IoT — From Praxis to Theory

Part I: The Practical Part

Florian Metzger – March 2, 2018

comnet.informatik.uni-wuerzburg.de

How to participate

- Slides contain further literature references to the topics
- Interrupt and ask at any time
- Share your experiences, recommendations, “war stories”!
- Slides are at: `https://www.tru42.org/fm/mmb2018-iotpraxis-tutorial.pdf`

Why me?

Topical

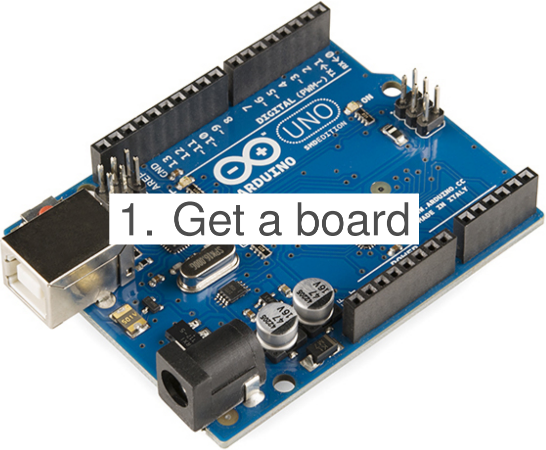
- Dissertation about 3G core network signaling (and video streaming)
- Wrote a data-sensing smartphone app
- Ongoing IoT projects (student and industrial)
- Licensed radio amateur (DL4TCP)
- Gave up on soldering in school (too many cold joints), rejoiced when Arduinos and Raspberries came along

Other interests

- Always interested in the current Internet topology (new application types, and especially L7 and L4 protocols)
- Interactive applications, vidoe games, and QoE research
- Performance evaluation and data analysis

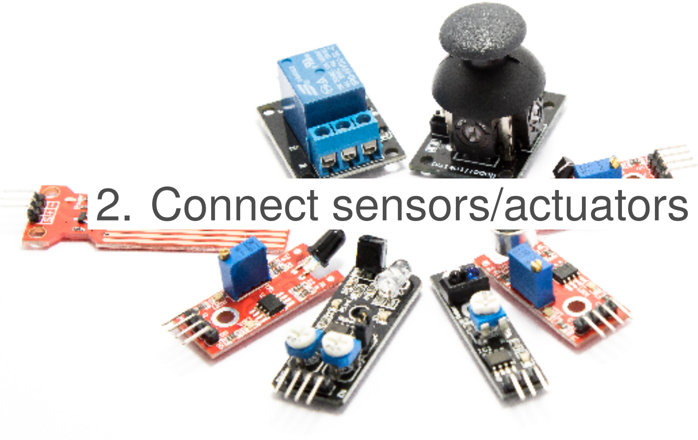
Five simple steps to practical IoT

Five simple steps to practical IoT



1. Get a board

Five simple steps to practical IoT



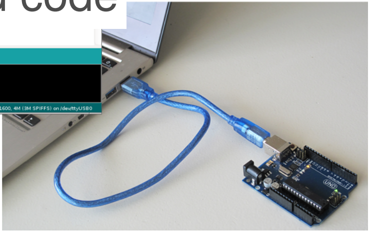
2. Connect sensors/actuators

Five simple steps to practical IoT

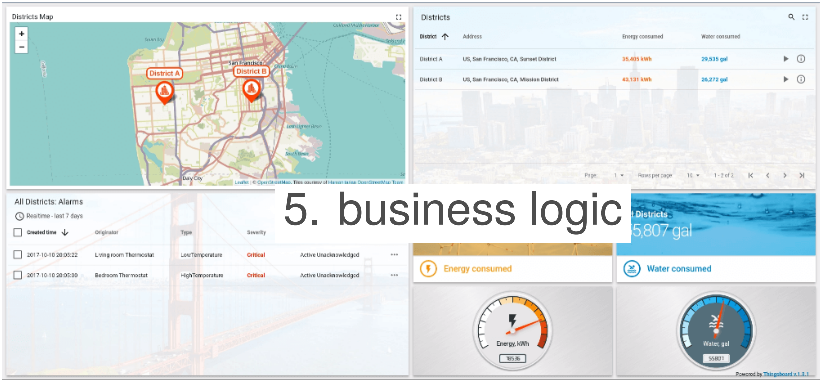
3. Hook it up to a gateway with a RF TX

Five simple steps to practical IoT

4. Upload code



Five simple steps to practical IoT



5. business logic

6. Profit? Done?

6. Profit? Done?

But before you start...

6. Profit? Done?

But before you start...

- Data? Data protection?
- Board? System?
- Protocols? Stack?
- RF TX? Network architecture?
- Traffic Analysis and Modeling? (→ **part ii**)

6. Profit? Done?

But before you start...

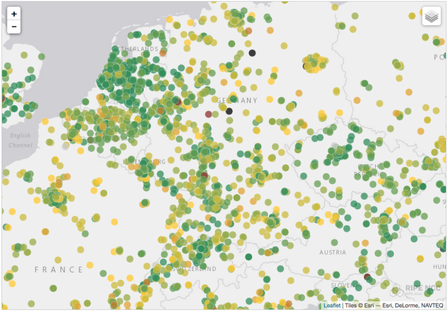
- Data? Data protection?
- Board? System?
- Protocols? Stack?
- RF TX? Network architecture?
- Traffic Analysis and Modeling? (→ **part ii**)

⇒ **A top-down....ish approach**

IoT Project Examples

RIPE Atlas[1]

- Not-for-profit EMEA Internet registrar
- Volunteers can apply for wired network probes to hook up to their Internet access



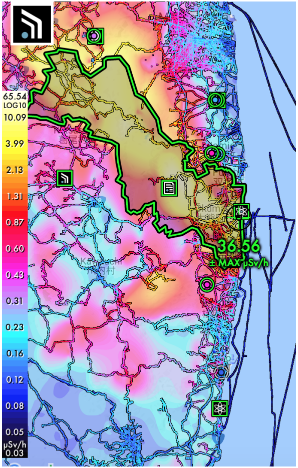
RTT to fixed destinations (e.g. root servers)

[1] https://atlas.ripe.net/landing/measurements-and-tools/

IoT Project Examples

Safecast

- Open data project to collect environmental data (radiation)
- BT-connected probes to mobile apps
- 71M data points, 1000 community probes worldwide



[1] https://blog.safecast.org/

Community, NGO, and Academic IoT Projects

Common Motifs

- Often centered around data collection and **sensing**
  - Often situated in places with no immediate Internet access, ideally suited for **LPWAN**
  - Or in home automation: relies on residential Internet link plus WLAN or **WPAN**
- Crowdsourcing and participatory **Crowdsensing**
- Operate through **volunteers** and **donated resources**
- Recurring and operational costs are undesirable
- Often based on cheap, hackable boards (e.g. **Arduino and derivatives**) and other ready-made tools

Section 1

Data and Data Protection

Crowdsensing and Crowdsourcing

- Focus on data collection and preparation in a meaningful way
- Crowdsensing with dedicated IoT devices, or using existing mobile **phones**
- Plethora of built-in **sensors** and ways to interact with environment and user
- Incentivised through **participatory** aspects or with monetary compensation
  - ⇒ Citizen science
- Simple participation, huge potential user base
- Suitable for sensing and crowdsourcing projects
  - Must be aware of **Quality of Information** and engagement issues (amongst others)
  - Requires strict security and data protection and **privacy** considerations

Participatory Mobile Sensing and Mobile Testbeds

Overview

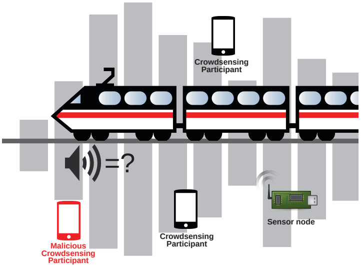
- Community-driven and citizen science projects show very promising results
- Can integrate data from many sources, participants and external
- Different types of projects
  - Act as large-scale, real-world network testbeds
  - Automated data collection (more akin to sensor networks and IoT), e.g. crowdsensing or crowdmapping
  - Questionnaires or user-generated reports/events (onetime, or ongoing/triggered, or hybrid of both; akin to crowdsourcing)
- Emphasis on location-based aspects, context factors
- Best practice: Open data (can also help with engagement)

Project Examples

Noise Sensing[2]

- Goal: Accurate and verified measurement of noise level (high QoI)
- But: Heterogeneous and unreliable devices and users
- How do we separate good from bad (or even malicious) data?
- Importance of systematic coverage of area

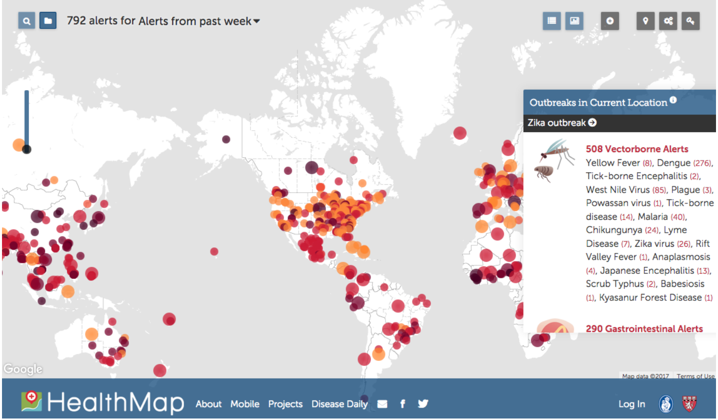
⇒ mixed smartphone and LPWAN use case



[2] Sebastian Surminski. “Reliable Noise Level Measurement Using Crowdsensing (Talk)”. In: *ITG FA 5.2 Workshop on Smart Cities*. Lübeck, Germany, 2017.

Project Examples

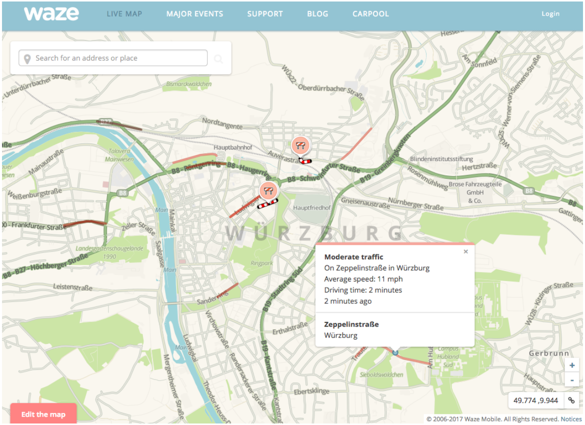
HealthMap



User-reported outbreaks combined with data from formal sources

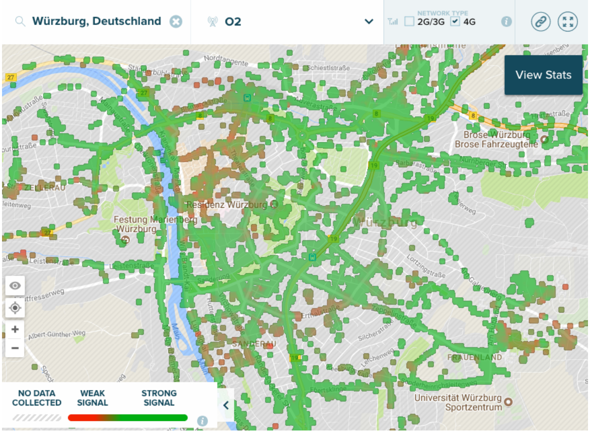
Project Examples

Traffic Information: Waze



Project Examples

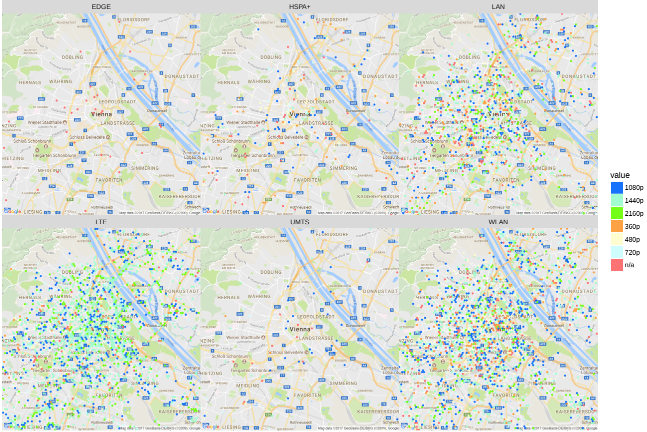
OpenSignal



Cellular radio coverage

Work-in-progress project

“QoE” Crowdmapping



Estimating application quality through throughput data collection and open data sets (here: “Which YouTube video quality can I get in my network at this position?”)

Project Examples

Network Testbed Projects

- Computer network research relies on simulated and real testbeds
- Local-only testbed installations only give limited results
- Global testbeds: e.g. PlanetLab, G-Lab
  - Aging infrastructure, not representative of actual user device environments

[3] https://www.iot-lab.info/

Project Examples

Network Testbed Projects

- Computer network research relies on simulated and real testbeds
- Local-only testbed installations only give limited results
- Global testbeds: e.g. PlanetLab, G-Lab
  - Aging infrastructure, not representative of actual user device environments
- Solution: Provide virtualized testbed environment on representative user devices (or distributed IoT testbeds)
  - (Implicitly, involuntarily) Chrome (Firefox): You tested e.g. SPDY/HTTP/2 and QUIC
  - Seattle Testbed: Resource-restricted Python VM slices on participants' devices
  - Sensibility Testbed: Same as Seattle, but for smartphones and with sensors
  - IoT-LAB[3]: 2000 centrally managed IoT nodes spread across France

[3] https://www.iot-lab.info/

The Dark Side of IoT and Crowdsensing

- Mobile devices and sensors are part of daily lives
- Experience/store all kinds of sensitive data
  - Location, call/chat/browsing logs, A/V recordings,…
- Metadata and other data points might at first glance seem totally inconspicuous and OK to collect

The Dark Side of IoT and Crowdsensing

- Mobile devices and sensors are part of daily lives
- Experience/store all kinds of sensitive data
  - Location, call/chat/browsing logs, A/V recordings,…
- Metadata and other data points might at first glance seem totally inconspicuous and OK to collect
  - E.g. inferring inputs/passwords through accelerometer
  - Exploiting side channels, sensor fusion, machine learning
- Privacy and data minimization mandated by law

The Dark Side of IoT and Crowdsensing

“Use Cases”

- “Are my employees in the office on time and for 8h?”

The Dark Side of IoT and Crowdsensing

“Use Cases”

- “Are my employees in the office on time and for 8h?”
  - ⇒ temperature, barometric pressure, humidity, loudness, …

The Dark Side of IoT and Crowdsensing

"Use Cases"

- "Are my employees in the office on time and for 8h?"
  - ⇒ temperature, barometric pressure, humidity, loudness, …
  - ⇒ RF propagation (body water)

The Dark Side of IoT and Crowdsensing

“Use Cases”

- “Are my employees in the office on time and for 8h?”
  - ⇒ temperature, barometric pressure, humidity, loudness, …
  - ⇒ RF propagation (body water)
- “What movie is she watching?”

The Dark Side of IoT and Crowdsensing

“Use Cases”

- “Are my employees in the office on time and for 8h?”
  - ⇒ temperature, barometric pressure, humidity, loudness, …
  - ⇒ RF propagation (body water)
- “What movie is she watching?”
  - ⇒ Smart meter live readings correlated with video decoder power usage

The Dark Side of IoT and Crowdsensing

"Use Cases"

- "Are my employees in the office on time and for 8h?"
  - ⇒ temperature, barometric pressure, humidity, loudness, …
  - ⇒ RF propagation (body water)
- "What movie is she watching?"
  - ⇒ Smart meter live readings correlated with video decoder power usage
- "How many people are watching this live broadcast sports event?"

The Dark Side of IoT and Crowdsensing

“Use Cases”

- “Are my employees in the office on time and for 8h?”
  - ⇒ temperature, barometric pressure, humidity, loudness, …
  - ⇒ RF propagation (body water)
- “What movie is she watching?”
  - ⇒ Smart meter live readings correlated with video decoder power usage
- “How many people are watching this live broadcast sports event?”
  - ⇒ Fresh water consumption, waste water production correlated with breaks

The Dark Side of IoT and Crowdsensing

"Use Cases"

- "Are my employees in the office on time and for 8h?"
  - ⇒ temperature, barometric pressure, humidity, loudness, …
  - ⇒ RF propagation (body water)
- "What movie is she watching?"
  - ⇒ Smart meter live readings correlated with video decoder power usage
- "How many people are watching this live broadcast sports event?"
  - ⇒ Fresh water consumption, waste water production correlated with breaks
- "Find out where someone lives or find secret army bases?"

The Dark Side of IoT and Crowdsensing

“Use Cases”

- “Are my employees in the office on time and for 8h?”
  - ⇒ temperature, barometric pressure, humidity, loudness, …
  - ⇒ RF propagation (body water)
- “What movie is she watching?”
  - ⇒ Smart meter live readings correlated with video decoder power usage
- “How many people are watching this live broadcast sports event?”
  - ⇒ Fresh water consumption, waste water production correlated with breaks
- “Find out where someone lives or find secret army bases?”
  - ⇒ Use (Strava) fitness tracker data.

The Dark Side of IoT and Crowdsensing

"Use Cases"

- "Are my employees in the office on time and for 8h?"
  - ⇒ temperature, barometric pressure, humidity, loudness, …
  - ⇒ RF propagation (body water)
- "What movie is she watching?"
  - ⇒ Smart meter live readings correlated with video decoder power usage
- "How many people are watching this live broadcast sports event?"
  - ⇒ Fresh water consumption, waste water production correlated with breaks
- "Find out where someone lives or find secret army bases?"
  - ⇒ Use (Strava) fitness tracker data.
- In automation: "Can I harm someone with this device?"

The Dark Side of IoT and Crowdsensing

"Use Cases"

- "Are my employees in the office on time and for 8h?"
  - ⇒ temperature, barometric pressure, humidity, loudness, …
  - ⇒ RF propagation (body water)
- "What movie is she watching?"
  - ⇒ Smart meter live readings correlated with video decoder power usage
- "How many people are watching this live broadcast sports event?"
  - ⇒ Fresh water consumption, waste water production correlated with breaks
- "Find out where someone lives or find secret army bases?"
  - ⇒ Use (Strava) fitness tracker data.
- In automation: "Can I harm someone with this device?"
  - ⇒ Destroying nuclear centrifuges (Stuxnet)

The Dark Side of IoT and Crowdsensing

“Use Cases”

- “Are my employees in the office on time and for 8h?”
  - ⇒ temperature, barometric pressure, humidity, loudness, …
  - ⇒ RF propagation (body water)
- “What movie is she watching?”
  - ⇒ Smart meter live readings correlated with video decoder power usage
- “How many people are watching this live broadcast sports event?”
  - ⇒ Fresh water consumption, waste water production correlated with breaks
- “Find out where someone lives or find secret army bases?”
  - ⇒ Use (Strava) fitness tracker data.
- In automation: “Can I harm someone with this device?”
  - ⇒ Destroying nuclear centrifuges (Stuxnet)
  - ⇒ Redirect a self-driving car into a river?

The Dark Side of IoT and Crowdsensing

“Use Cases”

- “Are my employees in the office on time and for 8h?”
  - ⇒ temperature, barometric pressure, humidity, loudness, …
  - ⇒ RF propagation (body water)
- “What movie is she watching?”
  - ⇒ Smart meter live readings correlated with video decoder power usage
- “How many people are watching this live broadcast sports event?”
  - ⇒ Fresh water consumption, waste water production correlated with breaks
- “Find out where someone lives or find secret army bases?”
  - ⇒ Use (Strava) fitness tracker data.
- In automation: “Can I harm someone with this device?”
  - ⇒ Destroying nuclear centrifuges (Stuxnet)
  - ⇒ Redirect a self-driving car into a river?
  - ⇒ Cryptocurrency mining on your smart fridge?

The Dark Side of IoT and Crowdsensing

Sensitive Data and Lack of Security

And What About Security?

- *Disclaimer: I am not an expert, go ask one!*
- Security is a basic requirement for privacy and data protection
- IoT security encompasses many aspects
  - Appropriate threat model
  - More than access control
  - Attestation/trusted computing
  - Transmission confidentiality and integrity
  - Keeping your data safe (or not storing it at all)
  - No side-channels, and much more
- Requires **constant maintenance**
  - Secure update path for devices

Regulation (EU) 2016/679

General Data Protection Regulation (GDPR)

- Binding for any member state, enforceable from 25 May 2018
- Fines of up to €20M
- Accompanied by Privacy and Electronic Communications Directive 2002/58/EC
- Concerns any kind of personal data (“personal data is any information relating to an individual, whether it relates to his or her private, professional or public life. It can be anything from a name, a home address, a photo, an email address, bank details, posts on social networking websites, medical information, or a computer’s IP address.”)
- Implications for research?

Regulation (EU) 2016/679

General Data Protection Regulation (GDPR)

- “Privacy by default”, “privacy by design”
  - E.g. non-reversible anonymization (or pseudonymization) as early as possible
  - **Pseudonymized data is still considered personal data**
- Principle of data minimization, only absolutely required data may be stored
- Data must only be stored for a specific, predetermined purpose, deleted immediately afterwards
- Data breaches must be reported within 72 h
- Right of access, right to erasure, data portability right
- Explicit consent required for processing
- Records of processing activities must be maintained

General Privacy Solution Approaches

- Administrative/governmental approaches
  - Establish strict oversight, privacy policy
  - Carefully select only data to be collected that is absolutely necessary
  - Oversight by an internal review board, checks and approves each data point
  - Give control of data to user and let her decide

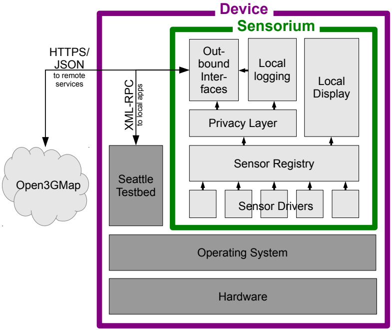
General Privacy Solution Approaches

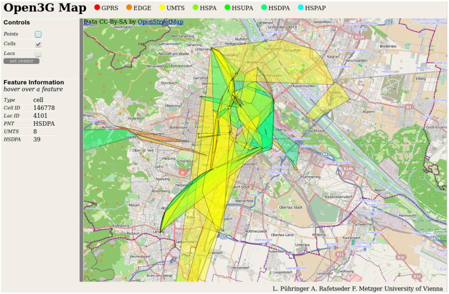
- Administrative/governmental approaches
  - Establish strict oversight, privacy policy
  - Carefully select only data to be collected that is absolutely necessary
  - Oversight by an internal review board, checks and approves each data point
  - Give control of data to user and let her decide
- Technical solutions
  - Decouple data from specific users
  - Anonymize or pseudonymize data at the earliest possible time
  - Blur data (i.e. reduce resolution or precision)
  - Client-side data perturbation and pooling
  - Differential privacy

Built-in Capabilities of Smartphone OSs

- User-choice on install (older phones) or on first use
- Can be later changed (your app must be able to respect and handle this)
- Similar (but not the same) on most mobile platforms
- However
  - Many apps will refuse to work if configured more restrictive (i.e. not really a user-choice)
  - Permissions are coarse-grained, do not cover everything and are binary
    - E.g. Android apps don't need permission to access the Internet any more
  - No precise per app access logs for sensors/data

Sensorium & O3GM[4]





User choice & technical solutions (blurring)

[4] A. Rafetseder et al. "Sensorium – A Generic Sensor Framework". In: *PIK - Praxis der Informationsverarbeitung und Kommunikation* 36.1 (Feb. 2013), p. 46.

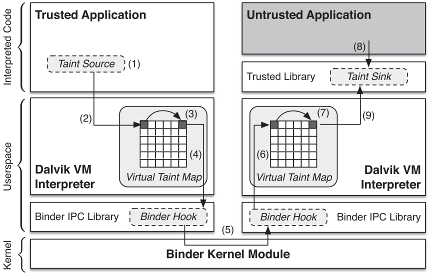
Sensibility Testbed[5]

- Generic, centrally-managed virtual testbed, isolated experiment slices
- Runs on donated resources
- Privacy policy and IAB approval for each experiment
- Sensor blurring concepts
  - Blur location to city, state, country,…
  - Rate-limit and low-pass filter, quantize accelerometer, gyroscope, magnetometer
  - Randomize/anonymize WiFi/BT names/addresses
  - Prohibit access to actual sensitive data (e.g. address books)

[5] Yanyan Zhuang, Albert Rafetseder, and Justin Cappos. "Privacy-Preserving Experimentation with Sensibility Testbed". In: *USENIX ;login:* 40.4 (Aug. 2015), pp. 18–21.

TaintDroid[6]

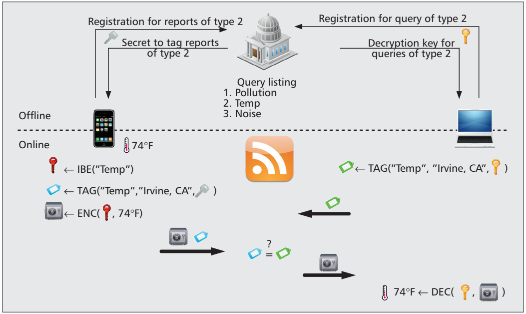
- Modified Android base system
- Tags and tracks sensor data on its way from the source through the OS and app layers and on outgoing channels
- Can monitor 3rd-party apps and identify privacy leaks



[6] William Enck et al. "TaintDroid: An Information-Flow Tracking System for Realtime Privacy Monitoring on Smartphones". In: *ACM Trans. Comput. Syst.* 32.2 (June 2014), 5:1–5:29.

PEPSI: Privacy-Enhanced Participatory Sensing Infrastructure[7]

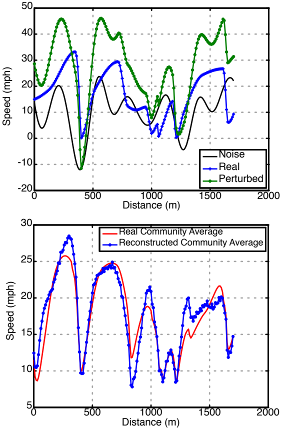
- Aimed at both node and query/querier privacy
- Location privacy
- Unable to link any two data points as originating from the same device



[7] E. De Cristofaro and C. Soriente. "Participatory privacy: Enabling privacy in participatory sensing". In: *IEEE Network* 27.1 (Jan. 2013), pp. 32–36.

PoolView[8]

- Client-side data perturbation
  - Add scaled noise from a specifically chosen random distribution
- Merge perturbed data with global pool
- Reconstruct summary statistics and distribution of unperturbed data



[8] Raghu K. Ganti et al. “PoolView: Stream Privacy for Grassroots Participatory Sensing”. In: *Proceedings of the 6th ACM Conference on Embedded Network Sensor Systems*. SenSys ’08. Raleigh, NC, USA: ACM, 2008, pp. 281–294.

Differential Privacy[9]

Definition

A randomized function $\mathcal{K}$ gives ϵ-differential privacy if for all data sets D_1 and D_2 differing on at most one element, and all $S \subseteq Range(\mathcal{K})$,

$$Pr[\mathcal{K}(D_1) \in S] \leq e^{\epsilon} \times Pr[\mathcal{K}(D_2) \in S]$$

- Result from statistical query on database does not significantly change in the absence of one specific entry
- ϵ: trade-off parameter between privacy and statistical accuracy, needs to be public to determine actual privacy
- In use, e.g., in iOS, but ϵ not public and possibly skewed towards accuracy

[9] Cynthia Dwork. "Differential Privacy: A Survey of Results". In: *Theory and Applications of Models of Computation*. Ed. by Manindra Agrawal et al. Berlin, Heidelberg: Springer Berlin Heidelberg, 2008, pp. 1–19.

Section 2

Upper Protocol Stack and Boards

Data and Data Formats, Wire Protocols

Data serialization for the resource constrained

- Trade-offs between
  - Compactness, transmission size
  - Processing demands
  - Descriptive and semantic
  - Extensibility
  - Compatibility and availability of implementations
  - Human-readability
- Often already predetermined by the choice of L7 protocol

Some typical examples

- XML, e.g. with an O-DF IoT scheme
- JSON
- TLV
- ASN.1, ProtoBuf and other interface description languages, lightweight derivatives like ‘nanopb’
- CBOR (IETF RFC 7049, recommended for CoAP)
- Predetermined binary fields in a custom wire protocol

Constrained Application Protocol

CoAP, IETF RFC7252, RFC8323

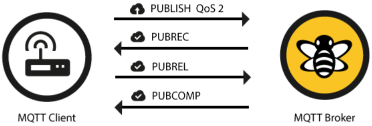
- RESTful request/response design, multicast support
- Less overhead (binary header), on top of UDP/DTLS (and typically 6LoWPAN)
  - With RFC 8323 now also over TCP and WebSockets
- Stateless, each request-response pair is independent (but can be bundled into a block transfer)
- Typical payloads: XML, JSON, CBOR (RFC7049)
- Message should fit into single datagram, should fit into single 802.15.4 frame
- Extensions tailored towards, e.g., resource observation (e.g.[10])

[10] Girum Ketema Teklemariam et al. "Facilitating the creation of IoT applications through conditional observations in CoAP". In: *EURASIP Journal on Wireless Communications and Networking* 2013.1 (June 2013), p. 177.

Message Queue Telemetry Transport

MQTT, ISO/IEC PRF 20922

- Publish-subscribe system with a message broker
- TCP/IP, WebSockets also possible
- Additional application-layer reliability possible (QoS levels)



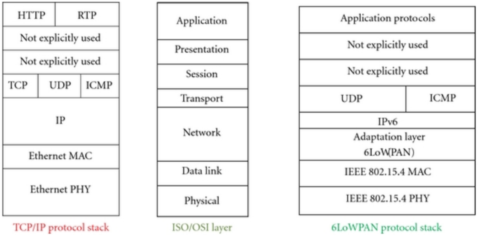
- **MQTT-SN** (sensor networks)[11]
  - Maps to UDP/non-IP for ZigBee, BLE, 802.15.4, …
  - Restricted message size
  - Needs gateway to connect to MQTT broker
  - Currently less software support for IoT devices as CoAP

[11] M. Collina et al. “Internet of Things application layer protocol analysis over error and delay prone links”. In: *2014 7th Advanced Satellite Multimedia Systems Conference and the 13th Signal Processing for Space Communications Workshop (ASMS/SPSC)*. Sept. 2014, pp. 398–404.

IP for IoT

6LoWPAN (IETF RFCs 4944, 6282, 6775, 4919, 7668)

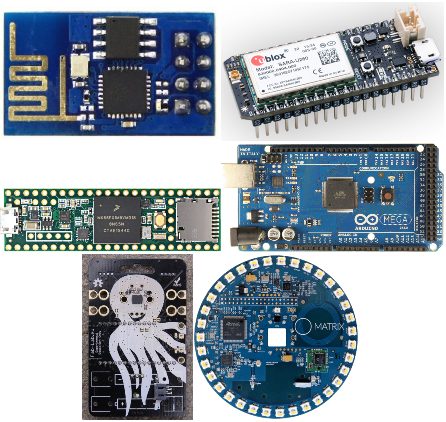
- Regular TCP/IP protocols not necessarily well suited for resource-constrained networks
  - E.g. statefulness, “chattiness”, routing
- Low-cost, relaxed throughput requirements
- Maps between 802.15.4 and IP
- Lightweight routing approaches, mesh-capable
  - E.g. RPL (RFC6550)



Quick Synopsis on Hackable IoT Boards

Or: μC vs ARM/SoC vs x86

- 8/16bit controller, 32bit ARMs
- ATMega, Atmel AVR, MSP430 RISC
- Choice governs power profile, interface selection, ADC/DAC
- Dev boards: Arduino and derivates, Raspberry Pi, …
- Implementation: Microcontrollers, ARM SoCs, custom PCBs



A Selection of Operating Systems

Based on Use Case and Board

- Linux
  - Needs an MMU (e.g. Raspberry and up), not lightweight
  - Familiar environment, wide selection of languages

A Selection of Operating Systems

Based on Use Case and Board

- Linux
  - Needs an MMU (e.g. Raspberry and up), not lightweight
  - Familiar environment, wide selection of languages
- Riot
  - Main platforms x86, Cortex M0/M3
  - Realtime, multithreading, 6LoWPAN, CCN, RPL, further stacks, …

A Selection of Operating Systems

Based on Use Case and Board

- Linux
  - Needs an MMU (e.g. Raspberry and up), not lightweight
  - Familiar environment, wide selection of languages
- Riot
  - Main platforms x86, Cortex M0/M3
  - Realtime, multithreading, 6LoWPAN, CCN, RPL, further stacks, …
- Contiki
  - Cortex M3, MSP430, AVR, ATMega
  - Multithreading, IPC, TCP/IP stack, GUI/Web browser(!)
  - Extensive simulation framework (“Cooja”)

A Selection of Operating Systems

Based on Use Case and Board

- Linux
  - Needs an MMU (e.g. Raspberry and up), not lightweight
  - Familiar environment, wide selection of languages
- Riot
  - Main platforms x86, Cortex M0/M3
  - Realtime, multithreading, 6LoWPAN, CCN, RPL, further stacks, …
- Contiki
  - Cortex M3, MSP430, AVR, ATMega
  - Multithreading, IPC, TCP/IP stack, GUI/Web browser(!)
  - Extensive simulation framework ("Cooja")
- "Bare Metal"
  - Lightweight code tailored to specific needs; more likely to exihibt correctness, security, or maintenance issues

Section 3

Radio and Antennae

Connectivity Considerations

Or: To wireless or not to wireless?

- For many projects (serial) wired communication interfaces might suffice.
  - Bit-banging directly over GPIO pins (enables e.g. SPI, 1-Wire, I^2C)
  - CAN bus, USB, Ethernet
  - If needed, backhaul through existing Internet connectivity
- Industrial IoT / smart factory setting[12]
  - E.g. 802.1 / 802.3 Time-Sensitive Networking, PROFIBUS, SCADA, and other approaches with real-time guarantees
  - Cabling might become financially and spatially intensive

[12] M. Wollschlaeger, T. Sauter, and J. Jasperneite. "The Future of Industrial Communication: Automation Networks in the Era of the Internet of Things and Industry 4.0". In: *IEEE Industrial Electronics Magazine* 11.1 (Mar. 2017), pp. 17–27.

Connectivity Considerations

Or: To wireless or not to wireless?

Advantages of wired communication:

- Power draw, but also Power over Ethernet
- Much higher bandwidths (at least possible)
- Exclusive medium usage, no/less collisions, interference, surveillance
- easier real-time guarantees, QoS
- Shallower protocol stack

Connectivity Considerations

Or: To wireless or not to wireless?

Advantages of wired communication:

- Power draw, but also Power over Ethernet
- Much higher bandwidths (at least possible)
- Exclusive medium usage, no/less collisions, interference, surveillance
- easier real-time guarantees, QoS
- Shallower protocol stack

Disadvantages:

- Mostly limited range
- Difficult for many-device experiments
- Cable management
- Limited topology choices

Topology Consideration

Project Scope

Experiment scope influences selection of viable communication interfaces

- (B)AN (health)
- (W)PAN; LR-WPAN (low-rate wireless personal area network)
- (W)LAN
- HAN (home automation)
- MAN (smart cities, municipal wireless, community nets)
- WAN; LPWAN

[12] M. Chen et al. "A Survey of Recent Developments in Home M2M Networks". In: *IEEE Communications Surveys Tutorials* 16.1 (Jan. 2014), pp. 98–114.

Radio Interface Considerations

Or: Finding the Radio that Best Fits Your Needs

Most flexible answer: Building a custom radio or using SDR (e.g.[13])

[13] Y. Chen et al. "A low power software-defined-radio baseband processor for the Internet of Things". In: *2016 IEEE International Symposium on High Performance Computer Architecture (HPCA)*. Mar. 2016, pp. 40–51.

Radio Interface Considerations

Or: Finding the Radio that Best Fits Your Needs

Most flexible answer: Building a custom radio or using SDR (e.g.[13])

However, some caveats apply:

- Radio operation requires a license
- Must comply with radio regulations, even outside of licensed spectrum
- Spurious emissions can incur legal issues
- Unlicensed spectrum is crowded

---

[13] Y. Chen et al. “A low power software-defined-radio baseband processor for the Internet of Things”. In: *2016 IEEE International Symposium on High Performance Computer Architecture (HPCA)*. Mar. 2016, pp. 40–51.

Radio Interface Considerations

Or: Finding the Radio that Best Fits Your Needs

Most flexible answer: Building a custom radio or using SDR (e.g.[13])

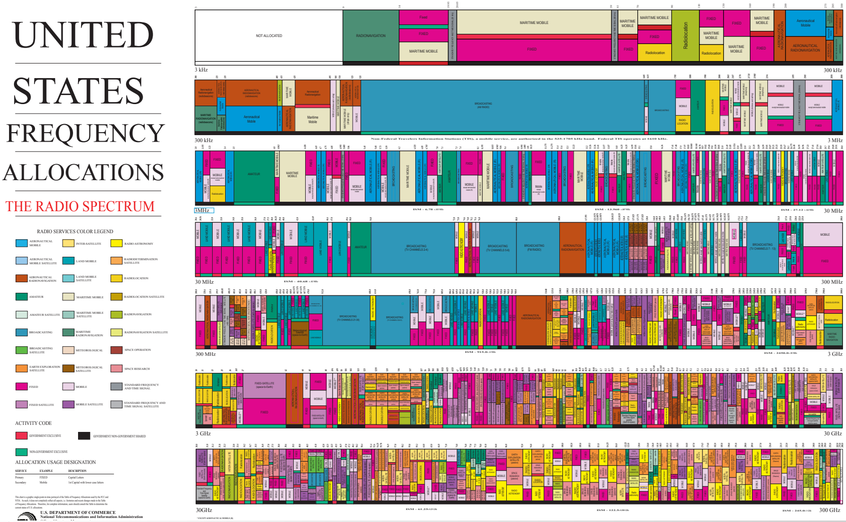
However, some caveats apply:

- Radio operation requires a license
- Must comply with radio regulations, even outside of licensed spectrum
- Spurious emissions can incur legal issues
- Unlicensed spectrum is crowded
- Existing protocols are quite exhaustive
- Implementing a packet radio communication service correctly and efficiently is non-trivial
  - 802.11 specs are >3k pages
  - 3GPP specs are roughly >100k pages

[13] Y. Chen et al. “A low power software-defined-radio baseband processor for the Internet of Things”. In: *2016 IEEE International Symposium on High Performance Computer Architecture (HPCA)*. Mar. 2016, pp. 40–51.

The Radio Spectrum

Example for the US Region



Types of Radio Licenses, Simplified

Licensed Bands

- Bands allocated for use with a specific mode
- May only operate purchased *licensed* devices
- May not be modified in any way
- E.g. CB/PRS radio (citizens band, ”Walkie-Talkies”)

Types of Radio Licenses, Simplified

Licensed Bands

- Bands allocated for use with a specific mode
- May only operate purchased *licensed* devices
- May not be modified in any way
- E.g. CB/PRS radio (citizens band, ”Walkie-Talkies”)

Cellular Frequencies

- Mobile services
- In Europe mostly 800 MHz, 900 MHz, 1800 MHz, 2100 MHz, 2600 MHz
- Spectrum allotted, e.g. auctioned off, to specific operators
- Usually fixed to specific radio type or mode of operation and power (2G–5G)

Types of Radio Licenses

Personal license

- Restricted to specific bands, mode of operation, power
- Airband/Aviation, Maritime mobile service, Amateur Radio

[14] A. Sikora and V. F. Groza. "Coexistence of IEEE802.15.4 with other Systems in the 2.4 GHz-ISM-Band". In: *2005 IEEE Instrumentationand Measurement Technology Conference Proceedings*. Vol. 3. May 2005, pp. 1786–1791.

Types of Radio Licenses

Personal license

- Restricted to specific bands, mode of operation, power
- Airband/Aviation, Maritime mobile service, Amateur Radio

Unlicensed Bands

- May operate any kind of radio compliant with (national) restrictions
  - E.g. WLAN@2.4GHz: 100mW EIRP; @5GHz only with DFS on the higher channels
- ISM and SRD bands
- Must tolerate noise (e.g. microwave ovens)
- Limited resources, interference between technologies[14]

[14] A. Sikora and V. F. Groza. "Coexistence of IEEE802.15.4 with other Systems in the 2.4 GHz-ISM-Band". In: *2005 IEEE Instrumentationand Measurement Technology Conference Proceedings*. Vol. 3. May 2005, pp. 1786–1791.

Spectrum Allocations

And the Regulators

- Allocations done by national regulators
- Coordinated by CEPT (in Europe) and ITU-R (globally)
- Bundesnetzagentur in Germany
- E.g. through the ITU RR (“radio regulations”) or “VO Funk” (“Vollzugsordnung Funk”)
- Monitor licensed spectrum for interference
- Define rules on band usage
  - Power, polarization, modulation, duty ratio, time of day, regional/directional restrictions, P/S status (think 5Ghz WiFi + DFS and weather radar)

ISM and SRD bands

- Bands differ from country to country
  - 433 and 868 bands **only** in Europe, 915 only in the Americas
- ISM and SRD can overlap, but different rules

ISM and SRD bands

- Bands differ from country to country
  - 433 and 868 bands **only** in Europe, 915 only in the Americas
- ISM and SRD can overlap, but different rules
- SRD limited to $< 100\,\text{mW}$ ERP (often less), 1% duty cycle (depends on band)
- Type A: authorization required
- Type B: use for general ISM applications

F_l	F_h	Type
6.765 MHz	6.795 MHz	A
13.553 MHz	13.567 MHz	B, RFID
26.957 MHz	27.283 MHz	B, CB
40.66 MHz	40.7 MHz	B
433.05 MHz	434.79 MHz	A. LPD433
863 MHz	870	B, SRD860
902 MHz	928 MHz	B
2.4 GHz	2.5 GHz	B
5.725 GHz	5.875 GHz	B
24 GHz	24.25 GHz	B
61 GHz	61.5 GHz	A
122 GHz	123 GHz	A
244 GHz	246 GHz	A

(List not exhaustive)

Radio Propagation and Antennae

- IoT antenna depends on topology (BAN[15]to WAN), and band selection
- Propagation properties
    - Mostly Line-of-sight propagation (not, e.g., ground wave or ionosphere refraction)
    - Must consider absorption (through walls and water)

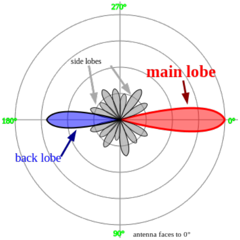
[15] S. Sojuyigbe and K. Daniel. “Wearables/IOT devices: Challenges and solutions to integration of miniature antennas in close proximity to the human body”. In: *2015 IEEE Symposium on Electromagnetic Compatibility and Signal Integrity*. Mar. 2015, pp. 75–78.

Radio Propagation and Antennae

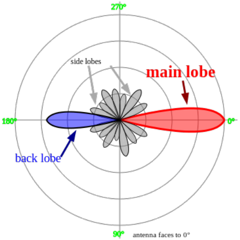
- IoT antenna depends on topology (BAN[15] to WAN), and band selection
- Propagation properties
  - Mostly Line-of-sight propagation (not, e.g., ground wave or ionosphere refraction)
  - Must consider absorption (through walls and water)
- Wavelength governs optimal antenna dimensioning
- Antennae forms
  - Isotropic radiators
  - Various radiation patterns, directional antennae
  - Dipoles, monopoles, arrays, apertures

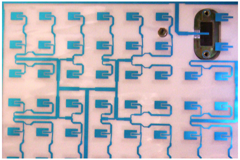
[15] S. Sojuyigbe and K. Daniel. "Wearables/IOT devices: Challenges and solutions to integration of miniature antennas in close proximity to the human body". In: *2015 IEEE Symposium on Electromagnetic Compatibility and Signal Integrity*. Mar. 2015, pp. 75–78.

Radio Antennae Shapes and Emissions Patterns

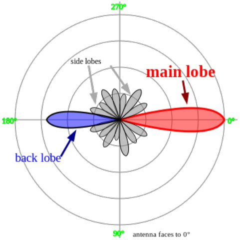


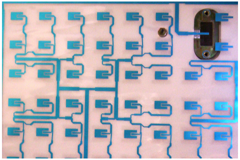
Radio Antennae Shapes and Emissions Patterns

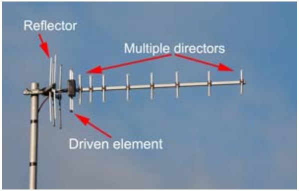




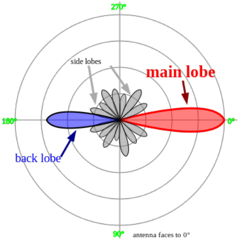
Radio Antennae Shapes and Emissions Patterns

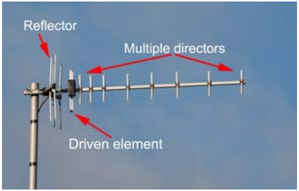


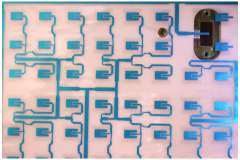




Radio Antennae Shapes and Emissions Patterns



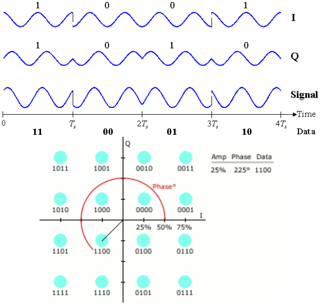




Packet Radio Modulation Schemes

QPSK, QAM16, CSS

QPSK, QAM16

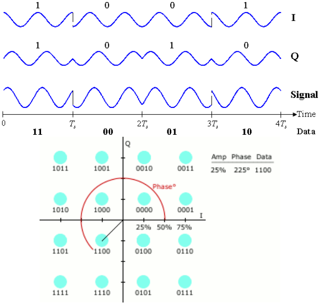


[16] B. Reynders and S. Pollin. "Chirp spread spectrum as a modulation technique for long range communication". In: *2016 Symposium on Communications and Vehicular Technologies (SCVT)*. Nov. 2016, pp. 1–5.

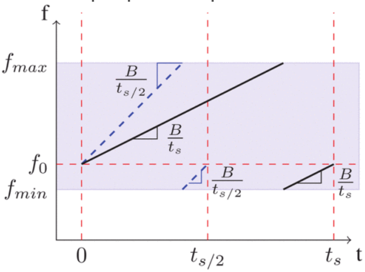
Packet Radio Modulation Schemes

QPSK, QAM16, CSS

QPSK, QAM16



Chirp Spread Spectrum[16]



symbol encoded with offset f_0 and spreading factors s and $\frac{s}{2}$

[16] B. Reynders and S. Pollin. “Chirp spread spectrum as a modulation technique for long range communication”. In: *2016 Symposium on Communications and Vehicular Technologies (SCVT)*. Nov. 2016, pp. 1–5.

Section 4

Mobile and wireless radio standards

IoT Connectivity Landscape[17]

- Existing cellular networks or their IoT variants
- Utilize unlicensed spectrum (esp. ISM & SRD)
- WLAN/WPAN with existing residential Internet access
- RF IoT networks
- Custom radio (e.g. SDR)

[17] S. Andreev et al. “Understanding the IoT connectivity landscape: a contemporary M2M radio technology roadmap”. In: *IEEE Communications Magazine* 53.9 (Sept. 2015), pp. 32–40.

IoT Connectivity Landscape[17]

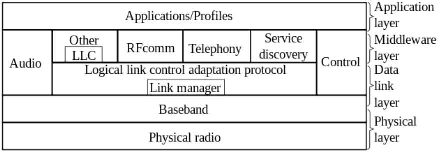
- Existing cellular networks or their IoT variants
- Utilize unlicensed spectrum (esp. ISM & SRD)
- WLAN/WPAN with existing residential Internet access
- RF IoT networks
- Custom radio (e.g. SDR)

Standard	f	**Range**	**BW**
BT 4.0 LE	2.4 GHz	< 100 m	1 Mbit/s
ZigBee / 802.15.4	868, 2400 MHz	10 m to 100 m	20, 250 kbit/s
Z-Wave	900 MHz	30 m	9.6, 40, 100 kbit/s
WiFi /802.11n/ac	2.4, 5 GHz	100 m	1.27 Gbit/s for 80 MHz 6.77 Gbit/s with MU-MIMO
NFC	13.56 MHz	10 cm	100 kbit/s to 420 kbit/s
LoRaWAN	433, 868 MHz	< 15 km	0.3 kbit/s to 50 kbit/s
SigFox	900 MHz	< 50 km	10 kbit/s to 1000 kbit/s

[17] S. Andreev et al. "Understanding the IoT connectivity landscape: a contemporary M2M radio technology roadmap". In: *IEEE Communications Magazine* 53.9 (Sept. 2015), pp. 32–40.

Bluetooth Low Energy

- Low latency (6 ms),
  low power (15 mA peak)
- Readily available, builtin to smartphones and home appliances
- Intended for explicit one-to-one comm (mesh net spec since 2017)
- Different application profiles implemented as part of the stack, define usage



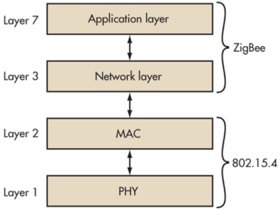
Chipset	Advertising Interval	Est. Battery Life CR2032	Est. Battery Life CR2045	Est. Battery Life CR2477
Gimbal	100ms	n/a	n/a	n/a
Gimbal	645ms	1 month	2.5 months	4.1 months
Gimbal	900ms	n/a	n/a	n/a
Nordic Semiconductors	100ms	1.2 months	3.1 months	5.1 months
Nordic Semiconductors	645ms	7.0 months	18.19 month	29.3 months
Nordic Semiconductors	900ms	11.1 months	28.7 months	46.29 months
Bluegiga	100ms	0.9 months	2.4 months	3.8 months
Bluegiga	645ms	5.9 months	15.4 months	24.8 months
Bluegiga	900ms	9.3 months	23.9 months	38.5 months
Texas Instruments	100ms	0.7 months	1.8 months	2.9 months
Texas Instruments	645ms	4.1 months	10.6 months	17.1 months
Texas Instruments	900ms	5.6 months	14.4 months	23.1 months

Aislelabs

[17] Carles Gomez, Joaquim Oller, and Josep Paradells. “Overview and Evaluation of Bluetooth Low Energy: An Emerging Low-Power Wireless Technology”. In: *Sensors* 12.9 (2012), pp. 11734–11753.

ZigBee and 802.15.4

- 802.15.4 defines PHY and MAC only
- 6LowPAN stack on top for IP interop
- Low-cost embedded devices
- Peer-to-peer/mesh and centralized (coordinator) topologies
- Alternative: ZigBee stack with additions for auth, encryption, mesh forwarding/routing



[17] Z. Sheng et al. "A survey on the ietf protocol suite for the internet of things: standards, challenges, and opportunities". In: *IEEE Wireless Communications* 20.6 (Dec. 2013), pp. 91–98, S. D. T. Kelly, N. K. Suryadevara, and S. C. Mukhopadhyay. "Towards the Implementation of IoT for Environmental Condition Monitoring in Homes". In: *IEEE Sensors Journal* 13.10 (Oct. 2013), pp. 3846–3853.

LPWAN (Low-Power Wide-Area Network)

IoT on a Smart City scale, Smart Grids, …

- Typical requirements: large coverage, low power draw, many devices
  - But low bandwidth, and favors aggregation instead of meshes
- Limited coverage of earlier tech (BT, 802.15.4) while preserving low power consumption and complexity
- 3GPP not ideal for low power and high density (in the past)

[17] M. Centenaro et al. "Long-range communications in unlicensed bands: the rising stars in the IoT and smart city scenarios". In: *IEEE Wireless Communications* 23.5 (Oct. 2016), pp. 60–67.

LPWAN (Low-Power Wide-Area Network)

IoT on a Smart City scale, Smart Grids, ...

- Typical requirements: large coverage, low power draw, many devices
  - But low bandwidth, and favors aggregation instead of meshes
- Limited coverage of earlier tech (BT, 802.15.4) while preserving low power consumption and complexity
- 3GPP not ideal for low power and high density (in the past)
- Now: new(-ish) transceiver and PHY design on unlicensed lower RF bands with high receiver sensitivity
  - Future trouble with increasing band occupation
- E.g. Sigfox, LoRa, DASH7, but also IoT 3GPP variants
- Custom L2 stacks (e.g. LoRaWAN), but also IETF WG "IPv6 over LPWAN"

[17] M. Centenaro et al. "Long-range communications in unlicensed bands: the rising stars in the IoT and smart city scenarios". In: *IEEE Wireless Communications* 23.5 (Oct. 2016), pp. 60–67.

3GPP Cellular Networks for IoT

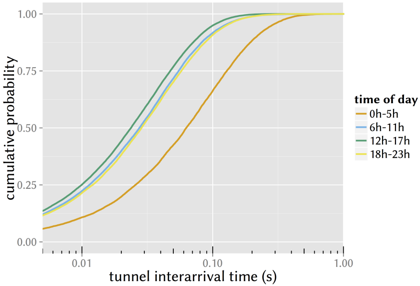
- Network operation outsourced to network operators
  - Incurs, e.g. continuing **subscription** costs
- Well-developed infrastructure with **coverage** pretty much everywhere
- Long range, high throughput
- HW and embeddable components widely available

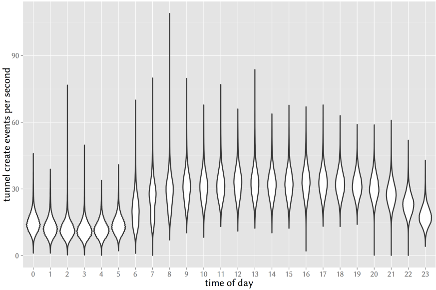
3GPP Cellular Networks for IoT

- Network operation outsourced to network operators
  - Incurs, e.g. continuing **subscription** costs
- Well-developed infrastructure with **coverage** pretty much everywhere
- Long range, high throughput
- HW and embeddable components widely available
- Not necessarily tuned for low energy appliances
- Fixed, deep stack
- Users/SIMs are associated to a person/identity
- Older networks (GSM/UMTS) might be turned off soon
- Scaling issues of cellular networks to IoT device density
  - Radio and core stateful and **signaling**-heavy, vertical integration

3G Core Network Signaling Traffic Analysis[18]

Tunnel Arrivals by Time of Day



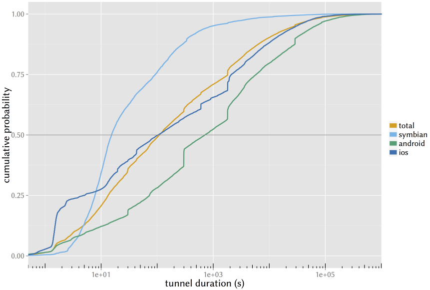


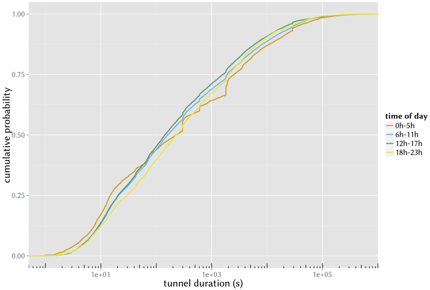
- 1 week in 2012 traffic trace of an European operator, usually only one tunnel between SGSN and GGSN per device
- Strong time of day dependence with busy hour in the early afternoon
- Bimodal character of arrival rate over the total time of day

[18] F. Metzger et al. "Exploratory Analysis of a GGSN's PDP Context Signaling Load". In: *Journal of Computer Networks and Communications* (Feb. 2014).

3G Core Network Signaling Traffic Analysis

Tunnel Durations





- Radio link ON-OFF behavior is (partially) reflected in core signaling
- “Signaling storm” in CN: many short tunnels for specific devices
- IoT devices also try to keep comm short, turn off radio and conserve power
  - Will result in short tunnels and increased signaling

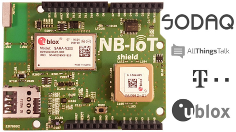
IoT-friendly Variants of 3GPP Networks

- E.g. random access channels, narrower RF bandwidth, guard-band usage, cost reductions
- EPC/EPS mostly unchanged
  - Specific IoT data can now alternatively be routed through the control plane over the MME, not passing the P-GW nor using bearers
  - Ratio of regular vs new style data flows? Effects on load?
- **EC-GSM-IoT**: Extended coverage optimizations to 2G, up to 2 Mbit/s
  - No rollouts yet?
- **eMTC/LTE-M**: 1.08 MHz in-band LTE with 1 Mbit/s
  - Limited commercial use
- **NB-IoT**: single random-access PRB (180 kHz, 250 kbit/s)
  - Limited rollout in EU/Australia

NB-IoT[19] and its Rollout

LTE Cat NB1

- Using a single regular PRB or operates in guard-band
- Tailored towards LPWAN requirements, esp. for device density and power
- Contractual models akin to conventional cellular networks (SIMs, subscriptions, data caps), same deep stack
- Currently scarce availability of NB-IoT devices and modules
  - Dev kit announced by STM last week



[19] Y. P. E. Wang et al. "A Primer on 3GPP Narrowband Internet of Things". In: *IEEE Communications Magazine* 55.3 (Mar. 2017), pp. 117–123.

NB-IoT Contractual Models

Cellular IoT & Starter Kits

MEDIA | 06-26-2017 | CAROLINE BERGMANN | 0 COMMENTS

First NarrowBand IoT service packages launched in Germany

Share Print Read out

- Two entry packages available to experience and pilot NB-IoT solutions
- NB-IoT based smart parking solutions introduced in several German cities
- Rapid NB-IoT network expansion in Germany and across Europe with nationwide rollout in the Netherlands already accomplished

€199 for 25 SIMs, 6 months, 500 kB each

INTERNET DER DINGE

T-Mobile startet Narrowband-IoT-Netz

16.11.17, 10:34 Mail an die Redaktion

Im Februar hat T-Mobile Narrowband-IoT erstmals bei einem Showcase vor dem T-Center in Wien gezeigt: Dort wurden smarte Parkplätze installiert, die mitteilen können, ob sie belegt sind - Foto: T-Mobile

INTERNET DER DINGE

T-Mobile startet Narrowband-IoT-Netz

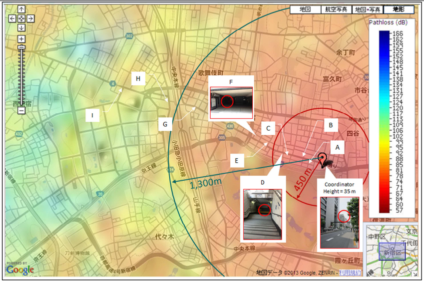
St. Pölten ist die erste Stadt, die T-Mobile mit dem Kommunikations-Standard Narrowband-IoT für vernetzte Geräte ausstattet. 2018 soll das ganze Land versorgt sein.

T-MOBILE, MOBILFUNK, INTERNET OF THINGS, INTERNET DER DINGE, IOT

€99 for 10 SIMs, 6 months, 500 kB each

LoRa

- Proprietary (Semtech) chirp spread spectrum modulation aimed at low energy
- 169, 433, 868, and 915 bands in several blocks of 125 kHz
- Link budget of 156 dB
- Spreading factor adapts between throughput and resilience
- Different spreading factors can coexist in the same block

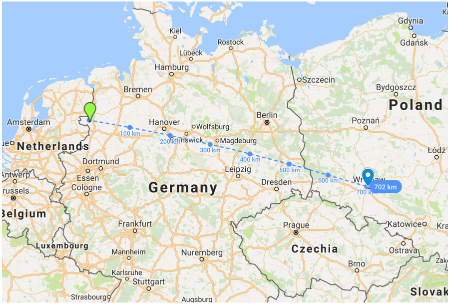


Ref. #	Distance (m)	2-FSK: 4.8 kb/s Rssi (dBm)	2-FSK: 4.8 kb/s PER (%)	LoRa: 125 kHz BW, SF = 8 (3.125 kb/s) Rssi (dBm)	LoRa: 125 kHz BW, SF = 8 (3.125 kb/s) PER (%)
A	80	-97	0	-91	0
B	150	-100	0	-102	0
C	280	-112	1	-114	0
D	330	-	100	-124	10
E	480	-118	8	-120	0
F	560	-	100	-121	0
G	1180	-	100	-112	0
H	1350	-	100	-126	10
I	1750	-	100	-127	100

Figure 9: Shinjuku Urban Range Test

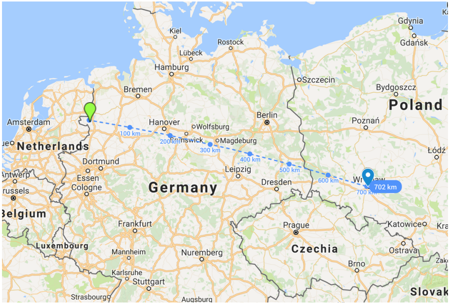
[19] J. Petajajarvi et al. "On the coverage of LPWANs: range evaluation and channel attenuation model for LoRa technology". In: *2015 14th International Conference on ITS Telecommunications (ITST)*. Dec. 2015, pp. 55–59.

LoRa



Sensor data TX with 14 dBm TPO received

LoRa



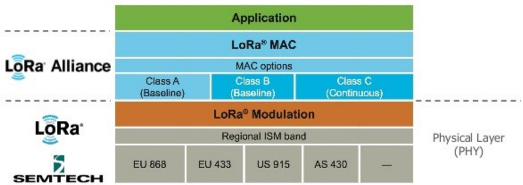
Sensor data TX with 14 dBm TPO received

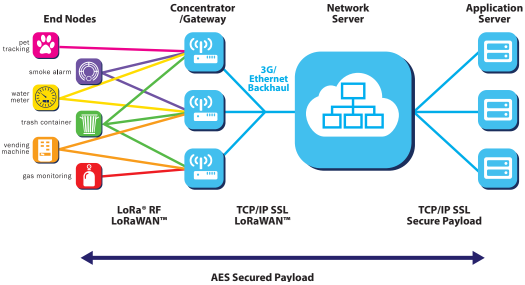
…mounted to a weather balloon at an elevation of 39 km

https://www.thethingsnetwork.org/article/ground-breaking-world-record-lorawan-packet-received-at-702-km-436-miles-distance

LoRaWAN

- Standardized LoRaWAN MAC layer on top of LoRa
- 32 bit addressing scheme, session and data encryption
- Reliability (ACKs)
- Three device classes
  - A: Receive only briefly after own transmission
  - B: Scheduled receive slots
  - C: Continuous reception
- Secured communication with cloud applications via distributed gateways





Community-run “Cellular” IoT Networks

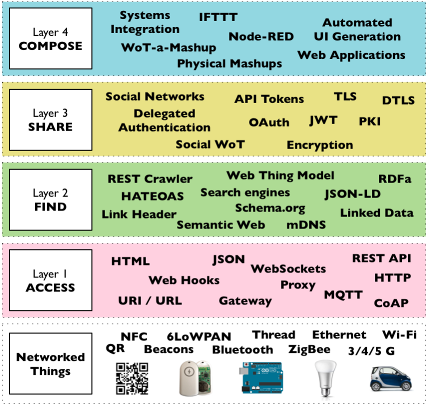
- LPWANs are ideally suited to build regional IoT gateways
  - Single gateway can cover entire city
- Example: The Things Network
  - Crowdsourced LoRaWAN gateways
  - Gateways listen on 868 MHz on 8 or more channels and all spreading factors
  - Distributed overlay network with a common API
  - Schedules and manages gateway transmissions, duty cycle limits
  - Service discovery and traffic routing

1500 active gateways

[19] Keyi Zhang and A. Marchiori. “Crowdsourcing low-power wide-area IoT networks”. In: *2017 IEEE International Conference on Pervasive Computing and Communications (PerCom)*. Mar. 2017, pp. 41–49.

Web of Things and Mozilla Things Gateway[21]

- Mozilla Things Gateway
  - Raspbian-based gateway, connectivity over USB sticks
  - W3C Web Things API draft: things descriptions, REST API, WebSocket API
  - GUI for home automation with IFTTT rules and floorplans
- Many other high-level IoT Web application frameworks
  - E.g. ThingSpeak[20]: Web platform for sensor applications and data exchange, closely tied to MATLAB



Source: Building the Web of Things: book.webofthings.io

[20] https://thingspeak.com/
[21] https://iot.mozilla.org/

Section 5

Synopsis and Example

Practical Considerations

- Specific goal and scope of project
  - Data collection? Automation?…
  - Target audience? (Research, home users, environmental monitoring, citizen science, …)
  - Scope from personal and home automation to metropolitan or international
- Build everything from scratch to a specific purpose or use more general, ready-made frameworks?
  - How much customization do you need?
  - E.g. are existing cellular networks sufficient
- What are the right tools for your experiment?
  - Boards
  - Connectivity
  - Network protocols
  - Network topology

Crowdsensing Considerations

- Data protection regulations and participatory effects

⇒ Distinguish between data you absolutely need and data that would be nice to have

⇒ Know all privacy implications and side effects

⇒ Implement appropriate privacy preservation techniques

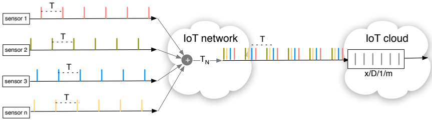
⇒ Keep your participant's data safe

Connectivity Considerations

- Governed by project requirements
- Familiarize yourself with RF technology, protocols and standards, and available devices
- Check national and local regulations, licensed/unlicensed operation
- Choose
  - Bandwidth requirements
  - Transceiver and modulation according to distance requirements
  - Transmission power according to regulations
  - Antenna size and shape
  - Stack and framework requirements ("Can i do MQTTS over TCP/IP in this environment?", "Is this supported by Node-RED?")

A very simple LoRa example

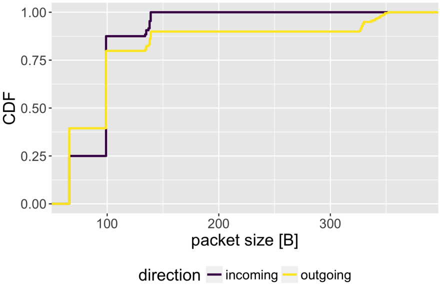
- Student project
- **Demo**
- 4 Arduino sensing nodes (temp, pressure, loudness, humidity, dust, brightness), sensing every 60 s
- LoRa with custom and encrypted link layer protocol on top to a central Raspberry gateway
- MQTT to a cloud instance for processing and visualization



- Tapped at aggregated link, three weeks of recording, $20M$ packets
- Signaling and data clearly separable

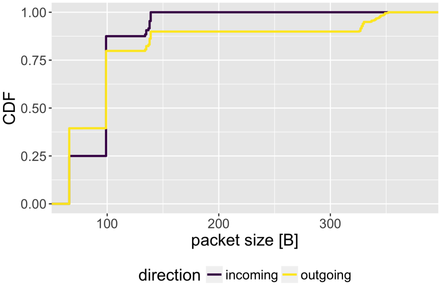
A very simple LoRa example

Data packets only $> 300\,\mathrm{B}$, rest is signaling



A very simple LoRa example

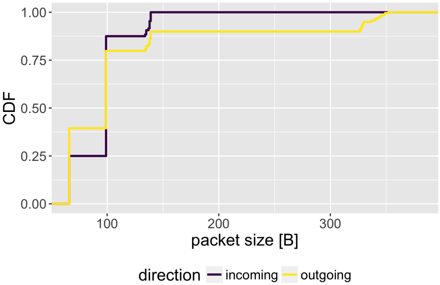
Data packets only > 300 B, rest is signaling



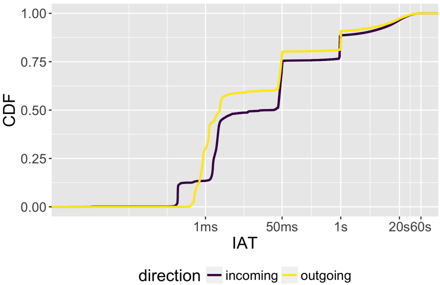
IAT expectation: One dominant mode, deterministic distribution

A very simple LoRa example

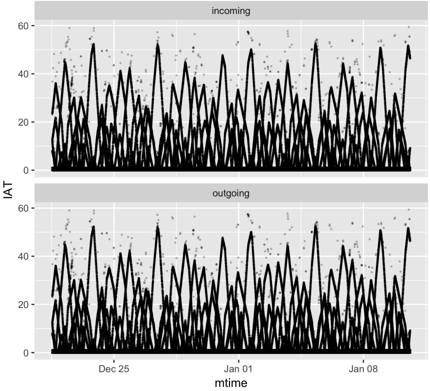
Data packets only $>$ 300 B, rest is signaling



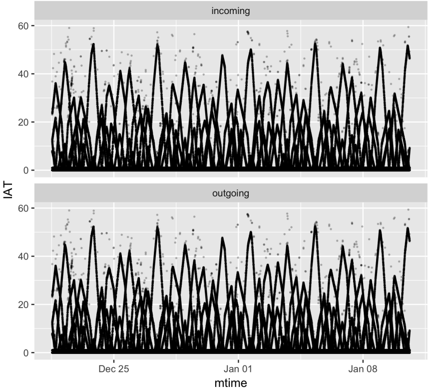
IAT expectation: One dominant mode, deterministic distribution



A very simple LoRa example



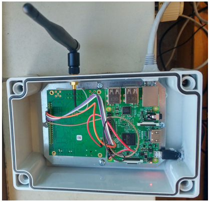
A very simple LoRa example

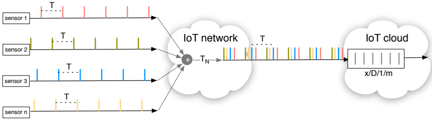


- Strong clock drift in sensor sending behavior
- Ceramic resonator with 0.5 % tolerance on Arduino as clock source
- Cheaper and smaller than quartz crystals
- Simple linear regression model per sender suffices

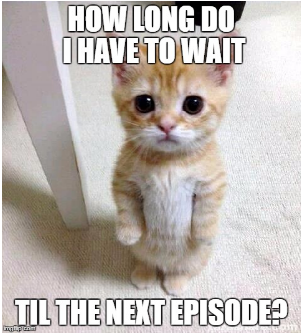
Summary

- Different requirements between non-commercial IoT, participatory projects and commercial applications
  - Very well established technologies for local (PAN/WLAN) applications, between BT, 802.11, and 802.15.4
  - Both licensed and unlicensed LPWAN approaches can be interesting propositions
  - Disruptive LoRa?
- Unique opportunities to investigate these IoT traffic models





And now to part two!



Contact: florian.metzger@uni-due.de
Web and slides: https://www.tru42.org/fm/
Key fingerprint: C98A 32B7 554F C5CC 4E5A 60FB 1CE5 B541 7B20 99C7

Bibliography I

- S. Andreev et al. "Understanding the IoT connectivity landscape: a contemporary M2M radio technology roadmap". In: *IEEE Communications Magazine* 53.9 (Sept. 2015), pp. 32–40.
- M. Centenaro et al. "Long-range communications in unlicensed bands: the rising stars in the IoT and smart city scenarios". In: *IEEE Wireless Communications* 23.5 (Oct. 2016), pp. 60–67.
- M. Chen et al. "A Survey of Recent Developments in Home M2M Networks". In: *IEEE Communications Surveys Tutorials* 16.1 (Jan. 2014), pp. 98–114.
- Y. Chen et al. "A low power software-defined-radio baseband processor for the Internet of Things". In: *2016 IEEE International Symposium on High Performance Computer Architecture (HPCA)*. Mar. 2016, pp. 40–51.

Bibliography II

- M. Collina et al. “Internet of Things application layer protocol analysis over error and delay prone links”. In: *2014 7th Advanced Satellite Multimedia Systems Conference and the 13th Signal Processing for Space Communications Workshop (ASMS/SPSC)*. Sept. 2014, pp. 398–404.
- E. De Cristofaro and C. Soriente. “Participatory privacy: Enabling privacy in participatory sensing”. In: *IEEE Network* 27.1 (Jan. 2013), pp. 32–36.
- Cynthia Dwork. “Differential Privacy: A Survey of Results”. In: *Theory and Applications of Models of Computation*. Ed. by Manindra Agrawal et al. Berlin, Heidelberg: Springer Berlin Heidelberg, 2008, pp. 1–19.
- William Enck et al. “TaintDroid: An Information-Flow Tracking System for Realtime Privacy Monitoring on Smartphones”. In: *ACM Trans. Comput. Syst.* 32.2 (June 2014), 5:1–5:29.

Bibliography III

- Raghu K. Ganti et al. "PoolView: Stream Privacy for Grassroots Participatory Sensing". In: *Proceedings of the 6th ACM Conference on Embedded Network Sensor Systems*. SenSys '08. Raleigh, NC, USA: ACM, 2008, pp. 281–294.
- Carles Gomez, Joaquim Oller, and Josep Paradells. "Overview and Evaluation of Bluetooth Low Energy: An Emerging Low-Power Wireless Technology". In: *Sensors* 12.9 (2012), pp. 11734–11753.
- S. D. T. Kelly, N. K. Suryadevara, and S. C. Mukhopadhyay. "Towards the Implementation of IoT for Environmental Condition Monitoring in Homes". In: *IEEE Sensors Journal* 13.10 (Oct. 2013), pp. 3846–3853.
- F. Metzger et al. "Exploratory Analysis of a GGSN's PDP Context Signaling Load". In: *Journal of Computer Networks and Communications* (Feb. 2014).
- J. Petajajarvi et al. "On the coverage of LPWANs: range evaluation and channel attenuation model for LoRa technology". In: *2015 14th International Conference on ITS Telecommunications (ITST)*. Dec. 2015, pp. 55–59.

Bibliography IV

- A. Rafetseder et al. "Sensorium – A Generic Sensor Framework". In: *PIK - Praxis der Informationsverarbeitung und Kommunikation* 36.1 (Feb. 2013), p. 46.
- B. Reynders and S. Pollin. "Chirp spread spectrum as a modulation technique for long range communication". In: *2016 Symposium on Communications and Vehicular Technologies (SCVT)*. Nov. 2016, pp. 1–5.
- Z. Sheng et al. "A survey on the ietf protocol suite for the internet of things: standards, challenges, and opportunities". In: *IEEE Wireless Communications* 20.6 (Dec. 2013), pp. 91–98.
- A. Sikora and V. F. Groza. "Coexistence of IEEE802.15.4 with other Systems in the 2.4 GHz-ISM-Band". In: *2005 IEEE Instrumentationand Measurement Technology Conference Proceedings*. Vol. 3. May 2005, pp. 1786–1791.

Bibliography V

- S. Sojuyigbe and K. Daniel. “Wearables/IOT devices: Challenges and solutions to integration of miniature antennas in close proximity to the human body”. In: *2015 IEEE Symposium on Electromagnetic Compatibility and Signal Integrity*. Mar. 2015, pp. 75–78.
- Sebastian Surminski. “Reliable Noise Level Measurement Using Crowdsensing (Talk)”. In: *ITG FA 5.2 Workshop on Smart Cities*. Lübeck, Germany, 2017.
- Girum Ketema Teklemariam et al. “Facilitating the creation of IoT applications through conditional observations in CoAP”. In: *EURASIP Journal on Wireless Communications and Networking* 2013.1 (June 2013), p. 177.
- Y. P. E. Wang et al. “A Primer on 3GPP Narrowband Internet of Things”. In: *IEEE Communications Magazine* 55.3 (Mar. 2017), pp. 117–123.

Bibliography VI

- M. Wollschlaeger, T. Sauter, and J. Jasperneite. “The Future of Industrial Communication: Automation Networks in the Era of the Internet of Things and Industry 4.0”. In: *IEEE Industrial Electronics Magazine* 11.1 (Mar. 2017), pp. 17–27.
- Keyi Zhang and A. Marchiori. “Crowdsourcing low-power wide-area IoT networks”. In: *2017 IEEE International Conference on Pervasive Computing and Communications (PerCom)*. Mar. 2017, pp. 41–49.
- Yanyan Zhuang, Albert Rafetseder, and Justin Cappos. “Privacy-Preserving Experimentation with Sensibility Testbed”. In: *USENIX ;login:* 40.4 (Aug. 2015), pp. 18–21.