Aspects on the Flow-Level Performance of Wireless Fading Channels

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in parts joint work with
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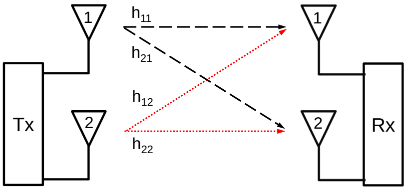
Outline

- Application of network calculus to MIMO wireless channels
- Ongoing work: Delays introduced on Layer 2 in a real world LTE system

Motivation



- MIMO employed by modern wireless/cellular networks for high data rate (IEEE 802.11n, 3GPP LTE)
- fundamental tradeoff robustness vs. capacity
- MIMO studies focused mainly on capacity limits
- modern wireless applications are delay-sensitive

Goal:

- *Non-asymptotic* delay analysis of MIMO wireless channels with memory in *spatial multiplexing mode*

Analytical performance evaluation of wireless networks

- Tools: Queueing theory, effective capacity, network calculus,.. e.g.: [Jiang'05], [Wu'06], [Fidler'06], [Li'07], [Ciucu'11]..
- Challenge: Time varying nature of the wireless channel

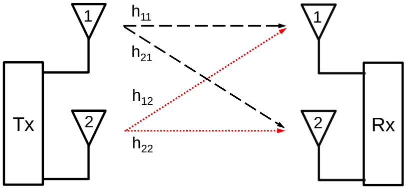
Goal:

- Non-asymptotic probabilistic delay bound of the form

$$\mathsf{P}\left[W > d\right] \leq \varepsilon$$

using stochastic network calculus based on moment generating functions (MGF)

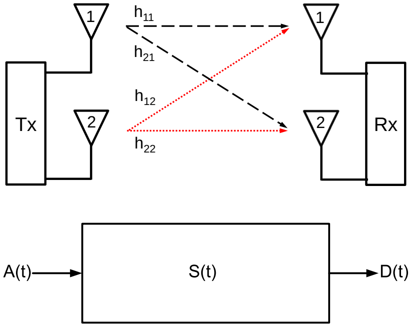
Focus: MIMO under spatial multiplexing: Example (N=2)



- block fading characteristic for all sub-channels $\{h_{11}, h_{21}, h_{12}, h_{22}\}$
- CSI at transmitter such that arrivals are transmitted in FIFO manner
- Capacity $C = \log_2 \left[\det\left(\mathbf{I} + \frac{\rho}{N}\mathbf{H}\mathbf{H}^\dagger\right)\right]$
- Channel matrix describing the scattering environment

  $\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}$, finite scatter model (NLOS, Rayleigh)

A stochastic network calculus approach



- Stochastic modeling of traffic arrivals and node service (MGF)
- Performance bounds, e.g., $\mathrm{P}\left[W > d\right] \leq \varepsilon$
- Multiplexing and composition results (independence)

Moment generating function

MGF of a stationary process $X(t)$ for $\theta > 0$, $t \geq 0$

$$\mathsf{M}_X(\theta, t) = \mathsf{E}\left[e^{\theta X(t)}\right]$$

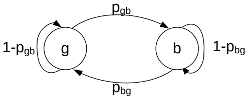
- Backlog and delay bounds are known [Fidler'06], using Chernoff's bound, Boole's inequality:

$$\mathsf{P}\left[W > \inf_{\theta > 0}\left[\inf\left[\tau : \frac{1}{\theta}\left(\ln \sum_{s=\tau}^{\infty} \mathsf{M}_A(\theta, s-\tau)\overline{\mathsf{M}}_S(\theta, s) - \ln \varepsilon\right) \leq 0\right]\right]\right] \leq \varepsilon$$

where $\overline{\mathsf{M}}_S(\theta, t) = \mathsf{M}_S(-\theta, t)$.

Discrete time block fading model

On-Off Markov chain (Gilbert-Elliot) model for each sub-channel

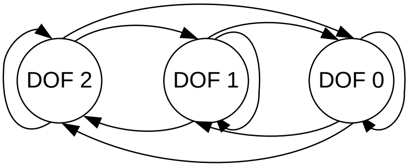


Model the $N \times N$ MIMO channel by a MC consisting of 2^{N^2} states

- For $N = 2$ the MC consists of 16 permutations/states of the form $\{g, g, g, g\}, \{g, g, g, b\} \dots \{b, b, b, b\}$ for $\{h_{11}, h_{12}, h_{21}, h_{22}\}$
- Group the states according to degree of freedom (DOF): The receiver can decode **two**, **one** or **no** spatial streams.
- A receiver antenna can only decode one spatial stream at a time (i.e. $\{g, g, b, b\}$ belongs to DOF 1)

Channel model cont. (Example N = 2)

- The state space is reduced to $N + 1$



The MGF of the service process

The MGF of such a Markov chain is known [Chang'00]

$$\overline{\mathsf{M}}_S(\theta, t) = \boldsymbol{\pi}(\mathbf{R}(-\theta)\mathbf{Q})^{t-1}\mathbf{R}(-\theta)\mathbf{1}$$

- The service rates r_i are ordered into a matrix $\mathbf{R}(\theta) = \text{diag}\left(\mathbf{e}^{\theta \mathbf{r_1}, \cdots, \theta \mathbf{r_{N+1}}}\right)$
- The transition probability matrix $\mathbf{Q}$ has the elements $\{p_{ij}\}$ denoting the transition probability from state i to state j
- The steady state probability vector $\boldsymbol{\pi} = \boldsymbol{\pi} \cdot \mathbf{Q}$

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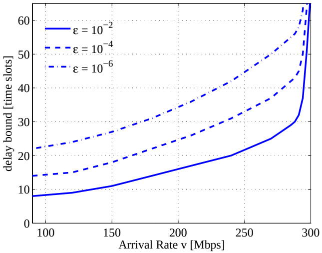
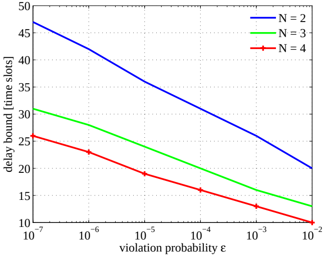
Nevertheless no analytical expression for $\overline{\mathsf{M}}_S$ for more than two states -> numerical evaluation.

Example: Flow level delay bounds for IEEE 802.11n

- periodic arrival source with known $\mathsf{M}_A(\theta, t)$
- parametrize arrivals according to MCS
- parametrize MC: normalized Doppler frequency to block transmission rate [Zorzi'98] -> p_{bg}, p_{gb}

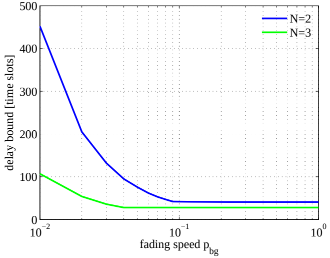


Stochastic delay bounds for $N = 2$.

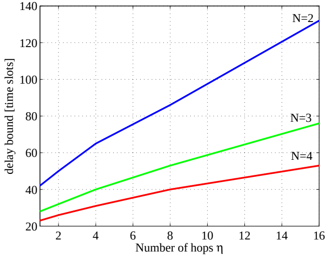


Exponential decay due to Chernoff's bound. Arrival rate $v = 240$ Mbps.

Fading speed and end-to-end delay bounds



- Impact of statistical multiplexing vs. memory



End-to-end bounds for statistically independent wireless links.

- Bound scales at most linearly
- Slope changes with the number of antennas N (increase in capacity)

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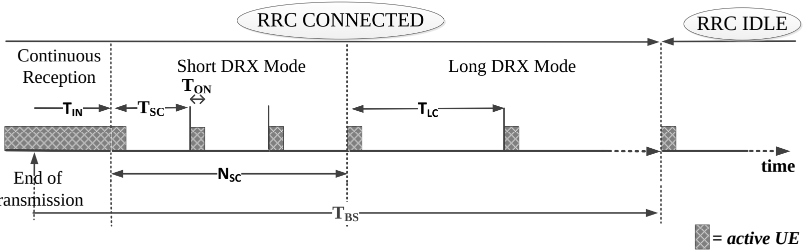
Measurement study in a major commercial LTE network

- Measurements from user equipment (UE) perspective
- Layer 2 mechanism: Discontinuous Reception Mode (DRX)
  1. UE turns off circuitry to save power
  2. UE monitors control channel in intervals seeking paging messages
  3. If UE idles for too long -> logical connection tear down

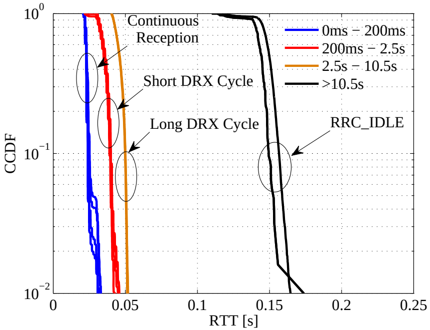
Discontinuous reception mode (DRX)

- UE is in one of the radio resource control (RRC) states:
  1. RRC_CONNECTED state
     1.1 Continuous Reception
     1.2 Short DRX Mode
     1.3 Long DRX Mode
  2. RRC_IDLE state



Discontinuous reception mode (DRX)

- we measure packet round-trip times (RTT) for periodic ping packets
- we vary the period length, i.e., the inter-packet gap and measure for each gap 5×10^3 RTTs
- delay increase due to "wake up time"

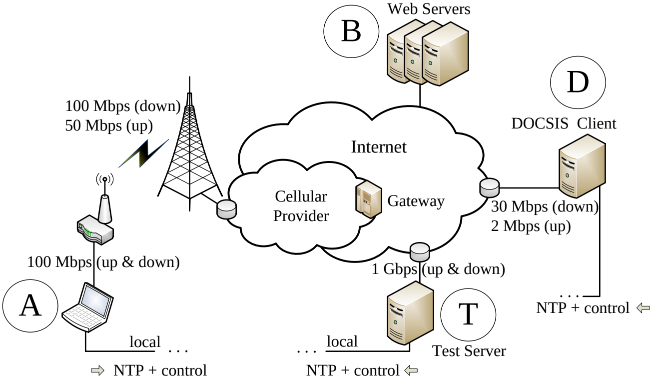


Summary

- Delay analysis of MIMO wireless channels in spatial multiplexing using MGF network calculus
  1. impact of channel memory (fading speed)
  2. impact of the number of antennas

- Real world measurements: Layer 2 mechanism that contributes substantially to packet delay.

Backup


Web Servers
B
D
100 Mbps (down)
50 Mbps (up)
DOCSIS Client
Internet
Cellular Provider
Gateway
30 Mbps (down)
2 Mbps (up)
100 Mbps (up & down)
1 Gbps (up & down)
A
T
. . .
NTP + control
local
. . .
local
Test Server
NTP + control
. . .
NTP + control

HARQ-retransmissions

Block retransmission after error detection. Combination of multiple copies of the data block to increase decoding likelihood.
Out-of-order blocks wait in the receive buffer.

- we measure packet round-trip times (RTT) in continuous reception mode.
- LTE specifies HARQ-retransmissions in rigid 8 ms intervals.
- substantial delay increase for short RTT connections.