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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.

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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:

- o What is the use case?
- o How is it addressed today?
- o How would you like it to be addressed in the future?
- o 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 and Video

[2.1.](#) Use Case Description

The professional audio and video industry ("ProAV") includes:

- o Music and film content creation
- o Broadcast

- o Cinema
- o Live sound
- o Public address, media and emergency systems at large venues (airports, stadiums, churches, theme parks).

These industries have already transitioned audio and video signals from analog to digital. However, the digital 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 transitioning to packet-based infrastructure to reduce cost, increase routing flexibility, and integrate with existing IT infrastructure.

Today ProAV applications have no way to establish deterministic streams from a standards-based Layer 3 (IP) interface, which is a fundamental limitation to the use cases described here. Today deterministic streams can be created within standards-based layer 2 LANs (e.g. using IEEE 802.1 AVB) however these are not routable via IP and thus are not effective for distribution over wider areas (for example broadcast events that span wide geographical areas).

It would be highly desirable if such streams could be routed over the open Internet, however solutions with more limited scope (e.g. enterprise networks) would still provide a substantial improvement.

The following sections describe specific ProAV use cases.

2.1.1. Uninterrupted Stream Playback

Transmitting audio and video streams for live playback is unlike common file transfer because uninterrupted stream playback in the presence of network errors 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. Buffering can be used to provide enough delay to allow time for one or more retries, however this is not an effective solution in applications where large delays (latencies) are not acceptable (as discussed below).

Streams with guaranteed bandwidth can eliminate congestion on the network as a cause of transmission errors that would lead to playback interruption. Use of redundant paths can further mitigate transmission errors to provide greater stream reliability.

2.1.2. Synchronized Stream Playback

Latency in this context is the time between when a signal is initially sent over a stream and when it is received. A common example in ProAV is time-synchronizing audio and video when they take separate paths through the playback system. In this case the latency of both the audio and video streams must be bounded and consistent if the sound is to remain matched to the movement in the video. 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) delay (buffer) 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.

2.1.3. Sound Reinforcement

Consider the latency (delay) from when a person speaks into a microphone to when their voice emerges from the speaker. If this delay is longer than about 10-15 milliseconds it is noticeable and can make a sound reinforcement system unusable (see slide 6 of [\[SRP_LATENCY\]](#)). (If you have ever tried to speak in the presence of a delayed echo of your voice you may know this experience).

Note that the 15ms latency bound includes all parts of the signal path, not just the network, so the network latency must be significantly less than 15ms.

In some cases local performers must perform in synchrony with a remote broadcast. In such cases the latencies of the broadcast stream and the local performer must be adjusted to match each other, with a worst case of one video frame (33ms for NTSC video).

In cases where audio phase is a consideration, for example beam-forming using multiple speakers, latency requirements can be in the 10 microsecond range (1 audio sample at 96kHz).

2.1.4. 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 [[IS07240-16](#)].

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 (video stream) to another (see [[STUDIO_IP](#)] and [[ESPN_DC2](#)]).

2.1.5. Secure Transmission

2.1.5.1. Safety

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).

2.1.5.2. Digital Rights Management (DRM)

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.

2.2. Pro Audio Today

Some proprietary systems have been created which enable deterministic streams at Layer 3 however they are "engineered networks" which require careful configuration to operate, often require that the system be over-provisioned, 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.

2.3. Pro Audio Future

2.3.1. Layer 3 Interconnecting Layer 2 Islands

It would be valuable to enable IP to connect multiple Layer 2 LANs.

As an example, 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 [[ESPN DC2](#)]).

In designing DC2 they replaced as much point-to-point technology as they 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. However to interconnect these layer 2 LAN islands together they ended up using dedicated paths in a custom SDN (Software Defined Networking) router because there is no standards-based routing solution available.

2.3.2. High Reliability Stream Paths

On-air and other live media streams are often 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.

2.3.3. 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.

2.3.4. 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.

2.3.5. 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 reserve large quantities of bandwidth and then never un-reserve it even though they are not using it, and soon the network will have no bandwidth left").

2.3.6. 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.

2.3.6.1. 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.

2.3.6.2. 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.

2.3.7. Latency Optimization by a Central Controller

A central network 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](#)].

2.3.8. Reduced Device Cost Due To Reduced Buffer Memory

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 today's 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.

2.4. Pro Audio Asks

- o Layer 3 routing on top of AVB (and/or other high QoS networks)
- o Content delivery with bounded, lowest possible latency
- o IntServ and DiffServ integration with AVB (where practical)
- o Single network for A/V and IT traffic
- o Standards-based, interoperable, multi-vendor
- o IT department friendly
- o Enterprise-wide networks (e.g. size of San Francisco but not the whole Internet (yet...))

3. Electrical Utilities

3.1. Use Case Description

Many systems that an electrical utility deploys today rely on high availability and deterministic behavior of the underlying networks. Here we present use cases in Transmission, Generation and Distribution, including key timing and reliability metrics. We also discuss security issues and industry trends which affect the architecture of next generation utility networks

3.1.1. Transmission Use Cases

3.1.1.1. Protection

Protection means not only the protection of human operators but also the protection of the electrical equipment and the preservation of the stability and frequency of the grid. If a fault occurs in the transmission or distribution of electricity then severe damage can occur to human operators, electrical equipment and the grid itself, leading to blackouts.

Communication links in conjunction with protection relays are used to selectively isolate faults on high voltage lines, transformers, reactors and other important electrical equipment. The role of the teleprotection system is to selectively disconnect a faulty part by transferring command signals within the shortest possible time.

3.1.1.1.1. Key Criteria

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:

- o 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.
- o 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.
- o 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 elements of the the teleprotection system that impact its performance include:

- o Network bandwidth
- o Failure recovery capacity (aka resiliency)

3.1.1.1.2. Fault Detection and Clearance Timing

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.

3.1.1.1.3. Symmetric Channel Delay

Teleprotection channels which are differential must be synchronous, which means that any delays on the transmit and receive paths must match each other. Teleprotection systems ideally support zero asymmetric delay; typical legacy relays can tolerate delay discrepancies of up to 750us.

Some tools available for lowering delay variation below this threshold are:

- o For legacy systems using Time Division Multiplexing (TDM), jitter buffers 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.
- o For jitter-prone IP packet networks, traffic management tools can ensure that the teleprotection signals receive the highest transmission priority to minimize jitter.
- o Standard packet-based synchronization technologies, such as 1588-2008 Precision Time Protocol (PTP) and Synchronous Ethernet (Sync-E), can help keep networks stable by maintaining a highly accurate clock source on the various network devices.

3.1.1.1.4. Teleprotection Network Requirements (IEC 61850)

The following table captures the main network metrics as based on the IEC 61850 standard.

Teleprotection Requirement	Attribute
One way maximum delay	4-10 ms
Asymmetric 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

3.1.1.1.5. Inter-Trip Protection scheme

"Inter-tripping" is the signal-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.

Inter-Trip protection Requirement	Attribute
One way maximum delay	5 ms
Asymmetric 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

3.1.1.1.6. Current Differential Protection Scheme

Current differential protection is commonly used for line protection, and is typical for protecting parallel circuits. At both end of the lines the current is measured by the differential relays, and 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. 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
Asymmetric 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 metrics

[3.1.1.1.7.](#) Distance Protection Scheme

Distance (Impedance Relay) protection scheme is based on voltage and current measurements. The network metrics are similar (but not identical to) Current Differential protection.

Distance protection Requirement	Attribute
One way maximum delay	5 ms
Asymmetric 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

3.1.1.1.8. 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 MU 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
Asymmetric 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

3.1.1.2. Intra-Substation Process Bus Communications

This use case describes the data flow from the CT/VT to the IEDs in the substation via the MU. The CT/VT in the substation send the sampled value (analog voltage or current) to the MU over hard wire. The MU 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 the MU through a serial port or

IEEE 1588 protocol via a 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
Asymmetric 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

3.1.1.3. 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
Asymmetric 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

3.1.1.4. 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. Table 8 summarizes 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

3.1.2. Generation Use Case

The electrical power generation frequency should be maintained within a very narrow band. Deviations from the acceptable frequency range are detected and the required signals are sent to the power plants for frequency regulation.

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.

FCAG (Frequency Control Automatic Generation) Requirement	Attribute
One way maximum delay	500 ms
Asymmetric 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 9: FCAG Communication Requirements

3.1.3. Distribution use case

3.1.3.1. Fault Location Isolation and Service Restoration (FLISR)

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. This will likely be the first widespread application of distributed intelligence in the grid.

Static power switch status (open/closed) in the network dictates the power flow to secondary substations. Reconfiguring the network in the event of a fault is typically done manually on site to energize/de-energize alternate paths. Automating the operation of substation switchgear allows the flow of power to be altered automatically under fault conditions.

FLISR can be managed centrally from a Distribution Management System (DMS) or executed locally through distributed control via intelligent switches and fault sensors.

FLISR Requirement	Attribute
One way maximum delay	80 ms
Asymmetric 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	Depends on customer impact
performance management	Yes, Mandatory
Redundancy	Yes
Packet loss	0.1%

Table 10: FLISR Communication Requirements

3.2. Electrical Utilities Today

Many utilities still rely on complex environments formed of multiple application-specific proprietary networks, including TDM networks.

In this kind of environment there is no mixing of OT and IT applications on the same network, and information is siloed between operational areas.

Specific calibration of the full chain is required, which is costly.

This kind of environment prevents utility operations from realizing the operational efficiency benefits, visibility, and functional integration of operational information across grid applications and data networks.

In addition, there are many security-related issues as discussed in the following section.

3.2.1. Security Current Practices and Limitations

Grid monitoring and control devices are already targets for cyber attacks, and legacy telecommunications protocols have many intrinsic network-related vulnerabilities. For example, 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:

- o Network or transport errors (e.g. malformed packets or excessive latency) can cause protocol failure.
- o 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.
- o Protocol commands may be available that are capable of restarting communications and otherwise interrupting processes.
- o Protocol commands may be available that are capable of clearing, erasing, or resetting diagnostic information such as counters and diagnostic registers.
- o Protocol commands may be available that are capable of requesting sensitive information about the controllers, their configurations, or other need-to-know information.
- o 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.
- o Protocol commands may be available that are capable of broadcasting messages to many devices at once (i.e. a potential DoS).
- o Protocol commands may be available to query the device network to obtain defined points and their values (i.e. a configuration scan).
- o Protocol commands may be available that will list all available function codes (i.e. a function scan).

These inherent vulnerabilities, along with increasing connectivity between IT and 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.

3.3. Electrical Utilities Future

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.

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 telecommunications 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.

IPv6 is seen as a future telecommunications technology for the Smart Grid; the 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.

3.3.1. 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:

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

3.3.2. Telecommunications Trends

These general telecommunications topics are in addition to the use cases that have been addressed so far. These include both current and future telecommunications related topics that should be factored into the network architecture and design.

3.3.2.1. General Telecommunications Requirements

- o IP Connectivity everywhere
- o Monitoring services everywhere and from different remote centers
- o Move services to a virtual data center
- o Unify access to applications / information from the corporate network

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

3.3.2.2. 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 system 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, with individual runs as long as 280 km.

3.3.2.3. 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 (PTP, [[IEEE1588](#)]), distributing the synchronization signal over the IP/MPLS network. PTP 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 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, however 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 delay asymmetry in the paths taken by event messages. Asymmetry is not detectable by PTP, however, if such delays are known a priori, PTP can correct for asymmetry.

IEC 61850 will recommend the use of the IEEE PTP 1588 Utility Profile (as defined in [IEC62439-3:2012] Annex B) which offers the support of redundant attachment of clocks to Parallel Redundancy Protocol (PRP) and High-availability Seamless Redundancy (HSR) networks.

3.3.3. Security Trends in Utility Networks

Although advanced telecommunications networks can assist in transforming the energy industry by 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:

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

- o Integrity : data cannot be altered undetectably
- o Authenticity : the telecommunications parties involved must be validated as genuine
- o Authorization : only requests and commands from the authorized users can be accepted by the system
- o Confidentiality : data must not be accessible to any unauthenticated users

When designing and deploying new smart grid devices and telecommunications systems, it is 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:

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

3.4. Electrical Utilities Asks

- o Mixed L2 and L3 topologies
- o Deterministic behavior
- o Bounded latency and jitter
- o High availability, low recovery time
- o Redundancy, low packet loss
- o Precise timing
- o Centralized computing of deterministic paths
- o Distributed configuration may also be useful

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:

- o Periodically measures states of devices, for example humidity and illuminance of rooms, open/close state of doors, FAN speed, etc.
- o Stores the measured data.
- o Provides the measured data to BAS systems and operators.
- o Generates alarms for abnormal state of devices.
- o 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.

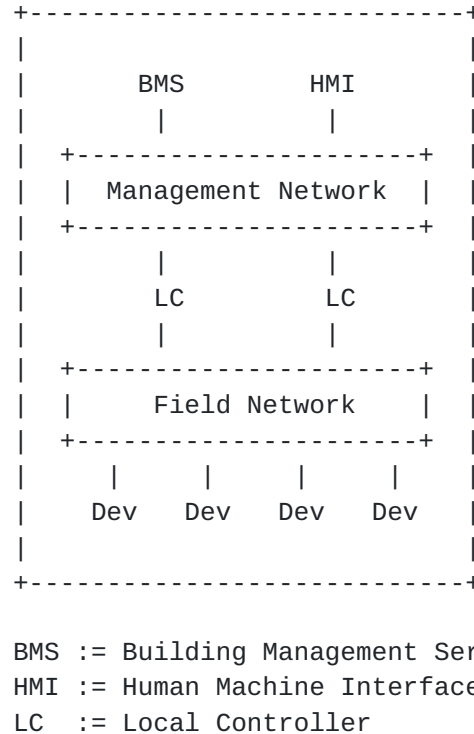


Figure 1: BAS architecture

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.

- o Collect and store device states from LCs at regular intervals.
- o Send control values to LCs according to a building schedule.
- o 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:

- o Measure device states and provide the information to BMS or HMI.
- o 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.

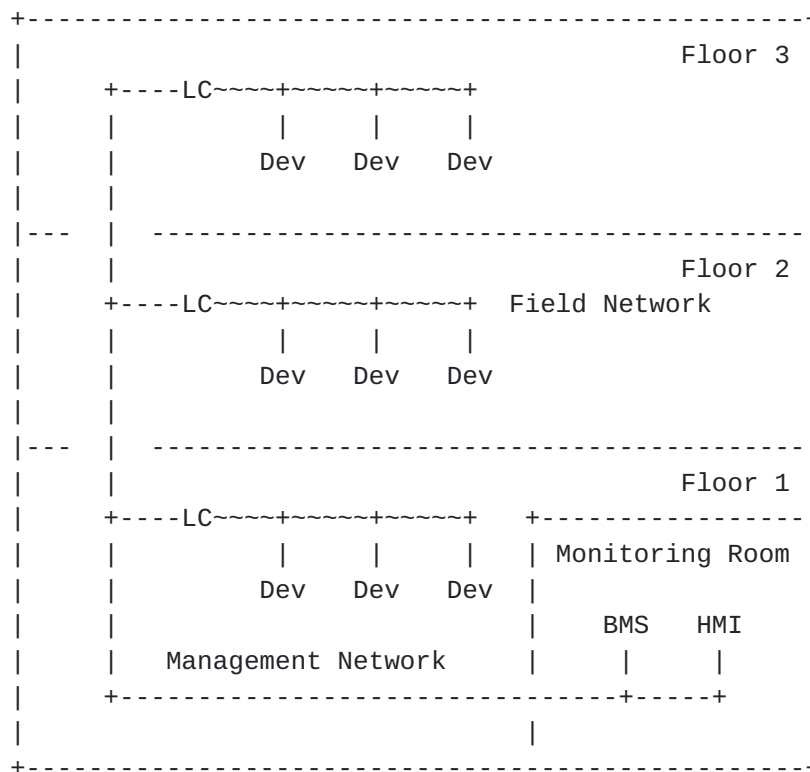


Figure 2: BAS Deployment model for Medium/Large Buildings

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.

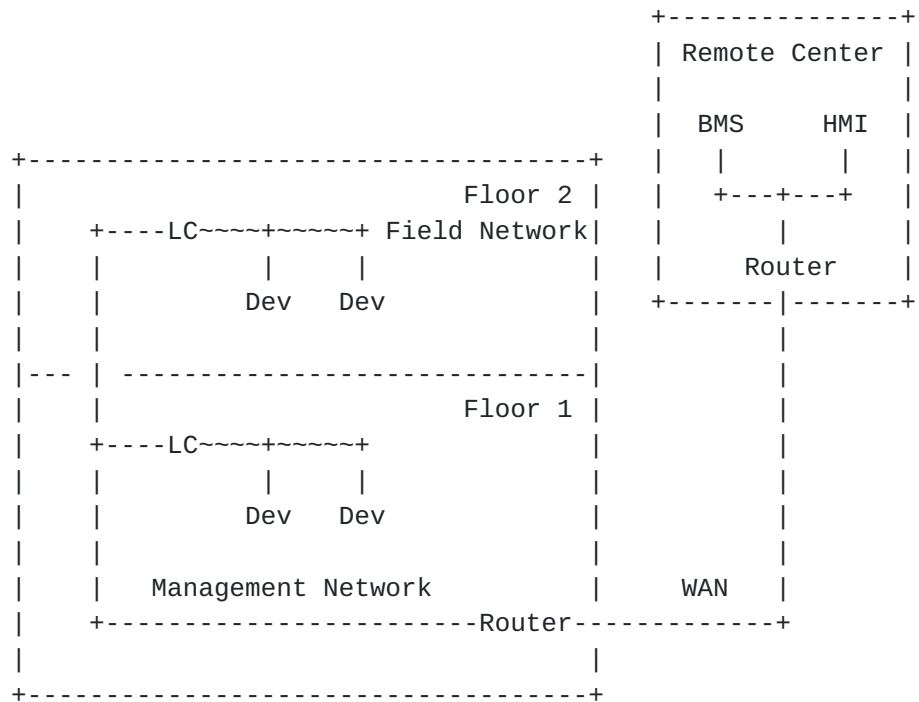


Figure 3: Deployment model for Small Buildings

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-critical 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

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

5. Wireless for Industrial

5.1. Use Case Description

Wireless networks are useful for industrial applications, for example when portable, fast-moving or rotating objects are involved, and for the resource-constrained devices found in the Internet of Things (IoT).

Such network-connected sensors, actuators, control loops (etc.) typically require that the underlying network support real-time quality of service (QoS), as well as specific classes of other network properties such as reliability, redundancy, and security.

These networks may also contain very large numbers of devices, for example for factories, "big data" acquisition, and the IoT. Given the large numbers of devices installed, and the potential pervasiveness of the IoT, this is a huge and very cost-sensitive

market. For example, a 1% cost reduction in some areas could save \$100B

5.1.1. Network Convergence using 6TiSCH

Some wireless network technologies support real-time QoS, and are thus useful for these kinds of networks, but others do not. For example WiFi is pervasive but does not provide guaranteed timing or delivery of packets, and thus is not useful in this context.

In this use case we focus on one specific wireless network technology which does provide the required deterministic QoS, which is "IPv6 over the TSCH mode of IEEE 802.15.4e" (6TiSCH, where TSCH stands for "Time-Slotted Channel Hopping", see [[I-D.ietf-6tisch-architecture](#)], [[IEEE802154](#)], [[IEEE802154e](#)], and [[RFC7554](#)]).

There are other deterministic wireless busses and networks available today, however they are incompatible with each other, and incompatible with IP traffic (for example [[ISA100](#)], [[WirelessHART](#)]).

Thus the primary goal of this use case is to apply 6TiSCH as a converged IP- and standards-based wireless network for industrial applications, i.e. to replace multiple proprietary and/or incompatible wireless networking and wireless network management standards.

5.1.2. Common Protocol Development for 6TiSCH

Today there are a number of protocols required by 6TiSCH which are still in development, and a second intent of this use case is to highlight the ways in which these "missing" protocols share goals in common with DetNet. Thus it is possible that some of the protocol technology developed for DetNet will also be applicable to 6TiSCH.

These protocol goals are identified here, along with their relationship to DetNet. It is likely that ultimately the resulting protocols will not be identical, but will share design principles which contribute to the efficiency of enabling both DetNet and 6TiSCH.

One such commonality is that although at a different time scale, in both TSN [[IEEE802.1TSNTG](#)] and TSCH a packet crosses the network from node to node follows a precise schedule, as a train that leaves intermediate stations at precise times along its path. This kind of operation reduces collisions, saves energy, and enables engineering the network for deterministic properties.

Another commonality is remote monitoring and scheduling management of a TSCH network by a Path Computation Element (PCE) and Network

Management Entity (NME). The PCE/NME manage timeslots and device resources in a manner that minimizes the interaction with and the load placed on resource-constrained devices. For example, a tiny IoT device may have just enough buffers to store one or a few IPv6 packets, and will have limited bandwidth between peers such that it can maintain only a small amount of peer information, and will not be able to store many packets waiting to be forwarded. It is advantageous then for it to only be required to carry out the specific behavior assigned to it by the PCE/NME (as opposed to maintaining its own IP stack, for example).

6TiSCH depends on [PCE] and [I-D.finn-detnet-architecture], and we expect that DetNet will maintain consistency with [IEEE802.1TSNTG].

5.2. Wireless Industrial Today

Today industrial wireless is accomplished using multiple deterministic wireless networks which are incompatible with each other and with IP traffic.

6TiSCH is not yet fully specified, so it cannot be used in today's applications.

5.3. Wireless Industrial Future

5.3.1. Unified Wireless Network and Management

We expect DetNet and 6TiSCH together to enable converged transport of deterministic and best-effort traffic flows between real-time industrial devices and wide area networks via IP routing. A high level view of a basic such network is shown in Figure 4.

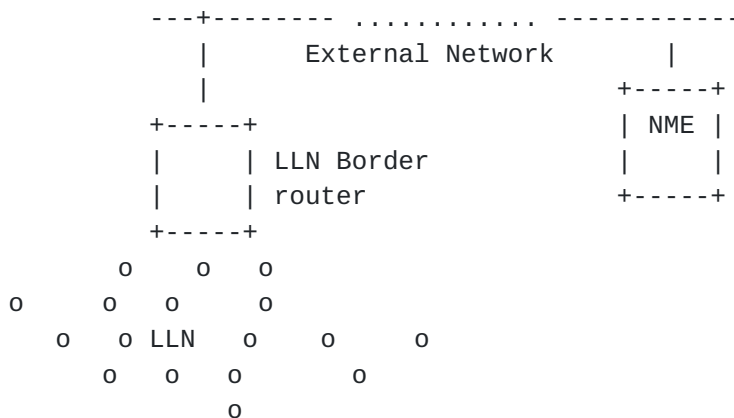


Figure 4: Basic 6TiSCH Network

Figure 5 shows a backbone router federating multiple synchronized 6TiSCH subnets into a single subnet connected to the external network.

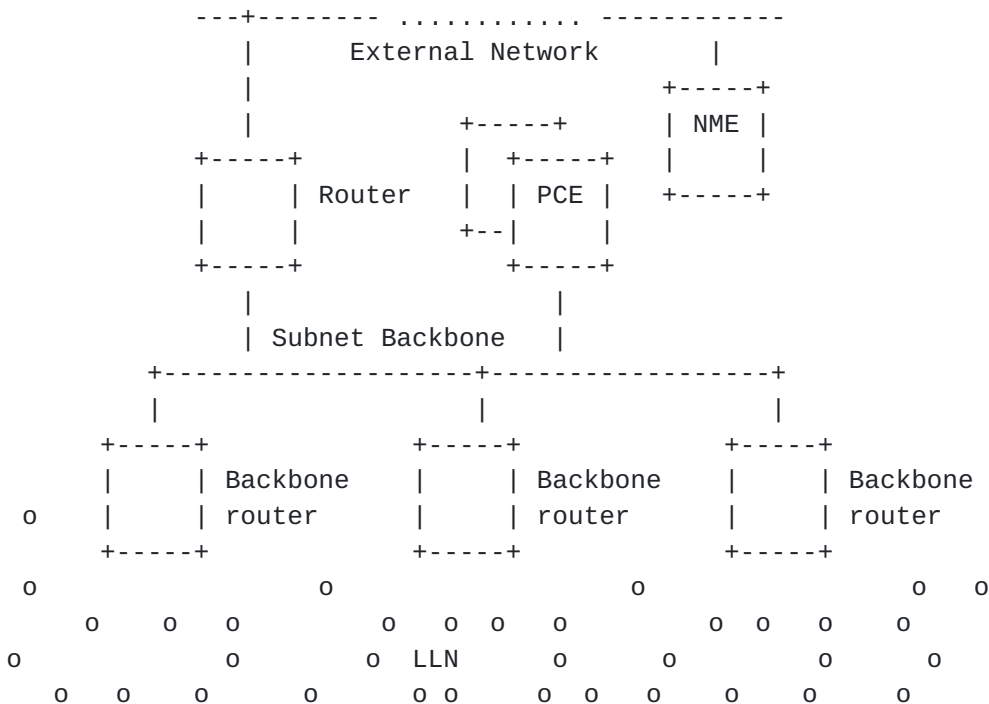


Figure 5: Extended 6TiSCH Network

The backbone router must ensure end-to-end deterministic behavior between the LLN and the backbone. We would like to see this accomplished in conformance with the work done in [\[I-D.finn-detnet-architecture\]](#) with respect to Layer-3 aspects of deterministic networks that span multiple Layer-2 domains.

The PCE must compute a deterministic path end-to-end across the TSCH network and IEEE802.1 TSN Ethernet backbone, and DetNet protocols are expected to enable end-to-end deterministic forwarding.

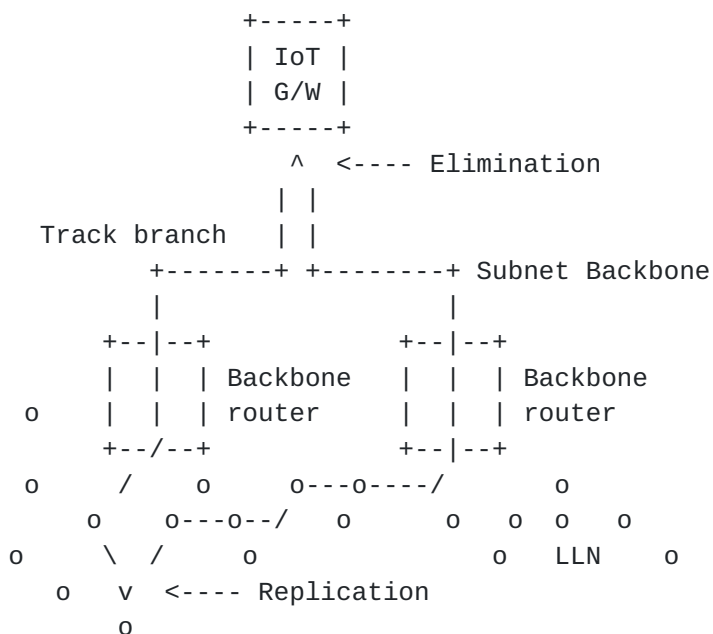


Figure 6: 6TiSCH Network with PRE

5.3.1.1. PCE and 6TiSCH ARQ Retries

6TiSCH uses the IEEE802.15.4 Automatic Repeat-reQuest (ARQ) mechanism to provide higher reliability of packet delivery. ARQ is related to packet replication and elimination because there are two independent paths for packets to arrive at the destination, and if an expected packet does not arrive on one path then it checks for the packet on the second path.

Although to date this mechanism is only used by wireless networks, this may be a technique that would be appropriate for DetNet and so aspects of the enabling protocol could be co-developed.

For example, in Figure 6, 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 arrives within the allocated 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).

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.

5.3.2. Schedule Management by a PCE

A common feature of 6TiSCH and DetNet is the action of a PCE to configure paths through the network. Specifically, what is needed is a protocol and data model that the PCE will use to get/set the relevant configuration from/to the devices, as well as perform operations on the devices. We expect that this protocol will be developed by DetNet with consideration for its reuse by 6TiSCH. The remainder of this section provides a bit more context from the 6TiSCH side.

5.3.2.1. PCE Commands and 6TiSCH CoAP Requests

The 6TiSCH device does not expect to place the request for bandwidth between itself and another device in the network. Rather, an operation control system invoked through a human interface specifies the required traffic specification and the end nodes (in terms of latency and reliability). Based on this information, the PCE must compute a path 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 recognizing that a certain packet belongs to a certain path, 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 paths. 6TiSCH expects that the programming of the schedule will be done over COAP as discussed in [\[I-D.ietf-6tisch-coap\]](#).

6TiSCH expects that the PCE commands will be issued directly as CoAP requests or 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. Related

information about 6TiSCH can be found at [\[I-D.ietf-6tisch-6top-interface\]](#) and RPL [\[RFC6550\]](#).

If it appears that a path through the network does not perform as expected, a protocol may be used to update the state in the devices, but in 6TiSCH 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.

A "slotFrame" is the base object that the PCE needs to manipulate to program a schedule into an LLN node ([\[I-D.ietf-6tisch-architecture\]](#)).

The PCE should be able to read energy data from devices, and compute paths that will implement policies on how energy in devices is consumed, for instance to ensure that the spent energy does not exceeded the available energy over a period of time.

6TiSCH devices can discover their neighbors over the radio using a mechanism such as beacons, but even though the neighbor information is available in the 6TiSCH interface data model, 6TiSCH does not describe a protocol to proactively push the neighborhood information to a PCE. DetNet should define this protocol, and it should operate over CoAP. The protocol should be able to carry multiple metrics, in particular the same metrics as used for RPL operations [\[RFC6551\]](#)

[5.3.2.2.](#) 6TiSCH IP Interface

"6top" ([\[I-D.wang-6tisch-6top-sublayer\]](#)) 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 data model and management interfaces are further discussed in [\[I-D.ietf-6tisch-6top-interface\]](#) and [\[I-D.ietf-6tisch-coap\]](#).

An IP packet that is sent along a 6TiSCH path uses the Differentiated Services Per-Hop-Behavior Group called Deterministic Forwarding, as described in [\[I-D.svshah-tsvwg-deterministic-forwarding\]](#).

[5.3.3.](#) 6TiSCH Security Considerations

On top of the classical requirements for protection of control signaling, it must be noted that 6TiSCH networks operate on limited resources that can be depleted rapidly in a DoS attack on the system, for instance by placing a rogue device in the network, or by obtaining management control and setting up unexpected additional paths.

5.4. Wireless Industrial Asks

6TiSCH depends on DetNet to define:

- o Configuration (state) and operations for deterministic paths
- o End-to-end protocols for deterministic forwarding (tagging, IP)
- o Protocol for packet replication and elimination
- o Protocol for packet automatic retries (ARQ) (specific to wireless)

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 7 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 7 "eNB" ("E-UTRAN Node B") is the hardware that is connected to the mobile phone network which communicates directly with mobile handsets ([[TS36300](#)]).

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. $1/4 T_c$).
- * For intra-band contiguous carrier aggregation, with or without MIMO or TX diversity, TAE shall not exceed 130 ns (i.e. $1/2 T_c$).
- * For intra-band non-contiguous carrier aggregation, with or without MIMO or TX diversity, TAE shall not exceed 260 ns (i.e. one T_c).
- * 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 frequency 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 $2.4 \cdot 10^{-9}$ (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:

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

Today's Midhaul and Backhaul networks typically consist of:

- o Mostly normal IP networks, MPLS-TP, etc.
- o 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:

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

- o 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:

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

A standard for data flow information models that are:

- o Aware of the time sensitivity and constraints of the target networking environment
- o 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:

- o Zero congestion loss.
- o 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

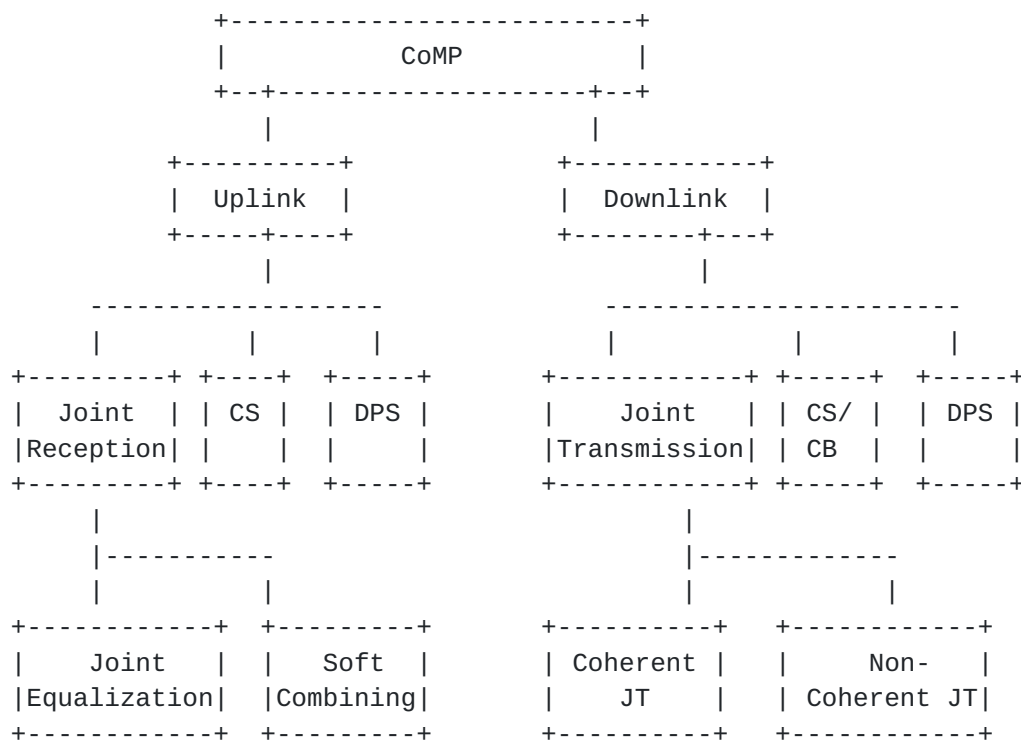


Figure 8: Framework of CoMP Technology

As shown in Figure 8, 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):

- o 1000 times higher mobile data volume per area
- o 10 times to 100 times higher typical user data rate
- o 10 times to 100 times higher number of connected devices
- o 10 times longer battery life for low power devices
- o 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:

- o Unified protocols and delay-guaranteed forwarding network equipment that is capable of delivering deterministic latency services.
- o Unified management and protocols which take delay and timing into account.
- o Unified deterministic latency data model and signaling for resource reservation.

[7.4.](#) CoMP Asks

To fully utilize the power of CoMP, it requires:

- o Very tight absolute delay bound (100-500us) within 7-10 hops.
- o Standardized data plane with highly deterministic networking capability.
- o 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:

- o Network-aware constraints on the networking environment

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 a converged IP-standards-based network with deterministic properties that can satisfy the timing, security and reliability constraints described above. Today's proprietary networks could then be interfaced to such a network via gateways or, in the case of new installations, devices could be connected directly to the converged network.

8.4. Industrial M2M Asks

- o Converged IP-based network
- o Deterministic behavior (bounded latency and jitter)
- o High availability (presumably through redundancy) (99.999 %)
- o Low message delivery time (100us - 50ms)
- o Low packet loss (burstless, 0.1-1 %)
- o Precise time synchronization accuracy (1us)
- o 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

- o Unified control and management protocols to handle time-critical data flow
- o Application-aware flow filtering mechanism to recognize the timing critical flow without doing 5-tuple matching
- o Unified control plane to provide low latency service on Layer-3 without changing the data plane
- o 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:

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

- o 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)
- o 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)
- o 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)
- o 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))
- o 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)
- o High availability (99.9999 percent up time requested, but may be up to twelve 9s)
- o Reliability, redundancy (lives at stake)
- o Security (from failures, attackers, misbehaving devices - sensitive to both packet content and arrival time)

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Pascal Thubert, CTAO Cisco

11.3. Building Automation Systems

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11.4. Wireless for Industrial

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11.5. Cellular Radio

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