Communication in Distributed Systems

6 WiLD - MAC, 802.11n and (recent research)

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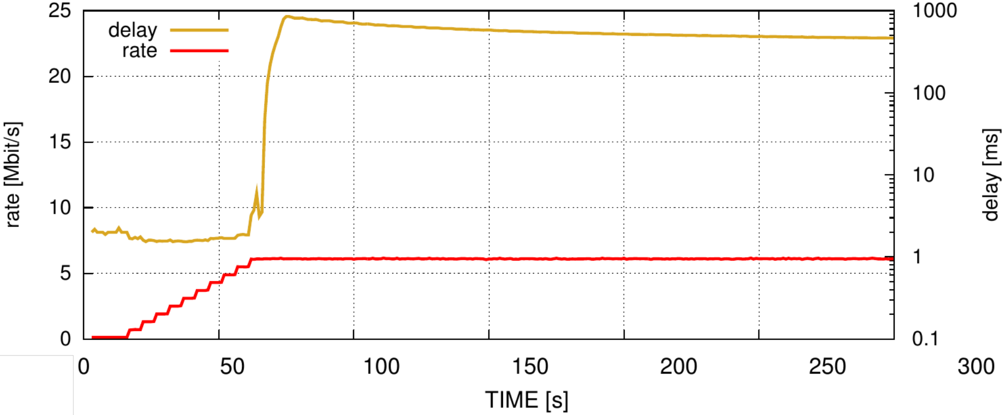
First throughput measurements on WiLD links

First throughput measurements and results

- Measurements were conducted at a link distance of 10.3 km
  - Unidirectional UDP traffic with 1450 Byte payload (iperf)
  - Increasing packets per seconds
- ✓ Link Budget calculation are fine
- Theoretical value including all overhead: **21,6 Mbps**



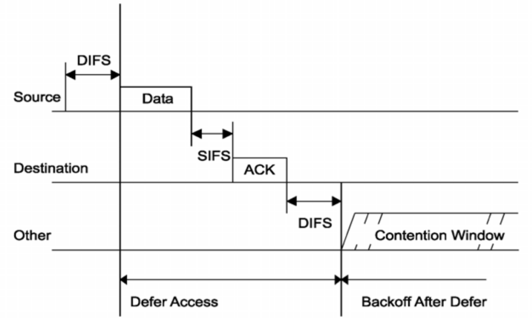
- First results - 6 Mbps :(

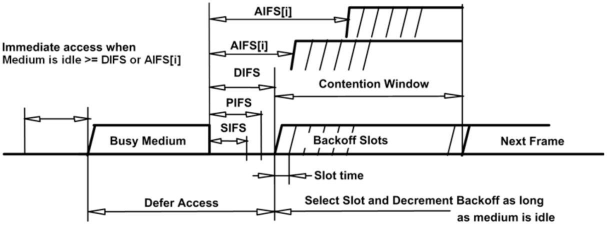
The WiFi MAC Layer

Medium Access Control with CSMA/CA

- Carrier Sense Multiple Access (CSMA)
  - Sense the medium before transmitting (listen before talk)
- Collision Avoidance/CA
  - Transmitting and Receiving at the same time is difficult for Wi-Fi
  - Transmitting signal has much more power compared to the received one
  - Half-duplex operation (mostly)
- The method which implements CSMA/CA for 802.11 is called **Distributed Co-ordination Function (DCF)**
  - Co-ordinate the medium access among distributed clients without a centralized entity

Distributed Co-ordination Function

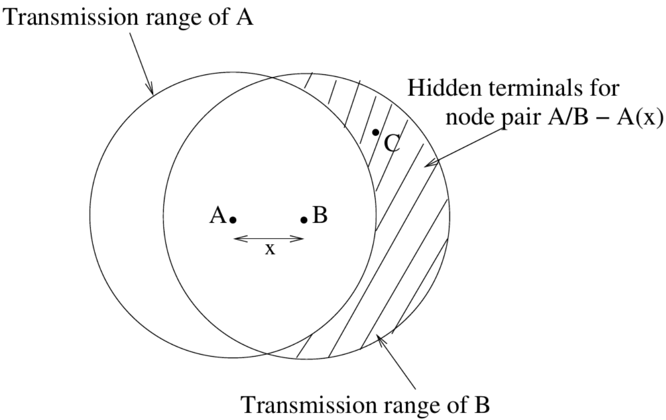




- Sense: If free longer DIFS -> transmit
- Other: Defer and after another DIFS start contention window (CW)
- CW: Exponential Backoff scheme. Count if the medium is free. Transmission allowed when counter reaches zero.
- Each packet is acknowledged, otherwise retry

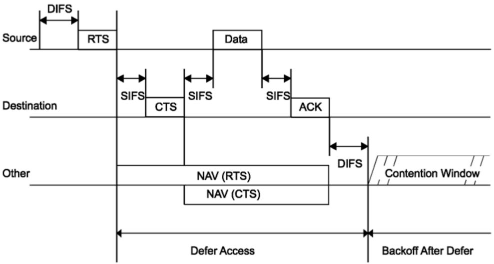
- Inter-Frame Spaces (IFS)
  - Short IFS: Before ACK
  - DCF IFS: Before Data/Contention
  - Arbitration IFS: QoS

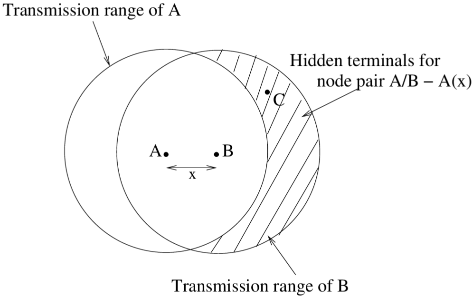
The Hidden Node Problem [3]



- A wants to transmit to B
- A is not able to hear transmission from any node C in the dashed area.
- If A and C transmit at the same time to B: Collision

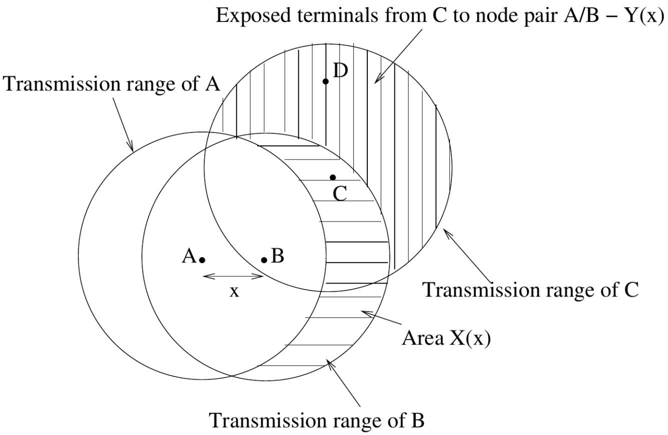
Virtual Carrier Sensing Function





- Transmitter: RTS with NAV
- Receiver: CTS with NAV
- Other: Be quite for time of NAV
- RTS/CTS solves the hidden node problem:
  - A sends a RTS
  - B sends a CTS
  - C is quite

The Exposed Terminal Problem [3]



RTS/CTS introduces a new Problem:

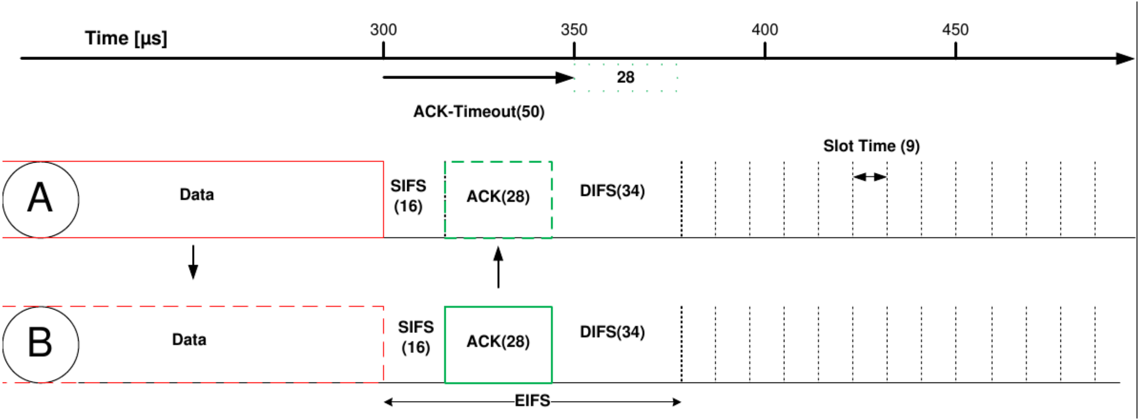
- Node A transmits an RTS and waits for B's CTS
- Node D transmits an RTS to C just before A's RTS
- C transmits a CTS
- B enters a backoff and do not transmit the CTS despite the fact that a simultaneous transmission from A to B and D to C is possible. (C is out of range of A and B is out of range of D)

WiFi MAC Problem on long-distance links

WiFi MAC Problem on long-distance links

- **Observation: Every packet is retried always six times.**

Default 802.11 MAC-layer known as DCF:

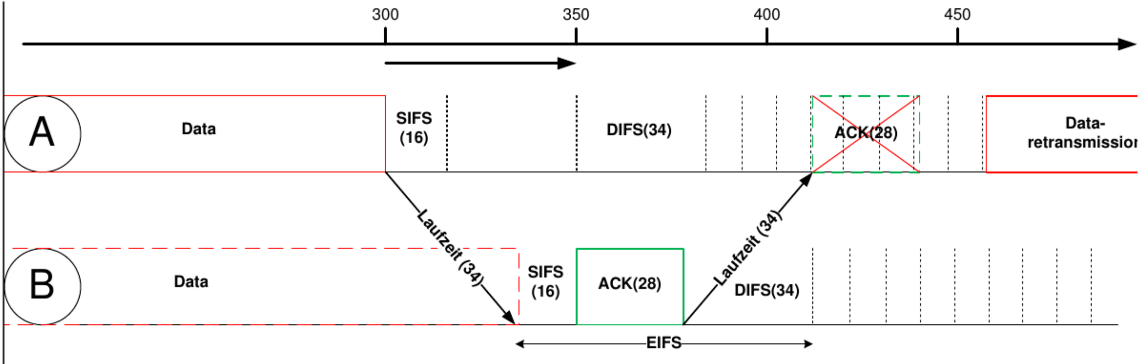


Propagation time / AirTime

For long-distance WiFi links the propagation time of a packet leads to unwanted timing effects in the protocol! For a 10.3 kilometer link:

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

Unwanted timing effects for the default 802.11 MAC-layer:



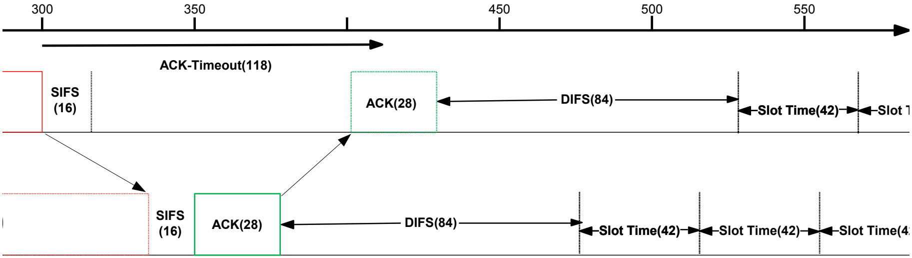
Solution: Adaption of all MAC timings

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

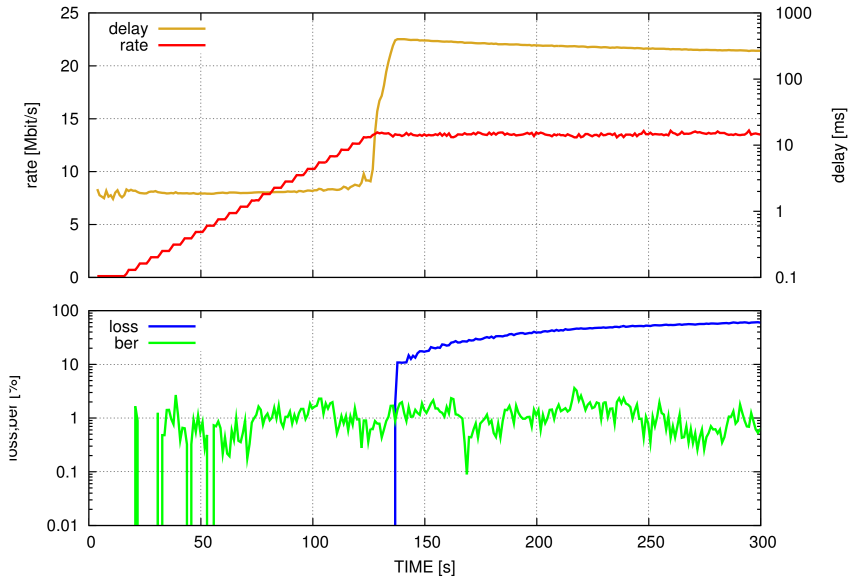
$$SlotTime = \text{MAC and PHY delays} + AirPropTime_{max} = 43\mu s$$

$$AckTimeout = AirPropTime_{max} + SIFS + TimeTxACK + AirPropTime_{max} = 112\mu s$$

$$DIFS = aSIFSTime + 2 * aSlotTime = 84$$



Results after adaption of the timings - 14 Mbps



WiLD - 802.11n/ac

Motivation for further enhancements with IEEE802.11n

- IEEE802.11a:

=> Throughput limitation - **best-case** - of approximately **30 Mbit/s**

- This limitation can easily lead to a **bottleneck** in the network where
  - ... the topology is **predefined** by geographical conditions
  - ... a high number of peers is consuming simultaneously
- Two different options
  1. Raising the overall number of devices or interfaces
  2. Enlarging **the efficiency of the radio**
- Updated IEEE802.11 standards promises a radical increase in the possible throughput of WiFi but can we make use of the enhancements on long-distance links?
- **Focusing on IEEE802.11n and IEEE802.11ac**

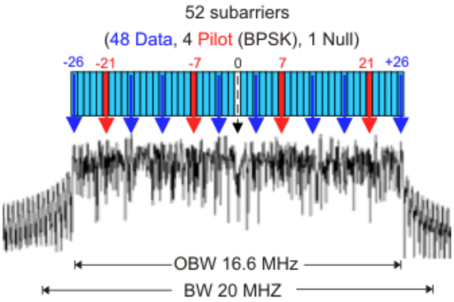
OFDM enhancements - subcarrier

- **802.11a**: 20 MHz (allocated) channel divided in **53** sub-carrier
  - 48 containing data bits and 4 pilot channels sending predefined symbols
  - Subcarrier width 0.3125 MHz $->$ channel width 16.5625 MHz
- **802.11n/802.11ac**: 20 MHz channel divided in **57** subcarrier
  - 52 containing data bits, channel width 17.1825 MHz

$$54\text{Mbps} * \frac{52}{48} = \mathbf{58.5}\text{ Mbps}$$

Modulation:
64-QAM 3/4

$$\frac{log2(64)\text{ bit} * 48 * 3/4}{4\mu s} = 54\text{ Mbps}$$



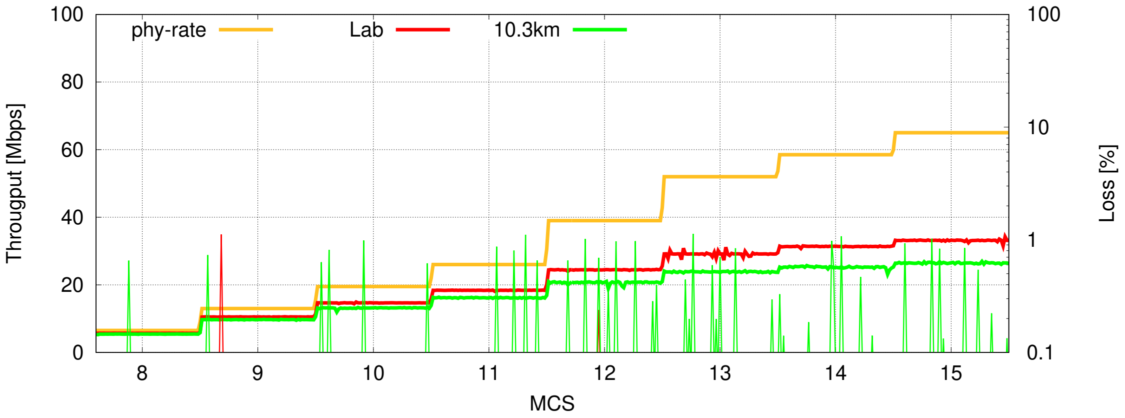
Modulation enhancements

- **802.11a**: Convolutional code with rates of $\frac{1}{2}, \frac{2}{3}$ and $\frac{3}{4}$
- **802.11n**: Additional code rate of $\frac{5}{6}$ $=>$ 58.5 Mbps $* \frac{4}{3} * \frac{5}{6} =$ **65** Mbps
- **802.11ac**: Additional modulation 256-QAM $=> \frac{log2(256)\ \text{bit}*52*3/4}{4\mu s} = 78$ Mbps

[1]

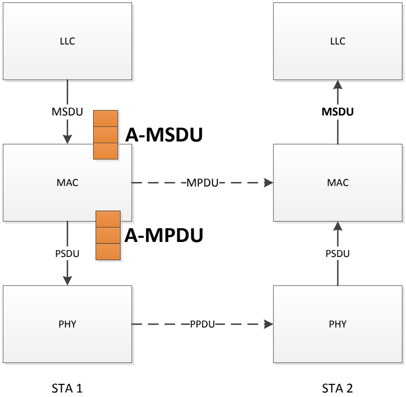
[1] Use http://mcsindex.com/ for an easy overview.

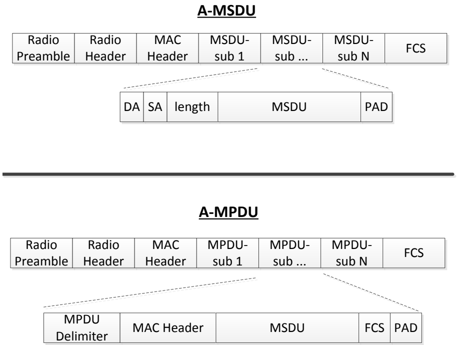
80211.n OFDM enhancements - Results



- There is still a huge **gap** between physical- and real-throughput
- Induced by times where no data is transmitted
    1. Back-off
    2. Interframe spaces

MAC-Layer aggregation - A-MPDU vs. A-MSDU





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

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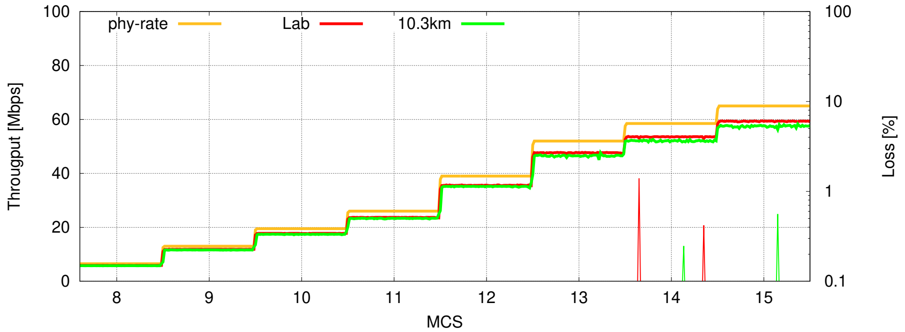
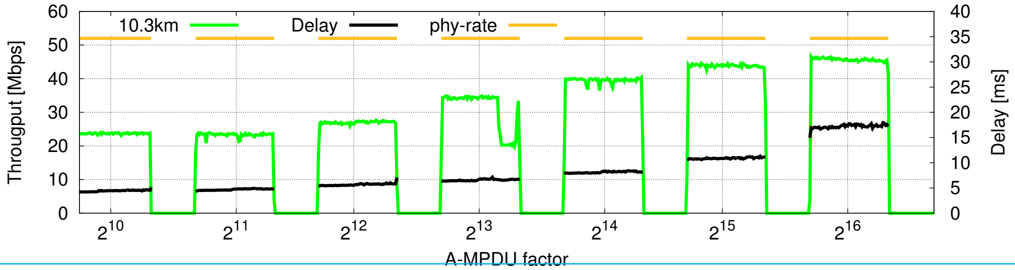
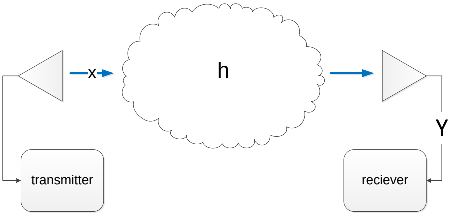
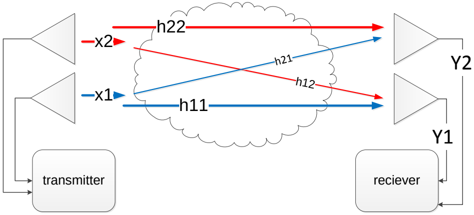
MAC-Layer aggregation - results





Multiple Input Multiple Output - theory





$$y = h * x + z$$

Receiver extract information x from y

$$y * h^{-1} = \widehat{x} = x + z * (h)^{-1}$$
$$x = \widehat{x} - z * (h)^{-1}$$

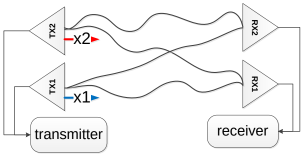
$$\begin{pmatrix} y_1 \\ y_2 \end{pmatrix} = \begin{pmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{pmatrix} * \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + \begin{pmatrix} z_1 \\ z_2 \end{pmatrix}$$

... math ...

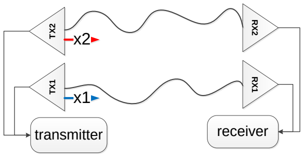
$$\begin{pmatrix} x_1 \\ x_2 \end{pmatrix} = \widehat{\begin{pmatrix} x_1 \\ x_2 \end{pmatrix}} - z * (H)^{-1}$$

Signal recovery with the inversed channel matrix (h^{-1} or H^{-1})

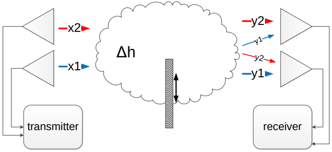
Multiple Input Multiple Output - theory



- $H = \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$, singular, not invertible



- $H = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$, non-singular, invertible

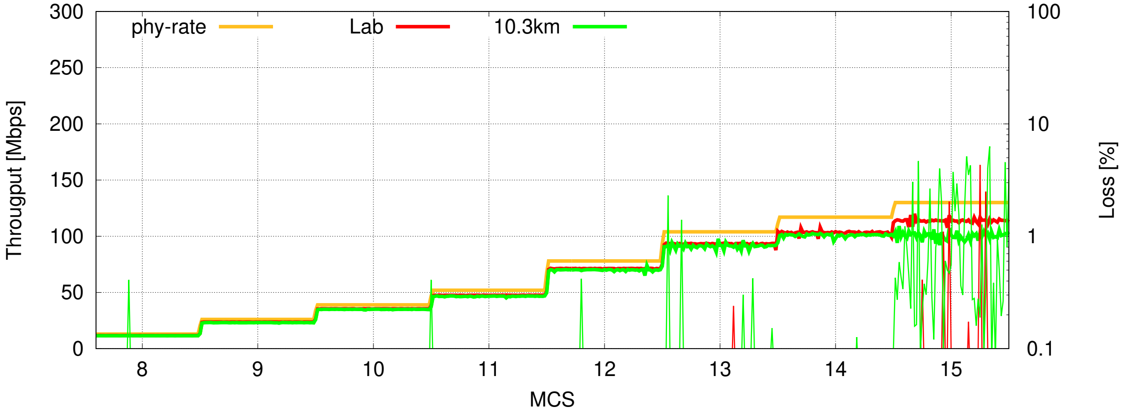


- Increasing throughput due to a fading iron plate

Multiple Input Multiple Output - theory

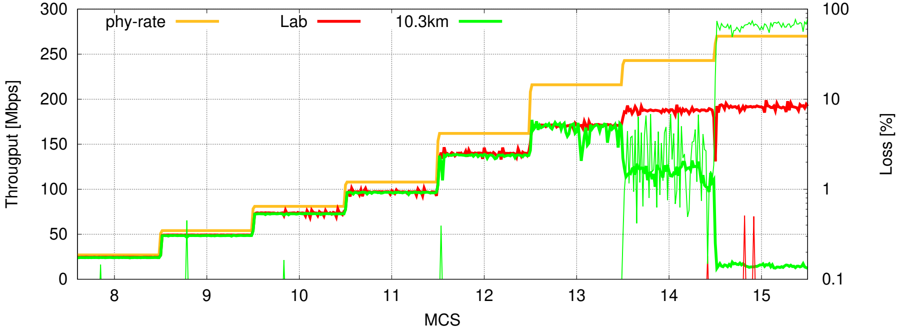
- The channel matrix must be **well conditioned** for MIMO
  - Terms are randomly distributed and uncorrelated
  - Indoor: Rays bouncing from walls, furnitures etc.
- How-to **decorrelate signals** on long-distance WiFi-links?
  - Spatial antenna diversity
  - Force multi path propagation due to a reflexion
  - **Cross polarized antennas** $H = \begin{pmatrix} 1 & 1-\Delta \\ 1-\Delta & 1 \end{pmatrix}$
- **Spatial Multiplexing**: Transmit independent and separately encoded data signals (streams)
  - $N_s = min(N_t, N_r)$
  - In theory, we can double the throughput with cross-polarized antennas

MIMO - results



- 65 Mbps $*$ 2 Streams $=$ **130** Mbps

IEEE802.11n - overall results



- Bundle two direct 20 MHz neighbor channels
- $->$ 40 MHz, 116 OFDM sub-carriers, 108 with data

$$130 \text{ Mbps} * \frac{108}{52} = \mathbf{270} \text{ Mbps} \quad | \quad 2x2 \ MIMO$$

Our Research - Quantifying the Spectrum Occupancy

Our research - Quantifying the U-NII band Spectrum Occupancy [6]

"But Michael, you can not do backhauling in the 5 GHz U-NII band, it is completly occupied with private WiFi Access Points."

— Statement on every conference I have visited in the last 5 years.

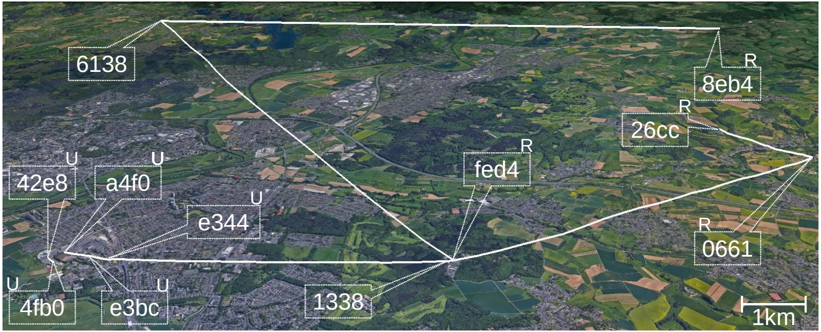
Related work

- Survey of spectrum occupancy measurement, 2016 [2]:
  - **Wide-band** studies using high performance **spectrum analyzer** attached to **omni-directional antennas** at **single locations**
  - **Limited previous work in the U-NII band**
  - Focused campaigns are of greater interest than more generalized ones

- Aachen, 2007 [8]:
  - U-NII band is vacant
- Chicago and Turku, 2013 [7] :
  - Occupancy in the U-NII band $< 5\%$
  - Exception: Exposed radio tower - occupancy rises up to 50%

- Similar methodology, 2014 [1]:
  - 16 WiFi cards in an urban parking lot quantifying the 2.4 GHz band

Methodology: Testbed

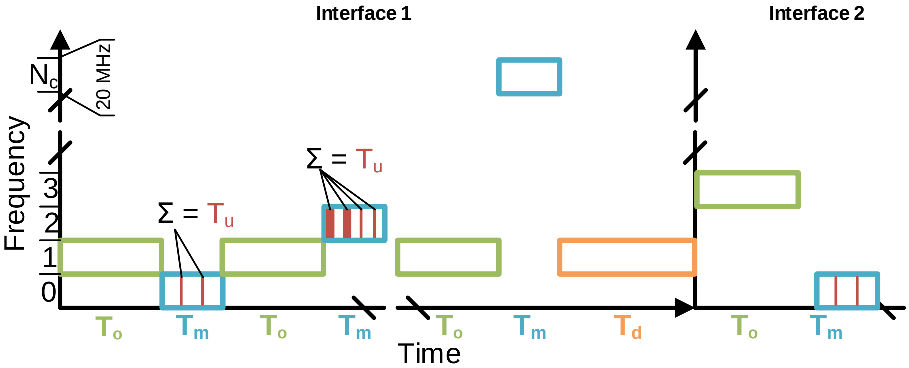


Measurement nodes. Image credit: Landsat / Copernicus. Imagery Date 08/24/2016.

Node at location e3bc.

- Testbed near Bonn: Rural and urban areas
  - SBC with multiple slots holding 802.11n (WiFi) cards (ath9k)
  - Cross-polarized antennas with 19 and 25 dBi gain
  - Orchestrated by our network management software, WiBACK [4]
- **Campaign: Evaluate the occupancy of the U-NII band**
  - 19 Channels: **5.180 GHz–5.320 GHz** and **5.500 GHz–5.700 GHz**
  - **Using the same WiFi cards, parallel to an operational network**
  - Duration: **One week** from 05-Jul-2017 2:30 pm to 12-Jul 2:30 pm

Methodology: Scanning process



$$o_{i,c,t} = \frac{T_u}{T_m}$$

$$T_s = N_i * [N_c * (T_m + T_o) + T_d]$$

$T_o = 1\ s$

$T_m = 69\ ms$

$N_c = 19$

$N_i = \{1, 2, 3\}$

$\bar{T}_s = 50.3 \pm 7.8s$

Down-sampling multiple scan results $(o_{i,c,t})$ in a certain time period T_P to a single value O_{i,c,T_P}.

$T_P = 15\,\text{min}$

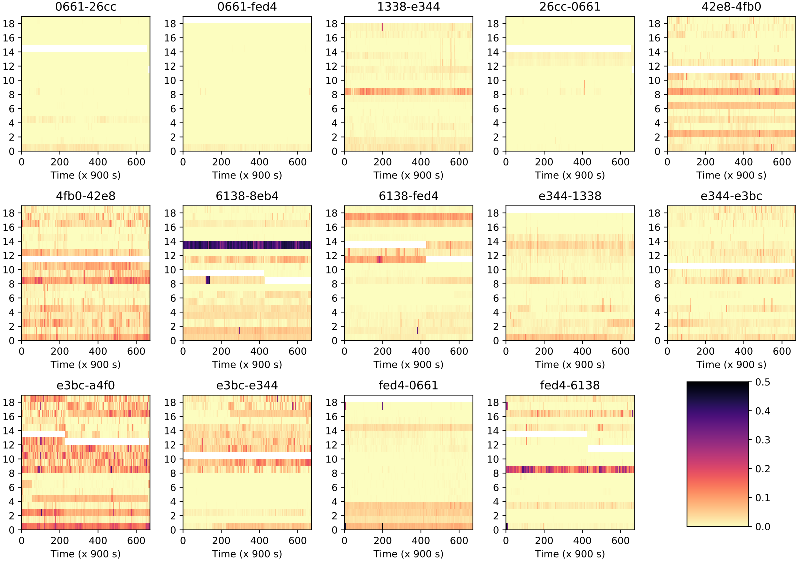
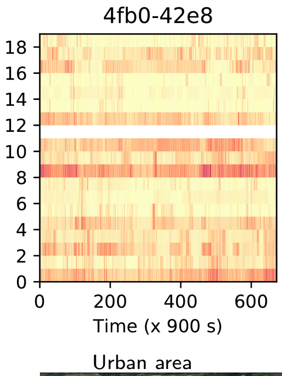
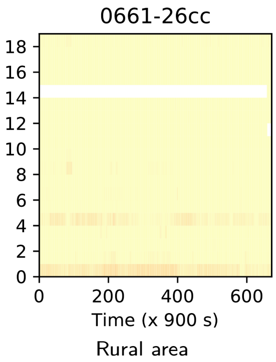
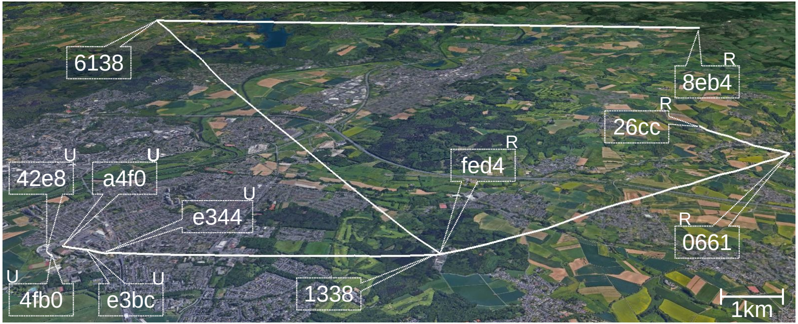


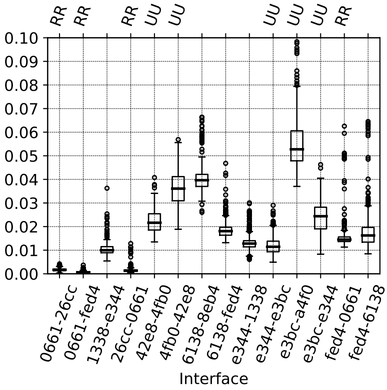
Figure: Spectrum occupancy results for all evaluated links. Down-sampled to $T_P = 900s = 15\,\text{min}$ for a single data-point. The y-axis of each subplot shows the $N_c = 19$ different channels. White indicates an operational channel.


4fb0-42e8
18
16
14
12
10
8
6
4
2
0
0
200
400
600
Time (x 900 s)
Urban area


0661-26cc
18
16
14
12
10
8
6
4
2
0
0
200
400
600
Time (x 900 s)
Rural area

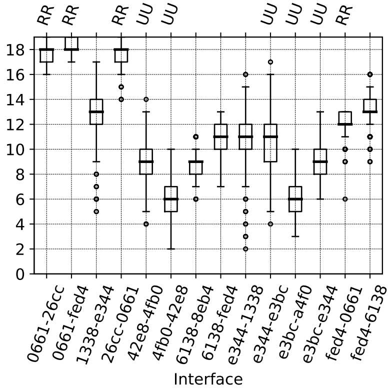

6138
8eb4
R
26cc
R
fed4
R
U
42e8
U
a4f0
U
e344
R
0661
U
4fb0
e3bc
U
1338
1km

Results: Occupancy and vacant channels



Channel occupancy

$$\bar{O}_{i,T_P} = \frac{1}{N_C} \sum_{c=0}^{c=N_c} O_{i,c,T_P}$$



Number of vacant channels

$$s_{i,c,T_P} = \begin{cases} 1, & \text{if } O_{i,c,T_P} < \lambda \quad (\textit{vacant}) \\ 0, & \text{otherwise} \quad (\textit{occupied}) \end{cases}$$

$$\text{VacantChannels} = \sum_{i=0}^{c=Nc} s_{i,c,T_P}$$

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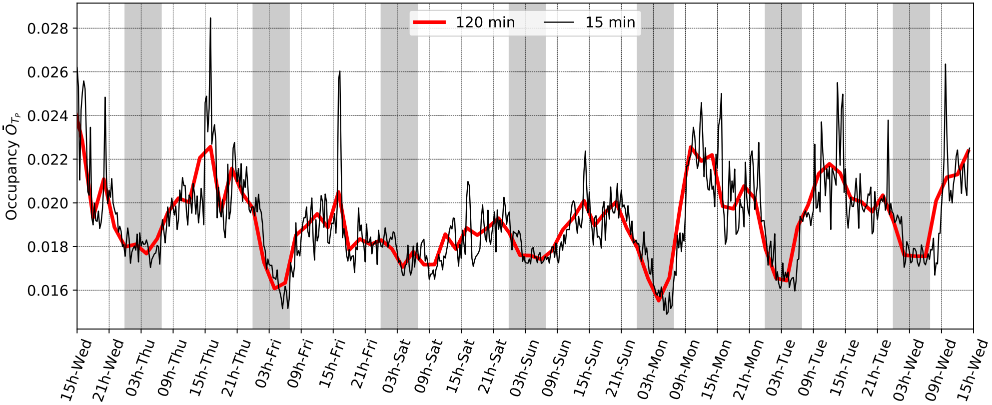
Results: Time of the day

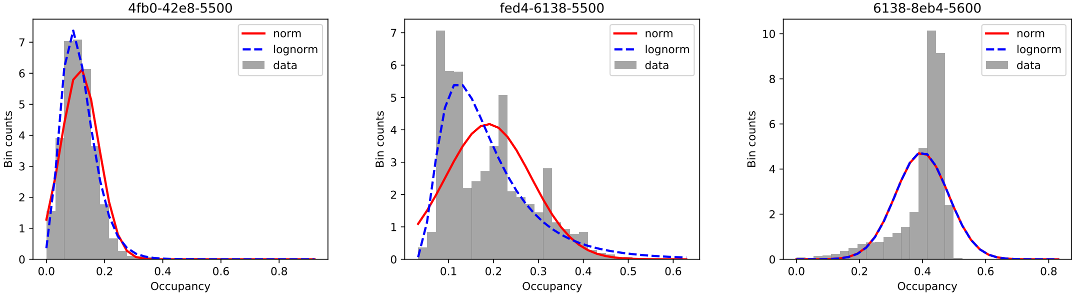


$$\bar{O}_{T_P} = \frac{1}{N_I N_c} \sum_{i=1}^{i=N_I} \sum_{c=1}^{c=N_c} O_{i,c,T_P} \quad \Big| \quad T_P = 15\,\text{min} \text{ and } T_P = 120\,\text{min}$$

- Result: **There is a daily seasonality** - seven minimal turning points, which all occur in the early morning

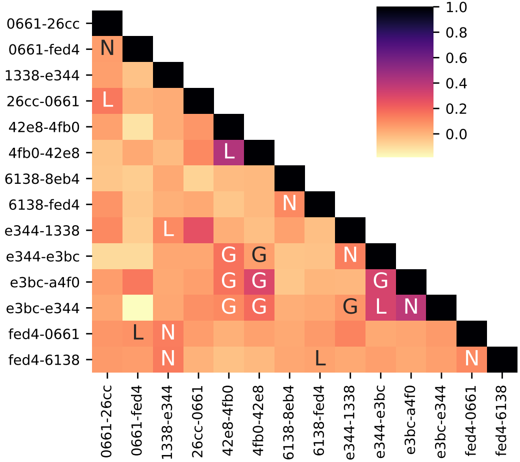
Results: Occupancy modeling

- Hypothesis: The occupancy at an interface on a certain channel is drawn from a common probability distribution.
- Evaluation: Kolmogorov-Smirnov (K-S) test with 77 different distributions:
  - **normal, lognormal**
  - chi and chi-squared
  - Student-t
  - Weibull
  - ...
- Result: **No statistically significant indication that spectrum occupancy is drawn from one of the evaluated distributions**



Correlation among interfaces

- Idea: Correlations for the occupancy among interfaces could reduce the needed sensing effort (for channel allocation algorithms).
- Evaluation: Calculate R^2 among the occupancy on all interfaces
- Result: **Only a weak mean correlation exists for two interfaces on the same link**
  - A mutual decision is necessary for channel allocation algorithms



- “L”: interfaces are part of the same link
- “N”: interfaces are on same node
- “G”: corresponding nodes are in proximity to each other

Lecture next week

- The lecture in the next two weeks will be given by Prof. Karl Jonas.
- Same place, same date.

A Token-Based MAC For Long-Distance IEEE802.11 Point-To-Point Links

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Abstract: WiFi-based Long Distance (WiLD) networks have emerged as a promising alternative approach for Internet in rural areas. However, the MAC layer, which is based on the IEEE802.11 standard, comprises contiguous stations in a cell and is spatially restricted to a few hundred meters at most. In this work, we summarize efforts by different researchers to use IEEE802.11 over long-distances. In addition, we introduce WiLDToken, our solution to optimizing the throughput and fairness and reducing the delay on WiLD links. Compared to previous alternative MAC layers protocols for WiLD, our focus is on optimizing a single link in a multi-radio multi-channel mesh. We implement our protocol in the ns-3 network simulator and show that WiLDToken is superior to an adapted version of the Distributed Coordination Function (DCF) for different link distances. We find that the throughput on a single link is close to the physical data-rate without a major decrease over longer distances [5].

Thank you for your attention.
Are there any questions left?

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https://michael-rademacher.net

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