UNICO I+D Project
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RAW extensions: initial release

Abstract

This report includes a set of proposed RAW extensions required for industrial scenarios, including a roadmap for potential adoption at the IETF.

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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

Resumen Ejecutivo

Este documento proporciona un análisis de extensiones/soluciones RAW (Reliable and Available Wireless) necesarias para entornos industriales para el proyecto 6G-DATADRIVEN-04, así como un plan de potencial adopción de algunas de las soluciones planteadas en el IETF. El documento dibuja a alto nivel algunas de las soluciones que se estudiarán y desarrollarán en mayor detalle a lo largo del proyecto.

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 inicial de algunas de las extensiones anteriores; y
- una planificación de contribuciones y su potencial adopción en el IETF.

Parte de estos resultados se han enviado y presentado ya al IETF, como versiones iniciales. En concreto, se ha participado como co-autor y/o editor en las siguientes contribuciones:

- Bernardos, C. J., & Mourad, A. (2022, September). *Extensions to enable wireless reliability and availability in multi-access edge deployments*. Internet-Draft, IETF Secretariat. Retrieved from https://www.ietf.org/archive/id/draft-bernardos-raw-mec-04.txt
- Bernardos, C. J., & Mourad, A. (2022, September). *RAW multidomain extensions*. Internet-Draft, IETF Secretariat. Retrieved from https://www.ietf.org/archive/id/draft-bernardos-raw-multidomain-01.txt
- Bernardos, C. J., & Mourad, A. (2022, July). *RAW multidomain extensions*. Internet-Draft, IETF Secretariat. Retrieved from https://www.ietf.org/archive/id/draft-bernardos-detnet-multidomain-00.txt
- Bernardos, C. J., & Mourad, A. (2022, September). *Terminal-based joint selection and configuration of MEC host and RAW network*. Internet-Draft, IETF Secretariat. Retrieved from https://www.ietf.org/archive/id/draft-bernardos-raw-joint-selection-raw-mec-03.txt
- Bernardos, C. J., Papadopoulos, G. Z., Thubert, P., & Theoleyre, F. (2022, October). *RAW Use-Cases*. Internet-Draft, IETF Secretariat. Retrieved from https://www.ietf.org/archive/id/draft-ietf-raw-use-cases-08.txt
- Mirsky, G., Theoleyre, F., Papadopoulos, G. Z., Bernardos, C. J., Varga, B., & Farkas, J. (2022, 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-07.txt

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

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Executive Summary

This document provides an analysis of RAW (Reliable and Available Wireless) extensions/solutions needed for industrial environments for the project 6G-DATADRIVEN-04, and also a potential plan for adoption of some of the proposed solutions in the IETF. The document sketches at high-level several of the solutions that will be studied and developed in more detail throughout the project.

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 initial design of some of the previous extensions; and
- a contribution roadmap and its potential adoption at the IETF.

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:

- Bernardos, C. J., & Mourad, A. (2022, September). *Extensions to enable wireless reliability and availability in multi-access edge deployments*. Internet-Draft, IETF Secretariat. Retrieved from https://www.ietf.org/archive/id/draft-bernardos-raw-mec-04.txt
- Bernardos, C. J., & Mourad, A. (2022, September). *RAW multidomain extensions*. Internet-Draft, IETF Secretariat. Retrieved from https://www.ietf.org/archive/id/draft-bernardos-raw-multidomain-01.txt
- Bernardos, C. J., & Mourad, A. (2022, July). *RAW multidomain extensions*. Internet-Draft, IETF Secretariat. Retrieved from https://www.ietf.org/archive/id/draft-bernardos-detnet-multidomain-00.txt
- Bernardos, C. J., & Mourad, A. (2022, September). *Terminal-based joint selection and configuration of MEC host and RAW network*. Internet-Draft, IETF Secretariat. Retrieved from https://www.ietf.org/archive/id/draft-bernardos-raw-joint-selection-raw-mec-03.txt
- Bernardos, C. J., Papadopoulos, G. Z., Thubert, P., & Theoleyre, F. (2022, October). *RAW Use-Cases*. Internet-Draft, IETF Secretariat. Retrieved from https://www.ietf.org/archive/id/draft-ietf-raw-use-cases-08.txt
- Mirsky, G., Theoleyre, F., Papadopoulos, G. Z., Bernardos, C. J., Varga, B., & Farkas, J. (2022, 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-07.txt

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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, 2022) 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. Then, it explains three main gaps identified in current RAW/DetNet work: extensions for multidomain operation, integration of RAW and edge and mobility in RAW domains. We conclude the document with a summary and potential roadmap of contributions and adoptions at the IETF.

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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 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 drinking 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, on the order of milliseconds. Motion control that monitors dynamic activities may require even faster rates on the order of and below the millisecond. Finally, some industries exhibit hybrid behaviors, like canned soup that will start as a process industry while mixing the food and then operate as a discrete manufacturing when putting the final product in cans and shipping them.

In all those cases, a packet must flow reliably between the sensor and the PLC, be processed by the PLC, and 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 4 losses 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. But few industries would afford the associated cost and the Holy Grail 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. But 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 carpeted floor over IP, which means the potential for a security breach via the interconnection of the Operational Technology (OT) network with the Internet technology (IT) network and possibly enable 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 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.

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[1] http://www.odva.org/

[2] http://us.profinet.com/technology/profinet/

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.

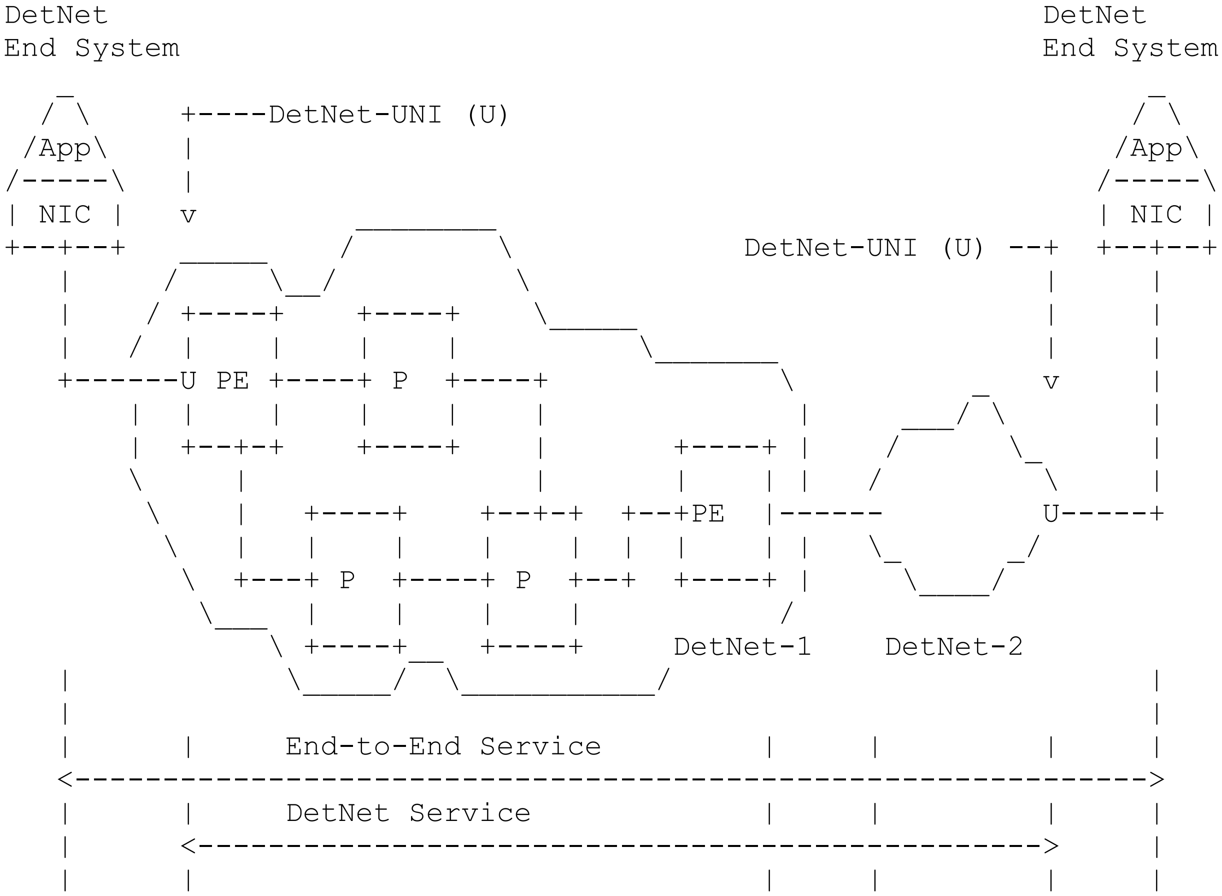

FIGURE 1: DETNET SERVICE REFERENCE MODEL (MULTIDOMAIN) (FROM RFC8655)

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.
- 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 reponsibilities (e.g., if the application plane is taking care of splitting what needs to be provided by each domain).

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, 2022) 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.

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.

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).

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|                  *     | RAW |P|          |
| ( ( o ) )*      *      |node |S|          |
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|   /   \       / \    **                +------+
|  +-----+     /   \     *( ( o ) )         |
|  |host1|    ------+--       ^             |
|  |     |    | RAW |P|      / \            |
|  |     |    |node |S|     /   \           |
|  |  o  |    | 1-2 |E|    ------+--        |
|  +-----+    ------+--    | RAW |P|        |
|              \   /       |node |S|        |
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|       | RAW |P|       *   | 2-1 |E|    +------+
|       |node |S|        *  ------+--    | PCE2 |
|       | 2-2 |E|         *              +------+
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|                 /   \    | RAW |P|        |
|                +-----+   |node |S|        |
|       RAW      |host2|   | 2-3 |E|        |
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FIGURE 2: EXEMPLARY SCENARIO SHOWING MULTIPLE RAW DOMAINS

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) (summarized in Section 3.4) 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, 2022) to monitor the quality of the selected paths.

4. RAW in multi-access edge deployments

4.1. Introduction

Multi-access Edge Computing (MEC) -- formerly known as Mobile Edge Computing -- capabilities deployed in the edge of the mobile network can facilitate the efficient and dynamic provision of services to mobile users. The ETSI ISG MEC working group, operative from end of 2014, intends to specify an open environment for integrating MEC capabilities with service providers' networks, including also applications from 3rd parties. These distributed computing capabilities will make available IT infrastructure as in a cloud environment for the deployment of functions in mobile access networks.

One relevant exemplary scenario showing the need for an integration of RAW and MEC is introduced next. One of the main (and distinct) use cases of 5G is Ultra Reliable and Low Latency Communications (URLLC). Among the many so-called "verticals" that require URLLC features, the Industry 4.0 (also referred to as Wireless for Industrial Applications) is probably the one with more short-term potential. As identified in (Bernardos, Papadopoulos, Thubert, & Theoleyre, 2022), this scenario also calls for RAW solutions, as cables are not that suitable for the robots and mobile vehicles typically used in factories. This is also a very natural scenario for MEC deployments, as bounded, and very low latencies are needed between the robots and physical actuators and the control logic managing them. Figure 3 depicts an exemplary scenario of a factory where terminals (robots and mobile automated guided vehicles) are wirelessly connected. Control applications running in the edge (implemented as MEC applications) require bounded low latencies and a guaranteed availability, despite the mobility of the terminals and the changing wireless conditions. A heterogeneous wireless mesh network is used to provide connectivity inside the factory.

```
                -----------
                |   PCE   |
                -----+-----
                     |
                   --+--
                  (     )
                 (       )
                  (     )
                   --+--
                     |
                -----------
                | RAW PSE |
                -----+-----
                     |
 ____________________+__________________________________
|                                  *( ( o ) )           |
|    RAW                          * *   ^               |
|  network                  ****** *   / \              |
|                    *******      *   /   \    -----    |
|                   *           **   -------   |app|    |
|                  *           *     | RAW | -------    |
|             ( ( o ) )*      *      |node |-| MEC |    |
|   -----         ^     *( ( o ) )   ------- -------    |
|   |app|        / \         ^    *                     |
|   -----       /   \       / \    **                   |
|   |app|      -------     /   \     *( ( o ) )         |
| -------      | RAW |    -------         ^     (o      |
| | MEC |------|node |    | RAW |        / \     -\---- |
| -------      -------    |node |       /   \    |term| |
|        o)          o)   -------      -------   -0--0- |
|   ----/-      ----/-                 | RAW |          |
|   |term|      |term|                 |node |          |
|   -0--0-      -0--0-                 -------          |
|_______________________________________________________|
```

FIGURE 3: EXEMPLARY SCENARIO DEPICTING MEC AND RAW IN AN INDUSTRIAL ENVIRONMENTS

This scenario includes a wireless domain, involving multiple MEC platforms to ensure low latency to applications, by being able to host MEC applications in several locations, and dynamically migrate the apps as the terminals move around and the serving MEC platform might no longer be capable of meeting the latency requirements.

4.2. Problem Statement

With current standards, the MEC platform(s) would have to interact with a Path Computation Element (PCE) for data plane requests and updates. This tremendously limits the capabilities to guarantee real-time forwarding decisions, as it will make it challenging and not possible to manage forwarding decisions in real or near-real time.

RAW solutions and approaches being explored today consider the role of the PSE, which computes at a short time scale which of the available paths (called tracks) -- computed by a PCE -- should be used per flow/packet and also which PAREO functions can be used, in order to provide the flow with the required availability and reliability features. The PSE interacts with the PCE and with the RAW nodes so they can setup the required per-flow state, to recognize the flow and determine the forwarding policy to be applied. These RAW forwarding decisions can be distributed among the necessary nodes using in-band signaling (e.g., extending Segment Routing, BIER-TE or DETNET tagging) or can be taken autonomously by each forwarding node locally (based on its knowledge of the status of the network, gained via OAM RAW-specific mechanisms).

Figure 3 shows an exemplary scenario, depicting an industrial environment where different nodes are wirelessly connected to provide connectivity to several stationary and mobile terminals (i.e., robots). Industry environments are a good example of applications where reliability and availability are critical. Ensuring this in wireless heterogeneous and multi-hop networks requires using multiple paths, using PAREO functions and even using dual or multiple connectivity. Terminal mobility makes it even more challenging to guarantee certain reliability and availability levels, due to the dynamic and fast changes that this needs at the data plane level. The short-time scale forwarding decisions that are required to ensure reliability and availability with terminal mobility cannot be managed if MEC platforms can only interact with the data plane through the PCE.

The PCE is responsible for routing computation and maintenance in a network and it is typically a centralized entity that can even reside outside the network. It is meant to compute and establish redundant paths, but not to be sensitive/reactive to transient changes, and therefore is not capable of ensuring a certain level of reliability and availability in a wireless heterogeneous mesh network, especially if some of the nodes (e.g., the end terminals) might be mobile. With currently standardized solutions, a MEC platform could only interact with the RAW network through the PCE, most possibly through the Mp2 reference point defined by ETSI MEC. This reference point is defined between the MEC platform and the data plane of the virtualization infrastructure to instruct the data plane on how to route traffic among applications, networks, services, etc. This reference point is not further specified by ETSI MEC, but it would be the one that could be used by current solutions to allow for MEC to request the data plane on the RAW network a certain behavior (in terms of availability and reliability) for MEC app traffic flows. With existing solutions, the PCE would be the entry point for configuring and managing the RAW network, probably through the Mp2 reference point. Note that the PCE might reside outside the RAW network, the path between the RAW network and the PCE might be expensive and slow (e.g., it might need to traverse the whole RAW network) and reaching to the PCE can also be slow in regards to the speed of events that affect the forwarding operation at the radio layer.

Additionally, the MEC architecture as currently defined by ETSI does not have any component designed to deal with the specifics of an heterogeneous wireless multi-hop networks (such a RAW one), and therefore, it is very limited in terms of what a MEC app (through the MEC platform) can request to the data plane of an heterogeneous wireless multi-hop network. Besides, this lack of RAW-aware component at the ETSI MEC architecture prevents any enhancement at either the MEC side (e.g., MEC app migrations triggered by RAW status updates) or the RAW side (e.g., PAREO function updates triggered by MEC app/terminal mobility).

Because of all these aforementioned reasons, it is needed to define a new RAW-enabled component at the ETSI MEC architecture, aimed at enabling a more direct interaction between the MEC platform and the RAW network, allowing the MEC platform to notify events and/or request actions to the RAW network quick enough. This involves some challenges, as the RAW PSE has to understand the needs from the running MEC applications, so it can properly configure the RAW nodes so the data plane provides the required reliability and availability.

4.3. RAW and MEC integration

This document defines a new entity inside the MEC platform: the RAW ctrl. This entity is responsible for computing what to instruct the RAW PSE, based on the requirements of the MEC apps, as well as to take decisions at the MEC side (e.g., migration of apps) based on information about the RAW network status.

As a result of the introduction of the RAW ctrl and the actions it is responsible of, new interactions and interface semantics are added. These interactions and semantics can be terminated at either the PCE or the RAW PSE, depending on the requirements of the MEC apps. For near real-time coordination and control between MEC and RAW mechanisms, the interactions are between the RAW ctrl and the RAW PSE. We mostly refer to this deployment model from now on, as it is the one that allow for near real-time updates on the forwarding plane, but note that an alternative deployment model in which the RAW ctrl interacts with the PCE is also possible, though only supporting non real-time interactions.

The MEC-RAW new interface semantics/extensions depicted in Figure 4 allows the MEC platform to issue requests to the RAW network, through the RAW PSE, so it can behave as required by MEC apps.

```
             ------------                          --- Data plane
             | MEC host |                 -------  ··· Control plane
----------   ------------          ·······+ PCE +··
| Mobile |         ·               ·      ---+---  ·( ( o ) ) ( ( o ) )
|  edge  |   ------+---------------·------   |    ·    ^         ^
|  orch. |   |         MEC host    ·     |   |    ·   / \       / \
----+-----   |         ------------·---- |   |    ·  /   \     /   \
    ·      ·············+  ------ ---+-- | --+--  ··+------   -------
----+----- · |  -----  | | ME | |RAW +·····+RAW|    | RAW +···+ RAW |
| Mobile | · |  |app+··+ |serv| |ctrl| | | |PSE+····+node |   |node +
|  edge  +·· |  -----  | ------ ------ | | -----    ---+--+---+------
|platform|   |  |app+··+  MEC platform | |             |
|manager |   |  --+--  ----------------- |             |
----------   -----|-----------------------             |
                  |                                    |
                  +------------------------------------+
```

FIGURE 4: RAW AND MEC INTEGRATION: BLOCK DIAGRAM

The new semantics of the interface between the MEC platform and the RAW PSE do not only serve to convey the requests, but also to synchronize the status and topology of the RAW (relevant portion of the) network, enabling to perform real-time or near-real time forwarding decisions.

4.4. Terminal-based joint selection and configuration of MEC host and RAW network

We next define extensions to: (i) enable a terminal to discover any RAW-enabled network on the path between the terminal and the MEC app host, and the RAW network associated capabilities; (ii) enable the terminal to request desired reliability and availability requirements to be met simultaneously by the MEC+RAW system; and, (iii) enable direct notifications from the RAW network to the terminal, to help with end-to-end application-level optimization. Most of the required extensions are related to ETSI MEC components and interfaces, and therefore are out of the scope of the IETF. However, we still briefly describe them for completeness, putting the main focus on the IETF RAW components and interactions.

Figure 5 shows the components and interfaces impacted by the extensions described in this document. The MEC UALCMP is logically extended with a RAW controller (RAW ctrl) functionality, to enable a terminal to learn about the RAW and MEC capabilities of the 5G network it is attached to, and specify its requirements in terms of availability and reliability for joint MEC app instantiation and RAW network configuration.

```
                             ------------
                             | MEC host |
                             ------+-----
------------   ----------          |
|   User   |   | Mobile |    ------+---------------------
| App. LCM +---+  edge  |    |         MEC host         |
|  Proxy   |   |  orch. |    |        ----------------- |
------------   ----------    |        + ------ ------ | |
     | RAW |                 | -----  | | ME | |RAW | | |
     | ctrl|      -----------+ |app+··+ |serv| |ctrl| | |
     ---+---      |          | -----  | ------ ------ | |
        |      +--+--+       | |app+··+  MEC platform | |
        |      | RAW |       | -----  ----------------- |
        +-----.+ PSE |       ----------------------------
               +-+-+-+
                 | |          ( ( o ) )     ( ( o ) )
                 | |              ^             ^
                 | |             / \           / \
                 | |            /   \         /   \
                 | |           -------       -------
                 | +-----------| RAW |-------+ RAW |
                 +-------------+node |       |node |
                               -------       -------
```

FIGURE 5: TERMINAL-BASED JOINT SELECTION AND CONFIGURATION OF MEC HOST AND RAW NETWORK: BLOCK DIAGRAM

5. Mobility in single RAW domains

5.1. 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.

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

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6. Conclusions and IETF contributions roadmap

This document has explored the need for new RAW and DetNet extensions for industrial scenarios. Among the identified gaps, we have focused on support for multidomain, integration with edge and mobility support.

This document has described in detail the motivation for these extensions and outlined the required extensions/solutions. Initial contributions have been made to the IETF, presenting them in some meetings in 2022 and collecting very good feedback.

Based on the discussions at the IETF, the adoption and progress pace of the RAW and DetNet WGs and the experience of the UC3M IETF delegate, we enumerate below a roadmap for contributions and potential adoption of some of these extensions:

- "RAW Use-Cases," draft-ietf-raw-use-cases. At least an update is expected in 2023. This document went through the IETF final approval phase with some pending comments to be addressed. It is expected that it will be published as an RFC in 2023.
- "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. This document is expected to be updated in 2023 and 2024. 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 2023 or 2024.
- "Extensions to enable wireless reliability and availability in multi-access edge deployments. Internet-Draft," draft-bernardos-raw-mec. Updates are expected in 2023 and 2024. Depending on the final content of the DetNet controller framework and the RAW WG potential re-chartering, this document might be called for adoption in 2024.
- "RAW multidomain extensions," draft-bernardos-raw-multidomain. Updates are expected in 2023 and 2024. Depending on the RAW WG potential re-chartering, this document might be called for adoption in 2024.
- "Terminal-based joint selection and configuration of MEC host and RAW network," draft-bernardos-raw-joint-selection-raw-mec. Updates are expected in 2023 and 2024. This document is not expected to be considered for adoption before 2024 or 2025.

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