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RFC 9913
Reliable and Available Wireless (RAW) Technologies

Abstract

This document surveys the short- and middle-range radio technologies over which providing a Deterministic Networking (DetNet) / Reliable and Available Wireless (RAW) service is suitable, presents the characteristics that RAW may leverage, and explores the applicability of the technologies to carry deterministic flows, as of the time of publication. The studied technologies are Wi-Fi 6/7, Time-Slotted Channel Hopping (TSCH), 3GPP 5G, and L-band Digital Aeronautical Communications System (LDACS).

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Table of Contents

1. Introduction

Deterministic Networking (DetNet) [RFC8557] provides a capability to carry specified unicast or multicast data flows for real-time applications with extremely low data loss rates and bounded latency within a network domain. Techniques that might be used include (1) reserving data plane resources for individual (or aggregated) DetNet flows in some or all of the intermediate nodes along the path of the flow, (2) providing explicit routes for DetNet flows that do not immediately change with the network topology, and (3) distributing data from DetNet flow packets over time and/or space (e.g., different frequencies or non-shared risk links) to ensure delivery of each packet in spite of the unavailability of a path.

DetNet operates at the IP layer and typically delivers service over wired lower-layer technologies such as Time-Sensitive Networking (TSN) as defined by IEEE 802.1 and IEEE 802.3.

The Reliable and Available Wireless (RAW) architecture [RFC9912] extends the DetNet architecture [RFC8655] to adapt to the specific challenges of the wireless medium, in particular, intermittently lossy connectivity, by optimizing the use of diversity and multipathing. [RFC9912] defines the concepts of reliability and availability that are used in this document. In turn, this document presents wireless technologies with capabilities, such as time synchronization and scheduling of transmission, that would make RAW/DetNet operations possible over such media. The technologies studied in this document were identified in the charter during the RAW Working Group (WG) formation and inherited by DetNet (when the WG picked up the work on RAW).

Making wireless reliable and available is even more challenging than it is with wires, due to the numerous causes of radio transmission losses that add up to the congestion losses and the delays caused by overbooked shared resources.

RAW, like DetNet, needs and leverages lower-layer capabilities such as time synchronization and traffic shapers. To balance the adverse effects of the radio transmission losses, RAW leverages additional lower-layer capabilities, some of which may be specific or at least more typically applied to wireless. Such lower-layer techniques include:

- per-hop retransmissions (also known as Automatic Repeat Request (ARQ)),
- variation of the Modulation and Coding Scheme (MCS),
- short-range broadcast,
- Multi-User - Multiple Input Multiple Output (MU-MIMO),
- constructive interference, and
- overhearing whereby multiple receivers are scheduled to receive the same transmission, which saves both energy on the sender and spectrum.

These capabilities may be offered by the lower layer and may be controlled by RAW, separately or in combination.

RAW defines a network-layer control loop that optimizes the use of links with constrained spectrum and energy while maintaining the expected connectivity properties, typically reliability and latency. The control loop involves communication monitoring through Operations, Administration, and Maintenance (OAM); path control through a Path Computation Element (PCE) and a runtime distributed Path Selection Engine (PSE); and extended Packet Replication, Elimination, and Ordering Functions (PREOF).

This document surveys the short- and middle-range radio technologies over which providing a DetNet/RAW service is suitable, presents the characteristics that RAW may leverage, and explores the applicability of the technologies to carry deterministic flows. The studied technologies are Wi-Fi 6/7, Time-Slotted Channel Hopping (TSCH), 3GPP 5G, and L-band Digital Aeronautical Communications System (LDACS). The purpose of this document is to support and enable work on the these (and possibly other similar compatible technologies) at the IETF, specifically in the DetNet Working Group working on RAW.

This document surveys existing networking technology; it does not define protocol behaviors or operational practices. The IETF specifications referenced herein each provide their own security considerations, and lower-layer technologies provide their own security at Layer 2; a security study of the technologies is explicitly not in scope.

2. Terminology

This document uses the terminology and acronyms defined in Section 2 of [RFC8655] and Section 3 of [RFC9912].

3. Towards Reliable and Available Wireless Networks

3.1. Scheduling for Reliability

A packet network is reliable for critical (e.g., time-sensitive) packets when the undesirable statistical effects that affect the transmission of those packets (e.g., delay or loss) are eliminated.

The reliability of a deterministic network [RFC8655] often relies on precisely applying a tight schedule that controls the use of time-shared resources such as CPUs and buffers, and maintains at all times the number of the critical packets within the available resources of the communication hardware (e.g., buffers) and the transmission medium (e.g., bandwidth, transmission slots). The schedule can also be used to shape the flows by controlling the time of transmission of the packets that compose the flow at every hop.

To achieve this, there must be a shared sense of time throughout the network. The sense of time is usually provided by the lower layer and is not in scope for RAW. As an example, the Precision Time Protocol (PTP), standardized as IEEE 1588 and IEC 61588, has mapping through profiles to Ethernet, industrial and SmartGrid protocols, and Wi-Fi with IEEE Std 802.1AS.

3.2. Diversity for Availability

Equipment (e.g., node) failure can be the cause of multiple packets being lost in a row before the flows are rerouted or the system recovers. Examples of equipment failure include a broken switch, an access point rebooting, a broken wire or radio adapter, or a fixed obstacle to the transmission.

Equipment failure is not acceptable for critical applications such as those related to safety. A typical process control loop will tolerate an occasional packet loss, but a loss of several packets in a row will cause an emergency stop. In an amusement ride (e.g., at Disneyland, Universal Studios, or MGM Studios parks), a continuous loss of packets for a few 100 ms may trigger an automatic interruption of the ride and cause the evacuation of the attraction floor to restart it.

Network availability is obtained by making the transmission resilient against hardware failures and radio transmission losses due to uncontrolled events such as co-channel interferers, multipath fading, or moving obstacles. The best results are typically achieved by pseudorandomly cumulating all forms of diversity -- in the spatial domain with replication and elimination, in the time domain with ARQ and diverse scheduled transmissions, and in the frequency domain with frequency hopping or channel hopping between frames.

3.3. Benefits of Scheduling

Scheduling redundant transmissions of the critical packets on diverse paths improves the resiliency against breakages and statistical transmission loss, such as those due to cosmic particles on wires and interferences on wireless. While transmission losses are orders of magnitude more frequent on wireless, redundancy and diversity are needed in all cases for life- and mission-critical applications.

When required, the worst-case time of delivery can be guaranteed as part of the end-to-end schedule, and the sense of time that must be shared throughout the network can be exposed to and leveraged by other applications.

In addition, scheduling provides specific value over the wireless medium:

- Scheduling allows a time-sharing operation, where every transmission is assigned its own time/frequency resource. The sender and receiver are synchronized and scheduled to talk on a given frequency resource at a given time and for a given duration. This way, scheduling can avoid collisions between scheduled transmissions and enable a high ratio of critical traffic (think 60% or 70% of high-priority traffic with ultra low loss) compared to statistical priority-based schemes.
- Scheduling can be used as a technique for both time and frequency diversity (e.g., between transmission retries), allowing the next transmission to happen on a different frequency as programmed in both the sender and the receiver. This is useful to defeat co-channel interference from uncontrolled transmitters as well as multipath fading.
- Transmissions can be also scheduled on multiple channels in parallel, which enables the use of the full available spectrum while avoiding the hidden terminal problem, e.g., when the

next packet in a same flow interferes on a same channel with the previous one that progressed a few hops farther.

- Scheduling optimizes the bandwidth usage. Compared to classical collision avoidance techniques, there is no blank time related to Interframe Space (IFS) and exponential back-off in scheduled operations. A minimal clear channel assessment may be needed to comply with the local regulations such as ETSI 300-328, but that will not detect a collision when the senders are synchronized.
- Scheduling plays a critical role in saving energy. In the Internet of Things (IoT), energy is the foremost concern, and synchronizing the sender and listener enables always maintaining them in deep sleep when there is no scheduled transmission. This avoids idle listening and long preambles, and it enables long sleep periods between traffic and resynchronization, allowing battery-operated nodes to operate in a mesh topology for multiple years.

4. IEEE 802.11

In recent years, the evolution of the IEEE Std 802.11 standard has taken a new direction, emphasizing improved reliability and reduced latency in addition to minor improvements in speed, to enable new fields of application such as industrial IoT and Virtual Reality (VR).

Leveraging IEEE Std 802.11, the Wi-Fi Alliance [WFA] delivered Wi-Fi 6, 7, and now 8 with more capabilities to schedule and deliver frames in due time at fast rates. Still, as with any radio technology, Wi-Fi is sensitive to frame loss, which can only be combated with the maximum use of diversity in space, time, channel, and even technology.

In parallel, the Avnu Alliance [Avnu], which focuses on applications of TSN for real-time data, formed a workgroup for uses case with TSN capabilities over wireless, leveraging both 3GPP and IEEE Std 802.11 standards.

To achieve the latter, the reliability must be handled at an upper layer that can select Wi-Fi and other wired or wireless technologies for parallel transmissions. This is where RAW comes into play.

This section surveys the IEEE 802.11 features that are most relevant to RAW, noting that there are a great many more in the specification, some of which may also possibly be of interest for a RAW solution. For instance, frame fragmentation reduces the impact of a very transient transmission loss, both on latency and energy consumption.

4.1. Provenance and Documents

The IEEE 802 LAN/MAN Standards Committee (SC) develops and maintains networking standards and recommended practices for local, metropolitan, and other area networks using an open and accredited process, and it advocates them on a global basis. The most widely used standards are for Ethernet, Bridging and Virtual Bridged LAN, Wireless LAN, Wireless Personal Area Network (PAN), Wireless MAN, Wireless Coexistence, Media Independent Handover Services, and Wireless Radio Access Network (RAN). An individual working group provides the focus for each area.

The IEEE 802.11 Wireless LAN (WLAN) standards define the underlying Medium Access Control (MAC) and Physical (PHY) layers for the Wi-Fi technology. While previous 802.11 generations, such as 802.11n and 802.11ac, focused mainly on improving peak throughput, more recent generations are also considering other performance vectors, such as efficiency enhancements for dense environments in IEEEE Std 802.11ax [IEEE802.11ax] (approved in 2021) and throughput, latency, and reliability enhancements in IEEE Std 802.11be [IEEE802.11be] (approved in 2024).

IEEE Std 802.11-2012 includes support for TSN time synchronization based on IEEE 802.1AS over the 802.11 Timing Measurement protocol. IEEE Std 802.11-2016 additionally includes an extension to the 802.1AS operation over 802.11 for Fine Timing Measurement (FTM), as well as the Stream Reservation Protocol (IEEE 802.1Qat). 802.11 WLANs can also be part of 802.1Q bridged networks with enhancements enabled by the 802.11ak amendment retrofitted in IEEE Std 802.11-2020. Traffic classification based on 802.1Q VLAN tags is also supported in 802.11. Other 802.1 TSN capabilities such as 802.1Qbv and 802.1CB, which are media agnostic, can already operate over 802.11. The IEEE Std 802.11ax-2021 defines additional scheduling capabilities that can enhance the timeliness performance in the 802.11 MAC and achieve lower-bounded latency. IEEE 802.11be introduces features to enhance the support for 802.1 TSN capabilities, especially those related to worst-case latency, reliability, and availability.

The IEEE 802.11 Working Group has been working in collaboration with the IEEE 802.1 Working Group for several years, extending some 802.1 features over 802.11. As with any wireless media, 802.11 imposes new constraints and restrictions to TSN-grade QoS, and trade-offs between latency and reliability guarantees must be considered as well as managed deployment requirements. An overview of 802.1 TSN capabilities and challenges for their extensions to 802.11 are discussed in [Cavalcanti_2019].

The Wi-Fi Alliance is the worldwide network of companies that drives global Wi-Fi adoption and evolution through thought leadership, spectrum advocacy, and industry-wide collaboration. The WFA work helps ensure that Wi-Fi devices and networks provide users the interoperability, security, and reliability they have come to expect.

The Avnu Alliance is also a global industry forum developing interoperability testing for TSN-capable devices across multiple media including Ethernet, Wi-Fi, and 5G.

The following IEEE Std 802.11 specifications/certifications [IEEE802.11] are relevant in the context of reliable and available wireless services and support for TSN capabilities:

- Time synchronization: IEEE Std 802.11-2016 with IEEE Std 802.1AS; WFA TimeSync Certification
- Congestion control: IEEE Std 802.11-2016 Admission Control; WFA Admission Control
- Security: WFA Wi-Fi Protected Access, WPA2, and WPA3
- Interoperating with IEEE 802.1Q bridges: IEEE Std 802.11-2020 incorporating 802.11ak
- Stream Reservation Protocol (part of [IEEE802.1Qat]): AIEEE802.11-2016
- Scheduled channel access: IEEE 802.11ad enhancements for very high throughput in the 60 GHz band [IEEE802.11ad]

- 802.11 Real-Time Applications: Topic Interest Group (TIG) ReportDoc [IEEE_doc_11-18-2009-06]

In addition, major amendments being developed by the IEEE 802.11 Working Group include capabilities that can be used as the basis for providing more reliable and predictable wireless connectivity and support time-sensitive applications:

- [IEEE802.11ax]: Enhancements for High Efficiency (HE)
- [IEEE802.11be]: Extreme High Throughput (EHT)
- [IEEE802.11ay]: Enhanced throughput for operation in license-exempt bands above 45 GHz

The main 802.11ax, 802.11be, 802.11ad, and 802.11ay capabilities and their relevance to RAW are discussed in the remainder of this section. As P802.11bn is still in early stages of development, its capabilities are not included in this document.

4.2. 802.11ax High Efficiency (HE)

4.2.1. General Characteristics

The next generation Wi-Fi (Wi-Fi 6) is based on the IEEE Std 802.11ax amendment [IEEE802.11ax], which includes specific capabilities to increase efficiency, control and reduce latency. Some of these features include higher-order 1024-QAM modulation, support for uplink Multi-User - Multiple Input Multiple Output (MU-MIMO), Orthogonal Frequency-Division Multiple Access (OFDMA), trigger-based access, and Target Wake Time (TWT) for enhanced power savings. The OFDMA mode and trigger-based access enable the Access Point (AP), after reserving the channel using the clear channel assessment procedure for a given duration, to schedule multi-user transmissions, which is a key capability required to increase latency predictability and reliability for time-sensitive flows. 802.11ax can operate in up to 160 MHz channels, and it includes support for operation in the new 6 GHz band, which has been open to unlicensed use by the Federal Communications Commission (FCC) and other regulatory agencies worldwide.

4.2.1.1. Multi-User OFDMA and Trigger-Based Scheduled Access

802.11ax introduced an OFDMA mode in which multiple users can be scheduled across the frequency domain. In this mode, the Access Point (AP) can initiate multi-user uplink (UL) transmissions in the same PHY Protocol Data Unit (PPDU) by sending a trigger frame. This centralized scheduling capability gives the AP much more control of the channel in its Basic Service Set (BSS), and it can remove contention between associated stations for uplink transmissions, therefore reducing the randomness caused by access based on Carrier Sense Multiple Access (CSMA) between stations within the same BSS. The AP can also transmit simultaneously to multiple users in the downlink direction by using a downlink (DL) MU OFDMA PPDU. In order to initiate a contention-free Transmission Opportunity (TXOP) using the OFDMA mode, the AP still follows the typical listen-before-talk procedure to acquire the medium, which ensures interoperability and compliance with unlicensed band access rules. However, 802.11ax also includes a Multi-User Enhanced Distributed Channel Access (MU-EDCA) capability, which allows the AP to get higher channel access priority than other devices in its BSS.

4.2.1.2. Traffic Isolation via OFDMA Resource Management and Resource Unit Allocation

802.11ax relies on the notion of an OFDMA Resource Unit (RU) to allocate frequency chunks to different stations over time. RUs provide a way to allow multiple stations to transmit simultaneously, starting and ending at the same time. The way this is achieved is via padding, where extra bits are transmitted with the same power level. The current RU allocation algorithms provide a way to achieve traffic isolation per station. While this does not support time-aware scheduling per se, it is a key aspect to assist reliability, as it provides traffic isolation in a shared medium.

4.2.1.3. Improved PHY Robustness

The 802.11ax PHY can operate with a 0.8, 1.6, or 3.2 microsecond Guard Interval (GI). The larger GI options provide better protection against multipath, which is expected to be a challenge in industrial environments. The possibility of operating with smaller RUs (e.g., 2 MHz) enabled by OFDMA also helps reduce noise power and improve Signal-to-Noise Ratio (SNR), leading to better Packet Error Rate (PER) performance.

802.11ax supports beamforming as in 802.11ac but introduces UL MU-MIMO, which helps improve reliability. The UL MU-MIMO capability is also enabled by the trigger-based access operation in 802.11ax.

4.2.1.4. Support for 6 GHz Band

The 802.11ax specification [IEEE802.11ax] includes support for operation in the 6 GHz band. Given the amount of new spectrum available, as well as the fact that no legacy 802.11 device (prior 802.11ax) will be able to operate in this band, 802.11ax operation in this new band can be even more efficient.

4.2.2. Applicability to Deterministic Flows

TSN capabilities, as defined by the IEEE 802.1 TSN standards, provide the underlying mechanism for supporting deterministic flows in a Local Area Network (LAN). The IEEE 802.11 Working Group has incorporated support for absolute time synchronization to extend the TSN 802.1AS protocol so that time-sensitive flows can experience precise time synchronization when operating over 802.11 links. As IEEE 802.11 and IEEE 802.1 TSN are both based on the IEEE 802 architecture, 802.11 devices can directly implement some TSN capabilities without the need for a gateway/translation protocol. Basic features required for operation in a 802.1Q LAN are already enabled for 802.11. Some TSN capabilities, such as 802.1Qbv, can already operate over the existing 802.11 MAC SAP [Sudhakaran2021]. Implementation and experimental results of TSN capabilities (802.1AS, 802.1Qbv, and 802.1CB) extended over standard Ethernet and Wi-Fi devices have also been described in [Fang_2021]. Nevertheless, the IEEE 802.11 MAC/PHY could be extended to improve the operation of IEEE 802.1 TSN features and achieve better performance metrics [Cavalcanti1287].

TSN capabilities supported over 802.11 (which also extends to 802.11ax) include:

1. 802.1AS-based time synchronization (other time synchronization techniques may also be used)

2. Interoperating with IEEE 802.1Q bridges
3. Time-sensitive traffic stream classification

The existing 802.11 TSN capabilities listed above, and the 802.11ax OFDMA and AP-controlled access within a BSS, provide a new set of tools to better serve time-sensitive flows. However, it is important to understand the trade-offs and constraints associated with such capabilities, as well as redundancy and diversity mechanisms that can be used to provide more predictable and reliable performance.

4.2.2.1. 802.11 Managed Network Operation and Admission Control

Time-sensitive applications and TSN standards are expected to operate in a managed network (e.g., an industrial/enterprise network). This enables careful management and integration of the Wi-Fi operation with the overall TSN management framework, as defined in [IEEE802.1Qcc].

Some of the random-access latency and interference from legacy/unmanaged devices can be reduced under a centralized management mode as defined in [IEEE802.1Qcc].

Existing traffic stream identification, configuration, and admission control procedures defined in the QoS mechanism in [IEEE802.11] can be reused. However, given the high degree of determinism required by many time-sensitive applications, additional capabilities to manage interference and legacy devices within tight time constraints need to be explored.

4.2.2.2. Scheduling for Bounded Latency and Diversity

As discussed earlier, the OFDMA mode in [IEEE802.11ax] introduces the possibility of assigning different RUs (time/frequency resources) to users within a PPDU. Several RU sizes are defined in the specification (26, 52, 106, 242, 484, and 996 subcarriers). In addition, the AP can also decide on a Modulation and Coding Scheme (MCS) and grouping of users within a given OFMDA PPDU. Such flexibility can be leveraged to support time-sensitive applications with bounded latency, especially in a managed network where stations can be configured to operate under the control of the AP, in a controlled environment (which contains only devices operating on the unlicensed band installed by the facility owner and where unexpected interference from other systems and/or radio access technologies only sporadically happens), or in a deployment where channel and link redundancy is used to reduce the impact of unmanaged devices and interference.

When the network is lightly loaded, it is possible to achieve latencies under 1 msec when Wi-Fi is operated in a contention-based mode (i.e., without OFDMA). It also has been shown that it is possible to achieve 1 msec latencies in a controlled environment with higher efficiency when multi-user transmissions are used (enabled by OFDMA operation) [Cavalcanti_2019]. Obviously, there are latency, reliability, and capacity trade-offs to be considered. For instance, smaller RUs result in longer transmission durations, which may impact the minimal latency that can be achieved, but the contention latency and randomness elimination in an interference-free environment due to multi-user transmission is a major benefit of the OFDMA mode.

The flexibility to dynamically assign RUs to each transmission also enables the AP to provide frequency diversity, which can help increase reliability.

4.3. 802.11be Extreme High Throughput (EHT)

4.3.1. General Characteristics

[IEEE802.11be] was the next major 802.11 amendment (after IEEE Std 802.11ax-2021) for operation in the 2.4, 5, and 6 GHz bands. 802.11be includes new PHY and MAC features, and it is targeting extremely high throughput (at least 30 Gbps), as well as enhancements to worst-case latency and jitter. It is also expected to improve the integration with 802.1 TSN to support time-sensitive applications over Ethernet and Wireless LANs.

The main features of 802.11be that are relevant to this document include:

1. 320 MHz bandwidth and more efficient utilization of non-contiguous spectrum
2. Multi-Link Operation (MLO)
3. QoS enhancements to reduce latency and increase reliability

4.3.2. Applicability to Deterministic Flows

The 802.11 Real-Time Applications (RTA) Topic Interest Group (TIG) provided detailed information on use cases, issues, and potential solution directions to improve support for time-sensitive applications in 802.11. The RTA TIG report [IEEE_doc_11-18-2009-06] was used as input to the 802.11be project scope.

Improvements for worst-case latency, jitter, and reliability were the main topics identified in the RTA report, which were motivated by applications in gaming, industrial automation, robotics, etc. The RTA report also highlighted the need to support additional TSN capabilities, such as time-aware (802.1Qbv) shaping and packet replication and elimination as defined in 802.1CB.

IEEE Std 802.11be builds on and enhances 802.11ax capabilities to improve worst case latency and jitter. Some of the enhancement areas are discussed next.

4.3.2.1. Enhanced Scheduled Operation for Bounded Latency

In addition to the throughput enhancements, 802.11be leverages the trigger-based scheduled operation enabled by 802.11ax to provide efficient and more predictable medium access.

802.11be introduced QoS signaling enhancements, such as an additional QoS characteristics element, that enables stations to provide detailed information about deterministic traffic stream to the AP. This capability helps AP implementations to better support scheduling for deterministic flows.

4.3.2.2. Multi-Link Operation

802.11be introduces new features to improve operation over multiple links and channels. By leveraging multiple links and channels, 802.11be can isolate time-sensitive traffic from network congestion, one of the main causes of large latency variations. In a managed 802.11be network, it should be possible to steer traffic to certain links and channels to isolate time-sensitive traffic from other traffic and help achieve bounded latency. The Multi-Link Operation (MLO) is a major feature in the 802.11be amendment that can enhance latency and reliability by enabling data frames to be duplicated across links.

4.4. 802.11ad and 802.11ay (mmWave Operation)

4.4.1. General Characteristics

The IEEE 802.11ad amendment defines PHY and MAC capabilities to enable multi-Gbps throughput in the 60 GHz millimeter wave (mmWave) band. The standard addresses the adverse mmWave signal propagation characteristics and provides directional communication capabilities that take advantage of beamforming to cope with increased attenuation. An overview of the 802.11ad standard can be found in [Nitsche_2015].

The IEEE 802.11ay is currently developing enhancements to the 802.11ad standard to enable the next generation mmWave operation targeting 100 Gbps throughput. Some of the main enhancements in 802.11ay include MIMO, channel bonding, improved channel access, and beamforming training. An overview of the 802.11ay capabilities can be found in [Ghasempour_2017].

4.4.2. Applicability to Deterministic Flows

The high-data rates achievable with 802.11ad and 802.11ay can significantly reduce latency down to microsecond levels. Limited interference from legacy and other unlicensed devices in 60 GHz is also a benefit. However, the directionality and short range typical in mmWave operation impose new challenges such as the overhead required for beam training and blockage issues, which impact both latency and reliability. Therefore, it is important to understand the use case and deployment conditions in order to properly apply and configure 802.11ad/ay networks for time-sensitive applications.

The 802.11ad standard includes a scheduled access mode in which the central controller, after contending and reserving the channel for a dedicated period, can allocate to stations contention-free service periods. This scheduling capability is also available in 802.11ay, and it is one of the mechanisms that can be used to provide bounded latency to time-sensitive data flows in interference-free scenarios. An analysis of the theoretical latency bounds that can be achieved with 802.11ad service periods is provided in [Cavalcanti_2019].

5. IEEE 802.15.4 Time-Slotted Channel Hopping (TSCH)

IEEE Std 802.15.4 TSCH was the first IEEE radio specification aimed directly at industrial IoT applications, for use in process control loops and monitoring. It was used as a base for the major industrial wireless process control standards, Wireless Highway Addressable Remote Transducer Protocol (HART) and ISA100.11a.

While the MAC/PHY standards enable the relatively slow rates used in process control (typically in the order of 4-5 per second), the technology is not suited for the faster periods used in factory automation and motion control (1 to 10 ms).

5.1. Provenance and Documents

The IEEE 802.15.4 Task Group has been driving the development of low-power, low-cost radio technology. The IEEE 802.15.4 physical layer has been designed to support demanding low-power scenarios targeting the use of unlicensed bands, both the 2.4 GHz and sub-GHz Industrial, Scientific and Medical (ISM) bands. This has imposed requirements in terms of frame size, data rate, and bandwidth to achieve reduced collision probability, reduced packet error rate, and acceptable range with limited transmission power. The PHY layer supports frames of up to 127 bytes. The Medium Access Control (MAC) sublayer overhead is in the order of 10-20 bytes, leaving about 100 bytes to the upper layers. IEEE 802.15.4 uses spread spectrum modulation such as the Direct Sequence Spread Spectrum (DSSS).

The Time-Slotted Channel Hopping (TSCH) mode was added to the 2015 revision of the IEEE 802.15.4 standard [IEEE802.15.4]. TSCH is targeted at the embedded and industrial world, where reliability, energy consumption, and cost drive the application space.

Building on IEEE 802.15.4, TSN on low-power constrained wireless networks has been partially addressed by ISA100.11a [ISA100.11a] and WirelessHART [WirelessHART]. Both technologies involve a central controller that computes redundant paths for industrial process control traffic over a TSCH mesh. Moreover, ISA100.11a introduces IPv6 capabilities [RFC8200] with a link-local address for the join process and a global unicast address for later exchanges, but the IPv6 traffic typically ends at a local application gateway and the full power of IPv6 for end-to-end communication is not enabled.

At the IETF, the 6TiSCH Working Group [TiSCH] has enabled distributed routing and scheduling to exploit the deterministic access capabilities provided by TSCH for IPv6. The group designed the essential mechanisms, the 6TiSCH Operation (6top) sublayer and the Scheduling Functions (SFs), to enable the management plane operation while ensuring IPv6 is supported.

- The 6top Protocol (6P) is defined in [RFC8480] and provides a pairwise negotiation mechanism to the control plane operation. The protocol supports agreement on a schedule between neighbors, enabling distributed scheduling.
- 6P goes hand in hand with an SF, the policy that decides how to maintain cells and trigger 6P transactions. The Minimal Scheduling Function (MSF) [RFC9033] is the default SF defined by the 6TiSCH WG.
- With these mechanisms, 6TiSCH can establish Layer 2 links between neighboring nodes and support best-effort traffic. The Routing Protocol for Low-Power and Lossy Networks (RPL) [RFC8480] provides the routing structure, enabling the 6TiSCH devices to establish the links with well-connected neighbors, thus forming the acyclic network graphs.

A Track at 6TiSCH is the application to wireless of the concept of a recovery graph in the RAW architecture. A Track can follow a simple sequence of relay nodes, or it can be structured as a more complex Destination-Oriented Directed Acyclic Graph (DODAG) to a unicast destination. Along a Track, 6TiSCH nodes reserve the resources to enable the efficient transmission of packets while aiming to optimize certain properties such as reliability and ensure small jitter or bounded latency. The Track structure enables Layer 2 forwarding schemes, reducing the overhead of making routing decisions at Layer 3.

The 6TiSCH architecture [RFC9030] identifies different models to schedule resources along so-called Tracks (see Section 5.2.1), exploiting the TSCH schedule structure; however, the focus in 6TiSCH is on best-effort traffic, and the group was never chartered to produce standards work related to Tracks.

There are several works that can be used to complement the overview provided in this document. For example, [vilajosana21] provides a detailed description of the 6TiSCH protocols, how they are linked together, and how they are integrated with other standards like RPL and 6Lo.

5.2. General Characteristics

As a core technique in IEEE 802.15.4, TSCH splits time in multiple time slots that repeat over time. Each device has its own perspective of when the send or receive occurs and on which channel the transmission happens. This constitutes the device's Slotframe, where the channel and destination of a transmission by this device are a function of time. The overall aggregation of all the Slotframes of all the devices constitutes a time/frequency matrix with at most one transmission in each cell of the matrix (see more in Section 5.3.1.4).

The IEEE 802.15.4 TSCH standard does not define any scheduling mechanism but only provides the architecture that establishes a slotted structure that can be managed by a proper schedule. This schedule represents the possible communications of a node with its neighbors and is managed by a Scheduling Function such as the Minimal Scheduling Function (MSF) [RFC9033]. In MSF, each cell in the schedule is identified by its slotoffset and channeloffset coordinates. A cell's timeslot offset indicates its position in time, relative to the beginning of the slotframe. A cell's channel offset is an index that maps to a frequency at each iteration of the slotframe. Each packet exchanged between neighbors happens within one cell. The size of a cell is a timeslot duration, between 10 to 15 milliseconds. An Absolute Slot Number (ASN) indicates the number of slots elapsed since the network started. It increments at every slot. This is a 5-byte counter that can support networks running for more than 300 years without wrapping (assuming a 10 ms timeslot). Channel hopping provides increased reliability to multipath fading and external interference. It is handled by TSCH through a channel-hopping sequence referred to as macHopSeq in the IEEE 802.15.4 specification.

The Time-Frequency Division Multiple Access provided by TSCH enables the orchestration of traffic flows, spreading them in time and frequency, and hence enabling an efficient management of the bandwidth utilization. Such efficient bandwidth utilization can be combined with OFDM modulations also supported by the IEEE 802.15.4 standard [IEEE802.15.4] since the 2015 version.

TSCH networks operate in ISM bands in which the spectrum is shared by different coexisting technologies. Regulations such as the FCC, ETSI, and ARIB impose duty cycle regulations to limit the use of the bands, but interference may still constrain the probability of delivering a packet.

Part of these reliability challenges are addressed at the MAC introducing redundancy and diversity, thanks to channel hopping, scheduling, and ARQ policies. Yet, the MAC layer operates with a 1-hop vision, being limited to local actions to mitigate underperforming links.

5.2.1. 6TiSCH Tracks

A Track in the 6TiSCH architecture [RFC9030] is the application to 6TiSCH networks of the concept of a protection path in the DetNet architecture [RFC8655]. A Track can be structured as a Destination-Oriented Directed Acyclic Graph (DODAG) to a destination for unicast traffic. Along a Track, 6TiSCH nodes reserve the resources to enable the efficient transmission of packets while aiming to optimize certain properties such as reliability and ensure small jitter or bounded latency. The Track structure enables Layer 2 forwarding schemes, reducing the overhead of making routing decisions at Layer 3.

Serial Tracks can be understood as the concatenation of cells or bundles along a routing path from a source towards a destination. The serial Track concept is analogous to the circuit concept where resources are chained into a multi-hop topology; see more in Section 5.2.1.2 on how that is used in the data plane to forward packets.

Whereas scheduling ensures reliable delivery in bounded time along any Track, high availability requires the application of PREOF functions along a more complex DODAG Track structure. A DODAG has forking and joining nodes where concepts like replication and elimination can be exploited. Spatial redundancy increases the overall energy consumption in the network but significantly improves the availability of the network as well as the packet delivery ratio. A Track may also branch off and rejoin, for the purpose of so-called Packet Replication and Elimination (PRE), over non-congruent branches. PRE may be used to complement Layer 2 ARQ and receiver-end ordering to complete/extend the PREOF functions. This enables meeting industrial expectations of packet delivery within bounded delay over a Track that includes wireless links, even when the Track extends beyond the 6TiSCH network.

The RAW Track described in the RAW architecture [RFC9912] inherits directly from that model. RAW extends the graph beyond a DODAG as long as a given packet cannot loop within the Track.

```
                  +-----+
                  | IoT |
                  | G/W |
                  +-----+
                     ^  <---- Elimination
                    | |
     Track branch   | |
            +-------+ +--------+ Subnet backbone
            |                  |
         +--|--+            +--|--+
         |  |  | Backbone   |  |  | Backbone
    o    |  |  | router     |  |  | router
         +--/--+            +--|--+
    o     /    o     o---o----/       o
        o    o---o--/   o      o   o  o   o
   o     \  /     o               o   LLN    o
      o   v  <---- Replication
          o
```

Figure 1: End-to-End Deterministic Track

In Figure 1, a Track is laid out from a field device in a 6TiSCH network to an IoT gateway that is located on an IEEE 802.1 TSN backbone.

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

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

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

Methods to implement complex Tracks are described in [RFC9914] and complemented by extensions to the RPL routing protocol in [NSA-EXT] for best-effort traffic, but a centralized routing technique such as one promoted in DetNet is still missing.

5.2.1.1. Track Scheduling Protocol

Section 4.4 of the 6TiSCH architecture [RFC9030] describes four approaches to manage the TSCH schedule of the Low-Power and Lossy Network (LLN) nodes: static scheduling, neighbor-to-neighbor scheduling, remote monitoring and scheduling management, and hop-by-hop scheduling. The Track operation for DetNet corresponds to a remote monitoring and scheduling management by a PCE.

5.2.1.2. Track Forwarding

In the 6TiSCH architecture [RFC9030], forwarding is the per-packet operation that allows a packet to be delivered to a next hop or an upper layer in a node. Forwarding is based on preexisting state that was installed as a result of the routing computation of a Track by a PCE. The 6TiSCH architecture supports three different forwarding models: GMPLS Track Forwarding (TF), 6LoWPAN Fragment Forwarding (FF), and IPv6 Forwarding (6F), which is the classical IP operation [RFC9030]. The DetNet case relates to the Track Forwarding operation under the control of a PCE.

A Track is a unidirectional path between a source and a destination. Time and frequency resources called cells (see Section 5.3.1.4) are allocated to enable the forwarding operation along the Track. In a Track cell, the normal operation of IEEE 802.15.4 ARQ usually happens, though the acknowledgment may be omitted in some cases, for instance, if there is no scheduled cell for a retry.

Track Forwarding is the simplest and fastest. A bundle of cells set to receive (RX-cells) is uniquely paired to a bundle of cells that are set to transmit (TX-cells), representing a Layer 2 forwarding state that can be used regardless of the network-layer protocol. This model can effectively be seen as a Generalized Multiprotocol Label Switching (GMPLS) operation in that the information used to switch a frame is not an explicit label but is rather related to other properties about the way the packet was received (a particular cell, in the case of 6TiSCH). As a result, as long as the TSCH MAC (and Layer 2 security) accepts a frame, that frame can be switched regardless of the protocol, whether this is an IPv6 packet, a 6LoWPAN fragment, or a frame from an alternate protocol such as WirelessHART or ISA100.11a.

A data frame that is forwarded along a Track normally has a destination MAC address that is set to broadcast (or a multicast address, depending on MAC support). This way, the MAC layer in the intermediate nodes accepts the incoming frame, and 6top switches it without incurring a change in the MAC header. In the case of IEEE 802.15.4, this means effectively broadcast, so that the short address for the destination of the frame is set to 0xFFFF along the Track.

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

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

On the other hand, it might happen that there are not enough TX-cells in the transmit bundle to accommodate the Track traffic, for instance, if more retransmissions are needed than provisioned. In that case, the frame can be placed for transmission in the bundle that is used for Layer 3 traffic towards the next hop along the Track as long as it can be routed by the upper layer, that is, typically, if the frame transports an IPv6 packet. The MAC address should be set to the next-hop MAC address to avoid confusion. It results that a frame that is received over a Layer 3 bundle may be in fact associated with a Track. In a classical IP link such as an Ethernet, off-Track traffic is typically in excess over reservation to be routed along the non-reserved path based on its QoS setting. However, with 6TiSCH, since the use of the Layer 3 bundle may be due to transmission failures, it makes sense for the receiver to recognize a frame that should be re-Tracked and to place it back on the appropriate bundle if possible. A frame should be re-Tracked if the per-hop-behavior group indicated in the Differentiated Services field in the IPv6 header is set to deterministic forwarding, as discussed in Section 5.3.1.1. A frame is re-Tracked by scheduling it for transmission over the transmit bundle associated with the Track, with the destination MAC address set to broadcast.

5.2.1.2.1. OAM

"An Overview of Operations, Administration, and Maintenance (OAM) Tools" [RFC7276] provides an overview of the existing tooling for OAM [RFC6291]. Tracks are complex paths and new tooling is necessary to manage them, with respect to load control, timing, and the Packet Replication and Elimination Functions (PREF).

An example of such tooling can be found in the context of Bit Index Explicit Replication (BIER) [RFC8279] and, more specifically, BIER Traffic Engineering (BIER-TE) [RFC9262].

5.3. Applicability to Deterministic Flows

In the RAW context, low-power reliable networks should address non-critical control scenarios such as Class 2 and monitoring scenarios such as Class 4, as defined by [RFC5673]. As a low-power technology targeting industrial scenarios, radio transducers provide low data rates (typically between 50 kbps to 250 kbps) and robust modulations to trade-off performance to reliability. TSCH networks are organized in mesh topologies and connected to a backbone. Latency in the mesh network is mainly influenced by propagation aspects such as interference. ARQ methods and redundancy techniques such as replication and elimination should be studied to provide the needed performance to address deterministic scenarios.

Nodes in a TSCH network are tightly synchronized. This enables building the slotted structure and ensures efficient utilization of resources thanks to proper scheduling policies. Scheduling is key to orchestrate the resources that different nodes in a Track or a path are using. Slotframes can be split in resource blocks, reserving the needed capacity to certain flows. Periodic and bursty traffic can be handled independently in the schedule, using active and reactive policies and taking advantage of overprovisioned cells. Along a Track (see Section 5.2.1), resource blocks can be chained so nodes in previous hops transmit their data before the next packet comes. This provides a tight control to latency along a Track. Collision loss is avoided for best-effort traffic by overprovisioning resources, giving time to the management plane of the network to dedicate more resources if needed.

5.3.1. Centralized Path Computation

When considering end-to-end communication over TSCH, a 6TiSCH device usually does not place a request for bandwidth between itself and another device in the network. Rather, an Operation Control System (OCS) invoked through a Human-Machine Interface (HMI) provides the traffic specification, in particular, in terms of latency and reliability, and the end nodes, to a PCE. With this, the PCE computes a Track between the end nodes and provisions every hop in the Track with per-flow state that describes the per-hop operation for a given packet, the corresponding timeSlots, and the flow identification to recognize which packet is placed in which Track, sort out duplicates, etc. An example of an OCS and HMI is depicted in Figure 2.

For a static configuration that serves a certain purpose for a long period of time, it is expected that a node will be provisioned in one shot with a full schedule, which incorporates the aggregation of its behavior for multiple Tracks. The 6TiSCH architecture expects that the programming of the schedule is done over the Constrained Application Protocol (CoAP) as discussed in [CoAP-6TiSCH].

However, a Hybrid mode may be required as well, whereby a single Track is added, modified, or removed (for instance, if it appears that a Track does not perform as expected). For that case, the expectation is that a protocol that flows along a Track (to be), in a fashion similar to classical Traffic Engineering (TE) [CCAMP], may be used to update the state in the devices. In general, that flow was not designed, and it is expected that DetNet will determine the appropriate end-to-end protocols to be used in that case.

Stream Management Entity

```
                   Operational Control System and HMI

 -+-+-+-+-+-+-+ Northbound -+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-

           PCE         PCE              PCE              PCE

 -+-+-+-+-+-+-+ Southbound -+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-

         --- 6TiSCH------6TiSCH------6TiSCH------6TiSCH--
6TiSCH /     Device      Device      Device      Device   \
Device-                                                    - 6TiSCH
       \     6TiSCH      6TiSCH      6TiSCH      6TiSCH   /  Device
         ----Device------Device------Device------Device--
```

Figure 2: Architectural Layers

5.3.1.1. Packet Marking and Handling

Section 4.7.1 of [RFC9030] describes the packet tagging and marking that is expected in 6TiSCH networks.

5.3.1.1.1. Tagging Packets for Flow Identification

Packets that are routed by a PCE along a Track are tagged to uniquely identify the Track and associated transmit bundle of timeSlots.

It results that the tagging that is used for a DetNet flow outside the 6TiSCH Low-Power and Lossy Network (LLN) must be swapped into 6TiSCH formats and back as the packet enters and then leaves the 6TiSCH network.

5.3.1.1.2. Replication, Retries, and Elimination

The 6TiSCH architecture [RFC9030] leverages PREOF over several alternate paths in a network to provide redundancy and parallel transmissions to bound the end-to-end delay. Considering the scenario shown in Figure 3, many different paths are possible for S to reach R. A simple way to benefit from this topology could be to use the two independent paths via nodes A, C, E and via B, D, F, but more complex paths are possible as well.

```
                              (A)   (C)   (E)

                source (S)                       (R) (destination)

                              (B)   (D)   (F)
```

Figure 3: A Typical Ladder Shape with Two Parallel Paths Toward the Destination

By employing a packet replication function, each node forwards a copy of each data packet over two different branches. For instance, in Figure 4, the source node S transmits the data packet to nodes A and B, in two different timeslots within the same TSCH slotframe. S transmits twice the same data packet to its Destination Parent (DP) (A) and to its Alternate Parent (AP) (B).

```
                     ===> (A) => (C) => (E) ===
                   //        \\//   \\//       \\
         source (S)          //\\   //\\         (R) (destination)
                   \\       //  \\ //  \\       //
                     ===> (B) => (D) => (F) ===
```

Figure 4: Packet Replication

By employing a packet elimination function once it receives the first copy of a data packet, a node discards the subsequent copies. Because the first copy that reaches a node is the one that matters, it is the only copy that will be forwarded upward.

Considering that the wireless medium is broadcast by nature, any neighbor of a transmitter may overhear a transmission. By employing the promiscuous overhearing function, nodes will have multiple opportunities to receive a given data packet. For instance, in Figure 4, when the source node S transmits the data packet to node A, node B may overhear the transmission.

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

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

The semantics of the configuration must enable correlated timeSlots to be grouped for transmit (and receive, respectively) with 'OR' relations, and then an 'AND' relation must be configurable between groups. The semantics are such that if the transmit (and receive, respectively) operation succeeded in one timeSlot in an 'OR' group, then all the other timeslots in the group are ignored. Now, if there are at least two groups, the 'AND' relation between the groups indicates that one operation must succeed in each of the groups. Further details can be found in the 6TiSCH architecture document [RFC9030].

5.3.1.2. Topology and Capabilities

6TiSCH nodes are usually IoT devices, characterized by a very limited amount of memory, just enough buffers to store one or a few IPv6 packets, and limited bandwidth between peers. It results that a node will maintain only a small amount of peering information and will not be able to store many packets waiting to be forwarded. Peers can be identified through MAC or IPv6 addresses.

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

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

5.3.1.3. Schedule Management by a PCE

6TiSCH supports a mixed model of centralized routes and distributed routes. Centralized routes can, for example, be computed by an entity such as a PCE [PCE]. Distributed routes are computed by RPL [RFC6550].

Both methods may inject routes in the routing tables of the 6TiSCH routers. In either case, each route is associated with a 6TiSCH topology that can be a RPL Instance topology or a Track. The 6TiSCH topology is indexed by an Instance ID, in a format that reuses the RPLInstanceID as defined in RPL.

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

5.3.1.4. SlotFrames and Priorities

IEEE 802.15.4 TSCH avoids contention on the medium by formatting time and frequencies in cells of transmission of equal duration. In order to describe that formatting of time and frequencies, the 6TiSCH architecture defines a global concept that is called a Channel Distribution and Usage (CDU) matrix; a CDU matrix is a matrix of cells with a height equal to the number of available channels (indexed by ChannelOffsets) and a width (in timeSlots) that is the period of the network scheduling operation (indexed by slotOffsets) for that CDU matrix.

The CDU matrix is used by the PCE as the map of all the channel utilization. This organization depends on the time in the future. The frequency used by a cell in the matrix rotates in a pseudorandom fashion, from an initial position at an epoch time, as the CDU matrix iterates over and over.

The size of a cell is a timeSlot duration, and values of 10 to 15 milliseconds are typical in 802.15.4 TSCH to accommodate for the transmission of a frame and an acknowledgement, including the security validation on the receive side, which may take up to a few milliseconds on some device architectures. The matrix represents the overall utilization of the spectrum over time by a scheduled network operation.

A CDU matrix is computed by the PCE, but unallocated timeSlots may be used opportunistically by the nodes for classical best-effort IP traffic. The PCE has precedence in the allocation in case of a conflict. Multiple schedules may coexist, in which case the schedule adds a dimension to the matrix, and the dimensions are ordered by priority.

A slotFrame is the base object that a PCE needs to manipulate to program a schedule into one device. The slotFrame is a device perspective of a transmission schedule; there can be more than one with different priorities so in case of a contention the highest priority applies. In other words, a slotFrame is the projection of a schedule from the CDU matrix onto one device. Elaboration on that concept can be found in section "SlotFrames and Priorities" of [RFC9030], and Figures 17 and 18 in [RFC9030] illustrate that projection.

6. 5G

5G technology enables deterministic communication. Based on the centralized admission control and the scheduling of the wireless resources, licensed or unlicensed, Quality of Service (QoS) such as latency and reliability can be guaranteed. 5G contains several features to achieve ultra-reliable and low-latency performance (e.g., support for different OFDM numerologies and slot durations), as well as fast processing capabilities and redundancy techniques that lead to achievable latency numbers of below 1 ms with 99.999% or higher confidence.

5G also includes features to support industrial IoT use cases, e.g., via the integration of 5G with TSN. This includes 5G capabilities for each TSN component, latency, resource management, time synchronization, and reliability. Furthermore, 5G support for TSN can be leveraged when 5G is used as the subnet technology for DetNet, in combination with or instead of TSN, which is the primary subnet for DetNet. In addition, the support for integration with TSN reliability was added to 5G by making DetNet reliability also applicable, due to the commonalities between TSN and DetNet reliability. Moreover, providing IP service is native to 5G, and 3GPP Release 18 adds direct support for DetNet to 5G.

Overall, 5G provides scheduled wireless segments with high reliability and availability. In addition, 5G includes capabilities for integration to IP networks. This makes 5G a suitable technology upon which to apply RAW.

6.1. Provenance and Documents

The 3rd Generation Partnership Project (3GPP) incorporates many companies whose business is related to cellular network operation as well as network equipment and device manufacturing. All generations of 3GPP technologies provide scheduled wireless segments, primarily in licensed spectrum, which is beneficial for reliability and availability.

In 2016, the 3GPP started to design New Radio (NR) technology belonging to the fifth generation (5G) of cellular networks. NR has been designed from the beginning to not only address enhanced Mobile Broadband (eMBB) services for consumer devices such as smart phones or tablets, but it is also tailored for future IoT communication and connected cyber-physical systems. In addition to eMBB, requirement categories have been defined on Massive Machine-Type Communication (M-MTC) for a large number of connected devices/sensors and on Ultra-Reliable Low-Latency Communications (URLLC) for connected control systems and critical communication as illustrated in Figure 5. It is the URLLC capabilities that make 5G a great candidate for reliable low-latency communication. With these three cornerstones, NR is a complete solution supporting the connectivity needs of consumers, enterprises, and the public sector for both wide-area and local-area (e.g., indoor) deployments. A general overview of NR can be found in [TS38300].

```
            enhanced
        Mobile Broadband
               ^
              / \
             /   \
            /     \
           /       \
          /   5G    \
         /           \
        /             \
       /               \
      +-----------------+
   Massive          Ultra-Reliable
 Machine-Type        Low-Latency
Communication       Communication
```

Figure 5: 5G Application Areas

As a result of releasing the first NR specification in 2018 (Release 15), it has been proven by many companies that NR is a URLLC-capable technology and can deliver data packets at 10^{-5} packet error rate within a 1 ms latency budget [TR37910]. Those evaluations were consolidated and forwarded to ITU to be included in the work on [IMT2020].

In order to understand communication requirements for automation in vertical domains, 3GPP studied different use cases [TR22804] and released a technical specification with reliability, availability, and latency demands for a variety of applications [TS22104].

As an evolution of NR, multiple studies that focus on radio aspects have been conducted in scope of 3GPP Release 16, including the following two:

1. "Study on physical layer enhancements for NR ultra-reliable and low latency case (URLLC)" [TR38824]
2. "Study on NR industrial Internet of Things (IoT)" [TR38825]

As a result of these studies, further enhancements to NR have been standardized in 3GPP Release 16 and are available in [TS38300] and continued in 3GPP Release 17 standardization (according to [RP210854]).

In addition, several enhancements have been made on the system architecture level, which are reflected in "System architecture for the 5G System (5GS)" [TS23501]. These enhancements include multiple features in support of Time-Sensitive Communications (TSC) by Release 16 and Release 17. Further improvements, such as support for DetNet [TR2370046], are provided in Release 18.

The adoption and the use of 5G is facilitated by multiple organizations. For instance, the 5G Alliance for Connected Industries and Automation (5G-ACIA) brings together widely varying 5G stakeholders including Information and Communication Technology (ICT) players and Operational Technology (OT) companies (e.g., industrial automation enterprises, machine builders, and end users). Another example is the 5G Automotive Association (5GAA), which bridges ICT and automotive technology companies to develop end-to-end solutions for future mobility and transportation services.

6.2. General Characteristics

The 5G Radio Access Network (5G RAN) with its NR interface includes several features to achieve Quality of Service (QoS), such as a guaranteeably low latency or tolerable packet error rates for selected data flows. Determinism is achieved by centralized admission control and scheduling of the wireless frequency resources, which are typically licensed frequency bands assigned to a network operator.

NR enables short transmission slots in a radio subframe, which benefits low-latency applications. NR also introduces mini-slots, where prioritized transmissions can be started without waiting for slot boundaries, further reducing latency. As part of giving priority and faster radio access to URLLC traffic, NR introduces preemption, where URLLC data transmission can preempt ongoing non-URLLC transmissions. Additionally, NR applies very fast processing, enabling retransmissions even within short latency bounds.

NR defines extra-robust transmission modes for increased reliability for both data and control radio channels. Reliability is further improved by various techniques, such as multi-antenna transmission, the use of multiple frequency carriers in parallel, and packet duplication over independent radio links. NR also provides full mobility support, which is an important reliability aspect not only for devices that are moving, but also for devices located in a changing environment.

Network slicing is seen as one of the key features for 5G, allowing vertical industries to take advantage of 5G networks and services. Network slicing is about transforming a Public Land Mobile Network (PLMN) from a single network to a network where logical partitions are created, with appropriate network isolation, resources, optimized topology, and specific configurations to serve various service requirements. An operator can configure and manage the mobile network to support various types of services enabled by 5G (e.g., eMBB and URLLC), depending on the different needs of customers.

Exposure of capabilities of 5G systems to the network or applications outside the 3GPP domain have been added to Release 16 [TS23501]. Applications can access 5G capabilities like communication service monitoring and network maintenance via exposure interfaces.

For several generations of mobile networks, 3GPP has considered how the communication system should work on a global scale with billions of users, taking into account resilience aspects, privacy regulation, protection of data, encryption, access and core network security, as well as interconnect. Security requirements evolve as demands on trustworthiness increase. For example, this has led to the introduction of enhanced privacy protection features in 5G. 5G also employs strong security algorithms, encryption of traffic, protection of signaling, and protection of interfaces.

One particular strength of mobile networks is the authentication, based on well-proven algorithms and tightly coupled with a global identity management infrastructure. Since 3G, there is also mutual authentication, allowing the network to authenticate the device and the device to authenticate the network. Another strength is secure solutions for storage and distribution of keys, fulfilling regulatory requirements and allowing international roaming. When connecting to 5G, the user meets the entire communication system, where security is the result of standardization, product security, deployment, operations, and management as well as incident-handling capabilities. The mobile networks approach the entirety in a rather coordinated fashion, which is beneficial for security.

6.3. Deployment and Spectrum

The 5G system allows deployment in a vast spectrum range, addressing use cases in both wide-area and local-area networks. Furthermore, 5G can be configured for public and non-public access.

When it comes to spectrum, NR allows combining the merits of many frequency bands, such as the high bandwidths in millimeter waves (mmWaves) for extreme capacity locally and the broad coverage when using mid- and low-frequency bands to address wide-area scenarios. URLLC is achievable in all these bands. Spectrum can be either licensed, which means that the license holder is the only authorized user of that spectrum range, or unlicensed, which means that anyone who wants to use the spectrum can do so.

A prerequisite for critical communication is performance predictability, which can be achieved by full control of access to the spectrum, which 5G provides. Licensed spectrum guarantees control over spectrum usage by the system, making it a preferable option for critical communication. However, unlicensed spectrum can provide an additional resource for scaling non-critical communications. While NR was initially developed for usage of licensed spectrum, the functionality to also access unlicensed spectrum was introduced in 3GPP Release 16. Moreover, URLLC features are enhanced in Release 17 [RP210854] to be better applicable to unlicensed spectrum.

Licensed spectrum dedicated to mobile communications has been allocated to mobile service providers, i.e., issued as longer-term licenses by national administrations around the world. These licenses have often been associated with coverage requirements and issued across whole countries or large regions. Besides this, configured as a non-public network (NPN) deployment, 5G can also provide network services to a non-operator defined organization and its premises such as a factory deployment. With this isolation, QoS requirements as well as security requirements can be achieved. An integration with a public network, if required, is also possible. The non-public (local) network can thus be interconnected with a public network, allowing devices to roam between the networks.

In an alternative model, some countries are now in the process of allocating parts of the 5G spectrum for local use to industries. These non-service providers then have the choice to apply for a local license themselves and operate their own network or to cooperate with a public network operator or service provider.

6.4. Applicability to Deterministic Flows

6.4.1. System Architecture

The 5G system [TS23501] consists of the User Equipment (UE) at the terminal side, the Radio Access Network (RAN) with the gNodeB (gNB) as radio base station node, and the Core Network (CN), which is connected to the external Data Network (DN). The CN is based on a service-based architecture with the following central functions: Access and Mobility Management Function (AMF), Session Management Function (SMF), and User Plane Function (UPF) as illustrated in Figure 6. (Note that this document only explains key functions; however, Figure 6 provides a more detailed view, and [SYSTOVER5G] summarizes the functions and provides the full definitions of the acronyms used in the figure.)

The gNB's main responsibility is radio resource management, including admission control and scheduling, mobility control, and radio measurement handling. The AMF handles the UE's connection status and security, while the SMF controls the UE's data sessions. The UPF handles the user plane traffic.

The SMF can instantiate various Packet Data Unit (PDU) sessions for the UE, each associated with a set of QoS flows, i.e., with different QoS profiles). Segregation of those sessions is also possible; for example, resource isolation in the RAN and CN can be defined (slicing).

```
  +----+  +---+   +---+    +---+    +---+   +---+
  |NSSF|  |NEF|   |NRF|    |PCF|    |UDM|   |AF |
  +--+-+  +-+-+   +-+-+    +-+-+    +-+-+   +-+-+
     |      |       |        |        |       |
Nnssf|  Nnef|   Nnrf|    Npcf|    Nudm|    Naf|
     |      |       |        |        |       |
  ---+------+-+-----+-+------------+--+-----+-+---
              |       |            |         |
         Nausf|  Nausf|        Nsmf|         |
              |       |            |         |
           +--+-+   +-+-+        +-+-+     +-+-+
           |AUSF|   |AMF|        |SMF|     |SCP|
           +----+   +++-+        +-+-+     +---+
                    / |            |
                   /  |            |
                  /   |            |
                 N1   N2           N4
                /     |            |
               /      |            |
              /       |            |
          +--+-+   +--+--+      +--+---+      +----+
          | UE +---+(R)AN+--N3--+ UPF  +--N6--+ DN |
          +----+   +-----+      ++----++      +----+
                                 |    |
                                 +-N9-+
```

Figure 6: 5G System Architecture

To allow UE mobility across cells/gNBs, handover mechanisms are supported in NR. For an established connection (i.e., connected mode mobility), a gNB can configure a UE to report measurements of received signal strength and quality of its own and neighboring cells, periodically or based on events. Based on these measurement reports, the gNB decides to hand over a UE to another target cell/gNB. Before triggering the handover, it is handshaked with the target gNB based on network signaling. A handover command is then sent to the UE, and the UE switches its connection to the target cell/gNB. The Packet Data Convergence Protocol (PDCP) of the UE can be configured to avoid data loss in this procedure, i.e., to handle retransmissions if needed. Data forwarding is possible between source and target gNB as well. To improve the mobility performance further (i.e., to avoid connection failures due to too-late handovers), the mechanism of conditional handover is introduced in Release 16 specifications. Therein, a conditional handover command, defining a triggering point, can be sent to the UE before the UE enters a handover situation. A further improvement that has been introduced in Release 16 is the Dual Active Protocol Stack (DAPS), where the UE maintains the connection to the source cell while connecting to the target cell. This way, potential interruptions in packet delivery can be avoided entirely.

6.4.2. Overview of the Radio Protocol Stack

The protocol architecture for NR consists of the Layer 1 Physical (PHY) layer and, as part of Layer 2, the sublayers of Medium Access Control (MAC), Radio Link Control (RLC), Packet Data Convergence Protocol (PDCP), and Service Data Adaption Protocol (SDAP).

The PHY layer handles actions related to signal processing, such as encoding/decoding of data and control bits, modulation, antenna precoding, and mapping.

The MAC sublayer handles multiplexing and priority handling of logical channels (associated with QoS flows) to transport blocks for PHY transmission, as well as scheduling information reporting and error correction through Hybrid Automated Repeat Request (HARQ).

The RLC sublayer handles sequence numbering of higher-layer packets, retransmissions through Automated Repeat Request (ARQ), if configured, as well as segmentation and reassembly and duplicate detection.

The PDCP sublayer consists of functionalities for ciphering/deciphering, integrity protection/verification, reordering and in-order delivery, and duplication and duplicate handling for higher-layer packets. This sublayer also acts as the anchor protocol to support handovers.

The SDAP sublayer provides services to map QoS flows, as established by the 5G core network, to data radio bearers (associated with logical channels), as used in the 5G RAN.

Additionally, in RAN, the Radio Resource Control (RRC) protocol handles the access control and configuration signaling for the aforementioned protocol layers. RRC messages are considered Layer 3 and are thus also transmitted via those radio protocol layers.

To provide low latency and high reliability for one transmission link (i.e., to transport data or control signaling of one radio bearer via one carrier), several features have been introduced on the user plane protocols for PHY and Layer 2, as explained below.

6.4.3. Radio (PHY)

NR is designed with native support of antenna arrays utilizing benefits from beamforming, transmissions over multiple MIMO layers, and advanced receiver algorithms allowing effective interference cancellation. Those antenna techniques are the basis for high signal quality and the effectiveness of spectral usage. Spatial diversity with up to four MIMO layers in UL and up to eight MIMO layers in DL is supported. Together with spatial-domain multiplexing, antenna arrays can focus power in the desired direction to form beams. NR supports beam management mechanisms to find the best suitable beam for UE initially and when it is moving. In addition, gNBs can coordinate their respective DL and UL transmissions over the backhaul network, keeping interference reasonably low, and even make transmissions or receptions from multiple points (multi-TRP). Multi-TRP can be used for repetition of a data packet in time, in frequency, or over multiple MIMO layers, which can improve reliability even further.

Any downlink transmission to a UE starts from resource allocation signaling over the Physical Downlink Control Channel (PDCCH). If it is successfully received, the UE will know about the scheduled transmission and may receive data over the Physical Downlink Shared Channel (PDSCH). If retransmission is required according to the HARQ scheme, a signaling of negative acknowledgement (NACK) on the Physical Uplink Control Channel (PUCCH) is involved, and PDCCH together with PDSCH transmissions (possibly with additional redundancy bits) are transmitted and soft-combined with previously received bits. Otherwise, if no valid control signaling for scheduling data is received, nothing is transmitted on PUCCH (discontinuous transmission (DTX)), and upon detecting DTX, the base station will retransmit the initial data.

An uplink transmission normally starts from a Scheduling Request (SR), a signaling message from the UE to the base station sent via PUCCH. Once the scheduler is informed about buffer data in the UE (e.g., by SR), the UE transmits a data packet on the Physical Uplink Shared Channel (PUSCH). Pre-scheduling, not relying on SR, is also possible (see Section 6.4.4).

Since transmission of data packets requires usage of control and data channels, there are several methods to maintain the needed reliability. NR uses Low Density Parity Check (LDPC) codes for data channels, polar codes for PDCCH, as well as orthogonal sequences and polar codes for PUCCH. For ultra-reliability of data channels, very robust (low-spectral efficiency) Modulation and Coding Scheme (MCS) tables are introduced containing very low (down to 1/20) LDPC code rates using BPSK or QPSK. Also, PDCCH and PUCCH channels support multiple code rates including very low ones for the channel robustness.

A connected UE reports downlink (DL) quality to gNB by sending Channel State Information (CSI) reports via PUCCH while uplink (UL) quality is measured directly at gNB. For both uplink and downlink, gNB selects the desired MCS number and signals it to the UE by Downlink Control Information (DCI) via PDCCH channel. For URLLC services, the UE can assist the gNB by advising that MCS targeting a 10^-5 Block Error Rate (BLER) are used. Robust link adaptation algorithms can maintain the needed level of reliability, considering a given latency bound.

Low latency on the physical layer is provided by short transmission duration, which is possible by using high Subcarrier Spacing (SCS) and the allocation of only one or a few Orthogonal Frequency Division Multiplexing (OFDM) symbols. For example, the shortest latency for the worst case is 0.23 ms in DL and 0.24 ms in UL (according to Section 5.7.1 in [TR37910]). Moreover, if the initial transmission has failed, HARQ feedback can quickly be provided and an HARQ retransmission scheduled.

Dynamic multiplexing of data associated with different services is highly desirable for efficient use of system resources and to maximize system capacity. Assignment of resources for eMBB is usually done with regular (longer) transmission slots, which can lead to blocking of low-latency services. To overcome the blocking, eMBB resources can be preempted and reassigned to URLLC services. In this way, spectrally efficient assignments for eMBB can be ensured while providing the flexibility required to ensure a bounded latency for URLLC services. In downlink, the gNB can notify the eMBB UE about preemption after it has happened, while in uplink there are two preemption mechanisms: special signaling to cancel eMBB transmission and URLLC dynamic power boost to suppress eMBB transmission.

6.4.4. Scheduling and QoS (MAC)

One integral part of the 5G system is the Quality of Service (QoS) framework [TS23501]. QoS flows are set up by the 5G system for certain IP or Ethernet packet flows, so that packets of each flow receive the same forwarding treatment (i.e., in scheduling and admission control). For example, QoS flows can be associated with different priority levels, packet delay budgets, and tolerable packet error rates. Since radio resources are centrally scheduled in NR, the admission control function can ensure that only QoS flows for which QoS targets can be reached are admitted.

NR transmissions in both UL and DL are scheduled by the gNB [TS38300]. This ensures radio resource efficiency and fairness in resource usage of the users, and it enables differentiated treatment of the data flows of the users according to the QoS targets of the flows. Those QoS flows are handled as data radio bearers or logical channels in NR RAN scheduling.

The gNB can dynamically assign DL and UL radio resources to users, indicating the resources as DL assignments or UL grants via control channel to the UE. Radio resources are defined as blocks of OFDM symbols in spectral domain and time domain. Different lengths are supported in time domain, (i.e., multiple slot or mini-slot lengths). Resources of multiple frequency carriers can be aggregated and jointly scheduled to the UE.

Scheduling decisions are based, e.g., on channel quality measured on reference signals and reported by the UE (cf. periodical CSI reports for DL channel quality). The transmission reliability can be chosen in the scheduling algorithm, i.e., chosen by link adaptation where an appropriate transmission format (e.g., robustness of modulation and coding scheme, controlled UL power) is selected for the radio channel condition of the UE. Retransmissions, based on HARQ feedback, are also controlled by the scheduler. The feedback transmission in HARQ loop introduces delays, but there are methods to minimize it by using short transmission formats, sub-slot feedback reporting, and PUCCH carrier switching. If needed to avoid HARQ round-trip time delays, repeated transmissions can be also scheduled beforehand, to the cost of reduced spectral efficiency.

In dynamic DL scheduling, transmission can be initiated immediately when DL data becomes available in the gNB. However, for dynamic UL scheduling, when data becomes available but no UL resources are available yet, the UE indicates the need for UL resources to the gNB via a (single bit) scheduling request message in the UL control channel. When thereupon UL resources are scheduled to the UE, the UE can transmit its data and may include a buffer status report that indicates the exact amount of data per logical channel still left to be sent. More UL resources may be scheduled accordingly. To avoid the latency introduced in the scheduling request loop, UL radio resources can also be pre-scheduled.

In particular, for periodical traffic patterns, the pre-scheduling can rely on the scheduling features DL Semi-Persistent Scheduling (SPS) and UL Configured Grant (CG). With these features, periodically recurring resources can be assigned in DL and UL. Multiple parallels of those configurations are supported in order to serve multiple parallel traffic flows of the same UE.

To support QoS enforcement in the case of mixed traffic with different QoS requirements, several features have recently been introduced. This way, e.g., different periodical critical QoS flows can be served, together with best-effort transmissions by the same UE. These features (partly Release 16) include the following:

- UL logical channel transmission restrictions, allowing logical channels of certain QoS to only be mapped to intended UL resources of a certain frequency carrier, slot length, or CG configuration.
- intra-UE preemption and multiplexing, allowing critical UL transmissions to either preempt non-critical transmissions or be multiplexed with non-critical transmissions keeping different reliability targets.

When multiple frequency carriers are aggregated, duplicate parallel transmissions can be employed (beside repeated transmissions on one carrier). This is possible in the Carrier Aggregation (CA) architecture where those carriers originate from the same gNB or in the Dual Connectivity (DC) architecture where the carriers originate from different gNBs (i.e., the UE is connected to two gNBs in this case). In both cases, transmission reliability is improved by this means of providing frequency diversity.

In addition to licensed spectrum, a 5G system can also utilize unlicensed spectrum to offload non-critical traffic. This version of NR, called NR-U, is part of 3GPP Release 16. The central scheduling approach also applies for unlicensed radio resources and the mandatory channel access mechanisms for unlicensed spectrum (e.g., Listen Before Talk (LBT) is supported in NR-U). This way, by using NR, operators have and can control access to both licensed and unlicensed frequency resources.

6.4.5. Time-Sensitive Communications (TSC)

Recent 3GPP releases have introduced various features to support multiple aspects of Time-Sensitive Communication (TSC), which includes Time-Sensitive Networking (TSN) and beyond, as described in this section.

The main objective of TSN is to provide guaranteed data delivery within a guaranteed time window (i.e., bounded low latency). IEEE 802.1 TSN [IEEE802.1TSN] is a set of open standards that provide features to enable deterministic communication on standard IEEE 802.3 Ethernet [IEEE802.3]. TSN standards can be seen as a toolbox for traffic shaping, resource management, time synchronization, and reliability.

A TSN stream is a data flow between one end station (talker) to another end station (listener). In the centralized configuration model, TSN bridges are configured by the Central Network Controller (CNC) [IEEE802.1Qcc] to provide deterministic connectivity for the TSN stream through the network. Time-based traffic shaping provided by scheduled traffic [IEEE802.1Qbv] may be used to achieve bounded low latency. The TSN tool for time synchronization is the generalized Precision Time Protocol (gPTP) [IEEE802.1AS], which provides reliable time synchronization that can be used by end stations and by other TSN tools (e.g., scheduled traffic [IEEE802.1Qbv]). High availability, as a result of ultra-reliability, is provided for data flows by the Frame Replication and Elimination for Reliability (FRER) mechanism [IEEE802.1CB].

3GPP Release 16 includes integration of 5G with TSN, i.e., specifies functions for the 5G System (5GS) to deliver TSN streams such that the meet their QoS requirements. A key aspect of the integration is the 5GS appears from the rest of the network as a set of TSN bridges, in particular, one virtual bridge per User Plane Function (UPF) on the user plane. The 5GS includes TSN Translator (TT) functionality for the adaptation of the 5GS to the TSN bridged network and for hiding the 5GS internal procedures. The 5GS provides the following components:

1. interface to TSN controller, as per [IEEE802.1Qcc] for the fully centralized configuration model
2. time synchronization via reception and transmission of gPTP PDUs [IEEE802.1AS]
3. low latency, hence, can be integrated with scheduled traffic [IEEE802.1Qbv]
4. reliability, hence, can be integrated with FRER [IEEE802.1CB]

3GPP Release 17 [TS23501] introduced enhancements to generalize support for TSC beyond TSN. This includes IP communications to provide time-sensitive services (e.g., to Video, Imaging, and Audio for Professional Applications (VIAPA)). The system model of 5G acting as a "TSN bridge" in Release 16 has been reused to enable the 5GS acting as a "TSC node" in a more generic sense (which includes TSN bridge and IP node). In the case of TSC that does not involve TSN, requirements are given via exposure interfaces, and the control plane provides the service based on QoS and time synchronization requests from an Application Function (AF).

Figure 7 shows an illustration of 5G-TSN integration where an industrial controller (Ind Ctrlr) is connected to industrial Input/Output devices (I/O dev) via 5G. The 5GS can directly transport Ethernet frames since Release 15; thus, end-to-end Ethernet connectivity is provided. The 5GS implements the required interfaces towards the TSN controller functions such as the CNC, thus adapting to the settings of the TSN network. A 5G user plane virtual bridge interconnects TSN bridges or connects end stations (e.g., I/O devices to the TSN network). TTs, i.e., the Device-Side TSN Translator (DS-TT) at the UE and the Network-Side TSN Translator (NW-TT) at the UPF, have a key role in the interconnection. Note that the introduction of 5G brings flexibility in various aspects, e.g., a more flexible network topology because a wireless hop can replace several wireline hops, thus significantly reducing the number of hops end to end. [TSN5G] dives more into the integration of 5G with TSN.

```
                 +------------------------------+
                 | 5G System                    |
                 |                         +---+|
                 |     +-+ +-+ +-+ +-+ +-+ |TSN||
                 |     | | | | | | | | | | |AF |......+
                 |     +++ +++ +++ +++ +++ +-+-+|     .
                 |      |   |   |   |   |    |  |     .
                 |     -+---+---++--+-+-+--+-+- |     .
                 |          |    |    |    |    |  +--+--+
                 |         +++  +++  +++  +++   |  | TSN |
                 |         | |  | |  | |  | |   |  |Ctrlr+.......+
                 |         +++  +++  +++  +++   |  +--+--+       .
                 |                              |     .          .
                 |                              |     .          .
                 | +..........................+ |     .          .
                 | .      Virtual Bridge      . |     .          .
+---+            | . +--+--+   +---+ +---+--+ . |  +--+---+      .
|I/O+----------------+DS|UE+---+RAN+-+UPF|NW+------+ TSN  +----+ .
|dev|            | . |TT|  |   |   | |   |TT| . |  |bridge|    | .
+---+            | . +--+--+   +---+ +---+--+ . |  +------+    | .
                 | +..........................+ |     .      +-+-+-+
                 |                              |     .      | Ind |
                 | +..........................+ |     .      |Ctrlr|
                 | .      Virtual Bridge      . |     .      +-+---+
+---+  +------+  | . +--+--+   +---+ +---+--+ . |  +--+---+    |
|I/O+--+ TSN  +------+DS|UE+---+RAN+-+UPF|NW+------+ TSN  +----+
|dev|  |bridge|  | . |TT|  |   |   | |   |TT| . |  |bridge|
+---+  +------+  | . +--+--+   +---+ +---+--+ . |  +------+
                 | +..........................+ |
                 +------------------------------+

    <----------------- end-to-end Ethernet ------------------->
```

Figure 7: 5G - TSN Integration

NR supports accurate reference time synchronization in 1us accuracy level. Since NR is a scheduled system, an NR UE and a gNB are tightly synchronized to their OFDM symbol structures. A 5G internal reference time can be provided to the UE via broadcast or unicast signaling, associating a known OFDM symbol to this reference clock. The 5G internal reference time can be shared within the 5G network (i.e., radio and core network components). Release 16 has introduced interworking with gPTP for multiple time domains, where the 5GS acts as a virtual gPTP time-aware system and supports the forwarding of gPTP time synchronization information between end stations and bridges through the 5G user plane TTs. These account for the residence time of the 5GS in the time synchronization procedure. One special option is when the 5GS internal reference time is not only used within the 5GS, but also to the rest of the devices in the deployment, including connected TSN bridges and end stations. Release 17 includes further improvements (i.e., methods for propagation delay compensation in RAN), further improving the accuracy for time synchronization over the air, as well as the possibility for the TSN grandmaster clock to reside on the UE side. More extensions and flexibility were added to the time synchronization service, making it general for TSC, with additional support of other types of clocks and time distribution such as boundary clock, transparent clock peer-to-peer, and transparent clock end-to-end, aside from the time-aware system used for TSN. Additionally, it is possible to use internal access stratum signaling to distribute timing (and not the usual (g)PTP messages), for which the required accuracy can be provided by the AF [TS23501]. The same time synchronization service is expected to be further extended and enhanced in Release 18 to support Timing Resiliency (according to study item [SP211634]), where the 5G system can provide a backup or alternative timing source for the failure of the local GNSS source (or other primary timing source) used by the vertical.

IETF DetNet is the technology to support time-sensitive communications at the IP layer. 3GPP Release 18 includes a study [TR2370046] on interworking between 5G and DetNet. Along the TSC framework introduced for Release 17, the 5GS acts as a DetNet node for the support of DetNet; see Figure 7.1-1 in [TR2370046]. The study provides details on how the 5GS is exposed by the Time Sensitive Communication and Time Synchronization Function (TSCTSF) to the DetNet controller as a router on a per-UPF granularity (similar to the per-UPF Virtual TSN Bridge granularity shown in Figure 11). In particular, it lists the parameters that are provided by the TSCTSF to the DetNet controller. The study also includes how the TSCTSF maps DetNet flow parameters to 5G QoS parameters. Note that TSN is the primary subnetwork technology for DetNet. Thus, the work on DetNet over TSN, e.g., [RFC9023], can be leveraged via the TSN support built in 5G.

Redundancy architectures were specified in order to provide reliability against any kind of failure on the radio link or nodes in the RAN and the core network. Redundant user plane paths can be provided based on the dual connectivity architecture, where the UE sets up two PDU sessions towards the same data network, and the 5G system makes the paths of the two PDU sessions independent as illustrated in Figure 9. There are two PDU sessions involved in the solution: The first spans from the UE via gNB1 to UPF1, acting as the first PDU session anchor, while the second spans from the UE via gNB2 to UPF2, acting as second the PDU session anchor.

The independent paths may continue beyond the 3GPP network. Redundancy Handling Functions (RHFs) are deployed outside of the 5GS, i.e., in Host A (the device) and in Host B (the network). RHF can implement replication and elimination functions as per [IEEE802.1CB] or the Packet Replication, Elimination, and Ordering Functions (PREOF) of IETF DetNet [RFC8655].

```
+........+
. Device . +------+      +------+      +------+
.        . + gNB1 +--N3--+ UPF1 |--N6--+      |
.        ./+------+      +------+      |      |
. +----+ /                             |      |
. |    |/.                             |      |
. | UE + .                             |  DN  |
. |    |\.                             |      |
. +----+ \                             |      |
.        .\+------+      +------+      |      |
+........+ + gNB2 +--N3--+ UPF2 |--N6--+      |
           +------+      +------+      +------+
```

Figure 8: Reliability with Single UE

An alternative solution is that multiple UEs per device are used for user plane redundancy as illustrated in Figure 9. Each UE sets up a PDU session. The 5GS ensures that the PDU sessions of the different UEs are handled independently internal to the 5GS. There is no single point of failure in this solution, which also includes RHF outside of the 5G system, e.g., as per the FRER or PREOF specifications.

```
                +.........+
                .  Device .
                .         .
                . +----+  .  +------+      +------+      +------+
                . | UE +-----+ gNB1 +--N3--+ UPF1 |--N6--+      |
                . +----+  .  +------+      +------+      |      |
                .         .                              |  DN  |
                . +----+  .  +------+      +------+      |      |
                . | UE +-----+ gNB2 +--N3--+ UPF2 |--N6--+      |
                . +----+  .  +------+      +------+      +------+
                .         .
                +.........+
```

Figure 9: Reliability with Dual UE

Note that the abstraction provided by the RHF and the location of the RHF being outside of the 5G system make 5G equally supporting integration for reliability with both FRER of TSN and PREOF of DetNet, as they both rely on the same concept.

7. L-Band Digital Aeronautical Communications System (LDACS)

One of the main pillars of the modern Air Traffic Management (ATM) system is the existence of a communication infrastructure that enables efficient aircraft guidance and safe separation in all phases of flight. Although current systems are technically mature, they suffer from the VHF band's increasing saturation in high-density areas and the limitations posed by analog radio. Therefore, aviation (globally and in the European Union (EU) in particular) strives for a sustainable modernization of the aeronautical communication infrastructure.

In the long term, ATM communication shall transition from analog VHF voice and VDL Mode 2 communication to more spectrum-efficient digital data communication. The European ATM Master Plan foresees this transition to be realized for terrestrial communications by the development and implementation of the L-band Digital Aeronautical Communications System (LDACS).

LDACS has been designed with applications related to the safety and regularity of the flight in mind. It has therefore been designed as a deterministic wireless data link (as far as possible).

It is a secure, scalable, and spectrum-efficient data link with embedded navigation capability; thus, it is the first truly integrated Communications, Navigation, and Surveillance (CNS) system recognized by the International Civil Aviation Organization (ICAO). During flight tests, the LDACS capabilities have been successfully demonstrated. A viable rollout scenario has been developed, which allows gradual introduction of LDACS with immediate use and revenues. Finally, ICAO is developing LDACS standards to pave the way for the future.

LDACS shall enable IPv6-based air-ground communication related to the safety and regularity of the flight. The particular challenge is that no new frequencies can be made available for terrestrial aeronautical communication. It was thus necessary to develop procedures to enable the operation of LDACS in parallel with other services in the same frequency band; see [RFC9372] for more information.

7.1. Provenance and Documents

The development of LDACS has already made substantial progress in the Single European Sky ATM Research (SESAR) framework, and it is currently being continued in the follow-up program, SESAR2020 [RIH18]. A key objective of the SESAR activities is to develop, implement, and validate a modern aeronautical data link able to evolve with aviation needs over the long term. To this end, an LDACS specification has been produced [GRA19] and is continuously updated; transmitter demonstrators were developed to test the spectrum compatibility of LDACS with legacy systems operating in the L-band [SAJ14], and the overall system performance was analyzed by computer simulations, indicating that LDACS can fulfill the identified requirements [GRA11].

LDACS standardization within the framework of the ICAO started in December 2016. The ICAO standardization group has produced an initial Standards and Recommended Practices (SARPs) document [ICAO18]. The SARPs document defines the general characteristics of LDACS.

Up to now, the LDACS standardization has been focused on the development of the physical layer and the data link layer; only recently have higher layers come into the focus of the LDACS development activities. There is currently no "IPv6 over LDACS" specification; however, SESAR2020 has started the testing of IPv6-based LDACS testbeds. The IPv6 architecture for the aeronautical telecommunication network is called the Future Communications Infrastructure (FCI). FCI shall support QoS, diversity, and mobility under the umbrella of the "multi-link concept". This work is conducted by the ICAO WG-I Working Group.

In addition to standardization activities, several industrial LDACS prototypes have been built. One set of LDACS prototypes has been evaluated in flight trials, confirming the theoretical results predicting the system performance [GRA18] [BEL22] [GRA23].

7.2. General Characteristics

LDACS will become one of several wireless access networks connecting aircraft to the Aeronautical Telecommunications Network (ATN). The LDACS access network contains several ground stations, each of which provides one LDACS radio cell. The LDACS air interface is a cellular data link with a star topology connecting aircraft to ground stations with a full duplex radio link. Each ground station is the centralized instance controlling all air-ground communications within its radio cell.

The user data rate of LDACS is 315 kbit/s to 1428 kbit/s on the forward link and 294 kbit/s to 1390 kbit/s on the reverse link, depending on coding and modulation. Due to strong interference from legacy systems in the L-band, the most robust coding and modulation should be expected for initial deployment, i.e., 315 kbit/s on the forward link and 294 kbit/s on the reverse link.

In addition to the communications capability, LDACS also offers a navigation capability. Ranging data, similar to DME (Distance Measuring Equipment), is extracted from the LDACS communication links between aircraft and LDACS ground stations. This results in LDACS providing an APNT (Alternative Position, Navigation and Timing) capability to supplement the existing on-board GNSS (Global Navigation Satellite System) without the need for additional bandwidth. Operationally, there will be no difference for pilots whether the navigation data are provided by LDACS or DME. This capability was flight tested and proven during the MICONAV flight trials in 2019 [BAT19].

In previous works and during the MICONAV flight campaign in 2019, it was also shown that LDACS can be used for surveillance capability. Filip et al. [FIL19] have shown the passive radar capabilities of LDACS, and Automatic Dependence Surveillance - Contract (ADS-C) was demonstrated via LDACS during the flight campaign 2019 [SCH19].

Since LDACS has been mainly designed for air traffic management communication, it supports mutual entity authentication, integrity and confidentiality capabilities of user data messages, and some control channel protection capabilities [MAE18] [MAE191] [MAE192] [MAE20].

Overall, this makes LDACS the world's first truly integrated CNS system and is the most mature, secure, and terrestrial long-range CNS technology for civil aviation worldwide.

7.3. Deployment and Spectrum

LDACS has its origin in merging parts of the B-VHF [BRA06], B-AMC [SCH08], TIA-902 (P34) [HAI09], and WiMAX IEEE 802.16e [EHA11] technologies. In 2007, the spectrum for LDACS was allocated at the World Radio Conference (WRC).

It was decided to allocate the spectrum next to Distance Measuring Equipment (DME), resulting in an in-lay approach between the DME channels for LDAC [SCH14].

LDACS is currently being standardized by ICAO and several rollout strategies are discussed.

The LDACS data link provides enhanced capabilities to existing aeronautical communications infrastructures, enabling them to better support user needs and new applications. The deployment scalability of LDACS allows its implementation to start in areas where it is most needed to immediately improve the performance of and already-fielded infrastructure. Later, the deployment is extended based on operational demand. An attractive scenario for upgrading the existing VHF communication systems by adding an additional LDACS data link is described below.

When considering the current VDL Mode 2 infrastructure and user base, a very attractive win-win situation comes about when the technological advantages of LDACS are combined with the existing VDL Mode 2 infrastructure. LDACS provides at least 50 times more capacity than VDL

Mode 2 and is a natural enhancement to the existing VDL Mode 2 business model. The advantage of this approach is that the VDL Mode 2 infrastructure can be fully reused. Beyond that, it opens the way for further enhancements [ICAO19].

7.4. Applicability to Deterministic Flows

As LDACS is a ground-based digital communications system for flight guidance and communications related to safety and regularity of flight, time-bounded deterministic arrival times for safety critical messages are a key feature for its successful deployment and rollout.

7.4.1. System Architecture

Up to 512 Aircraft Stations (ASes) communicate to an LDACS Ground Station (GS) in the reverse link (RL). A GS communicates to an AS in the Forward Link (FL). Via an Access-Router (AC-R), GSs connect the LDACS subnetwork to the global Aeronautical Telecommunications Network (ATN) to which the corresponding Air Traffic Services (ATS) and Aeronautical Operational Control (AOC) end systems are attached.

7.4.2. Overview of the Radio Protocol Stack

The protocol stack of LDACS is implemented in the AS and GS; it consists of the physical (PHY) layer with five major functional blocks above it. Four are placed in the data link layer (DLL) of the AS and GS:

1. Medium Access Layer (MAC),
2. Voice Interface (VI),
3. Data Link Service (DLS), and
4. LDACS Management Entity (LME).

The last entity resides within the subnetwork layer: the Subnetwork Protocol (SNP). The LDACS network is externally connected to voice units, radio control units, and the ATN network layer.

Communications between the MAC and LME layers is split into four distinct control channels:

1. the Broadcast Control Channel (BCCH), where LDACS ground stations announce their specific LDACS cell, including physical parameters and cell identification;
2. the Random Access Channel (RACH), where LDACS airborne radios can request access to an LDACS cell;
3. the Common Control Channel (CCCH), where LDACS ground stations allocate resources to aircraft radios, enabling the airborne side to transmit the user payload; and
4. the Dedicated Control Channel (DCCH), where LDACS airborne radios can request user data resources from the LDACS ground station so the airborne side can transmit the user payload.

Communications between the MAC and DLS layers is handled by the Data Channel (DCH) where the user payload is handled.

Figure 10 shows the protocol stack of LDACS as implemented in the AS and GS.

```
        IPv6                   Network Layer
          |
          |
+------------------+  +----+
|        SNP       |--|    |   Subnetwork
|                  |  |    |   Layer
+------------------+  |    |
          |           | LME|
+------------------+  |    |
|        DLS       |  |    |   Logical Link
|                  |  |    |   Control Layer
+------------------+  +----+
          |              |
         DCH         DCCH/CCCH
          |          RACH/BCCH
          |              |
+--------------------------+
|           MAC            |   Medium Access
|                          |   Layer
+--------------------------+
          |
+--------------------------+
|           PHY            |   Physical Layer
+--------------------------+
          |
          |
        ((*))
        FL/RL              radio channels
                           separated by
                           frequency division duplex
```

Figure 10: LDACS Protocol Stack in AS and GS

7.4.3. Radio (PHY)

The physical layer provides the means to transfer data over the radio channel. The LDACS ground station supports bidirectional links to multiple aircraft under its control. The forward link direction (which is ground to air) and the reverse link direction (which is air to ground) are separated by frequency division duplex. Forward link and reverse link use a 500 kHz channel each. The ground station transmits a continuous stream of OFDM symbols on the forward link. In the reverse link, different aircrafts are separated in time and frequency using a combination of Orthogonal Frequency-Division Multiple Access (OFDMA) and Time-Division Multiple-Access (TDMA). Thus, aircraft transmit discontinuously on the reverse link with radio bursts sent in precisely defined transmission opportunities allocated by the ground station. The most important service on the PHY layer of LDACS is the PHY time framing service, which indicates that the PHY layer is ready to transmit in a given slot and indicates PHY layer framing and timing to the MAC time framing service. LDACS does not support beam-forming or Multiple Input Multiple Output (MIMO).

7.4.4. Scheduling, Frame Structure, and QoS (MAC)

The data link layer provides the necessary protocols to facilitate concurrent and reliable data transfer for multiple users. The LDACS data link layer is organized in two sublayers: the medium access sublayer and the logical link control sublayer. The medium access sublayer manages the organization of transmission opportunities in slots of time and frequency. The logical link control sublayer provides acknowledged point-to-point logical channels between the aircraft and the ground station using an automatic repeat request protocol. LDACS also supports unacknowledged point-to-point channels and ground-to-air broadcast.

Next, the frame structure of LDACS is introduced, followed by a more in-depth discussion of the LDACS medium access.

The LDACS framing structure for FL and RL is based on Super-Frames (SF) of 240 ms duration. Each SF corresponds to 2000 OFDM symbols. The FL and RL SF boundaries are aligned in time (from the view of the GS).

In the FL, an SF contains a broadcast frame with a duration of 6.72 ms (56 OFDM symbols) for the Broadcast Control Channel (BCCH) and four Multi-Frames (MF), each with a duration of 58.32 ms (486 OFDM symbols).

In the RL, each SF starts with a Random Access (RA) slot with a length of 6.72 ms with two opportunities for sending RL random access frames for the Random Access Channel (RACH), followed by four MFs. These MFs have the same fixed duration of 58.32 ms as in the FL but a different internal structure.

Figures 11 and 12 illustrate the LDACS frame structure. This fixed frame structure allows for the reliable and dependable transmission of data.

```
^
|     +------+------------+------------+------------+------------+
|  FL | BCCH |     MF     |     MF     |     MF     |     MF     |
F     +------+------------+------------+------------+------------+
r     <---------------- Super-Frame (SF) - 240 ms --------------->
e
q     +------+------------+------------+------------+------------+
u  RL | RACH |     MF     |     MF     |     MF     |     MF     |
e     +------+------------+------------+------------+------------+
n     <---------------- Super-Frame (SF) - 240 ms --------------->
c
y
|
----------------------------- Time ------------------------------>
|
```

Figure 11: SF Structure for LDACS

```
^
|     +------------+------+------------+
|  FL |     DCH    | CCCH |     DCH    |
F     +------------+------+------------+
r     <--- Multi-Frame (MF) - 58.32 ms -->
e
q     +------+---------------------------+
u  RL | DCCH |            DCH            |
e     +------+---------------------------+
n     <--- Multi-Frame (MF) - 58.32 ms -->
c
y
|
-------------------- Time ------------------>
|
```

Figure 12: MF Structure for LDACS

Next, the LDACS medium access layer is introduced.

LDACS medium access is always under the control of the ground station of a radio cell. Any medium access for the transmission of user data has to be requested with a resource request message stating the requested amount of resources and class of service. The ground station performs resource scheduling on the basis of these requests and grants resources with resource allocation messages. Resource request and allocation messages are exchanged over dedicated contention-free control channels.

LDACS has two mechanisms to request resources from the scheduler in the ground station. Resources can either be requested "on demand" or permanently allocated by a LDACS ground station with a given class of service. On the forward link, this is done locally in the ground station; on the reverse link, a dedicated contention-free control channel is used (the Dedicated Control Channel (DCCH); roughly 83 bits every 60 ms). A resource allocation is always announced in the control channel of the forward link (Common Control Channel (CCCH); variable sized). Due to the spacing of the reverse link control channels of every 60 ms, a medium access delay in the same order of magnitude is to be expected.

Resources can also be requested "permanently". The permanent resource request mechanism supports requesting recurring resources at given time intervals. A permanent resource request has to be canceled by the user (or by the ground station, which is always in control). User data transmissions over LDACS are therefore always scheduled by the ground station, while control data uses statically (i.e., at net entry) allocated recurring resources (DCCH and CCCH). The current specification documents specify no scheduling algorithm. However, performance evaluations so far have used strict priority scheduling and round robin for equal priorities for simplicity. In the current prototype implementations, LDACS classes of service are thus realized as priorities of medium access and not as flows. Note that this can starve out low-priority flows. However, this is not seen as a big problem since safety-related messages always go first in any case. Scheduling of reverse link resources is done in physical Protocol Data Units (PDU) of 112 bits (or larger if more aggressive coding and modulation is used). Scheduling on the forward link is done byte wise since the forward link is transmitted continuously by the ground station.

In order to support diversity, LDACS supports handovers to other ground stations on different channels. Handovers may be initiated by the aircraft (break before make) or by the ground station (make before break). Beyond this, FCI diversity shall be implemented by the multi-link concept.

8. IANA Considerations

This document has no IANA actions.

9. Security Considerations

Most RAW technologies integrate some authentication or encryption mechanisms that are defined outside the IETF. The IETF specifications referenced herein each provide their own security considerations, and the lower-layer technologies used provide their own security at Layer 2.

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