Intelligent Transportation Systems

Basics of Wireless Communications

Prof. Dr. Thomas Strang
Outline

- Wireless Signal Propagation
  - Electro-magnetic waves
  - Signal impairments
    - Attenuation, Distortion, Noise
- Frequency Spectrum
- Modulation
  - Amplitude Shift Keying, Frequency Shift Keying, Phase Shift Keying
- Spreading
- Channel Coding
  - Scrambling, Error correction, Interleaving
Wireless Signal Propagation
Wireless Signal Propagation
Electro-magnetic waves

- Wireless communication is based on the exchange of **electro-magnetic waves** between a sender and \( n \geq 0 \) receivers.
- An electro-magnetic wave can be characterized by:
  - its **amplitude** \( A \), the height of the wave as a measure for the intensity of the wave, and
  - its **frequency** \( f \), the number of cycles per second measured in Hertz (Hz) according to the German physicist Heinrich Hertz, or
  - its **wave length** \( \lambda \), the length of a single wave period measured in meter (m).
- Wave length and frequency are inversely proportional by the **wave speed** \( v \): \[ \lambda = v \times \frac{1}{f} \]

<table>
<thead>
<tr>
<th>Medium</th>
<th>Wave Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum</td>
<td>( \approx 3 \times 10^8 )</td>
</tr>
<tr>
<td>Air</td>
<td>( \approx 2.99 \times 10^8 )</td>
</tr>
<tr>
<td>Water</td>
<td>( \approx 2.25 \times 10^8 )</td>
</tr>
<tr>
<td>Copper</td>
<td>( \approx 2 \times 10^8 )</td>
</tr>
<tr>
<td>Optical Fiber</td>
<td>( \approx 2 \times 10^8 )</td>
</tr>
</tbody>
</table>
Wireless Signal Propagation
Electro-magnetic waves

- An electro-magnetic wave consists of an **electric field** and a corresponding **magnetic field** which are perpendicular to each other and to the direction of the wave travel.

- Electric and magnetic fields vary sinusoidally.

- According to their wavelength and the medium (e.g. vacuum, metal, walls), electro-magnetic waves have a **characteristic behavior**:
  - Reflection
  - Transmission
  - Absorption
Wireless Signal Propagation

Intensity

- Transmitter as well as receiver are specified by their intensity (transmit power & receive sensitivity)
- Intensity is measured in **Watt** \( W \) (often \( mW \))
- Watt is a **linear** unit (“twice the number of Watts \( \rightarrow \) twice the intensity”)
- An alternative measure for intensity is **dBm** (deciBel as opposed to \( mW \)) as an **logarithmic** unit (“+3dBm \( \rightarrow \) twice the intensity”)

\[
P_{[\text{dBm}]} = 10 \log_{10}(P_{[\text{mW}]}) \quad \Leftrightarrow \quad P_{[\text{mW}]} = 10^{(P_{[\text{dBm}]/10})}
\]

**Example:**

- A high-power WLAN transmitter with 28 dBm output power transmits with an intensity of 630 mW
- A high-power WLAN receiver with -94dBm sensitivity can receive signals with an intensity of 0.000 000 398 mW = 3.98*10^{-10} mW
- A GPS receiver with -160 dBm sensitivity can receive signals with an intensity of 0.000 000 000 000 000 1 mW = 1*10^{-16} mW
Wireless Signal Propagation
Signal Impairment

On the way between the signal source and the signal sink the signal gets impaired by attenuation, distortion and noise.
Wireless Signal Propagation

Signal attenuation

Basic factors:

- Receiver sensitivity $P_r$
- Transmit power $P_t$
- Receiver antenna gain $G_r$
- Transmitter antenna gain $G_t$
- Frequency $f$
- Distance $d$

Free-space path loss: 

$$FSPL = \left(\frac{4\pi d}{\lambda}\right)^2$$

$$= \left(\frac{4\pi df}{c}\right)^2$$

Friis free-space equation:

$$\frac{P_r[mW]}{P_t[mW]} = G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2$$

At transmitter:

Spreading of electro-magnetic energy

$$S = P_t[mW] \frac{1}{4\pi d^2}$$

At receiver:

Absorption of electro-magnetic energy

$$P_t[mW] = S\frac{\lambda^2}{4\pi}$$
Is it possible to communicate with a data rate of 54Mbps in 5.4 GHz-channel over a range of 200 m (no antenna gains)?

- FSPL = 93 dBm
- Power at receiver = -70 dBm → communication possible

Theoretical max. range for 6Mbps transmission in 5.2 GHz channel (no antenna gains):

- Max. range = 5780 m

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### TX SPECIFICATIONS

<table>
<thead>
<tr>
<th>DataRate</th>
<th>Avg.Power</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>6Mbps</td>
<td>28 dBm</td>
<td>+/-1.5dB</td>
</tr>
<tr>
<td>9Mbps</td>
<td>28 dBm</td>
<td>+/-1.5dB</td>
</tr>
<tr>
<td>12Mbps</td>
<td>28 dBm</td>
<td>+/-1.5dB</td>
</tr>
<tr>
<td>18Mbps</td>
<td>28 dBm</td>
<td>+/-1.5dB</td>
</tr>
<tr>
<td>24Mbps</td>
<td>28 dBm</td>
<td>+/-1.5dB</td>
</tr>
<tr>
<td>36Mbps</td>
<td>26 dBm</td>
<td>+/-1.5dB</td>
</tr>
<tr>
<td>48Mbps</td>
<td>24 dBm</td>
<td>+/-1.5dB</td>
</tr>
<tr>
<td>54Mbps</td>
<td>23 dBm</td>
<td>+/-1.5dB</td>
</tr>
</tbody>
</table>

### RX SPECIFICATIONS

<table>
<thead>
<tr>
<th>DataRate</th>
<th>Sensitivity</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>6Mbps</td>
<td>94 dBm</td>
<td>+/-1.5dB</td>
</tr>
<tr>
<td>9Mbps</td>
<td>-93 dBm</td>
<td>+/-1.5dB</td>
</tr>
<tr>
<td>12Mbps</td>
<td>-91 dBm</td>
<td>+/-1.5dB</td>
</tr>
<tr>
<td>18Mbps</td>
<td>-90 dBm</td>
<td>+/-1.5dB</td>
</tr>
<tr>
<td>24Mbps</td>
<td>-86 dBm</td>
<td>+/-1.5dB</td>
</tr>
<tr>
<td>36Mbps</td>
<td>83 dBm</td>
<td>+/-1.5dB</td>
</tr>
<tr>
<td>48Mbps</td>
<td>-77 dBm</td>
<td>+/-1.5dB</td>
</tr>
<tr>
<td>54Mbps</td>
<td>-74 dBm</td>
<td>+/-1.5dB</td>
</tr>
</tbody>
</table>
Wireless Signal Propagation
Antenna Gains

- Isotropic radiation is generated by an isotropic radiator
  → only a theoretical concept
- Real antennas always have **directive effects** (vertically and/or horizontally)

- Dipole antenna:

- Directed antenna:

- Sectorized antenna:

Based on: Schiller (2008): Mobile Communications

M. Röckl and T. Strang, 2009
Wireless Signal Propagation
Antenna Gains

Antenna Gain: 10 dBi

Source: WiMo

Antenna Gain: 15 dBi

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Wireless Signal Propagation
Noise & Interference

- **Noise:**
  - Signal alteration due to effects in transmitter and receiver electronics

- **Interference:**
  - Signal distortion due to superimposition with other signals
  - Types:
    - Co-channel interference: another sender uses the same channel in the frequency spectrum
    - Adjacent-channel interference: another sender uses an adjacent channel of the radio spectrum with overlapping frequencies
    - Inter-symbol interference: self-interference caused by multipath propagation
Wireless Signal Propagation
Sources of signal distortion

- **Shadowing:**
  Signal reception is suppressed by objects

- **Reflection:**
  Signal is reflected on large objects

- **Refraction:**
  Part of the signal is reflected, rest is absorbed

- **Diffraction:**
  Sharp edges cause signal splitting

- **Scattering:**
  Small objects cause multiple reflections of the signal

- **Doppler fading:**
  Sender/receiver movement cause frequency shift

Based on: Schiller (2008): Mobile Communications

M. Röckl and T. Strang, 2009
Wireless Signal Propagation
Multipath

- Signal can take more than one path (multipath) between transmitter and receiver
- Direct path according to Line Of Sight (LOS) has shortest path, all other paths travel a longer path
- Different paths have different length → signals will be received with different delays → resulting in Delay Spread (dispersion of time)
- Multipath can cause inter-symbol-interference

Inter-symbol Interference

Based on: Schiller (2008): Mobile Communications
Wireless Signal Propagation

Fading

- Fading:
  - Variation of the signal strength at the receiver

- Large-scale fading:
  - Long-term fading effect due to signal attenuation and reflection with slow movement

- Small-scale fading:
  - Short-term fading effect due to multi-path and doppler spread propagation with fast movement

Based on Küpper (2008): Mobilkommunikation
Wireless Signal Propagation
Signal impairment in V2X communications

V2X protocol design has to take into account these bad wireless propagation conditions

Source: Car-2-Car Communication Consortium

Source: Minack (2005)

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Frequency Spectrum
Frequency Spectrum
Frequency bands

- VLF = Very Low Frequency
- LF = Low Frequency
- MF = Medium Frequency
- HF = High Frequency
- VHF = Very High Frequency
- UHF = Ultra High Frequency
- SHF = Super High Frequency
- EHF = Extra High Frequency
- UV = Ultraviolet Light

Based on: Schiller (2008): Mobile Communications
Frequency Spectrum
U.S. frequency allocation table

Frequency Spectrum
2.4 GHz ISM bands

- 2.4 GHz Industrial-Scientific-Medical (ISM) band: 2.400 – 2.483 GHz

Pros:
- Available world-wide
- Licensee-free
- Large bandwidth (80 MHz)
- 100% duty cycle allowed

Cons:
- Low power (up 0.1 W in Europe, depends on national regulations)
  - short range
- No exclusive usage → crowded
  - Bluetooth, Zigbee
  - Wireless keyboard & mouse
  - Cordless phone (e.g. DECT)
  - Microwave ovens

In order to enable safety critical systems, V2X communication requires a license-free, high-power, dedicated frequency band

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Modulation
Modulation

Modulation is the process of altering a electromagnetic wave to carry a message.

**Analog modulation:**
- Superimposition of an analog signal (baseband signal) on a carrier signal
- Motivation:
  - Smaller antennas
  - Different channels for different users or bidirectional traffic
  - Propagation characteristics

**Digital modulation:**
- Alteration of the state (symbol) of the carrier signal to carry digital data
- Also called *shift keying*

**Basic schemes:**
- Amplitude Modulation (AM)
- Frequency Modulation (FM)
- Phase Modulation (PM)

\[ s(t) = A_t \sin(2\pi f_t t + \phi_t) \]

Amplitude, Frequency, Phase

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Modulation
Wireless modulation & demodulation

Based on: Schiller (2008): Mobile Communications

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Modulation
Amplitude Shift Keying (ASK)

- Amplitude of the carrier is altered in accordance to digital data
- Digital data is encoded by amplitude shifts (e.g. “1” normal amplitude, “0” no amplitude)

Examples:
- Optical transmission (light on / light off)
- Morse code

+ Simple
+ Low bandwidth requirements
- Susceptible to interference and signal distortion

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Modulation

Frequency Shift Keying (FSK)

- Frequency of the carrier is altered in accordance to digital data
- Digital data is encoded by frequency shifts
  (e.g. “0” is frequency A, “1” is frequency B)

Examples:
- Dual Tone Multi Frequency (DTMF)

- Less susceptible to interference
- Requires larger bandwidth than ASK
Modulation
Phase Shift Keying (PSK)

- Phase of the carrier is altered in accordance to digital signal
- Digital data is encoded by phase shifts
  - Absolute coding: “0” is phase A, “1” is phase B
  - Differential coding: “0” keeps phase, “1” alters phase

![Waveform diagram]

- Types:
  - Binary Phase Shift Keying (BPSK): Coding of a single bit (0 or 1) per symbol
  - Quadrature Phase Shift Keying (QPSK): Coding of two bits (00, 01, 10 or 11) per symbol, phase shifts of multiples of 90 degrees

- Examples:
  - IEEE 802.15.4 ZigBee
  - WLAN

+ Less susceptible to interference
+ Bandwidth efficient
- Requires synchronization in frequency and phase
  \( \rightarrow \) complicates receivers and transmitters
Modulation
Combinations of shift keyings: QAM

- Quadrature Amplitude Modulation (QAM)
  - Combination of ASK and QPSK
  - Digital data is encoded by amplitude and phase shifts
  - Example (8-QAM):
    - 3 bits are encoded per symbol → 8 signal states required
    - Signal states: 0°, 90°, 180°, 270° each with two amplitude levels
  - Usage: DVB-T (16-QAM / 64-QAM), DVB-C (256-QAM), WLAN
Modulation
Multi-carrier modulation

Problem: To achieve higher throughput we can increase the symbol rate (=number of symbols per second)
→ But this also increases inter-symbol interference in multi-path situations

Idea: **Split the high-speed carrier in \( n \) low-speed sub-carriers**

→ Transmission of multiple symbols on each sub-carrier in parallel
→ Transmission of a fraction of the data in each sub-carrier
→ Symbol rate can be decreased which reduces inter-symbol interference

Pros:
→ Less susceptible to interference, narrow-band interferences affect only a single sub-carrier
→ Less inter-symbol interference (ISI)
→ High bandwidth efficiency
Modulation
Orthogonal Frequency Division Multiplexing (OFDM)

- Orthogonality of the sub-carriers: Peak at the center frequency of each sub-carrier corresponds to a zero level of all other sub-carriers → no Inter-Carrier Interference
- Orthogonality is achieved by spacing apart the sub-carrier frequencies by the inverse of the symbol duration $T$
- Orthogonal sub-carriers prevent Inter-Carrier Interference, i.e. cross-talk between sub-carriers

Higher bandwidth efficiency than non-overlapping sub-carriers
Modulation
OFDM error resistance


Frequencies remain orthogonal → No Inter-Carrier Interference
Modulation

OFDM

- Each sub-carrier can have an individual modulation (e.g. QPSK or QAM)
- Guardband (aka Guardinterval) per symbol reduce Inter-Symbol Interference
- Synchronization by pilot signals in specific sub-carriers
- Channel estimation with training symbols

Advantages of OFDM:
- High spectrum efficiency
- Resistance against narrow-band interferers and signal distortions
- Resistance against multipath errors
Spreading
Spreading

Methods for spreading the bandwidth of the transmitted signal over a frequency band (spectrum) which is wider than the minimum bandwidth required to transmit the signal

Pros:
- Resistance to narrow-band interferers:
  - Effect of narrow-band interferers is low for wide-band signals
- Prevention of interception
  - e.g. for military applications
  - Only receivers that know the spreading code can receive the signal
- Used in GPS, Galileo
- Multiple access capability
  - Different spreadings allow co-existence of different channels
  - Used in UMTS

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**Spreading**

Frequency Hopping Spreading Spectrum (FHSS)

- Transmission frequency is changed over time
- Transmitter and receiver agree on a hopping pattern (pseudo random sequences)
- Different hopping sequences enable coexistence of multiple channels
- Examples:
  - Bluetooth (fast FHSS)
  - WLAN (slow FHSS)

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Spreading
Direct Sequence Spreading Spectrum (DSSS)

- Data is spread by a wide bandwidth pseudo-random code sequence (chip sequence) with $n$ chips per bit
- Transmitter and receiver agree on a chip sequence
- Signals appear as wideband noise to unintended receivers
- Different chip sequences enable co-existence of multiple channels
- Example:
  - GPS, Galileo
  - WLAN IEEE 802.11
- Chip sequence can also be used for modulation: a specific chip sequence is assigned to a specific bit sequence (e.g. in IEEE 802.11b)
Channel Coding
Channel Coding
Scrambling

- Sophisticated modulation (e.g. OFDM) requires highly synchronized transceivers
- Signal-based synchronization requires frequent signal edges
- Problem: PHY-SDU may contain large number of identical bits (e.g. in the MAC header fields)
- Scrambling eliminates identical bits by mapping structured bit sequences to seemingly random bit sequences

WLAN 802.11a Scrambler

\[ S = x^7 + x^4 + 1 \]
Channel Coding
Forward Error Correction (FEC)

- FEC: Insertion of **additional redundant bits** for error detection/correction
- **Block coding:**
  - Encoder **successive** maps $k$-bit block into an $n$-bit codeword
  - Decoder makes **hard decisions**: valid or invalid codeword
  - Examples: CRC, parity check

Example message to transmit

<table>
<thead>
<tr>
<th>11000000110111110000000000000000</th>
<th>Filler</th>
</tr>
</thead>
<tbody>
<tr>
<td>1100010110011001</td>
<td></td>
</tr>
<tr>
<td>00000101001101001000</td>
<td></td>
</tr>
<tr>
<td>1100010110011001</td>
<td></td>
</tr>
<tr>
<td>0110001100001001000</td>
<td></td>
</tr>
<tr>
<td>1100010110011001</td>
<td></td>
</tr>
<tr>
<td>000001111000101100000000</td>
<td></td>
</tr>
<tr>
<td>1100010110011001</td>
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<tr>
<td>010001001011001</td>
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</tr>
<tr>
<td>1100010110011001</td>
<td></td>
</tr>
<tr>
<td>011000101100110011111110</td>
<td></td>
</tr>
<tr>
<td>1100010110011001</td>
<td></td>
</tr>
<tr>
<td>011101000110000000000000</td>
<td></td>
</tr>
<tr>
<td>1100010110011001</td>
<td></td>
</tr>
<tr>
<td>0010110101011111</td>
<td></td>
</tr>
</tbody>
</table>

**Remainder used as CRC checksum**

G(x) = $x^{15} + x^{14} + x^{10} + x^{8} + x^{7} + x^{4} + x^{3} + 1$

$= 1100010110011001$

DIV mod 2 is equal to XOR

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Channel Coding
Forward Error Correction (FEC)

**Convolutional coding:**
- Encoder *continuously* maps \( k \)-input bits at a time and produces an output of \( n \)-bits for each incoming \( K \)-bits
- \( n \)-bit output not only depends on the \( k \)-bit input, but also on the previous \((K-1)\)-blocks of \( k \)-bit input
- Decoder makes *soft decisions*: what was the most probable valid codeword?
- \((n, k, K)\) code
  - Input processes \( k \) bits at a time
  - Output produces \( n \) bits for every \( k \) input bits
  - \( K \) = constraint factor (memory depth)
- Coding rate = \( k/n \)

\[ (2,1,3)\)-Convolutional Encoder
Coding rate = 1/2

\begin{align*}
\text{Input data bits} & \quad \rightarrow \quad (n,k,K) \\
\text{Encoder} & \quad \rightarrow \quad \text{n bits} \\
\text{First coded bit} & \quad n_1 \\
\text{Second coded bit} & \quad n_2
\end{align*}
Channel Coding
Forward Error Correction (FEC)

Message to encode: \( m = 101 \) [000]

Based on: C. Logothetis (2007): Digital Communications I
Channel Coding
Forward Error Correction (FEC)

\[ m = 101 \ [000] \rightarrow \text{Encoder} \rightarrow U = (11 \ 10 \ 00 \ 10 \ 11) \]
Channel Coding
Interleaving

- In wireless transmission burst errors (affecting several consecutive bits) are more probable than single bit errors due to fading effects
  - high number of bit errors near together
  - bad error correction capability

- Idea: Spread burst errors far apart
  - independent error correction mechanisms

- **Frequency interleaving** ensures that the bit errors that would result from those sub-carriers in the faded part of the bandwidth are spread out in the bit-stream rather than being concentrated

- **Time interleaving** ensures that bits that are originally close together in the bit-stream are transmitted far apart in time