Mobilkommunikation - Mobile Communications

Lecture 8: Wireless Local Area Networks

Prof. Dr.-Ing. Markus Fidler

Institute of Communications Technology
Leibniz Universität Hannover

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Outline

Fading and diversity

Multiple-input multiple-output (MIMO)
- Spatial diversity
- Spatial multiplexing

Attenuation of the signal

- slow fading: macro effects, signal strength varies slowly due to movement or changes in the environment
  - free space path loss
  - shadowing
- fast fading: micro effects, signal strength varies quickly
  - multi-path propagation: constructive or destructive interference depending on the relative phase of received signals
    - small changes of the path length (in the order of the wavelength 12, resp., 6 cm in case of 2.4, resp., 5 GHz) can cause severe differences
    - frequency selective
  - received signal varies quickly over time, frequency, and space

Diversity

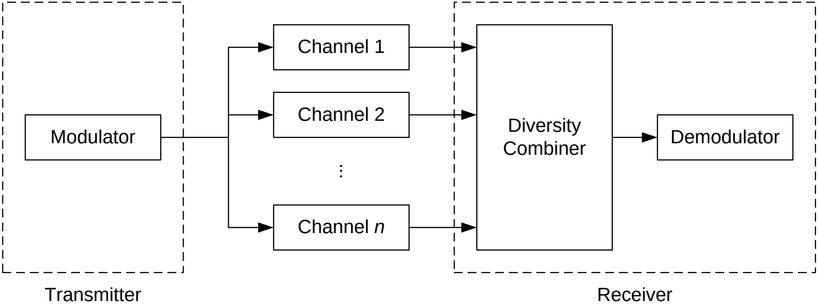
Diversity can deal with degradations (fading) of the radio channel. Basic concept:

- receivers get more than one version of the transmitted signal
- each signal version is received on an independent channel
- independence reduces the probability that all channels see a deep fade simultaneously
- e.g. the signal received on a channel cannot be decoded with probability $p = 0.1$; using $n = 2$ independent channels the probability is reduced to $p^n = 0.01$

Diversity requires that

- fading on different channels is only weakly correlated
- receive power on different channels is almost equal

Diversity channel model



Types of diversity

Major options of diversity include

- **frequency diversity**: signals are transmitted on n different frequencies
- **time diversity**: signals are transmitted in n time slots; in practice also frequently used by interleaving, forward error correction (FEC) and automatic repeat request (ARQ)
- **spatial diversity**: signals are transmitted using n spatially separated paths (n receive or transmit antennas)
- **path diversity**: multiple signal components are created by multi-path propagation; can be resolved in CDMA systems by so-called Rake receivers that separate the signal components using code correlation to tune to individual components

Diversity in IEEE 802.11a/g/n

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Spreading of information across independently faded channels

- frequency diversity
  - OFDM divides the carrier into subcarriers
  - if fading is frequency selective, OFDM subcarriers are independently faded
  - coding adds redundancy across the subcarriers that can recover errors due to deep fades on some of the subcarriers
- time diversity
  - OFDM subcarriers have a smaller symbol rate, respectively, longer symbol duration
  - the increased symbol duration mitigates difficulties due to inter-symbol interference
  - short fades can be averaged out over the longer symbol duration if fading is independent over time
- spatial diversity
  - multiple antennas to use independently faded spatial paths

Multiple antenna systems

MIMO research started in the mid '90s with the aim to increase

- data rate
- reliability
- range

Multiple antenna pairs can provide independent spatial paths, e.g. if signals are highly scattered. MIMO systems can use this "spatial degree of freedom" in two different modes of operation

- spatial diversity: redundant streams improve reliability, range
- spatial multiplexing: independent streams improve data rate

Today MIMO is used e.g. in IEEE 802.11n, LTE, and WiMAX.

The first IEEE 802.11n draft was issued in Jan. 2006 and the standard in Sep. 2009. Since 2007 IEEE 802.11n draft hardware is on the market.

MIMO vs. multiple antenna SISO

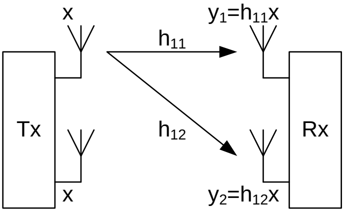
IEEE 802.11a/g access points with multiple antennas

- choose the best antenna to send or receive
- single-input single-output (SISO) systems

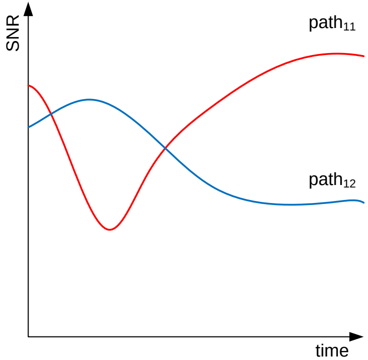
IEEE 802.11n uses multiple antennas at sender and/or receiver

- at the same time and on the same frequency band
- requires multiple radio frequency processing chains
- requires sophisticated signal processing techniques

Receive diversity

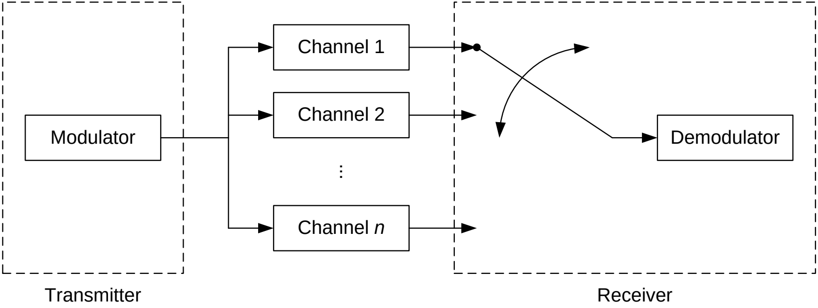


channel gain h_{ij}
- attenuation
- phase shift



Goal: Combine the received signals

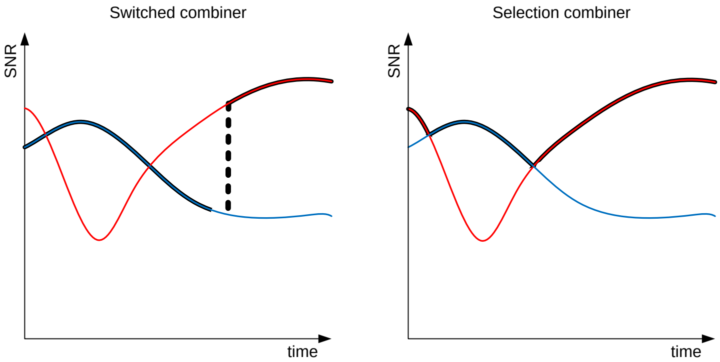
Switched combiner and selection combiner



The combiner selects the signal with the highest SNR

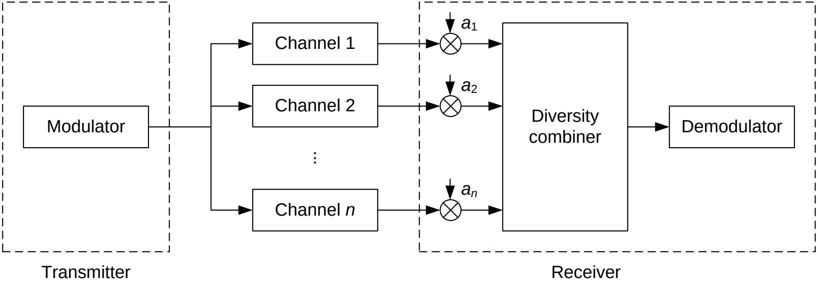
- Switched combiner: switches only if the currently selected signal falls below a threshold; needs only one receiver
- Selection combiner: monitors all signals simultaneously and selects the strongest signal instantaneously

Switched combiner and selection combiner continued



- the selection combiner selects the strongest signal instantly
- the selection combiner does, however, still waste information; the receive power of the weaker signal is ignored entirely

Maximal ratio combiner



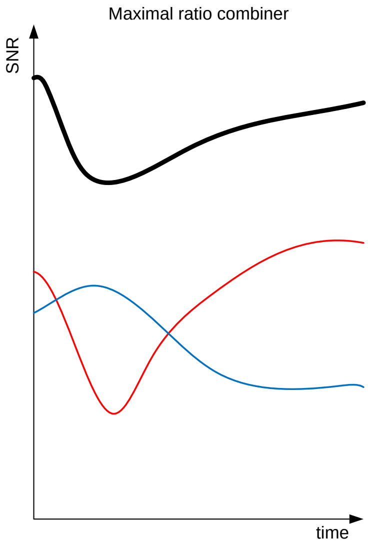
The signal components are

- weighted by their SNR
- delayed until they are in phase
- and summed afterwards

Maximal ratio combiner continued

Maximal ratio combining

- is known to be optimal
- achieves an SNR that is the sum of the components' SNRs
- is performed for each of the subcarriers in OFDM systems

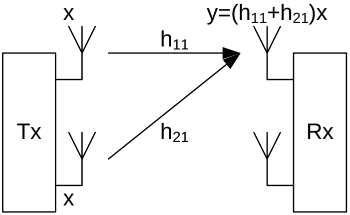


Modes of operation

- select only the single best antenna for transmission
- transmit on all antennas; delay signals such that they add constructively at the receiver

Drawback

- transmitter must know the channel in advance
- requires signalling from the receiver
- signalled information may be outdated



Channel capacity

Recall Shannon's limit for AWGN channels

$$C = B \log_2 \left(1 + \frac{S}{N}\right)$$

where

- C = theoretical limit of the data rate [bit/s]
- B = channel bandwidth [Hz]
- S/N = signal-to-noise ratio

With maximal ratio combining the SNR is the sum of the SNR of the signal components. Receive diversity $1 \times n$ or transmit diversity $n \times 1$ achieves

$$C = B \log_2 \left(1 + n\frac{S}{N}\right) .$$

Channel capacity continued

Receive and transmit diversity $n \times n$ achieves n^2 degrees of freedom (potentially independent channels) such that

$$C = B \log_2 \left(1 + n^2 \frac{S}{N} \right).$$

Assuming $S/N \gg 1$ the capacity achieved with n transmit and receive antennas is $B(2 \log_2 n + \log_2(S/N))$ i.e. the gain is $2 \log_2 n$ bit/s/Hz, e.g. $n = 2, 4, 8, \ldots$ antennas increase the spectral efficiency C/B additively by $2, 4, 6, \ldots$ bit/s/Hz.

Using n independent spatial paths to send n independent streams of information (spatial multiplexing) yields, however,

$$C = nB \log_2 \left(1 + \frac{S}{N} \right)$$

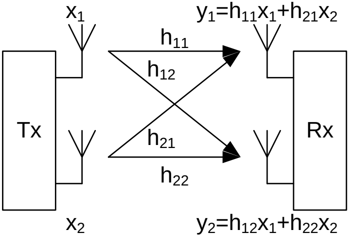
providing an n-fold capacity increase.

Direct mapped MIMO

- transmit different spatial streams on each antenna
- h_{ij} is the channel gain (attenuation, phase shift)
- since electromagnetic waves superimpose we deal with a linear system with channel matrix H

$$\vec{y} = H\vec{x} + \vec{n}$$

where $\vec{n}$ is the noise that is unknown



Spatial multiplexing continued

IEEE 802.11n includes a training sequence in the MIMO packet preamble that enables the receiver to measure h_{ij} for each OFDM subcarrier and each pair of transmit and receive antennas.

Solving the linear set of equations $\overrightarrow{y} = H\overrightarrow{x} + \overrightarrow{n}$ gives

$$H^{-1}\overrightarrow{y} = \overrightarrow{x} + H^{-1}\overrightarrow{n}$$

permitting the estimation of $\overrightarrow{x}$ if $H^{-1}\overrightarrow{n}$ is small.

If the spatial paths are, however, correlated the solution H^{-1} will cause noise amplification, such that decoding may not be possible.

Literature

- Jochen Schiller, Mobile Communications, Second Edition, Addison-Wesley, 2003.
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- Daniel Halperin, Wenjun Hu, Anmol Sheth, David Wetherall, 802.11 with Multiple Antennas for Dummies, ACM SIGCOMM Computer Communications Review, 40(1):19-25, 2010.