Docent Lecture

Dependable Low-Power Wireless Communication

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Agenda

- Definitions and challenges in low-power wireless communication system
- Past and current research projects
- Future research directions and plans

IoT Applications using low-power radios

Increase in number of low-power IoT devices

- Short-range (low-power radio) devices are expected to increase more, and consequently more revenue
- More devices powered by Bluetooth, WiFi, 802.15.4
- Need to devise more efficient communication protocols
- Consider future IoT applications with more stringent requirements

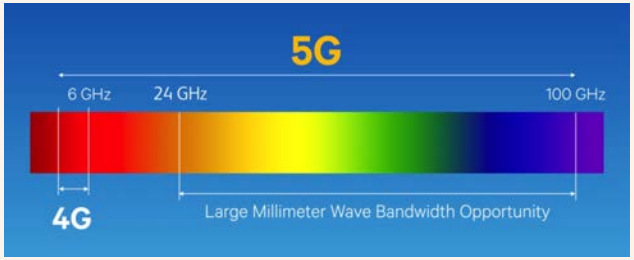
Figure 15: IoT connections (billion)

IoT	2023	2029	CAGR
Wide-area IoT	3.3	6.6	12%
Cellular IoT	3.0	6.1	12%
Short-range IoT	12.4	32.3	17%
Total	**15.7**	**38.9**	**16%**

https://www.ericsson.com/en/reports-and-papers/mobility-report/reports/november-2023

Wireless Communication Technologies (power perspective)

- **High-power (high-data rate)**
  - LTE, HSPA, GPRS, EDGE, GSM, WCDMA, UMTS, WiMax, (5G → lower power)
  - 5G: 450 MHz to 6 GHz, and 24.25 GHz to 52.6 GHz
  - 4G: 600 MHz to 2.5 GHz



- **Low-power long-range (low-data rate)**
  - SigFox, LoRa, RPMA, Symphony Link, Weightless, Dash7

Sub-1GHz
Robustness, long range

- **Low-power short-range**
  - WiFi, Bluetooth, ZigBee (IEEE 802.15.4)

Low-power, low-data rate, short-range

2.4 GHz

- Low transmission power (1 mW compared to 400 mW in phone)
- Short transmission range
- Low data rate (250 kbps)
- ISM band (2.4 GHz)

Dependability

Attributes:

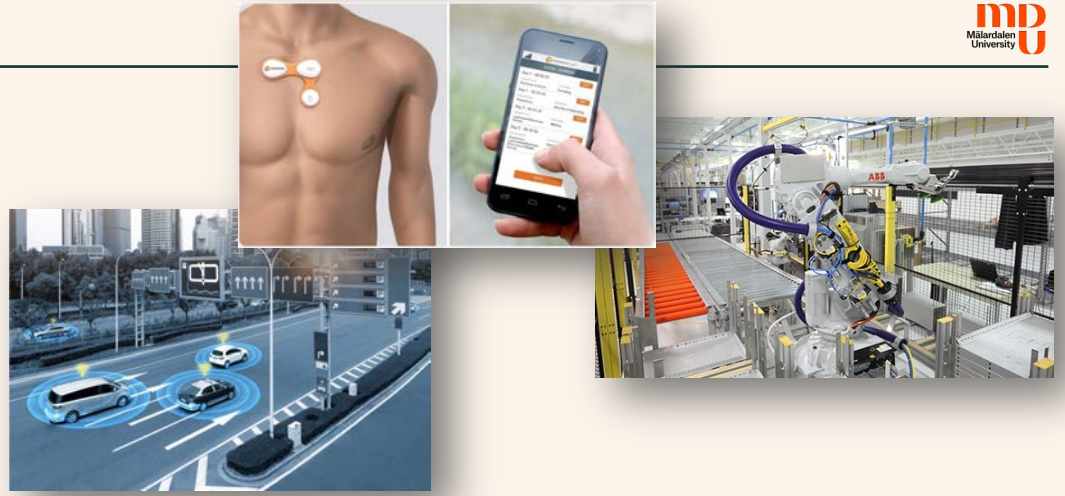
- Availability: always operational
- Reliability: function consistently without errors
- Safety: prevent accidents
- Confidentiality: protect information
- Integrity: information unchanged
- Maintainability: possible to update

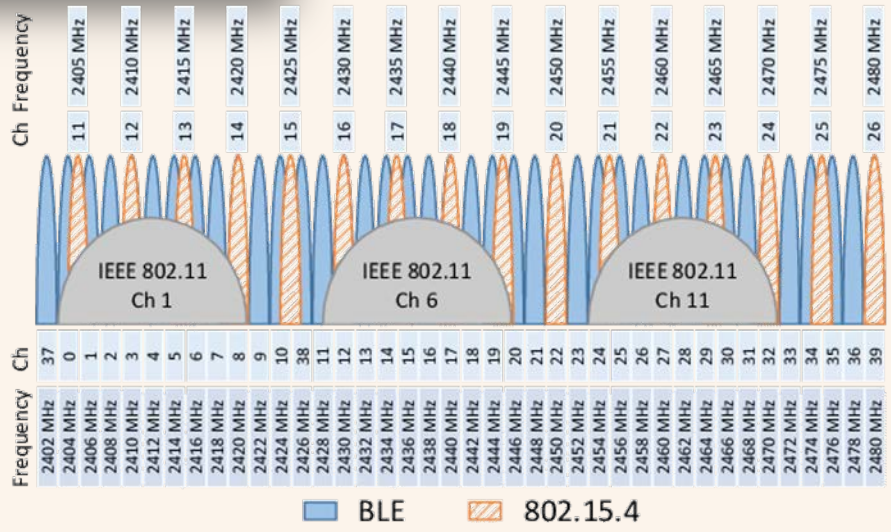
Performance metrics:

- Delay
- Packet delivery ratio
- Overhead
- Power consumption

External parameters

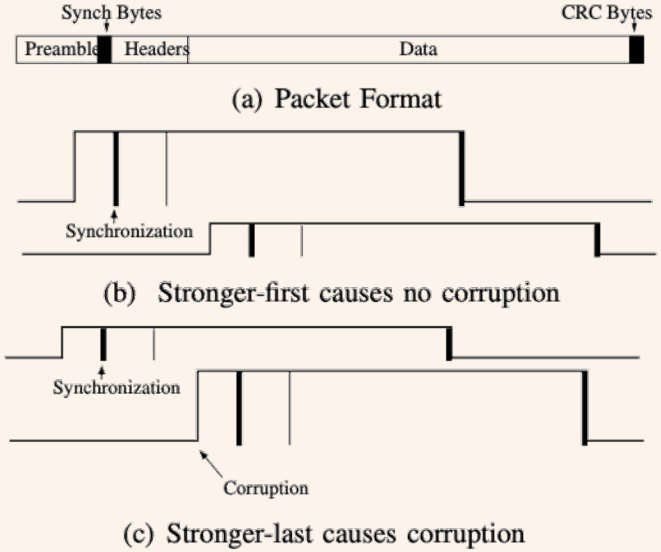
- Environment
  - Radio model
- Radio interference
  - Co-existing radios
- Mobility of devices
  - Dynamic topology





Collision (avoid or allow?)

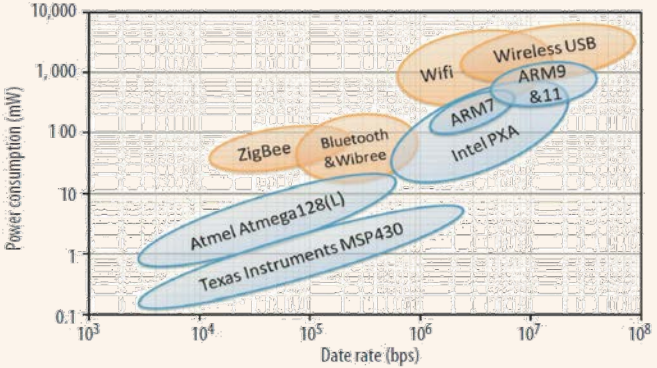
- Packet collision leads to packet losses and degraded performance
- Capture effect: receive packet despite interference
  - Stronger first
  - 3 dB greater SINR
  - Short arrival time difference
- Benefit of collision (flooding):
  - Concurrent transmission
  - Routing tree creation
  - Clock synchronization
  - Code dissemination
  - Node localization
  - Cluster formation

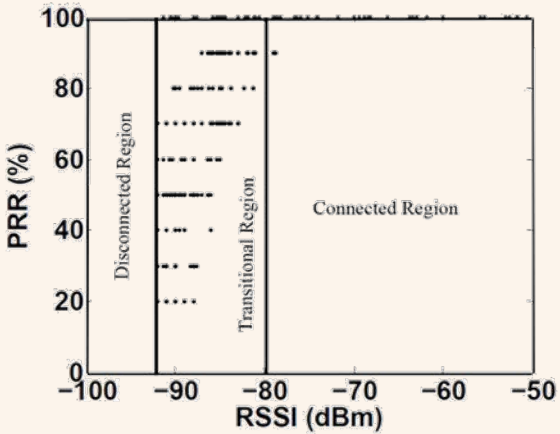


1. Lu, Jiakang, and Kamin Whitehouse. "***Flash flooding**: Exploiting the capture effect for rapid flooding in wireless sensor networks*." INFOCOM, 2009.
2. Ferrari, Federico, Marco Zimmerling, Lothar Thiele, and Olga Saukh. "Efficient network flooding and time synchronization with **glossy**." IPSN, 2011.

Link characteristics

- Low transmission power: unreliability and asymmetric
- Wireless link regions: connected, transitional, disconnected
  - Connected region: links are often of good quality, stable, symmetric.
  - Transitional region: unreliable, asymmetric links.
  - Disconnected region: no practical link for transmission
- 50% of links are in transitional region





Experiments in low-power wireless domain (3Rs?)

- Same testbed does not provide fair comparison among different protocols
  - Repeatability
  - Replicability
  - Reproducibility

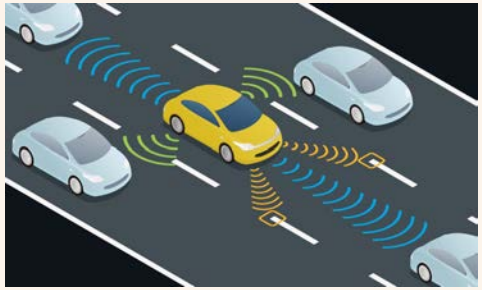
"*non-reproducible single occurrences are of no significance to science*"
Karl Popper (philosopher), 1959

Term	Characteristics		
Repeatability	*same* result	*same* team	*same* experimental setup
Replicability	*same* result	*different* team	*same* experimental setup
Reproducibility	*same* result	*different* team	*different* experimental setup

ACM Digital Library Terminology (computation domain)

- Experiments in low-power wireless domain should result in same conclusion/consistent results

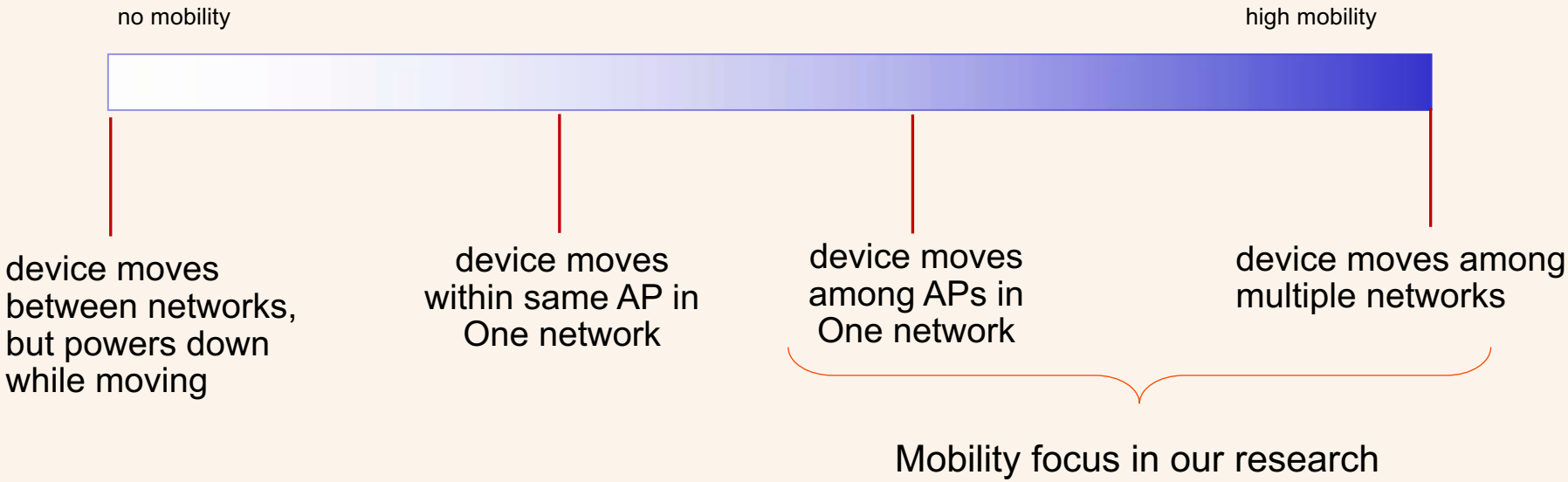
Mobility in IoT applications



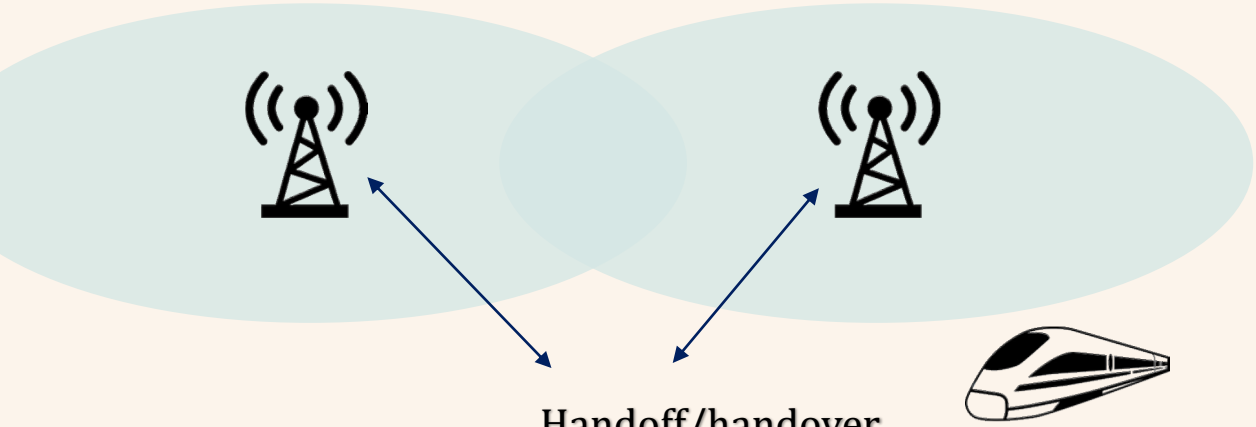
- Mobility makes wireless links even more unreliable, highly affects the QoS performance
- Focus on **mobility management** in low-power radios

What is mobility?

- Spectrum of mobility, from the network perspective:

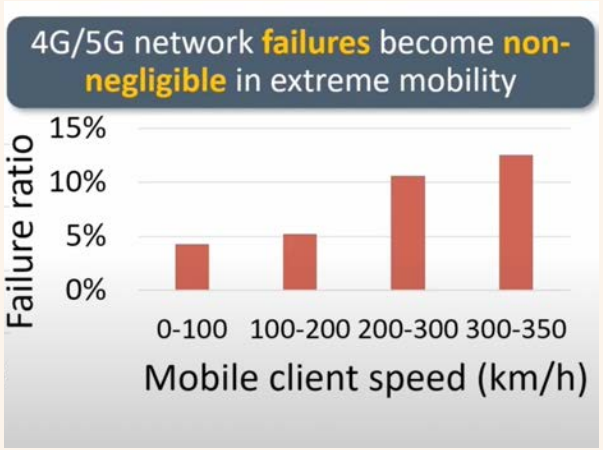


Handoff process



Handoff/handover

Process of switching from one base station to another base station

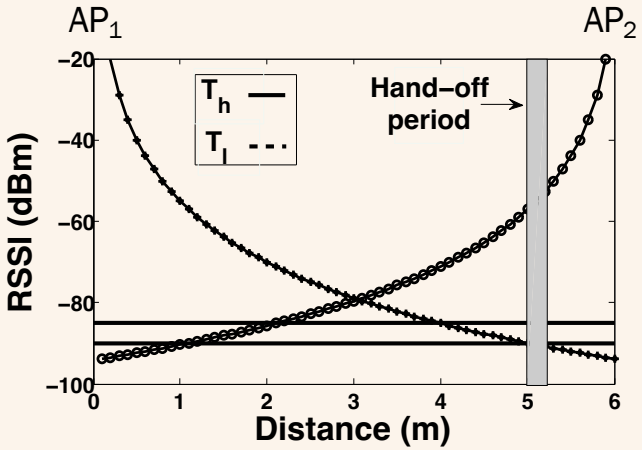


Cellular networks with strong backbone infrastructure are still suffering from failures due to mobility

Reason: lack of intelligence, no mobility pattern detection/estimation

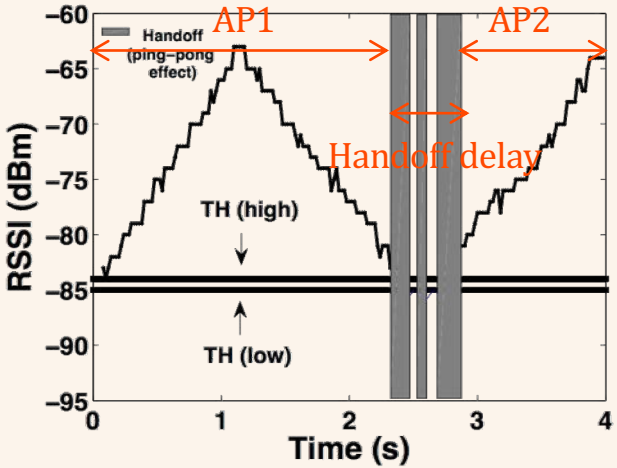
Handoff process

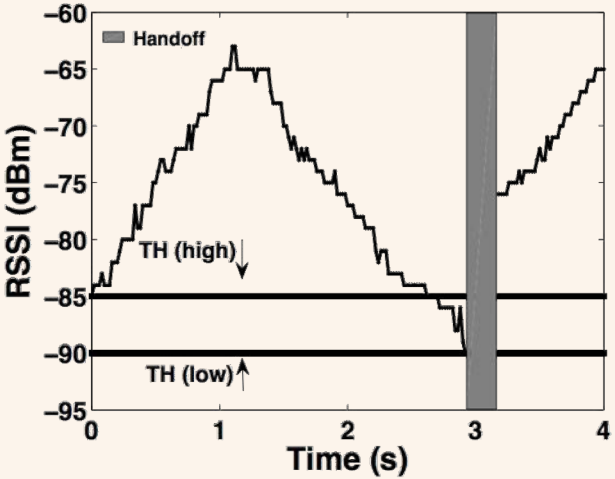
- **Handoff delay** is the distance that the mobile node moves from one point of attachment to other; disconnection period.
- **Hard handoff:** when the mobile node disconnect from an AP, and then looks for a new AP.
- **Soft handoff:** when the mobile node looks for a new AP before disconnecting from the current



Ping-pong effect

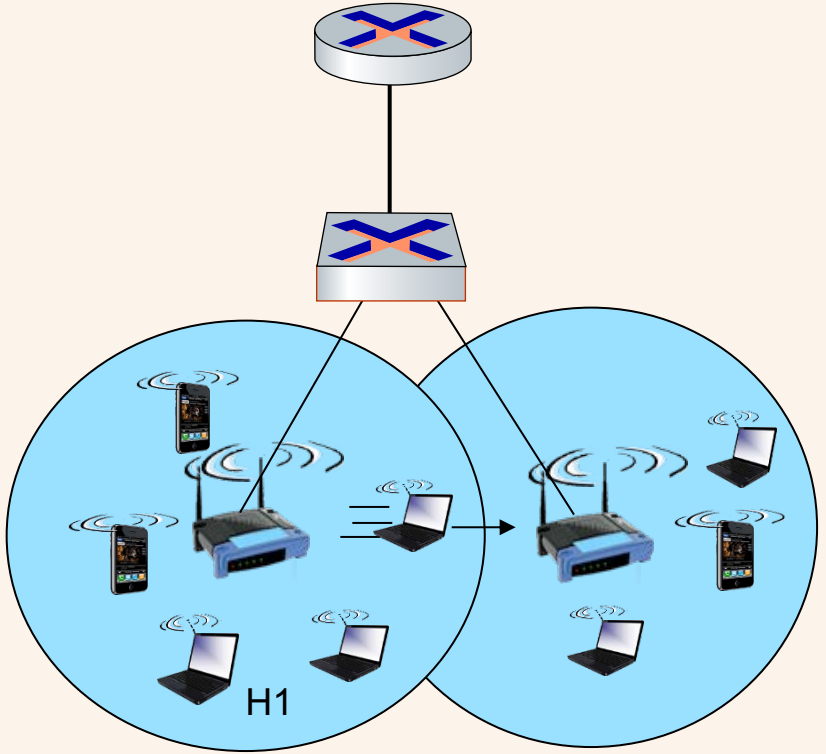
- Ping-pong effect: Switching between APs back and forth
- Not realistic to rely on single measurements of RSSI due to sudden fluctuations





Mobility in WiFi networks

- APs periodically broadcast beacons
- Host associates with the AP has strongest RSSI (high link quality)
- Host sends request to join, then AP approves
- MN disconnects from an AP if the link degrades

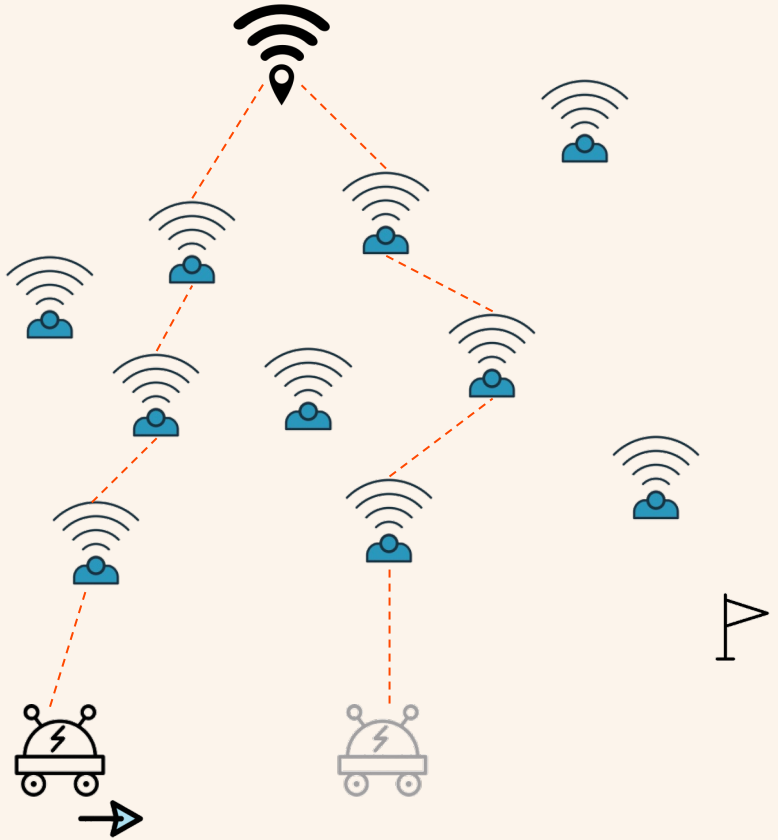


WiFi technologies (mobility support)

- **802.11ah (WiFi HaLow)**: low-speed coordinated communication for M2M
- **802.11ad (WiGig):** Gigabit Wireless, 60 GHz
- **WiFi Direct**: Point-to-point WiFi without access point
- **802.11u**: Authentication for 802.11 hotspots
- **802.11r:** fast base station transition  **Supports handoff**
- **802.11ac (WiFi 5)**: 500 Mbps– 1 Gbps WiFi
- **802.11ax (WiFi 6):** User throughput 4x 802.11ac
- **802.22 (Super WiFi):** long distance Internet access using TV white spaces.

Mobility in low-power networks (802.15.4)

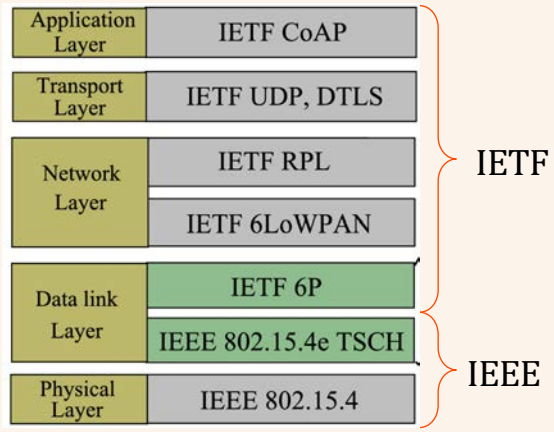
- No infrastructure like cellular
- No large bandwidth like WiFi
- Periodic beaconing not practical (collision)
- Mobility solutions:
  1. Broadcast when there is a reading (redundancy, collision)
  2. Hardware (use other radios, costly)
  3. Handoff (more intelligence is required)

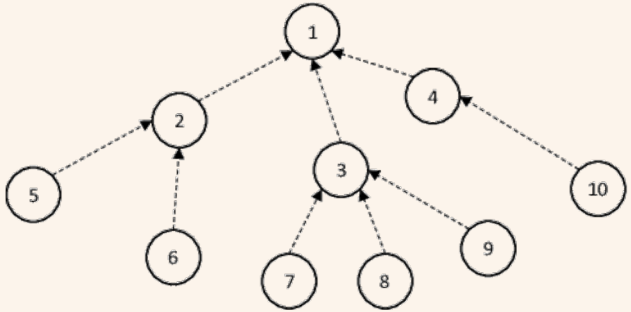


Mobility solutions within standard protocols

- Standard protocol stack for low-power communication
- Joint effort by IEEE and IETF
- IEEE 802.15.4 PHY layer
- IEEE 802.15.4e TSCH (tome slotted channel hopping)
- Supports IPv6-based Internet connection
- 6LoWPAN adaption layer, header compression and fragmentation
- Tree-based routing protocol (RPL), forms DODAGs
- COAP application layer, low overhead, scalable, secure

6TiSCH protocol stack





Dependability in healthcare application (ESS-H(+), ecare@home, Health5G, FlexiHealth projects)

e-care@home

ESS-H

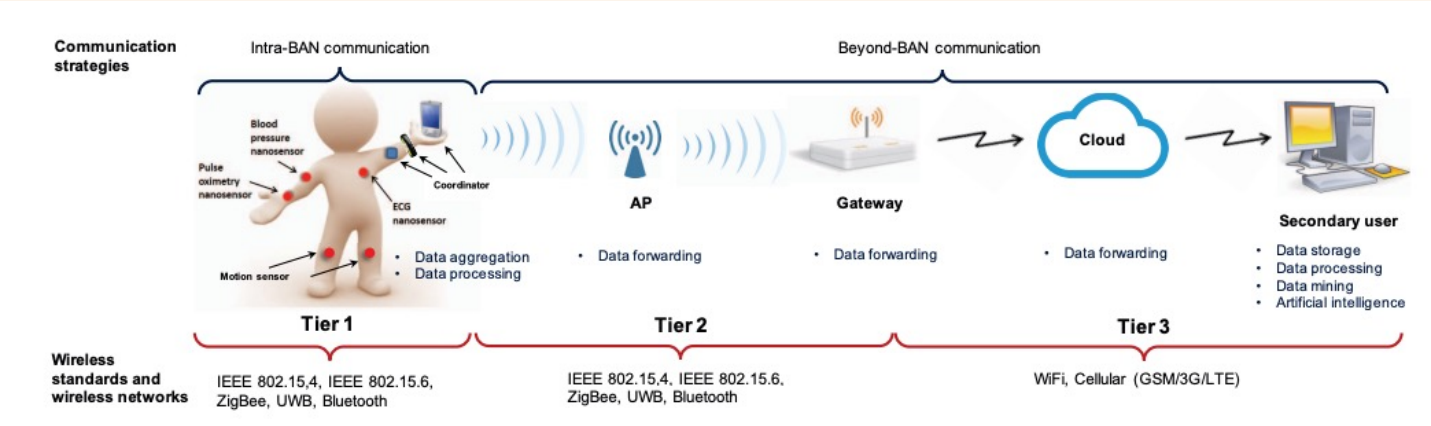
FlexiHealth

Health5G

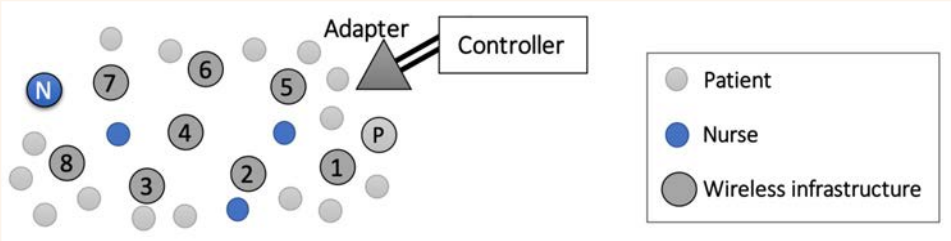
Knowledge Foundation

CELTIC-NEXT
Next Generation Telecommunications

Dependability in healthcare application

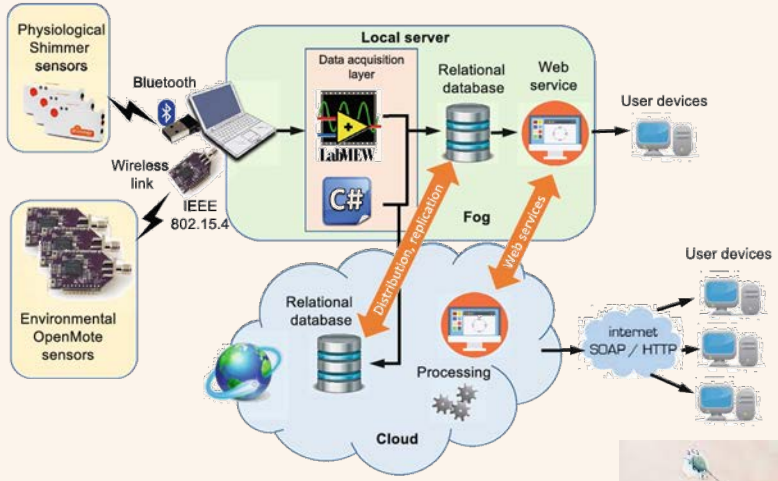


- Health monitoring frameworks
- Communication challenges (link characteristics and interference)
- Security measures
- Proposed multi-tier system architecture
- Centralized network management in dynamic systems in terms of traffic and mobility

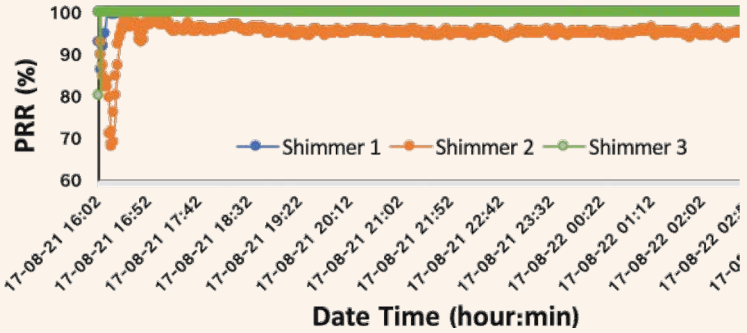


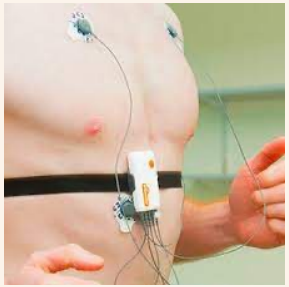
Dependability in healthcare application

- System architecture with heterogenous devices (communication, computation, storage)
- Low-power radio selection
- Run-time assurance (PRR and energy efficiency – duty cycling)



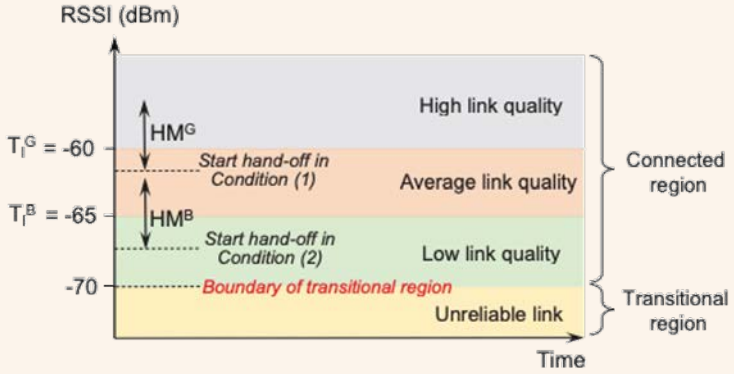
CONTIKI
NEXT GENERATION





Dependability in factory automation (external collaboration)

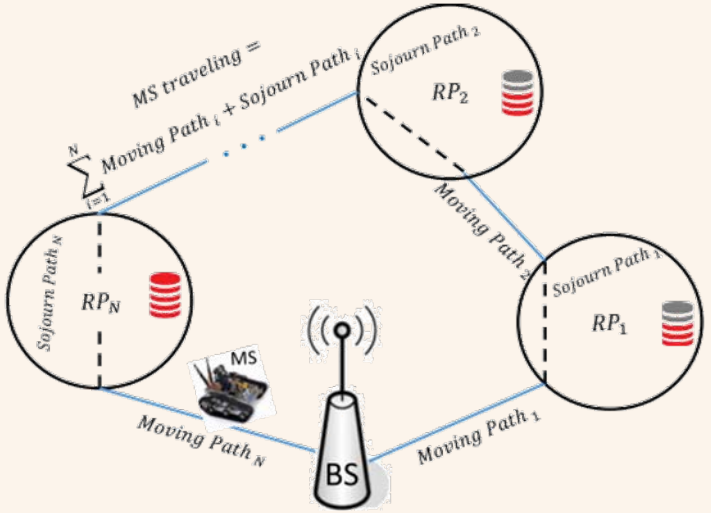
- Wireless real-time communication in mesh networks (soft real-time)
- Employed token passing protocol over 802.11
- Employ mobile robots, tested on robot tele-operation
- Devised double threshold handoff algorithm (DoTHa) → higher accuracy, lower ping-pong effect
- Regions (connected, transitional, disconnected)





Mobile sink scheduling (external collaboration)

- Mobile sink act as relay nodes (harsh environment, UAVs in disaster, battlefield, wildlife)
- Long distance leads to larger latencies and buffer overflows
- Routing strategy (trajectory planning algorithm) to reduce energy consumption (shorter distance) considering data volume
- Support emergency packets by establishing sub-paths



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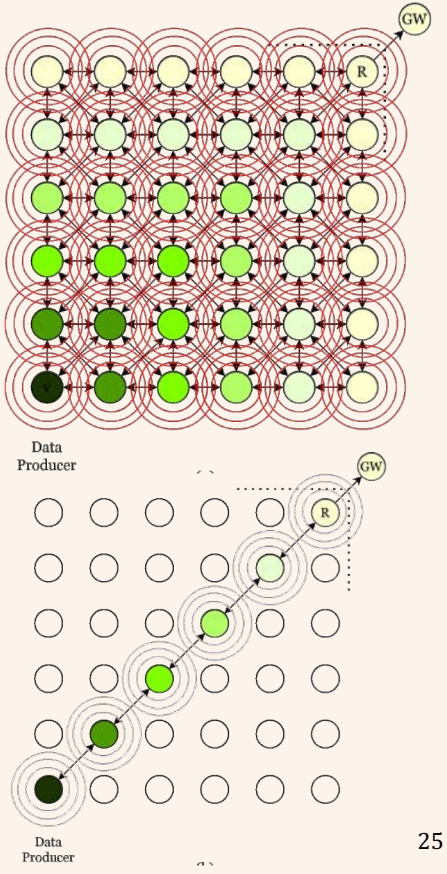
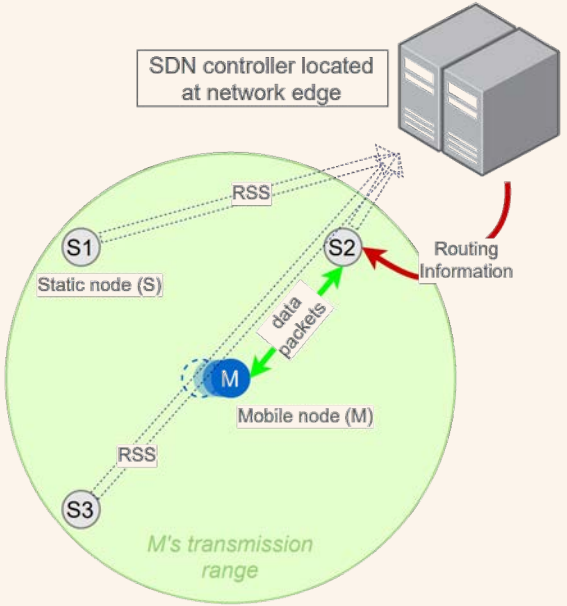
Network management in heterogeneous networks

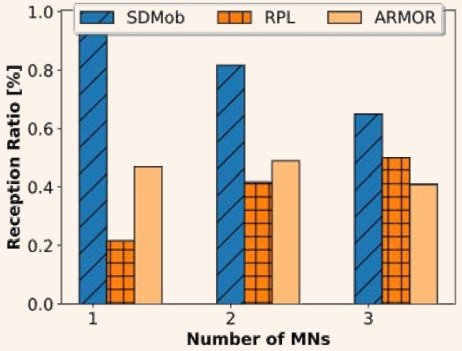
- Heterogeneity in terms of radio, network
- Network management at a lightweight SDN controller reside on a Gateway
- Heterogeneous radios
  - Gateway focuses on translation algorithms (different packet formats)
- Heterogeneous networks (e.g. Information centric networking and IP-based networking)
  - IP-based: packet goes to the sender address
  - ICN: publisher produces data under topics, forwarders cache the data, receiver subscribes



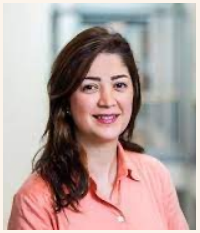
Mobility management in IoT networks (MobiFog project)

- SDN-based mobility management (SDMob)
- Lightweight SDN for low-power constrained networks
- Centralized handoff process at SDN controller
- Location estimation using Kalman Filter and Particle Filter
- Integration of SDMob within RPL routing





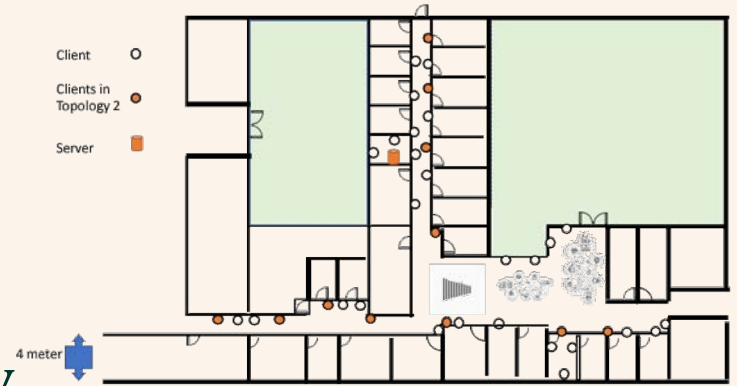


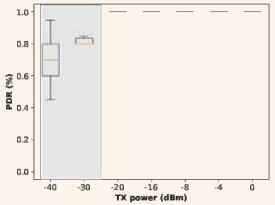



Vetenskapsrådet

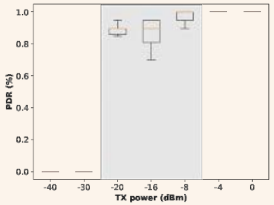
Reliability (MobiFog project)

- Transmit power control (ACTOR)
  - considers network density, distance between nodes, energy consumption
  - Blacklisting undesirable TX powers
- Confines channel contention among neighbor nodes
- Improves throughput in dense networks by passively exploring different transmission power levels.

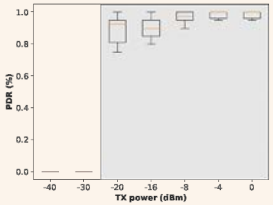




1 meter apart



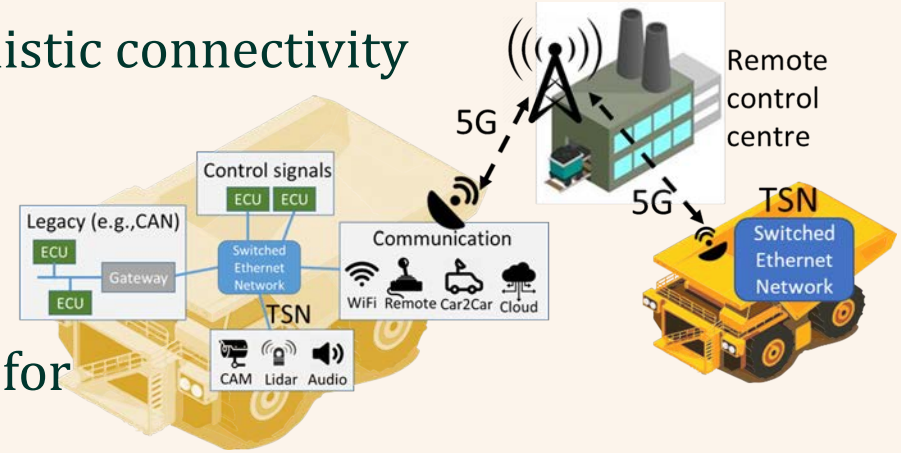
10 meter apart



20 meter apart

TSN-5G integration (PROVIDENT project)

- Dependability is crucial for real-time experiences (predictability)
- TSN (IEEE 802.1): provide deterministic connectivity
  - Controls wired data communication (time sync and prioritization of streams)
- 5G provides deterministic wireless
  - URLLC
- Seamless integration of TSN and 5G for future industrial applications
- Consider standard specification during the design and implementation



Dependability in construction sites (GREENER project)

Construction sites are **dynamic environments** with limited geographical area, usually requiring high reliability, real-time support, mobility support, and secure connection, which makes them suitable candidate for private 5G networks.

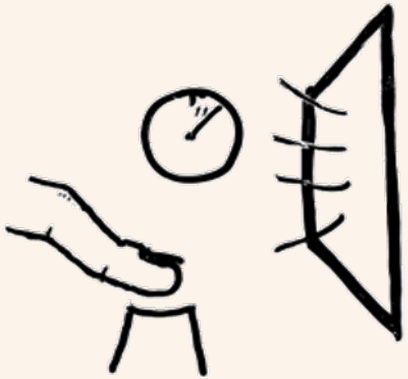
- Placement and number of fixed cells and cell on the wheels
- Selecting appropriate 5G cell (femtocell, picocell, microcell, macrocell) Mapping terrain model to wireless link quality
- It is possible to provide connectivity by adding more cell-on-the-wheel instead of fixed cells

Acknowledgement

FIC

FUTURE FACTORIES InTheCloud

READY



RENEW

AutoFL

SecureMicrogrid

XPRES

Potential future research directions

- Mobility in low-power wide area networks (e.g. LoRa, Sigfox)
- Federated learning in low-power networking
- Network security aspects in IoT networks (access control)
- Explore more application domains, their requirements, specifications, new networking paradigms (smart grid, smart building, transportation, factory automation)
- IoT solutions for sustainability (e.g. energy efficiency, circularity, e2e lifecycle)
- Satellite-IoT connectivity