

RAW
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RAW use cases
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Abstract

The wireless medium presents significant specific challenges to achieve properties similar to those of wired deterministic networks. At the same time, a number of use cases cannot be solved with wires and justify the extra effort of going wireless. This document presents wireless use cases demanding reliable and available behavior.

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1. Introduction

Based on time, resource reservation, and policy enforcement by distributed shapers, Deterministic Networking provides the capability to carry specified unicast or multicast data streams for real-time applications with extremely low data loss rates and bounded latency, so as to support time-sensitive and mission-critical applications on a converged enterprise infrastructure.

Deterministic Networking in the IP world is an attempt to eliminate packet loss for a committed bandwidth while ensuring a worst case end-to-end latency, regardless of the network conditions and across technologies. It can be seen as a set of new Quality of Service (QoS) guarantees of worst-case delivery. IP networks become more deterministic when the effects of statistical multiplexing (jitter and collision loss) are mostly eliminated. This requires a tight control of the physical resources to maintain the amount of traffic within the physical capabilities of the underlying technology, e.g., by the use of time-shared resources (bandwidth and buffers) per circuit, and/or by shaping and/or scheduling the packets at every hop.

Key attributes of Deterministic Networking include:

- o time synchronization on all the nodes,
- o centralized computation of network-wide deterministic paths,
- o multi-technology path with co-channel interference minimization,
- o frame preemption and guard time mechanisms to ensure a worst-case delay, and
- o new traffic shapers within and at the edge to protect the network.

Wireless operates on a shared medium, and transmissions cannot be fully deterministic due to uncontrolled interferences, including self-induced multipath fading. RAW (Reliable and Available Wireless) is an effort to provide Deterministic Networking on across a path that include a wireless physical layer. Making Wireless Reliable and Available is even more challenging than it is with wires, due to the numerous causes of loss in transmission that add up to the congestion losses and the delays caused by overbooked shared resources.

The wireless and wired media are fundamentally different at the physical level, and while the generic Problem Statement [RFC8557] for DetNet applies to the wired as well as the wireless medium, the

methods to achieve RAW necessarily differ from those used to support Time-Sensitive Networking over wires.

So far, Open Standards for Deterministic Networking have prevalently been focused on wired media, with Audio/Video Bridging (AVB) and Time Sensitive Networking (TSN) at the IEEE and DetNet [RFC8655] at the IETF. But wires cannot be used in a number of cases, including mobile or rotating devices, rehabilitated industrial buildings, wearable or in-body sensory devices, vehicle automation and multiplayer gaming.

Purpose-built wireless technologies such as [ISA100], which incorporates IPv6, were developped and deployed to cope for the lack of open standards, but they yield a high cost in OPEX and CAPEX and are limited to very few industries, e.g., process control, concert instruments or racing.

This is now changing [I-D.thubert-raw-technologies]:

- o IMT-2020 has recognized Ultra-Reliable Low-Latency Communication (URLLC) as a key functionality for the upcoming 5G.
- o IEEE 802.11 has identified a set of real-applications [ieee80211-rt-tig] which may use the IEEE802.11 standards. They typically emphasize strict end-to-end delay requirements.
- o The IETF has produced an IPv6 stack for IEEE Std. 802.15.4 TimeSlotted Channel Hopping (TSCH) and an architecture [I-D.ietf-6tisch-architecture] that enables Reliable and Available Wireless (RAW) on a shared MAC.

This draft extends the "Deterministic Networking Use Cases" document [RFC8578] and describes a number of additional use cases which require "reliable/predictable and available" flows over wireless links and possibly complex multi-hop paths called Tracks. This is covered mainly by the "Wireless for Industrial Applications" use case, as the "Cellular Radio" is mostly dedicated to the (wired) transport part of a Radio Access Network (RAN). Whereas the "Wireless for Industrial Applications" use case certainly covers an area of interest for RAW, it is limited to 6TiSCH, and thus its scope is narrower than the use cases described next in this document.

2. Amusement Parks

2.1. Use Case Description

The digitalization of Amusement Parks is expected to decrease significantly the cost for maintaining the attractions. By monitoring in real-time the machines, predictive maintenance will help to reduce the repairing cost as well as the downtime. Besides, the attractions may use wireless transmissions to interconnect sensors and actuators, to privilege reconfigurability, and standardization.

Attractions may rely on a large set of sensors and actuators, which react in real time. Typical applications comprise:

- o **Emergency:** safety has to be preserved, and must stop the attraction when a failure is detected.
- o **Video:** augmented and virtual realities are integrated in the attraction. Wearable devices (e.g., glasses, virtual reality headset) need to offload one part of the processing tasks.
- o **Real-time interactions:** visitors may interact with an attraction, like in a real-time video game. The visitors may virtually interact with their environment, triggering actions in the real world (through actuators) [robots].
- o **Geolocation:** visitors are tracked with a personal wireless tag so that their user experience is improved.
- o **Predictive maintenance:** statistics are collected to predict the future failures, or to compute later more complex statistics about the attraction's usage, the downtime, its popularity, etc.

2.2. Specifics

Amusement parks comprise a variable number of attractions, mostly outdoor, over a large geographical area. The IT infrastructure is typically multi-scale:

- o **Local area:** the sensors and actuators controlling the attractions are co-located. Control loops trigger only local traffic, with a small end-to-end delay, typically inferior than 10 milliseconds, like classical industrial systems [ieee80211-rt-tig].
- o **Wearable devices** are free to move in the park. They exchange traffic locally (identification, personalization, multimedia) or globally (billing, child tracking).

- o Computationally intensive applications offload some tasks to a cloud, and data analytics rely on a centralized infrastructure (predictive maintenance, marketing).

2.3. The Need for Wireless

Amusement parks cover large areas and a global interconnection would require a huge length of cables. Wireless also increases the reconfigurability, enabling to update cheaply the attractions. The frequent renewal helps to increase customer loyalty.

Some parts of the attraction are mobile, e.g., trucks of a roller-coaster, robots. Since cables are prone to frequent failures in this situation, wireless transmissions are recommended.

Wearable devices are extensively used for a user experience personalization. They typically need to support wireless transmissions. Personal tags may help to reduce the operating costs [disney-VIP] and to increase the number of charged services provided to the audience (VIP tickets, interactivity, etc.) Some applications rely on more sophisticated wearable devices such as digital glasses or Virtual Reality (VR) headsets for an immersive experience.

2.4. Requirements for RAW

The network infrastructure has to support heterogeneous traffic, with very different critical requirements. Thus, flow isolation has to be provided.

We have to schedule appropriately the transmissions, even in presence of mobile devices. While the [I-D.ietf-6tisch-architecture] already proposes an architecture for synchronized, IEEE Std. 802.15.4 Time-Slotted Channel Hopping (TSCH) networks, 6TiSCH does not address real-time IPv6 flows. RAW might provide mechanisms helping to automatically adapt the network (i.e., schedule appropriately the transmissions, across heterogeneous technologies, with strict SLA requirements).

Nowadays, long-range wireless transmissions are used for best-effort traffic, and [IEEE802.1TSN] is used for critical flows using Ethernet devices. However, we need an IP enabled technology to interconnect large areas, independent of the PHY and MAC layer to maximize the compliancy.

We expect to deploy several different technologies (long vs. short range) which have to cohabit in the same area. Thus, we need to schedule appropriately the transmissions to limit the co-technology interference, so that an end-to-end delay across multiple

technologies can be guaranteed. It is needed to understand which technologies RAW will cover and how they can be used cohabitating in the same area.

3. Wireless for Industrial Applications

3.1. Use Case Description

A major use case for networking in Industrial environments is the control networks where periodic control loops operate between a sensor that measures a physical property such as the temperature of a fluid, a Programmable Logic Controller (PLC) that decides an action such as warm up the mix, and an actuator that performs the required action, e.g., inject power in a resistor.

3.2. Specifics

3.2.1. Control Loops

Process Control designates continuous processing operations, e.g., heating Oil in a refinery or mixing drinking soda. Control loops in the Process Control industry operate at a very low rate, typically 4 times per second. Factory Automation, on the other hand, deal with discrete goods such as individual automobile parts, and requires faster loops, in the order of 10ms. Motion control that monitors dynamic activities may require even faster rates in the order of a few ms. Finally, some industries exhibit hybrid behaviours, like canned soup that will start as a process industry while mixing the food and then operate as a discrete manufacturing when putting the final product in cans and shipping them.

In all those cases, a packet must flow reliably between the sensor and the PLC, be processed by the PLC, and sent to the actuator within the control loop period. In some particular use cases that inherit from analog operations, jitter might also alter the operation of the control loop. A rare packet loss is usually admissible, but typically 4 losses in a row will cause an emergency halt of the production and incur a high cost for the manufacturer.

3.2.2. Unmeasured Data

A secondary use case deals with monitoring and diagnostics. This so-called unmeasured data is essential to improve the performances of a production line, e.g., by optimizing real-time processing or maintenance windows using Machine Learning predictions. For the lack of wireless technologies, some specific industries such as Oil and Gas have been using serial cables, literally by the millions, to perform their process optimization over the previous decades. But

few industries would afford the associated cost and the Holy Grail of the Industrial Internet of Things is to provide the same benefits to all industries, including SmartGrid, Transportation, Building, Commercial and Medical. This requires a cheap, available and scalable IP-based access technology.

Inside the factory, wires may already be available to operate the Control Network. But unmeasured data are not welcome in that network for a number of reasons. On the one hand it is rich and asynchronous, meaning that using they may influence the deterministic nature of the control operations and impact the production. On the other hand, this information must be reported to the carpeted floor over IP, which means the potential for a security breach via the interconnection of the Operational Technology (OT) network with the Internet technology (IT) network and possibly enable a rogue access.

3.3. The Need for Wireless

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

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

Even when wiring exists, e.g., in an existing control network, asynchronous IP packets such as diagnostics may not be welcome for operational and security reasons (see Section 3.2.1). An alternate network that can scale with the many sensors and actuators that equip every robot, every valve and fan that are deployed on the factory floor and may help detect and prevent a failure that could impact the production. IEEE Std. 802.15.4 Time-Slotted Channel Hopping (TSCH) [RFC7554] is a promising technology for that purpose, mostly if the scheduled operations enable to use the same network by asynchronous and deterministic flows in parallel.

3.4. Requirements for RAW

As stated by the "Deterministic Networking Problem Statement" [RFC8557], a Deterministic Network is backwards compatible with (capable of transporting) statistically multiplexed traffic while preserving the properties of the accepted deterministic flows. While the [I-D.ietf-6tisch-architecture] serves that requirement, the work

at 6TiSCH was focused on best-effort IPv6 packet flows. RAW should be able to lock so-called hard cells for use by a centralized scheduler, and program so-called end-to-end Tracks over those cells.

Over the course of the recent years, major Industrial Protocols, e.g., [ODVA] with EtherNet/IP [EIP] and [Profinet], have been migrating towards Ethernet and IP. In order to unleash the full power of the IP hourglass model, it should be possible to deploy any application over any network that has the physical capacity to transport the industrial flow, regardless of the MAC/PHY technology, wired or wireless, and across technologies. RAW mechanisms should be able to setup a Track over a wireless access segment such as TSCH and a backbone segment such as Ethernet or WI-Fi, to report a sensor data or a critical monitoring within a bounded latency.

4. Pro Audio and Video

4.1. Use Case Description

Many devices support audio and video streaming by employing 802.11 wireless LAN. Some of these applications require low latency capability. For instance, when the application provides interactive play, or when the audio takes plays in real time (i.e. live) for public addresses in train stations or in theme parks.

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

- o Virtual Reality / Augmented Reality (VR/AR)
- o Public address, media and emergency systems at large venues (airports, train stations, stadiums, theme parks).

4.2. Specifics

4.2.1. Uninterrupted Stream Playback

Considering the uninterrupted audio or video stream, a potential packet losses during the transmission of audio or video flows cannot be tackled by re-trying the transmission, as it is done with file transfer, because by the time the packet lost has been identified it is too late to proceed with packet re-transmission. Buffering might be employed to provide a certain delay which will allow for one or more re-transmissions, however such approach is not efficient in application where delays are not acceptable.

4.2.2. Synchronized Stream Playback

In the context of ProAV, latency is the time between the transmitted signal over a stream and its reception. Thus, for sound to remain synchronized to the movement in the video, the latency of both the audio and video streams must be bounded and consistent.

4.3. The Need for Wireless

The devices need the wireless communication to support video streaming via 802.11 wireless LAN for instance.

During the public address, the deployed announcement speakers, for instance along the platforms of the train stations, need the wireless communication to forward the audio traffic in real time.

4.4. Requirements for RAW

The network infrastructure needs to support heterogeneous types of traffic (including QoS).

Content delivery with bounded (lowest possible) latency.

The deployed network topology should allow for multipath. This will enable for multiple streams to have different (and multiple) paths through the network to support redundancy.

5. Wireless Gaming

5.1. Use Case Description

The gaming industry includes [IEEE80211RTA] real-time mobile gaming, wireless console gaming and cloud gaming. For RAW, wireless console gaming is the most relevant one. We next summarize the three:

- o Real-time Mobile Gaming: Different from traditional games, real time mobile gaming is very sensitive to network latency and stability. The mobile game can connect multiple players together in a single game session and exchange data messages between game server and connected players. Real-time means the feedback should present on screen as users operate in game. For good game experience, the end to end latency plus game servers processing time should not be noticed by users as they play the game.
- o Wireless Console Gaming: Playing online on a console has 2 types of internet connectivity, which is either wired or Wi-Fi. Most of the gaming consoles today support Wi-Fi 5. But Wi-Fi has an

especially bad reputation among the gaming community. The main reasons are high latency, lag spikes and jitter.

- o Cloud Gaming: The cloud gaming requires low latency capability as the user commands in a game session need to be sent back to the cloud server, the cloud server would update game context depending on the received commands, and the cloud server would render the picture/video to be displayed at user devices and stream the picture/video content to the user devices. User devices might very likely be connected wirelessly.

5.2. Specifics

While a lot of details can be found on [IEEE80211RTA], we next summarize the main requirements in terms of latency, jitter and packet loss:

- o Intra BSS latency: less than 5 ms.
- o Jitter variance: less than 2 ms.
- o Packet loss: less than 0.1 percent.

5.3. The Need for Wireless

It is clear that gaming is evolving towards wireless, as players demand being able to play anywhere. Besides, the industry is changing towards playing from mobile phones, which are inherently connected via wireless technologies.

5.4. Requirements for RAW

- o Time sensitive networking extensions. Extensions, such as time-aware shaping and redundancy (FRE) can be explored to address congestion and reliability problems present in wireless networks.
- o Priority tagging (Stream identification). One basic requirement to provide better QoS for time-sensitive traffic is the capability to identify and differentiate time-sensitive packets from other (e.g. best-effort) traffic.
- o Time-aware shaping. This capability (defined in IEEE 802.1Qbv) consists of gates to control the opening/closing of queues that share a common egress port within an Ethernet switch. A scheduler defines the times when each queue opens or close, therefore eliminating congestion and ensuring that frames are delivered within the expected latency bounds.

- o Dual/multiple link. Due to the competitions and interference are common and hardly in control under wireless network, in order to improve the latency stability, dual/multiple link proposal is brought up to address this issue. Two modes are defined: duplicate and joint.
- o Admission Control. Congestion is a major cause of high/variable latency and it is well known that if the traffic load exceeds the capability of the link, QoS will be degraded. QoS degradation maybe acceptable for many applications today, however emerging time-sensitive applications are highly susceptible to increased latency and jitter. In order to better control QoS, it is important to control access to the network resources.

6. UAV platooning and control

6.1. Use Case Description

Unmanned Aerial Vehicles (UAVs) are becoming very popular for many different applications, including military and civil use cases. The term drone is commonly used to refer to a UAV.

UAVs can be used to perform aerial surveillance activities, traffic monitoring (e.g., Spanish traffic control has recently introduced a fleet of drones for quicker reactions upon traffic congestion related events), support of emergency situations, and even transportation of small goods.

UAVs typically have various forms of wireless connectivity:

- o cellular: for communication with the control center, for remote maneuvering as well as monitoring of the drone;
- o IEEE 802.11: for inter-drone communications (e.g., platooning) and providing connectivity to other devices (e.g., acting as Access Point).

6.2. Specifics

Some of the use cases/tasks involving drones require coordination among drones. Others involve complex compute tasks that might not be performed using the limited computing resources that a drone typically has. These two aspects require continuous connectivity with the control center and among drones.

Remote maneuvering of a drone might be performed over a cellular network in some cases, however, there are situations that need very low latencies and deterministic behavior of the connectivity.

Examples involve platooning of drones or share of computing resources among drones (e.g., a drone offload some function to a neighboring drone).

6.3. The Need for Wireless

UAVs cannot be connected through any type of wired media, so it is obvious that wireless is needed.

6.4. Requirements for RAW

The network infrastructure is actually composed by the UAVs themselves, requiring self-configuration capabilities.

Heterogeneous types of traffic need to be supported, from extremely critical ones requiring ultra low latency and high resiliency, to traffic requiring low-medium latency.

When a given service is decomposed into functions -- hosted at different drones -- chained, each link connecting two given functions would have a well-defined set of requirements (latency, bandwidth and jitter) that have to be met.

7. Edge Robotics control

7.1. Use Case Description

The Edge Robotics scenario consists of several robots, deployed in a given area (for example a shopping mall), inter-connected via an access network to a network's edge device or a data center. The robots are connected to the edge so complex computational activities are not executed locally at the robots, but offloaded to the edge. This brings additional flexibility in the type of tasks that the robots do, as well as reducing the costs of robot manufacturing (due to their lower complexity), and enabling complex tasks involving coordination among robots (that can be more easily performed if robots are centrally controlled).

A simple example of the use of multiples robots is cleaning, delivering of goods from warehouses to shops or video surveillance. Multiple robots are simultaneously instructed to perform individual tasks by moving the robotic intelligence from the robots to the network's edge (e.g., data center). That enables easy synchronization, scalable solution and on-demand option to create flexible fleet of robots.

Robots would have various forms of wireless connectivity:

- o IEEE 802.11: for connection to the edge and also inter-robot communications (e.g., for coordinated actions).
- o Cellular: as an additional communication link to the edge, though primarily as backup, since ultra low latencies are needed.

7.2. Specifics

Some of the use cases/tasks involving robots might benefit from decomposition of a service in small functions that are distributed and chained among robots and the edge. These require continuous connectivity with the control center and among drones.

Robot control is an activity requiring very low latencies between the robot and the location where the control intelligence resides (which might be the edge or another robot).

7.3. The Need for Wireless

Deploying robots in scenarios such as shopping malls for the aforementioned applications cannot be done via wired connectivity.

7.4. Requirements for RAW

The network infrastructure needs to support heterogeneous types of traffic, from robot control to video streaming.

When a given service is decomposed into functions -- hosted at different robots -- chained, each link connecting two given functions would have a well-defined set of requirements (latency, bandwidth and jitter) that have to be met.

8. IANA Considerations

N/A.

9. Security Considerations

N/A.

10. Informative References

[disney-VIP]

Wired, "Disney's \$1 Billion Bet on a Magical Wristband",
March 2015,
<<https://www.wired.com/2015/03/disney-magicband/>>.

- [EIP] <http://www.odva.org/>, "EtherNet/IP provides users with the network tools to deploy standard Ethernet technology (IEEE 802.3 combined with the TCP/IP Suite) for industrial automation applications while enabling Internet and enterprise connectivity data anytime, anywhere.", <http://www.odva.org/Portals/0/Library/Publications_Numbered/PUB00138R3_CIP_Adv_Tech_Series_EtherNetIP.pdf>.
- [I-D.ietf-6tisch-architecture]
Thubert, P., "An Architecture for IPv6 over the TSCH mode of IEEE 802.15.4", draft-ietf-6tisch-architecture-28 (work in progress), October 2019.
- [I-D.thubert-raw-technologies]
Thubert, P., Cavalcanti, D., Vilajosana, X., and C. Schmitt, "Reliable and Available Wireless Technologies", draft-thubert-raw-technologies-03 (work in progress), July 2019.
- [IEEE802.1TSN]
IEEE standard for Information Technology, "IEEE 802.1AS-2011 - IEEE Standard for Local and Metropolitan Area Networks - Timing and Synchronization for Time-Sensitive Applications in Bridged Local Area Networks".
- [ieee80211-rt-tig]
IEEE, "IEEE 802.11 Real Time Applications TIG Report", Nov. 2018,
<http://www.ieee802.org/11/Reports/rtatig_update.htm>.
- [IEEE80211RTA]
IEEE standard for Information Technology, "IEEE 802.11 Real Time Applications TIG Report", Nov 2018.
- [ISA100] ISA/ANSI, "ISA100, Wireless Systems for Automation", <<https://www.isa.org/isa100/>>.
- [ODVA] <http://www.odva.org/>, "The organization that supports network technologies built on the Common Industrial Protocol (CIP) including EtherNet/IP.".
- [Profinet]
<http://us.profinet.com/technology/profinet/>, "PROFINET is a standard for industrial networking in automation.", <<http://us.profinet.com/technology/profinet/>>.

- [RFC7554] Watteyne, T., Ed., Palattella, M., and L. Grieco, "Using IEEE 802.15.4e Time-Slotted Channel Hopping (TSCH) in the Internet of Things (IoT): Problem Statement", RFC 7554, DOI 10.17487/RFC7554, May 2015, <<https://www.rfc-editor.org/info/rfc7554>>.
- [RFC8557] Finn, N. and P. Thubert, "Deterministic Networking Problem Statement", RFC 8557, DOI 10.17487/RFC8557, May 2019, <<https://www.rfc-editor.org/info/rfc8557>>.
- [RFC8578] Grossman, E., Ed., "Deterministic Networking Use Cases", RFC 8578, DOI 10.17487/RFC8578, May 2019, <<https://www.rfc-editor.org/info/rfc8578>>.
- [RFC8655] Finn, N., Thubert, P., Varga, B., and J. Farkas, "Deterministic Networking Architecture", RFC 8655, DOI 10.17487/RFC8655, October 2019, <<https://www.rfc-editor.org/info/rfc8655>>.
- [robots] Kober, J., Glisson, M., and M. Mistry, "Playing catch and juggling with a humanoid robot.", 2012, <<https://doi.org/10.1109/HUMANOIDS.2012.6651623>>.

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L-band Digital Aeronautical Communications System (LDACS)
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Abstract

This document provides an overview of the architecture of the L-band Digital Aeronautical Communications System (LDACS), which provides a secure, scalable and spectrum efficient terrestrial data link for civil aviation. LDACS is a scheduled, reliable multi-application cellular broadband system with support for IPv6.

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1. Introduction

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. Current systems are technically mature but suffering from the VHF band's increasing saturation in high-density areas and the limitations posed by analogue radio. Therefore, aviation globally and 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 analogue VHF voice and VDL2 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 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.

2. Terminology

2.1. Terms used in this document

The following terms are used in the context of DetNet in this document:

A/A Air-To-Air
AeroMACS Aeronautical Mobile Airport Communication System
A/G Air-To-Ground
AM(R)S Aeronautical Mobile (Route) Service
ANSP Air traffic Network Service Provider
AOC Aeronautical Operational Control
AS Aircraft Station
ATC Air-Traffic Control
ATM Air-Traffic Management
ATN Aeronautical Telecommunication Network
ATS Air Traffic Service
CCCH Common Control Channel
DCCH Dedicated Control Channel
DCH Data Channel
DLL Data Link Layer
DLS Data Link Service
DME Distance Measuring Equipment
DSB-AM Double Side-Band Amplitude Modulation

FAA Federal Aviation Administration
FCI Future Communication Infrastructure
FDD Frequency Division Duplex
FL Forward Link
GANP Global Air Navigation Plan
GNSS Global Navigation Satellite System
GS Ground Station
GSC Ground-Station Controller
HF High Frequency
ICAO International Civil Aviation Organization
IWF Interworking Function
kbit/s kilobit per second
LDACS L-band Digital Aeronautical Communications System
LLC Logical Link Layer
LME LDACS Management Entity
MAC Medium Access Layer
MF Multi Frame
MIMO Multiple Input Multiple Output
OFDM Orthogonal Frequency-Division Multiplexing
OFDMA Orthogonal Frequency-Division Multiplexing Access
PDU Protocol Data Units
PHY Physical Layer
QoS Quality of Service
RL Reverse Link
SARPs Standards And Recommended Practices
SESAR Single European Sky ATM Research
SF Super-Frame
SNP Sub-Network Protocol
SSB-AM Single Side-Band Amplitude Modulation
SND CF Sub-Network Dependent Convergence Function
TBO Trajectory-Based Operations
TDM Time Division Multiplexing
TDMA Time-Division Multiplexing-Access
VDL2 VHF Data Link mode 2
VHF Very High Frequency
VI Voice Interface

3. Motivation and Use Cases

Aircraft are currently connected to Air-Traffic Control (ATC) and Airline Operational Control (AOC) via voice and data communications systems through all phases of a flight. Within the airport terminal, connectivity is focused on high bandwidth communications, while during en-route high reliability, robustness, and range is the main focus. Voice communications may use the same or different equipment as data communications systems. In the following the main differences between voice and data communications capabilities are

summarized. The assumed use cases for LDACS completes the list of use cases stated in [RAW-USE-CASES] and the list of reliable and available wireless technologies presented in [RAW-TECHNOS].

3.1. Voice Communications Today

Voice links are used for Air-To-Ground (A/G) and Air-To-Air (A/A) communications. The communication equipment is either ground-based working in the High Frequency (HF) or Very High Frequency (VHF) frequency band or satellite-based. All voice communications is operated via open broadcast channels without any authentication, encryption or other protective measures. The use of well-proven communication procedures via broadcast channels helps to enhance the safety of communications by taking into account that other users may encounter communication problems and may be supported, if required. The main voice communications media is still the analogue VHF Double Side-Band Amplitude Modulation (DSB-AM) communications technique, supplemented by HF Single Side-Band Amplitude Modulation (SSB-AM) and satellite communications for remote and oceanic areas. DSB-AM has been in use since 1948, works reliably and safely, and uses low-cost communication equipment. These are the main reasons why VHF DSB-AM communications is still in use, and it is likely that this technology will remain in service for many more years. This however results in current operational limitations and becomes impediments in deploying new Air-Traffic Management (ATM) applications, such as flight-centric operation with point-to-point communications.

3.2. Data Communications Today

Like for voice, data communications into the cockpit is currently provided by ground-based equipment operating either on HF or VHF radio bands or by legacy satellite systems. All these communication systems are using narrowband radio channels with a data throughput capacity of some kilobits per second. While the aircraft is on ground some additional communications systems are available, like Aeronautical Mobile Airport Communication System (AeroMACS), operating in the Airport (APT) domain and able to deliver broadband communication capability.

The data communication networks used for the transmission of data relating to the safety and regularity of the flight must be strictly isolated from those providing entertainment services to passengers. This leads to a situation that the flight crews are supported by narrowband services during flight while passengers have access to inflight broadband services. The current HF and VHF data links cannot provide broadband services now or in the future, due to the lack of available spectrum. This technical shortcoming is becoming a

limitation to enhanced ATM operations, such as Trajectory-Based Operations (TBO) and 4D trajectory negotiations.

Satellite-based communications are currently under investigation and enhanced capabilities are under development which will be able to provide inflight broadband services and communications supporting the safety and regularity of the flight. In parallel, the ground-based broadband data link technology LDACS is being standardized by ICAO and has recently shown its maturity during flight tests [SCH191]. The LDACS technology is scalable, secure and spectrum efficient and provides significant advantages to the users and service providers. It is expected that both - satellite systems and LDACS - will be deployed to support the future aeronautical communication needs as envisaged by the ICAO Global Air Navigation Plan (GANP).

4. Provenance and Documents

The development of LDACS has already made substantial progress in the Single European Sky ATM Research (SESAR) framework, and 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 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 fulfil 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. The ICAO standardization group plans to produce an ICAO technical manual - the ICAO equivalent to a technical standard - within the next years. Generally, the group is open to input from all sources and develops LDACS in the open.

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 quality of service, diversity, and mobility under the umbrella of the "multi-link concept". This work is conducted by ICAO working group WG-I.

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] [SCH191].

5. Characteristics

LDACS will become one of several wireless access networks connecting aircraft to the Aeronautical Telecommunications Network (ATN). Access to the ATN is handled by the Ground-Station Controller (GSC), while several Ground-Stations (GS) are connected to one GSC. Thus the LDACS access network contains several GS, each of them providing one LDACS radio cell. LDACS can be therefore considered a cellular data link with a star-topology connecting Aircraft-Stations (AS) to GS with a full duplex radio link. Each GS is the centralized instance controlling all A/G communications within its radio cell. A GS supports up to 512 aircraft. All of this is depicted in Figure 1.

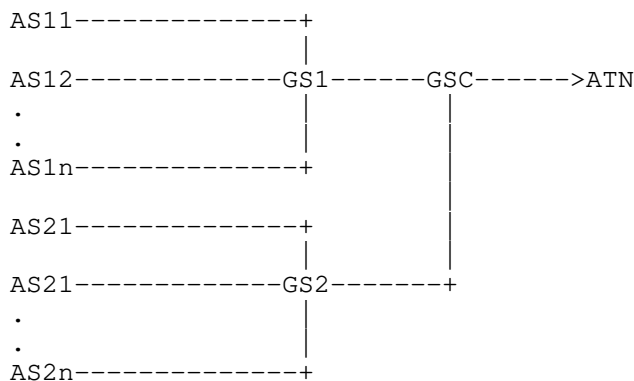


Figure 1: LDACS wireless topology

The LDACS air interface protocol stack defines two layers, the physical layer and the data link layer.

5.1. LDACS Physical Layer

The physical layer provides the means to transfer data over the radio channel. The LDACS GS supports bi-directional links to multiple aircraft under its control. The forward link direction (FL; ground-to-air) and the reverse link direction (RL; 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 Orthogonal Frequency-Division Multiplexing (OFDM) symbols on the forward link. In the reverse link different aircraft are separated in time and frequency using a combination of Orthogonal Frequency-Division Multiple-Access (OFDMA) and Time-Division Multiple-Access (TDMA). Aircraft thus transmit discontinuously on the reverse link with radio bursts sent in precisely defined transmission opportunities allocated by the ground-station. LDACS does not support beam-forming or Multiple Input Multiple Output (MIMO) [SCH192].

5.2. LDACS Data Link Layer

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 sub-layers: The medium access sub-layer and the logical link control sub-layer. The medium access sub-layer manages the organization of transmission opportunities in slots of time and frequency. The logical link control sub-layer provides acknowledged point-to-point logical channels between the aircraft and the ground-station using an automatic repeat request protocol. LDACS supports also unacknowledged point-to-point channels and ground-to-air broadcast.

5.3. LDACS Data Rates

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. 315/294 kbit/s on the forward/reverse link, respectively.

5.4. Reliability and Availability

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).

5.4.1. LDACS Medium Access

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.

5.4.2. LDACS Resource Allocation

LDACS has two mechanisms to request resources from the scheduler in the ground-station. Resources can either be requested "on demand" 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 called Dedicated Control Channel (DCCH); roughly 83 bit 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 in 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 message always go first in any case. Scheduling of reverse link resources is done in physical Protocol Data Units (PDU) of 112 bit (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.

5.4.3. LDACS Handovers

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) if it is connected to an alternative ground-station via the same ground-station controller. Beyond this, FCI diversity shall be implemented by the multi-link concept.

6. Architecture

Aircraft-Station (AS), Ground-Station (GS) and Ground-Station Controller (GSC) form the basic LDACS network. 512 aircraft can be served by one GS where the GS sends a continuous data stream in the Forward Link (FL) to the AS. The Reverse Link (RL) consists of individual bursts of data from each AS to GS. This means, for every RL communication the AS first needs to request the respective resource allocation within its cell from the GS before being able to send. Both FL and RL communication, including user and control data, is done via the air gap over the radio link between AS and GS. On the ground a GSC is responsible for serving several GSs on the control plane, forming an LDACS sub-network with its LDACS internal control plane infrastructure. The GSs are linked to an access router in the user plane, which in turn is linked to an Air/Ground router, being now the direct connection to the ground network. The ATN is used for example by Air traffic Network Services Providers (ANSP) and airlines to exchange Air Traffic Service (ATS) or Airline Operational Control (AOC) data between the ground infrastructure and the aircraft. Figure 2 provides a more detailed overview.

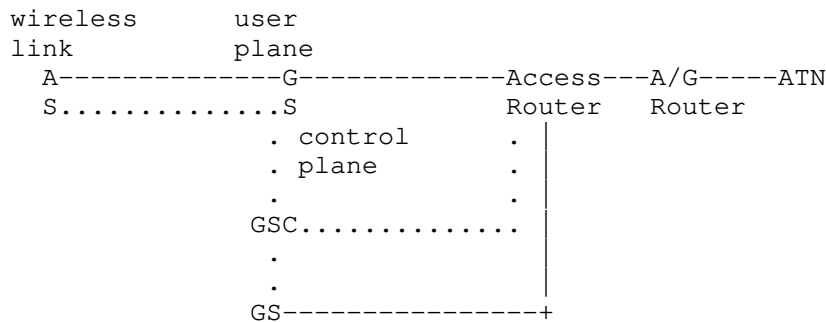


Figure 2: LDACS sub-network with two GSs

6.1. Protocol Stack

The protocol stack of LDACS is implemented in the AS and GS as follows: It consists of the Physical Layer (PHY) 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), (4) LDACS Management Entity (LME). The last entity resides within the sub-network layer: Sub-Network Protocol (SNP).

The LDACS network is externally connected to voice units, radio control units, and the ATN network layer through a Sub-Network Dependent Convergence Function (SNDCF; OSI network layers), Convergence Sub-layer, or Interworking Function (IWF; legacy networks) not discussed here.

The SNP connects the AS and GS DLL providing end-to-end user plane connectivity between the LDACS AS and GS.

The DLL provides Quality of Service (QoS) assurance. Multiplexing of different service classes is possible. Except for the initial aircraft cell-entry and a Type 1 handover, which is not discussed here, medium access is deterministic, with predictable performance. Optional support for adaptive coding and modulation is provided as well. The four functional blocks of the LDACS DLL are organised into two sub-layers, the MAC sub-layer and the Logical Link Control (LLC) sub-layer discussed in the next sections. [GRA19].

Figure 3 shows the protocol stack of LDACS as implemented in the AS and GS.

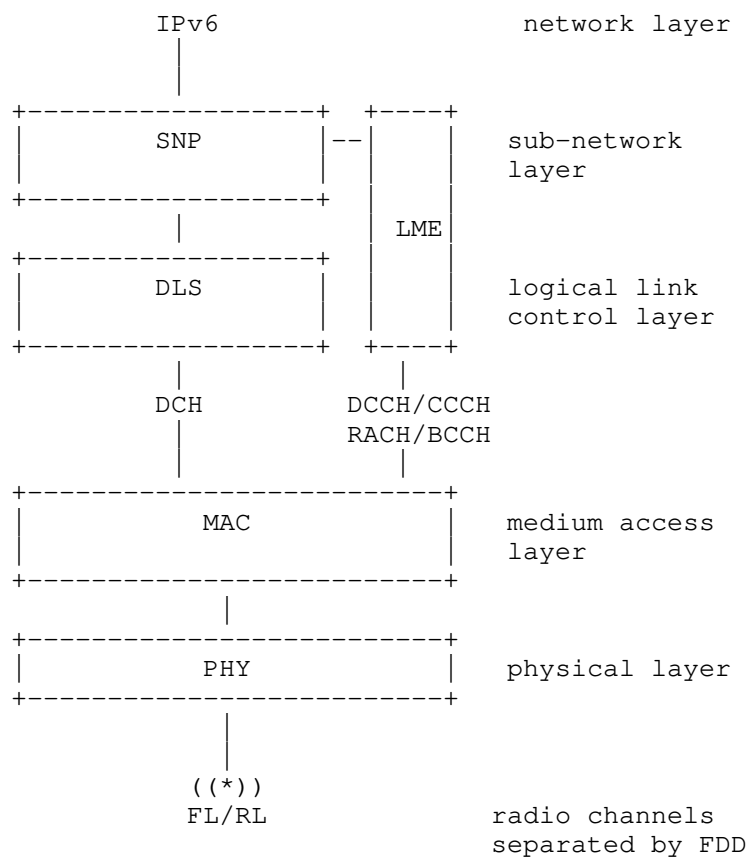


Figure 3: LDACS protocol stack

6.1.1.1. Medium Access Control (MAC) Entity Services

Time Framing Service: The MAC time framing service provides the frame structure necessary to realise slot-based Time Division Multiplex (TDM) access on the physical link. It provides the functions for the synchronisation of the MAC framing structure and the PHY layer framing. The MAC time framing provides a dedicated time slot for each logical channel. [GRA19]

Medium Access Service: The MAC sub-layer offers access to the physical channel to its service users. Channel access is provided through transparent logical channels. The MAC sub-layer maps logical channels onto the appropriate slots and manages the access to these

channels. Logical channels are used as interface between the MAC and LLC sub-layers. [GRA19]

6.1.2. Data Link Service (DLS) Entity Services

The DLS provides acknowledged and unacknowledged (including broadcast and packet mode voice) bi-directional exchange of user data. If user data is transmitted using the acknowledged data link service, the sending DLS entity will wait for an acknowledgement from the receiver. If no acknowledgement is received within a specified time frame, the sender may automatically try to retransmit its data. However, after a certain number of failed retries, the sender will suspend further retransmission attempts and inform its client of the failure. [GRA19]

6.1.3. Voice Interface (VI) Services

The VI provides support for virtual voice circuits. Voice circuits may either be set-up permanently by the GS (e.g. to emulate voice party line) or may be created on demand. The creation and selection of voice circuits is performed in the LME. The VI provides only the transmission services. [GRA19]

6.1.4. Link Management Entity (LME) Services

Mobility Management Service: The mobility management service provides support for registration and de-registration (cell entry and cell exit), scanning RF channels of neighbouring cells and handover between cells. In addition, it manages the addressing of aircraft/ASs within cells. It is controlled by the network management service in the GSC. [GRA19]

Resource Management Service: The resource management service provides link maintenance (power, frequency and time adjustments), support for adaptive coding and modulation (ACM), and resource allocation. [GRA19]

6.1.5. Sub-Network Protocol (SNP) Services

Data Link Service: The data link service provides functions required for the transfer of user plane data and control plane data over the LDACS sub-network. [GRA19]

Security Service: The security service shall provide functions for secure communication over the LDACS sub-network. Note that the SNP security service applies cryptographic measures as configured by the ground station controller. [GRA19]

6.2. LDACS Logical Communication Channels

Data Link Service: The data link service provides functions required for the transfer of user plane data and control plane data over the LDACS sub-network. [GRA19]

In order to communicate, LDACS uses several logical channels in the MAC layer [GRA19]:

1. The GS announces its existence and several necessary physical parameters in the Broadcast Channel (BCCH) to incoming AS.
2. The Random Access Channel (RACH) enables the AS to request access to an LDACS cell.
3. In the Forward Link (FL) the Common Control Channel (CCCH) is used by the GS to distribute and grant access to system resources.
4. The reverse direction is covered by the Reverse Link (RL), where aircraft need to request resources (in so called resource allocation) in order to be allowed to send. This happens via the Dedicated Common Control Channel (DCCH).
5. User data itself is communicated in the Data Channel (DCH) on the FL and RL.

Figure 4 shows in detail the distribution of each slot. The LDACS super-frame is repeated every 240 ms and carries all control plane and user plane logical channels in separate slots of variable length.

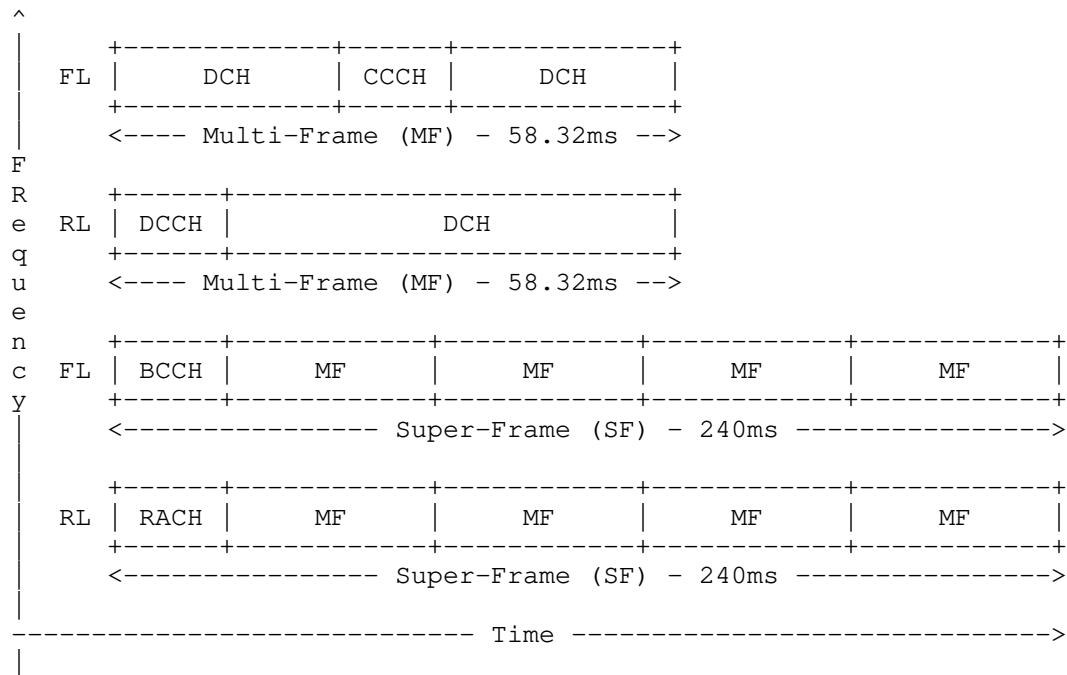


Figure 4: LDACS frame structure

6.3. LDASC Framing Structure

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).

6.3.1. Forward Link

In the FL, an SF contains a Broadcast Frame of duration $T_{BC} = 6.72$ ms (56 OFDM symbols), and four Multi-Frames (MF), each of duration $T_{MF} = 58.32$ ms (486 OFDM symbols).

6.3.2. Reverse Link

In the RL, each SF starts with a Random Access (RA) message of length $T_{RA} = 6.72$ ms with two opportunities for sending reverse link random access frames, followed by four MFs. These MFs have the same fixed duration of $T_{MF} = 58.32$ ms as in the FL, but a different internal structure.

7. Security Considerations

Aviation will require secure exchanges of data and voice messages for managing the air-traffic flow safely through the airspaces all over the world. The main communication method for ATC today is still an open analogue voice broadcast within the aeronautical VHF band. Currently, the information security is purely procedural based by using well-trained personnel and proven communications procedures. This communication method has been in service since 1948. Future digital communications waveforms will need additional embedded security features to fulfil modern information security requirements like authentication and integrity. These security features require sufficient bandwidth which is beyond the capabilities of a VHF narrowband communications system. For voice and data communications, sufficient data throughput capability is needed to support the security functions while not degrading performance. LDACS is a mature data link technology with sufficient bandwidth to support security.

Security considerations for LDACS are the official ICAO SARPS [ICAO18]:

1. LDACS shall provide a capability to protect the availability and continuity of the system.
2. LDACS shall provide a capability including cryptographic mechanisms to protect the integrity of messages in transit.
3. LDACS shall provide a capability to ensure the authenticity of messages in transit.
4. LDACS should provide a capability for nonrepudiation of origin for messages in transit.
5. LDACS should provide a capability to protect the confidentiality of messages in transit.
6. LDACS shall provide an authentication capability.
7. LDACS shall provide a capability to authorize the permitted actions of users of the system and to deny actions that are not explicitly authorized.
8. If LDACS provides interfaces to multiple domains, LDACS shall provide capability to prevent the propagation of intrusions within LDACS domains and towards external domains.

The cybersecurity architecture of LDACS [ICAO18], [MAE18] and its extensions [MAE191], [MAE192] regard all of the aforementioned requirements, since LDACS has been mainly designed for air traffic management communication. Thus it supports mutual entity authentication, integrity and confidentiality capabilities of user data messages and some control channel protection capabilities [MAE192].

More details can be found here [MAE18], [MAE192] and [ICAO18].

From the very beginning of the development process security for LDACS has been addressed by design and thus meets the security objectives as standardized by ICAO [ICAO18].

8. Privacy Considerations

LDACS provides a Quality of Service (QoS), and the generic considerations for such mechanisms apply.

9. IANA Considerations

This memo includes no request to IANA.

10. Acknowledgements

The authors want to thank all contributors to the development of LDACS. Further, thanks to SBA Research Vienna for fruitful discussions on aeronautical communications concerning security incentives for industry and potential economic spillovers.

11. Normative References

12. Informative References

- [MAE191] Maeurer, N., Graeupl, T., and C. Schmitt, "Evaluation of the LDACS Cybersecurity Implementation", IEEE 38th Digital Avionics Systems Conference (DACS), pp. 1-10, New York, NY, USA , November 2019.
- [MAE192] Maeurer, N. and C. Schmitt, "Towards Successful Realization of the LDACS Cybersecurity Architecture: An Updated Datalink Security Threat- and Risk Analysis", IEEE Integrated Communications, Navigation and Surveillance Conference (ICNS), pp. 1-13, New York, NY, USA , November 2019.
- [GRA19] Graeupl, T., Rihacek, C., and B. Haindl, "LDACS A/G Specification", German Aerospace Center (DLR), Germany, SESAR2020 PJ14-02-01 D3.3.010 , 2017.
- [MAE18] Maeurer, N. and A. Bilzhause, "A Cybersecurity Architecture for the L-band Digital Aeronautical Communications System (LDACS)", IEEE 37th Digital Avionics Systems Conference (DASC), pp. 1-10, New York, NY, USA , 2017.

- [GRA11] Graeupel, T. and M. Ehammer, "L-DACS1 Data Link Layer Evolution of ATN/IPS", 30th IEEE/AIAA Digital Avionics Systems Conference (DASC), pp. 1-28, New York, NY, USA , 2011.
- [GRA18] Graeupel, T., Schneckenburger, N., Jost, T., Schnell, M., Filip, A., Bellido-Manganell, M.A., Mielke, D.M., Maeurer, N., Kumar, R., Osechas, O., and G. Battista, "L-band Digital Aeronautical Communications System (LDACS) flight trials in the national German project MICONAV", Integrated Communications, Navigation, Surveillance Conference (ICNS), pp. 1-7, New York, NY, USA , 2018.
- [SCH191] Schnell, M., "DLR Tests Digital Communications Technologies Combined with Additional Navigation Functions for the First Time", November 2019.
- [SCH192] Schnell, M., "Update on LDACS - The FCI Terrestrial Data Link", 19th Integrated Communications, Navigation and Surveillance Conference (ICNS), pp. 1-10, New York, NY, USA , November 2019.
- [ICAO18] International Civil Aviation Organization (ICAO), "L-Band Digital Aeronautical Communication System (LDACS)", International Standards and Recommended Practices Annex 10 - Aeronautical Telecommunications, Vol. III - Communication Systems , 2018.
- [SAJ14] Sajatovic, M., Guenzel, H., and S. Mueller, "WA04 D22 Test Report for Assessing LDACS1 Transmitter Impact upon DME/TACAN Receivers", 19th Integrated Communications, Navigation and Surveillance Conference (ICNS), pp. 1-10, New York, NY, USA , 2014.
- [RIH18] Rihacek, C., Haindl, B., Fantappie, P., Pierattelli, S., Graeupl, T., Schnell, M., and N. Fistas, "LDACS A/G Specification", Integrated Communications Navigation and Surveillance Conference (ICNS), pp. 1-8, New York, NY, USA , 2018.
- [RAW-TECHNOS] Thubert, P., Cavalcanti, D., Vilajosana, X., and C. Schmitt, "Reliable and Available Wireless Technologies", Work in Progress, Internet-Draft, draft-thubert-raw-technologies-03, 1 July 2019, <<https://tools.ietf.org/html/draft-thubert-raw-technologies-03>>.

[RAW-USE-CASES]

Papadopoulos, G., Thubert, P., Theoleyre, F., and C. Bernardos, "RAW use cases", Work in Progress, Internet-Draft, draft-bernardos-raw-use-cases-00, 5 July 2019, <<https://tools.ietf.org/html/draft-bernardos-raw-use-cases-00>>.

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Exploiting Packet Replication and Elimination in Complex Tracks in LLNs
draft-papadopoulos-raw-pareo-reqs-00

Abstract

The Packet Replication and Elimination (PRE) mechanism duplicates data packets into several paths in the network to increase reliability and provide low jitter. PRE may be used to complement layer-2 Automatic Repeat reQuest (ARQ) and receiver-end Ordering to form the PAREO functions. Over a wireless medium, this technique can take advantage of communication Overhearing, when parallel transmissions over two adjacent paths are scheduled. This document presents the concept and details the required changes to the current specifications that will be necessary to enable the PAREO functions.

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1. Introduction

This draft describes industrial use cases which require deterministic flows over wireless multi-hop paths.

The RAW use cases explicitly do not propose any specific solution or design for the RAW architecture or protocols. These are the subjects of other RAW drafts. The RAW use cases are not considered to be concrete requirements by the RAW Working Group.

The industrial use cases covered in this draft are professional audio, wireless for industrial applications and amusement parks.

2. Terminology

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in [RFC2119].

3. Tracks

3.1. Tracks Overview

The 6TiSCH architecture introduces the concept of Tracks in 6TiSCH Architecture [I-D.ietf-6tisch-architecture]. A simple track is composed of a sequence of cells (a combination of a transmitter, a receiver and a given channel offset) to ensure the transmission of a single packet from a source node to a destination node across a multihop path.

3.2. Complex Tracks

A Complex Track is designed as a directed acyclic graph from a source node towards a destination node to support multi-path forwarding, as introduced in 6TiSCH Architecture [I-D.ietf-6tisch-architecture]. By employing DetNet [I-D.ietf-detnet-architecture] Packet Replication and Elimination (PRE) functions, several paths may be computed, and these paths may be more or less independent. For example, a complex Track may branch off and rejoin over non-congruent paths (branches).

Some more details for Deterministic Network PRE techniques are presented in the following Section.

4. Packet Replication and Elimination principles

In a nutshell, PRE establishes several paths in a network to provide redundancy and parallel transmissions to bound the end-to-end delay to traverse the network. Optionally, promiscuous listening between paths is possible, such that the nodes on one path may overhear transmissions along the other path. Considering the scenario shown in Figure 1, 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 by interleaving transmissions from the lower level of the path to the upper level.

PRE may also take advantage of the shared properties of the wireless medium to compensate for the potential loss that is incurred with radio transmissions. For instance, when the source sends to A, B may listen also and get a second chance to receive the frame without an additional transmission. Note that B would not have to listen if it

already received that particular frame at an earlier timeslot in a dedicated transmission towards B.

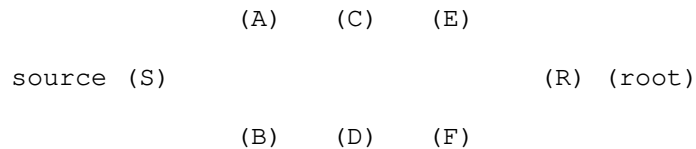


Figure 1: A Typical Ladder Shape with Two Parallel Paths Toward the Destination

The PRE model can be implemented in both centralized and distributed scheduling approaches. In the centralized approach, a Path Computation Element (PCE) scheduler calculates the routes and schedules the communication among the nodes along a circuit such as a Label switched path. In the distributed approach, each node selects its route to the destination, typically using a source routing header. In both cases, at each node in the paths, a default parent and alternative parent(s) should be selected to set up complex tracks.

In the following Subsections, all the required operations defined by PRE, namely, Alternative Path Selection, Packet Replication, Packet Elimination and Promiscuous Overhearing, are described.

4.1. Packet Replication

The objective of PRE is to provide deterministic networking properties: high reliability and bounded latency. To achieve this goal, determinism in every hop of the forwarding paths MUST be guaranteed. By employing a Packet Replication procedure, each node forwards a copy of each data packet to multiple parents: its Default Parent (DP) and multiple Alternative Parents (APs). To do so, each node (i.e., source and intermediate node) transmits the data packet multiple times in unicast to each parent. For instance, in Figure 2, the source node S is transmitting the packet to both parents, nodes A and B, in two different timeslots within the same TSCH slotframe. An example TSCH schedule is shown in Figure 3. Thus, the packet eventually obtains parallel paths to the destination.

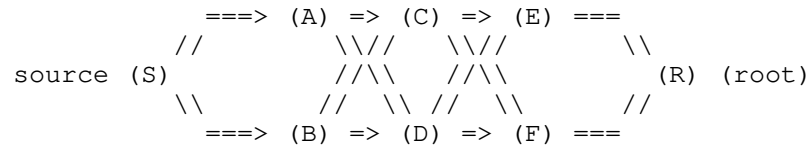


Figure 2: Packet Replication: S transmits twice the same data packet, to its DP (A) and to its AP (B).

Timeslot							
Channel	0	1	2	3	4	5	6
0	S->A	S->B	B->C	B->D	C->F	E->R	F->R
1		A->C	A->D	C->E	D->E	D->F	

Figure 3: Packet Replication: Sample TSCH schedule

4.2. Packet Elimination

The replication operation increases the traffic load in the network, due to packet duplications. Thus, a Packet Elimination operation SHOULD be applied at each RPL DODAG level to reduce the unnecessary traffic. To this aim, once a node receives the first copy of a data packet, it 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. Then, once a node performs the Packet Elimination operation, it will proceed with the Packet Replication operation to forward the packet toward the RPL DODAG Root.

4.3. Promiscuous Overhearing

Considering that the wireless medium is broadcast by nature, any neighbor of a transmitter may overhear a transmission. By employing the Promiscuous Overhearing operation, a DP and some AP(s) eventually have more chances to receive the data packets. In Figure 4, when node A is transmitting to its DP (node C), the AP (node D) and its sibling (node B) may decode this data packet as well. As a result, by employing correlated paths, a node may have multiple opportunities to receive a given data packet. This feature not only enhances the end-to-end reliability but also it reduces the end-to-end delay and increases energy efficiency.

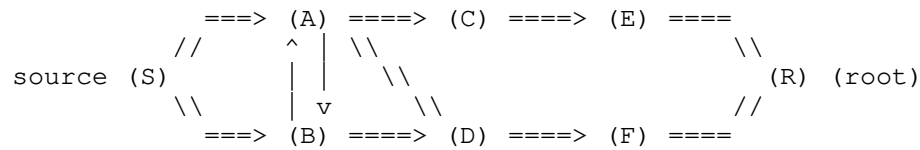


Figure 4: Unicast to DP with Overhearing: by employing Promiscuous Overhearing, DP, AP and the sibling nodes have more opportunities to receive the same data packet.

5. Requirements

5.1. Requirements Related to Alternative Parent Selection

To perform the Packet Replication procedure, it is necessary to define the Alternative Parent(s) and, consequently, the path to the destination node, for each node in the wireless network. An AP can be selected in many different ways, and is dependent on the implementation.

The requirements are:

Req1.1: The routing protocol SHOULD be extended to allow for each node to select AP(s) in addition to the DP. This enables packet replication to multiple parents.

Req1.2: Considering that the Packet Replication procedure significantly increases the traffic in a network, when proposing solutions for Alternative Parent Selection, they should be efficient enough to mitigate the potential uncontrolled packet duplications.

Req1.3: The topology SHOULD be defined when proposing solutions for Alternative Parent Selection. For instance, the ladder topology should be defined explicitly e.g., number of parallel paths, density.

5.2. Requirements Related to Propagated Information

For Alternative Parent(s) selection, nodes MAY need additional information about the network topology. This draft does not prescribe the information required for AP selection or how it is to be propagated to the nodes that need to select AP(s). TODO: To be discussed.

The requirement is:

Req2.1: Nodes MUST have a way of receiving the required information for efficient Alternative Parent Selection.

As an example, it is possible to use and extend the RPL [RFC6550] DODAG Information Object (DIO) Control Message to allow nodes to propagate information about themselves to potential children. For instance, "RPL DAG Metric Container (MC) Node State and Attribute (NSA) object type extension" [I-D.ietf-roll-nsa-extension] focuses on extending the DAG Metric Container [RFC6551] by defining a new type-length-value (TLV), entitled Parent Set (PS) which can be carried in the Node State and Attribute (NSA) object.

5.3. Requirements Related to Promiscuous Overhearing

As stated previously, to further increase the network reliability and to achieve deterministic packet deliveries at the destination node, Promiscuous Overhearing can be considered.

As it is described in BCP 210 [RFC8180], in TSCH mode, the data frames are transmitted in unicast mode and are acknowledged by the receiving neighbor. To perform the promiscuous overhearing procedure, there SHOULD be an option for the transmitted frames, i.e., in unicast, to be overheard by the potential neighborhood node.

Destination address filtering is performed at the Medium Access Control (MAC) layer. For example, according to IEEE std. 802.15.4 [IEEE802154-2015], a node receiving a packet with a destination address different than its own and different to 0xFF discards the packet. A change is needed to be able to receive packets whose destination address is neither multicast nor the overhearing node's MAC address.

The requirements are:

Req3.1: The MAC implementation MUST be able to disable MAC address filtering to accept the overheard frame.

Req3.2: The 6top Protocol [RFC8480] specification MUST be extended to indicate disabling MAC filtering in a receiving cell. This can be achieved by reserving a bit in the 6P CellOptions Bitmap (Section 6.2.6 [RFC8480]) for this purpose.

Req3.3: The overhearing node can be configured with the timeslot set to shared reception, thus, there will be no acknowledgement from it. However, there is the security issue that needs to be considered. Since the overhearing case implies that it is not possible to have per-pair keying, there MUST be a key that the overhearing node will be aware of. Hence, the Minimal Security

Framework for 6TiSCH [I-D.ietf-6tisch-architecture]
specification should consider such a scenario.

5.4. Requirements Related to Packet Elimination

By employing Packet Replication, the wireless network is expected to also perform Packet Elimination to restrict the number of the duplicated packets, i.e., the unnecessary traffic. As per the 6TiSCH Architecture [I-D.ietf-6tisch-architecture], 6TiSCH has no position about how the sequence numbers would be tagged in the packet.

The requirement is:

Req4.1: To perform Packet Elimination the packet copies MUST contain a sequence number which allows identifying the copies.

6. Security Considerations

TODO.

7. IANA Considerations

This document has no IANA considerations.

8. References

8.1. Informative references

[I-D.ietf-6tisch-architecture]

Thubert, P., "An Architecture for IPv6 over the TSCH mode of IEEE 802.15.4", draft-ietf-6tisch-architecture-20 (work in progress), March 2019.

[I-D.ietf-detnet-architecture]

Finn, N., Thubert, P., Varga, B., and J. Farkas, "Deterministic Networking Architecture", draft-ietf-detnet-architecture-13 (work in progress), May 2019.

[I-D.ietf-roll-nsa-extension]

Koutsiamanis, R., Papadopoulos, G., Montavont, N., and P. Thubert, "RPL DAG Metric Container Node State and Attribute object type extension", draft-ietf-roll-nsa-extension-01 (work in progress), March 2019.

[RFC2119]

Bradner, S., "Key words for use in RFCs to Indicate Requirement Levels", BCP 14, RFC 2119, DOI 10.17487/RFC2119, March 1997, <<https://www.rfc-editor.org/info/rfc2119>>.

- [RFC6550] Winter, T., Ed., Thubert, P., Ed., Brandt, A., Hui, J., Kelsey, R., Levis, P., Pister, K., Struik, R., Vasseur, JP., and R. Alexander, "RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks", RFC 6550, DOI 10.17487/RFC6550, March 2012, <<https://www.rfc-editor.org/info/rfc6550>>.
- [RFC6551] Vasseur, JP., Ed., Kim, M., Ed., Pister, K., Dejean, N., and D. Barthel, "Routing Metrics Used for Path Calculation in Low-Power and Lossy Networks", RFC 6551, DOI 10.17487/RFC6551, March 2012, <<https://www.rfc-editor.org/info/rfc6551>>.
- [RFC8180] Vilajosana, X., Ed., Pister, K., and T. Watteyne, "Minimal IPv6 over the TSCH Mode of IEEE 802.15.4e (6TiSCH) Configuration", BCP 210, RFC 8180, DOI 10.17487/RFC8180, May 2017, <<https://www.rfc-editor.org/info/rfc8180>>.
- [RFC8480] Wang, Q., Ed., Vilajosana, X., and T. Watteyne, "6TiSCH Operation Sublayer (6top) Protocol (6P)", RFC 8480, DOI 10.17487/RFC8480, November 2018, <<https://www.rfc-editor.org/info/rfc8480>>.

8.2. Other Informative References

- [IEEE802154-2015]
IEEE standard for Information Technology, "IEEE standard for Information Technology, "IEEE Std 802.15.4-2015 Standard for Low-Rate Wireless Personal Area Networks (WPANs)", December 2015".

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Operations, Administration and Maintenance (OAM) features for RAW
draft-theoleyre-raw-oam-support-01

Abstract

The wireless medium presents significant specific challenges to achieve properties similar to those of wired deterministic networks. At the same time, a number of use cases cannot be solved with wires and justify the extra effort of going wireless. This document presents some of these use-cases.

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1. Introduction

Reliable and Available Wireless (RAW) is an effort that extends DetNet to approach end-to-end deterministic performances over a network that includes scheduled wireless segments. The wireless and wired media are fundamentally different at the physical level. Enabling thus reliable and available wireless communications is even more challenging than it is in wired IP networks, due to the numerous causes of loss in transmission that add up to the congestion losses and the delays caused by overbooked shared resources. To provide quality of service along a multihop path that is composed of wired and wireless hops, additional methods needs to be considered to leverage the potential lossy wireless communication.

Traceability belongs to Operations, Administration, and Maintenance (OAM) which is the toolset for fault detection and isolation, and for performance measurement. More can be found on OAM Tools in [RFC7276].

The main purpose of this document is to detail the requirements of the OAM features recommended to construct a predictable communication infrastructure on top of a collection of wireless segments. This document describes the benefits, problems, and trade-offs for using OAM in wireless networks to provide availability and predictability.

In this document, the term OAM will be used according to its definition specified in [RFC6291]. We expect to implement an OAM framework in RAW networks to maintain a real-time view of the network infrastructure, and its ability to respect the Service Level Agreements (SLA), such as delay and reliability, assigned to each data flow.

1.1. Terminology

- o OAM entity: a data flow to be controlled;
- o OAM end-devices: the source or destination of a data flow;
- o defect: a temporary change in the network characteristics (e.g. link quality degradation because of temporary external interference, a mobile obstacle)
- o fault: a definite change which may affect the network performance, e.g. a node runs out of energy,

2. Needs for OAM in RAW

RAW networks expect to make the communications reliable and predictable on top of a wireless network infrastructure. Most critical applications will define a SLA to respect for the data flows it generates. RAW considers network plane protocol elements such as OAM to improve the RAW operation at the service and at the forwarding sub-layers.

To respect strict guarantees, RAW relies on a Path Computation Element (PCE) which will be responsible to schedule the transmissions in the deployed network. Thus, resources have to be provisioned a priori to handle any defect. OAM represents the core of the over provisioning process, and maintains the network operational by updating the schedule dynamically.

Fault-tolerance also assumes that multiple path have to be provisioned so that an end-to-end circuit keeps on existing whatever the conditions. OAM is in charge of controlling the replication/elimination processes.

To be energy-efficient, reserving some dedicated out-of-band resources for OAM seems idealistic, and only in-band solutions are considered here.

RAW supports both proactive and on-demand troubleshooting.

3. Operation

OAM features will enable RAW with robust operation both for forwarding and routing purposes.

3.1. Connectivity Verification

We need to verify that two endpoints are connected with each other. Since we reserve resources along the path independently for each flow, we must be able to verify that the path exists for a given flow label.

The control and data packets may not follow the same path, and the connectivity verification has to be triggered in-band without impacting the data traffic. In particular, the control plane may work while the data plane may be broken.

The ping packets must be labeled in the same way as the data packets of the flow to monitor.

3.2. Route Tracing

Ping and traceroute are two very common tools for diagnostic. They help to identify the list of routers in the route. However, to be predictable, resources are reserved per flow in RAW. Thus, we need to define route tracing tools able to track the route for a specific flow.

Because the network has to be fault-tolerant, multipath can be considered, with multiple Maintenance Intermediate Endpoints for each hop in the path. Thus, all the possible paths between two maintenance endpoints should be retrieved.

3.3. Fault verification / detection

RAW expects to operate fault-tolerant networks. Thus, we need mechanisms able to detect faults, before they impact the network performance.

The network has to detect when a fault occurred, i.e. the network has deviated from its expected behavior. While the network must report an alarm, the cause may not be identified precisely. For instance, the end-to-end reliability has decreased significantly, or a buffer overflow occurs.

We have to minimize the amount of statistics / measurements to exchange:

- o energy efficiency: low-power devices have to limit the volume of monitoring information since every bit consumes energy.
- o bandwidth: wireless networks exhibit a bandwidth significantly lower than wired, best-effort networks.
- o per-packet cost: is is often more expensive to send several packets instead of combining them in a single link-layer frame.

Thus, localized and centralized mechanisms have to be combined together, and additional control packets have to be triggered only after a fault detection.

3.4. Fault isolation / identification

The network has isolated and identified the cause of the fault. For instance, the quality of a specific link has decreased, requiring more retransmissions, or the level of external interference has locally increased.

4. Administration

To take proper decisions, the network has to expose a collection of metrics, including:

- o Packet losses: the time-window average and maximum values of the number of packet losses has to be measured. Many critical applications stop to work if a few consecutive packets are dropped;
- o Received Signal Strength Indicator (RSSI) is a very common metric in wireless to denote the link quality. The radio chipset is in charge of translating a received signal strength into a normalized quality indicator;
- o Delay: the time elapsed between a packet generation / enqueueing and its reception by the next hop;
- o Buffer occupancy: the number of packets present in the buffer, for each of the existing flows.

These metrics should be collected:

- o per virtual circuit to measure the end-to-end performance for a given flow. Each of the paths has to be isolated in multipath strategies;

- o per radio channel to measure e.g. the level of external interference, and to be able to apply counter-measures (e.g. blacklisting)
- o per device to detect misbehaving node, when it relays the packets of several flows.

4.1. Worst-case metrics

RAW aims to enable real-time communications on top of an heterogeneous architecture. Since wireless networks are known to be lossy, RAW has to implement strategies to improve the reliability on top of unreliable links. Hybrid Automatic Repeat reQuest (ARQ) has typically to enable retransmissions based on the end-to-end reliability and latency requirements.

To take correct decisions, the controller needs to know the distribution of packet losses for each flow, and for each hop of the paths. In other words, average end-to-end statistics are not enough. They must allow the controller to predict the worst-case.

4.2. Energy efficiency constraint

RAW targets also low-power wireless networks, where energy represents a key constraint. Thus, we have to take care of the energy and bandwidth consumption. The following techniques aim to reduce the cost of such maintenance:

piggybacking: some control information are inserted in the data packets if they do not fragment the packet (i.e. the MTU is not exceeded). Information Elements represent a standardized way to handle such information;

flags/fields: we have to set-up flags in the packets to monitor to be able to monitor the forwarding process accurately. A sequence number field may help to detect packet losses. Similarly, path inference tools such as [ipath] insert additional information in the headers to identify the path followed by a packet a posteriori.

5. Maintenance

RAW needs to implement a self-healing and self-optimization approach. The network must continuously retrieve the state of the network, to judge about the relevance of a reconfiguration, quantifying:

the cost of the sub-optimality: resources may not be used optimally (e.g. a better path exists);

the reconfiguration cost: the controller needs to trigger some reconfigurations. For this transient period, resources may be twice reserved, and control packets have to be transmitted.

Thus, reconfiguration may only be triggered if the gain is significant.

5.1. Multipath

To be fault-tolerant, several paths can be reserved between two maintenance endpoints. They must be node-disjoint, so that a path can be available at any time.

5.2. Replication / Elimination

When multiple paths are reserved between two maintenance endpoints, they may decide to replicate the packets to introduce redundancy, and thus to alleviate transmission errors and collisions. For instance, in Figure 1, the source node S is transmitting the packet to both parents, nodes A and B. Each maintenance endpoint will decide to trigger the replication / elimination process when a set of metrics passes through a threshold value.

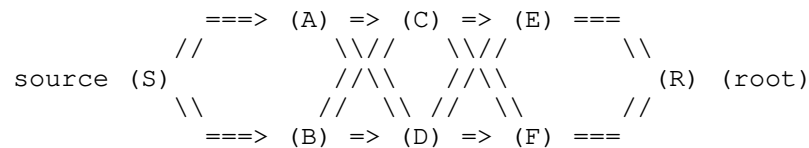


Figure 1: Packet Replication: S transmits twice the same data packet, to its DP (A) and to its AP (B).

5.3. Resource Reservation

Because the QoS criteria associated to a path may degrade, the network has to provision additional resources along the path. We need to provide mechanisms to patch a schedule (changing the channel offset, allocating more timeslots, changing the path, etc.).

5.4. Soft transition after reconfiguration

Since RAW expects to support real-time flows, we have to support soft-reconfiguration, where the novel resources are reserved before the ancient ones are released. Some mechanisms have to be proposed so that packets are forwarded through the novel track only when the

resources are ready to be used, while maintaining the global state consistent (no packet re-ordering, duplication, etc.)

6. Informative References

- [ipath] Gao, Y., Dong, W., Chen, C., Bu, J., Wu, W., and X. Liu, "iPath: path inference in wireless sensor networks.", 2016, <<https://doi.org/10.1109/TNET.2014.2371459>>.
- [RFC6291] Andersson, L., van Helvoort, H., Bonica, R., Romascanu, D., and S. Mansfield, "Guidelines for the Use of the "OAM" Acronym in the IETF", BCP 161, RFC 6291, DOI 10.17487/RFC6291, June 2011, <<https://www.rfc-editor.org/info/rfc6291>>.
- [RFC7276] Mizrahi, T., Sprecher, N., Bellagamba, E., and Y. Weingarten, "An Overview of Operations, Administration, and Maintenance (OAM) Tools", RFC 7276, DOI 10.17487/RFC7276, June 2014, <<https://www.rfc-editor.org/info/rfc7276>>.

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Reliable and Available Wireless Technologies
draft-thubert-raw-technologies-03

Abstract

This document presents a series of recent technologies that are capable of time synchronization and scheduling of transmission, making them suitable to carry time-sensitive flows with requirements of both reliable delivery in bounded time, and availability at all times, regardless of packet transmission or individual equipment failures.

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1. Introduction

When used in math or philosophy, the term "deterministic" generally refers to a perfection where all aspect are understood and predictable. A perfectly Deterministic Network would ensure that every packet reach its destination following a predetermined path along a predefined schedule to be delivered at the exact due time. In a real and imperfect world, a Deterministic Network must highly predictable, which is a combination of reliability and availability. On the one hand the network must be reliable, meaning that it will perform as expected for all packets and in particular that it will always deliver the packet at the destination in due time. On the other hand, the network must be available, meaning that it is resilient to any single outage, whether the cause is a software, a hardware or a transmission issue.

RAW (Reliable and Available Wireless) is an effort to provide Deterministic Networking on across a path that include a wireless physical layer. Making Wireless Reliable and Available is even more challenging than it is with wires, due to the numerous causes of loss in transmission that add up to the congestion losses and the delays caused by overbooked shared resources. In order to maintain a similar quality of service along a multihop path that is composed of wired and wireless hops, additional methods that are specific to wireless must be leveraged to combat the sources of loss that are also specific to wireless.

Such wireless-specific methods include per-hop retransmissions (HARQ) and P2MP overhearing whereby multiple receivers are scheduled to receive the same transmission, which balances the adverse effects of the transmission losses that are experienced when a radio is used as pure P2P.

2. Terminology

This specification uses several terms that are uncommon on protocols that ensure best effort transmissions for stochastic flows, such as found in the traditional Internet and other statistically multiplexed packet networks.

ARQ: Automatic Repeat Request, enabling an acknowledged transmission and retries. ARQ is a typical model at Layer-2 on a wireless medium. It is typically avoided end-to-end on deterministic flows because it introduces excessive indetermination in latency, but a limited number of retries within a bounded time may be used over a wireless link and yet respect end-to-end constraints.

Available: That is exempt of unscheduled outage, the expectation for a network being that the flow is maintained in the face of any single breakage.

FEC: Forward error correction, sending redundant coded data to help the receiver recover transmission errors without the delays incurred with ARQ.

HARQ: Hybrid ARQ, a combination of FEC and ARQ.

PCE: Path Computation Element.

PAREO (functions): the wireless extension of DetNet PREOF. PAREO functions include scheduled ARQ at selected hops, and expect the use of new operations like overhearing where available.

Reliable: That consistently performs as expected, the expectation for a network being to always deliver a packet in due time.

Track: A DODAG oriented to a destination, and that enables Packet ARQ, Replication, Elimination, and Ordering Functions.

3. On Scheduling

The operations of a Deterministic Network often rely on precisely applying a tight schedule, in order to avoid collision loss and guarantee the worst-case time of delivery. 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.

3.1. Benefits of Scheduling on Wires

A network is reliable when the statistical effects that affect the packet transmission are eliminated. This involves maintaining at all time the amount of critical packets within the physical capabilities of the hardware and that of the radio medium. This is achieved by controlling the use of time-shared resources such as CPUs and buffers, by shaping the flows and by scheduling the time of transmission of the packets that compose the flow at every hop.

Equipment failure, such as an access point rebooting, a broken radio adapter, or a permanent obstacle to the transmission, is a secondary source of packet loss. When a breakage occurs, multiple packets are lost in a row before the flows are rerouted or the system may recover. This is not acceptable for critical applications such as 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 (e.g., after 4 packets lost, within a period of 1 second).

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 pseudo randomly 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.

3.2. Benefits of Scheduling on Wireless

In addition to the benefits listed in Section 3.1, scheduling transmissions provides specific value to the wireless medium.

On the one hand, scheduling avoids collisions between scheduled transmissions and can ensure both time and frequency diversity between retries in order to defeat co-channel interference from uncontrolled transmitters as well as multipath fading. Transmissions can be scheduled on multiple channels in parallel, which enables to use 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.

On the other hand, scheduling optimizes the bandwidth usage: compared to classical Collision Avoidance techniques, there is no blank time related to inter-frame 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. And because scheduling allows a time-sharing operation, there is no limit to the ratio of isolated critical traffic.

Finally, scheduling plays a critical role to save energy. In IOT, energy is the foremost concern, and synchronizing sender and listener enables to always maintain them in deep sleep when there is no scheduled transmission. This avoids idle listening and long preambles and 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

4.1. Provenance and Documents

With an active portfolio of nearly 1,300 standards and projects under development, IEEE is a leading developer of industry standards in a broad range of technologies that drive the functionality, capabilities, and interoperability of products and services, transforming how people live, work, and communicate.

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 advocates them on a global basis. The most widely used standards are for Ethernet, Bridging and Virtual Bridged LANs Wireless LAN, Wireless PAN, Wireless MAN, Wireless Coexistence, Media Independent Handover Services, and Wireless RAN. An individual Working Group provides the focus for each area. Standards produced by the IEEE 802 SC are freely available from the IEEE GET Program after they have been published in PDF for six months.

The IEEE 802.11 LAN standards define the underlying MAC and PHY layers for the Wi-Fi technology. Wi-Fi/802.11 is one of the most successful wireless technologies, supporting many application domains. While previous 802.11 generations, such as 802.11n and 802.11ac, have focused mainly on improving peak throughput, more recent generations are also considering other performance vectors, such as efficiency enhancements for dense environments in 802.11ax, and latency and support for Time-Sensitive Networking (TSN) capabilities in 802.11be.

IEEE 802.11 already supports some 802.1 TSN standards and it is undergoing efforts to support for other 802.1 TSN capabilities required to address the use cases that require time synchronization and timeliness (bounded latency) guarantees with high reliability and availability. The IEEE 802.11 working group has been working in collaboration with the IEEE 802.1 group for several years extending 802.1 features over 802.11. As with any wireless media, 802.11 imposes new constraints and restrictions to TSN-grade QoS, and tradeoffs between latency and reliability guarantees must be considered as well as managed deployment requirements. An overview of 802.1 TSN capabilities and their extensions to 802.11 are discussed in [Cavalcanti_2019].

Wi-Fi Alliance (WFA) 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 following IEEE 802.11 specifications/certifications are relevant in the context of reliable and available wireless services and support for time-sensitive networking capabilities:

Time Synchronization: IEEE802.11-2016 with IEEE802.1AS; WFA TimeSync Certification.

Congestion Control: IEEE802.11-2016 Admission Control; WFA Admission Control.

Security: WFA Wi-Fi Protected Access, WPA2 and WPA3.

Interoperating with IEEE802.1Q bridges: IEEE802.11ak.

Stream Reservation Protocol (part of IEEE802.1Qat):
AIEEE802.11-2016.

Scheduled channel access: IEEE802.11ad 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 IEEE802.11 Working Group include capabilities that can be used as the basis for providing more reliable and predictable wireless connectivity and support time-sensitive applications:

IEEE 802.11ax D4.0: Enhancements for High Efficiency (HE). [IEEE802.11ax]

IEEE 802.11be Extreme High Throughput (EHT). [IEEE802.11be]

IEEE 802.11ay Enhanced throughput for operation in license-exempt bands above 45 GHz. [IEEE802.11ay]

The main 802.11ax and 802.11be capabilities and their relevance to RAW are discussed in the remainder of 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 IEEE802.11ax amendment [IEEE80211ax], which includes new capabilities to increase efficiency, control and reduce latency. Some of the new features include higher order 1024-QAM modulation, support for uplink multi-user MIMO, OFDMA, trigger-based access and Target Wake time (TWT) for enhanced power savings. The OFDMA mode and trigger-based access enable scheduled operation, which is a key capability required to support deterministic latency 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 is expected to be open to unlicensed use by the FCC and other regulatory agencies worldwide.

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

802.11ax introduced a new orthogonal frequency-division multiple access (OFDMA) mode in which multiple users can be scheduled across the frequency domain. In this mode, the Access Point (AP) can initiate multi-user (MU) 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, and it can remove contention between devices for uplink transmissions, therefore reducing the randomness caused by CSMA-based access between stations. 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.

4.2.1.2. Improved PHY Robustness

The 802.11ax PHY can operate with 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 to operate with smaller resource units (e.g. 2 MHz) enabled by OFDMA also helps reduce noise power and improve 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.

4.2.1.3. Support for 6GHz band

The 802.11ax specification [IEEE80211ax] includes support for operation in the new 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 new 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 802.11 working group has already incorporated support for several TSN capabilities, so that time-sensitive flow can experience precise time synchronization and timeliness when operating over 802.11 links. 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 IEEE802.1Q bridges
3. Time-sensitive Traffic Stream identification

The exiting 802.11 TSN capabilities listed above, and the 802.11ax OFDMA and scheduled access provide a new set of tools to better server time-sensitive flows. However, it is important to understand the tradeoffs 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 under a managed network (e.g. industrial/enterprise network). Thus, the Wi-Fi operation must also be carefully managed and integrated with the overall TSN management framework, as defined in the IEEE Std. 802.1Qcc specification [IEEE8021Qcc].

Some of the random-access latency and interference from legacy/unmanaged devices can be minimized under a centralized management mode as defined in IEEE Std. 802.1Qcc, in which admission control procedures are enforced.

Existing traffic stream identification, configuration and admission control procedures defined in IEEE Std. 802.11 QoS mechanism can be re-used. 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 802.11ax OFDMA mode introduces the possibility of assigning different RUs (frequency resources) to users within a PPDU. Several RU sizes are defined in the specification (26, 52, 106, 242, 484, 996 subcarriers). In addition, the AP can also decide on MCS and grouping of users within a given OFDMA 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.

As shown in [Cavalcanti_2019], it is possible to achieve latencies in the order of 1msec with high reliability in an interference free environment. Obviously, there are latency, reliability and capacity tradeoffs to be considered. For instance, smaller Resource Units (RU)s result in longer transmission durations, which may impact the minimal latency that can be achieved, but the contention latency and randomness elimination 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

The 802.11be is the next major 802.11 amendment (after 802.11ax) for operation in the 2.4, 5 and 6 GHz bands. 802.11be is expected to include 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 802.11be Task Group started its operation in May 2019, therefore, detailed information about specific features is not yet available. Only high level candidate features have been discussed so far, including:

1. 320MHz bandwidth and more efficient utilization of non-contiguous spectrum.
2. Multi-band/multi-channel aggregation and operation.
3. 16 spatial streams and related MIMO enhancements.
4. Multi-Access Point (AP) Coordination.
5. Enhanced link adaptation and retransmission protocol, e.g. Hybrid Automatic Repeat Request (HARQ).
6. Any required adaptations to regulatory rules for the 6 GHz spectrum.

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.

802.11be is expected to build on and enhance 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 will leverage the trigger-based scheduled operation enabled by 802.11ax to provide efficient and more predictable medium access. 802.11be is expected to include enhancements to reduce overhead and enable more efficient operation in managed network deployments [IEEE_doc_11-19-0373-00].

4.3.2.2. Multi-AP coordination

Multi-AP coordination is one of the main new candidate features in 802.11be. It can provide benefits in throughput and capacity and has the potential to address some of the issues that impact worst case latency and reliability. Multi-AP coordination is expected to

address the contention due to overlapping Basic Service Sets (OBSS), which is one of the main sources of random latency variations. 802.11be can define methods to enable better coordination between APs, for instance, in a managed network scenario, in order to reduce latency due to unmanaged contention.

Several multi-AP coordination approaches have been discussed with different levels of complexities and benefits, but specific coordination methods have not yet been defined.

4.3.2.3. Multi-band operation

802.11be will introduce new features to improve operation over multiple bands and channels. By leveraging multiple bands/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 bands/channels to isolate time-sensitive traffic from other traffic and help achieve bounded latency.

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, 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 include a scheduled access mode in which stations can be allocated contention-free service periods by a central controller. 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. 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

5.1. Provenance and Documents

The IEEE802.15.4 Task Group has been driving the development of low-power low-cost radio technology. The IEEE802.15.4 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. IEEE802.15.4 uses spread spectrum modulation such as the Direct Sequence Spread Spectrum (DSSS).

The Timeslotted Channel Hopping (TSCH) mode was added to the 2015 revision of the IEEE802.15.4 standard [IEEE802154]. TSCH is targeted at the embedded and industrial world, where reliability, energy consumption and cost drive the application space.

At the IETF, the 6TiSCH Working Group (WG) [TiSCH] deals with best effort operation of IPv6 [RFC8200] over TSCH. 6TiSCH has enabled distributed scheduling to exploit the deterministic access capabilities provided by TSCH. The group designed the essential mechanisms to enable the management plane operation while ensuring IPv6 is supported. Yet the charter did not focus to providing a solution to establish end to end Tracks while meeting quality of service requirements. 6TiSCH, through the RFC8480 [RFC8480] defines the 6P protocol which 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 a Scheduling Function (SF), the policy that decides how to maintain cells and trigger 6P transactions. The Minimal Scheduling Function (MSF) [I-D.ietf-6tisch-msf] is the default SF defined by the 6TiSCH WG; other standardized SFs can be defined in

the future. MSF extends the minimal schedule configuration, and is used to add child-parent links according to the traffic load.

Time sensitive networking on low power constrained wireless networks have 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 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. Compared to that state of the art, work at the IETF and in particular at RAW could provide additional techniques such as optimized P2P routing, PAREO functions, and end-to-end secured IPv6/CoAP connectivity.

The 6TiSCH architecture [I-D.ietf-6tisch-architecture] identifies different models to schedule resources along so-called Tracks (see Section 5.2.2.2) exploiting the TSCH schedule structure however the focus at 6TiSCH is on best effort traffic and the group was never chartered to produce standard work related to Tracks.

Useful References include:

1. IEEE Std 802.15.4: "IEEE Std. 802.15.4, Part. 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks" [IEEE802154]. The latest version at the time of this writing is dated year 2015.
2. Morell, A. , Vilajosana, X. , Vicario, J. L. and Watteyne, T. (2013), Label switching over IEEE802.15.4e networks. Trans. Emerging Tel. Tech., 24: 458-475. doi:10.1002/ett.2650" [morell13].
3. De Armas, J., Tuset, P., Chang, T., Adelantado, F., Watteyne, T., Vilajosana, X. (2016, September). Determinism through path diversity: Why packet replication makes sense. In 2016 International Conference on Intelligent Networking and Collaborative Systems (INCoS) (pp. 150-154). IEEE. [dearmas16].
4. X. Vilajosana, T. Watteyne, M. Vucinic, T. Chang and K. S. J. Pister, "6TiSCH: Industrial Performance for IPv6 Internet-of-Things Networks," in Proceedings of the IEEE, vol. 107, no. 6, pp. 1153-1165, June 2019. [vilajosana19].

5.2. TimeSlotted Channel Hopping

5.2.1. General Characteristics

As a core technique in IEEE802.15.4, TSCH splits time in multiple time slots that repeat over time. A set of timeslots constructs a Slotframe (see Section 5.2.2.1.4). For each timeslot, a set of available frequencies can be used, resulting in a matrix-like schedule (see Figure 1).

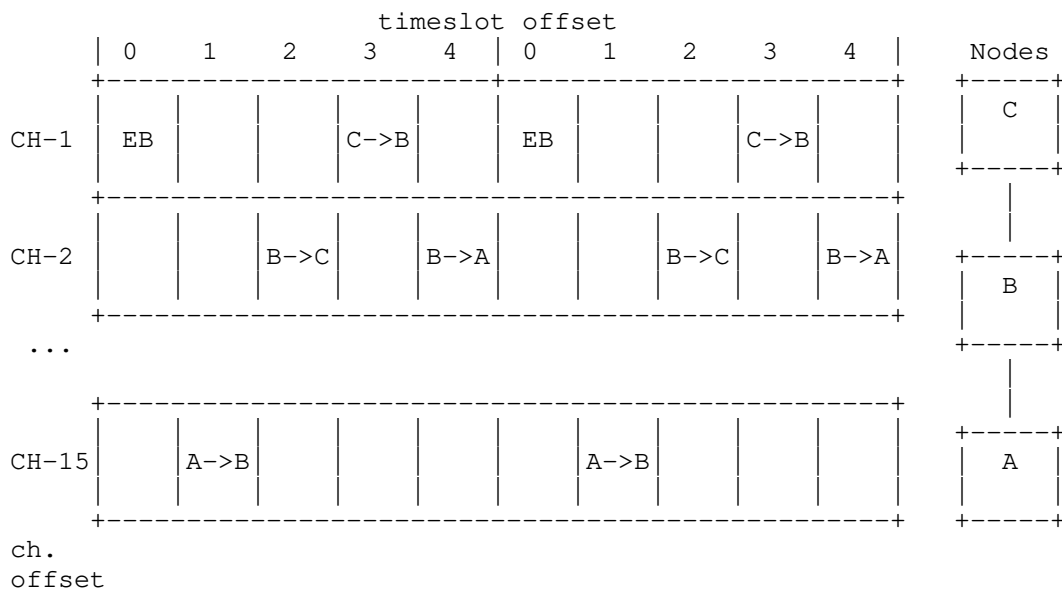


Figure 1: Slotframe example with scheduled cells between nodes A, B and C

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) [I-D.ietf-6tisch-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 which 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 multi-path fading

and external interference. It is handled by TSCH through a channel hopping sequence referred as macHopSeq in the IEEE802.15.4 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 to OFDM modulations also supported by the IEEE802.15.4 standard [IEEE802154] since the 2015 version.

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 defined by the RFC5673 [RFC5673]. As a low power technology targeting industrial scenarios radio transducers provide low data rates (typically between 50kbps to 250kbps) 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.

5.2.2. Applicability to Deterministic Flows

Nodes in a TSCH network are tightly synchronized. This enables to build the slotted structure and ensure efficient utilization of resources thanks to proper scheduling policies. Scheduling is a 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 overprovisionned cells to measureth excursion. Along a Track, 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 overprovisionning resources, giving time to the management plane of the network to dedicate more resources if needed.

5.2.2.1. Centralized Path Computation

In a controlled environment, 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 an Human/Machine Interface (HMI) iprovides the Traffic Specification, in particular in terms of latency and reliability, and the end nodes, to a Path Computation element (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. In Figure 2, an example of Operational Control System and HMI is depicted.

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 programing of the schedule is done over CoAP as discussed in "6TiSCH Resource Management and Interaction using CoAP" [I-D.ietf-6tisch-coap].

But an 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, say, Packet Delivery Ratio (PDR). 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. 6TiSCH provides means for a device to negotiate a timeSlot with a neighbor, but in general that flow was not designed and no protocol was selected and it is expected that DetNet will determine the appropriate end-to-end protocols to be used in that case.

Stream Management Entity

Operational Control System and HMI

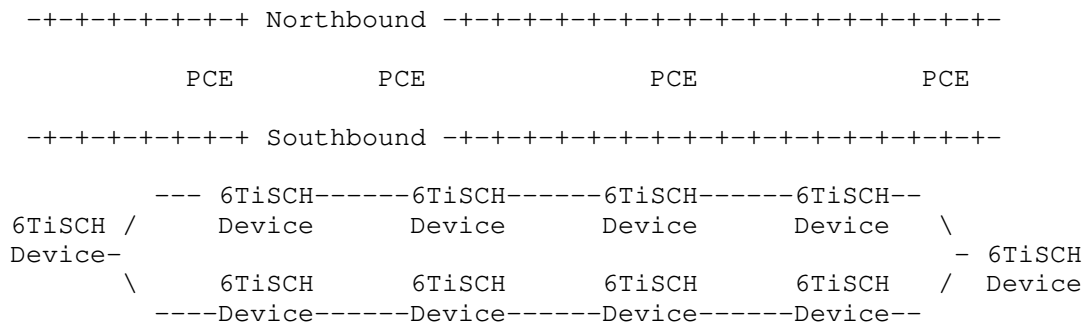


Figure 2

5.2.2.1.1. Packet Marking and Handling

Section "Packet Marking and Handling" of [I-D.ietf-6tisch-architecture] describes the packet tagging and marking that is expected in 6TiSCH networks.

5.2.2.1.1.1. Tagging Packets for Flow Identification

For packets that are routed by a PCE along a Track, the tuple formed by the IPv6 source address and a local RPLInstanceID is tagged in the packets to identify uniquely the Track and associated transmit bundle of timeSlots.

It results that the tagging that is used for a DetNet flow outside the 6TiSCH LLN MUST be swapped into 6TiSCH formats and back as the packet enters and then leaves the 6TiSCH network.

Note: The method and format used for encoding the RPLInstanceID at 6lo is generalized to all 6TiSCH topological Instances, which includes Tracks.

5.2.2.1.1.2. Replication, Retries and Elimination

PRE establishes several 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.

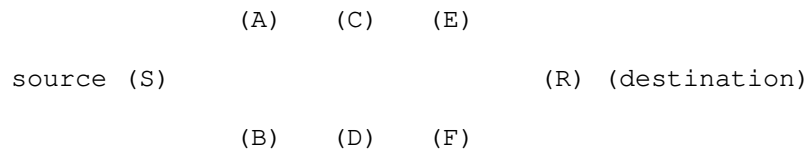


Figure 3: A Typical Ladder Shape with Two Parallel Paths Toward the Destination

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.

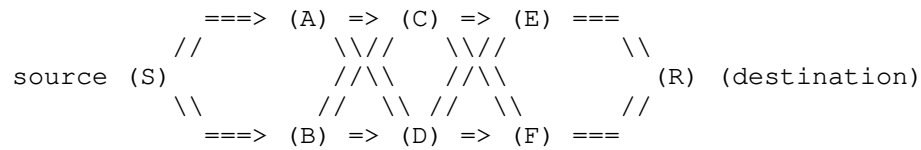


Figure 4: Packet Replication: S transmits twice the same data packet, to its DP (A) and to its AP (B).

By employing Packet Elimination function once a node receives the first copy of a data packet, it 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 this 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 a 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 respectively receive) with a 'OR' relations, and then a 'AND' relation MUST be configurable between groups. The semantics is that if the transmit (and respectively receive) operation succeeded in one timeSlot in a '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.

On the transmit side, timeSlots provisioned for retries along a same branch of a Track are placed a same 'OR' group. The 'OR' relation indicates that if a transmission is acknowledged, then further transmissions SHOULD NOT be attempted for timeSlots in that group. There are as many 'OR' groups as there are branches of the Track departing from this node. Different 'OR' groups are programmed for the purpose of replication, each group corresponding to one branch of the Track. The 'AND' relation between the groups indicates that transmission over any of branches MUST be attempted regardless of

whether a transmission succeeded in another branch. It is also possible to place cells to different next-hop routers in a same 'OR' group. This allows to route along multi-path Tracks, trying one next-hop and then another only if sending to the first fails.

On the receive side, all timeSlots are programmed in a same 'OR' group. Retries of a same copy as well as converging branches for elimination are converged, meaning that the first successful reception is enough and that all the other timeSlots can be ignored.

5.2.2.1.1.3. Differentiated Services Per-Hop-Behavior

Additionally, an IP packet that is sent along a Track uses the Differentiated Services Per-Hop-Behavior Group called Deterministic Forwarding, as described in [I-D.svshah-tsvwg-deterministic-forwarding].

5.2.2.1.2. Topology and capabilities

6TiSCH nodes are usually IoT devices, characterized by 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 number 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 mechanism such as Enhanced Beacons, but, though the neighbor information is available in the 6TiSCH interface data model, 6TiSCH does not describe a protocol to pro-actively 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 as used for RPL operations [RFC6551].

The energy that the device consumes in sleep, transmit and receive modes can be evaluated and reported. So can the amount of energy that is stored in the device and the power that it 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 balance between nodes, ensure that the spent energy does not exceeded the scavenged energy over a period of time, etc...

5.2.2.1.3. Schedule Management by a PCE

6TiSCH supports a mixed model of centralized routes and distributed routes. Centralized routes can for example be computed by a 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 a 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 a 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.

5.2.2.1.4. SlotFrames and Priorities

A slotFrame is the base object that a PCE needs to manipulate to program a schedule into an LLN node. Elaboration on that concept can be found in section "SlotFrames and Priorities" of [I-D.ietf-6tisch-architecture]

IEEE802.15.4 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 an 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 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 architecture.

The frequency used by a cell in the matrix rotates in a pseudo-random fashion, from an initial position at an epoch time, as the matrix iterates over and over.

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.

In a given network, there might be multiple CDU matrices that operate with different width, so they have different durations and represent different periodic operations. It is recommended that all CDU matrices in a 6TiSCH domain operate with the same cell duration and

are aligned, so as to reduce the chances of interferences from slotted-aloah operations. The PCE MUST compute the CDU matrices and shared that knowledge with all the nodes. The matrices are used in particular to define slotFrames.

A slotFrame is a MAC-level abstraction that is common to all nodes and contains a series of timeSlots of equal length and precedence. It is characterized by a slotFrame_ID, and a slotFrame_size. A slotFrame aligns to a CDU matrix for its parameters, such as number and duration of timeSlots.

Multiple slotFrames can coexist in a node schedule, i.e., a node can have multiple activities scheduled in different slotFrames, based on the precedence of the 6TiSCH topologies. The slotFrames may be aligned to different CDU matrices and thus have different width. There is typically one slotFrame for scheduled traffic that has the highest precedence and one or more slotFrame(s) for RPL traffic. The timeSlots in the slotFrame are indexed by the SlotOffset; the first cell is at SlotOffset 0.

The 6TiSCH architecture introduces the concept of chunks ([I-D.ietf-6tisch-architecture]) to operate such spectrum distribution for a whole group of cells at a time. The CDU matrix is formatted into a set of chunks, each of them identified uniquely by a chunk-ID, see Figure 5. The PCE MUST compute the partitioning of CDU matrices into chunks and shared that knowledge with all the nodes in a 6TiSCH network.

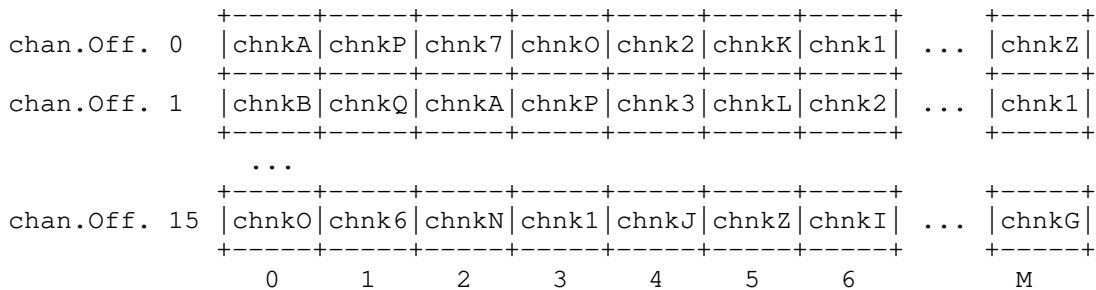


Figure 5: CDU matrix Partitioning in Chunks

The appropriation of a chunk can be requested explicitly by the PCE to any node. After a successful appropriation, the PCE owns the cells in that chunk, and may use them as hard cells to set up Tracks. Then again, 6TiSCH did not propose a method for chunk definition and a protocol for appropriation. This is to be done at RAW.

5.2.2.2. 6TiSCH Tracks

A Track at 6TiSCH is the application to wireless of the concept of a path in the Detnet architecture [I-D.ietf-detnet-architecture]. A Track can follow a simple sequence of relay nodes or 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 taking routing decisions at the 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 through the multi-hop topology. For example, A bundle of Tx Cells in a particular node is paired to a bundle of Rx Cells in the next hop node following a routing path.

Whereas scheduling ensures reliable delivery in bounded time along any Track, high availability requires the application of PAREO functions along a more complex DODAG Track structure. A DODAG has forking and joining nodes where the concepts such as Replication and Elimination can be exploited. Spatial redundancy increases the overall energy consumption in the network but improves significantly the availability of the network as well as the packet delivery ratio. A Track may also branch off and rejoin, for the purpose of the so-called Packet Replication and Elimination (PRE), over non congruent branches. PRE may be used to complement layer-2 Automatic Repeat reQuest (ARQ) and receiver-end Ordering to form the PAREO functions. PAREO functions enable to meet industrial expectations in PDR within bounded delivery time over a Track that includes wireless links, even when the Track extends beyond the 6TiSCH network.

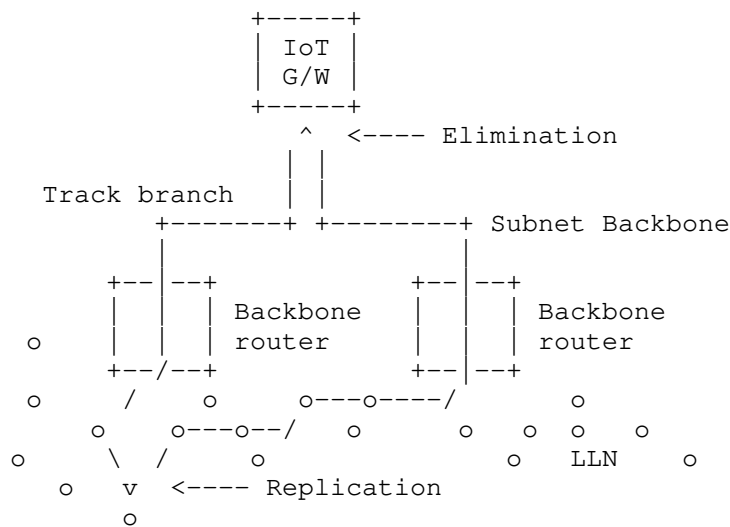


Figure 6: End-to-End deterministic Track

In the example above (see Figure 6), a Track is laid out from a field device in a 6TiSCH network to an IoT gateway that is located on a IEEE802.1 TSN backbone.

The Replication function in the field device sends a copy of each packet over two different branches, and 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 that the field device only uses the second branch if sending over the first branch fails.

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

Methods to implement complex Tracks are described in [I-D.papadopoulos-paw-pre-reqs] and complemented by extensions to the RPL routing protocol in [I-D.ietf-roll-nsa-extension] for best effort traffic, but a centralized routing technique such as promoted in DetNet is still missing.

5.2.2.2.1. Track Scheduling Protocol

Section "Schedule Management Mechanisms" of the 6TiSCH architecture describes 4 paradigms to manage the TSCH schedule of the 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.

Early work at 6TiSCH on a data model and a protocol to program the schedule in the 6TiSCH device was never concluded as the group focussed on best effort traffic. This work would be revived by RAW:

The 6top interface document [RFC8480] (to be reopened at RAW) was intended to specify the generic data model that can be used to monitor and manage resources of the 6top sublayer. Abstract methods were suggested for use by a management entity in the device. The data model also enables remote control operations on the 6top sublayer.

[I-D.ietf-6tisch-coap] (to be reopened at RAW) was intended to define a mapping of the 6top set of commands, which is described in RFC 8480, to CoAP resources. This allows an entity to interact with the 6top layer of a node that is multiple hops away in a RESTful fashion.

[I-D.ietf-6tisch-coap] also defined a basic set CoAP resources and associated RESTful access methods (GET/PUT/POST/DELETE). The payload (body) of the CoAP messages is encoded using the CBOR format. The PCE commands are expected to be issued directly as CoAP requests or to be mapped back and forth into CoAP by a gateway function at the edge of the 6TiSCH network. For instance, it is possible that a mapping entity on the backbone transforms a non-CoAP protocol such as PCEP into the RESTful interfaces that the 6TiSCH devices support.

5.2.2.2.2. Track Forwarding

By forwarding, this specification means the per-packet operation that allows to deliver a packet to a next hop or an upper layer in this node. Forwarding is based on pre-existing state that was installed as a result of the routing computation of a Track by a PCE. The

6TiSCH architecture supports three different forwarding model, G-MPLS Track Forwarding (TF), 6LoWPAN Fragment Forwarding (FF) and IPv6 Forwarding (6F) which is the classical IP operation [I-D.ietf-6tisch-architecture]. 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. In a Track cell, the normal operation of IEEE802.15.4 Automatic Repeat-reQuest (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 Multi-protocol Label Switching (G-MPLS) operation in that the information used to switch a frame is not an explicit label, but rather related to other properties of 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 IEEE802.15.4, this means effectively broadcast, so that along the Track the short address for the destination of the frame is set to 0xFFFF.

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, and a cell in such a bundle belongs to at most one Track. For a given iteration of the device schedule, the effective channel of the cell is obtained by adding a pseudo-random number to the channelOffset of the cell, which results in a rotation of the frequency that 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 follows:

In 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 frame 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 a 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 to 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. But 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-Track, and to place it back on the appropriate bundle if possible. A frame should be re-Track 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 5.2.2.1.1. A frame is re-Track by scheduling it for transmission over the transmit bundle associated to the Track, with the destination MAC address set to broadcast.

There are 2 modes for a Track, transport mode and tunnel mode.

5.2.2.2.2.1. Transport Mode

In transport mode, the Protocol Data Unit (PDU) is associated with flow-dependant meta-data that refers uniquely to the Track, so the 6top sublayer can place the frame in the appropriate cell without ambiguity. In the case of IPv6 traffic, this flow identification is transported in the Flow Label of the IPv6 header. Associated with the source IPv6 address, the Flow Label forms a globally unique identifier for that particular Track that is validated at egress

before restoring the destination MAC address (DMAC) and punting to the upper layer.

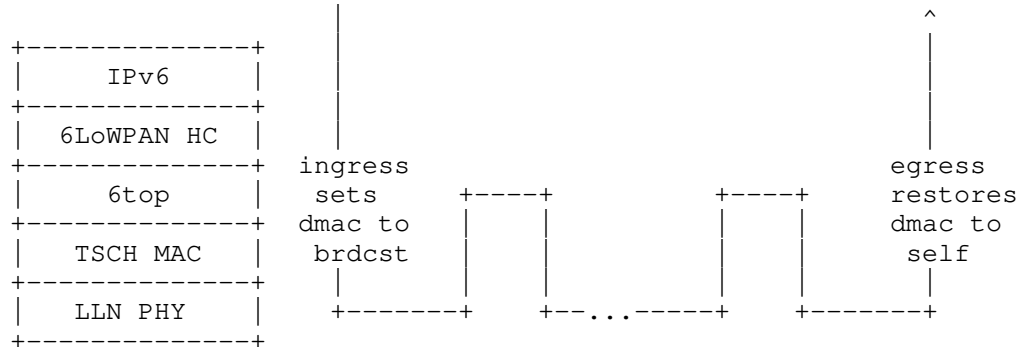


Figure 7: Track Forwarding, Transport Mode

5.2.2.2.2. Tunnel Mode

In tunnel mode, the frames originate from an arbitrary protocol over a compatible MAC that may or may not be synchronized with the 6TiSCH network. An example of this would be a router with a dual radio that is capable of receiving and sending WirelessHART or ISA100.11a frames with the second radio, by presenting itself as an Access Point or a Backbone Router, respectively.

In that mode, some entity (e.g. PCE) can coordinate with a WirelessHART Network Manager or an ISA100.11a System Manager to specify the flows that are to be transported transparently over the Track.

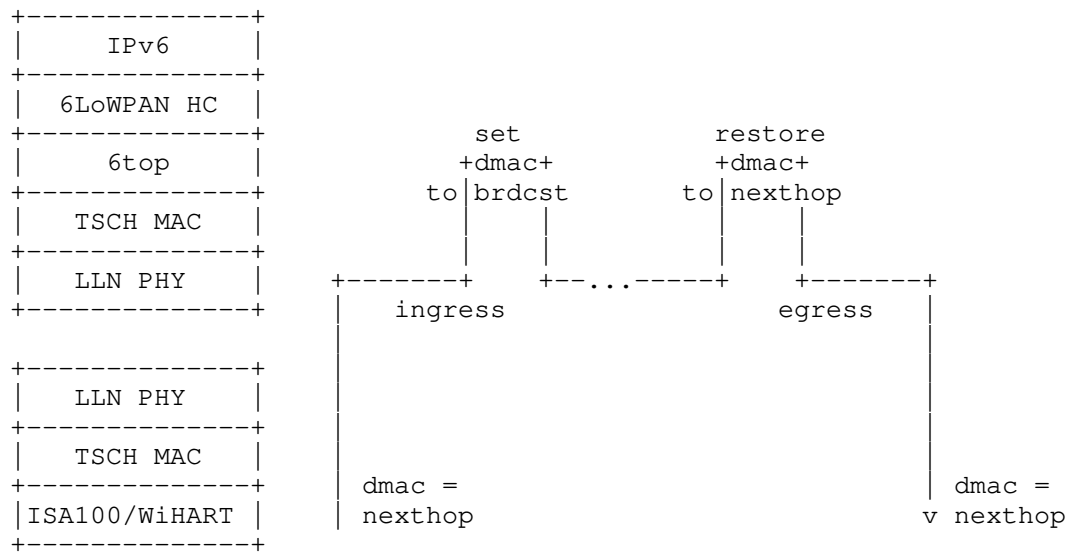


Figure 8: Track Forwarding, Tunnel Mode

In that case, the flow information that identifies the Track at the ingress 6TiSCH router is derived from the RX-cell. The dmac is set to this node but the flow information indicates that the frame must be tunneled over a particular Track so the frame is not passed to the upper layer. Instead, the dmac is forced to broadcast and the frame is passed to the 6top sublayer for switching.

At the egress 6TiSCH router, the reverse operation occurs. Based on metadata associated to the Track, the frame is passed to the appropriate link layer with the destination MAC restored.

5.2.2.2.2.3. Tunnel Metadata

Metadata coming with the Track configuration is expected to provide the destination MAC address of the egress endpoint as well as the tunnel mode and specific data depending on the mode, for instance a service access point for frame delivery at egress. If the tunnel egress point does not have a MAC address that matches the configuration, the Track installation fails.

In transport mode, if the final layer-3 destination is the tunnel termination, then it is possible that the IPv6 address of the destination is compressed at the 6LoWPAN sublayer based on the MAC address. It is thus mandatory at the ingress point to validate that the MAC address that was used at the 6LoWPAN sublayer for compression matches that of the tunnel egress point. For that reason, the node

that injects a packet on a Track checks that the destination is effectively that of the tunnel egress point before it overwrites it to broadcast. The 6top sublayer at the tunnel egress point reverts that operation to the MAC address obtained from the tunnel metadata.

5.2.2.2.2.4. 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 BIER [RFC8279] and more specifically BIER Traffic Engineering [I-D.ietf-bier-te-arch] (BIER-TE): [I-D.thubert-bier-replication-elimination] leverages BIER-TE to control the process of PREF, and to provide traceability of these operations, in the deterministic dataplane, along a complex Track. For the 6TiSCH type of constrained environment, [I-D.thubert-6lo-bier-dispatch] enables an efficient encoding of the BIER bitmap within the 6LoRH framework.

6. 3GPP Ultra-Reliable Low-Latency Communication

coming up

7. L-band Digital Aeronautical Communications System

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 are suffering from the VHF band's increasing saturation in high-density areas and the limitations posed by analogue radio. Therefore, aviation globally and 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 analogue VHF voice and VDL2 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 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.

7.1. Provenance and Documents

The development of LDACS has already made substantial progress in the Single European Sky ATM Research (SESAR) framework, and 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 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 fulfil the identified requirements [GRA11].

LDACS standardization within the framework of the International Civil Aviation Organization (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. The ICAO standardization group plans to produce an ICAO technical manual - the ICAO equivalent to a technical standard - within the next years. Generally, the group is open to input from all sources and develops LDACS in the open.

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 quality of service, diversity, and mobility under the umbrella of the "multi-link concept". This work is conducted by ICAO working group WG-I.

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][SCH19].

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 them

providing 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. A ground-station supports up to 512 aircraft.

The LDACS air interface protocol stack defines two layers, the physical layer and the data link layer.

The physical layer provides the means to transfer data over the radio channel. The LDACS ground-station supports bi-directional links to multiple aircraft under its control. The forward link direction (FL; ground-to-air) and the reverse link direction (RL; 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 aircraft are separated in time and frequency using a combination of Orthogonal Frequency-Division Multiple-Access (OFDMA) and Time-Division Multiple-Access (TDMA). Aircraft thus transmit discontinuously on the reverse link with radio bursts sent in precisely defined transmission opportunities allocated by the ground-station. LDACS does not support beam-forming or Multiple Input Multiple Output (MIMO).

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 sub-layers: The medium access sub-layer and the logical link control sub-layer. The medium access sub-layer manages the organization of transmission opportunities in slots of time and frequency. The logical link control sub-layer provides acknowledged point-to-point logical channels between the aircraft and the ground-station using an automatic repeat request protocol. LDACS supports also unacknowledged point-to-point channels and ground-to-air broadcast.

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. 315/294 kbit/s on the forward/reverse link, respectively.

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 [MAE19].

7.3. Applicability to Deterministic Flows

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).

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" 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 (Dedicated Control Channel (DCCH); roughly 83 bit 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 in 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 message always go first in any case. Scheduling of reverse link resources is done in physical Protocol Data Units (PDU) of 112 bit (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) if it is connected to an alternative ground-station via the same ground-station controller. Beyond this, FCI diversity shall be implemented by the multi-link concept.

8. IANA Considerations

This specification does not require IANA action.

9. Security Considerations

Most RAW technologies integrate some authentication or encryption mechanisms that were defined outside the IETF.

10. Contributors

Georgios Z. Papadopoulos: Contributed to the TSCH section.

Nils Maeurer: Contributed to the LDACS section.

Thomas Graeupl: Contributed to the LDACS section.

11. Acknowledgments

Many thanks to the participants of the RAW WG where a lot of the work discussed here happened.

12. References

12.1. Normative References

[I-D.ietf-6tisch-architecture]

Thubert, P., "An Architecture for IPv6 over the TSCH mode of IEEE 802.15.4", draft-ietf-6tisch-architecture-23 (work in progress), June 2019.

[I-D.ietf-detnet-architecture]

Finn, N., Thubert, P., Varga, B., and J. Farkas, "Deterministic Networking Architecture", draft-ietf-detnet-architecture-13 (work in progress), May 2019.

[RFC5673]

Pister, K., Ed., Thubert, P., Ed., Dwars, S., and T. Phinney, "Industrial Routing Requirements in Low-Power and Lossy Networks", RFC 5673, DOI 10.17487/RFC5673, October 2009, <<https://www.rfc-editor.org/info/rfc5673>>.

- [RFC8200] Deering, S. and R. Hinden, "Internet Protocol, Version 6 (IPv6) Specification", STD 86, RFC 8200, DOI 10.17487/RFC8200, July 2017, <<https://www.rfc-editor.org/info/rfc8200>>.
- [RFC8480] Wang, Q., Ed., Vilajosana, X., and T. Watteyne, "6TiSCH Operation Sublayer (6top) Protocol (6P)", RFC 8480, DOI 10.17487/RFC8480, November 2018, <<https://www.rfc-editor.org/info/rfc8480>>.

12.2. Informative References

- [Cavalcanti_2019] Dave Cavalcanti et al., "Extending Time Distribution and Timeliness Capabilities over the Air to Enable Future Wireless Industrial Automation Systems, the Proceedings of IEEE", June 2019.
- [CCAMP] IETF, "Common Control and Measurement Plane", <<https://dataTracker.ietf.org/doc/charter-ietf-ccamp/>>.
- [dearmas16] Jessica de Armas et al., "Determinism through path diversity: Why packet replication makes sense", September 2016.
- [Ghasempour_2017] Yasaman Ghasempour et al., "802.11ay: Next-Generation 60 GHz Communications for 100 Gb/s Wi-Fi", December 2017.
- [GRA11] Graeupl, T. and M. Ehammer, "L-DACS1 Data Link Layer Evolution of ATN/IPS", Proceedings of the 30th IEEE/AIAA Digital Avionics Systems Conference (DASC) Seattle, WA, USA, October 2011.
- [GRA18] al., T. G. E., "L-band Digital Aeronautical Communications System (LDACS) flight trials in the national German project MICONAV", Proceedings of the Integrated Communications, Navigation, Surveillance Conference (ICNS) Herndon, VA, USA, April 2018.
- [GRA19] Graeupl, T., Rihacek, C., and B. Haindl, "LDACS A/G Specification", SESAR2020 PJ14-02-01 D3.3.010, February 2019.

- [I-D.ietf-6tisch-coap]
Sudhaakar, R. and P. Zand, "6TiSCH Resource Management and Interaction using CoAP", draft-ietf-6tisch-coap-03 (work in progress), March 2015.
- [I-D.ietf-6tisch-msf]
Chang, T., Vucinic, M., Vilajosana, X., Duquennoy, S., and D. Dujovne, "6TiSCH Minimal Scheduling Function (MSF)", draft-ietf-6tisch-msf-03 (work in progress), April 2019.
- [I-D.ietf-bier-te-arch]
Eckert, T., Cauchie, G., Braun, W., and M. Menth, "Traffic Engineering for Bit Index Explicit Replication (BIER-TE)", draft-ietf-bier-te-arch-02 (work in progress), May 2019.
- [I-D.ietf-roll-nsa-extension]
Koutsiamanis, R., Papadopoulos, G., Montavont, N., and P. Thubert, "RPL DAG Metric Container Node State and Attribute object type extension", draft-ietf-roll-nsa-extension-03 (work in progress), June 2019.
- [I-D.papadopoulos-paw-pre-reqs]
Papadopoulos, G., Koutsiamanis, R., Montavont, N., and P. Thubert, "Exploiting Packet Replication and Elimination in Complex Tracks in LLNs", draft-papadopoulos-paw-pre-reqs-01 (work in progress), March 2019.
- [I-D.svshah-tsvwg-deterministic-forwarding]
Shah, S. and P. Thubert, "Deterministic Forwarding PHB", draft-svshah-tsvwg-deterministic-forwarding-04 (work in progress), August 2015.
- [I-D.thubert-6lo-bier-dispatch]
Thubert, P., Brodard, Z., Jiang, H., and G. Texier, "A 6loRH for BitStrings", draft-thubert-6lo-bier-dispatch-06 (work in progress), January 2019.
- [I-D.thubert-bier-replication-elimination]
Thubert, P., Eckert, T., Brodard, Z., and H. Jiang, "BIER-TE extensions for Packet Replication and Elimination Function (PREF) and OAM", draft-thubert-bier-replication-elimination-03 (work in progress), March 2018.
- [ICAO18] International Civil Aviation Organization (ICAO), "L-Band Digital Aeronautical Communication System (LDACS)", International Standards and Recommended Practices Annex 10 - Aeronautical Telecommunications, Vol. III - Communication Systems, July 2018.

- [IEEE80211]
"IEEE Standard 802.11 - IEEE Standard for Information Technology - Telecommunications and information exchange between systems Local and metropolitan area networks - Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications.".
- [IEEE80211ad]
"802.11ad: Enhancements for very high throughput in the 60 GHz band".
- [IEEE80211ak]
"802.11ak: Enhancements for Transit Links Within Bridged Networks", 2017.
- [IEEE80211ax]
"802.11ax D4.0: Enhancements for High Efficiency WLAN".
- [IEEE80211ay]
"802.11ay: Enhanced throughput for operation in license-exempt bands above 45 GHz".
- [IEEE80211be]
"802.11be: Extreme High Throughput".
- [IEEE802154]
IEEE standard for Information Technology, "IEEE Std. 802.15.4, Part. 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks".
- [IEEE8021Qat]
"802.1Qat: Stream Reservation Protocol".
- [IEEE8021Qcc]
"802.1Qcc: IEEE Standard for Local and Metropolitan Area Networks--Bridges and Bridged Networks -- Amendment 31: Stream Reservation Protocol (SRP) Enhancements and Performance Improvements".
- [IEEE_doc_11-18-2009-06]
"802.11 Real-Time Applications (RTA) Topic Interest Group (TIG) Report", November 2018.
- [IEEE_doc_11-19-0373-00]
Kevin Stanton et Al., "Time-Sensitive Applications Support in EHT", March 2019.

- [ISA100.11a] ISA/IEC, "ISA100.11a, Wireless Systems for Automation, also IEC 62734", 2011, < <http://www.isa100wci.org/en-US/Documents/PDF/3405-ISA100-WirelessSystems-Future-broch-WEB-ETSI.aspx>>.
- [MAE19] Maeurer, N. and C. Schmitt, "DLR tests digital communications technologies combined with additional navigation functions for the first time", Proceedings of the Integrated Communications, Navigation, Surveillance Conference (ICNS) Washington D.C., USA, April 2019.
- [morell113] Antoni Morell et al., "Label switching over IEEE802.15.4e networks", April 2013.
- [Nitsche_2015] Thomas Nitsche et al., "IEEE 802.11ad: directional 60 GHz communication for multi-Gigabit-per-second Wi-Fi", December 2014.
- [PCE] IETF, "Path Computation Element", <<https://dataTracker.ietf.org/doc/charter-ietf-pce/>>.
- [RFC6291] Andersson, L., van Helvoort, H., Bonica, R., Romascanu, D., and S. Mansfield, "Guidelines for the Use of the "OAM" Acronym in the IETF", BCP 161, RFC 6291, DOI 10.17487/RFC6291, June 2011, <<https://www.rfc-editor.org/info/rfc6291>>.
- [RFC6550] Winter, T., Ed., Thubert, P., Ed., Brandt, A., Hui, J., Kelsey, R., Levis, P., Pister, K., Struik, R., Vasseur, JP., and R. Alexander, "RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks", RFC 6550, DOI 10.17487/RFC6550, March 2012, <<https://www.rfc-editor.org/info/rfc6550>>.
- [RFC6551] Vasseur, JP., Ed., Kim, M., Ed., Pister, K., Dejean, N., and D. Barthel, "Routing Metrics Used for Path Calculation in Low-Power and Lossy Networks", RFC 6551, DOI 10.17487/RFC6551, March 2012, <<https://www.rfc-editor.org/info/rfc6551>>.
- [RFC7276] Mizrahi, T., Sprecher, N., Bellagamba, E., and Y. Weingarten, "An Overview of Operations, Administration, and Maintenance (OAM) Tools", RFC 7276, DOI 10.17487/RFC7276, June 2014, <<https://www.rfc-editor.org/info/rfc7276>>.

- [RFC8279] Wijnands, IJ., Ed., Rosen, E., Ed., Dolganow, A., Przygienda, T., and S. Aldrin, "Multicast Using Bit Index Explicit Replication (BIER)", RFC 8279, DOI 10.17487/RFC8279, November 2017, <<https://www.rfc-editor.org/info/rfc8279>>.
- [RIH18] Rihacek, C., Haindl, B., Fantappie, P., Pierattelli, S., Graeupl, T., Schnell, M., and N. Fistas, "L-band Digital Aeronautical Communications System (LDACS) Activities in SESAR2020", Proceedings of the Integrated Communications Navigation and Surveillance Conference (ICNS) Herndon, VA, USA, April 2018.
- [SAJ14] Sajatovic, M., Guenzel, H., and S. Mueller, "WA04 D22 Test Report for Assessing LDACS1 Transmitter Impact upon DME/TACAN Receivers", April 2014.
- [SCH19] Schnell, M., "DLR tests digital communications technologies combined with additional navigation functions for the first time", March 2019, <https://www.dlr.de/dlr/en/desktopdefault.aspx/tabid-10081/151_read-32951/#/gallery/33877>.
- [TiSCH] IETF, "IPv6 over the TSCH mode over 802.15.4", <<https://dataTracker.ietf.org/doc/charter-ietf-6tisch/>>.
- [vilajosana19] Xavier Vilajosana et al., "6TiSCH: Industrial Performance for IPv6 Internet-of-Things Networks", June 2019.
- [WirelessHART] www.hartcomm.org, "Industrial Communication Networks - Wireless Communication Network and Communication Profiles - WirelessHART - IEC 62591", 2010.

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