.org/info/rfc4291>.

[RFC4553] Vainshtein, A., Ed. and YJ. Stein, Ed., "Structure-Agnostic Time Division Multiplexing (TDM) over Packet (SAToP)", RFC 4553, DOI 10.17487/RFC4553, June 2006, <http://www.rfc-editor.org/info/rfc4553>.

[RFC4903] Thaler, D., "Multi-Link Subnet Issues", RFC 4903, DOI 10.17487/RFC4903, June 2007, <http://www.rfc-editor.org/info/rfc4903>.

[RFC4919] Kushalnagar, N., Montenegro, G., and C. Schumacher, "IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs): Overview, Assumptions, Problem Statement, and Goals", RFC 4919, DOI 10.17487/RFC4919, August 2007, <http://www.rfc-editor.org/info/rfc4919>.

[RFC5086] Vainshtein, A., Ed., Sasson, I., Metz, E., Frost, T., and P. Pate, "Structure-Aware Time Division Multiplexed (TDM) Circuit Emulation Service over Packet Switched Network (CESoPSN)", RFC 5086, DOI 10.17487/RFC5086, December 2007, <http://www.rfc-editor.org/info/rfc5086>.

[RFC5087] Stein, Y(J)., Shashoua, R., Insler, R., and M. Anavi, "Time Division Multiplexing over IP (TDMoIP)", RFC 5087, DOI 10.17487/RFC5087, December 2007, <http://www.rfc-editor.org/info/rfc5087>.

[RFC6282] Hui, J., Ed. and P. Thubert, "Compression Format for IPv6 Datagrams over IEEE 802.15.4-Based Networks", RFC 6282, DOI 10.17487/RFC6282, September 2011, <http://www.rfc-editor.org/info/rfc6282>.

[RFC6550] Winter, T., Ed., Thubert, P., Ed., Brandt, A., Hui, J., Kelsey, R., Levis, P., Pister, K., Struik, R., Vasseur, JP., and R. Alexander, "RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks", RFC 6550, DOI 10.17487/RFC6550, March 2012, <http://www.rfc-editor.org/info/rfc6550>.

[RFC6551] Vasseur, JP., Ed., Kim, M., Ed., Pister, K., Dejean, N., and D. Barthel, "Routing Metrics Used for Path Calculation in Low-Power and Lossy Networks", RFC 6551, DOI 10.17487/RFC6551, March 2012, <http://www.rfc-editor.org/info/rfc6551>.

[RFC6775] Shelby, Z., Ed., Chakrabarti, S., Nordmark, E., and C. Bormann, "Neighbor Discovery Optimization for IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs)", RFC 6775, DOI 10.17487/RFC6775, November 2012, <http://www.rfc-editor.org/info/rfc6775>.

[RFC7554] Watteyne, T., Ed., Palattella, M., and L. Grieco, "Using IEEE 802.15.4e Time-Slotted Channel Hopping (TSCH) in the Internet of Things (IoT): Problem Statement", RFC 7554, DOI 10.17487/RFC7554, May 2015, <http://www.rfc-editor.org/info/rfc7554>.

[SRP_LATENCY] Gunther, C., "Specifying SRP Latency", 2014, <http://www.ieee802.org/1/files/public/docs2014/cc-cgunther-acceptable-latency-0314-v01.pdf>.

[STUDIO_IP] Mace, G., "IP Networked Studio Infrastructure for Synchronized & Real-Time Multimedia Transmissions", 2007, <http://www.ieee802.org/1/files/public/docs2047/avb-mace-ip-networked-studio-infrastructure-0107.pdf>.

[SyncE] ITU-T, "G.8261 : Timing and synchronization aspects in packet networks", Recommendation G.8261, August 2013, <http://www.itu.int/rec/T-REC-G.8261>.

[TEAS] IETF, "Traffic Engineering Architecture and Signaling", <https://datatracker.ietf.org/doc/charter-ietf-teas/>.

[TS23401] 3GPP, "General Packet Radio Service (GPRS) enhancements for Evolved Universal Terrestrial Radio Access Network (E-UTRAN) access", 3GPP TS 23.401 10.10.0, March 2013.

[TS25104] 3GPP, "Base Station (BS) radio transmission and reception (FDD)", 3GPP TS 25.104 3.14.0, March 2007.

[TS36104] 3GPP, "Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) radio transmission and reception", 3GPP TS 36.104 10.11.0, July 2013.

[TS36133] 3GPP, "Evolved Universal Terrestrial Radio Access (E-UTRA); Requirements for support of radio resource management", 3GPP TS 36.133 12.7.0, April 2015.

[TS36211] 3GPP, "Evolved Universal Terrestrial Radio Access (E-UTRA); Physical channels and modulation", 3GPP TS 36.211 10.7.0, March 2013.

[TS36300] 3GPP, "Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2", 3GPP TS 36.300 10.11.0, September 2013.

[TSNTG] IEEE Standards Association, "IEEE 802.1 Time-Sensitive Networks Task Group", 2013, <http://www.IEEE802.org/1/pages/avbridges.html>.

[UHD-video] Holub, P., "Ultra-High Definition Videos and Their Applications over the Network", The 7th International Symposium on VICTORIES Project PetrHolub_presentation, October 2014, <http://www.aist-victories.org/jp/7th_sympo_ws/PetrHolub_presentation.pdf>.

[WirelessHART] www.hartcomm.org, "Industrial Communication Networks - Wireless Communication Network and Communication Profiles - WirelessHART - IEC 62591", 2010.

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