A PCE-Based Framework for Future Internet Deterministic and Time-Sensitive Networks

Daniel King, Lancaster University, UK
d.king@lancaster.ac.uk
Adrian Farrel, Old Dog Consulting, UK
adrian@olddog.co.uk

Abstract— **Deterministic and time-sensitive networking will be critical for enabling ultra-reliable low latency communication (URLLC) networks and services. However, limitations exist for using traditional IP technologies and current Internet architecture, for deterministic and time-sensitive networking. The emerging URLLC network types and traffic types require new fundamental cornerstones that include deterministic behaviour, real-time sensitivity, and capable of being highly resilient to network infrastructure failures. Various technologies exist with the current Internet to provide limited capabilities for each primitive. However, fully achieving the URLLC objectives will require a radical approach that moves beyond current network design and Internet architecture.**

This paper proposes a new approach and architecture for extending the data plane and control plane elements for future URLCC requirements. It provides a summary of applicable transport, control and service layers. How existing functions and mechanisms will need to be extended and combined to meet the future demands of Future Internet networks and services. Finally, the paper provides a theoretical PCE-based framework for future deterministic and time-sensitive networks, and the protocol work required to standardize and deploy.

Keywords—URLCC, IoT, Scheduling, determinism, Time-Sensitive Networks, Standardization, PCE, DetNet, TSN.

I. Introduction

For beyond 5G and Network 2030 [1] environments, known as "Future Internet" in this paper, we focus on Ultra-Reliable Low-Latency Communications (URLLC) applications, which require reliable communication between nodes and ultra-low latency communication [2]. We can state that URLLC presents strict network requirements on latency and reliability for mission-critical communications, including holographic type communications, driverless vehicles, and tactile Internet. In contrast, other application types including Massive Machine Type Communications (mMTC) require support for an exponentially large number of devices which may only transmit information sporadically, such as the massive Internet of Things (mIoT) factory use cases [2]. The concept of determinism must also be applied to these emerging network types, allowing resource allocation mechanisms to be intelligently controlled for lossless data transmission and energy efficiency.

Addressing the deterministic URLLC and mIoT use cases for Future Internet calls for novel approaches to network system design and development of new or enhanced protocol mechanisms. One of the current paradoxical research questions is also how to satisfy service requirements for future networks that are deterministic, time-sensitive and temporal [3], but potential using existing techniques that are designed for non-deterministic legacy networks. The latter requirement becomes increasingly crucial as a resource (communication channel/slot) assignment may occur before actual data transmission, and if the node is in sleep mode.

Expecting that existing Internet protocol frameworks and transport mechanisms apply to solve the resilience and latency requirements for Future Internet is a potential path to failure. Current limitations exist within the Internet, and we are only capable of delivering what the current IP protocol stack and ancillary protocols can provide. Therefore, for Future Internet networks that are expected to be in operation by 2030, we must begin to define the functional components, external interfaces, and protocol capabilities, that will be required for future deterministic and time-sensitive networks. Facilitating the development and prototyping of candidate technologies by 2024, and

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early deployment of standardized and interoperable solutions by 2026 to 2028, and general use by 2030, might be considered a tight schedule. Therefore, we must be pragmatic and consider how existing technology can be enhanced to meet future requirements.

This paper sets out the essential requirements for future networks will drive the augmentation of existing technology, and a proposed framework. It outlines a pragmatic approach with the key technologies and Path Computation Element-based framework to solve Future Internet deterministic and time-sensitive network use cases, with a focus on URLLC applications.

A. *Network Determinism*

A deterministic system is defined as a system in which no randomness is involved in the development of future states of the network. A deterministic model will thus always produce the same network path or allocation of resources, from a given set of conditions.

An emerging networking concept is "Explicit Determinism" [4], this is a stringent set of functional network requirements, with guarantees, as to how portions of the network infrastructure will need to behave. It includes a basis that accurate scheduling is available wherever it is needed to support the synchronization, assignment of resources, and activation of network operations, for Future Internet. These capabilities will be critical for the coordinated operation of low-latency and lossless network transmission.

B. *Time-Sensitive Networks*

The concept of "time" in networks has radically evolved in the last five years [5]. It plays a critical role to enable real-time communication over Ethernet networks, also blending deterministic quality of service (QoS) capabilities. Time-sensitive networking is separated into three main components:

1. Synchronized Network Time - All nodes that are participating in the network will have the same understanding of the current time.
2. Resource Scheduling - All nodes that are participating in the network conform to the same processing and forwarding rules for the planned transport of future traffic.
3. Path Computation and Traffic Engineering - All nodes that are participating in the network adhere to the same rules for path selection, bandwidth reservation, and allocation of timeslots. Where needed, services may also utilize more than one simultaneous path to achieve service resilience.

Current networks and protocols are designed based on the needs of legacy applications, where reliable eventual delivery was more important than delivering within a specific time. We typically do not see specific link metrics and path constraints for hop delay or time synchronization. Network congestion can also manage by throttling and retransmitting dropped packets at the transport layer, and typically preventing congestion at the link layer is secondary. To avoid delay or congestion, current networks are often overprovisioned and "always-on", otherwise congestion would break applications and adversely affect traffic.

Area	Application	QoS Requirements Latencies	Jitter
Medical [47]–[49]	Tele-Surgery, Haptic Feedback	3–10 ms	< 2 ms
Industry [50]	Indust. Automation, Control Syst.	0.2 μs–0.5 ms for netw. with 1 Gbit/s link speeds	meet lat. req.
		25 μs–2 ms for netw. with 100 Mbit/s link speeds	meet lat. req.
	Power Grid Sys.	approx. 8ms	few μs
Banking [51]	High-Freq. Trading	< 1 ms	few μs
Avionics [52]	AFDX Variants	1–128ms	few μs
Automotive [53]–[56]	Adv. Driver. Assist. Sys. (ADAS)	100–250 μs	few μs
	Power Train, Chassis Control	$< 10\mu s$	few μs
	Traffic Efficiency & Safety	< 5 ms	few μs
Infotainment [57]	Augmented Reality	7–20 ms	few μs
	Prof. Audio/Video	2–50 ms	< 100 μs

Table 1. Reliability and Delay Requirements for URLLC Applications [6]

Previous work has suggested very demanding limits on latency and jitter for URLLC services. The table above outlines those reliability and delay requirements.

II. CHALLENGES FOR URLLC SERVICES

A. *Limitations of Tradional IP Networks*

The TCP/IP protocol stack is almost 50 years old and has been exceptional successful in facilitating the development and deployment of the current Internet. However, with the advent of newer applications and services the assumption scaling the Internet to meet new application requirements such as URLLC, is simply a matter of adding additional bandwidth is no longer applicable. Especially as

URLLC devices will often be resource-constrained and connected via dynamic network topologies.

For URLLC applications over existing Internet infrastructure, potential data loss occurs may occur if buffers are too small or, the network bandwidth is insufficient. Bandwidth may also be a problem if incoming data rates exceed outgoing data capabilities. The data rate can also be a problem when the egress cannot handle the arrival rate. Traffic bursts in both scenarios could be handled with buffers, but buffers are finite and buffer resources soon become exhausted. The legacy mechanisms that may be employed are not suitable, as they often buffer data, but that would add excessive delay or jitter, which would unacceptable and break that end-to-end connection, especially when a minimum delay is required.

Based on the requirements discussed for URLLC applications and the issues identified with traditional Internet architecture, the following objective requirements (R1-R5) are identified for Future Internet deterministic and time-sensitive networks:

- **R1**: "Good enough" scheduling of network resources and paths.
- **R2**: Hard guarantees for packet loss and bounded latency.
- **R3**: Cost-effective use of physical (wired and wireless), and consideration of node and link energy efficiency.
- **R4**: A priori classification of service flows and network behaviour requirements.
- **R5**: Computation of redundant paths (that meet minimum delay requirements for applications), ensuring minimal, or negation of delay variation between primary and backup paths, that might impact the service.

III. CURRENT ENABLING TECHNOLOGIES

A. *IEEE Time-Sensitive Networks*

The IEEE Time-sensitive Networking (TSN) 802.1Q technology provides deterministic data transfer over industry-standards Ethernet. The TSN technology is centrally managed and provides guarantees of delivery and minimized jitter using time scheduling for those real-time applications that require determinism. This concept provides a baseline for our future framework for Ethernet-based services.

Table 2. Key TSN Standards

Standard	Technology Capability
IEEE 802.1ASrev, IEEE 1588	Timing and synchronization
IEEE 802.1Qbu and IEEE 802.3br	Forwarding and queuing
IEEE 802.1Qca	Path control and reservation
IEEE 802.1Qcc	Central configuration method
IEEE 802.1Qci	Time-based ingress policing
IEEE 802.1CB	Seamless redundancy

The above TSN standards provide the capability to ensure time synchronization, zero congestion loss, and ultra-reliability, in for Ethernet, MPLS and IP networking environments.

B. *IETF DetNet*

The IETF DetNet working group has similar objectives to the IEEE TSN effort. Therefore, DetNet also has features such as time synchronization, zero congestion loss and reliability. In contrast to IEEE TSN though, DetNet looks to extend the concepts of ultra-low latency and exceptionally reliability of services across layer-3 networking nodes.

Standard	Technology Capability
draft-ietf-detnet-architecture (RFC8655)	Architecture and techniques to carry real-time data
draft-ietf-detnet--data-plane-framework	Framework for control-plane
draft-ietf-detnet--dp-sol-ip	IP Data Plane Encapsulation
draft-ietf-detnet--ip-over-tsn	Operation in an IP over TSN
draft-ietf-detnet-security	Security Considerations
draft-ietf-detnet -topology-yang	Topology YANG Model
draft-ietf-detnet-yang	Configuration YANG Mod

Table 3. Key DetNet Standards

The objectives of the IEEE TSN and IETF DetNet technologies were to create reliable ultra-low-latency networks, capable of understanding time synchronization, zero congestion loss, and providing resilience for real-time latency-sensitive applications. These technologies are for networks that are under typically used in single technology domains or closed administrative regions. However, they have been proven to be applicable to URLLC requirements [6], also shown in Table 1.

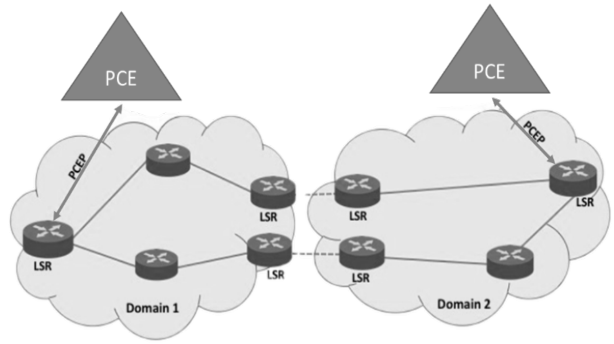
Our analysis shows that although both IEEE TSN and IETF DetNet solve R2 and R4 technical objectives that were outlined earlier in this document, there are significant gaps from a control (R1) and resource optimization (R3) perspective, and also future heterogeneous networks, from both technology developments. Furthermore, they do not address emerging requirements for resource and location identification [7]. Although the IPv6 fixed 128bit addressing helped with the constrained Internet address space, the protocols and mechanisms to operate IPv4 and IPv6 may be too complex for IoT and lossy and low power devices used in Smart City and Industry 4.0 applications.

IV. A Centralized Control Framework

The IETF Path Computation Element (PCE) [8] has been continuously evolving. Initially designed as a passive entity (only responding when asked) that provides online single-domain and multi-domain path computation responses, it has been extended to an active-stateful entity capable of making recommendations to the network when more optimal paths for existing connections are available, or remotely initiating single or global optimizations to defragment network resource that has been siloed.

Figure 1 below demonstrates the reference architecture for using PCE in network control implementations. The PCE may also be used in SDN controller applications as outlined within RFC7491 [9] "A PCE Architecture for Application-Based Network Operations", also known via the ABNO acronym.

Figure 1. Generic Reference Architecture for the Path Computation Element (PCE)



Recent IoT network control technologies, including 6LoWPAN and ROLL, introduced mechanisms to integrate low-power wireless networks for the current Internet. These technologies use distributed control for address assignment, path computation and setup. A centralized path computation entity might be applied, but would have some weaknesses, significantly when solving NP-complete problems. For multi-path and multi-dimensional route optimization, we find that generally centralized solutions using linear algorithms. As multi-path route optimizations also need to consider multiple overlapping and interacting constraints, and linear solutions do not typically scale to exceptionally large topologies, and multi-dimensional problem solving, and are too costly to address large scale node, link, and service monitoring efficiently.

Future Internet will integrate converged TSN, DetNet and IP-inspired technologies, allowing network infrastructure to deliver a variety of services to support the two requirements of variable traffic characteristics, and dynamic demands of services. In addition to the end-to-end assurance objective, there is an increasing demand to make the network more efficient and responsive to service requests, creating connections on demand and for the specific period required.

A. *The Applicability of PCE to URLLC Services*

A deterministic approach to time-sensitive networks would provide significant value. Scheduling reduces transmission losses via exploitation of time and frequency diversities, and applied bandwidth optimization will enable energy conservation and usage efficiencies. If it is possible to synchronize sender and listeners, it would be possible to maintain network devices in sleep-state between scheduled transmissions, minimizing the use of power spent in idle listening and eliminating the need for long preambles.

We use the term "logically centralized" to signify that network control may appear focused in a single entity, independent of its possible implementation in distributed form. The centralized control principle also facilitates the use of assigning resources more efficiently when viewed from a global perspective. Therefore, the use of a logically centralized controller principle provides the cornerstone for URLLC traffic assurance and more efficient deterministic multi-constraint-based networking and would provide a foundation for further service innovation in the future.

A PCE-based network controller would have the benefit of being well-defined and capable of being combined with other technology components, mechanisms and procedures; these include the following layers and functional components:

Application-Layer Policy – Requested by Edge-nodes or applications.

- Access control of entity and application requests for network resource information and connectivity. This functional component would apply service properties, including delay, latency, bandwidth, jitter, and protection requirements, when requesting a connection.

Controller Layer - Handling of path computation requests and responses.

- Topology Manager - Extraction of information about node and interface resources available in a network.
- Monitoring, Scheduling, and Power Management - Allocation, and provisioning and reservation of network resources of path setup and ongoing path monitoring.
- Flow Manager - Path switching and restoration in the event of network failure.

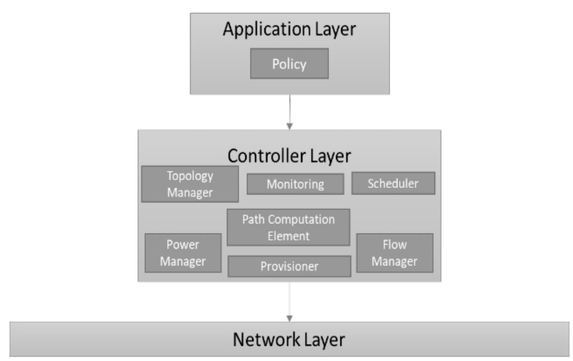
B. *A framework for a PCE-based Controller Framework for Future Internet*

A fundamental assumption of a PCE-based controller for deterministic and time-sensitive networks is that a protocol mechanism is available to reserve path and resources when required at a scheduled time or event. This capability might be fulfilled by TSN or DetNet, which we highlighted earlier, or might be an entirely new mechanism which would provide guaranteed data delivery within a guaranteed time window, i.e., bounded low latency with traffic shaping, resource management, time synchronization, and reliability.

The key modules of the PCE-based controller framework include:

- Application Policy Function: a module for input of the URLLC service requirement as defined by the service-type model, using YANG [10] or equivalent.
- Topology Discovery Function: a module that parses the node and link information, and abstracts the underlying logical network (fixed, wireless, or a combination of both) topology.
- Path Calculation Function: a module that centrally calculates the optimized end-to-end path using the declared policies for wireless channel allocation and preference.
- Path Provisioning, Assurance and Adjustment Function: this would apply the provisioning parameters to output the corresponding configuration stanza to all of the nodes on the path, monitor path performance and adjust paths as necessary, especially when redundant paths for resiliency are required.

Figure 1. Simple PCE-Based Framework for URLLC Networks



C. *PCE Protocol (PCEP) Enhancements Required*

In PCE-based networks, the PCE can generate a network topology, link properties (latency and power), by extracting networking topology directly from the online network elements, or via a higherlayer inventory management database. However, knowing the topology is not sufficient to compute a deterministic path. In URLLC networks, it would be essential to consider the number and size of buffers, queues types and length, time precision, and pre-emption, these parameters would be used to compute a workable service schedule.

The PCE has several objective functions and constraints which are currently standardized via the PCE protocol (PCEP), the following parameters and objective functions would need to be added for URLLC network types [11]; these include:

- Orthogonal Frequency-division Multiplexing Numerologies which define the subcarrier spacing and the cyclic prefix value, and associated transmission parameters, slot length, and frequency bands.
- Low power wireless nodes are typically equipped with a single radio interface with half-duplex properties. In this scenario, paths must be selected and reserved based on power, link, and end-to-end resource requirements
- Multiple flows may not be able to store even one frame per flow, and after a receiving data will need to be scheduled for transmitting and cleaning the buffer.

For each of these areas of behavioural function, the PCE must obtain the exact properties of each node, the topology that they can form, based on available radio propagation characteristics.

Given the additional information outlined in this sub-section, a PCE-enabled controller would be capable of computing paths for URLLC services. Once requested, it would schedule the path that optimizes (locally or globally) the energy constraints of the nodes, and enable an optimal duration within the constrained resources, and ensure latency bounds have been achieved.

The PCE could also be used to evaluate the energy consumption of the nodes and manage power efficiently. Network modes will enter a specific series of states that include deep sleep, wake, transmit and receive. Each node will also have specific energy properties, such as the capacity of the device to store energy, and the capability to renew its energy store with scavenging techniques.

V. Summary

The PCE has been an important evolutionary step in development of communication networks. The concept of PCE also provided the steppingstone towards Software-Defined Networking Controller architectures. Several current SDN controller platforms, including the Linux Foundation Open Daylight (ODL) and Open Networking Operating System (ONOS) controllers, utilize the PCE.

Leveraging PCE-based technology would enable deterministic communication, based on the centralized admission control and the scheduling of the Future Internet wireless, or wired, resources for URLLC, and with a quality of service such as latency and reliability that can be guaranteed.

As highlighted, current PCE technology would need to be enhanced to understand ultra-reliable and low latency performance metrics and parameters, e.g., support for different OFDM numerologies and slot-durations, as well as fast processing capabilities and redundancy techniques that lead to achievable latency numbers of below 1ms with reliability guarantees up to 99.999%.

To utilize the PCE-technology and calculate efficient paths for URLLC services the PCE, or controller, Transport layer understanding for the PCE would be done via the development of PCE Protocol (PCEP) Objective Functions (OF), PCEP Path Setup Type Length Values, that reflect the transport layer capabilities and behaviour for URLLC services. Additional, PCEP extensions could also be developed for discovery and capability negotiation. These new protocol developments would be pursued via the Internet Engineering Task Force PCE Working Group [13].

The PCE represents useful technology to facilitate URLLC and IoT use cases, e.g., via the integration of TSN and DetNet, and potentially other Future Internet transport technology where latency, resource management, time synchronization, and reliability, computation and optimization were managed using non-TSN or DetNet technologies.

The benefit of a new PCE-based framework is that the underlying transport technology may continue to evolve. Facilitating the evolution of network control by extending modular PCE mechanisms, to enhance or support new transport types and traffic requirements for URLLC and beyond.

A PCE-based framework for URLLC would also facilitate intent-based networking and control of URLLC services. This would be achieved via the application or end-users directly interacting with the network layer through an intermediate intent (or knowledge layer) based on the URLLC application and technical requirements. This intent requirement and capability are often documented in discussions on Future Internet [13].

Intent-based networking is seen as fundamental in allowing the Internet to evolve from a statically and human-driven resource management system, to an automated dynamic system, capable of continuously and consistently adapting to end-user and application demands. In the PCE framework outlined in this paper, the intent request would be applied via the declarative policy module that interacts with the URLLC application layer, this request would then be translated into imperative policy within the controller layer, as part of the PCE path computation process itself.

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