UNICO I+D Project
6G-DATADRIVEN-04

6G-DATADRIVEN-04-E10

RAW extensions: intermediate release

Abstract

This report includes a set of refined proposed RAW extensions required for industrial scenarios, including a summary of activities at the IETF.

Financiado por la Unión Europea NextGenerationEU
GOBIERNO DE ESPAÑA
MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL
SECRETARÍA DE ESTADO DE TELECOMUNICACIONES E INFRAESTRUCTURAS DIGITALES
Plan de Recuperación, Transformación y Resiliencia

Document properties

Document number	6G-DATADRIVEN-04-E10
Document title	RAW extensions: intermediate release
Document responsible	Carlos J. Bernardos
Document editor	Carlos J. Bernardos (UC3M)
Editorial team	Carlos J. Bernardos (UC3M)
Target dissemination level	Public
Status of the document	Final
Version	1.0
Delivery date	31/12/2023
Actual delivery date	31/12/2023

Production properties

Reviewers	Antonio de la Oliva (UC3M)

Disclaimer

This document has been produced in the context of the 6G-DATADRIVEN Project. The research leading to these results has received funding from the Spanish Ministry of Economic Affairs and Digital Transformation and the European Union-NextGenerationEU through the UNICO 5G I+D programme.

Table of Contents

List of Figures 5
List of Acronyms 6
Resumen Ejecutivo 7
Executive Summary 9
1. Introduction 11
2. Use case: Wireless for Industrial Applications 13
2.1. Specifics 13
2.1.1. Control Loops 13
2.1.2. Monitoring and diagnostics 13
2.2. The Need for Wireless 14
2.3. Requirements for RAW 14
2.3.1. Non-latency critical considerations 15
2.4. Status as of today and identified gaps 15
3. Multidomain extensions 16
3.1. Introduction 16
3.2. Application plane 17
3.3. Controller plane 17
3.4. Network/Data plane 18
3.5. RAW specific analysis 19
3.6. RAW multi-domain extensions 20
4. Mobility in single RAW domains 23
4.1. Problem Statement 23
4.2. RAW mobility extensions 24
4.2.1. UE-controlled RAW-enabled mobility 24
4.2.2. Network-controlled RAW-enabled mobility 26
4.3. Proxy Mobile IPv6 extensions 27
4.3.1. RAW HO Initiate 27
4.3.2. RAW HO ACK 28
4.3.3. New mobility options 29
5. Operations, Administration and Maintenance (OAM) for Deterministic Networking 32

Financiado por la Unión Europea NextGenerationEU
GOBIERNO DE ESPAÑA — MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL — SECRETARÍA DE ESTADO DE TELECOMUNICACIONES E INFRAESTRUCTURAS DIGITALES
Plan de Recuperación, Transformación y Resiliencia
UNICO I+D

6. Conclusions and IETF impact analysis 33
7. References 34
8. Annex A: Changes from 6G-DATADRIVEN-04-E9 36

Financiado por la Unión Europea NextGenerationEU
GOBIERNO DE ESPAÑA MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL SECRETARÍA DE ESTADO DE TELECOMUNICACIONES E INFRAESTRUCTURAS DIGITALES
Plan de Recuperación, Transformación y Resiliencia
UNICO I+D

List of Figures

Figure 1: DetNet Service Reference Model (Multidomain) (from RFC8655) 16

Figure 2: Exemplary scenario showing multiple RAW domains 19

Figure 3: Multi-domain RAW signaling 21

Figure 4: Exemplary scenario depicting RAW mobility 23

Figure 5: UE-controlled RAW-enabled mobility signalling 26

Financiado por la Unión Europea NextGenerationEU

GOBIERNO DE ESPAÑA MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL SECRETARÍA DE ESTADO DE TELECOMUNICACIONES E INFRAESTRUCTURAS DIGITALES

Plan de Recuperación, Transformación y Resiliencia

UNICO I+D

List of Acronyms

3GPP: 3rd Generation Partnership Project (3GPP)

AI/ML: Artificial Intelligence / Machine Learning

CPF: Controller Plane Function

DetNet: Deterministic Networking

DT: Digital Twin

IEEE: Institute of Electrical and Electronics Engineers

IETF: Internet Engineering Task Force

IoT: Internet of Things

IT: Internet technology

LDACS: L-band Digital Aeronautical Communications System

NFV: Network Function Virtualization

NME: a Network Management Entity

OAM: Operations, Administration and Management

OT: Operational Technology

PAREO: Packet (hybrid) ARQ, Replication, Elimination and Ordering

PCE: Path Computation Element

PLC: Programmable Logic Controller

PREOF: Packet Replication, Elimination, and Ordering Functions

PSE: Path Selection Engine

RAW: Reliable and Available Wireless

SDO: Standards Developing Organization

TSCH: IEEE Std. 802.15.4 timeslotted channel hopping

TSN: Time-Sensitive Networks

URLLC: Ultra-Reliable Low Latency Communications

Financiado por la Unión Europea NextGenerationEU
GOBIERNO DE ESPAÑA
MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL
SECRETARÍA DE ESTADO DE TELECOMUNICACIONES E INFRAESTRUCTURAS DIGITALES
Plan de Recuperación, Transformación y Resiliencia
UNICO I+D

Resumen Ejecutivo

Este documento proporciona una actualización del entregable 6G-DATADRIVEN-04-E9. Incluye un análisis de extensiones/soluciones RAW (Reliable and Available Wireless) necesarias para entornos industriales para el proyecto 6G-DATADRIVEN-04. El documento incluye el diseño actualizado de varias soluciones, identificadas en la versión inicial de este documento (6G-DATADRIVEN-04-E9). Se incluye también un reporte de las actividades realizadas en el IETF, junto con un análisis respecto a las actividades originalmente planificadas. De cara a facilitar la legibilidad y el impacto de este documento, se ha decidido que sea autocontenido, construyendo a partir de la versión inicial, e incluyendo un anexo en el que se enumeran los principales cambios comparados con dicha versión inicial.

Los principales resultados descritos en este entregable son:

- la identificación de extensiones necesarias a la arquitectura base de RAW y DetNet (Deterministic Networking) definidas en el IETF, para entornos industriales;
- el diseño de algunas de las extensiones anteriores; y
- un análisis de las actividades realizadas en el IETF durante 2023 y su impacto, así como una actualización de la planificación de contribuciones y su potencial adopción en el IETF durante 2024.

Siguiendo la planificación incluida en la versión inicial de este documento, parte de estos resultados se han enviado y presentado ya al IETF. En concreto, se ha participado como co-autor y/o editor en las siguientes contribuciones, incluyendo una ya publicada como RFC:

- Bernardos, C. J., Papadopoulos, G. Z., Thubert, P., & Theoleyre, F. (2023, September). *Reliable and Available Wireless (RAW) Use Cases*. RFC 9450. Retrieved from https://datatracker.ietf.org/doc/rfc9450/
- Bernardos, C. J., & Mourad, A. (2023, September). *RAW multidomain extensions*. Internet-Draft, IETF Secretariat. Retrieved from https://www.ietf.org/archive/id/draft-bernardos-detnet-raw-multidomain-00.txt
- Bernardos, C. J., & Mourad, A. (2023, July). *DETNET multidomain extensions*. Internet-Draft, IETF Secretariat. Retrieved from https://www.ietf.org/archive/id/draft-bernardos-detnet-multidomain-02.txt
- Bernardos, C. J., & Mourad, A. (2023, September). *MIPv6 RAW mobility*. Internet-Draft, IETF Secretariat. Retrieved from https://www.ietf.org/archive/id/draft-bernardos-detnet-raw-mobility-00.txt
- Mirsky, G., Theoleyre, F., Papadopoulos, G. Z., Bernardos, C. J., Varga, B., & Farkas, J. (2023, December). *Framework of Operations, Administration and Maintenance (OAM) for*

Financiado por la Unión Europea NextGenerationEU
GOBIERNO DE ESPAÑA MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL SECRETARÍA DE ESTADO DE TELECOMUNICACIONES E INFRAESTRUCTURAS DIGITALES
Plan de Recuperación, Transformación y Resiliencia
UNICO I+D

Deterministic Networking (DetNet). Internet-Draft, IETF Secretariat. Retrieved from https://www.ietf.org/archive/id/draft-ietf-detnet-oam-framework-10.txt

También se ha presentado un artículo en un workshop de una conferencia internacional, en el que se discuten algunas de las extensiones propuestas en este documento::

- CJ. Bernardos, et al., 2023. Using RAW as Control Plane for Wireless Deterministic Networks: Challenges Ahead. In Proceedings of the Twenty-fourth International Symposium on Theory, Algorithmic Foundations, and Protocol Design for Mobile Networks and Mobile Computing (MobiHoc '23). Association for Computing Machinery, New York, NY, USA, 328–333. https://doi.org/10.1145/3565287.3617608

El resto del documento está redactado en inglés, de cara a maximizar el impacto del trabajo realizado en este proyecto.

Financiado por la Unión Europea NextGenerationEU
GOBIERNO DE ESPAÑA MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL SECRETARÍA DE ESTADO DE TELECOMUNICACIONES E INFRAESTRUCTURAS DIGITALES
Plan de Recuperación, Transformación y Resiliencia
UNICO I+D

Executive Summary

This document provides an update of the deliverable 6G-DATADRIVEN-04-9. It includes an analysis of RAW (Reliable and Available Wireless) extensions/solutions needed for industrial environments for the project 6G-DATADRIVEN-04. The document includes an updated and more detailed design of several solutions, identified in the previous version of this document (6G-DATADRIVEN-04-E9). A report of the activities carried out at the IETF is also presented, together with an analysis of what was initially planned. In order to facilitate the readability of this document and improve its impact, it has been decided to keep the document self-contained, building on top of the previous (initial) version, and including an annex that enumerates the main changes compared to the previous version.

The main results described in this deliverable are:

- the identification of the extensions to the base RAW and DetNet (Deterministic Networking) architecture defined by the IETF, for industrial environments;
- the design of some of the previous extensions; and
- an analysis of the activities performed in the IETF in 2023, and its impact, as well as an update of the contribution roadmap and its potential adoption at the IETF during 2024.

Following the initial roadmap (included in the first version of this document), some of these results have been already submitted and presented at the IETF, as first versions. Namely, we have participated as co-author and/or editor of the following contributions, including one RFC:

- Bernardos, C. J., Papadopoulos, G. Z., Thubert, P., & Theoleyre, F. (2023, September). *Reliable and Available Wireless (RAW) Use Cases*. RFC 9450. Retrieved from https://datatracker.ietf.org/doc/rfc9450/
- Bernardos, C. J., & Mourad, A. (2023, September). *RAW multidomain extensions*. Internet-Draft, IETF Secretariat. Retrieved from https://www.ietf.org/archive/id/draft-bernardos-detnet-raw-multidomain-00.txt
- Bernardos, C. J., & Mourad, A. (2023, July). *DETNET multidomain extensions*. Internet-Draft, IETF Secretariat. Retrieved from https://www.ietf.org/archive/id/draft-bernardos-detnet-multidomain-02.txt
- Bernardos, C. J., & Mourad, A. (2023, September). *MIPv6 RAW mobility*. Internet-Draft, IETF Secretariat. Retrieved from https://www.ietf.org/archive/id/draft-bernardos-detnet-raw-mobility-00.txt
- Mirsky, G., Theoleyre, F., Papadopoulos, G. Z., Bernardos, C. J., Varga, B., & Farkas, J. (2023, December). *Framework of Operations, Administration and Maintenance (OAM) for Deterministic Networking (DetNet)*. Internet-Draft, IETF Secretariat. Retrieved from https://www.ietf.org/archive/id/draft-ietf-detnet-oam-framework-10.txt

Financiado por la Unión Europea NextGenerationEU
GOBIERNO DE ESPAÑA MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL SECRETARÍA DE ESTADO DE TELECOMUNICACIONES E INFRAESTRUCTURAS DIGITALES
Plan de Recuperación, Transformación y Resiliencia
UNICO I+D

A publication of some of the mechanisms reported in this document has been presented in an international workshop:

- CJ. Bernardos, et al., 2023. Using RAW as Control Plane for Wireless Deterministic Networks: Challenges Ahead. In Proceedings of the Twenty-fourth International Symposium on Theory, Algorithmic Foundations, and Protocol Design for Mobile Networks and Mobile Computing (MobiHoc '23). Association for Computing Machinery, New York, NY, USA, 328–333. https://doi.org/10.1145/3565287.3617608

Financiado por la Unión Europea NextGenerationEU
GOBIERNO DE ESPAÑA
MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL
SECRETARÍA DE ESTADO DE TELECOMUNICACIONES E INFRAESTRUCTURAS DIGITALES
Plan de Recuperación, Transformación y Resiliencia
UNICO I+D

1. Introduction

In Industry 4.0 scenarios the latency requirements are of paramount importance for tasks that require real time operation, or high synchronization; as remote control of factory robots. Having a network prone to huge jitter and latency harnesses the adequate behaviour of the industrial services. Although recent advances in access technologies have pushed the capabilities of wired and wireless technologies, the heterogeneity of SDOs and technologies make challenging to have a system that conveys all technologies to provide end-to-end network guarantees across sites.

Wireless operates on a shared medium, and transmissions cannot be fully deterministic due to uncontrolled interferences, including self-induced multipath fading. RAW (Reliable and Available Wireless) is an effort to provide Deterministic Networking on across a path that include a wireless interface. RAW provides for high reliability and availability for IP connectivity over a wireless medium. The wireless medium presents significant challenges to achieve deterministic properties such as low packet error rate, bounded consecutive losses, and bounded latency. RAW extends the DetNet Working Group concepts to provide for high reliability and availability for an IP network utilizing scheduled wireless segments and other media, e.g., frequency/time-sharing physical media resources with stochastic traffic: IEEE Std. 802.15.4 timeslotted channel hopping (TSCH), 3GPP 5G ultra-reliable low latency communications (URLLC), IEEE 802.11ax/be, and L-band Digital Aeronautical Communications System (LDACS), etc. Similar to DetNet, RAW technologies aim at staying abstract to the radio layers underneath, addressing the Layer 3 aspects in support of applications requiring high reliability and availability.

As introduced in (Thubert P. , 2022), RAW separates the path computation time scale at which a complex path is recomputed from the path selection time scale at which the forwarding decision is taken for one or a few packets. RAW operates at the path selection time scale. The RAW problem is to decide, amongst the redundant solutions that are proposed by the Patch Computation Element (PCE), which one will be used for each packet to provide a Reliable and Available service while minimizing the waste of constrained resources. To that effect, RAW defines the Path Selection Engine (PSE) that is the counter-part of the PCE to perform rapid local adjustments of the forwarding tables within the diversity that the PCE has selected for the Track. The PSE enables to exploit the richer forwarding capabilities with Packet (hybrid) ARQ, Replication, Elimination and Ordering (PAREO), and scheduled transmissions at a faster time scale.

There are several use cases (Bernardos, Papadopoulos, Thubert, & Theoleyre, 2023) where reliability and availability are key requirements for wireless heterogeneous networks. A couple of relevant examples are (i) the manufacturing sector, where a plethora of devices are interconnected and generate data that need to be reliably delivered to the control and monitoring agents; and (ii) the residential gaming, with eXtended Reality (XR).

The document is structured as follows. First, it presents the use case of industrial manufacturing, highlighting the need for additional RAW mechanisms. Then, overall system design for an Industry 4.0 scenario. Main gaps identified in current RAW/DetNet work are identified and ellaborated:

Financiado por la Unión Europea NextGenerationEU
GOBIERNO DE ESPAÑA MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL SECRETARÍA DE ESTADO DE TELECOMUNICACIONES E INFRAESTRUCTURAS DIGITALES
Plan de Recuperación, Transformación y Resiliencia
UNICO I+D

extensions for multidomain operation, mobility in RAW domains, and Operation, Administration and Management (OAM) specific mechanisms. A first set of detailed specifications are included in this version, building on top of the initial analysis performed in 6G-DATADRIVEN-04-E9. We conclude the document with a summary of IETF activities and an analysis of impact and follow-up actions.

We also identify the main differences of this document versus its initial version (6G-DATADRIVEN-04-E9) in an annex.

Financiado por la Unión Europea NextGenerationEU
GOBIERNO DE ESPAÑA MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL SECRETARÍA DE ESTADO DE TELECOMUNICACIONES E INFRAESTRUCTURAS DIGITALES
Plan de Recuperación, Transformación y Resiliencia
UNICO I+D

2. Use case: Wireless for Industrial Applications

A major use case for networking in industrial environments is the control networks where periodic control loops operate between a collection of sensors that measure a physical property (such as the temperature of a fluid), a Programmable Logic Controller (PLC) that decides on an action (such as "warm up the mix"), and actuators that perform the required action (such as the injection of power in a resistor).

2.1. Specifics

2.1.1. Control Loops

Process Control designates continuous processing operations, like heating oil in a refinery or mixing up soda. Control loops in the Process Control industry operate at a very low rate, typically four times per second. Factory Automation, on the other hand, deals with discrete goods, such as individual automobile parts, and requires faster loops, to the rate of milliseconds. Motion control that monitors dynamic activities may require even faster rates on the order of and below the millisecond.

In all those cases, a packet must flow reliably between the sensor and the PLC, be processed by the PLC, and be sent to the actuator within the control loop period. In some particular use cases that inherit from analog operations, jitter might also alter the operation of the control loop. A rare packet loss is usually admissible, but typically, a loss of multiple packets in a row will cause an emergency halt of the production and incur a high cost for the manufacturer.

Additional details and use-cases related to Industrial applications and their RAW requirements can be found in (Sofia, Kovatsch, & Mendes, 2021).

2.1.2. Monitoring and diagnostics

A secondary use-case deals with monitoring and diagnostics. This data is essential to improve the performance of a production line, e.g., by optimizing real-time processing or maintenance windows using Machine Learning predictions. For the lack of wireless technologies, some specific industries such as Oil and Gas have been using serial cables, literally by the millions, to perform their process optimization over the previous decades. However, few industries would afford the associated cost. One of the goals of the Industrial Internet of Things is to provide the same benefits to all industries, including SmartGrid, transportation, building, commercial, and medical. This requires a cheap, available, and scalable IP-based access technology.

Inside the factory, wires may already be available to operate the control network. However, monitoring and diagnostics data are not welcome in that network for several reasons. On the one hand it is rich and asynchronous, meaning that it may influence the deterministic nature of the control operations and impact the production. On the other hand, this information must be reported to the operators over IP, which means the potential for a security breach via the interconnection of

Financiado por la Unión Europea NextGenerationEU
GOBIERNO DE ESPAÑA MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL SECRETARÍA DE ESTADO DE TELECOMUNICACIONES E INFRAESTRUCTURAS DIGITALES
Plan de Recuperación, Transformación y Resiliencia
UNICO I+D

the Operational Technology network with the Internet Technology network and the potential of a rogue access.

2.2. The Need for Wireless

Ethernet cables used on a robot arm are prone to breakage after a few thousands of flexions, a lot faster than a power cable that is wider in diameter, and more resilient. In general, wired networking and mobile parts are not a good match, mostly in the case of fast and recurrent activities, as well as rotation.

When refurbishing older premises that were built before the Internet age, power is usually available everywhere, but data is not. It is often impractical, time consuming and expensive to deploy an Ethernet fabric across walls and between buildings. Deploying a wire may take months and cost tens of thousands of US Dollars.

Even when wiring exists, like in the case of an existing control network, asynchronous IP packets such as diagnostics may not be welcome for operational and security reasons. For those packets, the option to create a parallel wireless network offers a credible solution that can scale with the many sensors and actuators that equip every robot, every valve and fan that are deployed on the factory floor. It may also help detect and prevent a failure that could impact the production, like the degradation (vibration) of a cooling fan on the ceiling. IEEE Std. 802.15.4 Time-Slotted Channel Hopping (TSCH) (Watteyne, Palattella, & Grieco, 2015) is a promising technology for that purpose, mostly if the scheduled operations enable to use the same network by asynchronous and deterministic flows in parallel.

2.3. Requirements for RAW

As stated by the "Deterministic Networking Problem Statement" (Finn & Thubert, Deterministic Networking Problem Statement, 2019), a Deterministic Network is backwards compatible with (capable of transporting) statistically multiplexed traffic while preserving the properties of the accepted deterministic flows. While the 6TiSCH Architecture (Thubert P. , 2021) serves that requirement, the work at 6TiSCH was focused on best-effort IPv6 packet flows. RAW should be able to lock so-called hard cells (i.e., scheduled cells (Palattella, Thubert, Watteyne, & Wang, 2018)) for use by a centralized scheduler, and leverage time and spatial diversity over a graph of end-to-end paths called a Track that is based on those cells.

Over the course of the recent years, major Industrial Protocols (e.g., ODVA[1] with EtherNet/IP and Profinet[2]) have been migrating towards Ethernet and IP. In order to unleash the full power of the IP hourglass model, it should be possible to deploy any application over any network that has the physical capacity to transport the industrial flow, regardless of the MAC/PHY technology, wired or wireless, and across technologies. RAW mechanisms should be able to setup a Track over a wireless

[1] http://www.odva.org/
[2] http://us.profinet.com/technology/profinet/

Financiado por la Unión Europea NextGenerationEU
GOBIERNO DE ESPAÑA MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL SECRETARÍA DE ESTADO DE TELECOMUNICACIONES E INFRAESTRUCTURAS DIGITALES
Plan de Recuperación, Transformación y Resiliencia
UNICO I+D

access segment and a wired or wireless backbone to report both sensor data and critical monitoring within a bounded latency and maintain the high reliability of the flows over time. It is also important to ensure that RAW solutions are interoperable with existing wireless solutions in place, and with legacy equipment whose capabilities can be extended using retrofitting. Maintainability, as a broader concept than reliability is also important in industrial scenarios (Martinez, Cano, & Vilajosana, 2019).

2.3.1. Non-latency critical considerations

Monitoring and diagnostics applications do not require latency critical communications, but demand reliable and scalable communications. On the other hand, process control applications involve control loops that require a bounded latency, thus are latency critical, but can be managed end-to-end, and therefore DetNet mechanisms can be applied in conjunction with RAW mechanisms.

2.4. Status as of today and identified gaps

New WiFi standards, such as IEEE 802.11ax are gaining momentum in the industrial area, as the need for flexibility in infrastructure design and process support increases. It is true that IEEE 802.11 standards have reached a level of maturity where the technology can support the stringent requirements of industrial environments, while being compatible with traditional fixed core networks. Wi-Fi brings flexibility, lower operating costs and higher availability to industrial systems at the edge in scenarios that require support for mobility or large-scale integration of sensing devices.

However, there are clear barriers to the integration of IEEE 802.11 in industrial environments. Mostly related to the issues due to the fact WiFi networks operate over a shared unlicensed medium, making it harder to guarantee the levels of availability, resilience and security support of critical services required by industrial scenarios.

While the IETF DetNet WG (which recently absorbed the RAW work items) is addressing some of the basic challenges, there are additional features that Industrial environments would benefit from. This document elaborates on some of these required features/gaps, namely the following:

- Multi-domain support. There multiple scenarios and use cases that might involve multiple technology and/or administrative domains. This problem is addressed in section 3, including the definition of a solution.
- Mobility management. Mobility scenarios pose additional complexity that has not been tackled yet. This problem is addressed in section 4, including the definition of a solution.
- Integration with MEC architectures and solutions. Applications requiring ultra-low latencies and/or offloading some tasks to the edge can benefit from a proper architecture integration between DetNet and ETSI MEC. While this problem was already tackled in the first version of this document (6G-DATADRIVEN-04-E09), it has been moved to 6G-DATADRIVEN-04-E15 (and future versions of that document) as it has been considered that it fits it best.

Financiado por la Unión Europea NextGenerationEU
GOBIERNO DE ESPAÑA MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL SECRETARÍA DE ESTADO DE TELECOMUNICACIONES E INFRAESTRUCTURAS DIGITALES
Plan de Recuperación, Transformación y Resiliencia
UNICO I+D

3. Multidomain extensions

3.1. Introduction

The Deterministic Networking (DetNet) Working Group focuses on deterministic data paths that operate over Layer 2 bridged and Layer 3 routed segments, where such paths can provide bounds on latency, loss, and packet delay variation (jitter), and high reliability.

The DetNet architecture document (Finn, Thubert, Varga, & Farkas, 2019) includes the concept of multi-domain in the DetNet Service reference model (Fig. 5 of RFC 8655, reproduced here in Figure 1 for convenience. However, the WG has not yet worked in detail on the necessary protocol operations to support multi-domain at control and data plane.

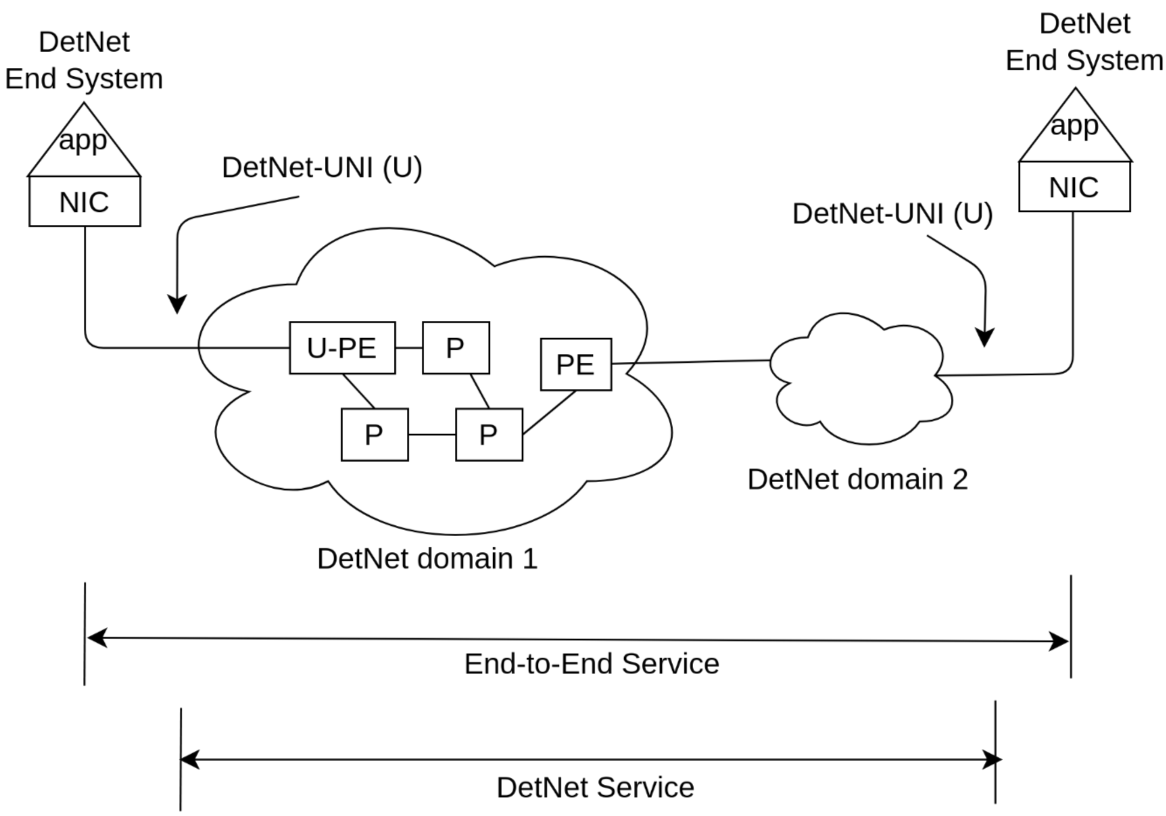

FIGURE 1: DETNET SERVICE REFERENCE MODEL (MULTIDOMAIN) (FROM RFC8655)

DetNet defines the Packet Replication, Elimination, and Ordering Functions (PREOF) as a way to provide service protection. PREOF involves 4 capabilities:

- Sequencing information, by adding a sequence number or time stamp as part of DetNet. This is typically done once, at or near the source.
- Replicating packets into multiple DetNet member flows, and typically sending them along multiple different paths to the destination(s).
- Eliminating duplicate packets of a DetNet flow based on the sequencing information and a history of received packets.

Financiado por la Unión Europea NextGenerationEU
GOBIERNO DE ESPAÑA MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL SECRETARÍA DE ESTADO DE TELECOMUNICACIONES E INFRAESTRUCTURAS DIGITALES
Plan de Recuperación, Transformación y Resiliencia
UNICO I+D

- Reordering DetNet flow's packets that are received out of order.

Packet (hybrid) ARQ, Replication, Elimination and Ordering (PAREO) is a superset of DetNet's PREOF, defined in RAW, that includes radio-specific techniques such as short range broadcast, MUMIMO, constructive interference and overhearing, which can be leveraged separately or combined to increase the reliability.

There multiple scenarios and use cases that might involve multiple technology and/or administrative domains in DetNet and RAW.

Next sections explore what the main multi-domain aspects for the application, controller and network/data planes in DetNet and RAW are, to then identify some existing gaps that would require further work at the IETF.

3.2. Application plane

As described in (Finn, Thubert, Varga, & Farkas, 2019), the Application Plane incorporates the User Agent, a specialized application that interacts with the end user and operator and performs requests for DetNet services via an abstract Flow Management Entity (FME), which may or may not be collocated with (one of) the end systems. At the Application Plane, a management interface enables the negotiation of flows between end systems.

In a multi-domain deployment, the User Agent might be aware of the existence of multiple domains, or it might be unaware. A multi-domain aware User Agent/application plane could take care of the negotiation of the flows at all involved domains, whereas a multi-domain unaware one will have to rely on the network to take care of it transparently.

3.3. Controller plane

We refer to the controller plane as the aggregation of the Control and Management planes. The term "Controller Plane Function (CPF)" refers to any device operating in that plane, whether it is a Path Computation Element (PCE) (Farrel, Vasseur, & Ash, 2006), a Network Management Entity (NME), or a distributed control protocol. The CPF is a core element of a controller, in charge of computing deterministic paths to be applied in the Network Plane. A (Northbound) Service Interface enables applications in the Application Plane to communicate with the entities in the Controller Plane.

In DetNet, one or more CPFs collaborate to implement the requests from the FME as per-flow, per-hop behaviors installed in the DetNet nodes for each individual flow. Adding multi-domain support might require some support at the CPF. For example, CPFs sitting at different domains need to discover themselves, authenticate and negotiate per-hop behaviors. Depending on the multi-domain support provided by the application plane, the controller plane might be relieved from some reponisibilities (e.g., if the application plane is taking care of splitting what needs to be provided by each domain).

Financiado por la Unión Europea NextGenerationEU · GOBIERNO DE ESPAÑA · MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL · SECRETARÍA DE ESTADO DE TELECOMUNICACIONES E INFRAESTRUCTURAS DIGITALES · Plan de Recuperación, Transformación y Resiliencia · UNICO I+D

While there exist inter-PCE solutions today, allowing one domain's PCE to learn some inter-domain paths, this would not be sufficient, as the PSE of one domain would not have full visibility nor capability to act on the other domains (e.g., there are no multi-domain OAM solutions in place yet), limiting its capability to guarantee any given SLA. Therefore, there is a need to define inter-PSE coordination mechanisms across domains.

There exist today standardized solutions, such as the ones in the context of Path Computation Element (PCE), enabling computing multi-/inter-domain paths. As an example, the Hierarchical PCE (G-PCE) was defined in RFC 6805 (King & Farrel, 2012) and is described hereafter. A parent PCE maintains a domain topology map that contains the child domains (seen as vertices in the topology) and their interconnections (links in the topology). The parent PCE has no information about the content of the child domains; that is, the parent PCE does not know about the resource availability within the child domains, nor does it know about the availability of connectivity across each domain because such knowledge would violate the confidentiality requirement and either would require flooding of full information to the parent (scaling issue) or would necessitate some form of aggregation. The parent PCE is used to compute a multi-domain path based on the domain connectivity information. A child PCE may be responsible for single or multiple domains and is used to compute the intra-domain path based on its own domain topology information.

Solutions like the above are not sufficient alone to solve the multi-domain RAW problem, as the PSEs need to have some additional information from the other involved domains to be sensitive/reactive to transient changes, in order to ensure a certain level of reliability and availability in a multi-domain wireless heterogeneous mesh network. Section 3.5 explores in more detail the RAW-specific multi-domain problem and proposes some initial solutions.

3.4. Network/Data plane

The Network Plane represents the network devices and protocols as a whole, regardless of the layer at which the network devices operate. It includes the Data Plane and Operational Plane (e.g., OAM) aspects. A Southbound (Network) Interface enables the entities in the Controller Plane to communicate with devices in the Network Plane.

At the Network Plane, DetNet nodes may exchange information regarding the state of the paths, between adjacent DetNet nodes and possibly with the end systems. In a multi-domain environment, nodes belonging to different domains might need to exchange information. This might require protocol translations and/or abstractions, as the different domains might not offer the same capabilities nor use the same network protocols. Additionally, OAM protocols (Mirsky, y otros, 2023), (Theoleyre, Papadopoulos, Mirsky, & Bernardos, 2023) might also need to be extended to support multi-domain operation.

Note as well, that performing PREOF or PAREO across multiple domains poses additional challenges, as knowledge of all the involved domains might not be available and/or the data planes at each domain could also be different.

Financiado por la Unión Europea NextGenerationEU
GOBIERNO DE ESPAÑA
MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL
SECRETARÍA DE ESTADO DE TELECOMUNICACIONES E INFRAESTRUCTURAS DIGITALES
Plan de Recuperación, Transformación y Resiliencia
UNICO I+D

3.5. RAW specific analysis

We can refer to domains managed by a single PCE, as "single-domain RAW", where nodes are typically run and managed by a single administration entity. In this scenario, the PSE can make use of "tracks" and paths involving only the nodes belonging to this RAW domain.

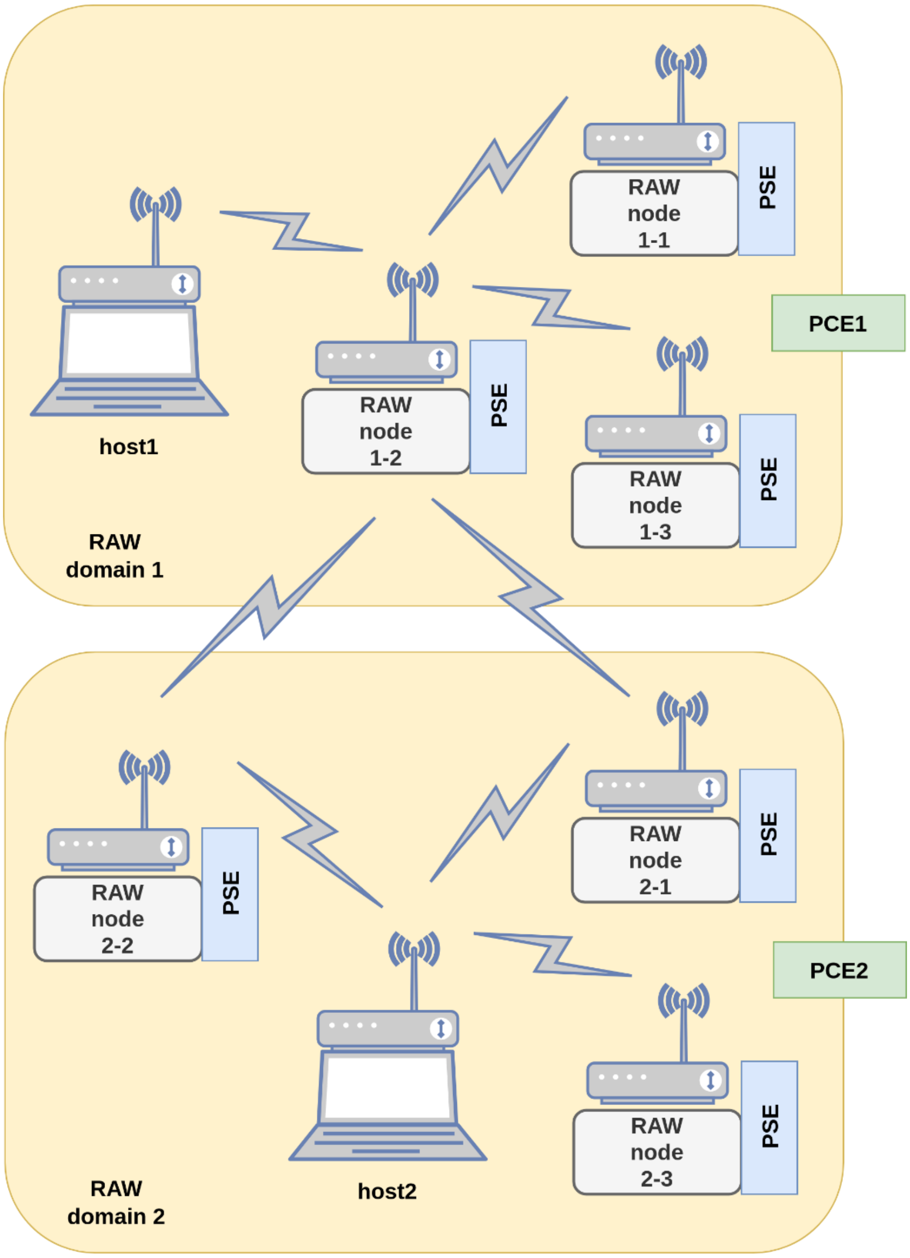

FIGURE 2: EXEMPLARY SCENARIO SHOWING MULTIPLE RAW DOMAINS

There are scenarios where hosts are connected to different RAW domains and they need to communicate to each other with certain reliability and/or availability guarantees, for example in large factories where networks might be organized in domains (per production lines or building/sites), in residential environments where there are different networks (e.g., one at home and one in the garden), or even vehicular scenarios (e.g., hosts connected to different vehicles).

Financiado por la Unión Europea NextGenerationEU
GOBIERNO DE ESPAÑA MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL SECRETARÍA DE ESTADO DE TELECOMUNICACIONES E INFRAESTRUCTURAS DIGITALES
Plan de Recuperación, Transformación y Resiliencia
UNICO I+D

Figure 2 shows an example of communication involving two RAW domains. As opposed to a single-domain scenario, where a single PCE may compute all possible "tracks" at longer time scale, and the PSE functionality may perform "subtrack" selection and optimization at a shorter time scale using all information available at the domain, multidomain scenarios pose additional burdens that are not solved yet.

Each RAW domain operates independently of the other domains. While there exist inter-PCE solutions today, allowing one domain's PCE to learn some inter-domain paths, this would not be sufficient, as the PSE of one domain would not have full visibility nor capability to act on the other domains (e.g., there are no multi-domain OAM solutions in place yet), limiting its capability to guarantee any given SLA. Therefore, there is a need to define inter-PSE coordination mechanisms across domains.

Solutions like Hierarchical PCE (G-PCE) are not sufficient alone to solve the multi-domain RAW problem, as the PSEs need to have some additional information from the other involved domains to be sensitive/reactive to transient changes, in order to ensure a certain level of reliability and availability in a multi-domain wireless heterogeneous mesh network.

Within a single domain, the RAW framework architecture works, by having the PCE in charge of computing the paths (tracks) and the PSE(s) taking the short time decisions of which sub-tracks to use. Note that the PSE is assumed to be either a distributed functionality (performed by every RAW router of the path, which takes forwarding decisions based on the local and OAM information that they have), or a centralized functionality played by the entry (ingress) router in the domain (note that if there are multiple ingress nodes, then there might be multiple PSEs), which then performs source routing.

In scenarios with multiple connected RAW domains, running uncoordinated RAW solutions in each domain is not sufficient. PSEs would need to have global end-to-end information as well as be capable of running OAM mechanisms (Mirsky, y otros, 2023) to monitor the quality of the selected paths.

3.6. RAW multi-domain extensions

In this section we specify the new mechanisms and signalling extensions to enable inter-domain RAW connectivity.

Financiado por la Unión Europea NextGenerationEU
GOBIERNO DE ESPAÑA MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL SECRETARÍA DE ESTADO DE TELECOMUNICACIONES E INFRAESTRUCTURAS DIGITALES
Plan de Recuperación, Transformación y Resiliencia
UNICO I+D

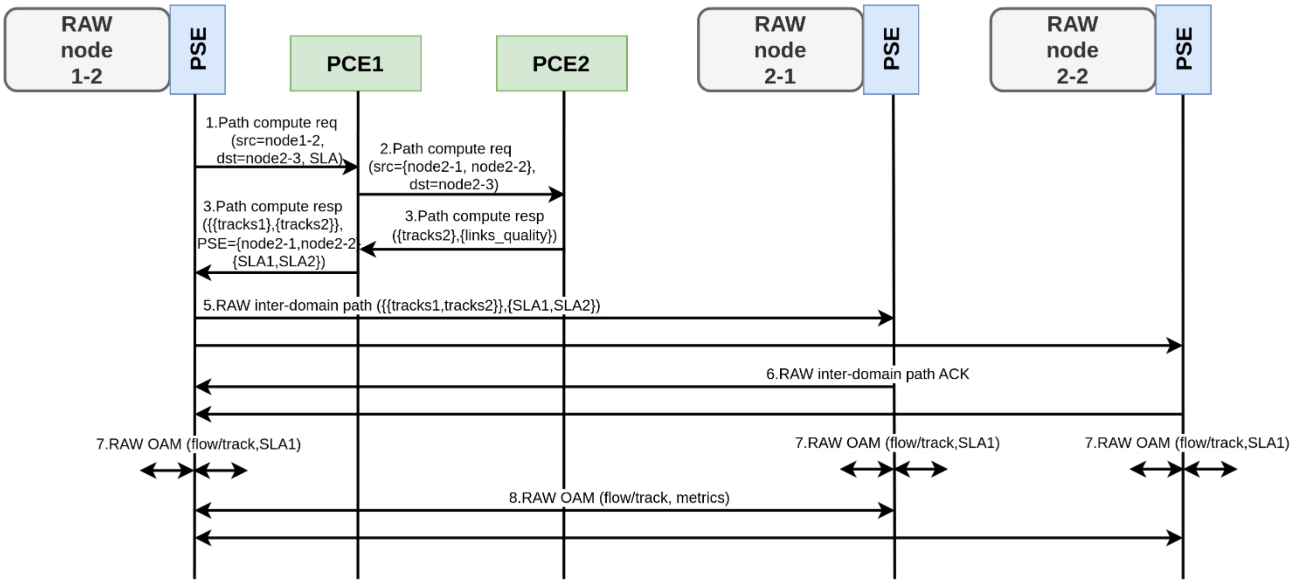

FIGURE 3: MULTI-DOMAIN RAW SIGNALING

Figure 3 shows a signalling flow diagram, taking as baseline scenario the one shown in Figure 2, where host1 (connected to node1-2) wants to communicate with host2 (connected to node2-3). An ingress RAW node (node1-2) gets a request for connectivity, with a given destination RAW node (node2-3) and the desired SLA in terms of reliability and availability. The source and/or destination RAW nodes might be hosts. We next explain each of the steps illustrated in the figure:

1. The ingress node plays the role of PSE (also referred to as PSE@domain1) and requests the computation of the tracks towards the destination node2-3 with the intended SLA to the PCE of the domain (PCE1).
2. PCE1 knows that the destination is in another domain (domain2) and that the PCE of the destination domain is PCE2. PCE1 also knows the ingress nodes in domain2 that are connected to domain1. How this is done is outside of the scope of this document. These nodes (node2-1 and node2-2) play the role of PSEs@domain2. PCE1 requests to PCE2 to compute the available tracks from PSEs@domain2 to the destination, and the characteristics of the links (link_quality) forming these tracks. The detail and nature of the information provided by PCE2 regarding the links might vary depending on the deployment, and is meant to be used by PCE1 and the PSE@domain1 (node1-2) to compute how to distribute the SLA among the domains.
3. PCE2 computes the tracks and responds to PCE1, including also the characteristics of the links (link_quality). Examples of potential information elements including in the link_quality are:
    a. available bandwidth, observed reliability, delay, link
    b. variability/mobility, etc.
4. PCE1 provides to the PSE@domain1 the tracks to reach the destination, as well as the split of SLAs among domain1 and domain2 (SLA1 and SLA2). An SLA, or a Quality of Service (QoS) figure, may include aspects such as, among others: max. delay, assured BW, max. Jitter, packet loss ratio, availability ratio, etc. PCE1 also provides the PSEs@domain2.

5. The PSE@domain1 sends a message to each PSE@domain2, in order to set-up a direct communication channel to provide OAM information useful to the PSE@domain1 for computing the subtracks to use for the traffic. This message includes the SLA that each domain has to monitor and guarantee (SLA1 and SLA2).
6. Each of the PSEs@domain2 acknowledges the message. At this point, the communication channel is established and the PSE@domain1 can start taking decisions at a forwarding time scale regarding which paths (subtracks) to use.
7. All PSEs, at each domain, start performing OAM procedures (Theoleyre, Papadopoulos, Mirsky, & Bernardos, 2023), which are key to observe if traffic is meeting the desired SLAs (SLA1 and SLA2) and adapt the subtracks and tracks if needed. OAM mechanisms can be applied in-band (sharing the traffic's fate) or out-of band. Note that this per-domain distributed OAM is critical to ensure that the required SLAs (reliability and availability) are met by reacting on a short time scale at each of the involved domains.
8. PSEs share aggregated and pre-processed information among them to facilitate early detection of issues and computation of subtracks. If a violation of an SLA is detected, the respective PSE would notify the domain PCE and the other PSE, so a reaction measure can be taken (e.g., selecting different subtracks, taking different PAREO decisions, requesting the PCEs to recompute the paths and/or adjust the split of the SLAs across the domains).

Note that this example covers the direction host1-to-host2. If there is traffic in the opposite direction, the process has to be repeated in the reverse direction, as paths might not be bidirectional.

Financiado por la Unión Europea NextGenerationEU
GOBIERNO DE ESPAÑA MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL SECRETARÍA DE ESTADO DE TELECOMUNICACIONES E INFRAESTRUCTURAS DIGITALES
Plan de Recuperación, Transformación y Resiliencia
UNICO I+D

4. Mobility in single RAW domains

4.1. Problem Statement

As opposed to static scenarios, where possible "tracks" (and therefore "subtracks") do not change due to mobility, mobility scenarios pose additional complexity that has not been tackled yet.

Figure 4 shows an example of communication involving a RAW domain, a mobile UE running an XR application (which requires connectivity with strict QoS to an XR server). As opposed to static scenarios, where possible "tracks" (and therefore "subtracks") do not change due to mobility, mobility scenarios pose additional complexity that has not been tackled yet.

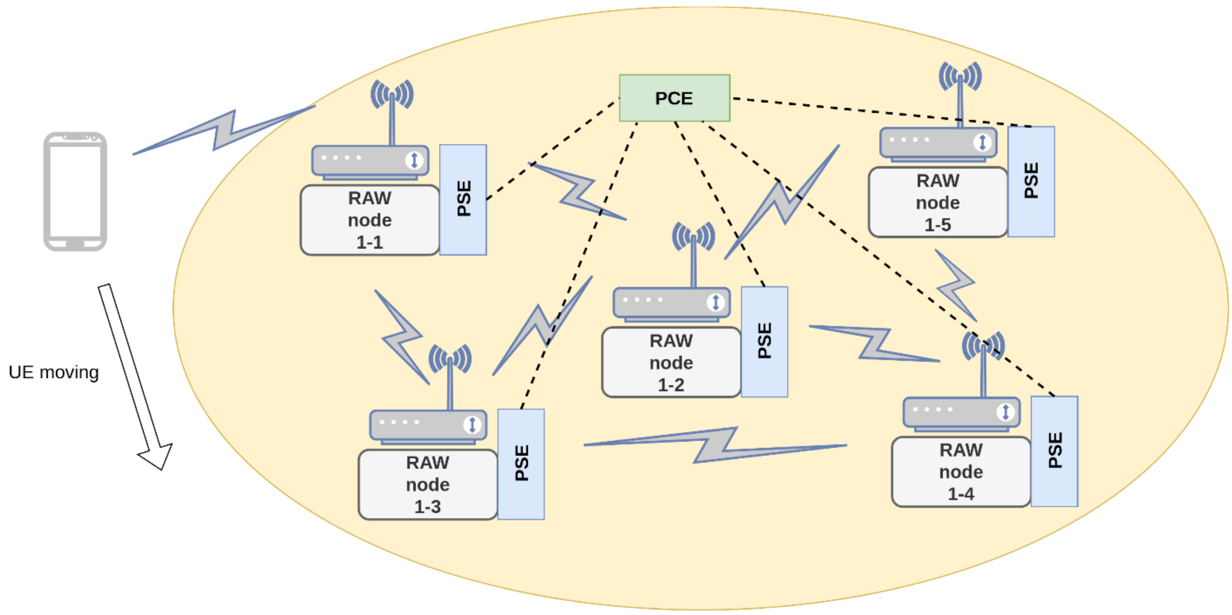

FIGURE 4: EXEMPLARY SCENARIO DEPICTING RAW MOBILITY

Control plane solutions need to cope with mobility, by proactively preparing the network for the change of point of attachment of the mobile node, and the impact that this has in terms of new subtracks used for the traffic. This requires inter-PSE coordination for the preparation of the handover.

L2-specific extensions can be used to aid the mobile node determine where to roam to if stringent conditions need to be maintained (requiring RAW support).

The IETF DETNET and RAW WGs are responsible for the definition of data and control plane mechanisms to support deterministic networking in wired and wireless multi-hop networks. Current solutions are limited to static scenarios, where neither the mobile nodes nor the internal/local network nodes move. Therefore, solutions are needed to solve the mobile node mobility problem in single domain RAW networks. For example, it is needed to enable mechanisms allowing a terminal to signal an imminent handover and convey its QoS requirements. The signalling messages among

Financiado por la Unión Europea NextGenerationEU
GOBIERNO DE ESPAÑA MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL SECRETARÍA DE ESTADO DE TELECOMUNICACIONES E INFRAESTRUCTURAS DIGITALES
Plan de Recuperación, Transformación y Resiliencia
UNICO I+D

RAW nodes (PSEs) to prepare and coordinate an imminent handover –so app QoS can be maintained– need to be specified.

4.2. RAW mobility extensions

This section specifies some RAW control plane extensions for UE mobility, for two scenarios: UE- and network-controlled.

4.2.1. UE-controlled RAW-enabled mobility

We describe below an example of operation and signalling (Figure 5) where a UE moves from one Point of Attachment (PoA) within a RAW domain (node1-1) to another PoA (node1-2). Signaling extensions between the UE and the RAW domain, and inter-PSE are shown. The different steps are elaborated below. We assume that the UE is running an XR application demanding stringent QoS, thus requiring from DETNET/RAW solutions. This generates a flow between the UE and an external node, in this example an XR server. A single RAW domain is considered. The mechanisms (from state of the art) to set-up this flow have already taken place and are out of the scope of this document.

0. (optional) The different PoAs of the RAW domain might advertise, using L2 extensions, RAW-specific information. This information might be obtained for example using IEEE 802.11 Neighbor report extensions, or other mechanisms. This information could aid the UE to decide whether to move and where (e.g., taking into account local policies and the advertised capabilities of each available PoA). Exemplary, non-limited, information elements that these advertisements (beacons) might include are, per available PoA in the region:
    a. PoA_ID: unique identifier (within the RAW domain) of the PoA. It might have the form of L2/L3 address or any other ID.
    b. PSE_ID: unique identifier (within the RAW domain) of the PSE associated with the PoA. In most cases, there will be a PSE instance collocated with every RAW node. It might have the form of L2/L3 address or any other ID.
    c. RAW_ID: unique identifier of the RAW domain.
1. The UE detects or decides (depending on whether only pure radio conditions or also other factors are considered) that a handover is imminent and sends a message to the network, e.g., to its current PoA. This message includes:
    a. UE_ID: an identifier of the UE.
    b. nPoA_ID: the identifier of the new PoA to which the UE is most likely to attach to. It might have the form of L2/L3 address or any other ID.
    c. nRAW_ID: unique identifier of the RAW domain the nPoA belongs to. It is only in the scope of this document the case of mobility within the same RAW domain.
    d. QoS: a description of the QoS parameters demanded by the flow. It might be a set of one of several parameters, such as: latency, resiliency, throughput, etc.

Financiado por la Unión Europea NextGenerationEU
GOBIERNO DE ESPAÑA MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL SECRETARÍA DE ESTADO DE TELECOMUNICACIONES E INFRAESTRUCTURAS DIGITALES
Plan de Recuperación, Transformación y Resiliencia
UNICO I+D

   e. Bicasting requested (Y/N): whether the UE requests bicasting of traffic during the handover for extra resilience. If not requested, the network can still perform it as deemed necessary to grant the required QoS.

   Note that some of these parameters might have been learned through the optional beacons mentioned in the previous step, or by any other means. Note as well that those beacons can also be used to help the UE filtering or ranking potential target PoAs, based on their support of RAW and the domain they belong to.

2. The current PoA sends a RAW handover initiate (RAW_HO_initiate) message to the target new PoA. It is considered that the UE is the entity making the PoA selection. The focus of this document is not on how the selection is done, but rather on the enablement mechanism for mobility in RAW networks. Hence, the selection process can be considered done using radio measurements, required throughput from the UE side, available throughput from the RAW node side, etc. Hence, the UE also indicates the target PoA in this message. This message contains:
   a. UE_ID: an identifier of the UE that is about to perform a handover.
   b. oPoA_ID: the identifier of the current (old) PoA to which the UE is currently attached to. It might have the form of L2/L3 address or any other ID.
   c. oRAW_ID: unique identifier of the RAW domain the oPoA belongs to. It is only in the scope of this document the case of mobility within the same RAW domain.
   d. QoS: a description of the QoS parameters demanded by the flow. It might be a set of one of several parameters, such as: latency, resiliency, throughput, etc. For the purpose of this document, these parameters consider basis QoS metrics and are described at high level and immediate single values. Addressing these in detail requires further work as their extensions and expansions result in further enhancements to the mobility process that are out of the scope of this document due to the complexity involved, and that provides solutions to other problems.

   Note that the nPoA would be generally obtained from message #2, but if the UE does not provide that information, the network might perform a selection based on the QoS demanded, the current location of the UE and additional information it might have. In that case, the target nPoA would be communicated to the UE in the step #6.

3. With the information provided in the previous step, the nPoA computes the tracks and subtracks required to support the QoS of the flow, by using RAW mechanisms. Note that if it is not possible to support the required QoS, the nPoA can propose a lower QoS in step #5.
4. The nPoA sends an acknowledgement message (RAW_HO_ACK) to the old PoA, containing:
   - UE_ID: an identifier of the UE that is about to perform a handover.
   - QoS: a description of the QoS parameters that can be granted to the flow. It might be a set of one of several parameters, such as: latency, resiliency, throughput, etc. Note that it might be equal or lower than the QoS requested in step #3. For the purpose of this document, these parameters consider basis QoS metrics and are described at high level

and immediate single values. Addressing these in detail requires further work as their extensions and expansions result in further enhancements to the mobility process that are out of the scope of this document due to the complexity involved, and that provides solutions to other problems.

5. The old PoA sends a command message to the UE, indicating that it can perform now the L2 handover, and providing the granted QoS and the target PoA.
6. In parallel to message #6, and as an optional feature decided by the network, a bicasting procedure can be initiated so downlink (DL) traffic received by the oPoA are duplicated and also sent to the nPoA, to minimize packet losses during the actual L2 handover. This bicasting procedure can be implemented by using the Packet Replication, Elimination, and Ordering Functions (PREOF) defined by IETF DETNET. The UE performs the L2 handover. Upon UE attachment detection by the nPoA, RAW mechanisms are used to activate the subtracks required for the UE's flow at its new location.
7. RAW signalling is used to set-up the new forwarding status /subtracks).
8. Once all the required RAW forwarding state is in place, bicasting is stopped (in case this feature was initiated).

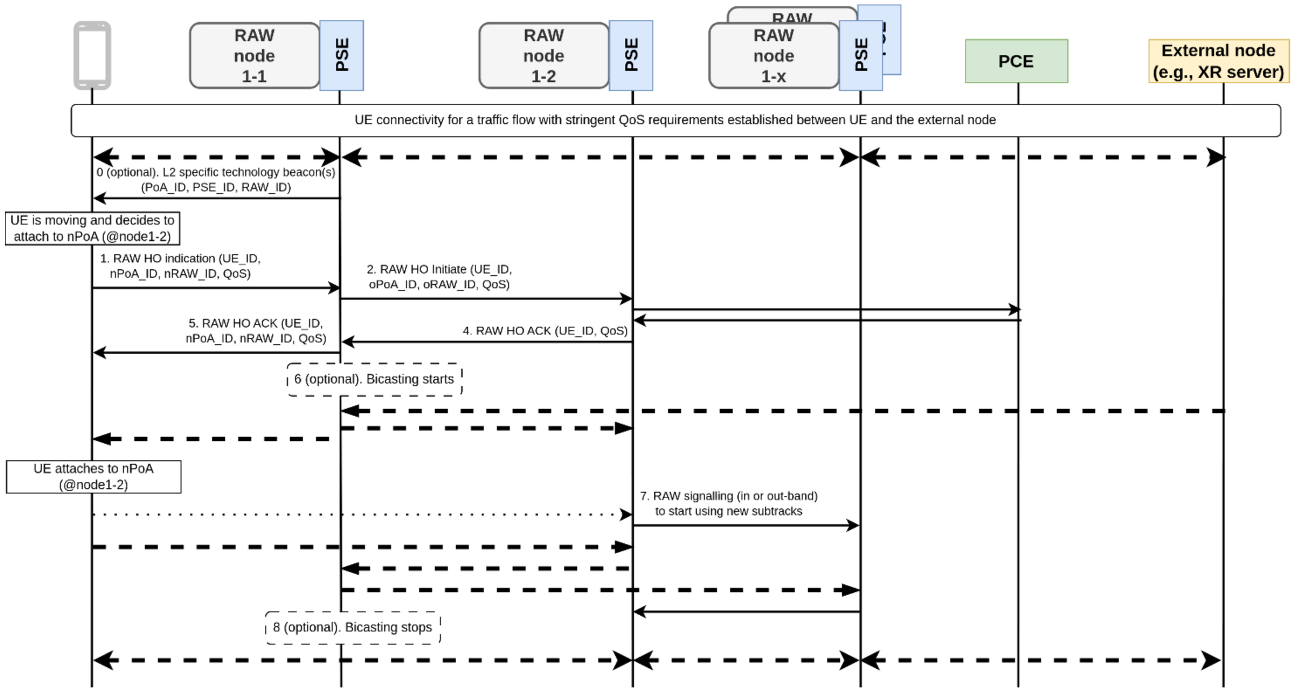

FIGURE 5: UE-CONTROLLED RAW-ENABLED MOBILITY SIGNALLING

4.2.2. Network-controlled RAW-enabled mobility

The specification of the network-controlled RAW-enabled mobility mechanism will be included in the final version of this document (6G-DATADRIVEN-04-E11).

4.3. Proxy Mobile IPv6 extensions

The control plane extensions introduced in the previous section can be implemented over different protocols. This section specifies extensions to Proxy Mobile IPv6 and Fast Handovers for Proxy Mobile IPv6.

The RAW HO Initiate and RAW HO ACK messages can be implemented by extending Handover Initiate and Handover Acknowledgement mobility headers RFC 5568 (Koodli, 2009), RFC 5949 (Yokota, 2010).

4.3.1. RAW HO Initiate

This section defines extensions to the HI message in RFC 5568 and RFC 5949. The format of the Message Data field in the Mobility Header is as follows:

```
  0                   1                   2                   3
  0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
                                 +-------------------------------+
                                 |          Sequence #           |
 +-+-+-+-+-------+---------------+-------------------------------+
 |S|U|P|F|Resv'd |      Code     |                               |
 +-+-+-+-+-------+---------------+                               |
 |                                                               |
 .                                                               .
 .                      Mobility options                         .
 .                                                               .
 |                                                               |
 +---------------------------------------------------------------+
```

IP Fields:

Source Address: the IP address of the oPoA.

Destination Address: the IP address of the nPoA.

Message Data:

Sequence #: Same as defined in RFC 5568.

'S' flag: Defined in RFC 5568, and MUST be set to zero in this specification.

'U' flag: Buffer flag. Same as defined in RFC 5568.

'P' flag: Proxy flag. Used to distinguish the message from that defined in RFC 5568, and MUST be set.

'F' flag: Forwarding flag. Used to request to setup bicasting for this flow.

Reserved: Same as defined in RFC 5568.

Code: RFC 5568 defines this field and its values, 0 and 1. This MUST be set to zero.

Financiado por la Unión Europea NextGenerationEU
GOBIERNO DE ESPAÑA MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL SECRETARÍA DE ESTADO DE TELECOMUNICACIONES E INFRAESTRUCTURAS DIGITALES
Plan de Recuperación, Transformación y Resiliencia
UNICO I+D

Mobility options:

This field contains one or more mobility options, whose encoding and formats are defined in RFC 6275.

In order to uniquely identify the target UE, the UE identifier MUST be contained in the Mobile Node Identifier option. This option is used to carry the UE_ID parameter described in this document.

The following new options can be used in this message: RAW_ID, PoA_ID, RAW QoS.

4.3.2. RAW HO ACK

This section defines extensions to the HAck message in RFC 5568. The format of the Message Data field in the Mobility Header is as follows:

```
  0                   1                   2                   3
  0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
                                 +-------------------------------+
                                 |           Sequence #          |
 +-+-+-+---------+---------------+-------------------------------+
 |U|P|F|Reserved |      Code     |                               |
 +-+-+-+---------+---------------+                               |
 |                                                               |
 .                                                               .
 .                       Mobility options                        .
 .                                                               .
 |                                                               |
 +---------------------------------------------------------------+
```

IP Fields:

Source Address: Copied from the destination address of the Handover Initiate message to which this message is a response.

Destination Address: Copied from the source address of the

Handover Initiate message to which this message is a response.

Message Data:

The usages of Sequence # and Reserved fields are exactly the same as those in RFC 5568.

‘U' flag: Buffer flag. Same as defined in RFC 5568.

'P' flag: Proxy flag. Used to distinguish the message from that defined in defined RFC 5568, and MUST be set.

'F' flag: Forwarding flag. Used to request to setup bicasting for this flow.

Reserved: Same as defined in RFC 5568.

Financiado por la Unión Europea NextGenerationEU
GOBIERNO DE ESPAÑA MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL SECRETARÍA DE ESTADO DE TELECOMUNICACIONES E INFRAESTRUCTURAS DIGITALES
Plan de Recuperación, Transformación y Resiliencia
UNICO I+D

Code: RFC 5568 defines this field and its values, 0 (Handover Accepted or Successful) to 4 and 128 to 130. Values 131 and 132 are defined in RFC 5949. For RAW mobility purposes the following new values are defined:

133: not possible to grant requested QoS, lower QoS proposed.

Mobility options:

This field contains one or more mobility options, whose encoding and formats are defined in RFC 6275. The mobility option that uniquely identifies the target mobile node MUST be copied from the corresponding RAW HO Initiate message.

The following new options can be used in this message: RAW_ID, PoA_ID, RAW QoS.

4.3.3. New mobility options

RAW_ID mobility option

The RAW_ID option has the following format:

```
  0                   1                   2                   3
  0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
                                 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
                                 |   Type = TBA  | Option Length |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |         RAW ID Length         |            Reserved           |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |                                                               |
 +                                                               +
 |                                                               |
 +                            RAW ID                             +
 |                                                               |
 +                                                               +
 |                                                               |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Option Type: TBA by IANA.

Option Length: 8-bit unsigned integer. Length of the option, in octets, excluding the Option Type and Option Length fields.

RAW ID Length: 8-bit unsigned integer. Length of the RAW ID field, in octets.

RAW ID: variable length field that identifies the RAW domain.

Financiado por la Unión Europea NextGenerationEU
GOBIERNO DE ESPAÑA MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL SECRETARÍA DE ESTADO DE TELECOMUNICACIONES E INFRAESTRUCTURAS DIGITALES
Plan de Recuperación, Transformación y Resiliencia
UNICO I+D

PoA_ID mobility option

The PoA_ID option has the following format:

```
    0                   1                   2                   3
    0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
                                   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
                                   |   Type = TBA  | Option Length |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |         PoA ID Length         |         PoA ID Format         |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                                                               |
   +                                                               +
   |                                                               |
   +                            PoA ID                             +
   |                                                               |
   +                                                               +
   |                                                               |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Option Type: TBA by IANA.

Option Length: 8-bit unsigned integer. Length of the option, in octets, excluding the Option Type and Option Length fields.

PoA ID Length: 8-bit unsigned integer. Length of the PoA ID field, in octets.

PoA ID Format: 8-bit unsigned integer. Identifies the format of the PoA ID. Possibles values:

0: Reserved.

1: IP address (v4 or v6, determined by PoA ID Length).

2: L2 address (48 or 64 bit, determined by PoA ID Length).

3: URI.

4-255: reserved for future use.

PoA ID: variable length field that identifies the PoA.

Financiado por la Unión Europea NextGenerationEU
GOBIERNO DE ESPAÑA
MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL
SECRETARÍA DE ESTADO DE TELECOMUNICACIONES E INFRAESTRUCTURAS DIGITALES
Plan de Recuperación, Transformación y Resiliencia
UNICO I+D

RAW QoS mobility option

The RAW QoS option has the following format:

```
    0                   1                   2                   3
    0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
                                   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
                                   |   Type = TBA  | Option Length |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   +                          MinBandwidth                         +
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                           MaxLatency                          |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                      MaxLatencyVariation                      |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                            MaxLoss                            |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                 MaxConsecutiveLossTolerance                   |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
   |                         MaxMisordering                        |
   +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Option Type: TBA by IANA.

Option Length: 8-bit unsigned integer. Length of the option, in octets, excluding the Option Type and Option Length fields. Set to 24.

MinBandwidth: 32-bit unsigned integer. MinBandwidth is the minimum bandwidth that has to be guaranteed for the flow. MinBandwidth is specified in octets per second.

MaxLatency: 32-bit unsigned integer. MaxLatency is the maximum latency from Ingress to Egress(es) for a single packet of the flow. MaxLatency is specified as an integer number of nanoseconds.

MaxLatencyVariation: 32-bit unsigned integer. MaxLatencyVariation is the difference between the minimum and the maximum end-to-end, one-way latency. MaxLatencyVariation is specified as an integer number of nanoseconds.

MaxLoss: 32-bit unsigned integer. MaxLoss defines the maximum Packet Loss Rate (PLR) requirement for the flow between the Ingress and Egress(es) and the loss measurement interval.

MaxConsecutiveLossTolerance: 32-bit unsigned integer. Some applications have special loss requirements, such as MaxConsecutiveLossTolerance. The maximum consecutive loss tolerance parameter describes the maximum number of consecutive packets whose loss can be tolerated. The maximum consecutive loss tolerance can be measured, for example, based on sequence number.

MaxMisordering: 32-bit unsigned integer. MaxMisordering describes the tolerable maximum number of packets that can be received out of order. The value zero for the maximum allowed misordering indicates that in-order delivery is required; misordering cannot be tolerated. The maximum allowed misordering can be measured, for example, based on sequence numbers. When a packet arrives at the egress after a packet with a higher sequence number, the difference between the sequence number values cannot be bigger than "MaxMisordering + 1".

Financiado por la Unión Europea NextGenerationEU
GOBIERNO DE ESPAÑA MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL SECRETARÍA DE ESTADO DE TELECOMUNICACIONES E INFRAESTRUCTURAS DIGITALES
Plan de Recuperación, Transformación y Resiliencia
UNICO I+D

5. Operations, Administration and Maintenance (OAM) for Deterministic Networking

The identification and initial specification of required OAM features for DetNet will be included in the final version of this document (6G-DATADRIVEN-04-E11).

Financiado por la Unión Europea NextGenerationEU
GOBIERNO DE ESPAÑA
MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL
SECRETARÍA DE ESTADO DE TELECOMUNICACIONES E INFRAESTRUCTURAS DIGITALES
Plan de Recuperación, Transformación y Resiliencia
UNICO I+D

6. Conclusions and IETF impact analysis

This document is an update of the initial analysis performed in 6G-DATADRIVEN-04-E9, where we explored the need for new RAW and DetNet extensions for industrial scenarios. Among the identified gaps, we have focused on support for multidomain and mobility support.

This document has described in detail the motivation for these extensions and provided a first detailed design of the required extensions/solutions. Contributions have been made to the IETF, presenting them in some meetings in 2023 and collecting very good feedback.

Regarding the impact of our IETF activities, we should highlight the final publication of the RAW use cases document as RFC (as expected in the roadmap included in 6G-DATADRIVEN-04-E9):

- Bernardos, C. J., Papadopoulos, G. Z., Thubert, P., & Theoleyre, F. (2023, September). *Reliable and Available Wireless (RAW) Use Cases*. RFC 9450 (Bernardos, Papadopoulos, Thubert, & Theoleyre, 2023). Retrieved from https://datatracker.ietf.org/doc/rfc9450/

Besides this, we have presented the multi-domain and mobility contributions to the DetNet WG in the last IETF meeting of 2023 (that took place in November in Prague). It is worth mentioning that during 2023 the RAW WG was closed, moving all the wireless DetNet (RAW) related activities to the IETF DetNet WG, as originally planned. This does not mean that RAW related work is no longer a topic for the IETF to work, but rather than the work is now done in the DetNet WG. The presentations got a lot of interest and good feedback from the DetNet WG chairs. Below we enumerate the updated list of IETF contributions, together with an updated analysis of potential adoption of these contributions:"Framework of Operations, Administration and Maintenance (OAM) for Deterministic Networking (DetNet)," draft-ietf-detnet-oam-framework. Updates are expected in 2023 to this document and its companion document in RAW. Publication as RFC is feasible in late 2023 or 2024.

- "DetNet multidomain extensions," draft-bernardos-detnet-multidomain (Carlos J. Bernardos A. M., draft-bernardos-detnet-multidomain-02, 2023). This document is expected to be updated in 2024, to address the comments received in the last IETF meeting. Based on its content, it is expected that some parts are adopted in the DetNet controller framework document, which might be published as an RFC in late 2024 or 2025.
- "RAW multidomain extensions," draft-bernardos-detnet-raw-multidomain (Bernardos & Mourad, RAW multidomain extensions, 2023). Updates are expected in 2024 and will be probably merged with the previous document. Depending on the pace of RAW related activities in the DetNET WG, this document might be called for adoption in 2024.
- "MIPv6 RAW mobility" draft-bernardos-detnet-raw-mobility (Carlos J. Bernardos A. M., draft-bernardos-detnet-raw-mobility-00, 2023). We plan to update this document in 2024, addressing the comments received in the last IETF meeting. Depending on the pace of RAW related activities in the DetNET WG, this document might be called for adoption in 2024.
- "Framework of Operations, Administration and Maintenance (OAM) for Deterministic Networking (DetNet)", draft-ietf-detnet-oam-framework (Mirsky, y otros, 2023). This document is quite advanced and we foresee publication as an RFC in 2024.

Financiado por la Unión Europea NextGenerationEU
GOBIERNO DE ESPAÑA MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL SECRETARÍA DE ESTADO DE TELECOMUNICACIONES E INFRAESTRUCTURAS DIGITALES
Plan de Recuperación, Transformación y Resiliencia
UNICO I+D

7. References

Bernardos, C. J., & Mourad, A. (2023, September). *RAW multidomain extensions.* Internet-Draft, IETF Secretariat. Retrieved from https://www.ietf.org/archive/id/draft-bernardos-detnet-raw-multidomain-00.txt

Bernardos, C. J., Papadopoulos, G. Z., Thubert, P., & Theoleyre, F. (2023, October). *Reliable and Available Wireless (RAW) Use Cases.* IETF Secretariat. doi:10.17487/RFC9450

Carlos J. Bernardos, A. M. (2023). *DETNET multidomain extensions.* Retrieved from https://www.ietf.org/archive/id/draft-bernardos-detnet-multidomain-02.txt

Carlos J. Bernardos, A. M. (2023). *MIPv6 RAW mobility.* Retrieved from https://www.ietf.org/archive/id/draft-bernardos-detnet-raw-mobility-00.txt

Carlos J. Bernardos, A. M. (2023). Using RAW as Control Plane for Wireless Deterministic Networks: Challenges Ahead. *Proceedings of the Twenty-fourth International Symposium on Theory, Algorithmic Foundations, and Protocol Design for Mobile Networks and Mobile Computing (MobiHoc '23)* (pp. 328–333). Washington: ACM. doi:https://doi.org/10.1145/3565287.3617608

Farrel, A., Vasseur, J.-P., & Ash, J. (2006, August). *A Path Computation Element (PCE)-Based Architecture.* RFC Editor. RFC Editor. Retrieved from http://www.rfc-editor.org/rfc/rfc4655.txt

Finn, N., & Thubert, P. (2019, May). *Deterministic Networking Problem Statement.* RFC Editor. RFC Editor. Retrieved from https://www.rfc-editor.org/info/rfc8557

Finn, N., Thubert, P., Varga, B., & Farkas, J. (2019, October). *Deterministic Networking Architecture.* RFC Editor. RFC Editor.

King, D., & Farrel, A. (2012, November). *The Application of the Path Computation Element Architecture to the Determination of a Sequence of Domains in MPLS and GMPLS.* RFC Editor. RFC Editor. Retrieved from https://www.rfc-editor.org/info/rfc6805

Koodli, R. E. (2009). *Mobile IPv6 Fast Handovers.* doi:10.17487/RFC5568

Martinez, B., Cano, C., & Vilajosana, X. (2019). A Square Peg in a Round Hole: The Complex Path for Wireless in the Manufacturing Industry. *IEEE Communications Magazine, 57*, 109-115. doi:10.1109/MCOM.2019.1800570

Mirsky, G., Theoleyre, F., Papadopoulos, G. Z., Bernardos, C. J., Varga, B., & Farkas, J. (2023, October). *Framework of Operations, Administration and Maintenance (OAM) for Deterministic Networking (DetNet).* Internet-Draft, IETF Secretariat. Retrieved from https://www.ietf.org/archive/id/draft-ietf-detnet-oam-framework-10.txt

Palattella, M. R., Thubert, P., Watteyne, T., & Wang, Q. (2018, March). *Terms Used in IPv6 over the TSCH mode of IEEE 802.15.4e.* Internet-Draft, IETF Secretariat. Retrieved from https://www.ietf.org/archive/id/draft-ietf-6tisch-terminology-10.txt

Financiado por la Unión Europea NextGenerationEU
GOBIERNO DE ESPAÑA MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL SECRETARÍA DE ESTADO DE TELECOMUNICACIONES E INFRAESTRUCTURAS DIGITALES
Plan de Recuperación, Transformación y Resiliencia
UNICO I+D

Sofia, R. C., Kovatsch, M., & Mendes, P. (2021, December). *Requirements for Reliable Wireless Industrial Services.* Internet-Draft, IETF Secretariat. Retrieved from https://www.ietf.org/archive/id/draft-ietf-raw-industrial-requirements-00.txt

Theoleyre, F., Papadopoulos, G. Z., Mirsky, G., & Bernardos, C. J. (2023, September). *Operations, Administration and Maintenance (OAM) features for RAW.* Internet-Draft, IETF Secretariat. Retrieved from https://www.ietf.org/archive/id/draft-ietf-raw-oam-support-06.txt

Thubert, P. (2021, May). *An Architecture for IPv6 over the Time-Slotted Channel Hopping Mode of IEEE 802.15.4 (6TiSCH).* RFC Editor. RFC Editor.

Thubert, P. (2022, December). *Reliable and Available Wireless Architecture.* Internet-Draft, IETF Secretariat. Retrieved from https://www.ietf.org/archive/id/draft-ietf-raw-architecture-11.txt

Watteyne, T., Palattella, M., & Grieco, L. (2015, May). *Using IEEE 802.15.4e Time-Slotted Channel Hopping (TSCH) in the Internet of Things (IoT): Problem Statement.* RFC Editor. RFC Editor. Retrieved from http://www.rfc-editor.org/rfc/rfc7554.txt

Yokota, H. C. (2010). *Fast Handovers for Proxy Mobile IPv6.* doi:10.17487/RFC5949

Financiado por la Unión Europea NextGenerationEU
GOBIERNO DE ESPAÑA MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL SECRETARÍA DE ESTADO DE TELECOMUNICACIONES E INFRAESTRUCTURAS DIGITALES
Plan de Recuperación, Transformación y Resiliencia
UNICO I+D

8. Annex A: Changes from 6G-DATADRIVEN-04-E9

We list below the different changes, updates, extensions and new sections that have been included in this document as an update of 6G-DATADRIVEN-04-E9:

- General updates in the text, also fixing some typos. Text added identifying gaps.
- New detailed solutions in sections 3 (namely section 3.6) and 4 (namely, sections 4.2 and 4.3.)
- Removed section on integration with MEC, moved to 6G-DATADRIVEN-E15 (and to be evolved in subsequent updates).
- Several figures redrawn and updated.
- References updated.
- Summary of IETF activities and assessment against the initially identified plan.

Financiado por la Unión Europea NextGenerationEU
GOBIERNO DE ESPAÑA MINISTERIO DE ASUNTOS ECONÓMICOS Y TRANSFORMACIÓN DIGITAL SECRETARÍA DE ESTADO DE TELECOMUNICACIONES E INFRAESTRUCTURAS DIGITALES
Plan de Recuperación, Transformación y Resiliencia
UNICO I+D