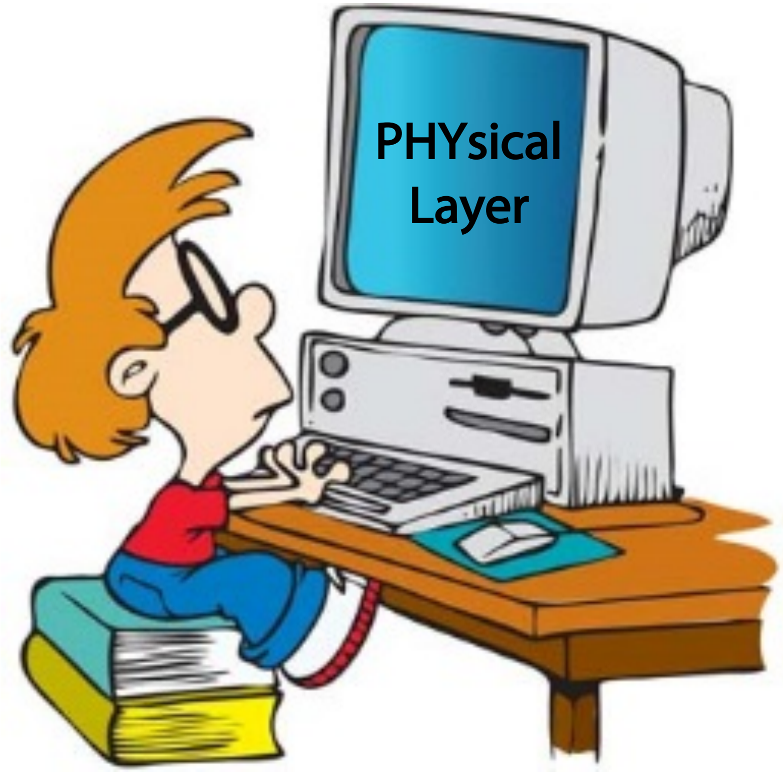
PHYsical Layer



Ramona Marfievici
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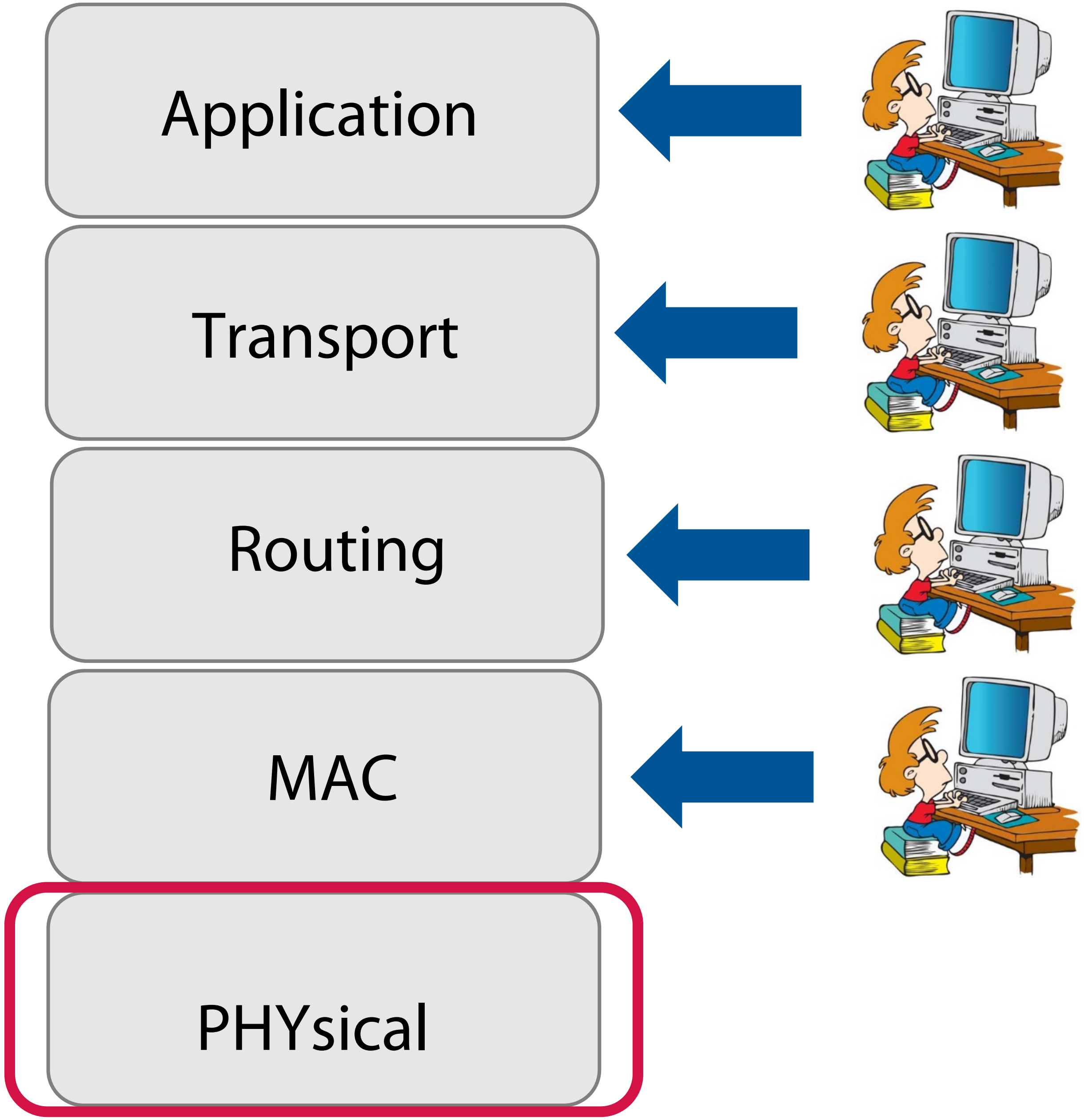
Some slides originally from Carlo Boano

Introduction



PHYsical Layer

Conversion of bit streams into signals best suited for communication across wireless channel

Responsible for

- Frequency selection
- Carrier frequency generation
- Signal detection
- Modulation

Nice to avoid wires, but…

The woes of wireless

- Limited communication range, non-isotropic, asymmetric links
- Collisions, hidden terminal problem
- Link quality affected by environmental parameters (e.g., temperature, humidity, foliage, obstacles)
- ”What-you-see-is-not-what-you-get” topologies (e.g., good connection to far nodes and bad to close ones)

Technologies

- **R**adio **F**requency (RF)
- Optical
- Acoustic
- Magnetic induction techniques

Radio Frequency (RF)

Communication through electromagnetic waves transmitted in RF bands

- Bands span from 3Hz to 300GHz spectrum
- ISM bands offers license-free communication in most countries
  - but…other frequencies bands are also used

RF communication techniques

- Narrow-band communication
  - Optimize bandwidth efficiency
- Spread spectrum
  - Uses chip codes of higher rate for spreading the spectrum
- Ultra wide band (UWB)
  - Relative positioning of UWB pulses w.r.t. a reference time

Narrow-band communication

High link budget by encoding signal in low bandwidth (less than 25kHz)

- Overall spectrum efficiently shared between multiple links
- Noise level experienced inside a narrowband is minimal
- Decode signal at receiver: no processing gain through frequency de-spreading required => simple and inexpensive transceiver design

Technologies

- NB-IoT, WEIGHTLESS-P
- Ultra narrow band (UNB)
  - Each carrier signal: 100Hz band, ultra long distance links
  - Further reduce the experienced noise
  - Increase number of supported end-devices per unit bandwidth
  - But…decreased data rate (~250kbps), increased radio ON time
  - SigFox, WEIGHTLESS-N, TELENESA

Spread Spectrum

A signal of limited bandwidth is spread over a much larger band using spread-spectrum techniques

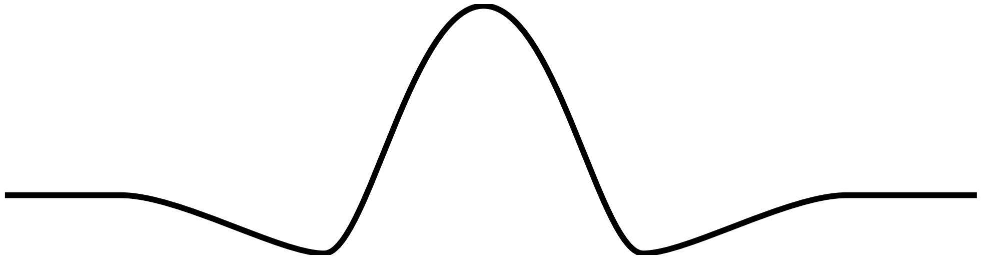
- Signal at particular band is observed as noise => improve resilience to interference from other signals

Techniques

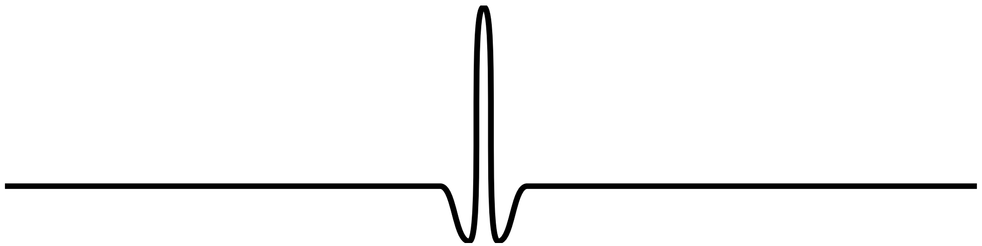
- FHSS (Frequency Hopping Spread Spectrum)
  - Wide-band spectrum divided into frequency channels
  - TX and RX pair through channels based on a predefined hopping scheme
  - Bluetooth
- DSSS (Direct Sequence Spread Spectrum)
  - Pseudo-noise (PN) codes: *chips*
  - Each bit is modulated with a number of chips (duration : chips < bits)
  - Information spread over a a much larger bandwidth (rate: chip > bit)
  - **De-facto standard for Wireless Sensor Networks: IEEE 802.15.4**

Ultra Wide Band (UWB)

Time Domain

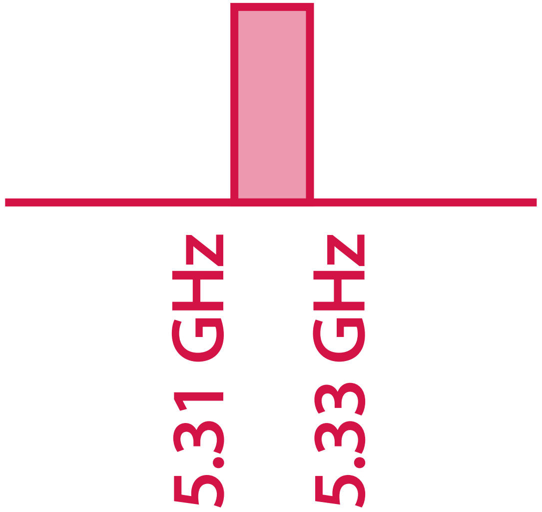


Narrowband



Ultra-Wideband

Frequency Domain



Ultra Wide Band (UWB)

Employs baseband transmissions

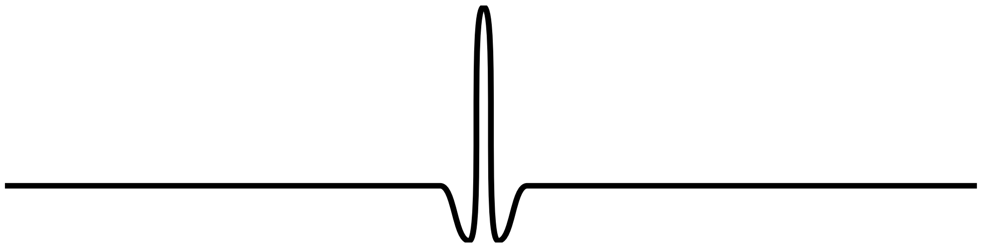
- No intermediate or radio carrier frequencies

Uses pulse position modulation (PPM)

- Spread the signals to be transmitted over a large bandwidth
  - High data rate (e.g., 6.8Mbps)
  - Robust against interference
  - Resilience to multi-path fading

Have driven success in high-fidelity RF-based localization (10cm)

802.15.4-2011: DecaWave DW1000



Ultra-Wideband

Comparison

1 Narrow band communication

2 Spread spectrum

3 Ultra Wide Band

- 1: trades bandwidth efficiency for energy efficiency, enable long range communication
- 2, 3: enable low-power communication with robustness against multi-fade
- 3 improves the advantages of 2 since much larger spectrum bands are used, has decreased circuitry but short communication range
- 2 provides a fine balance between system complexity and interference mitigation

APPLICATION REQUIREMENTS

Other techniques

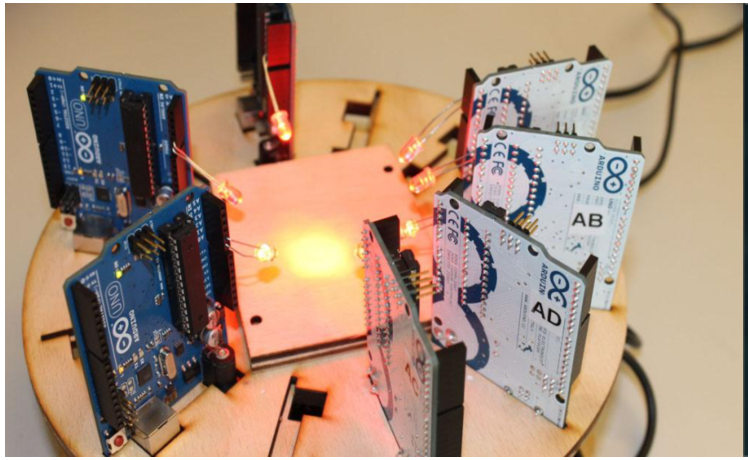
Optical

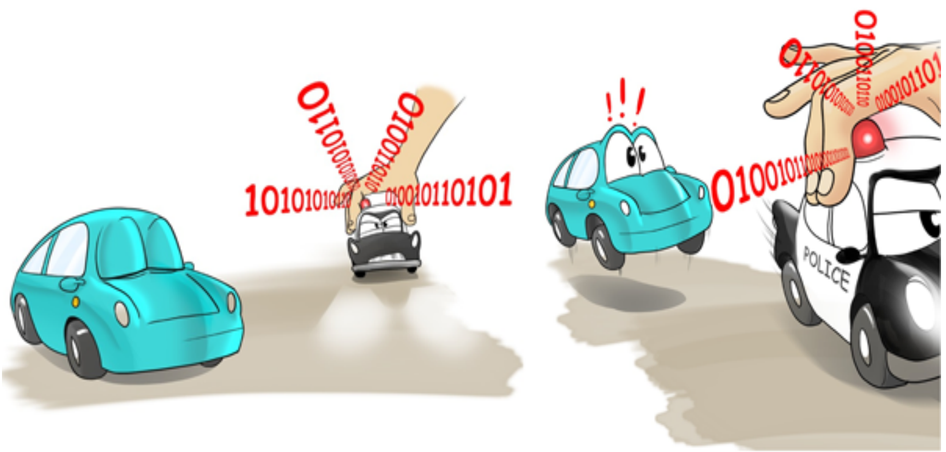
- Band at lower end of visible spectrum (750 to 1000nm wavelength)
- LED to photodiode
- Do not suffer from electromagnetic interference
- Short-range communication
- External light sources create interference

Other techniques

Visible Light Communication

- LED-to-LED communication
- DartNets Lab, Dartmouth College: StarLight (human sensing in the light), DarkLight (VLC communication in the dark when LEDs emit extremely-low luminance)
- Disney Research: VLC testbed & protocols, magic toys, car to car communication





https://www.disneyresearch.com/project/visible-light-communication/

Other techniques

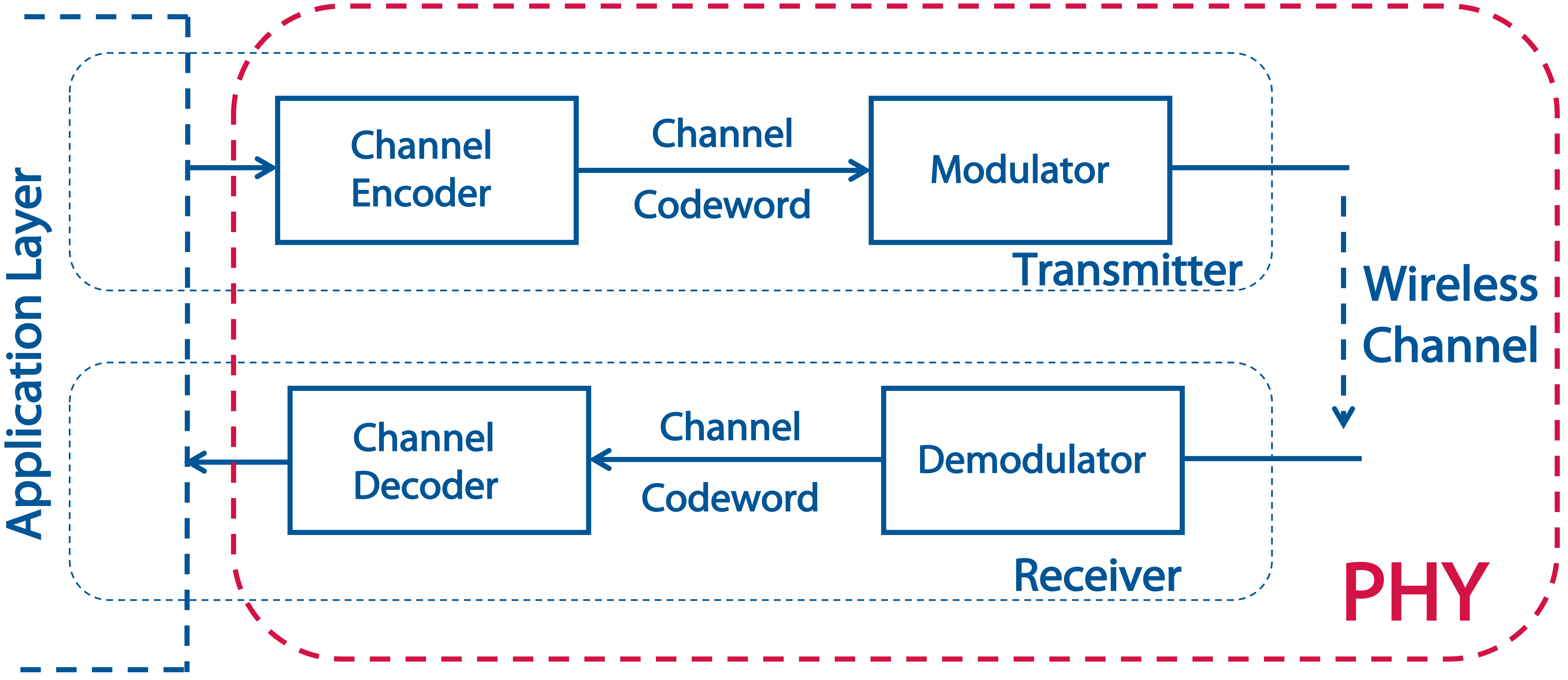
Acoustic

- Water limits the communication range of RF and optical communication
  - Path loss, noise, multi-path effects, Doppler spread, propagation delays
  - Depends on water properties
- Underwater sensor networks

Magnetic

- Underground sensor networks: soil, rocks
- EM waves: attenuation, path loss, need to operate at MHz or lower => huge antennas
- Magnetic induction (MI)

RF communication PHYsical layer blocks



RF communication depends on

The success of RF communication depends on

- Techniques used for each PHYsical layer block
- Wireless channel effects and operating parameters
  - Frequency, antenna properties
  - Ambient noise
  - Environmental parameters (e.g., temperature, humidity, obstacles)
- Energy efficiency: low-power communication

Channel coding

Exploit the statistical properties of the channel to inject redundancy into the information to be sent

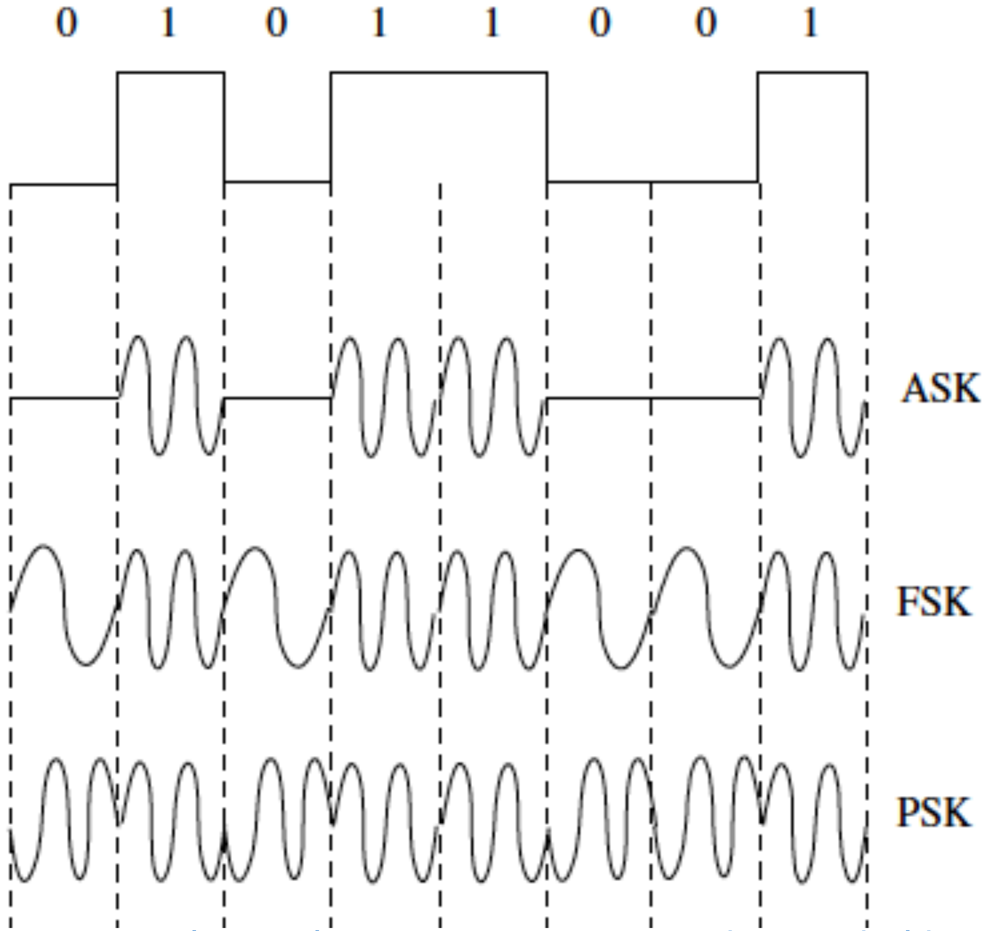
- Error Control Coding (ECC) or Forward Error Correction (FEC)
- Examples
  - Block codes
    - Preferred in WSNs*: simple implementation, small memory requirements
    - BCH, RS, Cyclic Redundancy Check (CRC)
  - Joint Source-Channel Coding

Note: WSNs* = Wireless Sensor Networks

Modulation

Conversion from bit streams to waveforms

- Channel coding: digital domain
- Wireless communication: analog domain, waveforms generated by the antenna are radiated



Waveform $s(t) = r(t)\cos[2\pi f_c t + \psi(t)]$

- Amplitude $r(t)$
- Frequency f_c
- Phase $\psi(t)$

Digital information is transmitted by modifying one of the components

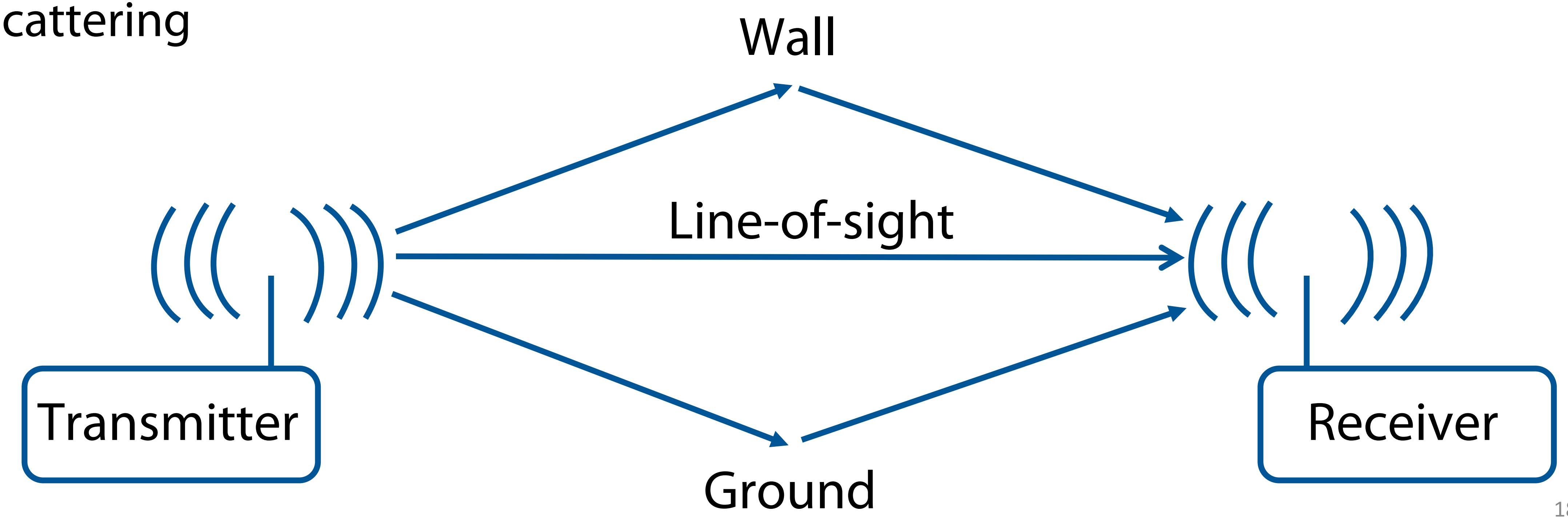
- Frequency: early platforms
- Quadrature phase shift keying: IEEE 802.15.4

http://doktora.kirbas.com/Kitaplar/Wireless%20Sensor%20Networks%20(Akyildiz).pdf

Wireless channel effects

Sources of distortion

- Attenuation => path loss
- Reflection and refraction: ground, walls => signal fades based on constructive or destructive effects of multiple waves
- Diffraction: sharp edges act as source => new waves are generated
- Scattering



Attenuation. Path loss

Signal strength decreases as a function of distance

Transmission range of a node, **receiver sensitivity**

Example TMoteSky CC2420 radio

- transmission range 50m indoors, 125m outdoors
- sensitivity threshold -95dBm

- Path loss model [1]

$$PL(d)[dB] = PL(d_0) + 10 \times n \times \log(\frac{d}{d_0})$$

  - Logarithmic decay of the average signal power as a function of distance d from TX
  - $PL(d_0)$: path loss at a known reference distance d_0
  - n : path loss exponent representing the attenuation rate with the distance
  - Parameters strictly dependent on the environment at hand
    - estimate empirically by curve fitting on large amounts of measurements collected in the target location

[1] T.S. Rappaport, Wireless communications: Principles and Practice. Vol.2, Prentice Hall, 1996

Multi-path effects

Path loss model : attenuation of signal with distance

But…reflection and scattering => multiple copies of the signal

Log-normal path loss model [1]

$$PL(d)[dB] = PL(d_0) + 10 \times n \times \log(\frac{d}{d_0}) + X_\sigma$$

X_σ: normal random variable, depends on the environment

[1] T.S. Rappaport, Wireless communications: Principles and Practice. Vol.2, Prentice Hall, 1996

Channel error rate

Sources of distortion

- Noise
  - Receiver electronics, environment, temperature
  - Signal to Noise Ratio (SNR): difference (in dB) between the signal strength and the noise floor
- Interference: other devices co-existing in the same wireless bands

Link Layer Technologies

Tens of different technologies

IEEE 802.15.4

ZigBee®

LoRa™

Bluetooth™

G3-PLC Alliance

WirelessHART™

ISA 100 WIRELESS

ANT+™

SIGFOX
One network A billion dreams

Z-WAVE®

One common denominator: low-power, limited data rate

Low-power long range technologies

	SIGFOX	LoRaWAN
Modulation	UNP DBPSK(UL), GFSK(DL)	CSS
Band	SUB-GHz ISM:EU(868MHz), US(902MHz)	SUB-GHz ISMU:EU (868MHz), US(915MHz), Asia (430MHz)
Data rate	100bps (UL) 600bps (DL)	0.3-37.5 kbps (LoRa) 50 kbps(FSK)
Range	10km (URBAN) 50km (RURAL)	5km (URBAN) 15km(RURAL)
Number of channels	360 channels	10 in EU, 64+8(UL) and 8(DL) in US
Topologies	star	star of stars

Low-power short range technologies IEEE 802.15.4

First introduced in 2003

- Targeting low-power & low data rate applications
- Low-cost radio transceivers
- Data rates up to 20, 40 and 250 kbps

Reference standard for smart objects

Specifies both PHYsical and MAC layer

- Transceiver management
- Channel access
- ZigBee, 6LoWPAN, WirelessHART, ISA 100.11a

IEEE 802.15.4 PHY available frequencies

IEEE 802.15.4 2003 →

2011 enhancements →

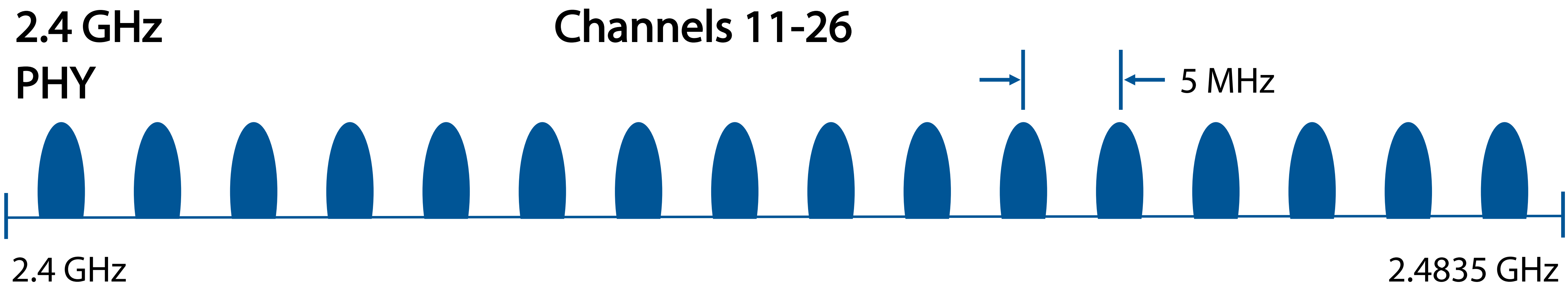
PHY (MHz)	Band (MHz)	kchip/s	Modulation	kb/s
2450 DSSS	2400-2483.5	2000	O-QPSK	250
2450 CSS	2400-2483.5			250
				1000
915 (USA)	902-928	600	BPSK	40
	902-928	1600 (PSS)	ASK	250
	902-928	1000	O-QPSK	250
868 (Europe)	868-868.06	300	BPSK	20
	868-868.06	400 (PSS)	ASK	250
	868-868.06	400	O-QPSK	100
780 (China)*	779-787	1000	O-QPSK	250
	779-787	1000	MPSK	250
950 (Japan)	950-956	-	GFSK	100
	950-956	300	BPSK	20
UWB Sub-GHz	250-750			
UWB Low Band	3244-4742			
UWB High Band	5944-10234			

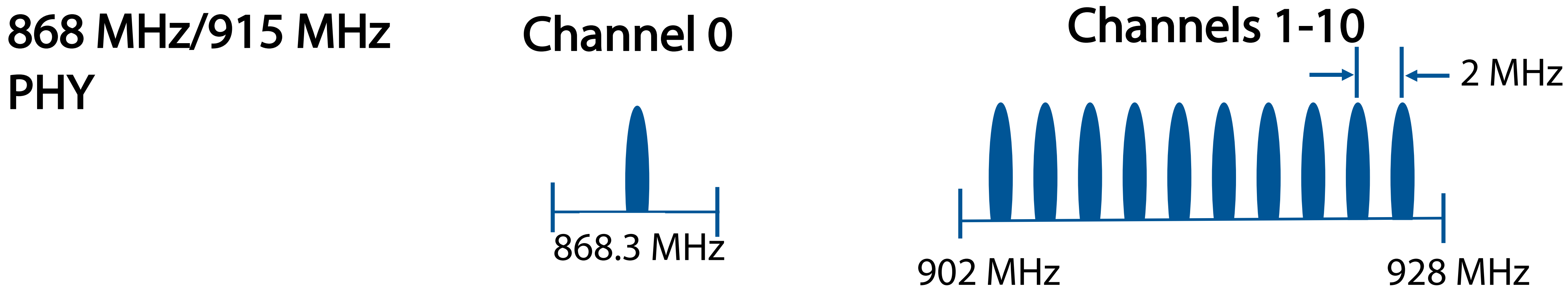
* Note: 314-316 MHz and 430-434 MHz bands are also used in China

	Channel	Center Frequency (MHz)	Availability
868 MHz Band	0	868.3	 Europe
915 MHz Band	1	906	 Americas
	2	908	
	3	910	
	4	912	
	5	914	
	6	916	
	7	918	
	8	920	
	9	922	
	10	924	
2.4 GHz Band	11	2405	 World Wide
	12	2410	
	13	2415	
	14	2420	
	15	2425	
	16	2430	
	17	2435	
	18	2440	
	19	2445	
	20	2450	
	21	2455	
	22	2460	
	23	2465	
	24	2470	
	25	2475	
	26	2480	

http://www.cse.wustl.edu7Ejain/cse574-14/ftp/j_12wpn.pdf/%

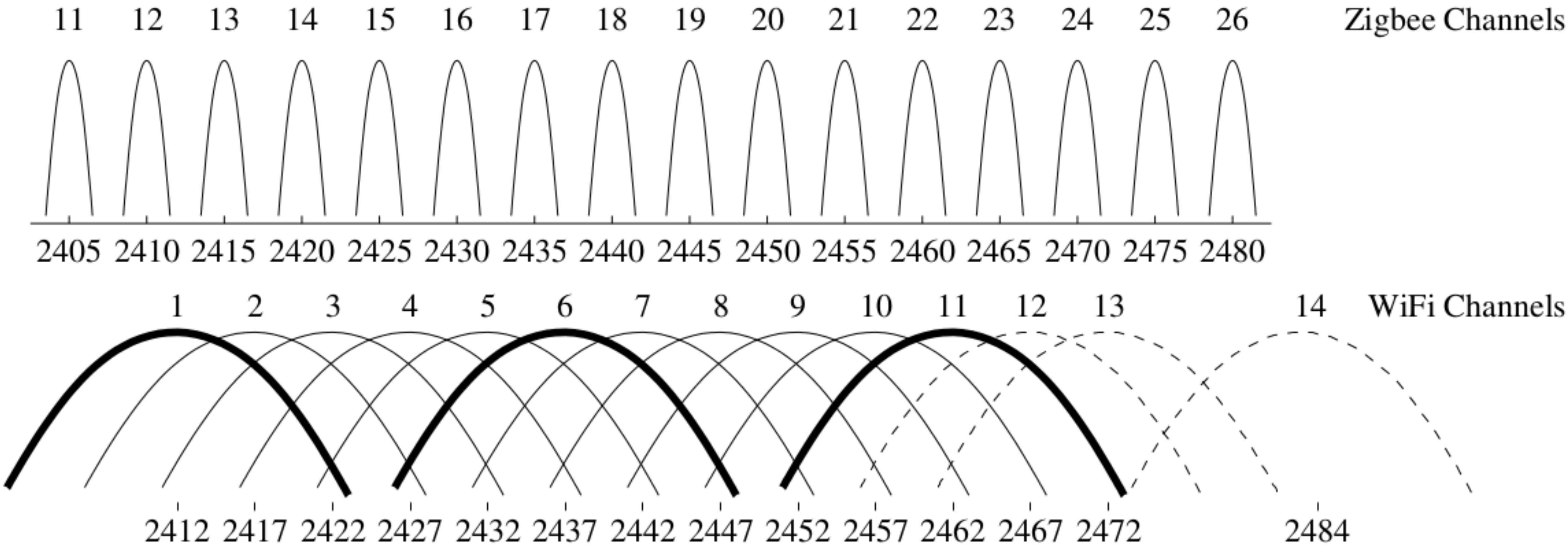
IEEE 802.15.4 PHY channels





Interference

ISM bands are public and shared with other technologies!
Susceptibility to radio interference (low-power devices)



http://www.ni.com/white-paper/10789/en/

Does it matter?

LAB	WHAT'S DIFFERENT?	REAL-WORLD
Simulators Testbeds	Behavior of applications Behavior of protocols Behavior of links	   Deployments

Lack of…

- Traces
- Tools for in-field connectivity assessment

Limited…

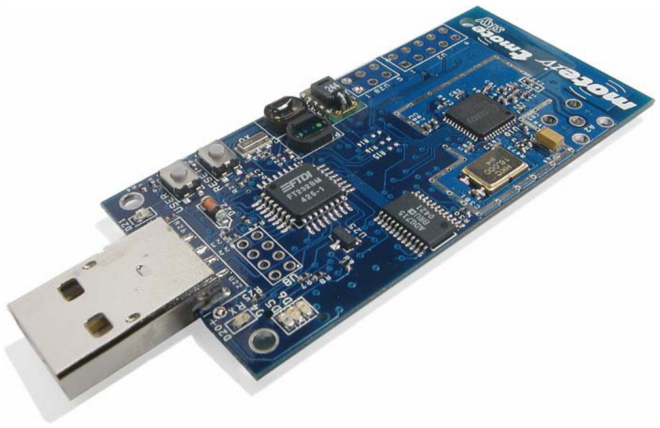
- Quantitative evidence for understanding
  - the impact of the environment on network stack
- Realistic enough models

WSN design and deployment is still mostly an *art*

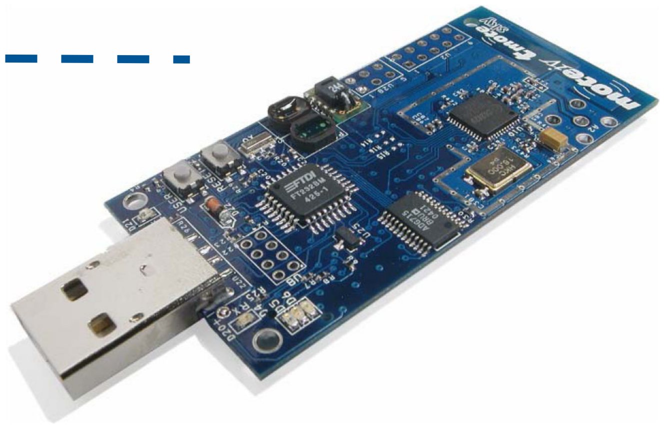
An example from the real-world

TMoteSky mote IEEE 802.15.4-compliant ChipCon 2420

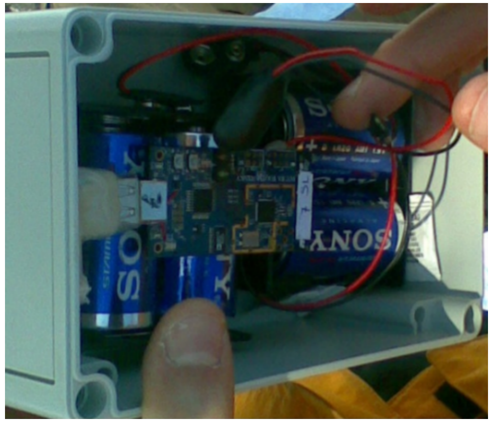
- Spread spectrum OQPSK modulation
- 16 channels in 2.4 GHz
- Metrics
  - Received Signal Strength (RSSI): signal strength of a received packet
  - Link Quality Indicator (LQI): correlation between a received symbol and the symbol that is mapped to after the radio completes decoding
  - Packet Delivery Ratio (PDR): ratio of packets received over those sent

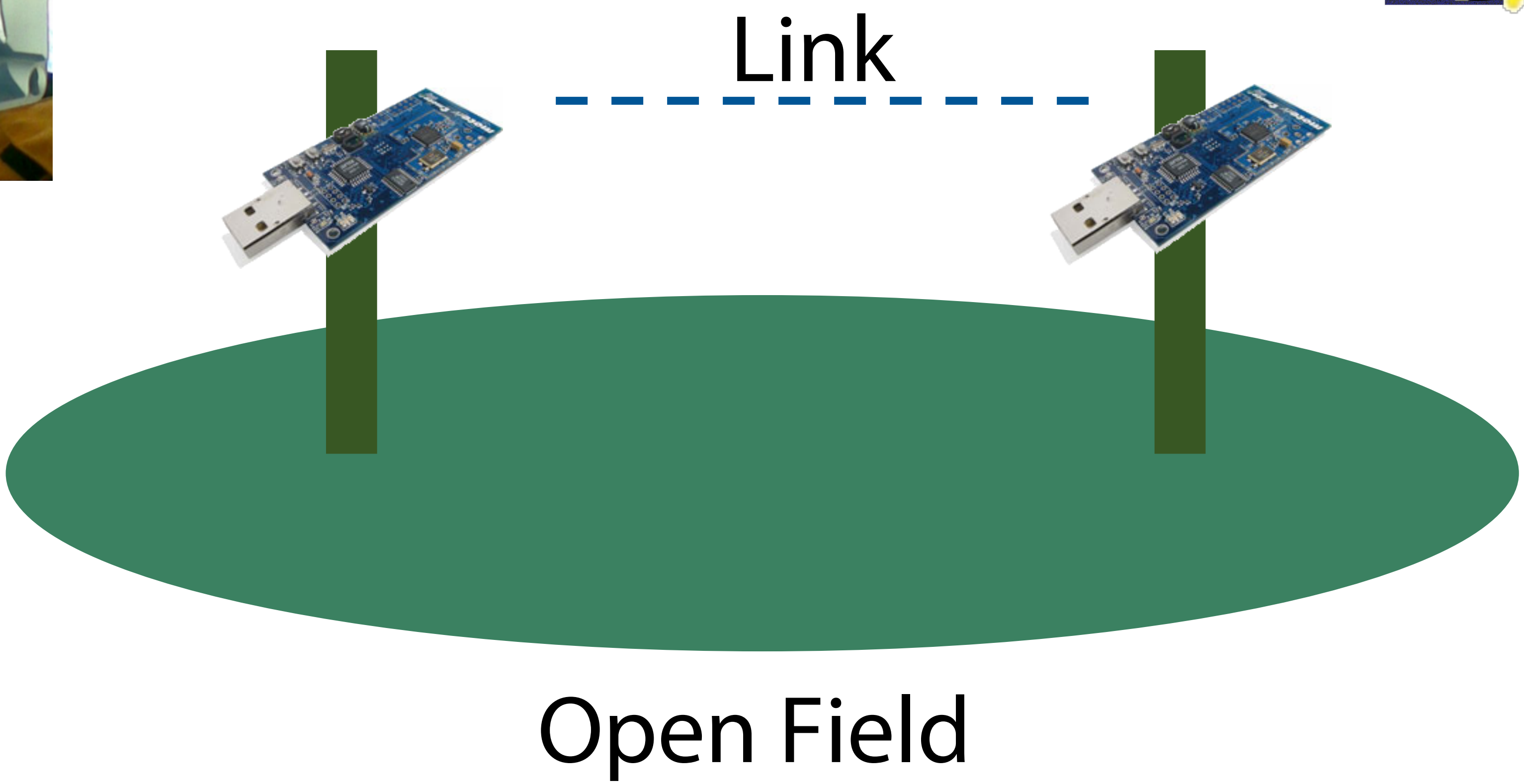


Link

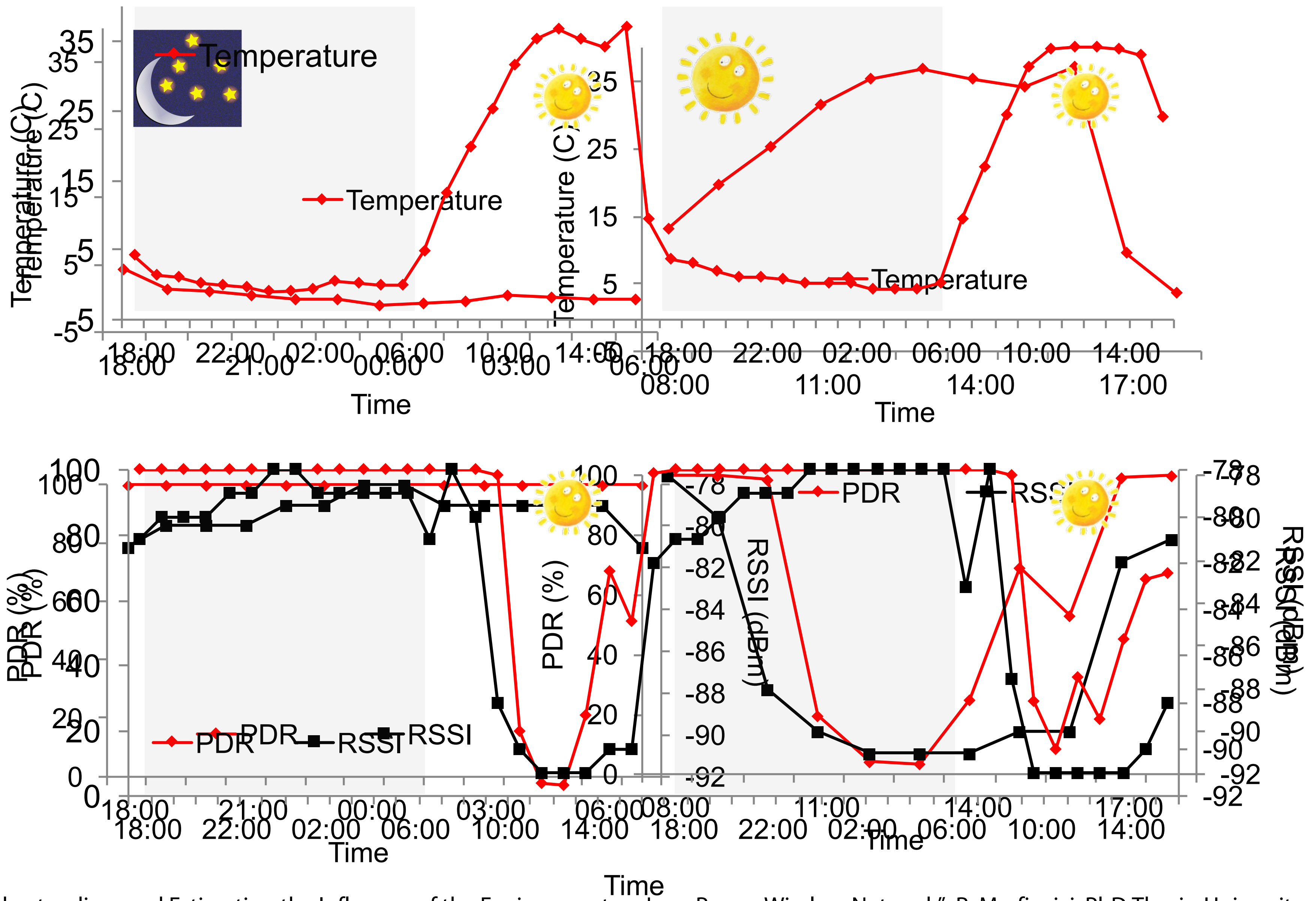


An example from the real-world



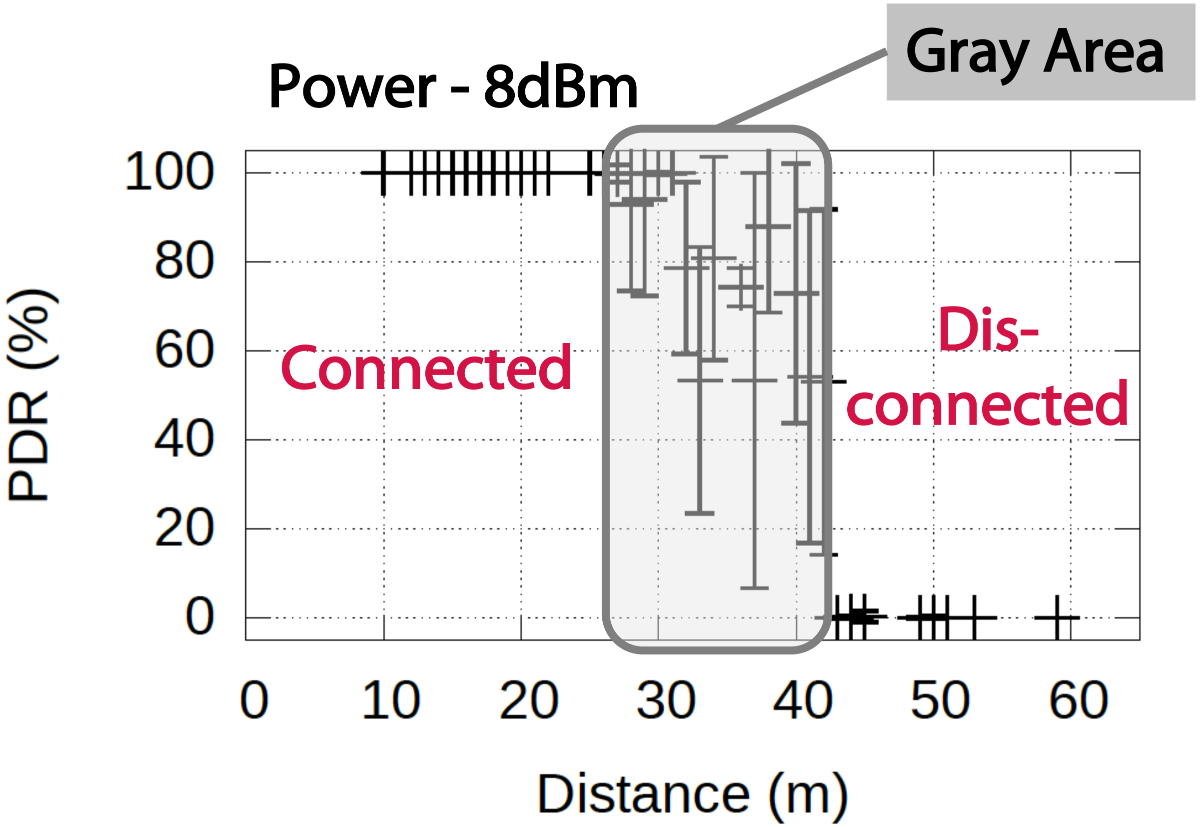


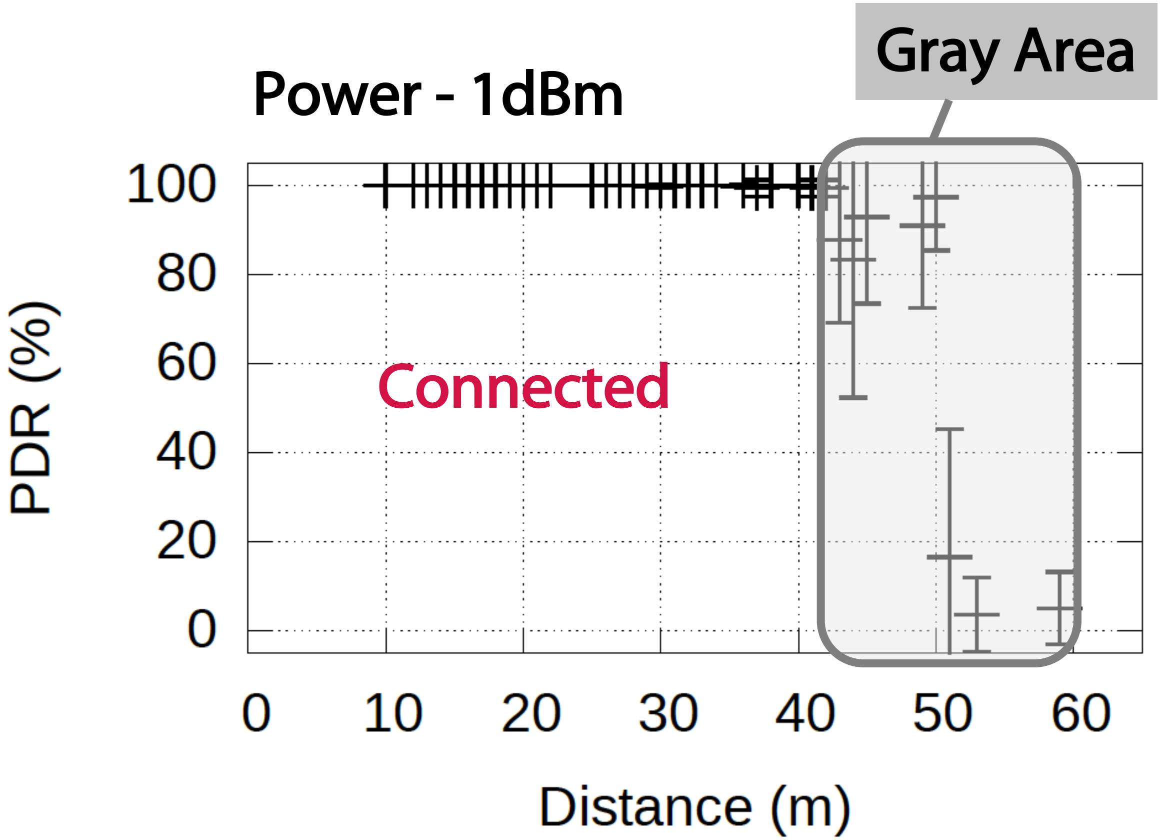
An example from the real-world: temperature



Plots are from “Measuring, Understanding, and Estimating the Influence of the Environment on Low-Power Wireless Network”, R. Marfievici, PhD Thesis, University of Trento, Italy, 2015

An example from the real-world: distance



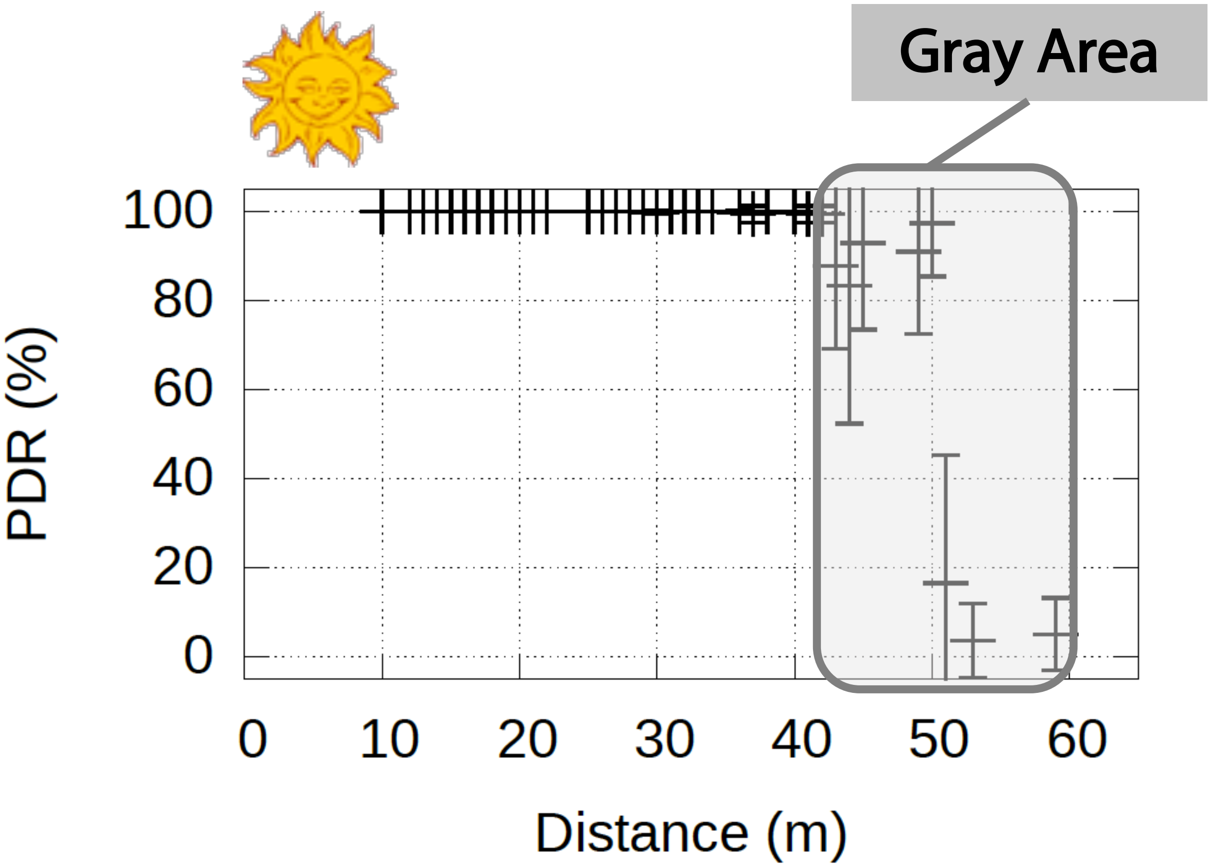


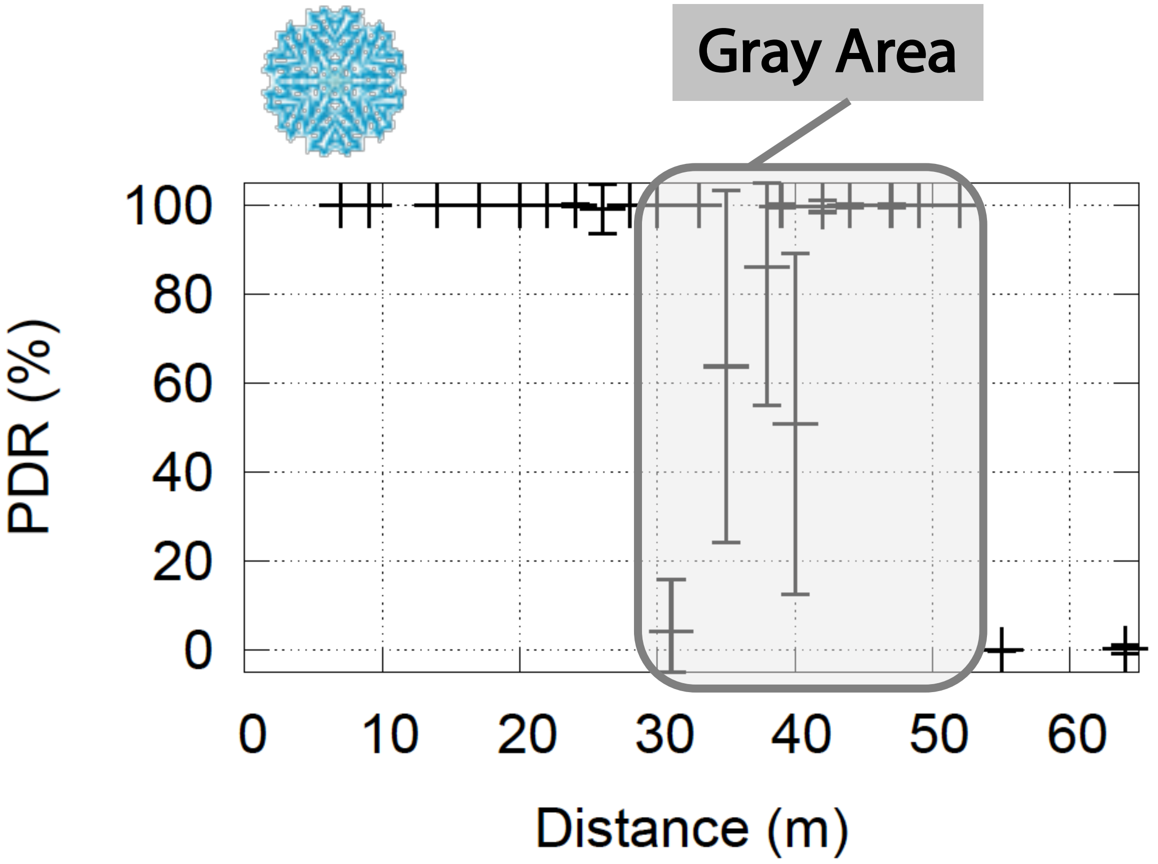
Transmission regions based on distance and PDR

- Connected: closest to the sender, links of good quality
- Transitional: links that exhibit high variance
- Disconnected: farthest from the sender, does not contain links usable for communication

Plots are from "Measuring, Understanding, and Estimating the Influence of the Environment on Low-Power Wireless Network", R. Marfievici, PhD Thesis, University of Trento, Italy, 2015

An example from the real-world: season

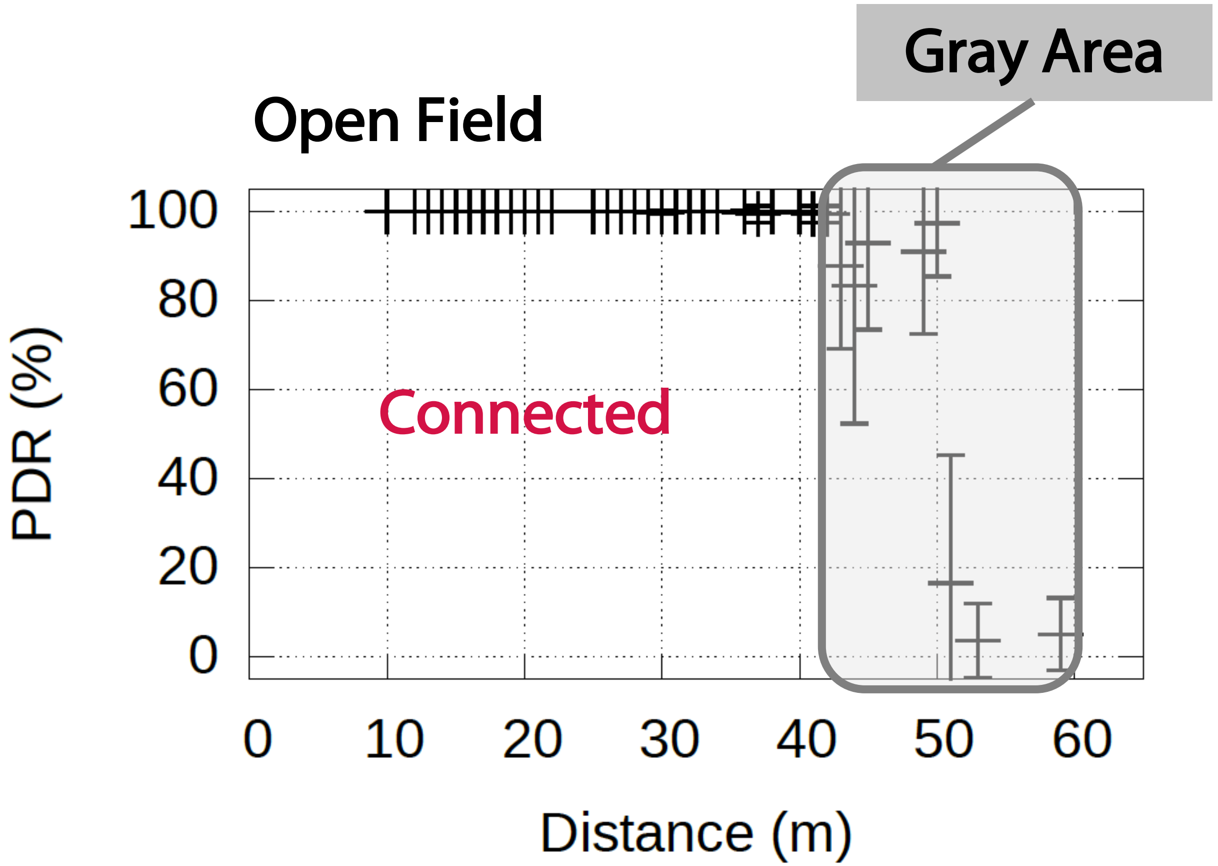


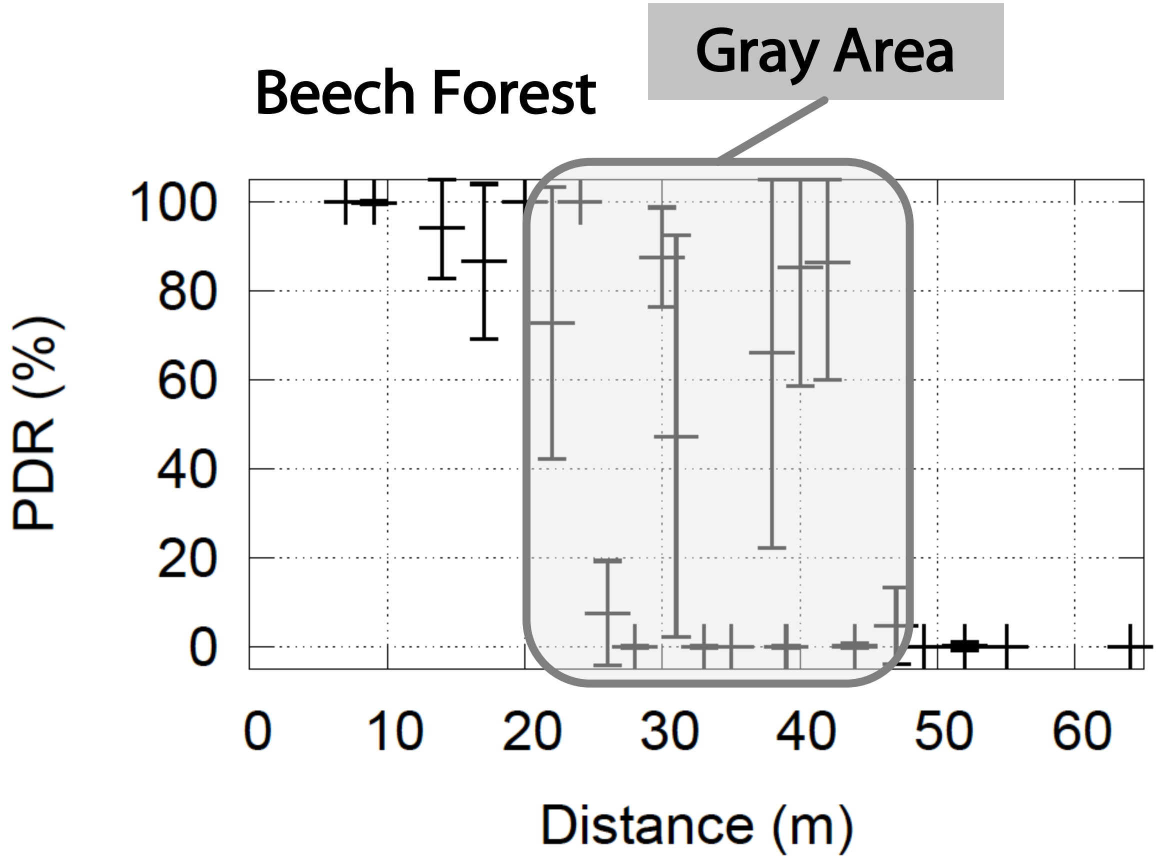


Seasonal variations induce dramatical changes with winter worse than summer

Plots are from "Measuring, Understanding, and Estimating the Influence of the Environment on Low-Power Wireless Network", R. Marfievici, PhD Thesis, University of Trento, Italy, 2015

An example from the real-world: environment

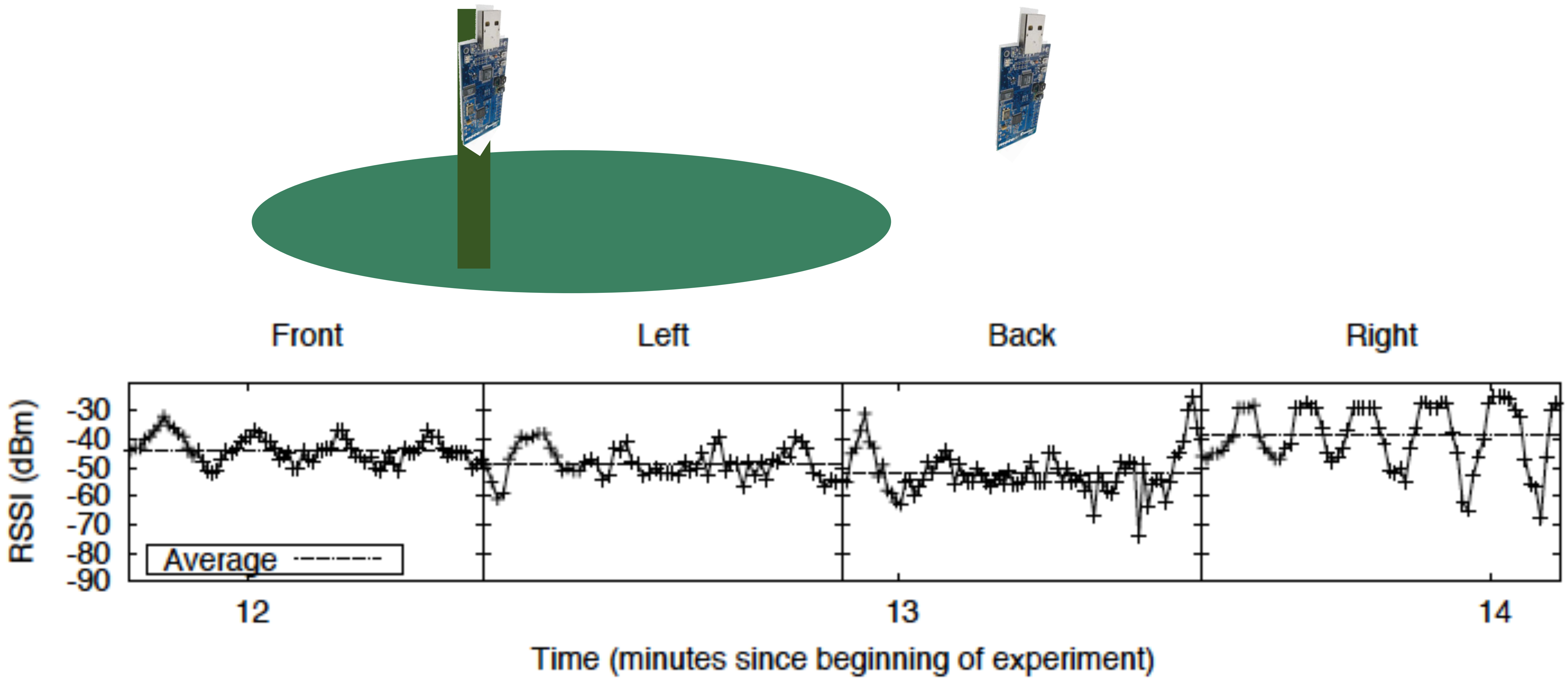




Quality of communication decreases OPEN FIELD → BEECH

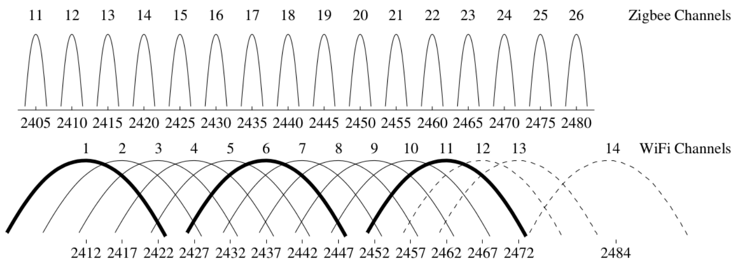
Plots are from "Measuring, Understanding, and Estimating the Influence of the Environment on Low-Power Wireless Network", R. Marfievici, PhD Thesis, University of Trento, Italy, 2015

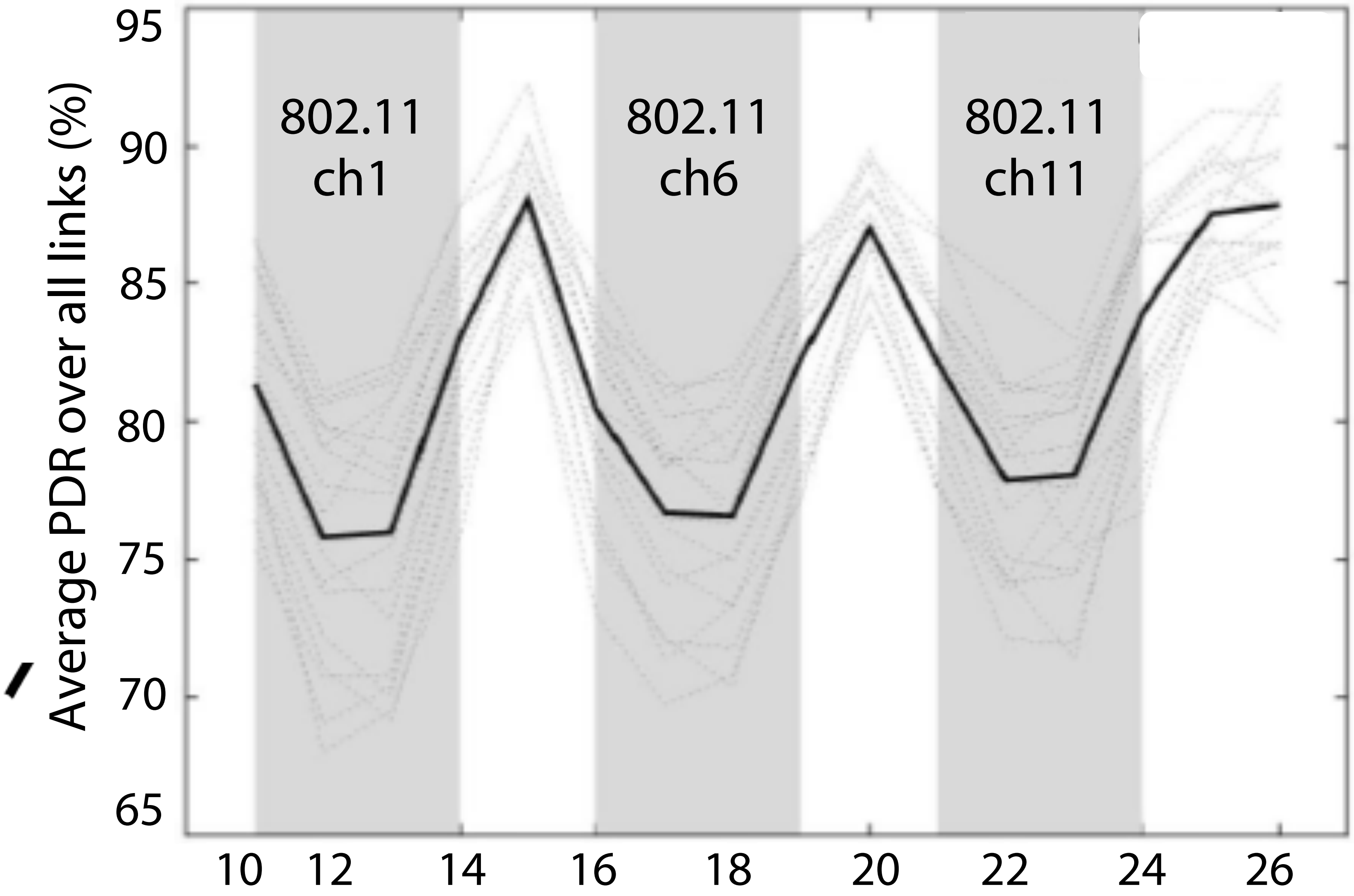
An example from the real-world: antenna

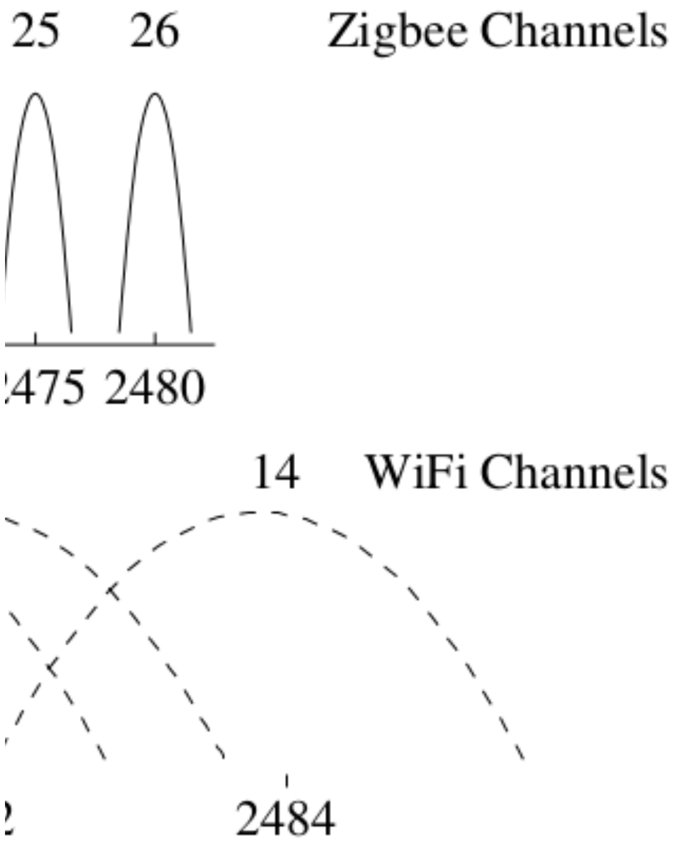


M. Ceriotti et al, “Motes in the Jungle: Lessons Learned from a Short-Term WSN Deployment in the Ecuador Cloud Forest”, 4th RealWSN Workshop, 2010

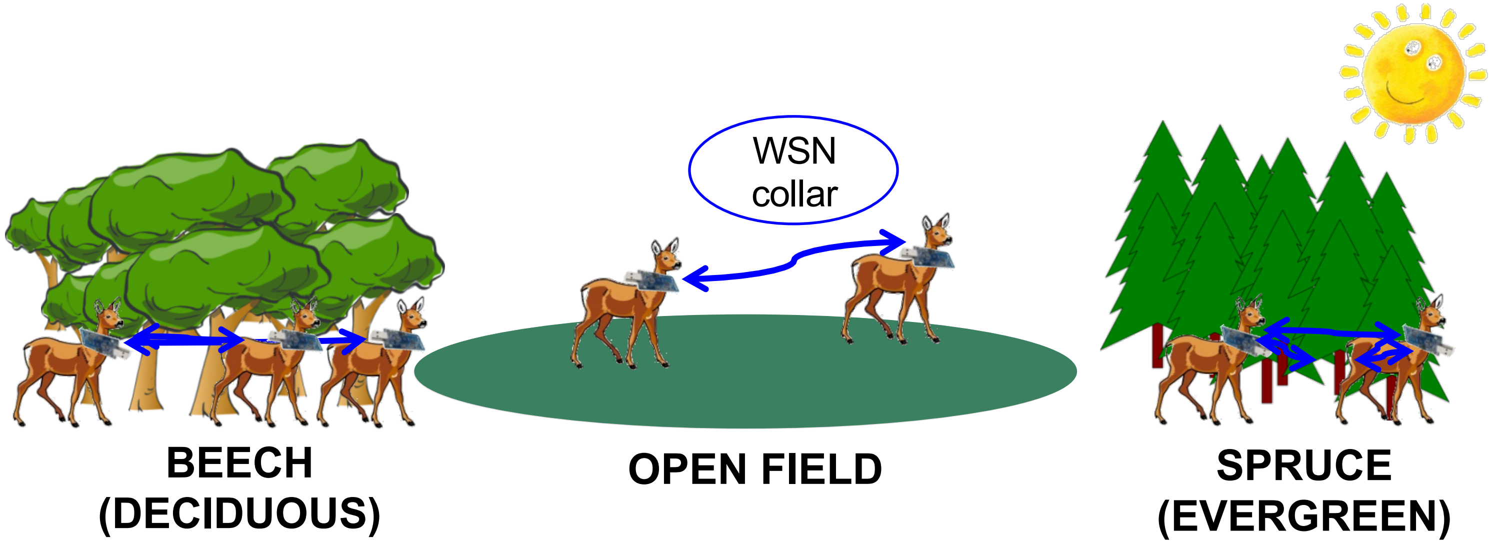
Interference





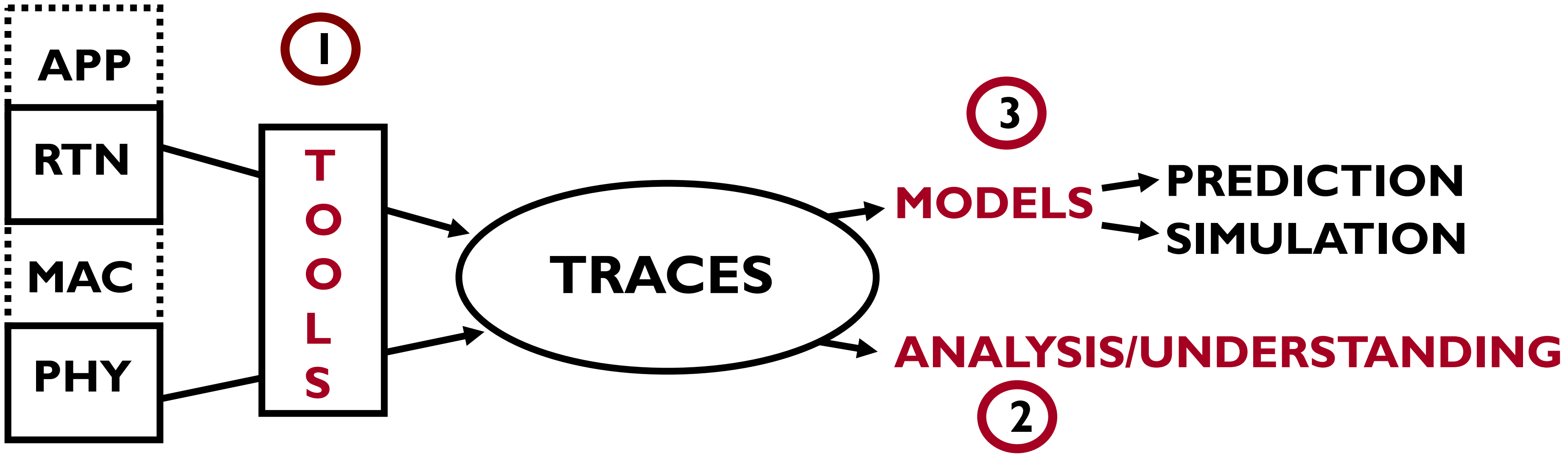


Assess PHYsical layer properties



- Example of concrete motivating application: in the wild
  - many different outdoor environments
  - year long
- Assess the characteristics of communication in-field, in the target environment

Tools



Tools: TRIDENT

http://wirelesstrident.sourceforge.net/description.html

Tools: Non-functional Requirements

No infrastructure needed

- Quick setups
- Lighter backpacks

Wireless interaction with the nodes

- Configuration
- Status check
- Download of the results

No coding required!

Decoupling from

- Hardware: TMote Sky, Waspmote

Tools: Functional Requirements

- Environmental parameters: temperature, humidity
- Time scale
  - long-term campaigns - up to several days unattended
  - quick interactive tests
- Granularity
  - aggregates over time
  - per-packet sampling
- Link metrics: PDR, RSSI, LQI
- Node metrics: noise floor

- MAC-free, no collisions
- Single packets and bursts

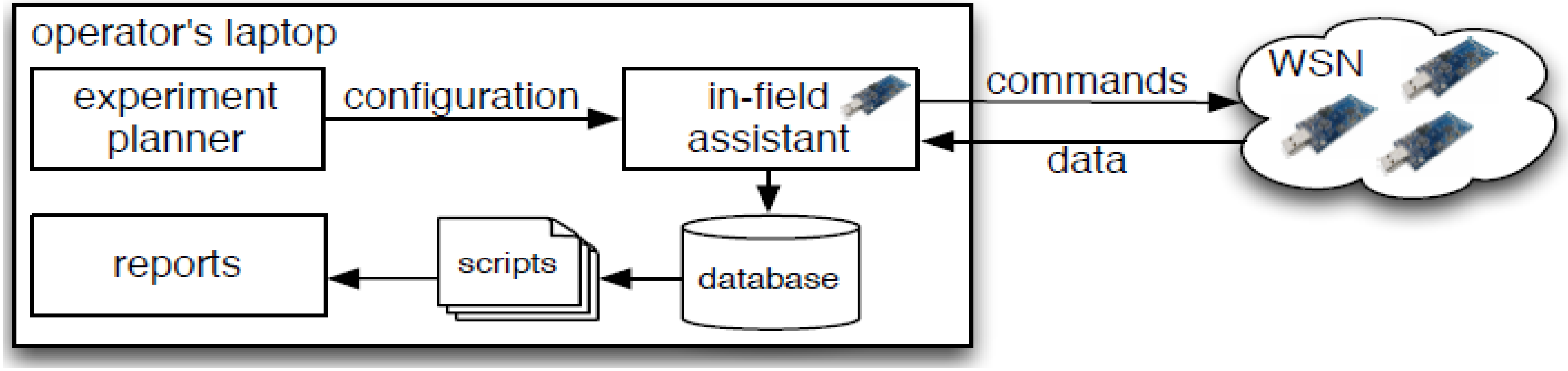
Long-term campaigns

Lab — In field — Lab

Plan → Deploy → Collect → Analyze

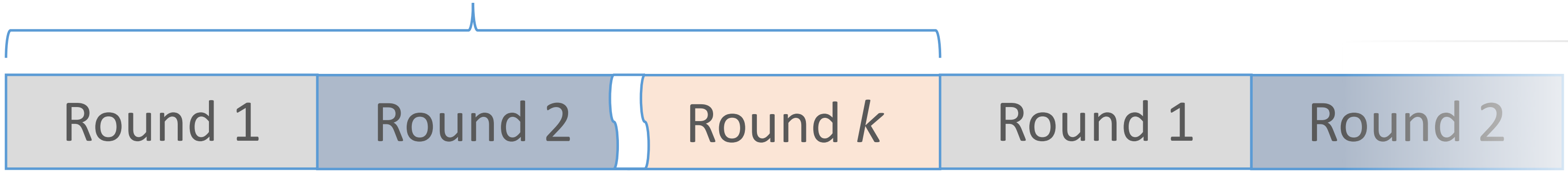
1. Place nodes
2. Run a test
3. View results

Quick assessment



Tools: Experiment Schedule

Repeat N times…



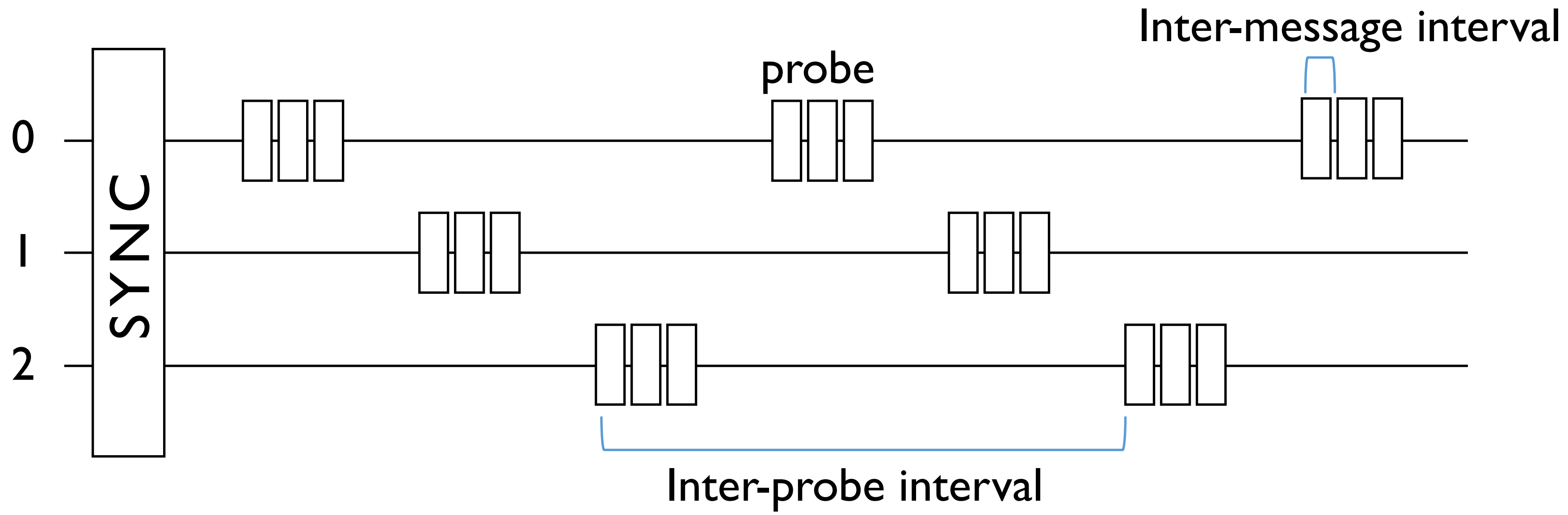
… go low-power when finished

Example

Two rounds:
- High power
- Low power

× 30 min each × 72 times = 3 days of tests

An example of a round



Round parameters

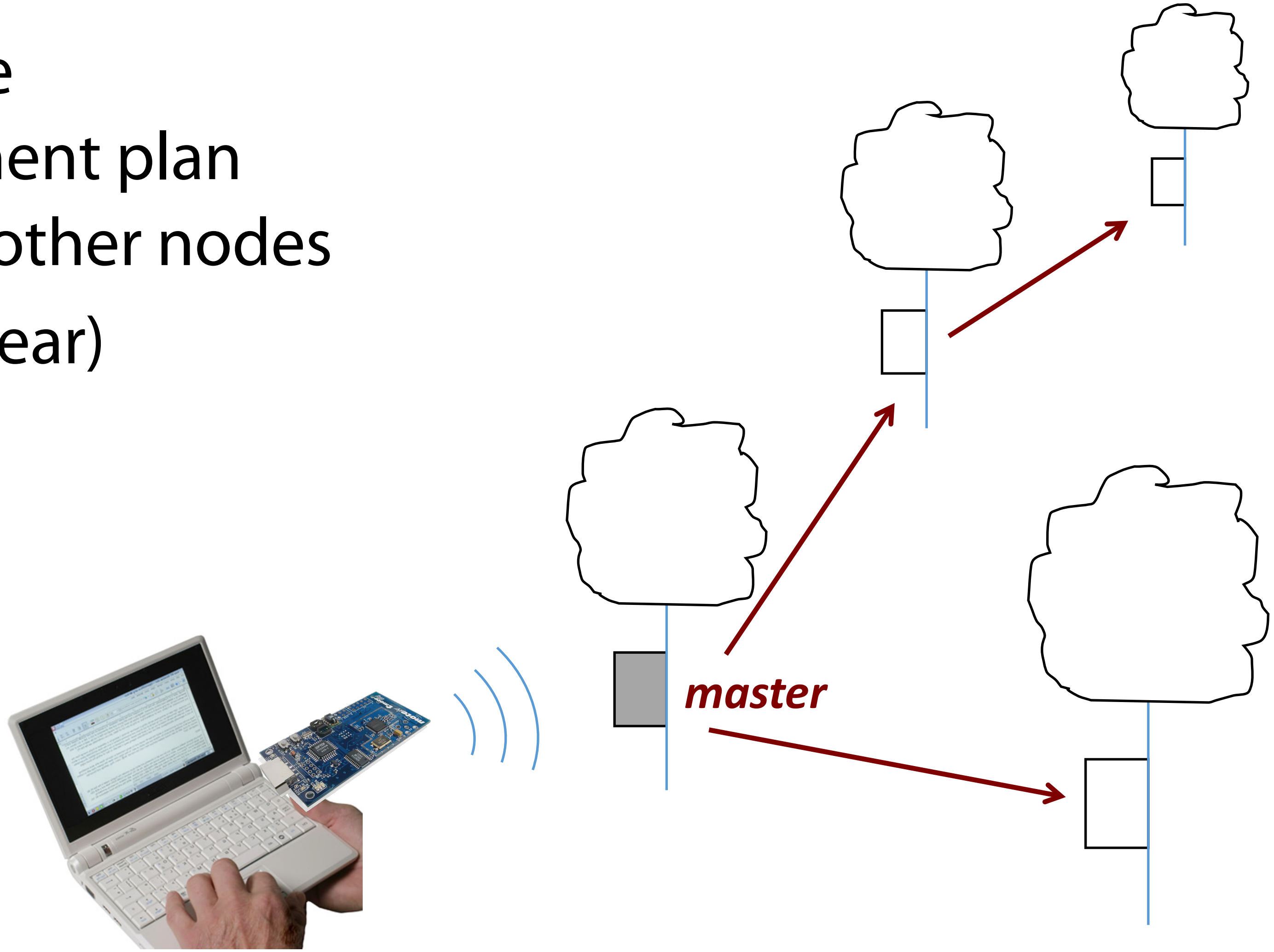
- Channel, TX power
- Who's sending
- How many probes

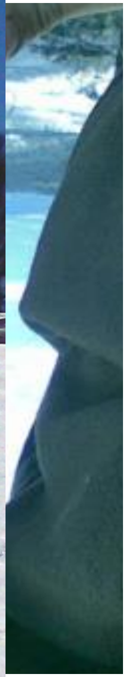
- Type of probe:
  - single packet
  - burst

- Probe timing
- What to log

Tool: start

- Special master node
  - receives experiment plan
  - coordinates the other nodes
- Check status (overhear)
- Leave them alone!





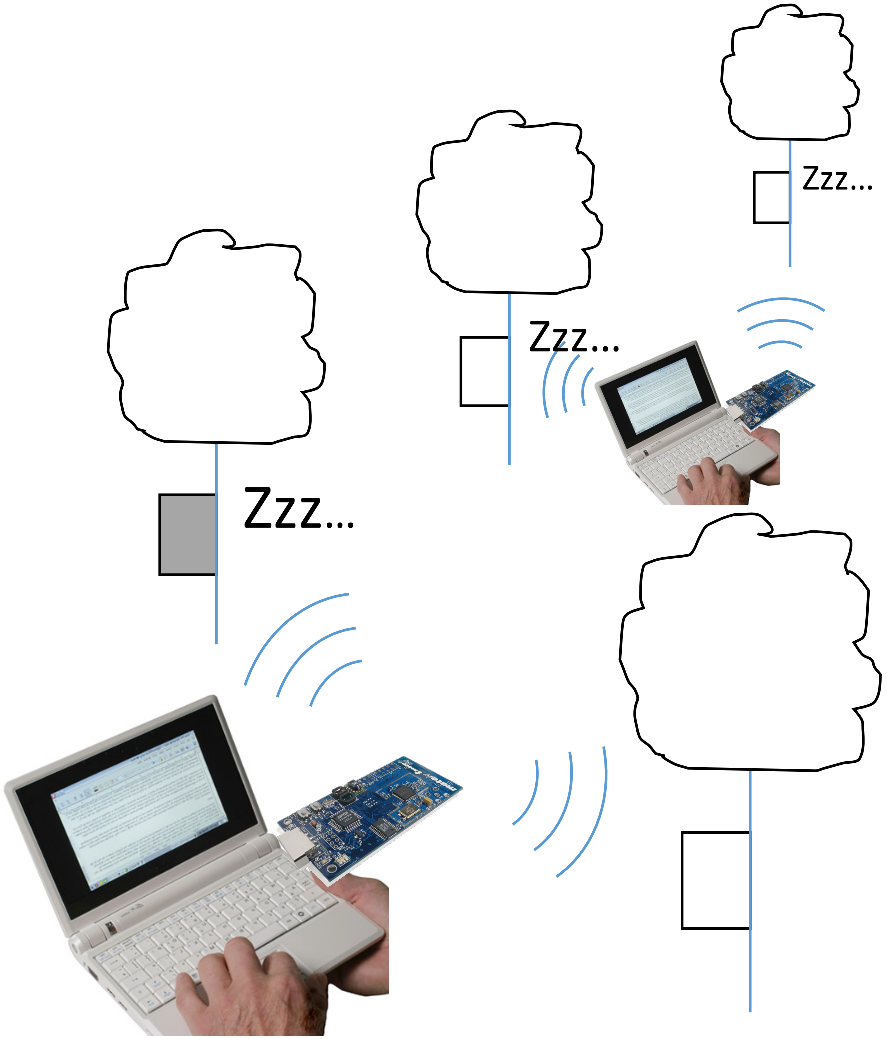
Tools: Collecting Results & Analysis

1-hop over-the-air operation

- Wake up the nodes
- Download the logs

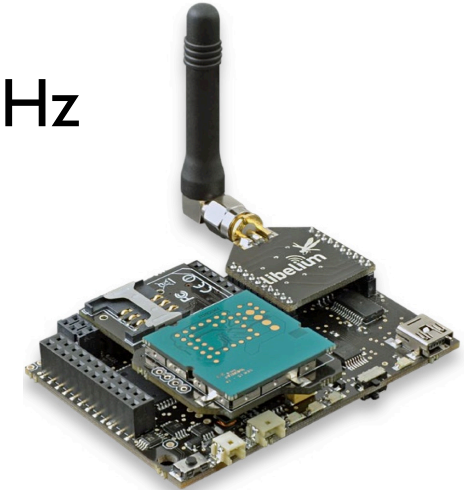
Need more data?

- Run again!
- But first check the battery levels and erase the flash — wirelessly!



Tool: supporting different platforms

802.15.4 2.4GHz
both

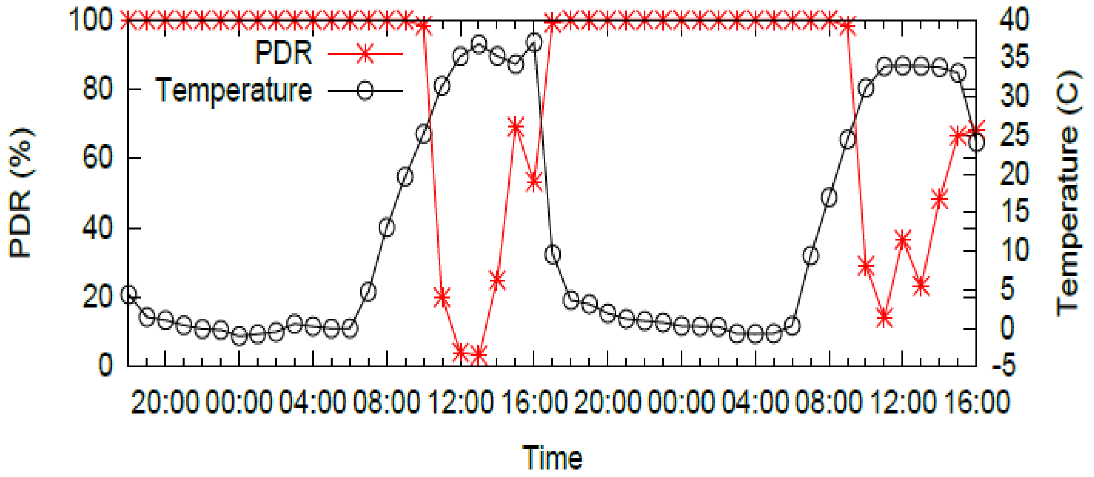


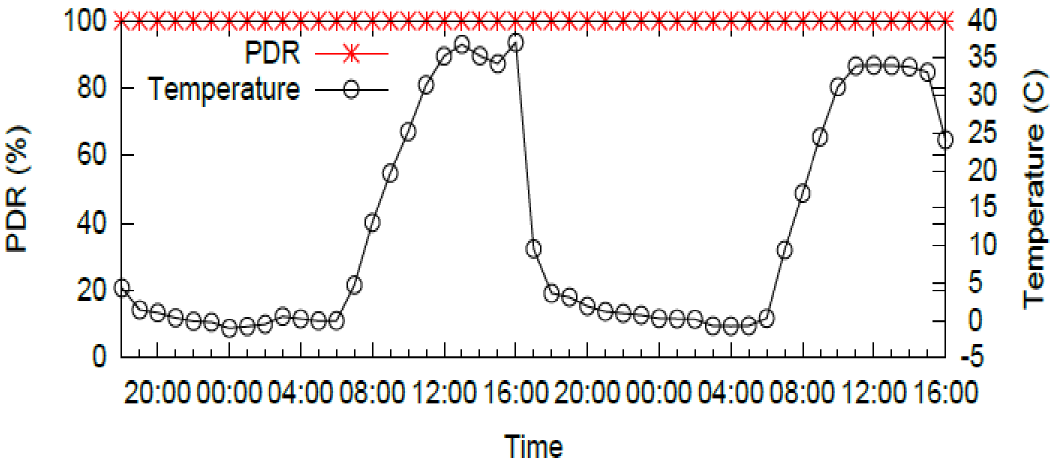
TMote Sky

TinyOS with rich
low- and high-level APIs

Waspmote

Arduino-based
with ZigBee-compliant
radio module (XBee)





Instead of conclusions

- Behavior of link -> protocols -> application
- Important to understand the impact of environment on PHYsical layer (links)
- Support deployment
- Inform selection of protocols and tune parameters
- Inform application-level strategies
- Estimate link quality at run-time
- Build realistic models