# Introduction to Deterministic Networks

ComNets
TUHH
Institute of Communication Networks

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# Course Contents

**Online Lectures**

- Lecture 1 - Introduction
- Lecture 2 – IEEE 802.15.4
- Lecture 3 – IETF 6TiSCH

**Physical Meeting 13th to 17th of April**

- Lecture 4 – Theoretical Analysis
- Cooja Simulations and Experiments
- Industrial visit and a talk
- Team Presentations on self learned material
- Lecture 5 – Research Project Results

More details on our padlet:
https://tuhh.padlet.org/c00zll01/enabling-industry-4-0-j88rkh1i3j7rzmv3

# Learning Outcome

**Learning objective 1: Understand Industry 4.0 challenges and IEEE 802.15.4**

You will be able to explain how TSCH mode of IEEE 802.15.4 helps to achieve strict Quality-of-Service of the industrial applications.

**Learning objective 2: Think critically about network communication in Industry 4.0**

You will be able to bridge the gap between theory and practice by applying learned methods to real-world challenges, thereby gaining a practical understanding of the concepts of network communication in Industry 4.0.

Additionally, you will develop skills in analysing and synthesising scientific research related to it, leading to a broader and deeper understanding of the field.

# Learning Outcome

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**<u>Learning objective 3:</u> Work in international, interdisciplinary teams**

You will be able to learn how to work in international, interdisciplinary teams in terms of knowing about the different roles, reflect on team dynamics, get to know tools for efficient online collaboration and how to provide constructive peer-feedback.

**<u>Learning objective 4:</u> Learn how to evaluate communication protocol performance**

You will be able to explain common performance metrics and to apply analytical modelling and simulations in Cooja. By conducting experiments in a real testbed you learn to compare measured results to expectation.

# Guidelines

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- Try to avoid the classical way of teaching
- Slides are integrated with short discussions in a team

- Discussions in smaller teams / Team based assignments
  - Try to discuss with your neighbors
  - Free to use Google, ChatGPT, etc.
  - Questions used for discussions are highlighted in pink

**Discussion questions**

- Best way to remember what you learn is to share/discuss what you know with your peers

"Though you hear the same contents, different students understand in different ways."

# Introduction:

Low Power Wireless Technologies
Industrial Applications (Industrial Internet of Things),
Deterministic Behavior, Low Power Solutions

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# Our Group

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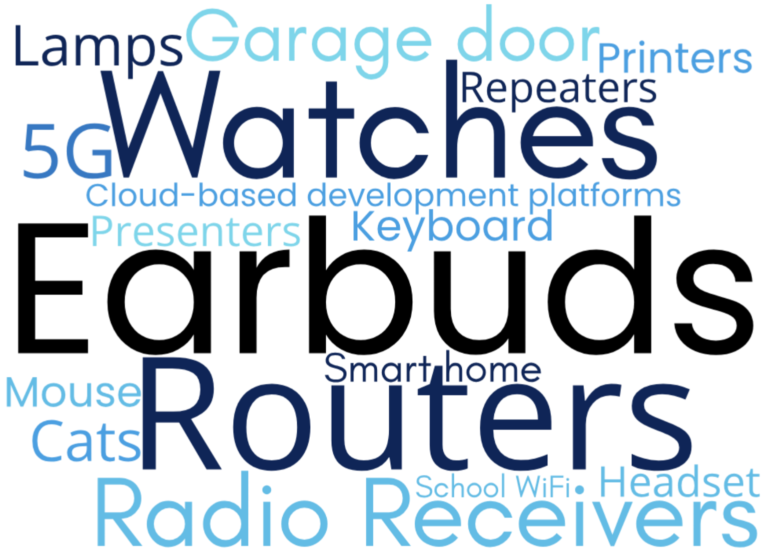
Q1: What kind of wireless technologies do you use?


Q2: What's one everyday device you wish had better wireless connectivity?



# Our Group

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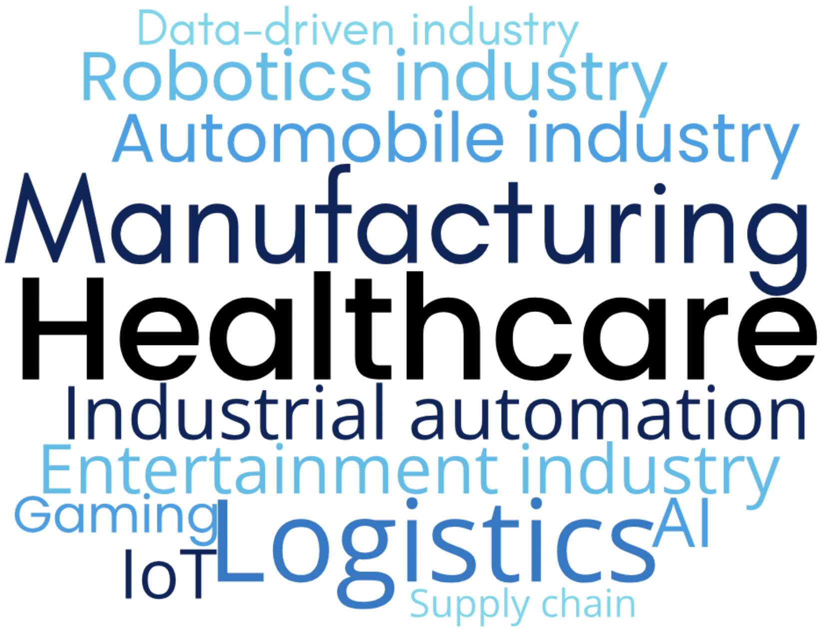
Q3: Which industry do you think will benefit the most from future wireless innovations, and why?



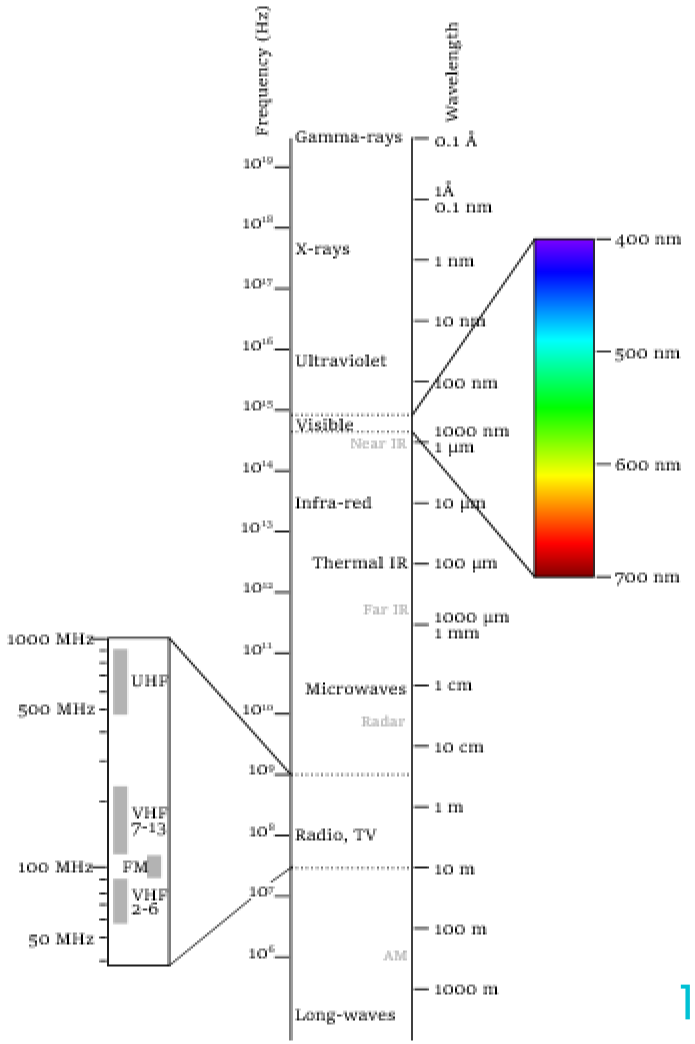
# Introduction to Wireless Communication

- Electromagnetic waves
- f = c/$\lambda$

  f = Frequency, c = speed of the light, $\lambda$ = wavelength

Transmitter

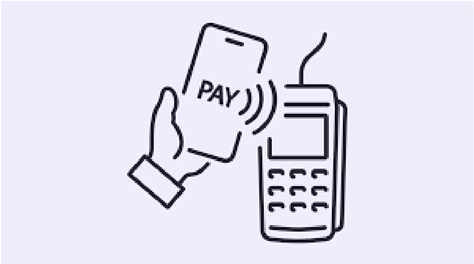
Receiver




[Electromagnetic spectrum from Wikipedia.](https://commons.wikimedia.org/w/index.php?curid=22428451)

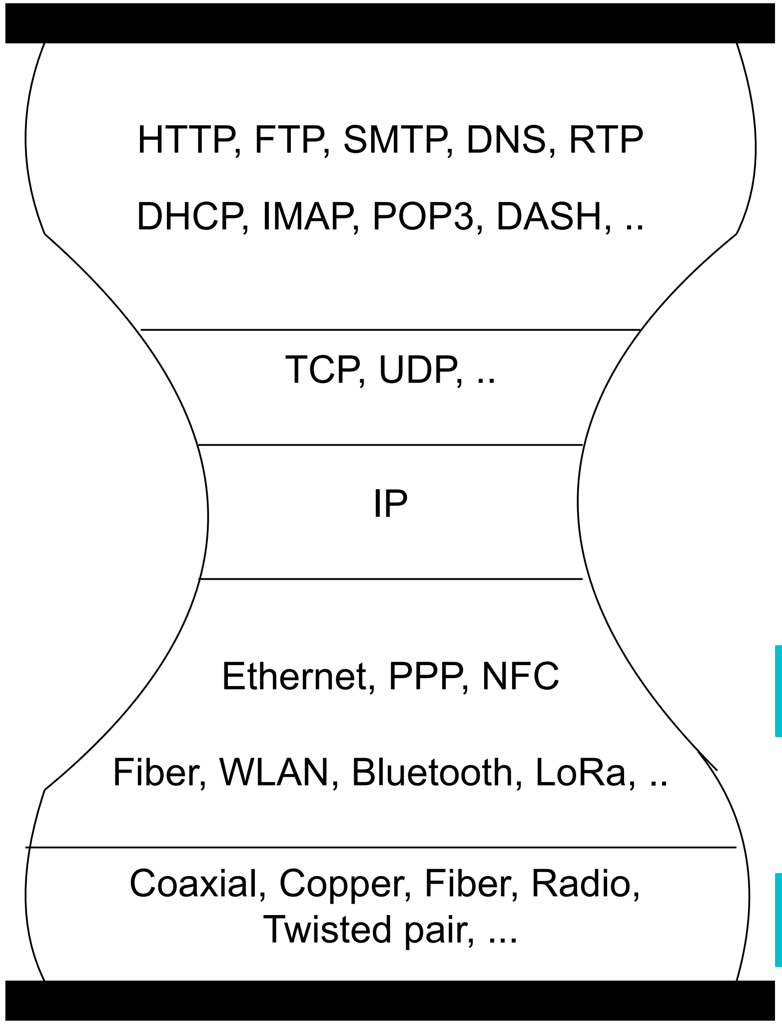
# Your Favorite Wireless Device

- Bluetooth
- Cellular
- WiFi
- NFC
- 802.15.4
- LoRa
- UWB
- RFID
- Apple airtag
- ….






# TCP/IP Protocol Stack




Application Layer

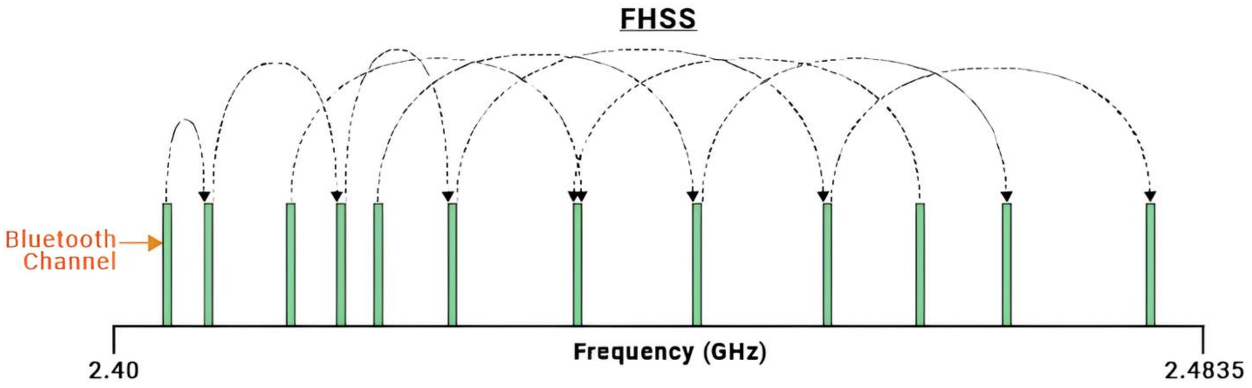
Transport Layer

Network Layer

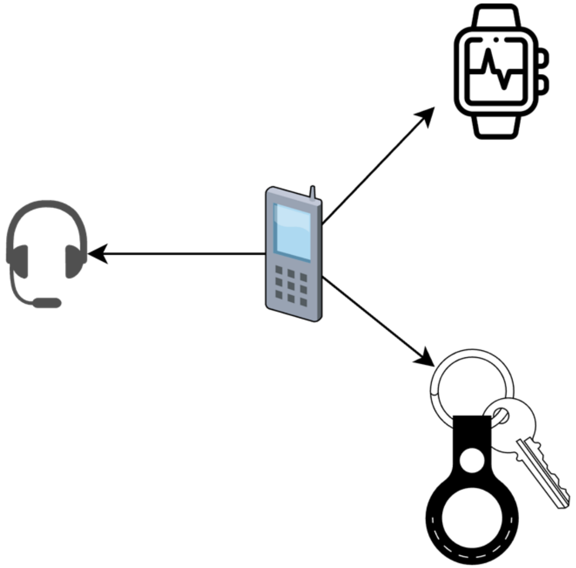
Link Layer

Physical Layer

# Bluetooth




Bluetooth Frequency Hopping Spread Spectrum (FHSS) [1]



Bluetooth piconet



[1] https://www.mathworks.com/help/wlan/ug/bluetooth_wlan_coexistence.html

# RFID - Radio-frequency identification

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- Main components
  - Tag (with microchip & antenna)
  - Reader (emits radio waves)
  - Database/System (stores & processes data)
- Steps
  - Step 1: The RFID reader sends a radio signal.
  - Step 2: The RFID tag is triggered by this signal & transmits data.
  - Step 3: The reader captures the data and sends it to a system for processing.
  - Step 4: The system identifies & records the tag information.

Range “10cm – 200m” depending on the Frequency used

# NFC – Near Field Communication

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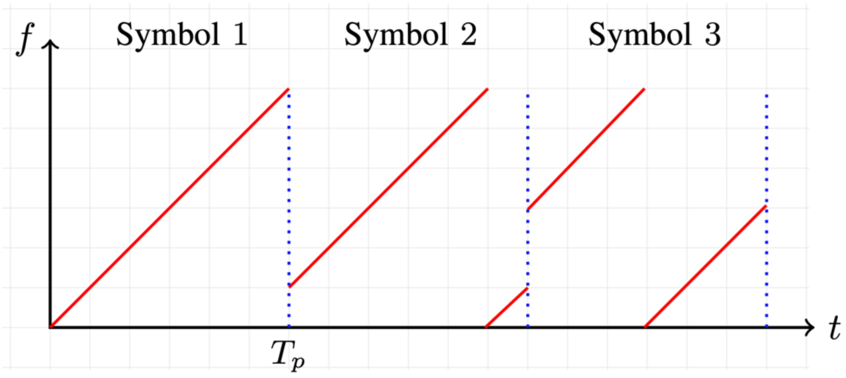
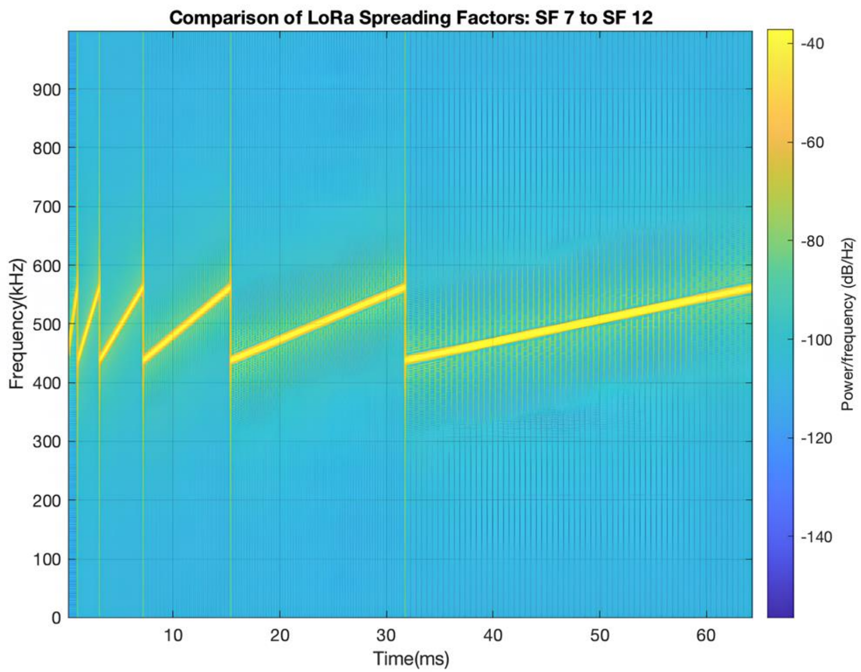
- Main components:
  - NFC Tag (Passive, stores data)
  - NFC Reader (Active, reads/writes data)
  - Smartphone or NFC-enabled device
- Steps
  - Step 1: The NFC reader (phone, terminal, or device) generates an electromagnetic field.
  - Step 2: The NFC tag gets powered by this field and transmits stored data.
  - Step 3: The reader processes this data for contactless payments, data transfer, or authentication.
  - Step 4: Secure communication completes within milliseconds.

Operates at 13.56 MHz and works within a few centimeters.

# LoRa




Encoding LoRa symbols using frequency chirps [2]

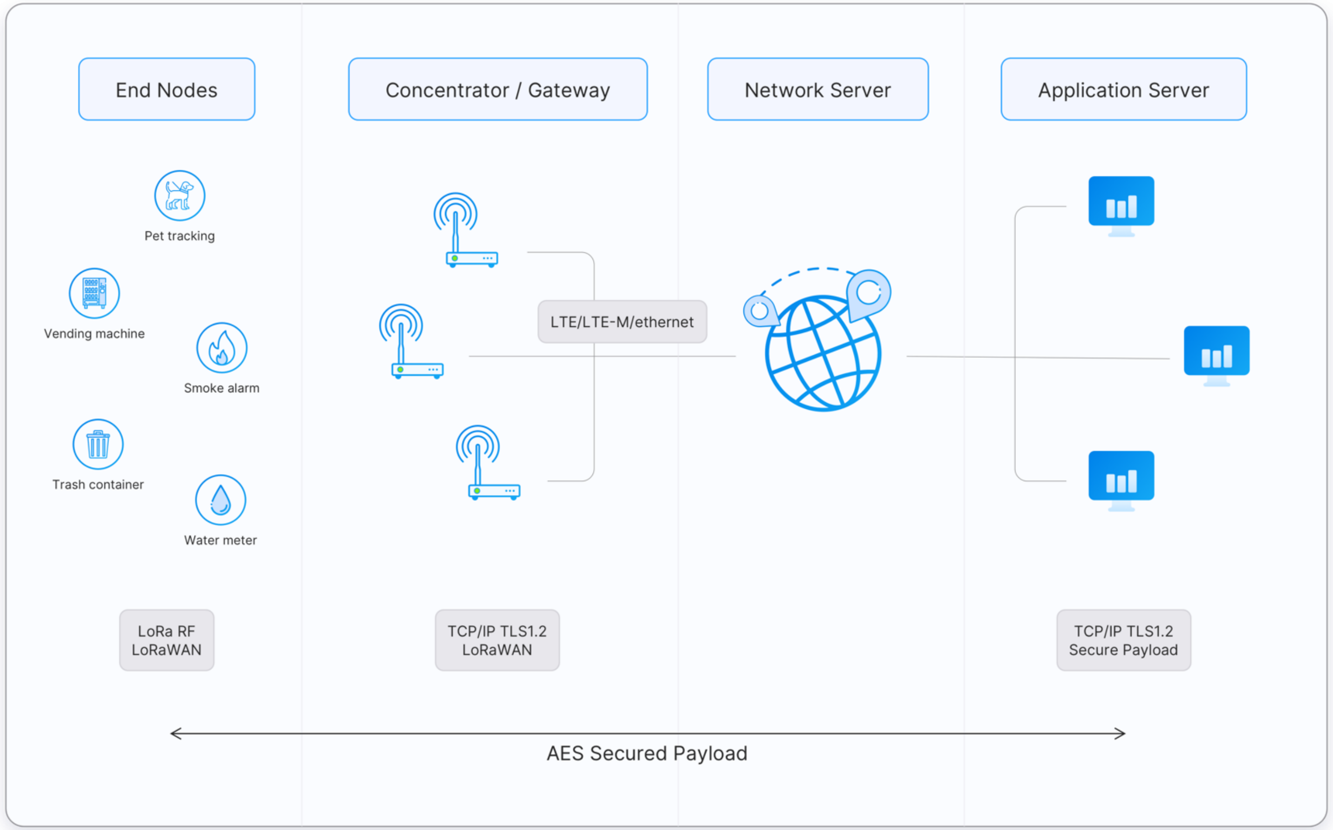



LoRa Spreading Factors compared [3]




[2] Lulu, Amro, and Bijan G. Mobasseri. "Dual-Use Chirp Spread Spectrum Waveform With Ranging Capability." *2019 IEEE Radar Conference (RadarConf)*. IEEE, 2019.
[3] Kim, Dong-Hoon, Eun-Kyu Lee, and Jibum Kim. "Experiencing LoRa network establishment on a smart energy campus testbed." *Sustainability* 11.7 (2019): 1917.

# LoRaWAN




A typical LoRaWAN network architecture [4]

[4] https://www.thethingsnetwork.org/docs/lorawan/architecture/

# Industry 4.0 (IIoT) vs Communication Network Challenges

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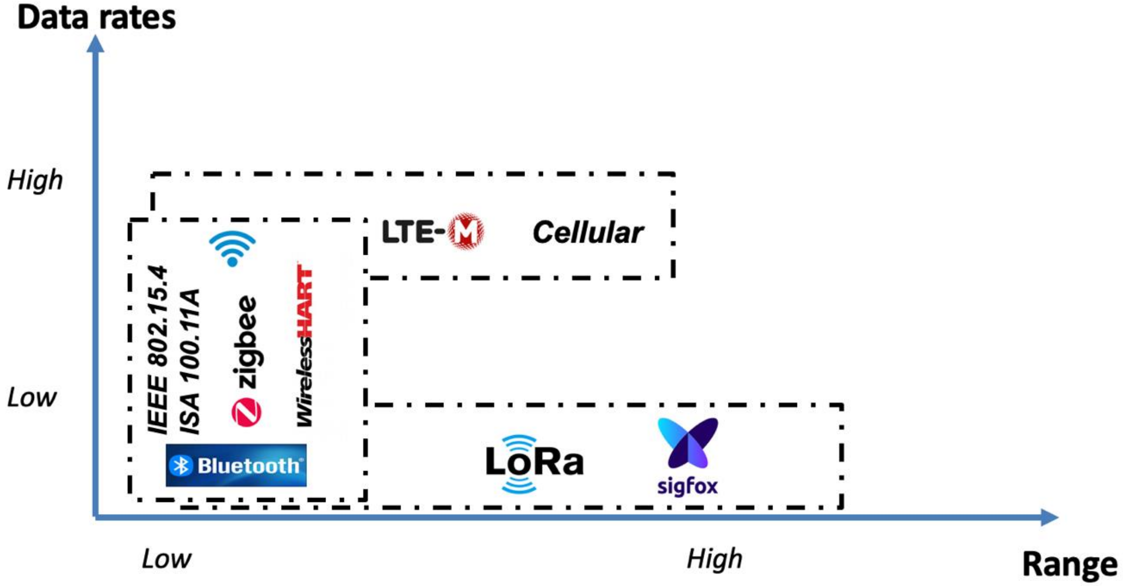


**What are the current wireless communication network challenges for industry 4.0 applications?**
**Can IEEE 802.11 based technologies (WLAN) be used for Industry 4.0 applications?**

# Industry 4.0 Application Requirements

| | | Diagnose & Wartung | | Diskrete Fertigung | | Lager und Logistik | | | Prozess-automa-tisierung | Augmen-ted Reality | Funktio-nale Sicher-heit |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Generell | Condi-tion Monito-ring | Generell | Motion Control | Generell | AGV | Kran-szenario | | | |
| Delay | Latenz (Sensor zu Controller zu Aktor) | > 20ms | 100ms | 1 ms – 12 ms | 250 µs – 1 ms | > 50 ms | 15 ms – 20 ms | 15 ms – 20 ms | 50 ms – Xs | 10 ms | 10 ms |
| Reliability | Zuverlässigkeit (i.S. „erfolgreich" innerh. der Latenzanf. ) | $1 - 10^{-4}$ | $1 - 10^{-5}$ | $1 - 10^{-9}$ | $1 - 10^{-9}$ | $> 1 - 10^{-2}$ | $> 1 - 10^{-6}$ | $> 1 - 10^{-6}$ | $1 - 10^{-5}$ | $1 - 10^{-5}$ | $1 - 10^{-9}$ |
| | Datenrate | kbit/s – Mbit/s | kbit/s | kbit/s – Mbit/s | kbit/s – Mbit/s | kbit/s – Mbit/s | kbit/s – Mbit/s | kbit/s – Mbit/s | kbit/s | Mbit/s – Gbit/s | kbit/s |
| Size of packet | Paketgrößen | > 200 Byte | 1 – 50 Byte | 20 – 50 Byte | 20 – 50 Byte | < 300 Byte | < 300 Byte | < 300 Byte | < 80 Byte | > 200 Byte | < 20 Byte |
| | Reichweiten (zw. komm. Geräten) | < 100 m | 100 m – 1 km | < 100 m | < 50 m | < 200 m | ~ 2 m | < 100 m | 100 m – 1 km | < 100 m | < 30 m |
| | Bewegungs-geschwindigkeit | 0 m/s | < 10 m/s | < 10 m/s | < 10 m/s | < 40 m/s | < 10 m/s | < 5 m/s | Generell keine, sonst < 10 m/s | < 3 m/s | <10 m/s |
| Mobility | Zeitkritische Mobilitäts-unterstützung | nein | nein | nein | nein | nein | ja | nein | nein | nein | ja |
| | Gerätedichte | 0,33 – 3 $m^{-2}$ | 10 – 20 $m^{-2}$ | 0,33 – 3 $m^{-2}$ | < 5 $m^{-2}$ | ~ 0,1 $m^{-2}$ | ~ 0,1 $m^{-2}$ | ~ 0,1 $m^{-2}$ | 10.000 / Fabrik | > 0,03 – 0,02 $m^{-2}$ | > 0,03 – 0,02 $m^{-2}$ |
| Energy efficiency | Energieeffizienz | n/a | 10 Jahre | n/a | n/a | n/a | < 8h | n/a | 10 Jahre | 1 Tag | n/a |
| | Lokalisierungs-genauigkeit | < 50 cm | < 50 cm | n/a | n/a | < 1 cm | < 5 cm | < 10 cm | < 50 cm | n/a | < 50 cm |

Table is taken from www.industrialradio.de - "Funktechnologien für Industrie 4.0", *available on https://industrial-radio-lab.eu/publikationen/#pubs_industrialradio, accessed on 08.08.2024.*

# Why not IEEE 802.11?

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- Unpredictable Latency:
  - if CSMA/CA random access is used
  - prone to interference, no frequency hopping
- High energy consumption, always on listening mode regardless of the traffic pattern

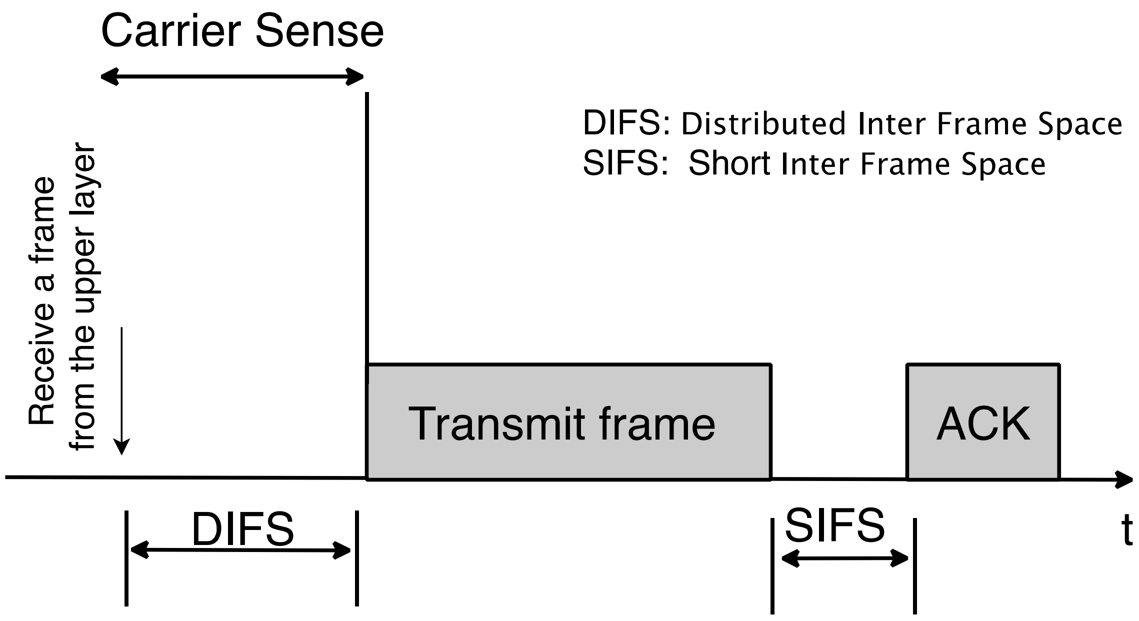
Radio Power consumption (PC) for the ESP32 MCU

| Mode | PC (mA) | PC (Watts) @3.3V |
|---|---|---|
| Idle | 15 | 0.0495 |
| Sleep | 0.8 | 0.00264 |
| Receive | 100 | 0.33 |
| Transmit | 180 | 0.594 |

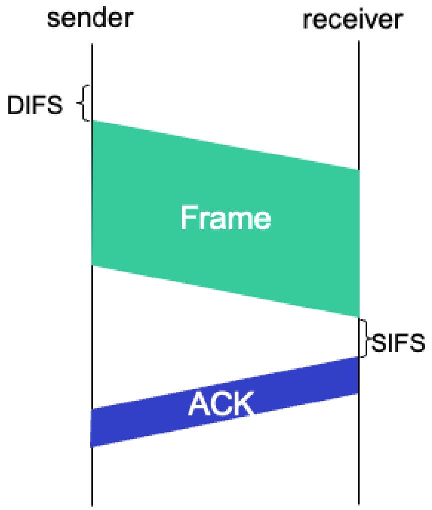
https://www.espressif.com/sites/default/files/documentation/esp32_datasheet_en.pdf

# CSMA/CA – Medium Free

- Direct access at the end of the DIFS period

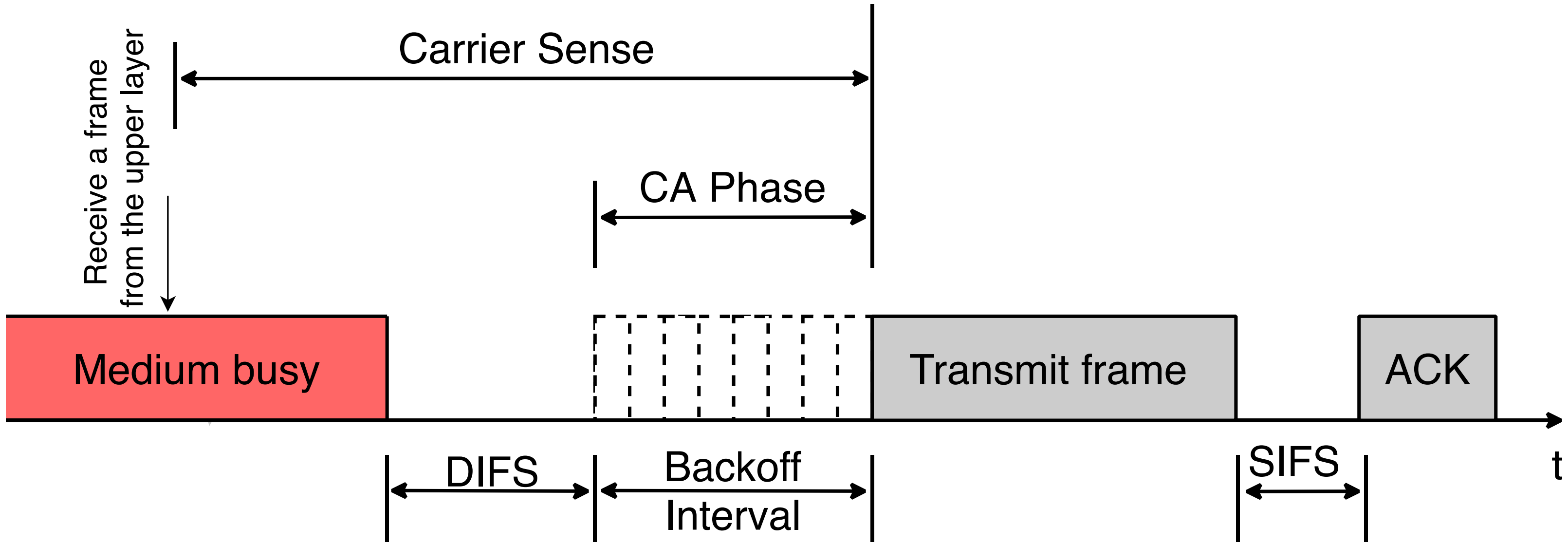



DIFS: Distributed Inter Frame Space
SIFS: Short Inter Frame Space



# CSMA/CA – Medium busy

- Wait till medium free, DIFS period and random backoff
- interval (Collision Avoidance)
- If medium is busy during the backoff interval: Stop the backoff timer



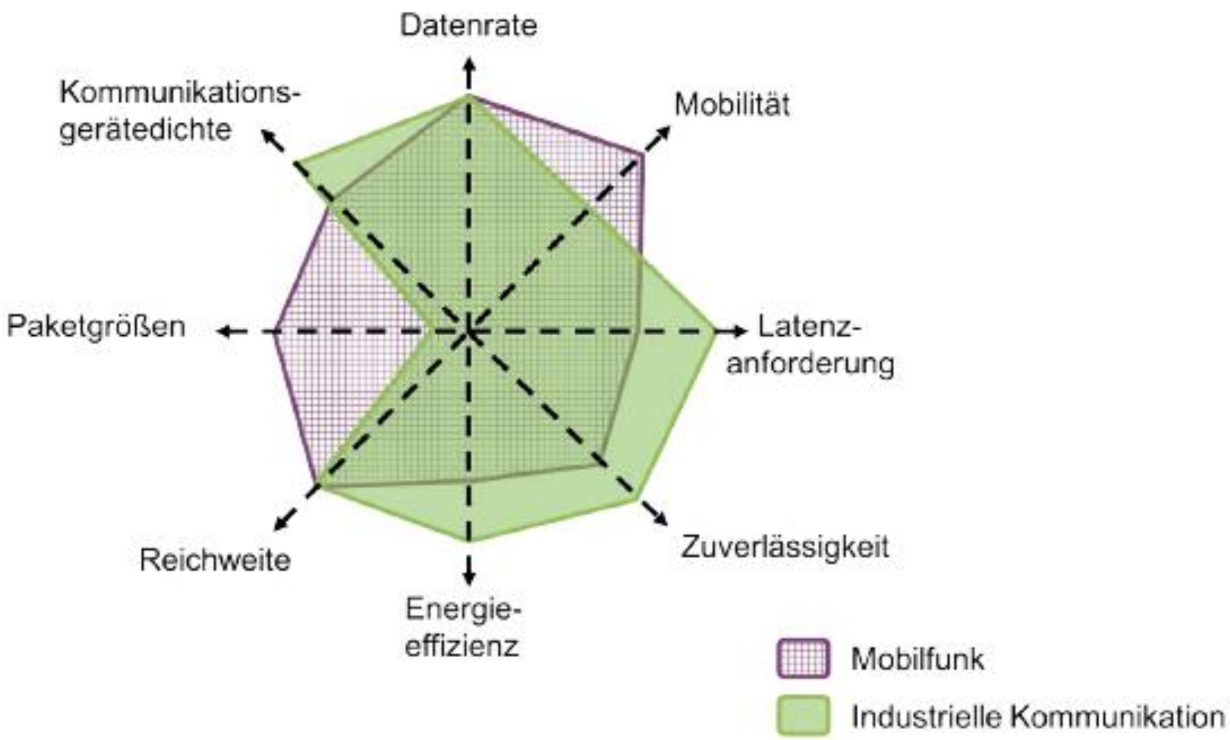

$$CW_{new} = 2 \cdot (CW_{old} + 1) - 1.$$

# Deterministic Networks

- Time and frequency based resource reservation, coupled with enforcement methods

- Eliminate congestion loss
- Guarantee latency

# Industry 4.0 Requirements




- Reliability
- Energy-efficiency
- Tightly bound delays

Deterministic Behavior

Figure is taken from www.industrialradio.de - "Funktechnologien für Industrie 4.0", *available on https://industrial-radio-lab.eu/publikationen/#pubs_industrialradio, accessed on 08.08.2024*

# Key Performance Indicators (KPIs) for Deterministic Networks

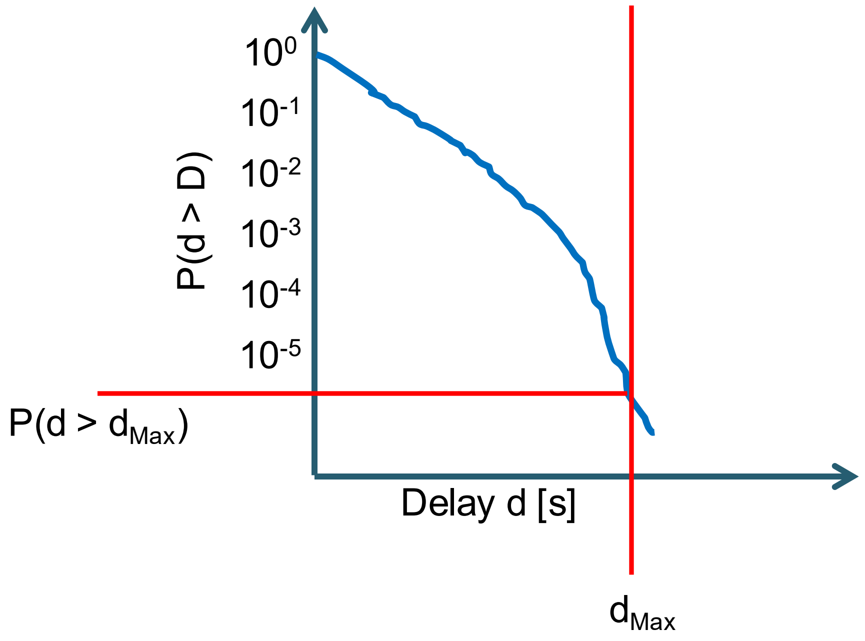
**Delay**

- Especially crucial in application areas like control
- Probability to violate an application-dependent upper delay bound $\mathbf{d_{Max}}$ , while considering a time-varying channel and offered traffic

**Packet Loss Rate**

- Adherence to a given bound
- Violation probability

$P(d > d_{Max}) = 10^{-6}$



# Other KPIs

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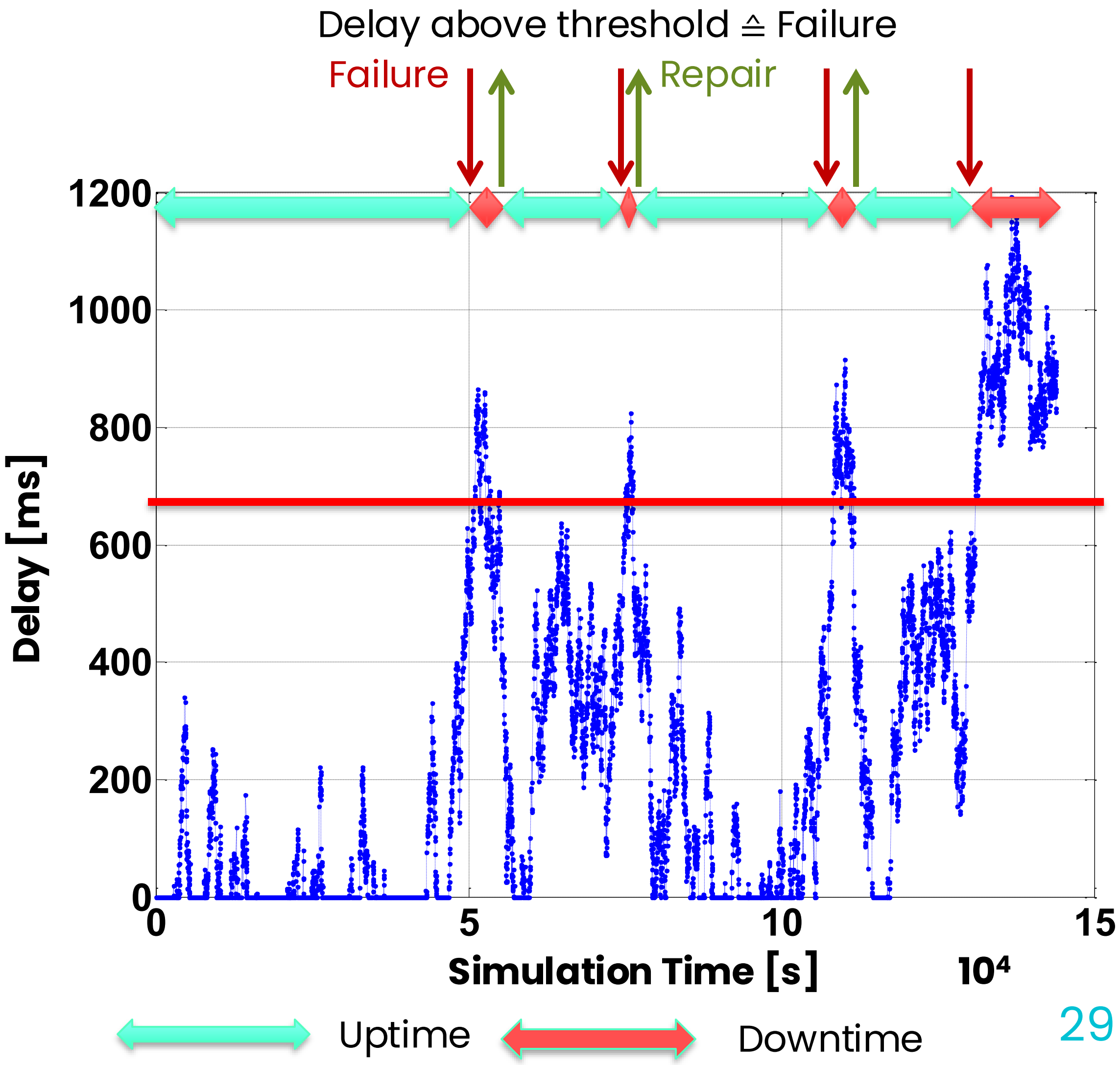
**Time To Failure (TTF)**

- Average elapsed time before a component fails

**Time To Repair (TTR)**

- Average time needed to repair a failure
- Some definitions also consider the time until failure detection

**“Five Nines Uptime” = 99.999%**
**How many minutes downtime per year?**



# 5 Nines Reliability – is this Enough?

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**"Five Nines Uptime" = 99.999%**
**How many minutes downtime per year?**

- Minutes per year – 365x24x60 = 525600 minutes
- Down time ~ 525600x0.00001 = ~ 5.256 minute

- What don't we know here?
  - Is this continuous or intermittent down time or not?
  - Continuous 5 minutes down time for a smart grid application has a huge impact

# Wireless Communication for Deterministic Networks

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- 2006: Dust Networks Time Sync Mesh Protocol (TSMP)
- 2008: WirelessHART
  - TDMA with fixed time slots
  - Vendor-driven
- 2011: ISA 100.11a
  - TDMA (variable time slots) + CSMA
- 2012: **IEEE 802.15.4 TSCH** (Time Slotted Channel Hopping) mode
  - Configurable TDMA – predictable latency, avoids idle listening and extends device lifetime
  - Channel hopping - improves the reliability in the presence of narrowband interference

**Any other wireless protocols that you heard about for industry 4.0?**

# Protocol Stack for Industry 4.0 Applications

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**TCP/IP Stack**

| |
|---|
| Application |
| … |
| Network |
| Data Link |
| PHY |

**Protocol stacks for Low Power applications**

Matter
ZigBee
ISA100a
Thread
6TiSCH
...

| | |
|---|---|
| IEEE 802.15.4 MAC (CSMA/CA, DSME, TSCH) | Bluetooth-LE LoRa, LTE-M, .. |
| IEEE 802.15.4 PHY | |