Technologies and Tools for the Design of Dependable Networked Embedded Systems

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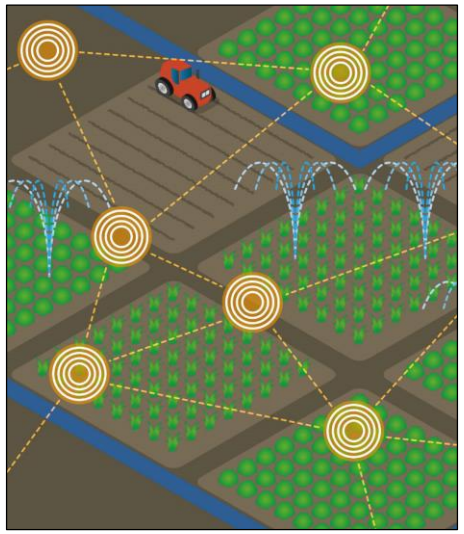
March 26, 2020

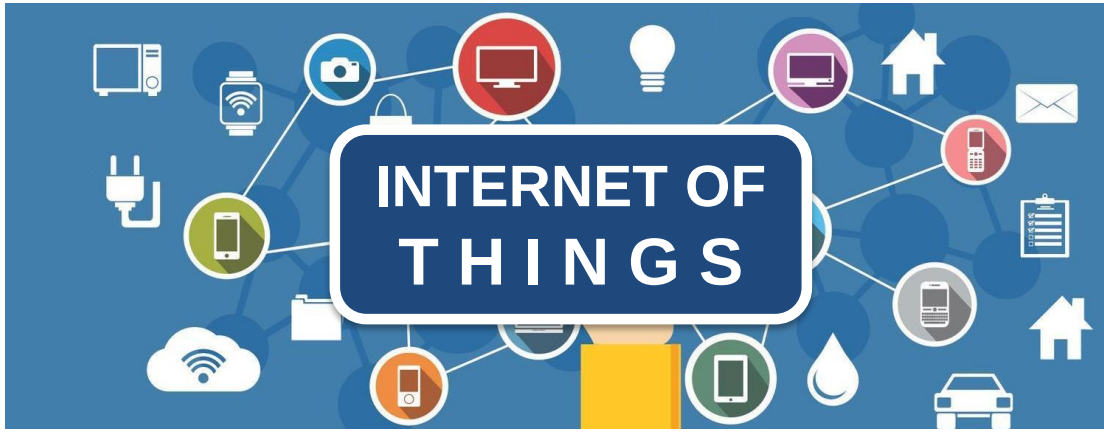
Agenda

- About me
- Designing dependable networked embedded systems
  - A grand challenge in today's IoT & CPS landscape
- Selected research contributions
  - Concepts and tools to benchmark low-power wireless systems
  - Adaptive protocols for dependable communication in harsh environments
  - Trustworthy services for dependable IoT applications
- Next steps and vision

Designing Dependable Networked Embedded Systems

A grand challenge in today's IoT & CPS landscape





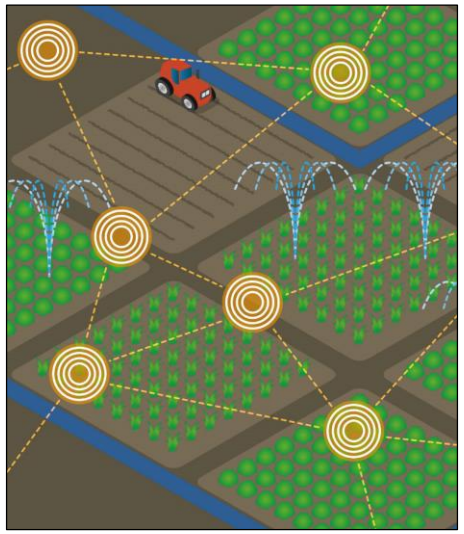
500 billion connected devices by 2030

CISCO

Most of them will be low-power wireless embedded devices!

Designing Dependable Networked Embedded Systems

A grand challenge in today's IoT & CPS landscape



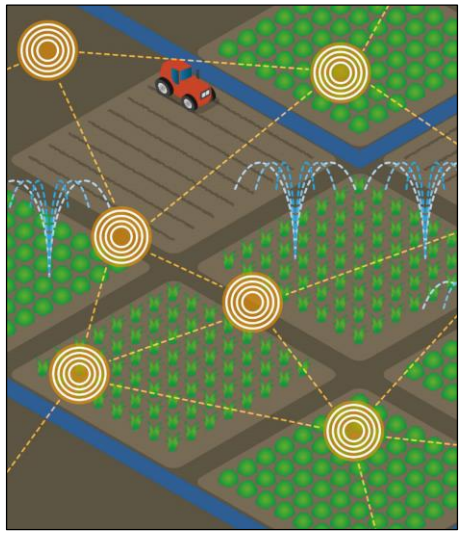
Dependability

"A dependable system can fulfill its mission in a reliable and trustable way throughout its lifetime"

- Availability → readiness for correct service
- Reliability → continuity of correct service
- Safety → absence of catastrophic consequence
- Integrity → absence of improper system alteration
- Maintainability → easy maintenance & repair

Designing Dependable Networked Embedded Systems

A grand challenge in today's IoT & CPS landscape



- Huge IoT application space (with diverse characteristics & requirements)
  - No "one-size-fits-all" solution
- Plethora of HW platforms, approaches, and technologies to choose from
  - Which ones to pick?

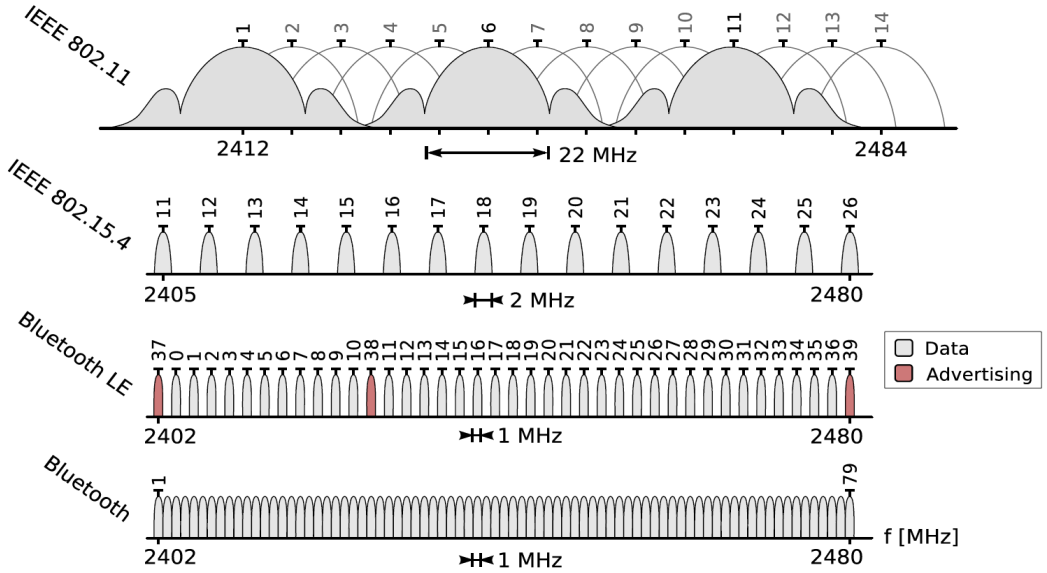
    → need for tools (e.g., benchmarks) quantitatively comparing performance!

Designing Dependable Networked Embedded Systems

A grand challenge in today's IoT & CPS landscape

- Distributed and networked nature of modern embedded systems
  - How to deal with the lossiness and latency of wireless communications?
  - How to deal with the dynamicity of the environment?

Example:
cross-technology interference in the 2.4 GHz ISM band



→ need for adaptive protocols!

Designing Dependable Networked Embedded Systems

A grand challenge in today's IoT & CPS landscape

- Expected longevity of embedded devices
  - Devices should operate in a trustable way for an extended time without human intervention
  - How to preserve the limited energy budget of a device, thereby increasing its availability?
  - How to ensure remote maintainability to cope with changing customer demands and security threats?
- Expected autonomy of embedded devices
  - How to gather context- and location-awareness to support mobile operations, ambient intelligence, and other self-healing and self-adaptation capabilities?

→ need for services enabling, e.g., accurate indoor localization & efficient SW updates

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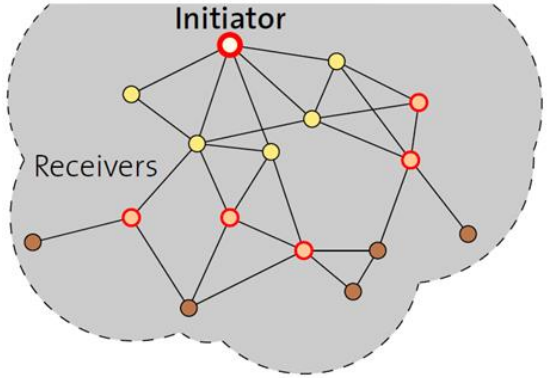
Benchmarking Low-Power Wireless Systems

- Application designers often need to choose between a plethora of platforms, networking approaches, and communication technologies
  - Plenty of choice!

1 Suitable (radio) technology

2 Suitable networking approach
→ Centralized or distributed scheduling?
→ Routing or flooding?



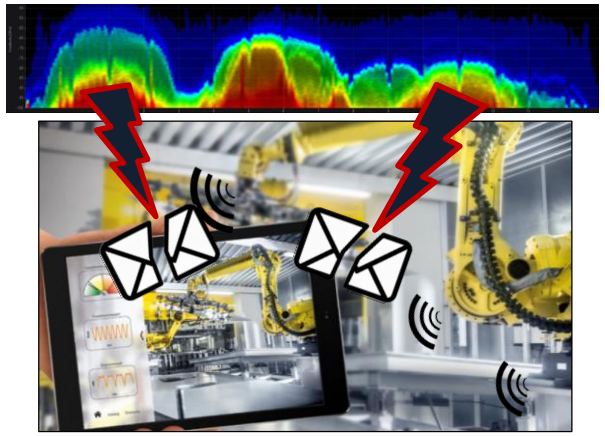
3 Suitable communication protocols and corresponding parameters

```
#define RX_D 20
#define RX_M 4
```

Benchmarking Low-Power Wireless Systems

- Application designers often need to choose between a plethora of platforms, networking approaches, and communication technologies

4 Does the chosen configuration perform well in the real-world?
(e.g., dynamic environments can have a strong impact on communication performance)



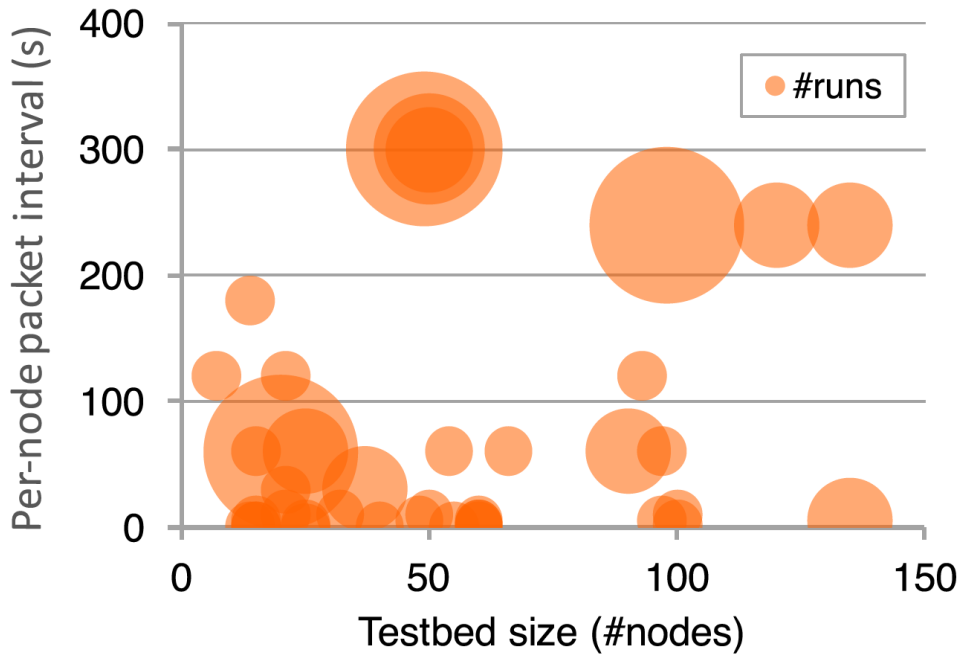
Example: radio interference

Example: temperature variations

→ We need the ability to quantitatively compare (i.e., benchmark) the performance of different solutions in various conditions

Benchmarking Low-Power Wireless Systems

- Today's sad reality
  1. Still no standard way to evaluate low-power wireless protocols



Experimental setup used to evaluate periodic data collection protocols in top IoT venues

→ Huge variety of settings!

System parameters
(# of nodes, topology & density, link quality, …)

Traffic parameters
(traffic load, pattern, …)

Experiment parameters
(# of repetitions, …)

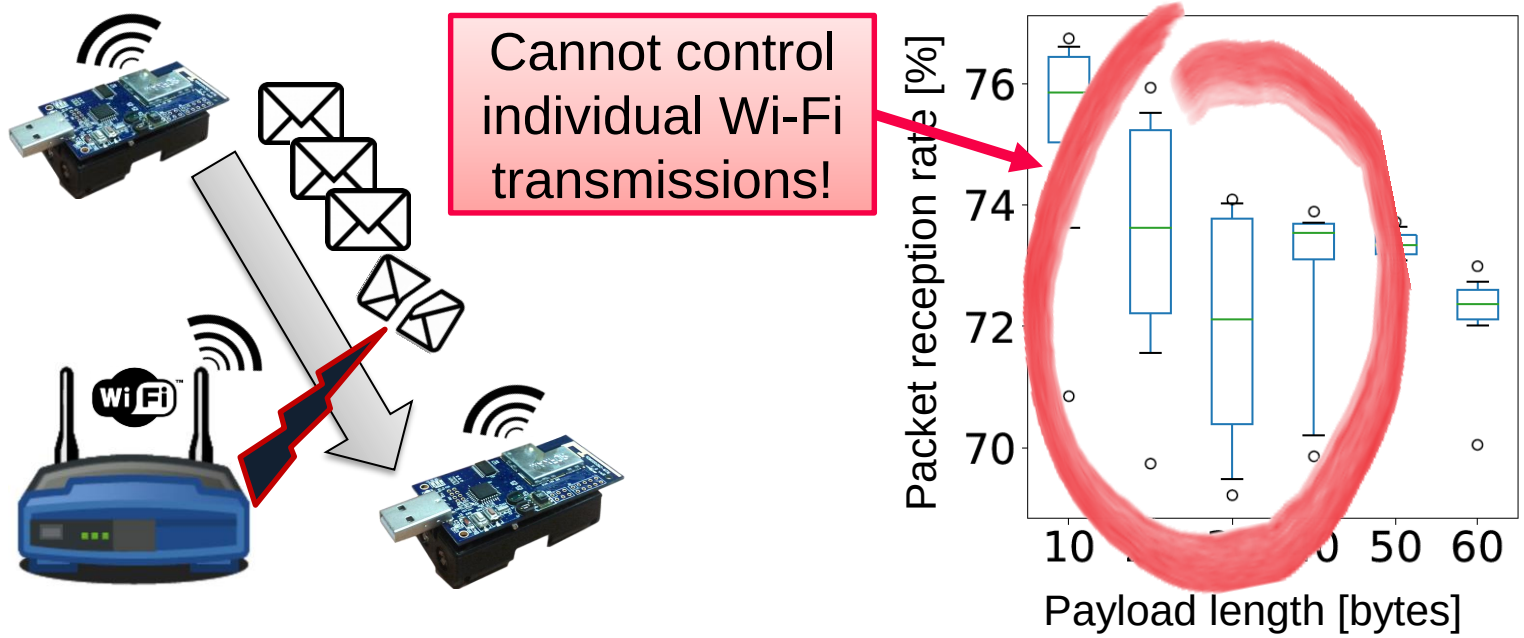
Performance metrics
(packet reception rate, end-to-end latency, energy, …)

Environmental parameters
(amount of interference, temperature variations, …)

More info: C.A. Boano et al. **Towards a Benchmark for Low-power Wireless Networking.** *In Proceedings of the 1st Workshop on Benchmarking Cyber-Physical Networks and Systems (CPSBench).* April 2018.

Benchmarking Low-Power Wireless Systems

- Today's sad reality
  1. Still no standard way to evaluate low-power wireless protocols
  2. Lack of tools supporting reproducible networking experiments



Packets correctly exchanged by two wireless sensors under Wi-Fi interference

- Protocol A → PRR = 99.1%
- Protocol B → PRR = 98.9%
- Intrinsic setup variability can be up to ≈5% PRR !!!

→ Reproducibility of experiments and comparability of results are **cornerstones of the scientific method**!

More info: M. Schuß, C.A. Boano et al. **JamLab-NG: Benchmarking Low-Power Wireless Protocols under Controllable and Repeatable Wi-Fi Interference**. *In Proc. of the 16th EWSN Conference. Feb 2019.*

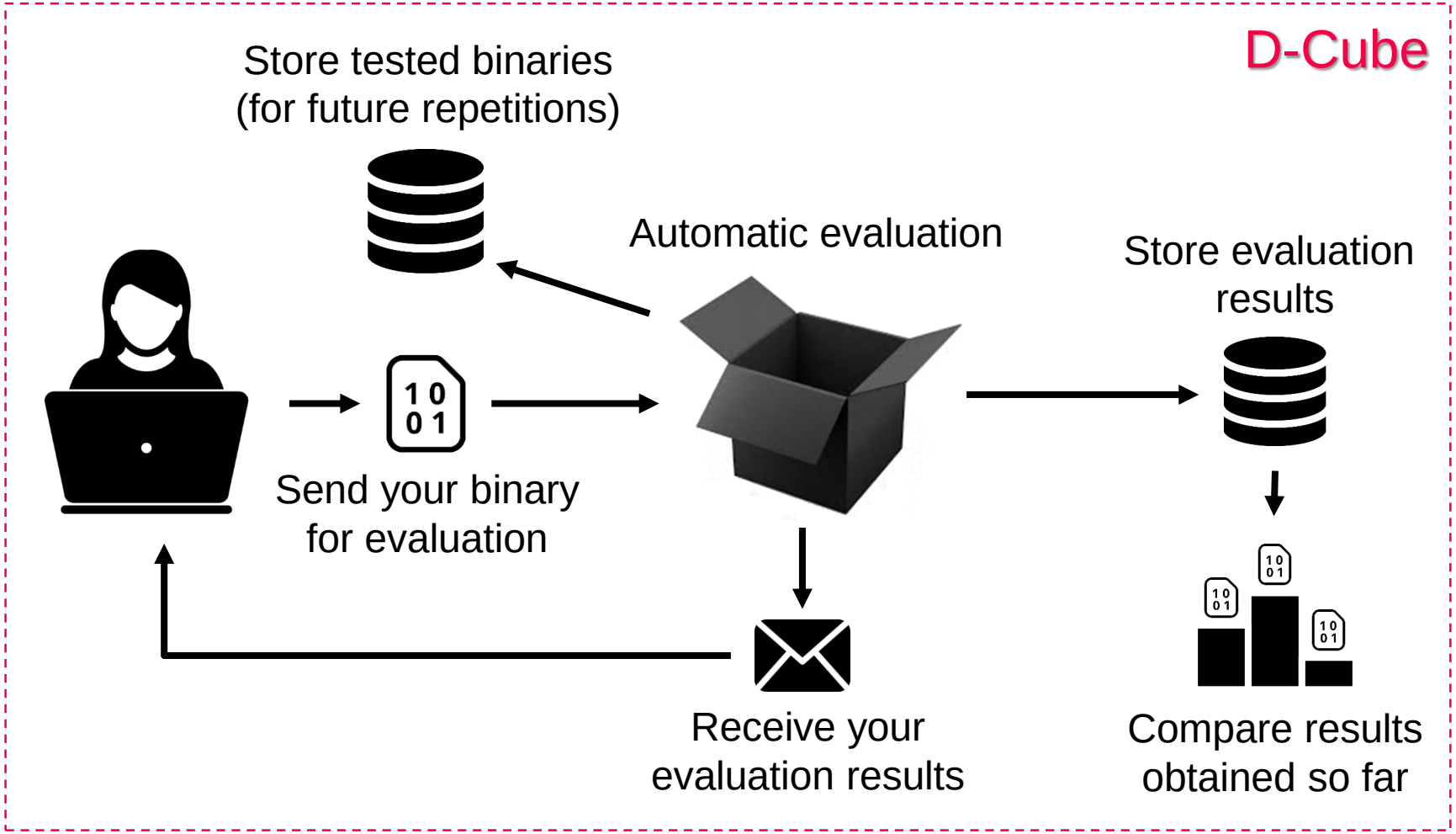
Benchmarking Low-Power Wireless Systems

- Building a low-power wireless benchmark: from roadmap to reality

IoTBench consortium

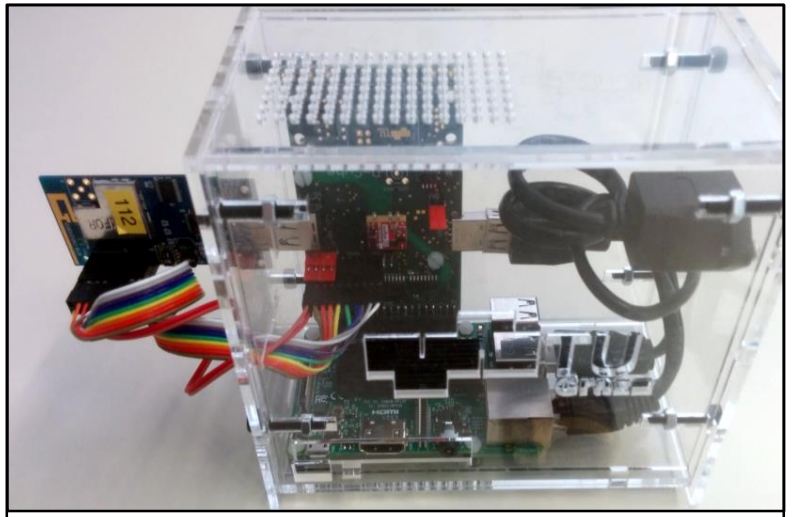
https://www.iotbench.ethz.ch

Roadmap towards a more rigorous experimental validation



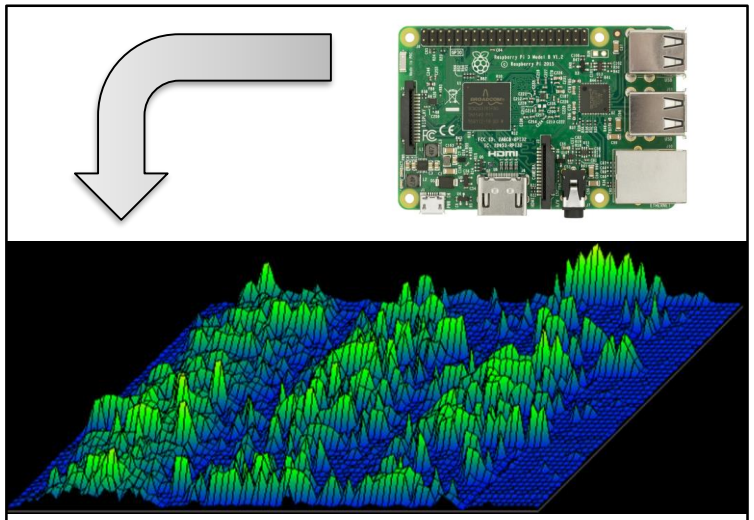
Benchmarking Low-Power Wireless Systems

- Building a low-power wireless benchmark: from roadmap to reality
  - Our main contributions: D-Cube, JamLab-NG, EWSN dependability competition



http://iti.tugraz.at/d-cube

The D-Cube low-cost & flexible benchmarking infrastructure



http://www.iti.tugraz.at/JamLab-NG

The JamLab-NG tool to generate repeatable Wi-Fi interference

https://iti-testbed.tugraz.at/ewsn2019/

The EWSN dependability competition to benchmark the state-of-the-art

Benchmarking Low-Power Wireless Systems

- Building a low-power wireless benchmark: from roadmap to reality
  - Our main contributions: D-Cube, JamLab-NG, EWSN dependability competition

Most of our research and its artefacts are publicly available!

(see QR codes in the offline version of these slides)

http://iti.tugraz.at/d-cube

The D-Cube low-cost & flexible benchmarking infrastructure

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The EWSN dependability competition to benchmark the state-of-the-art

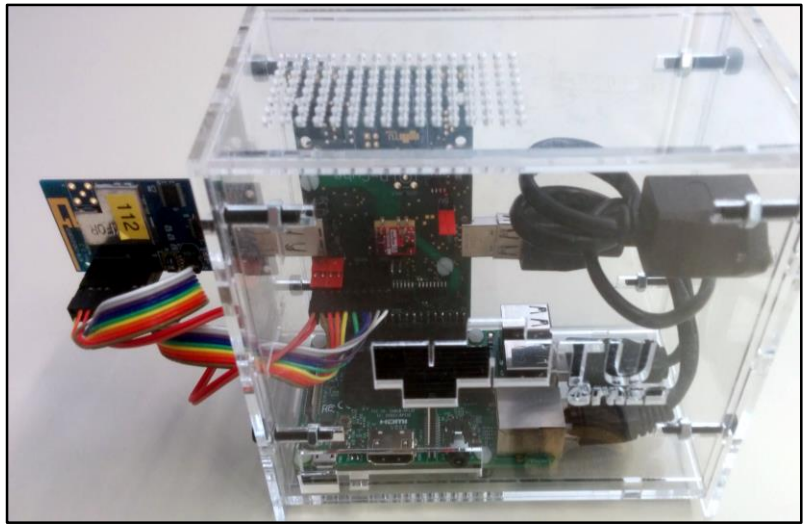
D-Cube: A Low-Cost Benchmarking Infrastructure

- Hardware allows to unobtrusively profile power, latency, and reliability
  - Off-the-shelf, low-cost components only (e.g., Raspberry Pi 3B as observers)

    → Power-profiling unit @125 kHz

    → Latency-profiling unit to timestamp events

    → GPIO tracing and actuation unit (to enable/disable nodes, vary network density, …)

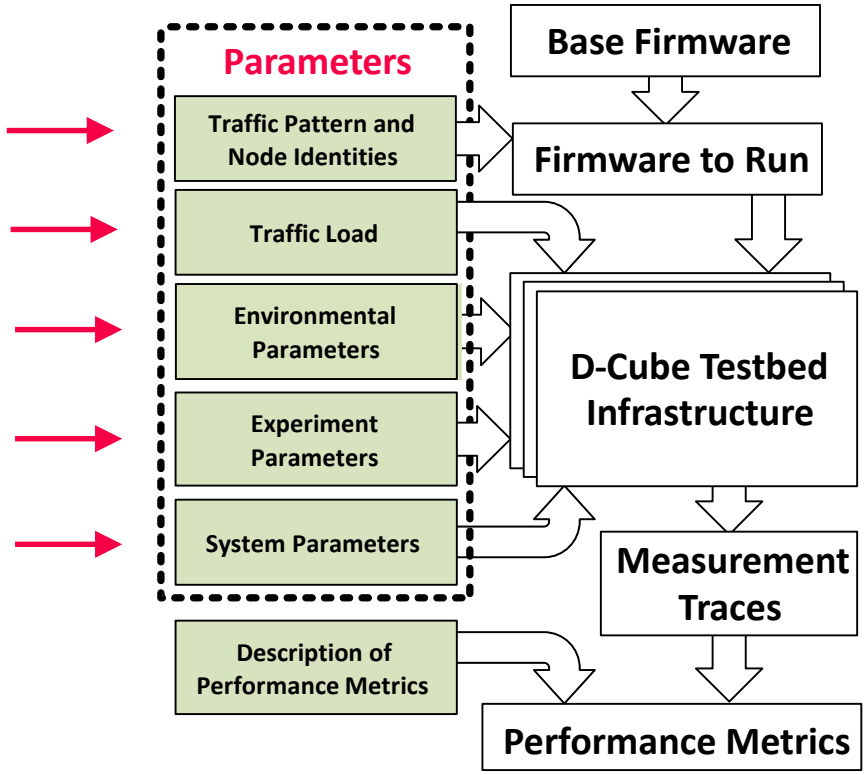


(enclosure and cabling removed)

More info: M. Schuß, C.A. Boano, M. Weber, and K. Römer. **A Competition to Push the Dependability of Low-Power Wireless Protocols to the Edge**. *In Proc. of the 14th EWSN Conference. Feb 2017.*

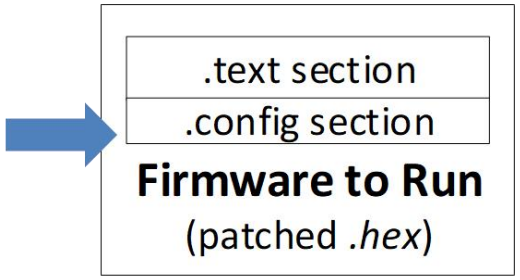
D-Cube: A Low-Cost Benchmarking Infrastructure

- Software allowing an automated & seamless execution of experiments
  - Binary patching unit to automatically replace parameters without the need to modify the firmware under test




```
//In flash configuration struct, will be replaced by binary patching
volatile config_t __attribute((section (".testbedConfigSection"))) cfg;
```

```
Section Headers:
  [Nr] Name              Type            Addr     Off    Size   ES
  [ 0]                   NULL            00000000 000000 000000 00
  [ 1] .sec1             PROGBITS        00004000 000034 0060fb 00
  [ 2] .sec2             PROGBITS        0000a0fc 00612f 0000be 00
  [ 3] .sec3             PROGBITS        0000d000 0061ed 000004 00
  [ 4] .sec4             PROGBITS        0000d400 0061f1 000100 00
```



→ Exposing a configuration struct to the developers

→ Configuration struct patched prior every execution of the firmware under test

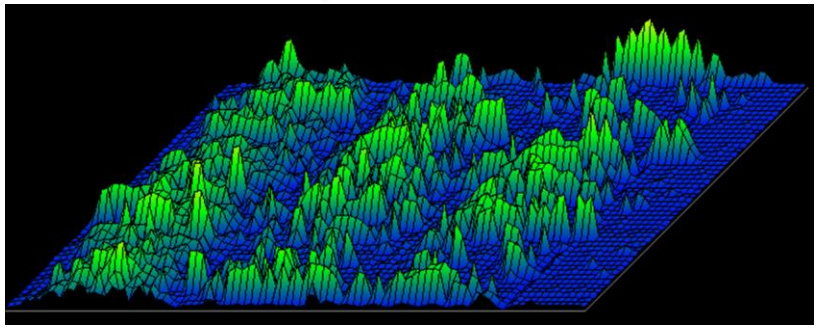
→ Allows us to control parameters such as traffic load, pattern, identity of source/destination nodes, payload length, ...

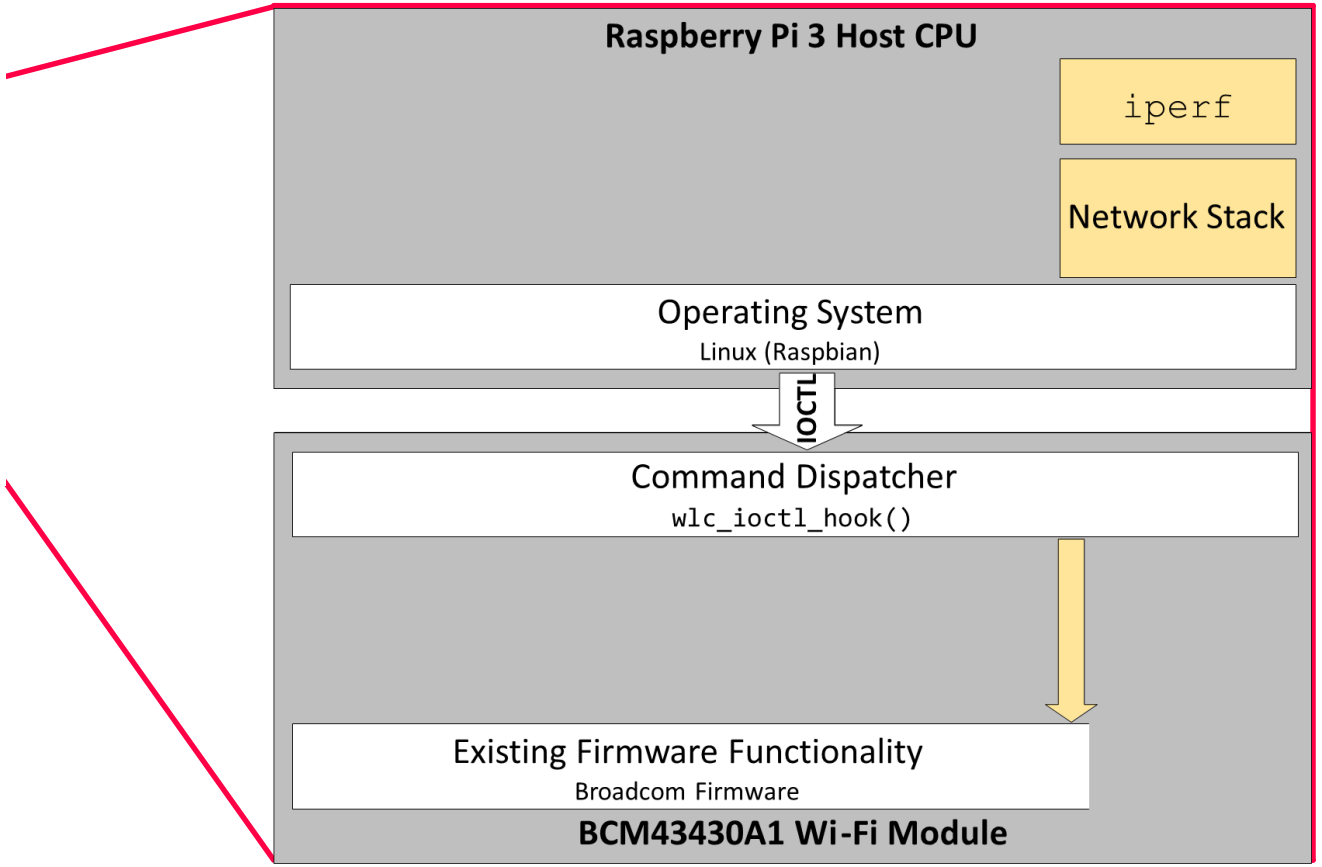
More info: M. Schuß, C.A. Boano, and K. Römer. **Moving Beyond Competitions: Extending D-Cube to Seamlessly Benchmark Low-Power Wireless Systems**. *In Proc. of the 1st CPSBench Workshop. Apr 2018.*

JamLab-NG: Repeatable Interference Generation

- Triggering the transmission of Wi-Fi packets within the radio module allows a fine-grained control of the interference properties

Repeatable Wi-Fi interference using off-the-shelf nodes





More info: M. Schuß, C.A. Boano et al. **JamLab-NG: Benchmarking Low-Power Wireless Protocols under Controllable and Repeatable Wi-Fi Interference**. *In Proc. of the 16th EWSN Conference. Feb 2019.*

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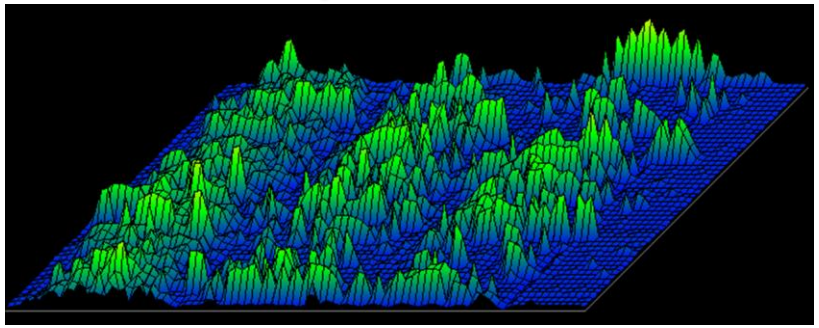

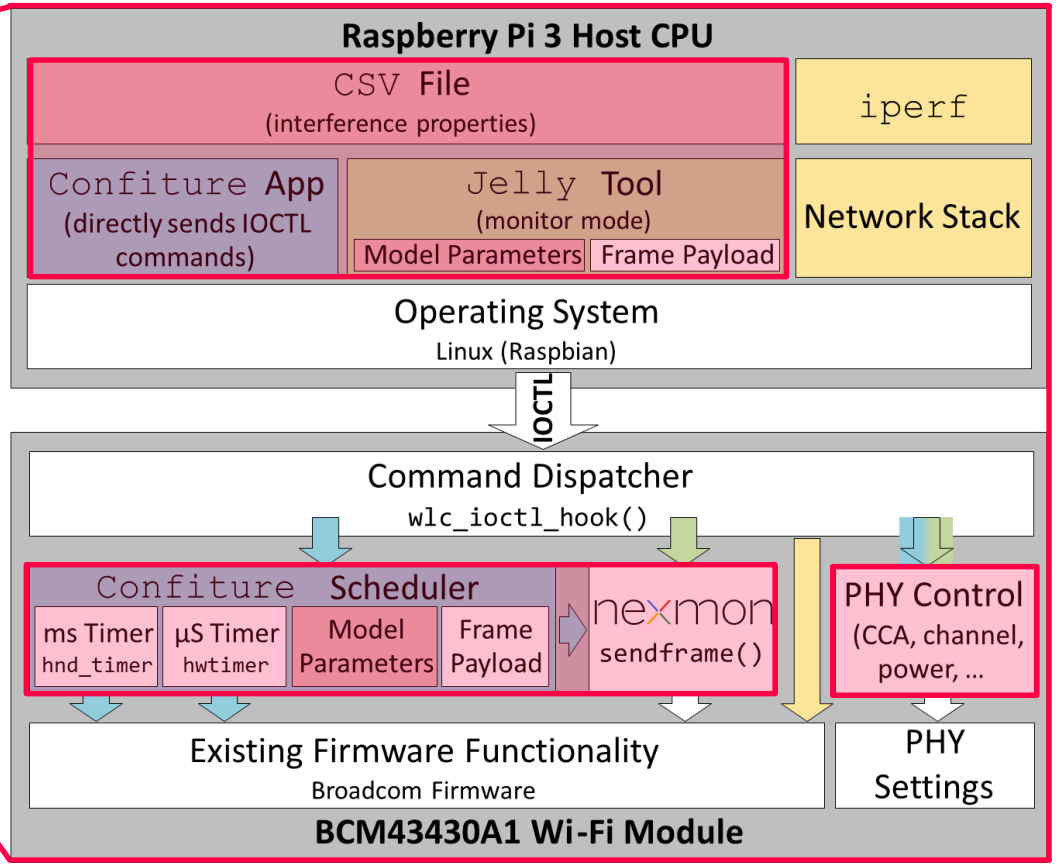

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JamLab-NG: Repeatable Interference Generation

- Triggering the transmission of Wi-Fi packets within the radio module allows a fine-grained control of the interference properties

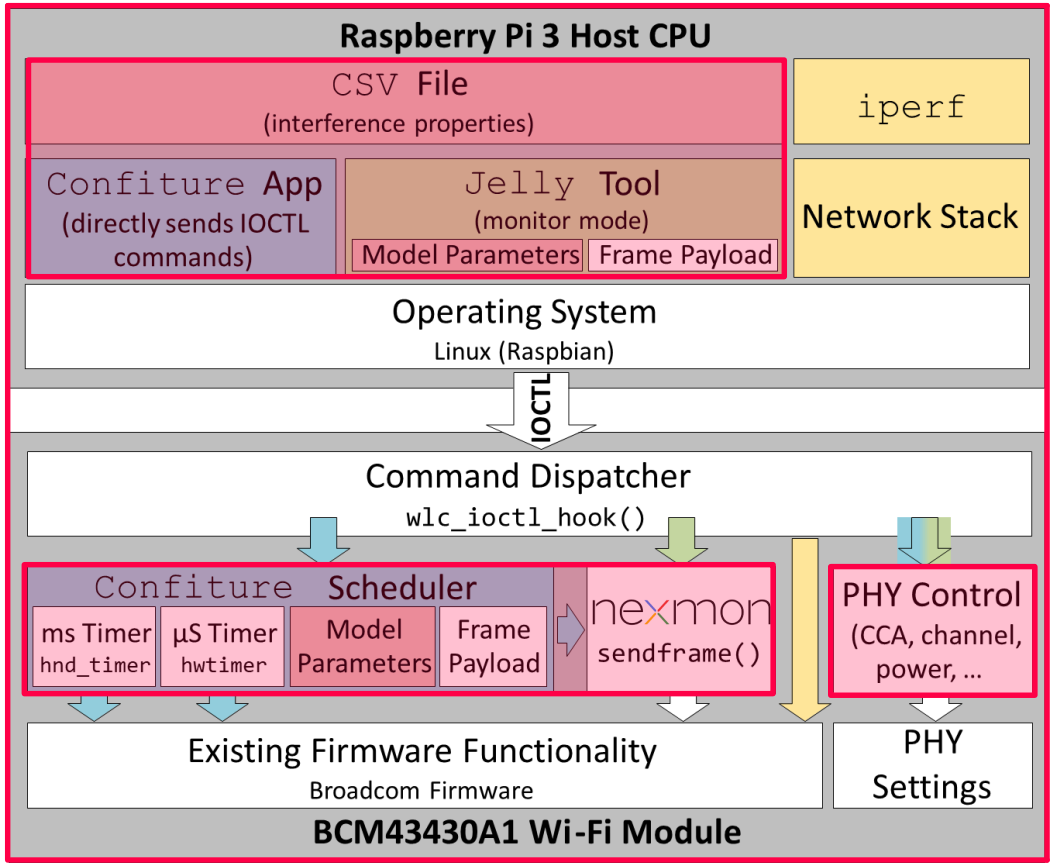
Send arbitrary raw frames ✓

No need of established connection to access point ✓

Configuration of PHY settings such as channel and transmission rate ✓

Disabling the CCA ✓

Controlling the delays introduced by OS and radio firmware ✓



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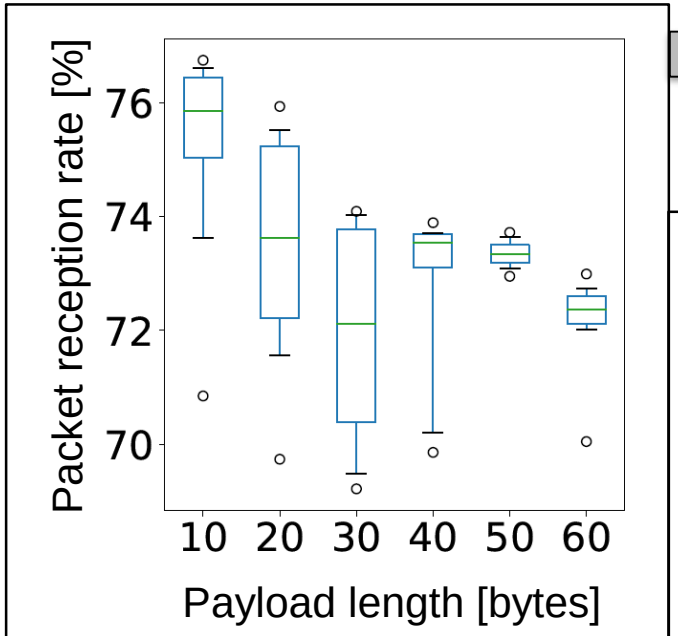
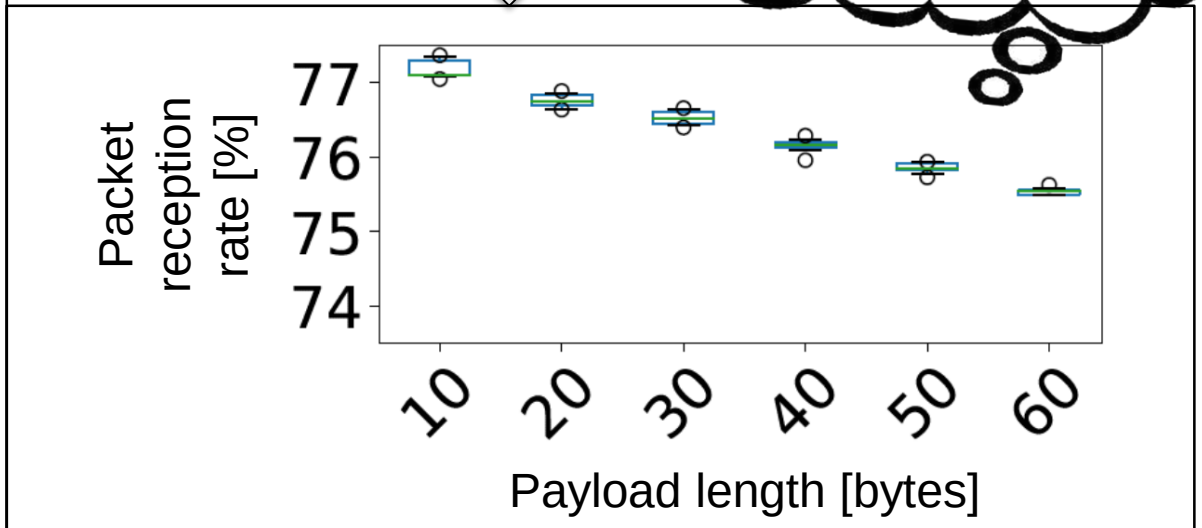
JamLab-NG: Repeatable Interference Generation

- Aftermath: comparison to standard approaches
  (rate-limited TCP connection with `iperf`)



Standard approach

Much better reproducibility!
(± 0.2%)



JamLab-NG

More info: M. Schuß, C.A. Boano et al. **JamLab-NG: Benchmarking Low-Power Wireless Protocols under Controllable and Repeatable Wi-Fi Interference**. *In Proc. of the 16th EWSN Conference. Feb 2019.*

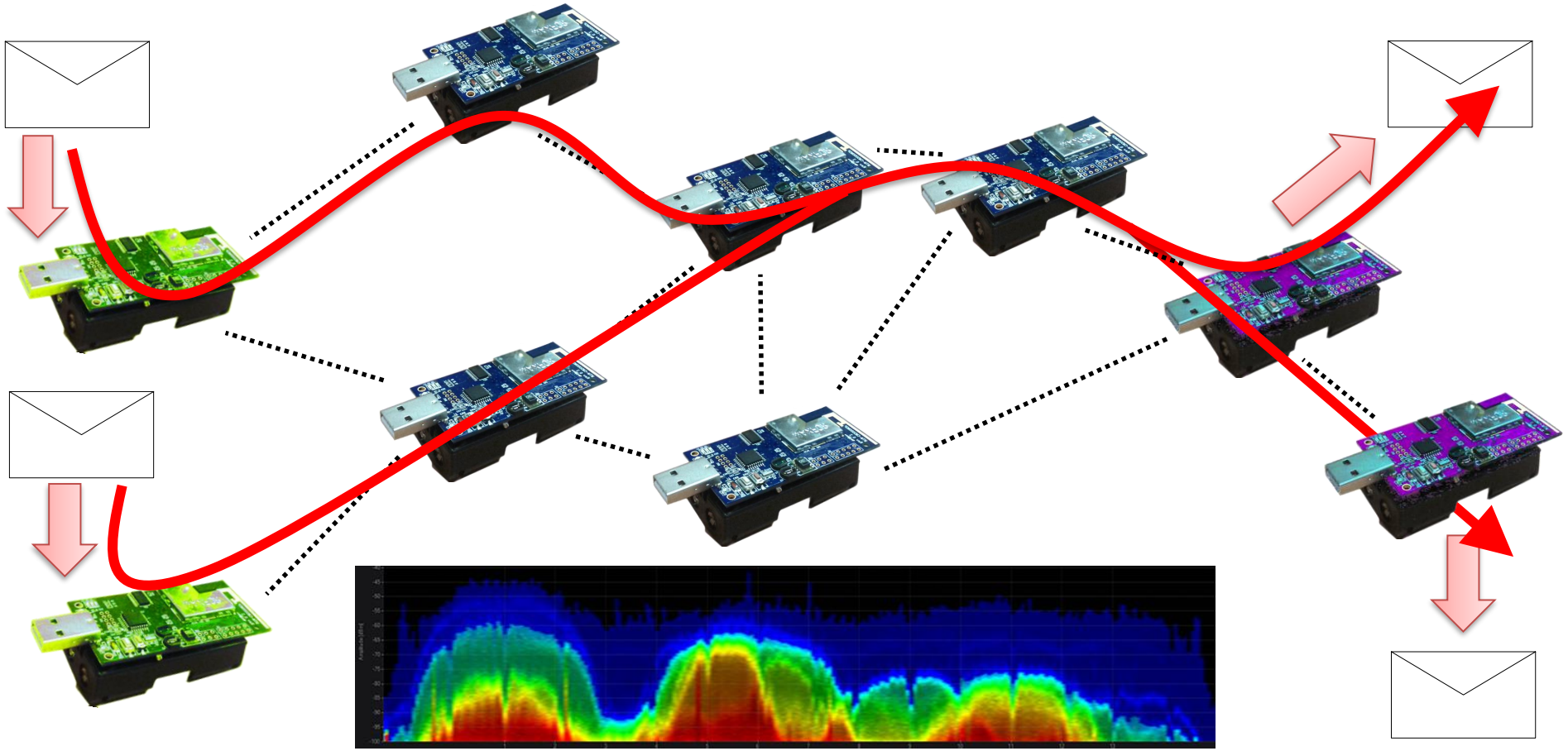
EWSN Dependability Competition Series

- Bringing researchers and practitioners together since 2016
  - Benchmarking IoT systems in the same harsh RF environments

... and many others!

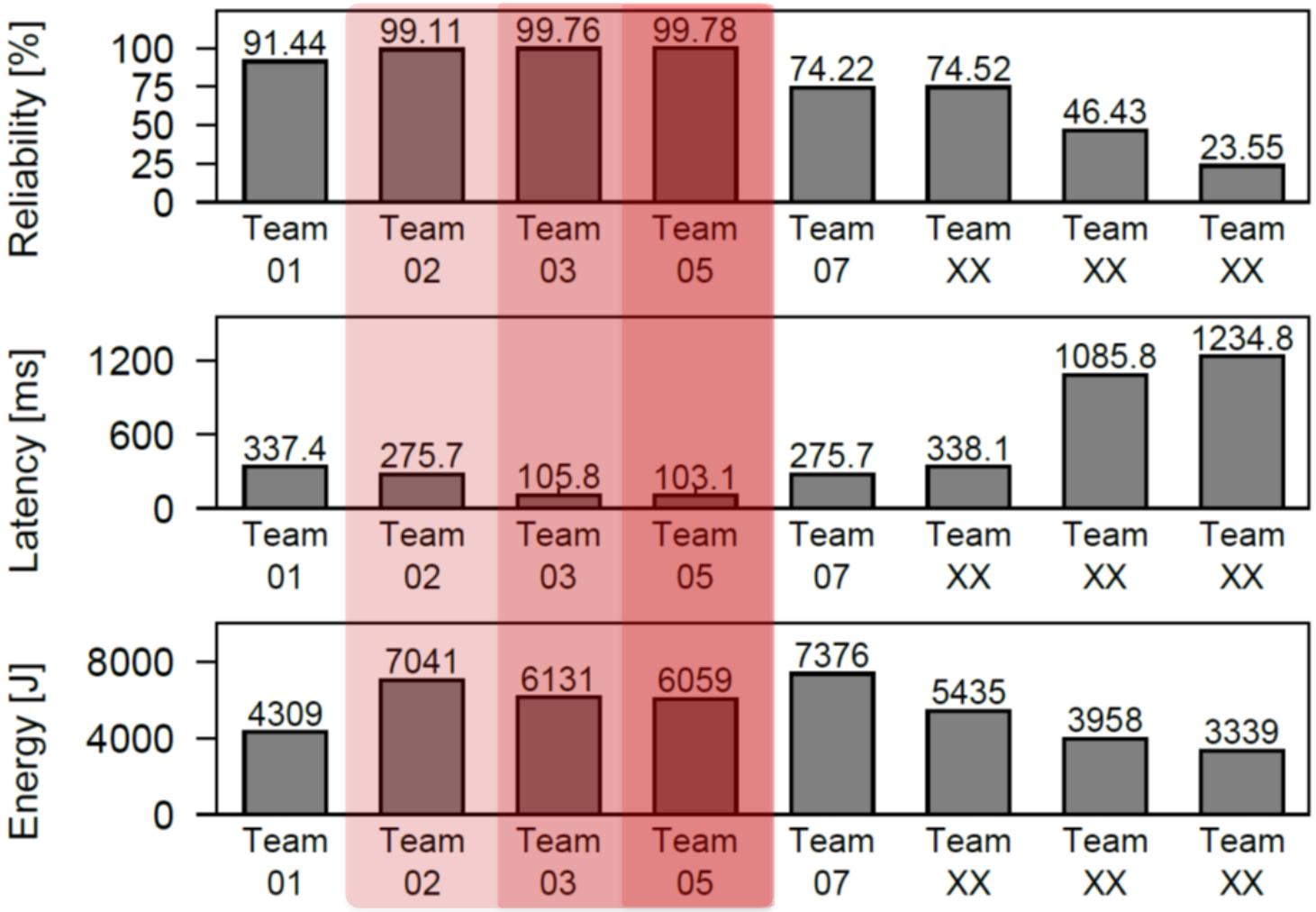
EWSN Dependability Competition Series

- Basic idea: communicating over a multi-hop network resembling an industrial setting (harsh RF environment)



EWSN Dependability Competition Series

- Evaluating key dependability metrics (reliability, timeliness, availability)

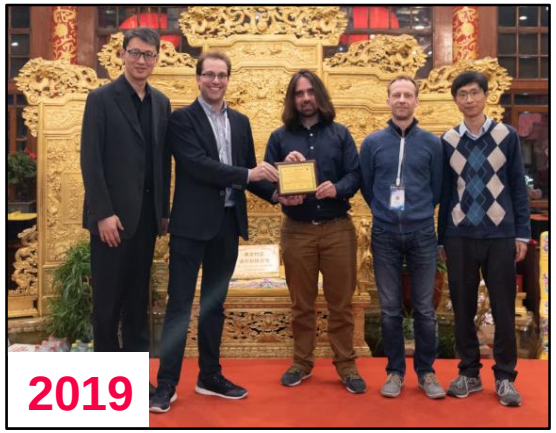


EWSN Dependability Competition Series

- Four years of EWSN dependability competition
  - Lesson learnt: synchronous transmissions are highly dependable

ETH zürich

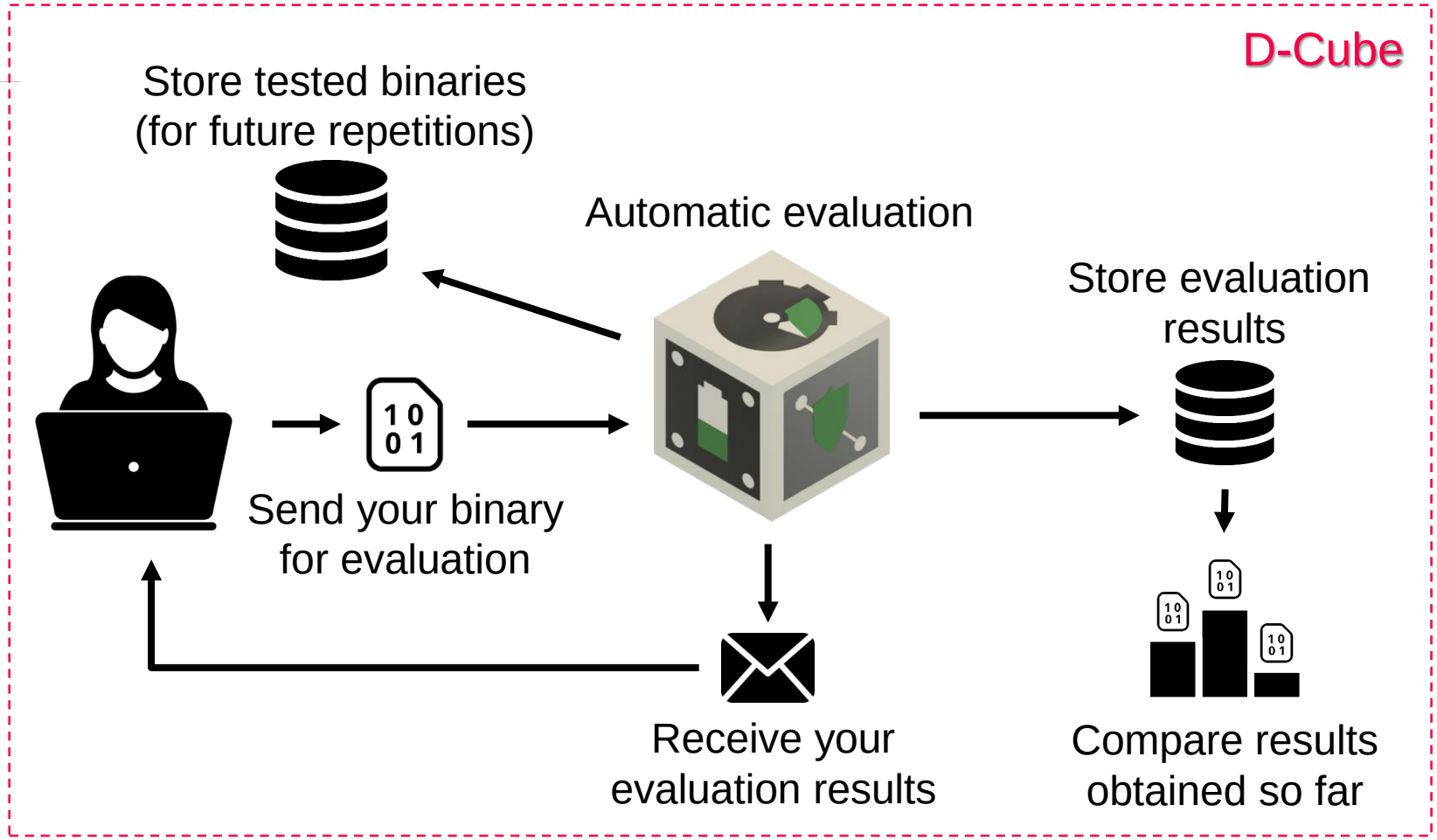
Category 1: Data collection
DeCoT+ (Shanghai Adv. Research Institute)



Category 2: Dissemination
RedNodeBus (RedNodeLabs, Germany)

From Competitions to the First Open Benchmark

- D-Cube is open to the community since November 2019



https://iti-testbed.tugraz.at

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Designing Adaptive Communication Protocols

- Requires: (i) to expose tuning knobs, (ii) to model and experimentally characterize how to use them, (iii) to devise an effective adaptation logic

Bluetooth SMART

ACM SenSys'17
ACM TIOT'19
EWSN'20

Adapt BLE connection parameters to sustain a timely and efficient performance at runtime

Ultra-wideband

IEEE WoWMoM'18

Adapt UWB link-layer settings for a better efficiency and to escape destructive interference

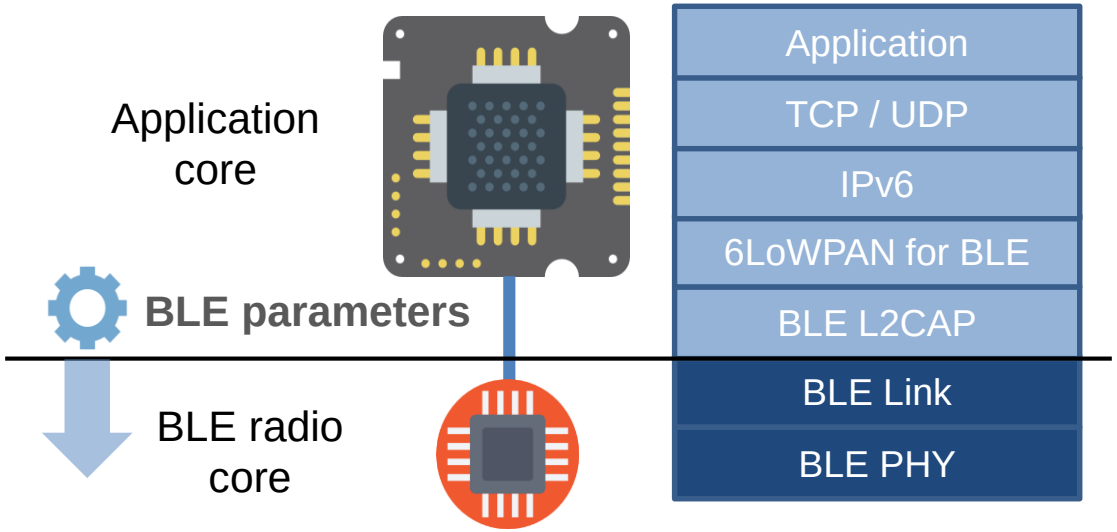
IEEE 802.15.4

IEEE INFOCOM'20

Adapt synchronous transmissions in IEEE 802.15.4 to achieve a high reliability in harsh RF environments

How to Sustain a Dependable BLE Communication?

- Recent communication standards such as BLE provide simplified APIs and networking primitives to abridge and speed-up application development



→ BLE radio = **black box**

→ No explicit radio control

→ Autonomous retransmissions

→ Autonomous frequency hopping

→ No feedback on communication

→ No info about latency, link quality, or # of retransmissions

"the BLE radio ensures that every packet queued in the transmission buffer will, eventually, be reliably transmitted"

More info: M. Spörk, C.A. Boano, et al. **BLEach: Exploiting the Full Potential of IPv6 over BLE in Constrained Embedded IoT Devices**. In Proc. of the 15th ACM SenSys Conference. November 2017.

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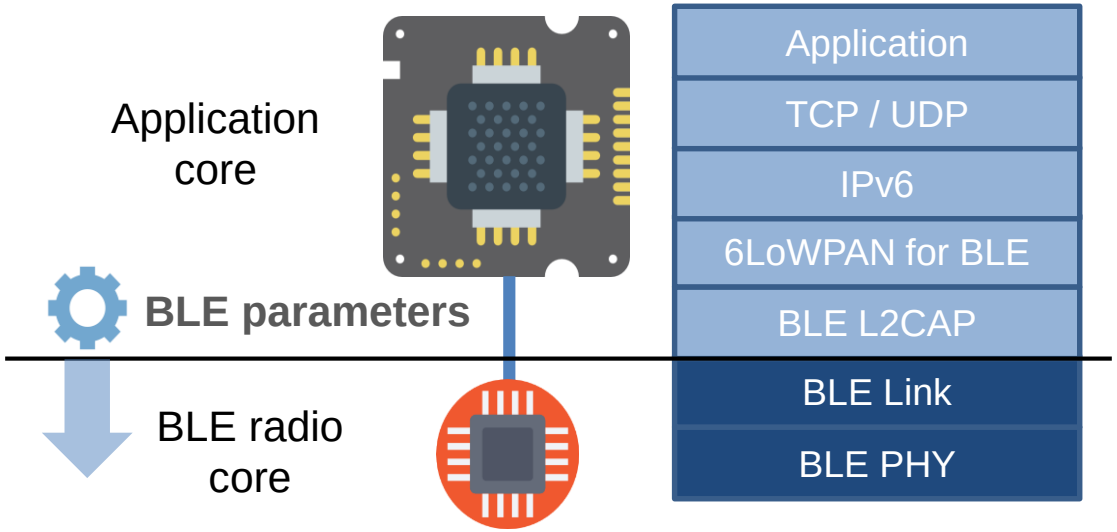
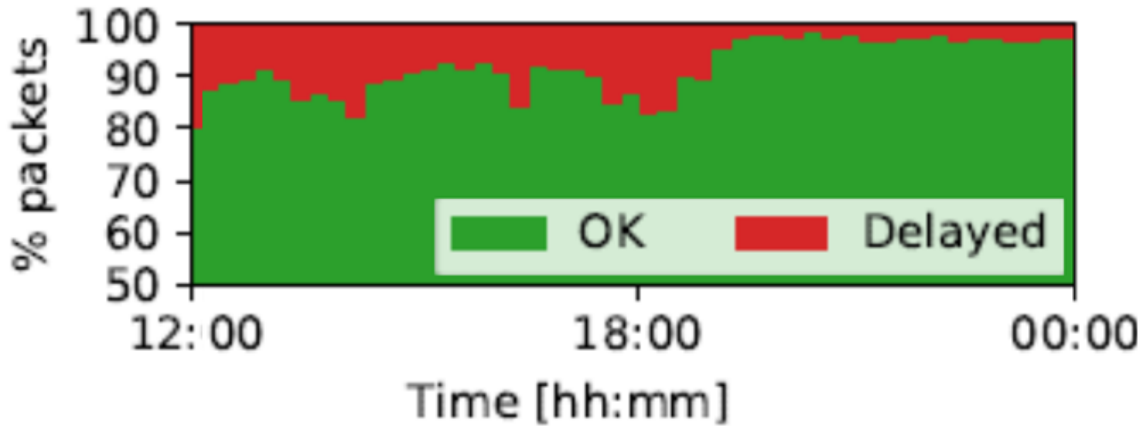




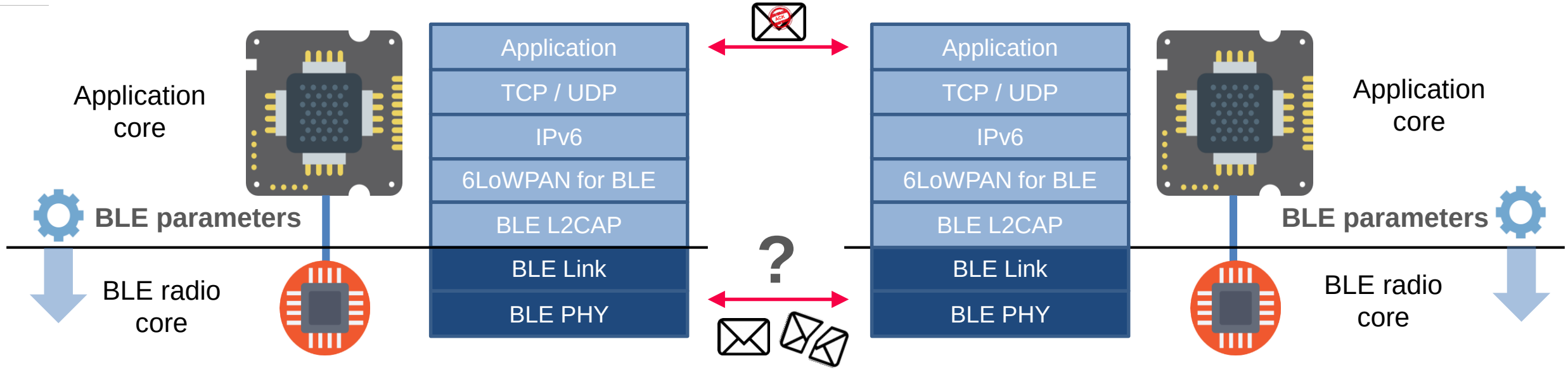
→ Consequence: several packets experience large latencies, especially under interference

"the BLE radio ensures that every packet queued in the transmission buffer will, eventually, be reliably transmitted"

More info: M. Spörk, C.A. Boano, M. Zimmerling, and K. Römer. **BLEach: Exploiting the Full Potential of IPv6 over BLE in Constrained Embedded IoT Devices**. In Proc. of the 15th ACM SenSys Conference. Nov. 2017.

How to Sustain a Dependable BLE Communication?

- How to change BLE parameters and increase the reliability and timeliness of BLE communications in an energy-efficient way?

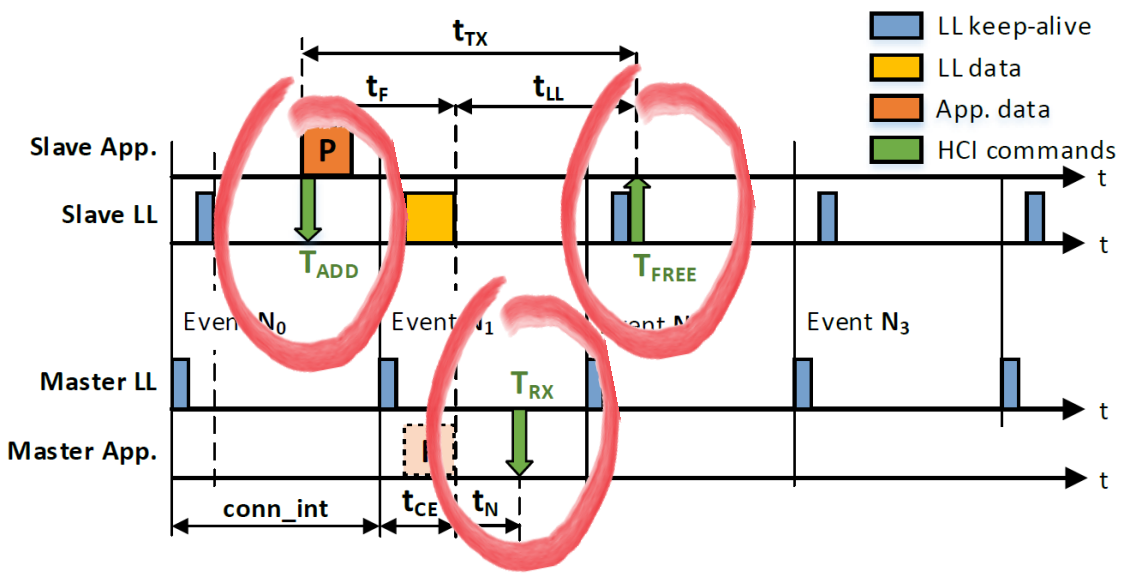


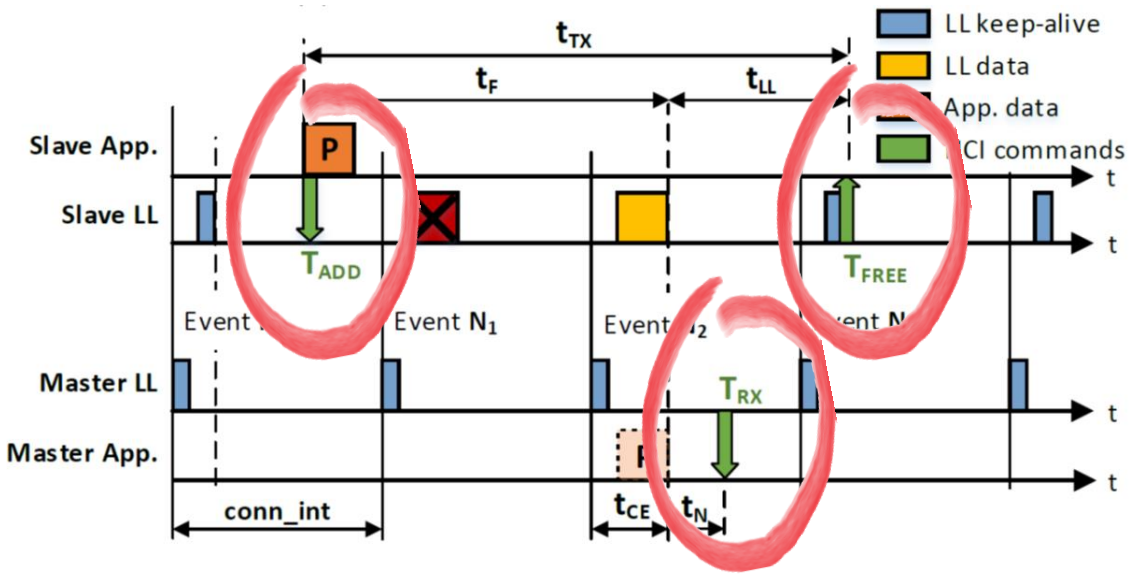
→ We started by inspecting BLE connections

More info: M. Spörk, C.A. Boano, and K. Römer. **Improving the Timeliness of Bluetooth Low Energy in Dynamic RF Environments**. (To appear in the) ACM Transactions on Internet of Things. 2020.

How to Sustain a Dependable BLE Communication?

- How to change BLE parameters and increase the reliability and timeliness of BLE communications in an energy-efficient way?
  1. Identify standard-compliant information providing insights about the link quality





→ We can use HCI timing information, e.g., when buffers are emptied/filled, to infer the activities of the link layer without the need to send explicit control packet on the application layer!

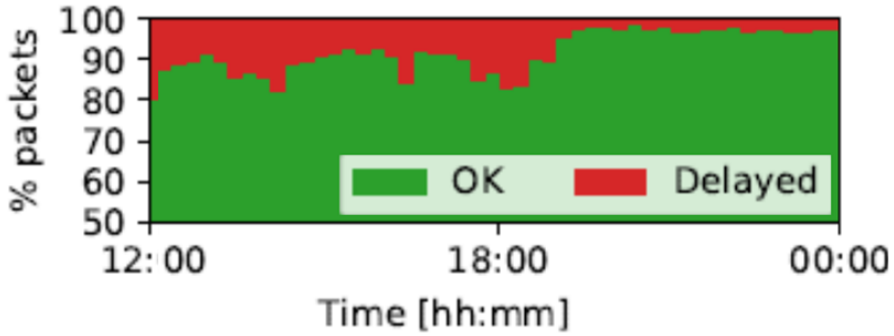
More info: M. Spörk, C.A. Boano, and K. Römer. **Improving the Timeliness of Bluetooth Low Energy in Dynamic RF Environments**. (To appear in the) ACM Transactions on Internet of Things. 2020.

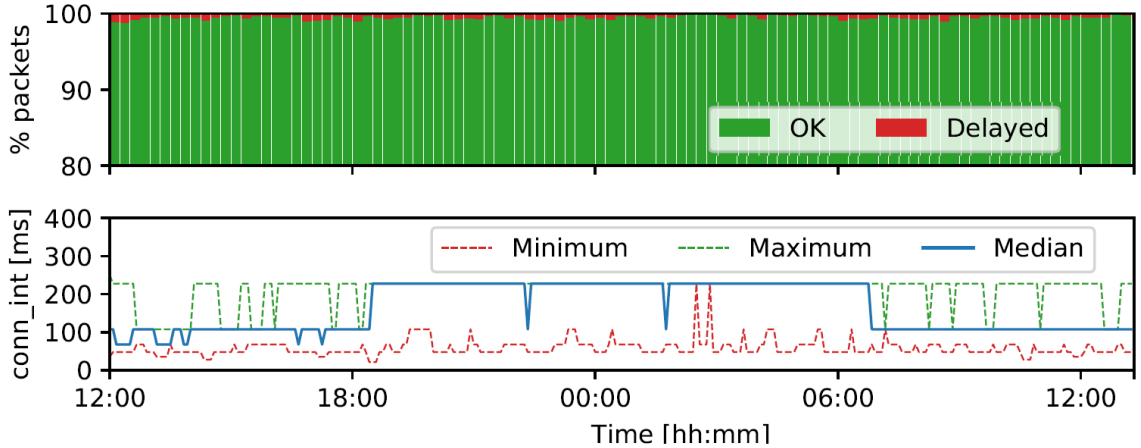
How to Sustain a Dependable BLE Communication?

- How to change BLE parameters and increase the reliability and timeliness of BLE communications in an energy-efficient way?
  1. Identify standard-compliant information providing insights about the link quality
  2. Derive models connecting this info to available BLE connection parameters

$$E = E_D + \left\lfloor \left(\left\lfloor \frac{t_D}{conn_int} \right\rfloor - n_F \right) \frac{1}{1+S_L} \right\rfloor \cdot E_K + \left(\left\lfloor \frac{t_D}{conn_int} \right\rfloor - n_F - n_K \right) \cdot E_S + E_I \qquad t_{max} = \left(\sum_{f=1}^{\lceil D/F \rceil} n_{CE_f} \cdot conn_int \right) + t_{CE} \qquad n_{CE_f} = \left\lceil \frac{t_{latency} - t_{CE}}{\lceil D/F \rceil \cdot conn_int} \right\rceil$$

  3. Build an adaptation logic improving performance at no additional energy cost





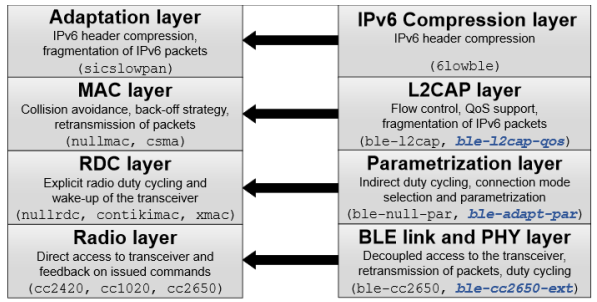
More info: M. Spörk, C.A. Boano, and K. Römer. **Improving the Timeliness of Bluetooth Low Energy in Dynamic RF Environments**. (To appear in the) ACM Transactions on Internet of Things. 2020.

How to Sustain a Dependable BLE Communication?

- How to change BLE parameters and increase the reliability and timeliness of BLE communications in an energy-efficient way?
  1. Identify standard-compliant information providing insights about the link quality
  2. Derive models connecting this info to available BLE connection parameters

$$E = E_D + \left\lfloor \left(\left\lfloor \frac{t_D}{conn_int} \right\rfloor - n_F \right) \frac{1}{1+S_L} \right\rfloor \cdot E_K + \left(\left\lfloor \frac{t_D}{conn_int} \right\rfloor - n_F - n_K \right) \cdot E_S + E_I \qquad t_{max} = \left(\sum_{f=1}^{\lceil D/F \rceil} n_{CE_f} \cdot conn_int \right) + t_{CE} \qquad n_{CE_f} = \left\lceil \frac{t_{latency} - t_{CE}}{\lceil D/F \rceil \cdot conn_int} \right\rceil$$

  3. Build an adaptation logic improving performance at no additional energy cost
  4. Build the 1st IPv6-over-BLE stack exposing these capabilities to the developer



http://iti.tugraz.at/BLEach

Open-source IPv6 over BLE stack for Contiki

More info: M. Spörk, C.A. Boano, et al. **BLEach: Exploiting the Full Potential of IPv6 over BLE in Constrained Embedded IoT Devices**. In Proc. of the 15th ACM SenSys Conference. November 2017.

Agenda

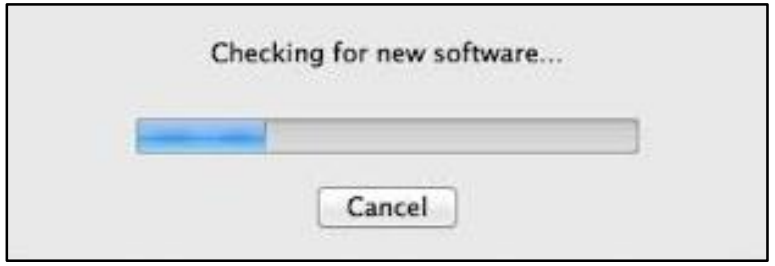
- About me
- Designing dependable networked embedded systems
  - A grand challenge in today's IoT & CPS landscape
- Selected research contributions
  - Concepts and tools to benchmark low-power wireless systems
  - Adaptive protocols for dependable communication in harsh environments
  - Trustworthy services for dependable IoT applications
- Next steps and vision

Trustworthy Services for Dependable IoT Applications

- Enabling remote maintenance and an efficient indoor positioning

UpKit: software update framework for constrained IoT devices
(*IEEE ICDCS'19*)

SecUp: software update framework for automotive systems
(*IEEE TII'17*)



Design of lightweight software update frameworks for constrained IoT devices

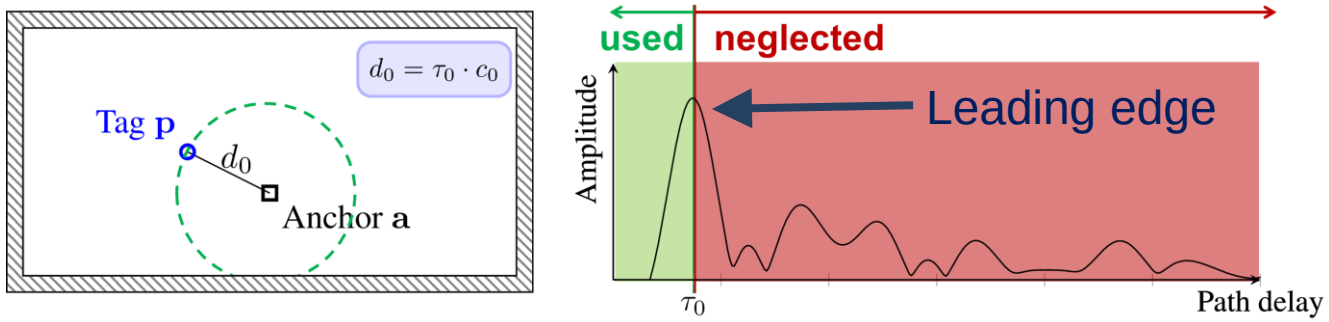
SALMA: single-anchor UWB localization
(*ACM SenSys'18*)

SnapLoc: passive UWB localization using simultaneous responses from multiple anchors
(*best paper @ ACM/IEEE IPSN'19*)

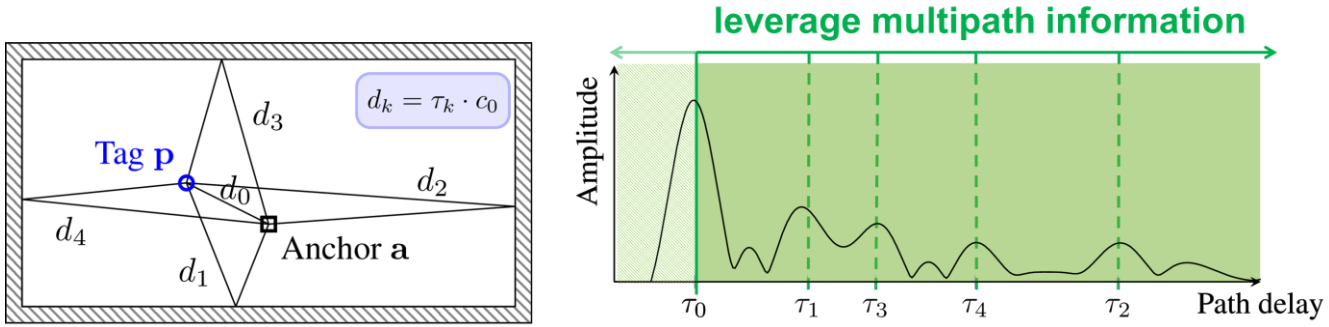
Design of low-cost, robust, efficient, and scalable indoor positioning systems based on ultra-wideband technology

Trustworthy Services for Dependable IoT Applications

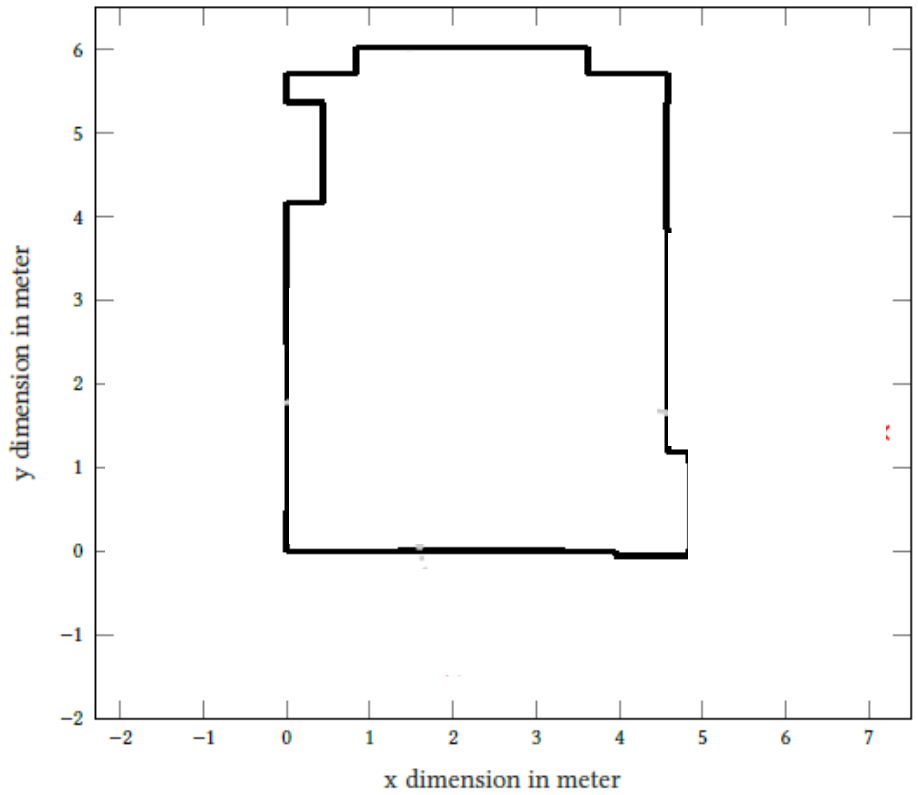
- Single-anchor UWB localization using multipath assistance (SALMA)
  - Exploit the multipath information contained in the channel impulse response (CIR)



Traditional systems: CIR provides multipath information that is neglected



SALMA: delays of multipath components contain position-related info

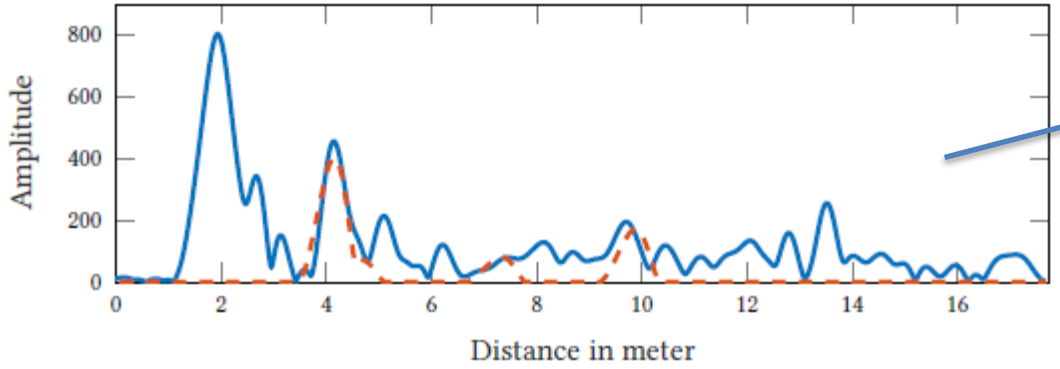


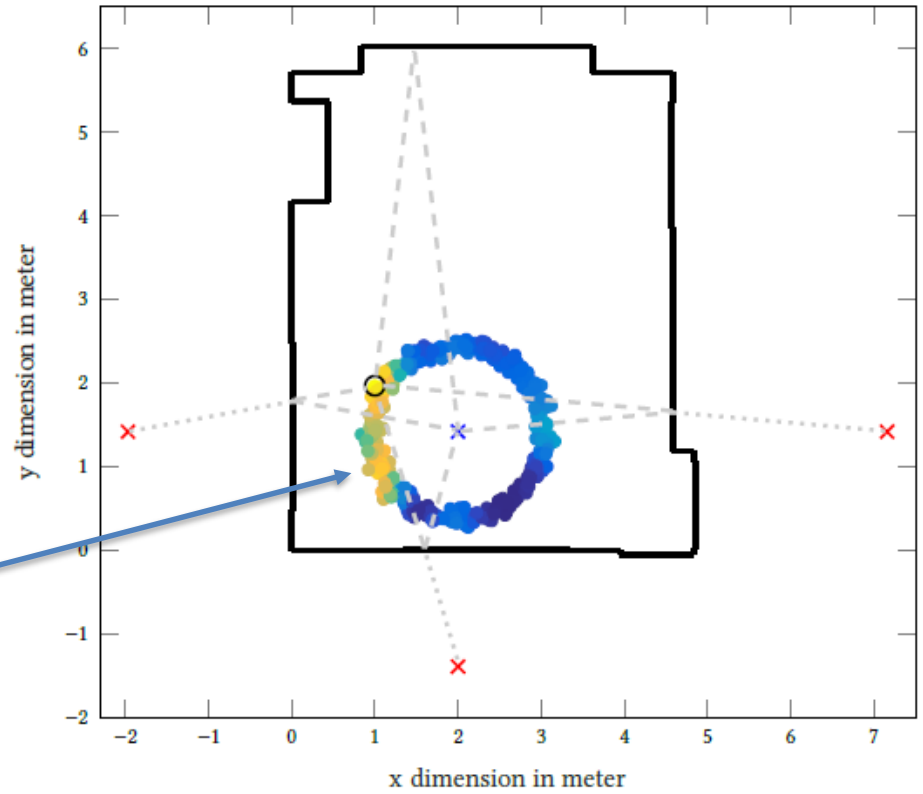
More info: B. Großwindhager, M.Rath, C.A. Boano, et al. **SALMA: UWB-based Single-Anchor Localization System using Multipath Assistance**. In Proc. of the 16th ACM SenSys Conference. Nov. 2018.

Trustworthy Services for Dependable IoT Applications

- Single-anchor UWB localization using multipath assistance (SALMA)
  - Exploit the multipath information contained in the channel impulse response (CIR)

1. Exploit known geometry of the room (crude floorplan)
2. Associate each multipath components to a virtual anchor by mirroring the single anchor at reflective surfaces
3. Choose candidate points and build an hypothesized channel impulse response for each candidate point
4. Pick those with highest similarity score (max likelihood)





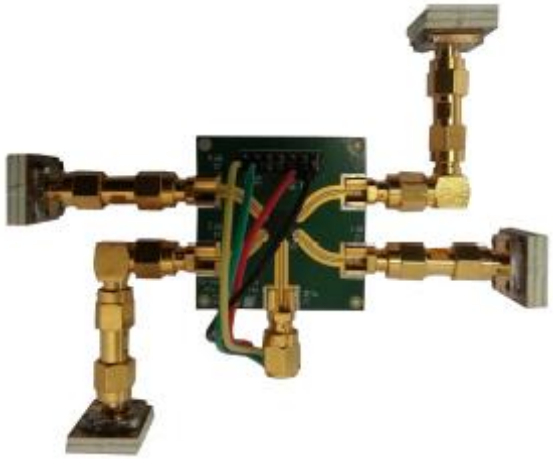
More info: B. Großwindhager, M.Rath, C.A. Boano, et al. **SALMA: UWB-based Single-Anchor Localization System using Multipath Assistance**. In Proc. of the 16th ACM SenSys Conference. Nov. 2018.

Trustworthy Services for Dependable IoT Applications

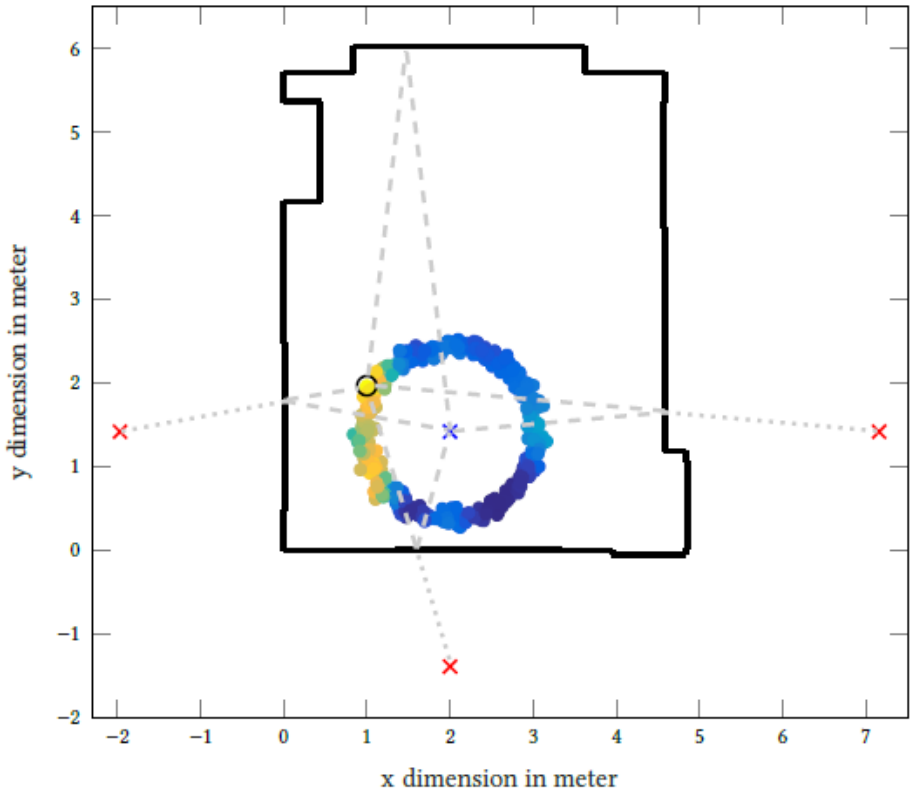
- Single-anchor UWB localization using multipath assistance (SALMA)
  - Exploit the multipath information contained in the channel impulse response (CIR)

5. Eliminate possible ambiguities using angular information
   → switchable directional antenna to refine results

Omnidirectional antenna



Directional antenna



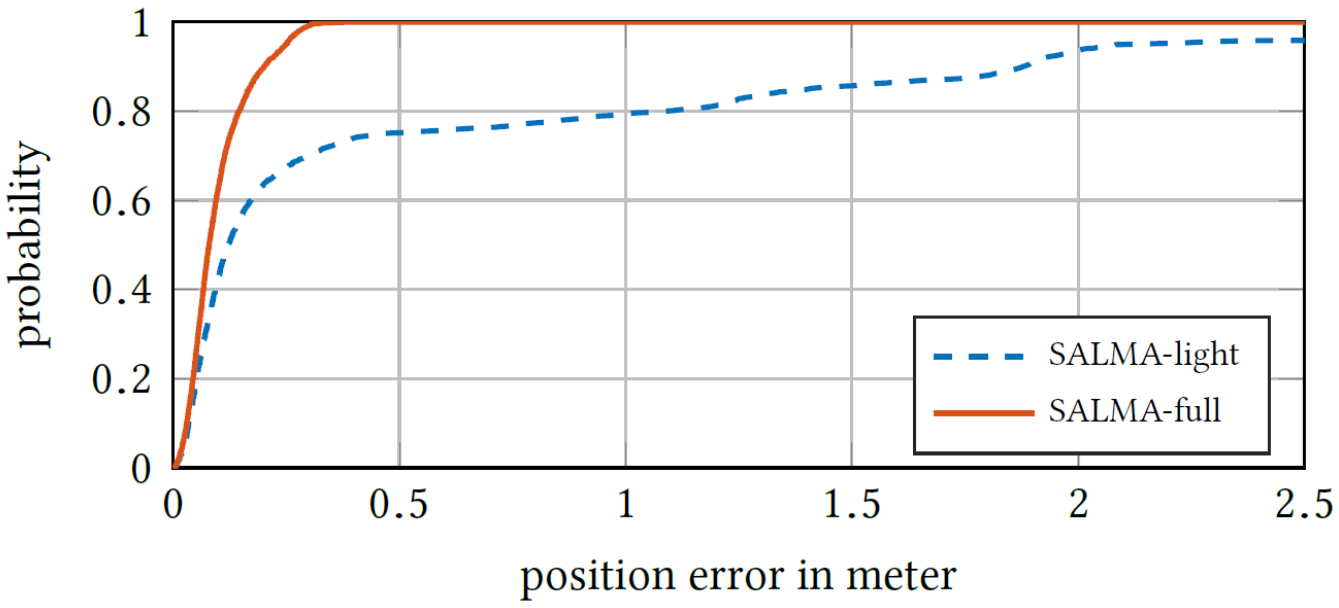
More info: B. Großwindhager, M.Rath, C.A. Boano, et al. **SALMA: UWB-based Single-Anchor Localization System using Multipath Assistance**. In Proc. of the 16th ACM SenSys Conference. Nov. 2018.

Trustworthy Services for Dependable IoT Applications

- Single-anchor UWB localization using multipath assistance (SALMA)
  - Exploit the multipath information contained in the channel impulse response (CIR)

Centimeter-level accuracy

- **LOS**: median error < 8cm
- **Obstructed LOS**: median error < 14cm



More info: B. Großwindhager, M.Rath, C.A. Boano, et al. **SALMA: UWB-based Single-Anchor Localization System using Multipath Assistance**. In Proc. of the 16th ACM SenSys Conference. Nov. 2018.

Wrapping Up

- Designing dependable networked embedded systems is a grand challenge
  - We need to support IoT and CPS designers!

- The research activities of our group provide them with:
  - Tools to benchmark low-power wireless systems
  - Protocols increasing the reliability and availability of communications even in harsh and dynamic environments
  - Services enabling an easier maintainability and accurate localization of networked embedded devices

→ Laying the foundations for more dependable CPS and IoT applications

Agenda

- About me
- Designing dependable networked embedded systems
  - A grand challenge in today's IoT & CPS landscape
- Selected research contributions
  - Concepts and tools to benchmark low-power wireless systems
  - Adaptive protocols for dependable communication in harsh environments
  - Trustworthy services for dependable IoT applications
- Next steps and vision

Next Steps and Vision

1. Harness the capabilities of next-generation IoT platforms
   - Concrete example:

TelosB mote
- 8 MHz, 16-bit TI MSP430
- 10 kB RAM, 48 kB Flash
- External IEEE 802.15.4 radio only

Nordic Semic. nRF52840DK
- 64 MHz, 32-bit Cortex-M4
- 256 kB RAM, 1 MB Flash
- Integrated IEEE 802.15.4 + BLE 5.0 radio + others

What is the role of the hardware platform / underlying radio technology?

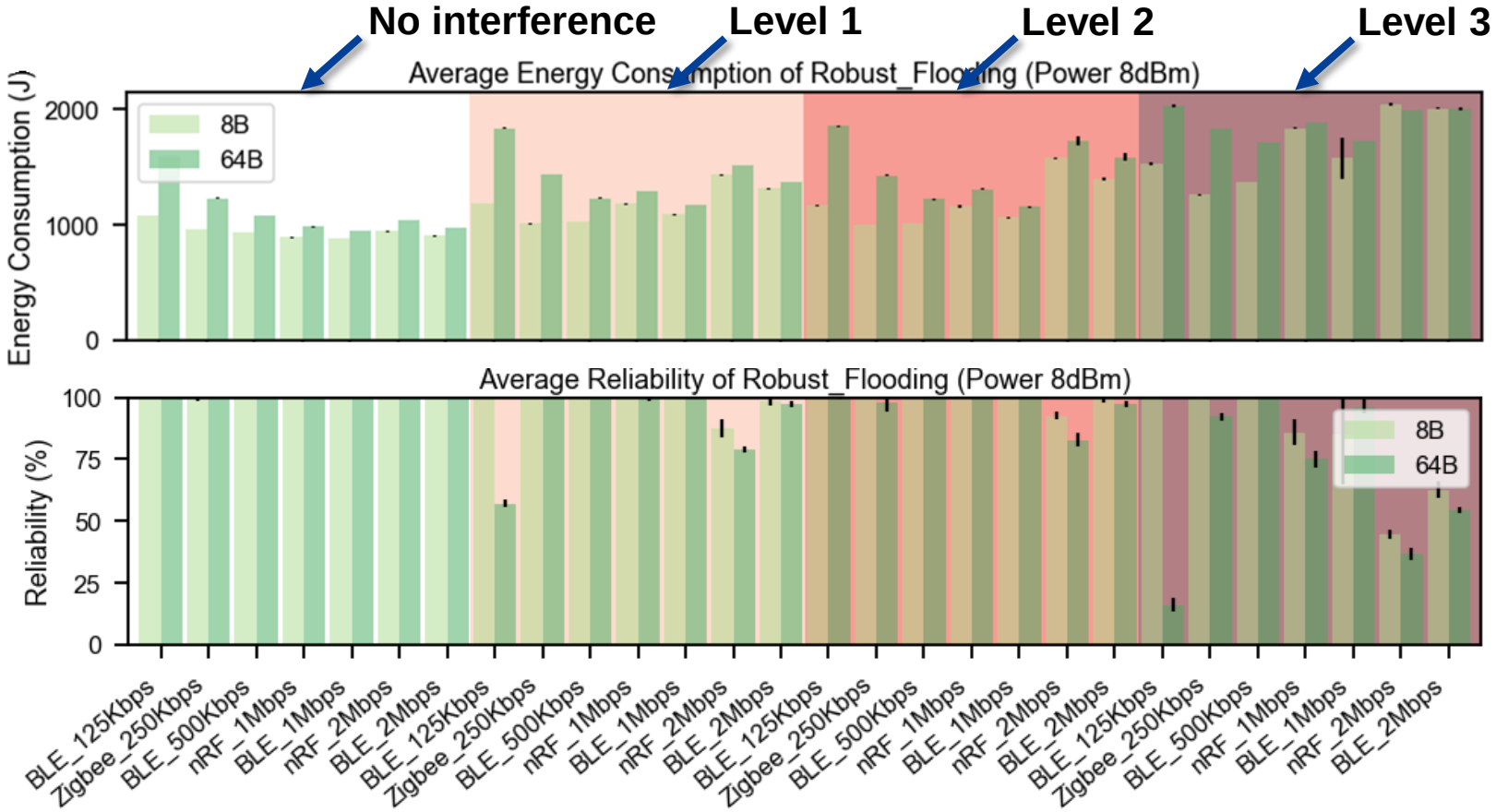
Which new tuning knobs can we exploit to improve communication performance?

→ We are using the D-Cube Benchmark to find an answer

Next Steps and Vision

1. Harness the capabilities of next-generation IoT platforms
   - Concrete example: impact of PHY layer used on dependability

- BLE 2 Mbps
- BLE 1 Mbps
- BLE 500 kbps
- BLE 125 kbps
- IEEE 802.15.4 (250 kbps)
- nRF proprietary (1 and 2 Mbps)

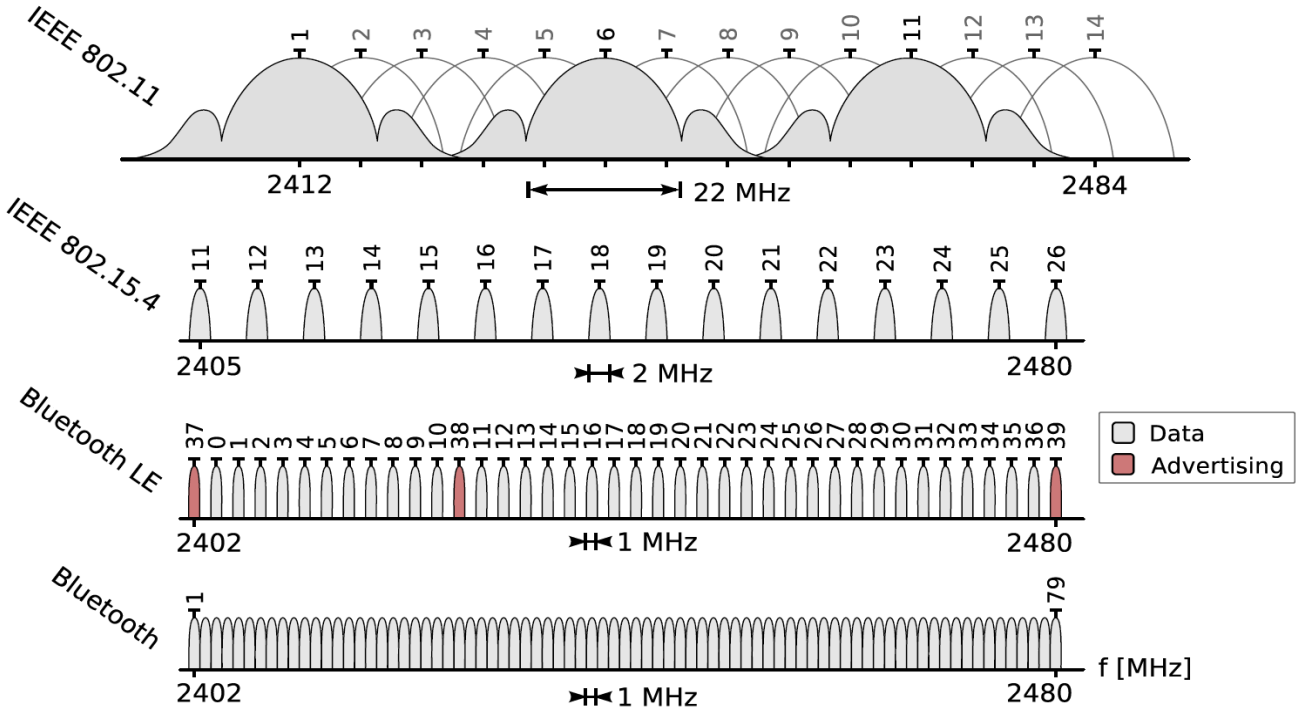


→ Exploit observations to build smarter protocols!

Next Steps and Vision

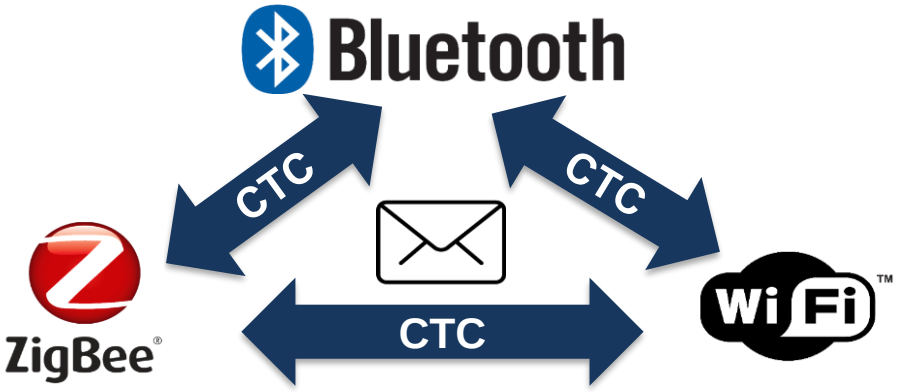
2. Enabling a seamless coexistence between co-located wireless devices
   - Will become even more important as the IoT scales up to 500 billion units
   - The trend of today's protocols is not exactly towards "*spectrum-friendliness*"

Example:
cross-technology interference in the 2.4 GHz ISM band

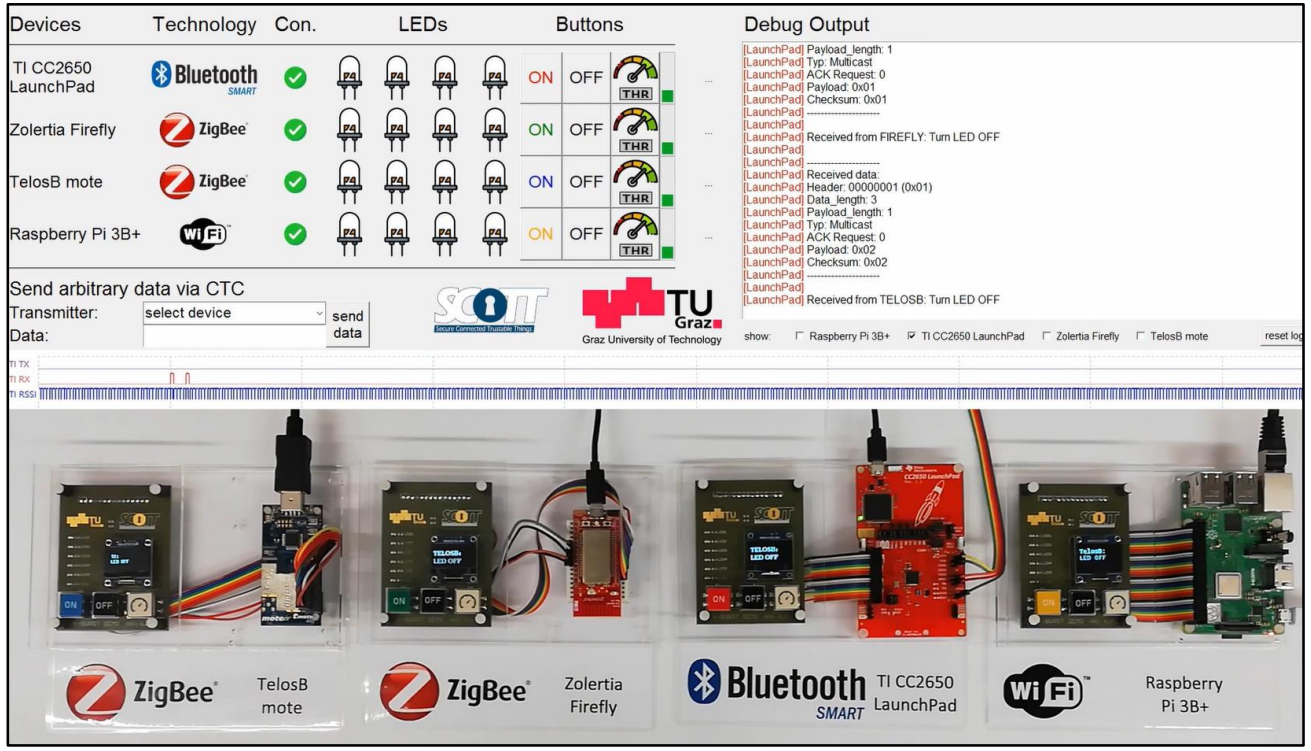


Next Steps and Vision

2. Enabling a seamless coexistence between co-located wireless devices
   - Stepping stone: generic cross-technology broadcast communication



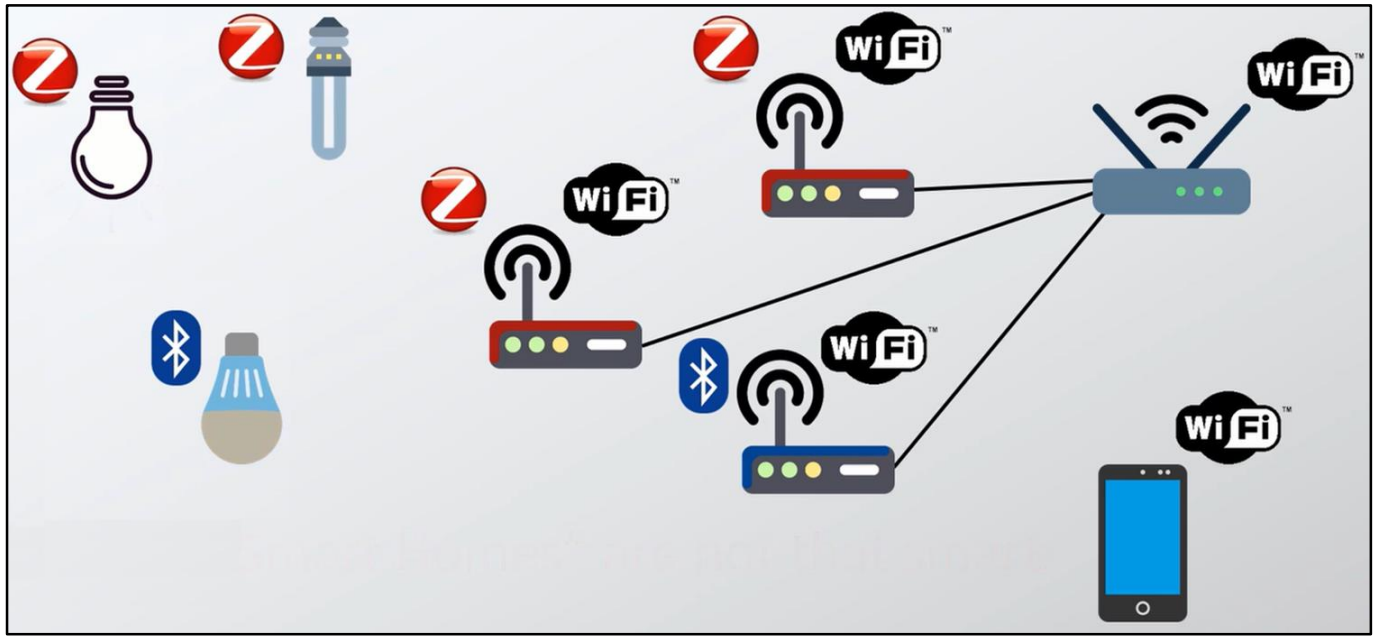
- Showcased at EWSN'20 on many off-the-shelf IoT platforms
- Broadcast across BLE, Zigbee, and Wi-Fi devices at ≥ 1kbps



More info: H. Brunner, C.A. Boano, et al. **Cross-Technology Broadcast Communication between Off-The-Shelf Wi-Fi, BLE, and IEEE 802.15.4 Devices.** *In Proc. of the 17th EWSN Conf.* Feb 2020. **Best demo award.**

Next Steps and Vision

2. Enabling a seamless coexistence between co-located wireless devices
   - Stepping stone: generic cross-technology broadcast communication across Wi-Fi, BLE, and IEEE 802.15.4 devices (up to several kbps)
   - Additional services
     - Clock synchronization
     - Device discovery and rendezvous
     - Channel allocation and arbitration
     - Coexistence management
   - Additional application areas
     - Example: smart home



More info: R. Hofmann, C.A. Boano, et al. **X-Burst: Enabling Multi-Platform Cross-Technology Communication between Constrained IoT Devices.** *In Proc. of the 16th IEEE SECON Conf.* June 2019. **Best Paper Award.**

Next Steps and Vision

3. Enabling a sustainable Internet of Things

- 500 billion devices by 2030 [Cisco]
- We should think now about how to prolong the usable lifetime of devices that become obsolete
- Cross-technology communication could enable communication with legacy devices

Technologies and Tools for the Design of Dependable Networked Embedded Systems

Tools

Protocols

Services

"laying the foundations for more dependable CPS and IoT applications"

Thank you for your attention!

Images from tecnoconsulenza.it (https://tinyurl.com/rvamha9), biz-architect.com (https://tinyurl.com/sx4cymr), pymnts.com (https://tinyurl.com/qpzexcv), dogtownmedia.com (https://tinyurl.com/smbvldw), industriahoje.com.br (https://tinyurl.com/wg2zlx5), marines.mil (https://tinyurl.com/ustevqx), wikimedia.org (https://tinyurl.com/tz6gkv6, https://tinyurl.com/sfmvl54), lectures.tik.ee.ethz.ch (https://tinyurl.com/shqqnlh), desertjet.com (https://tinyurl.com/wdhqx5y), wp.com (https://tinyurl.com/s85997s), dekalbcountyonline.com (https://tinyurl.com/sftzfrq), hp.com (https://support.hp.com/doc-images/95/c01867509.gif).