WiFi-based Long Distance networks (WiLD)

Michael Rademacher
michael.rademacher@h-brs.de

Bonn-Rhein-Sieg University of Applied Sciences

Last edited: April 1, 2017

Table of contents

Our Testbed

Hardware for WiLD

Link Budget

Propagation on long-distance IEEE802.11 links

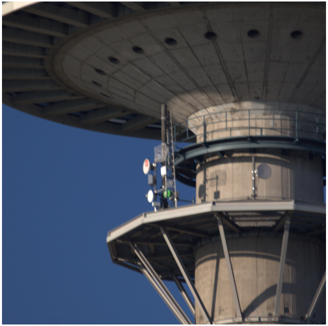
Example build-up

MAC-layer and long-distance links

Throughput Optimization
- IEEE802.11n
- MAC Layer estimation and optimization

WiBACK

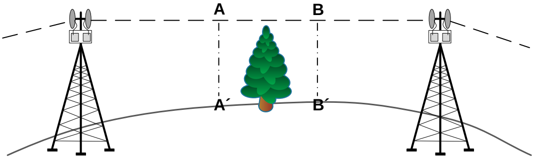
Our Testbed



Hardware for WiLD

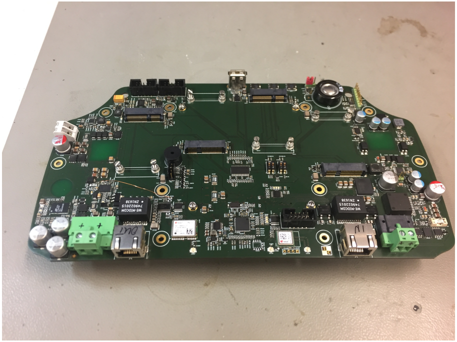
Important Hardware for WiLD:

1. Embedded boards and enclosures
2. IEEE802.11 transmitter (WiFi cards)
3. High-frequency cables
4. Antennas



Embedded boards and enclosures

- TP-Link 841nd are **not** appropriate
- Special embedded boards and enclosures
  - Outdoor usage (IP64 - IP67)
  - External antenna connectors
  - Concept for power supply: Power over Ethernet or Solar



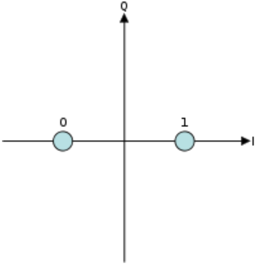
IEEE802.11 transmitter (WiFi cards)

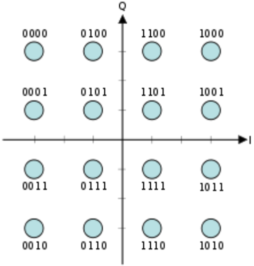
- The most important parameters are:
  - Transmission Power P_{TX}
  - Sensitivity $RXLevel_{min}$
- The more complex the modulation...

- ...the less the max. P_{TX}
- ...the higher $RXLevel_{min}$

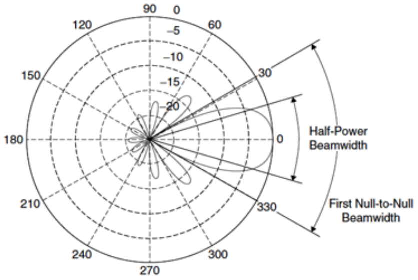
Example values:

	Phy-Rate	MCS	P_{TX}	$RXLevel_{min}$
802.11a	6 Mbps	BPSK - 1/2	28 dBm	-96 dBm
	54 Mbps	64QAM - 3/4	28 dBm	-81 dBm
802.11n	7.2 Mbps	BPSK - 1/2	28 dBm	-96 dBm
	72.2 Mbps	64QAM - 5/6	27 dBm	-77 dBm
802.11ac	7.2 Mbps	BPSK - 1/2	28 dBm	-96 dBm
	86.7 Mbps	256QAM - 3/4	24 dBm	-72 dBm





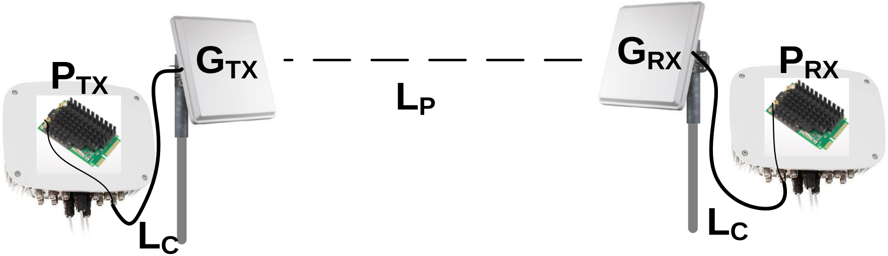
Antennas



Important: Impedance, Polarization, Antenna Gain,3 dB Beamwidth

Example Antenna	**Frequency [GHz]**	**Gain**	**3dB beamwidth**
2,4 GHz: WiMo	2,3 - 2,5	24 dBi	18°;20°h
5 GHz: H&S Pannel	5,18 - 5,87	18,5 dBi	18°v;18°h
5 GHz: Grid	4,9 -6,0	30 dBi	5°v;6°h

Link Budget calculations



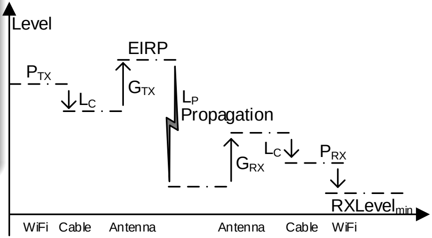
$$P_{RX} = P_{TX} - L_{C,TX} + G_{TX} - L_P + G_{RX} - L_{C,RX} >> RXLevel_{min}$$

- L_C, L_P in dB
- P_{RX}, $RXLevel_{min}$ in dBm
- G_{TX}, G_{RX} in dBi
- $RXLevel_{min}$ in dBm, (negative if < 1 mW)

Equivalent Isotropic Radiated Power

EIRP

Is the amount of power that a **theoretical isotropic antenna** (which evenly distributes power in all directions) would emit to produce the peak power density observed **in the direction of maximum antenna gain**.

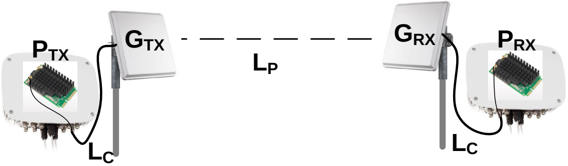


$$\textbf{EIRP}[\mathrm{dBm}] = P_{TX} - L_{C,TX} + G_{TX}$$

$$P_{RX}[\mathrm{dB}] = \textbf{EIRP} - L_P + G_{RX} - L_{C.RX}$$

Band		**Frequency [GHz]**	**Max EIRP [dBm] (min. gain [dBi])**		**DFS**
FCC	**ETSI**		**FCC** [5, 6, 7]	**ETSI** [4, 2, 3]	
ISM	ISM	2.400 - 2.4835	36 (6) - 52 (30)	20	no
U-NII-1	RLAN band I - indoor only sub-band I	5.150 - 5.250	53 (23)	23	no
U-NII-2	RLAN band I - indoor only sub-band II	5.250 - 5.350	30 (6)	23	yes
U-NII-2e	RLAN band II	5.470 - 5.725	30 (6)	30	yes
U-NII-3	BRAN	5.725 - 5.875	53 (23)	36	no

Propagation aspects of long-distance IEEE802.11 links



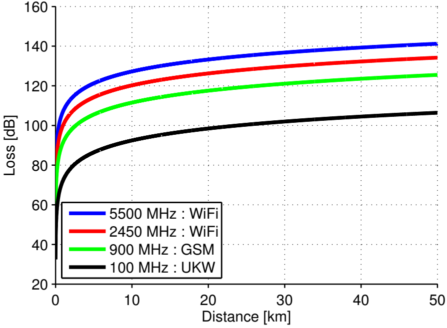
Is it possible to predict L_P?

- Free-Space Path Loss
- Fresnel Zones
- Earth curvature
- Weather conditions

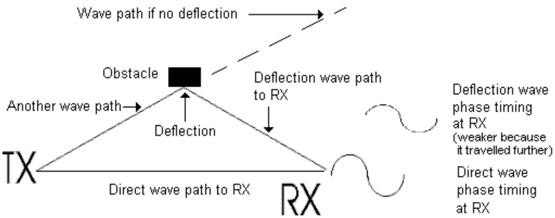
FSPL - neither for reflection nor diffraction

$$L_f[dB] = 20 * log_{10}(f_{MHz}) + 20 * log_{10}(d_{km}) + 32.4dB$$

- Doubling the frequency equals 6 dB more attenuation
- Doubling the distance equals 6 dB more attenuation
- Ten times more distance equals 20 dB more attenuation

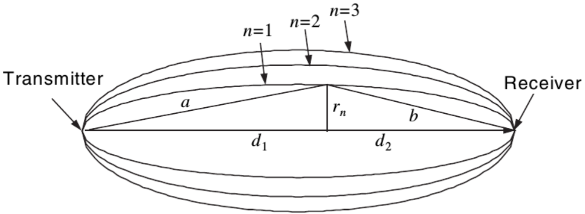


Fresnel zones. A simplification for reflection.



- Secondary waves can reflect on obstacles.
- Fresnel-Zones make it easy to calculate if they are in phase or out of phase at the receiver.

"Fresnel Zones are described as successive regions where secondary waves have a path length from the transmitter to receiver which are $n\lambda/2$ greater than the total path length of a LOS path". [11]



$$r_n = \sqrt{\frac{n \cdot \lambda \cdot d_1 \cdot d_2}{d_1 + d_2}}$$

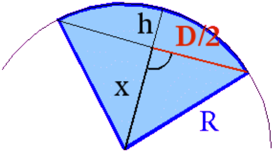
! **Negative correlation** for frequency and diameter

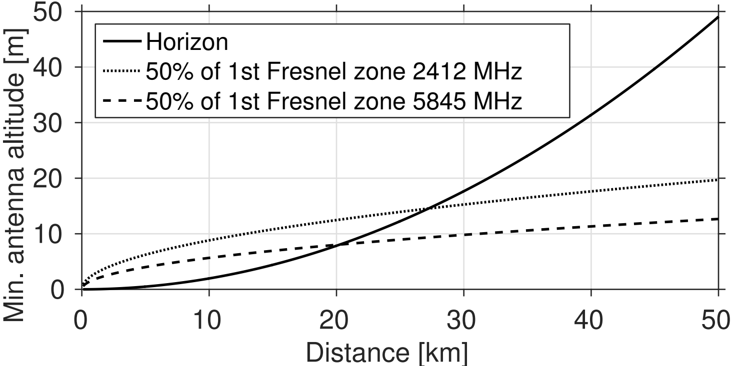
Earth Curvature

- Maybe you heard: the earth is not a flat surface but rather a sphere.
- The influence on the minimum tower high **can not** be neglected

$$x = \sqrt{R_{Earth}^2 - (\frac{d}{2})^2}$$

$$h = R_{earth} - x$$





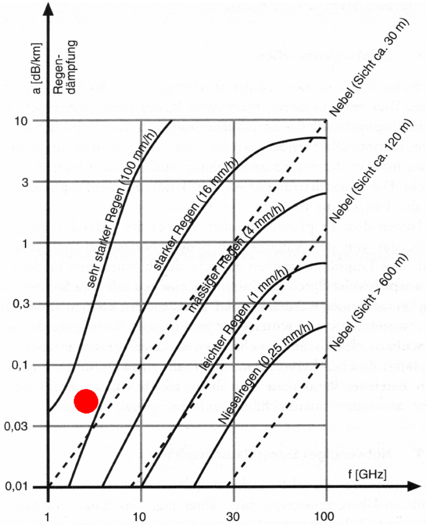
Weather conditions

Weather conditions can lead to additional attenuation and transmission errors (BER ↑). **But**

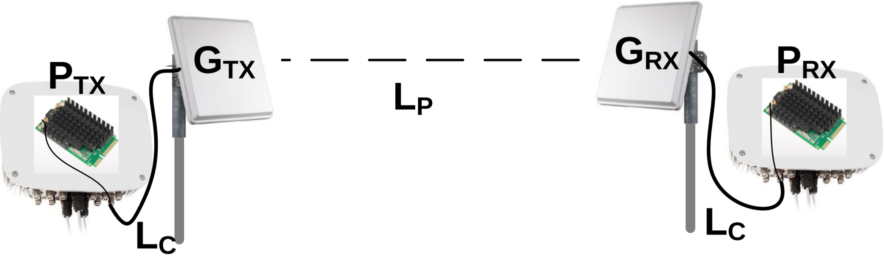
- Rain
- Fog
- Snow

have nearly no influence for frequencies < 6 GHz

Example: Rain $>=$ 25 mm/h leads to a weather warning in Germany.



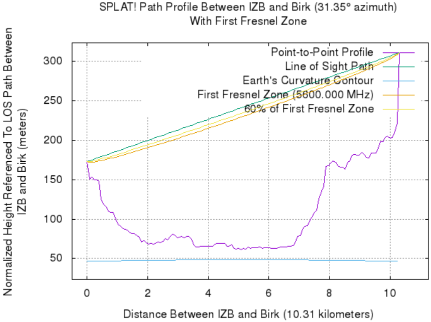
Link Budget calculation

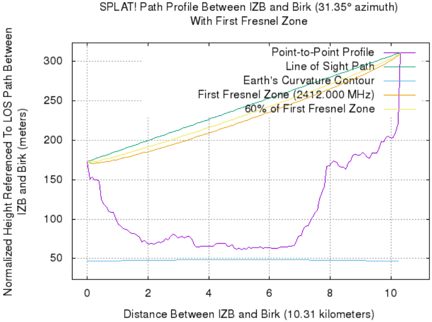


$$P_{RX} = P_{TX} - L_{C,TX} + G_{TX} - L_P + G_{RX} - L_{C,RX} >> RXLevel_{min}$$

- L_C, L_P in dB
- $P_{RX}, RXLevel_{min}$ in dBm
- G_{TX}, G_{RX} in dBi
- $RXLevel_{min}$ in dBm, (negative if < 1 mW)

First conducted build-up





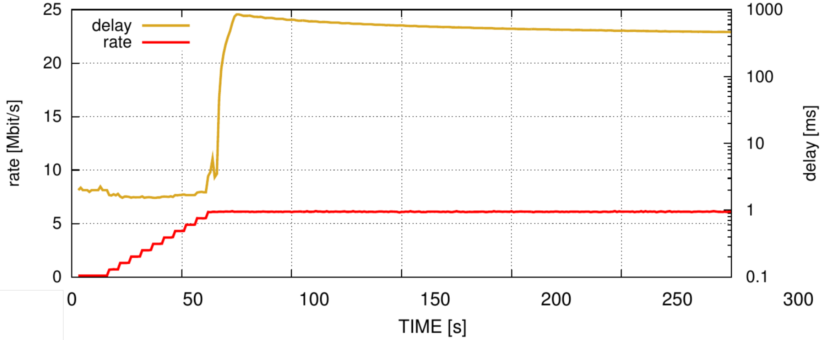
Spectrum	**2,4 GHz**		**5 GHz**	
Standard	IEEE802.11g		IEEE802.11/a	
Transfer method	OFDM		OFDM	
Bandwith [MHz]	20		20	
Spacing/Channels	5/13		20/19	
Frequency [MHz]	2412	2472	5180	5700
FSPL [dB]	**120,4**	**120,6**	**127**	**127,9**

Link Budget for 36 Mbps phy-rate

Spectrum	**2,4 GHz**	**5 GHz Panel**	**5 GHz Grid**
Transmitter:			
P_{TX} **[dBm]**	28	28	28
$L_{C,TX}$ **[dB]**	3	6	6
G_{TX} **[dBi]**	24	18,5	30
EIRP [dBm]	*49* (20)	*40,5* (36)	*52* (36)
Receiver:			
G_{RX} **[dBi]**	24	18,5	30
$L_{C.RX}$ **[dB]**	3	6	6
$RXLevel_{min}$**[dBm]**	-86	-86	-86
Path:			
L_P **[dB]**	120,4	127,5	127,5
Margin	***36* (7)**	***12* (7)**	***34,5 (18,5)***

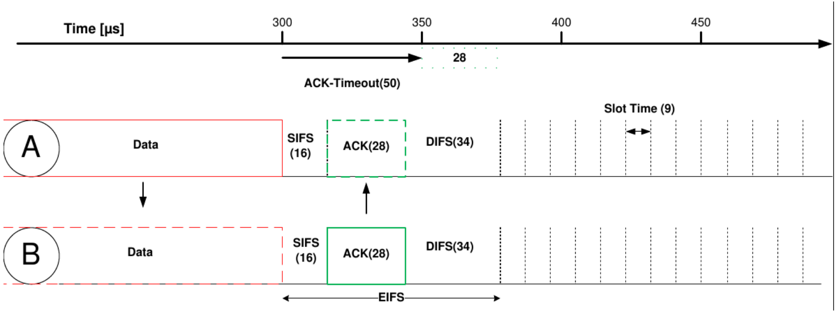
First measurements and results

- Measurements were conducted at a link distance of 10.3 km
- Link Budget calculations indicate a maximum modulation of 36 Mbps with a high margin > 13 dB
- Unidirectional UDP traffic with 1450 Byte payload
- Increasing packets per seconds
- Theoretical value: **21,6 Mbps**
- Measured results: **6 Mbps**



Problem: 802.11 MAC Layer

- Observation: Every packet is retried at a fixed number several times

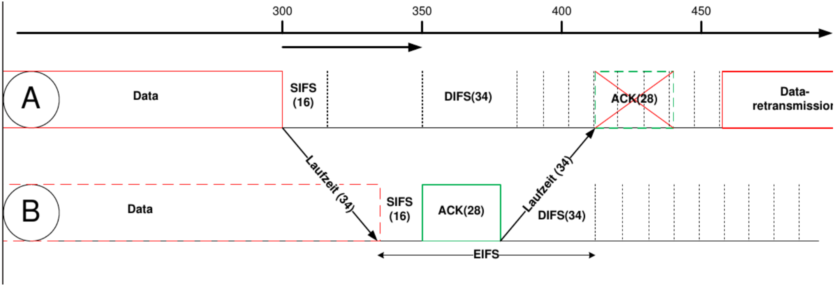


802.11 MAC layer

AirTime

For long-distance WiFi links the propagation time of a packet needs to be included in the protocol. The speed of light matters!

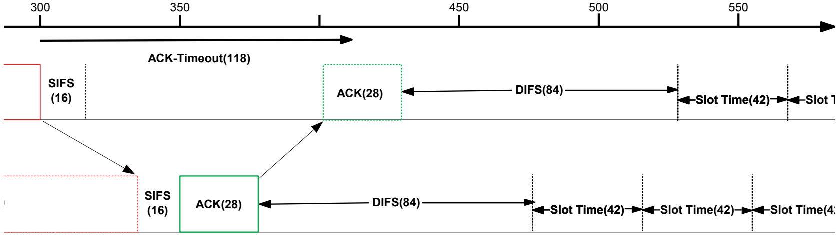
- $AirTime = \frac{s}{c} = \frac{10300m}{3 * 10^8 \frac{m}{s}} = 34\mu s$

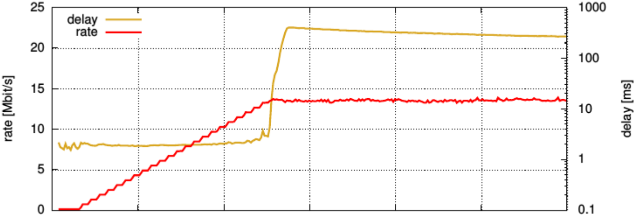


Solution: Adaption of a MAC timings

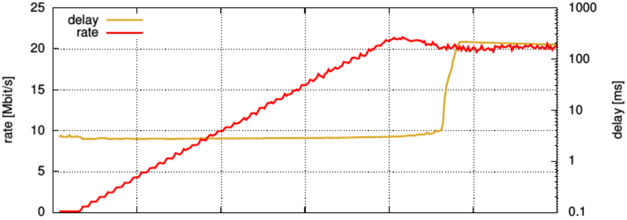
- The slot time is the basic timing for the MAC layer
- With an increase of $34\mu s$ all other timings increase accordingly

$$
\begin{aligned}
SlotTime &= \text{MAC and PHY delays} + AirPropTime_{max} = 43\mu s \\
AckTimeout &= AirPropTime_{max} + SIFS + TimeTxACK + AirPropTime_{max} = 112\mu s \\
DIFS &= aSIFSTime + 2 * aSlotTime = 84
\end{aligned}
$$





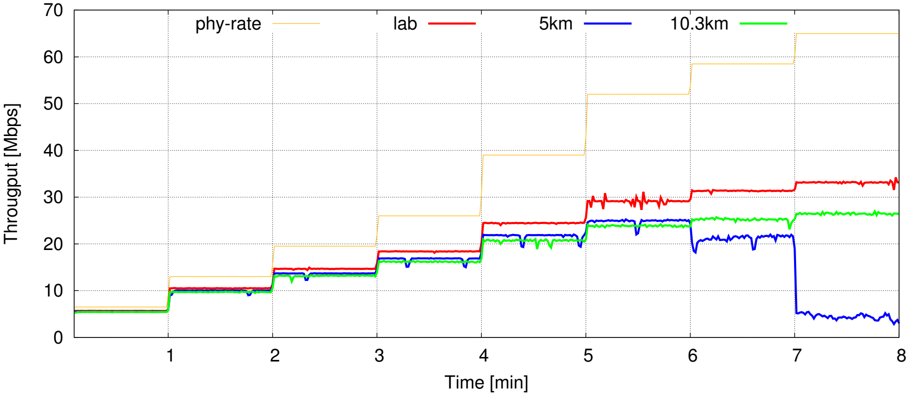
Leaving out acknowledgements (NO-ACK)



We want more througput

- The **IEEE802.11n** standard promises a radical increase in the possible throughput of WiFi but ...
  - WiLD is a different use-case
  - MIMO on long-distance point-to-point links?
- Enhancements to evaluate for long-distance links:
  - OFDM enhancements
  - MAC-Layer enhancements - aggregation
  - 40 MHz Channel width
  - MIMO

OFDM enhancements - Results



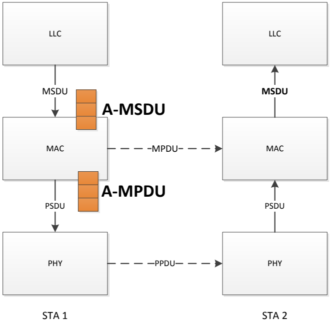
- More Sub-carrier and Modulations -> 65 Mbps vs. 54 Mbps

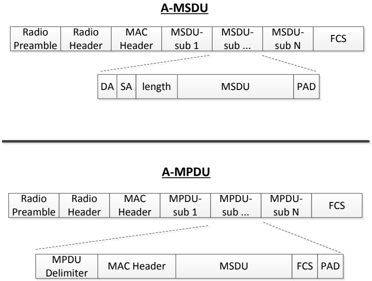
1. Laboratory environment using stubby antennas
2. 5 km bad propagation conditions
3. 10.3 km perfect propagation conditions but spare spectrum

- ≈ 27 Mbps for 10.3 km

MAC-Layer enhancements

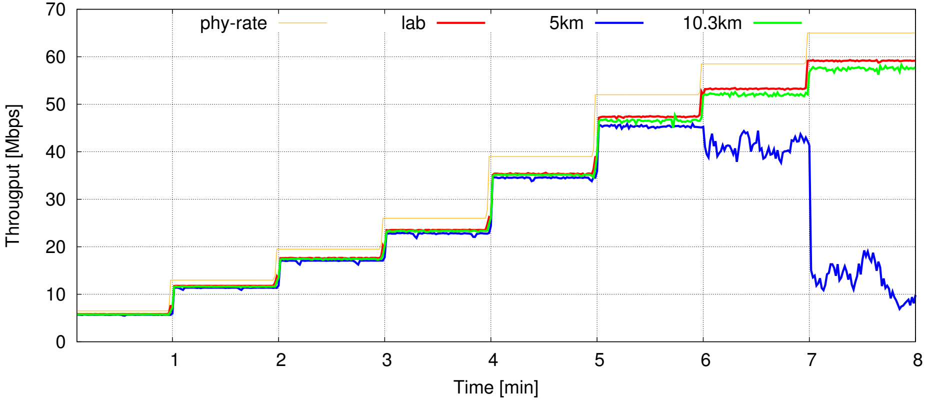
- There is still a huge **gap** between physical- and real-throughput
- Induced by "idle" times (Back-off, Interframe spaces) -> aggregation





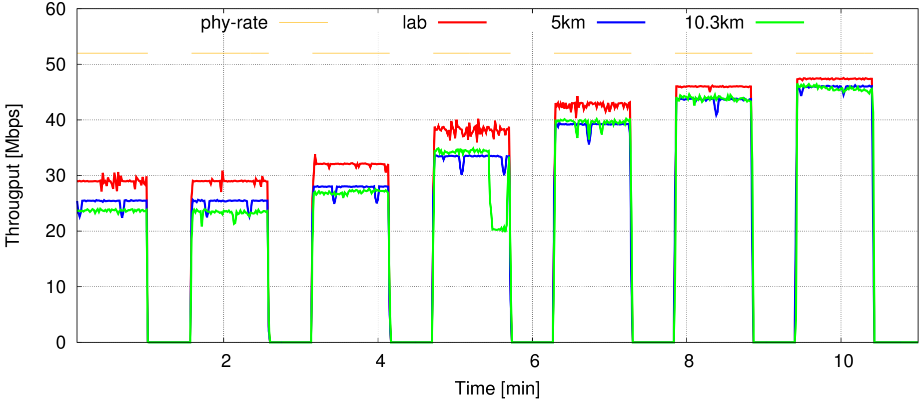
- Selective acknowledged through a single **Block-ACK**, reordering
- The aggregation is stepwise controllable by 2^{13-i} Byte, $i \in (-3, ..., 3)$

MAC-Layer aggregation **A-MPDU** - results



- $\approx$ 60 Mbps for 10.3 km

Influence of the A-MPDU Factor - results



- Aggregation Factor: 2^{13-i} Byte, $i \in (-3, ..., 3)$

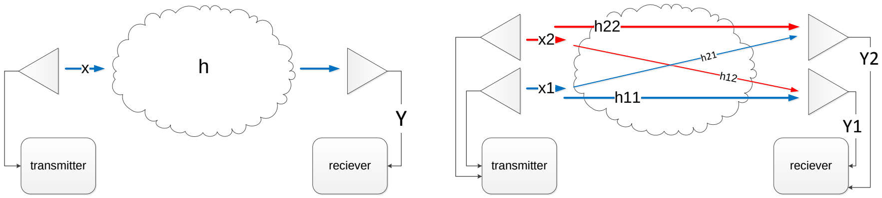
40 MHz channel width - results

- $->$ 40 MHz, 116 OFDM sub-carriers, 108 with data

$$65\text{Mbps} * \frac{108}{52} = \mathbf{135}\ \text{Mbps}$$

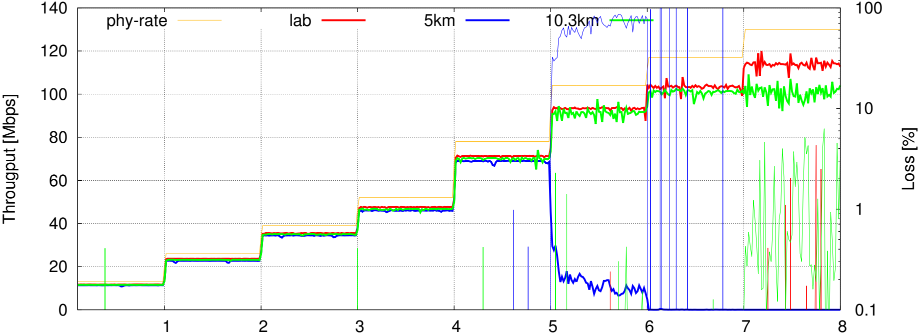
- $\approx$ 105 Mbps for 10.3 km

Multiple Input Multiple Output - theory



- The spatial streams needs to be decorrelate for MIMO
  - Indoor: Rays bouncing from walls, furnitures etc.
- How-to **decorrelate signals** on long-distance WiFi-links?
  - Spatial antenna diversity
  - Force multi path propagation due to a reflexion
  - **Cross polarized antennas** $H = \begin{pmatrix} 1 & 1-\Delta \\ 1-\Delta & 1 \end{pmatrix}$
- MIMO throughput increase -> Spatial Multiplexing

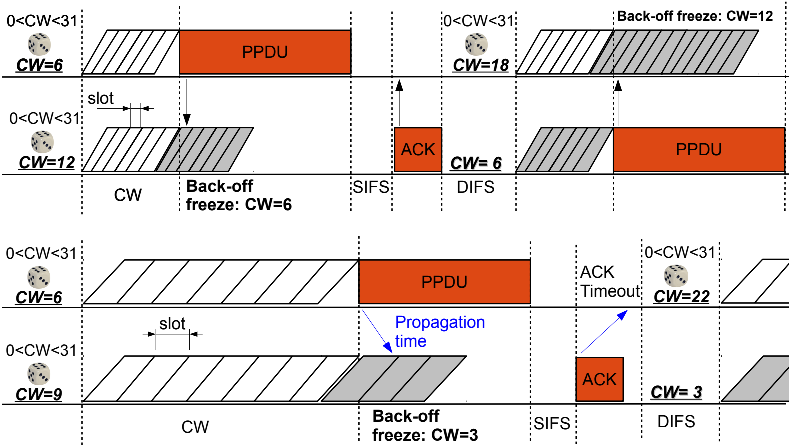
MIMO - results for 20 MHz



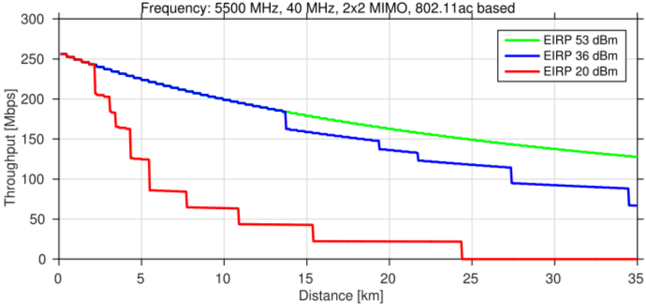
- ≈ 102 Mbps for 10.3 km 20 MHz

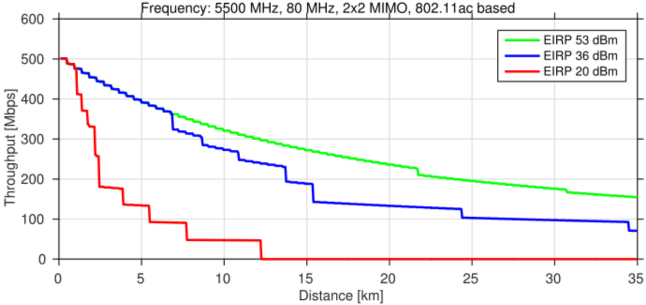
Further optimization: DCF of the MAC layer

- For P2P links how many slots are needed?
- For P2P links how many retries are needed?



Actual Throughput Results - No Marketing





Based on WiLD: The Idea of WiBACK

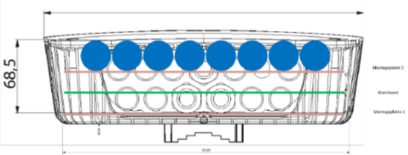
For Everyone. Everywhere.	Cost Efficiency	Quality
Plug & Play System	**Low CAPEX / OPEX**	**High Ability / Potential**
		
Networks can be build for and by everyone in need of connectivity - lower dependency, new buis. models	Cost efficiency, especially thanks to low need of labor allows to reach further	Technology needs to be reliable and of quality as people become dependend on the services and aplications.
✓ Auto Configuration	✓ Little Manual Maintenance	✓ Reliability and Quick Recovery
✓ Non-Expert Setup/Operation	✓ Integrates Technologies	✓ Carrier grade QoS
✓ Solar Powerable	✓ Low Power Consumption	✓ Reliable Hardware
✓ Reliable	✓ Off-the-shelf Hardware	✓ HQ-VideoStreaming, VoIP, ...

Specs of our new shiny Hardware

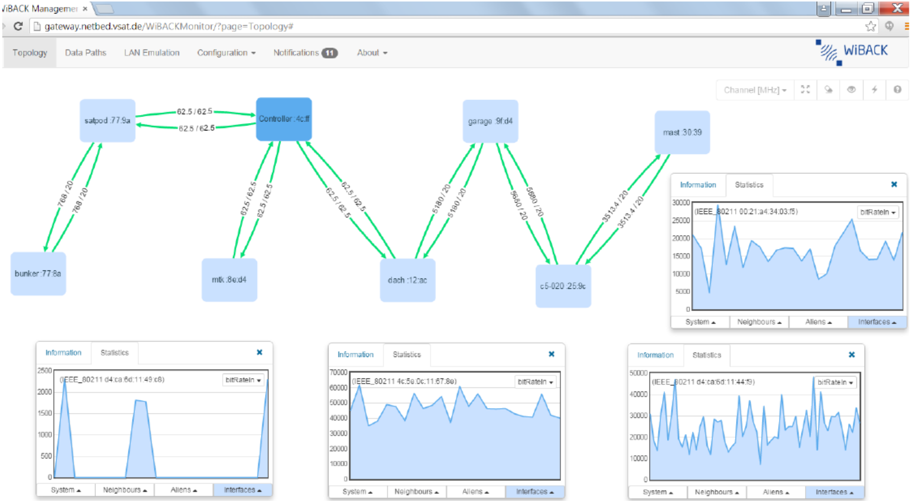
WiBACK Node N4C – Specs (Draft)

ETA 2Q17 – 4 Radios, incl. Battery, Designed for 5-Year lifetime

- Physical
  - 310 mm x 220 mm x 70 mm; 3.0 kg (w/o battery)
  - NEMA-67, Aluminum, weather and UV Protected
  - Power and status signaling LED
- Interfaces
  - 2x RJ45
    - 1000Tx Ethernet (Backhaul,Access), PoE Splitter
    - 1000Tx Ethernet (Backhaul,Access), PoE Inserter
  - 4 x Wireless LAN High power radios
    - IEEE 802.11n / .ac / access
  - Bluetooth, GPS
- System
  - Embedded Linux, x86 (2Core 1.7 GHz Intel Atom)
  - >1000 Mbps WiBACK Throughput
- Power
  - PoE, 48 V
  - External DC 7-32 V
  - Built-in LiFePo Charger (and Battery)
  - Maximum 15 W, average 7 W



Management-Interface



Thank you very much!

Are there any questions?

Hochschule
Bonn-Rhein-Sieg
University of Applied Sciences

M.Sc.
Michael Rademacher

Fachbereich Informatik

Grantham-Allee 20
53757 Sankt Augustin
Tel. +49 2241 865 151
Fax +49 2241 865 8151

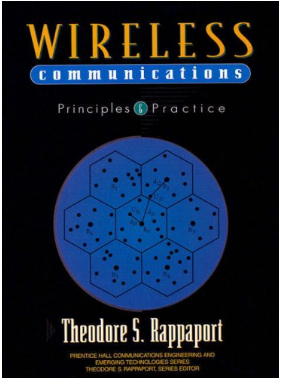
michael.rademacher@h-brs.de
www.h-brs.de

Read more about our work on:

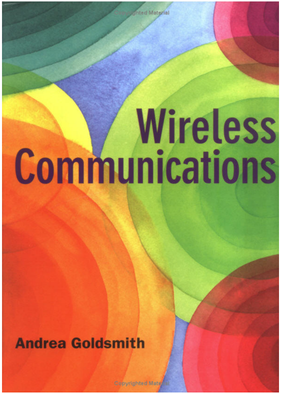
`www.mc-lab.de`

`www.wiback.org`

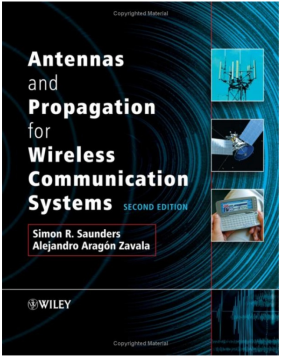
Books to be recommended - Propagation



Rappaport [11]

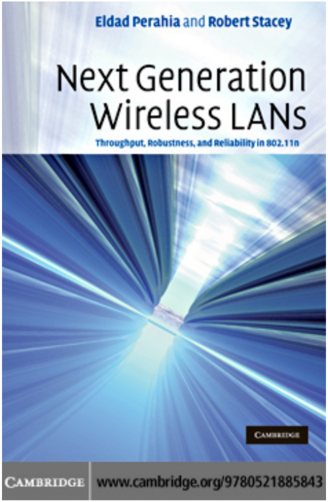


Goldsmith [8]

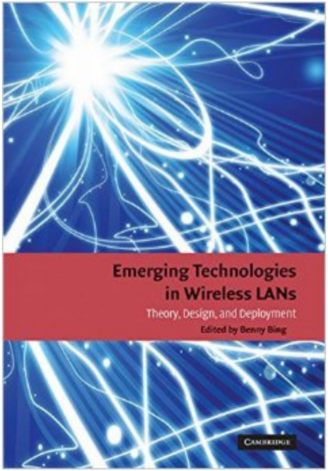


Saunders [12]

Books to be recommended - Wireless LANs



Perahia,Stacey [9]



Bing [1]

References I

[1] Bing, B.
Emerging Technologies in Wireless LANs.
Cambridge University Press, Cambridge, 2007.

[2] (ETSI), E. T. S. I.
Broadband Radio Access Networks (BRAN); 5 GHz high performance RLAN; Harmonized EN covering the essential requirements of article 3.2 of the R&TTE Directive.
Harmon. Eur. Stand. ETSI EN 30, v1.8.1.

[3] (ETSI), E. T. S. I.
Broadband Radio Access Networks (BRAN); 5,8 GHz fixed broadband data transmitting systems; Harmonized EN covering the essential requirements of article 3.2 of the R&TTE Directive.
Harmon. Eur. Stand. ETSI EN 30, v1.2.1.

[4] (ETSI), E. T. S. I.
Electromagnetic compatibility and Radio spectrum Matters (ERM); Wideband transmission systems; Data transmission equipment operating in the 2, 4 GHz ISM band and using wide band modulation techniques; Harmonized EN covering the essential requirements of a.
Harmon. Eur. Stand. ETSI EN 30, v1.9.1.

[5] (FCC), F. C. C.
CFR Title 47: Telecommunications - Part 15: Radio Frequency Devices - Paragraph 209: Subpart C: Intentional Radiator - Radiated emission limits; general requirements.
Code Fed. Regul..

[6] (FCC), F. C. C.
CFR Title 47: Telecommunications - Part 15: Radio Frequency Devices - Paragraph 247: Subpart C: Intentional Radiator - Radiated emission limits; additional provisions - Operation within the bands 902-928 MHz, 2400-2483.5 MHz and 5725-5850 MHz.
Code Fed. Regul..

References II

[7] (FCC), F. C. C.
CFR Title 47: Telecommunications - Part 15: Radio Frequency Devices - Paragraph 407: Subpart E: Unlicensed National Information Infrastructure Devices - Genereal technical requirements.
Code Fed. Regul..

[8] Goldsmith, A.
Wireless Communications.
Cambridge University Press, Cambridge, 2005.

[9] Perahia, E., and Stacey, R.
Next Generation Wireless LANs.
Cambridge University Press, Cambridge, 2013.

[10] Rademacher, M., and Kessel, M.
An Empirical Evaluation of the Received Signal Strength Indicator for fixed outdoor 802.11 links.
VDE ITG-Fachbericht Mobilkommunikation 20 (2015), 62–66.

[11] Rappaport, T. S.
Wireless Communications: Principles and Practice, 2002.

[12] Saunders, S. R., and Aragon Zavala, A.
Antennas and Propagation for Wireless Communication Systems.
2007.