Embedded Internet and the Internet of Things
WS 12/13

3. Physical Layer

Prof. Dr. Mesut Güneş
Distributed, embedded Systems (DES)
Institute of Computer Science
Freie Universität Berlin
Overview

- Overview of wireless communications
- Wireless channel
- Channel models
Overview of wireless communications
Protocol stack

- Application Layer
- Transport Layer
- Network Layer
- Link Layer
- Physical Layer

Prof. Dr. Mesut Güneş • 3. Physical Layer
Elements of robust communication

- **Application layer**: feasible workload
  - Packet rates, pattern, timing
- **Network layer**: finding and using good paths
  - Topology discovery and route selection
  - Route cost determination, selection
  - Forwarding
- **Link layer**: Framing, Media Management Protocol
  - On to receive during transmission
  - Frame structure, error detection, acknowledgement
  - Avoiding contention (MAC, CCA, Hidden Terminal)
  - Link quality estimation
- **Physical layer**: Signal to Noise Ratio
  - Device Transmission Power / Receive Sensitivity
  - Antenna design and orientation, obstructions, attenuation
  - Receive signal vs interference, noise, multipath
  - Modulation, channel coding
Protocol stack: Details

Application Layer

Physical Layer

Source Encoder

Source Codeword

Channel Encoder

Channel Codeword

Modulator

Wireless Channel
Source coding (data compression)

• At the transmitter end, the information source is first encoded with a source encoder
  • Exploit the information statistics
  • Represent the source with fewer number of bits
    -> source codeword

• Performed at the application layer
Channel coding (error control coding)

• Source codeword is then encoded by the channel encoder

-> channel codeword

• Goal: address the wireless channel errors that affect the transmitted information
Interleaving and modulation

• The encoded channel codeword is then **interleaved** to combat the bursty errors

• **Channel coding and the interleaving mechanism** help the receiver either to
  • identify bit errors to initiate retransmission (ARQ)
  • correct a limited number of bits in case of errors (FEC)
Interleaving and modulation

• Then, an analog signal (or a set thereof) is modulated by the digital information to create the waveform that will be sent over the channel

• Finally, the waveforms are transmitted through the antenna to the receiver
Wireless transmission

- The transmitted waveform travels through the channel
- Meanwhile, the waveform is attenuated and distorted by several wireless channel effects
Information Processing

Source stream → Source Encoder → Source codeword → Channel Encoder → Channel codeword

- Correlated bits
- Control bits
- Parity bits
Wireless Communication Basics

Transmission

- Transmit command provides data and starts MAC protocol.
- Data to be Transmitted
- Encode processing
- Encoded data to be Transmitted
- MAC Delay
- Transmitting encoded bits

Bit Modulations

Radio Samples
- Start Symbol Search
- Receiving individual bits
- Synchronization
- Start Symbol Detection
- Encoded data received

Reception

- Decode processing
- Data Received
Wireless Communication Basics
Frequency bands
Radio spectrum for communication

• Which part of the electromagnetic spectrum is used for communication
• Not all frequencies are equally suitable for all tasks, e.g.,
  • wall penetration
  • different atmospheric attenuation (oxygen resonances, ...)
Frequency allocation

- Some frequencies are allocated to specific uses
  - Cellular phones, analog television/radio broadcasting, DVB-T, radar, emergency services, radio astronomy, ...
- Particularly interesting: ISM bands (“Industrial, scientific, medicine”) – license-free operation

### Some typical ISM bands

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>13,553-13,567 MHz</td>
<td></td>
</tr>
<tr>
<td>26,957 - 27,283 MHz</td>
<td></td>
</tr>
<tr>
<td>40,66 - 40,70 MHz</td>
<td></td>
</tr>
<tr>
<td>433 – 464 MHz</td>
<td>Europe</td>
</tr>
<tr>
<td>900 - 928 MHz</td>
<td>Americas</td>
</tr>
<tr>
<td>2,4 - 2,5 GHz</td>
<td>WLAN/ WPAN</td>
</tr>
<tr>
<td>5,725 - 5,875 GHz</td>
<td>WLAN</td>
</tr>
<tr>
<td>24 - 24,25 GHz</td>
<td></td>
</tr>
</tbody>
</table>
Example: US frequency allocation
Wireless Communication Basics

Modulation
Transmitting Data Using Radio Waves

• Basics: Wireless communication is performed through radio waves
  • Transmitter can send a radio wave
  • Receiver can detect the wave and its parameters
• Typical radio wave = sine function:

\[ s(t) = A \cdot \sin(2\pi ft + \phi) \]

• Parameters: amplitude \( A \), frequency \( f \), phase \( \phi \)
• Modulation: Manipulate these parameters
Modulation

• Data to be transmitted is used to select transmission parameters as a function of time
• These parameters modify a basic sine wave, which serves as a starting point for modulating the signal onto it
• This basic sine wave has a center frequency $f_c$
• The resulting signal requires a certain bandwidth to be transmitted (centered around center frequency)
Modulation (Keying) examples

- **(ASK)**
  Amplitude Shift Keying

- **(FSK)**
  Frequency Shift Keying

- **(PSK)**
  Phase Shift Keying
Receiver: Demodulation

• Receiver tries to match the received waveform with the transmitted data bit
  • Necessary: one-to-one mapping between data and waveform

• Problems (Wireless Channel Errors)
  • Carrier synchronization: Frequency can vary between sender and receiver (drift, temperature changes, aging, ...)
  • Bit synchronization: When does symbol representing a certain bit start/end?
  • Frame synchronization: When does a packet start/end?

• Biggest problem: Received signal is not the transmitted signal!
Wireless channel
Wireless Channel

- Path-loss
- Multi-path effects
- Channel errors
- Signals-to-bits
- Bits-to-packets
Radio propagation

• **Attenuation:** As the signal wave propagates through air, the signal strength is attenuated.
  • Proportional to the distance traveled over the air
  • Results in *path loss* for radio waves
Radio propagation

• **Reflection and refraction:** When a signal wave is incident at a boundary between two different types of material
  • fraction of the wave bounces off the surface -> reflection
  • fraction of the wave propagates through the boundary->refraction
Radio propagation

- **Diffraction**: When signal wave propagates through sharp edges such as the tip of a mountain or a building, the sharp edge acts as a source
  - New waves are generated
  - Signal strength is distributed to the new generated waves

- **Scattering**: In reality, no perfect boundaries. When a signal wave is incident at a rough surface, it scatters in different directions
Wireless Channel

• Wireless transmission distorts any transmitted signal
  • Wireless channel describes these distortion effects

• Sources of distortion
  • Attenuation: Signal strength decreases with increasing distance
  • Reflection/refraction: Signal bounces off a surface; enter material
  • Diffraction: start “new wave” from a sharp edge
  • Scattering: multiple reflections at rough surfaces
Attenuation

• Results in path loss
• Received signal strength is a function of the distance \( d \) between sender and transmitter
• Friis free-space model
  • Signal strength at distance \( d \) relative to some reference distance \( d_0 < d \) for which strength is known
  • \( d_0 \) is **far-field distance**, depends on antenna technology

\[
P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 \ d^2 L}
\]

• \( P_r, P_t \) Receive, transmit power
• \( G_r, G_t \) Receive, transmit antenna gain
• \( d \) Distance between transmitter-receiver
• \( L \) System loss no related to propagation
Attenuation

• Friis free-space model

\[ P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \]

\[ = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d_0^2 L} \left( \frac{d_0}{d} \right)^2 \]

\[ = P_r(d_0) \left( \frac{d_0}{d} \right)^2 \]

\( P_r(d_0) \) Received power at reference distance \( d_0 \)
Attenuation

• Friis free-space model is only valid for $d$ in far-field distance of the transmitting antenna
  • Far-field region is also called Fraunhofer region
• Far-field distance is given by

$$d_f = \frac{2D^2}{\lambda}$$

• Additionally the following must be true

$$d_f >> D \quad \quad d_f >> \lambda$$

• $D$ largest physical linear dimension of the antenna
• $\lambda$ wavelength
Attenuation

• Example: Find the far-field distance for an antenna with max. dimension of 1m and f=900 MHz

• Solution:
  • $D = 1m$
  • $F = 900MHz$ ->
  
  $$\lambda = \frac{c}{f} = \frac{3 \times 10^8 \frac{m}{s}}{900 \times 10^6 Hz} = \frac{1}{3} m$$

  • Far-field distance
  
  $$d_f = \frac{2(1)^2}{\frac{1}{3}} = 6m$$

  -> $d_0$ needs to be in the far-field distance!
Attenuation

What is the path loss (PL)?

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}$$

$$\frac{P_t}{P_r(d)} = \left( \frac{G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \right)^{-1}$$

$$PL[dB] = 10 \log\left( \frac{P_t}{P_r(d)} \right) = -10 \log\left( \frac{G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \right)$$

Path loss at distance $d$ in dB
Attenuation

\[ PL[dB] = 10 \log \left( \frac{P_t}{P_r(d)} \right) = -10 \log \left( \frac{G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \right) \]

Set \( G_t = G_r = L = 1 \)

\[ PL(d)[dB] = -10 \log \left( \frac{\lambda^2}{(4\pi)^2 d^2} \right) \]
Attenuation

• Radio signal propagation
  • Free-Space-Model

• Model: \[ PL_{dB}(d) = -10 \log \left( \frac{\lambda^2}{(4\pi)^2 d^2} \right) \]

• Assumptions:
  • Direct line of sight (LOS) between communication peers
  • No obstacles

• Advantages:
  • Simple asymptotic formulae for open space

• Disadvantages:
  • Not really useful for indoor and city environments

---

Prof. Dr. Mesut Güneş • 3. Physical Layer
Radio propagation

- Received signal strength
- Distance
- Transmission range
- Sensitivity
Non-line-of-sight

- Because of reflection, scattering, ..., radio communication is not limited to direct line of sight communication
- Effects depend strongly on frequency, thus different behavior at higher frequencies
Non-line-of-sight

- Different paths have different lengths = propagation time
- Results in delay spread of the wireless channel

![Signal at receiver](image)
Multi-path

• Brighter color = stronger signal
• Simple (quadratic) free space attenuation formula is not sufficient to capture these effects
World example: Open surface

- 2003 study of 100-200 first generation motes placed in regular grid in open tennis court.
- RFM 916 MHz ASK RF transceivers with simple whip antenna.
- Variation in Packet Receive Rate (PRR) from each transmitter.

[Diagram showing variation in packet reception probability across a grid]

References:
- Woo [Ganesan]
RSSI: Stationary

Signal Strength (dBm) - Top View - Source Node: 1

Prof. Dr. Mesut Güneş • 3. Physical Layer
RSSI: Driving

Signal Strength (dBm) - Top View - Source Node: 1
Generalizing the Attenuation Formula

• To take into account stronger attenuation than only caused by distance (e.g., walls) use a larger exponent $\gamma > 2$

• $\gamma$ is the path-loss exponent

$$\overline{PL}(d) \propto \left( \frac{d}{d_0} \right)^\gamma$$

• Rewrite in logarithmic form (in dB):

$$\overline{PL}(d)[\text{dB}] = \overline{PL}(d_0)[\text{dB}] + 10\gamma \log_{10} \left( \frac{d}{d_0} \right)$$
Generalizing the Attenuation Formula

- Path loss exponents for different environments

<table>
<thead>
<tr>
<th>Environment</th>
<th>Path loss exponent $\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free space</td>
<td>2</td>
</tr>
<tr>
<td>Urban area cellular radio</td>
<td>$2.7 - 3.5$</td>
</tr>
<tr>
<td>Shadowed urban cellular radio</td>
<td>$3 - 5$</td>
</tr>
<tr>
<td>In building line-of-sight</td>
<td>$1.6 - 1.8$</td>
</tr>
<tr>
<td>Obstructed in building</td>
<td>$4 - 6$</td>
</tr>
<tr>
<td>Obstructed in factories</td>
<td>$2 - 3$</td>
</tr>
</tbody>
</table>
Generalizing the Attenuation Formula

Different path loss exponents

Distance $d$ vs. $PL(d)$ in dB for different path loss exponents ($\gamma = 2$, $\gamma = 3$, $\gamma = 4$).

Prof. Dr. Mesut Güneş • 3. Physical Layer
Generalizing the Attenuation Formula

- Obstacles, multi-path, etc.?
- Experiments show that these can be represented by a random variable
  - Equivalent to multiplying with a lognormal distributed random variable in metric units!

\[ \text{PL}(d)[\text{dB}] = \text{PL}(d_0)[\text{dB}] + 10\gamma \log_{10} \left( \frac{d}{d_0} \right) + X_\sigma[\text{dB}] \]
Log-normal Fading Channel model

\[ P_r(d) = P_t - PL(d_0) - 10\gamma \log \left( \frac{d}{d_0} \right) + X_\sigma \]

- \(P_r(d)\): Received Power
- \(P_t\): Transmit Power
- \(PL(d_0)\): Path loss
- \(\gamma\): Path loss exponent
- \(X_\sigma\): Log-normal Shadow fading
Log-normal Fading Channel model

Log-normal fading

Distance $d$

$PL(d)$ [dB]

$\gamma=2$, $\sigma=1.0$

$\gamma=2$, $\sigma=3.0$
Noise and interference

- So far: only a single transmitter assumed
  - Only disturbance: self-interference of a signal with multi-path “copies” of itself

- In reality, two further disturbances
  - **Noise**: due to effects in receiver electronics, depends on temperature
  - **Interference from third parties**
    - **Co-channel interference**: another sender uses the same spectrum
    - **Adjacent-channel interference**: another sender uses some other part of the radio spectrum, but receiver filters are not good enough to fully suppress it
Sources of interference

• **Intra-path**
  • Two links on the same path utilize the same channel

• **Inter-path**
  • Two links of two disjoint flows interfere
  • Spatial proximity

• **External interferences**
  • Co-deployed networks and devices operate on the same channels
Symbols and bit errors

• Extracting symbols out of a distorted/corrupted waveform is fraught with errors
  • Depends essentially on strength of the received signal compared to the corruption
  • Captured by signal-to-noise and interference ratio (SNIR)

\[
\text{SNIR} = 10 \log_{10} \left( \frac{P_r}{N_0 + \sum_{j=1}^{k} I_j} \right)
\]

• \( P_r \)  Receive power (signal strength)
• \( N_0 \)  Noise power
• \( I_j \)  Interferer j
• \( k \)  Number of neighbors that contribute to noise
Symbols and bit errors

• MAC limits the simultaneous communication
  • Interference is low
• Simplified definition of SNIR ~ SNR

\[ \text{SNR} = \Psi(d) = P_t - PL(d) - P_n \]

• \( \Psi(d) \) Simplified SNR
• \( P_t \) Transmit power
• \( PL(d) \) Path loss at distance \( d \)
• \( P_n \) Noise power (noise floor)
Noise Floor

- Changes with time
- Varies according to location (indoor vs. outdoor)
- Even if received power is the same, SNR varies with time!

![Empirical Noise Floor](image_url)

- **Indoor environment**
- **Outdoor environment**

Analytical Noise Floor (-115 dBm)
Bit Error Rate (BER)

- $p_b$ = Probability that a received bit will be in error
  - 1 sent $\rightarrow$ 0 received
- $p_b$ is proportional to SNR (channel quality)
  - Exact relation depends on modulation scheme
- Bit error rate depends on ratio of energy per bit to noise spectral density
  \[
  \frac{E_b}{N_0}
  \]
- can be expressed also as
  \[
  \frac{E_b}{N_0} = \Psi \frac{B_N}{R}
  \]
Bit Error Rate (BER)

• Example for FSK (e.g., Mica2)

\[ P_{b}^{FSK} = \frac{1}{2} \ e^{- \frac{E_b}{2N_0}} \]
Bit Error Rate

- **CC2420 (MicaZ, Tmote, SunSPOT)** use offset quadrature phase shift keying (O-QPSK) with direct sequence spread spectrum (DSSS)

\[
p_b^{OQPSK} = Q\left(\sqrt{\frac{Eb}{No}}\right)_{DS}
\]

\[
\left(\frac{Eb}{No}\right)_{DS} = \frac{2N(Eb/No)}{N + \frac{4}{3} \frac{Eb}{No} (K-1)}
\]

- \# of chips per bit (16)
- \(=2\) for MicaZ
Bit Error Rate

- CC2420 (MicaZ, Tmote, SunSPOT) use offset quadrature phase shift keying (O-QPSK) with direct sequence spread spectrum (DSSS)
Packet Error Rate (PER)

- Packet error rate (PER) can be given based on BER
  - Depends on channel coding scheme
- Assume all errors in a packet can be detected
- PER of a single transmission with a payload of $k$ bits when CRC is used is given by

$$PER^{CRC}(k) = 1 - (1 - p_b)^k$$
Wireless channel models
Channel Models

Unit disc graph model

Statistical channel model
Channel Models

• **Goal:** Capture the behavior of a wireless channel
  - Model the SNR
  - Model directly the bit errors

• **Simplest model**
  - Transmission power and attenuation constant
  - Noise an uncorrelated Gaussian variable
    - Additive White Gaussian Noise model
    - Results in constant SNR
Channel Models: Unit disc graph (UDG)

• Unit disc graph (UDG) model
  • Based on graph theory
  • Very simple
  • Communication range $r_{comm}$

• Pro
  • Useful for simplifying the analysis of protocols

• Contra
  • Unrealistic

$$p_b = \begin{cases} 
0 & \text{if } d \leq r_{comm} \\
1 & \text{if } d > r_{comm}
\end{cases}$$
Channel Models: Statistical channel model

- Non-deterministic characteristics
  - Random multi-path effects
- More accurate than UDG model
- SNR can be modeled as a Gaussian random variable

\[ \Psi(d) = P_t - PL(d_0) - 10\gamma \log \left( \frac{d}{d_0} \right) - P_n + X_\sigma \]
Channel Models: Statistical channel model

\[ \Psi(d) = P_t - PL(d_0) - 10\gamma \log\left(\frac{d}{d_0}\right) - P_n + X_{\sigma} \]

\[ \beta(d, \gamma) \]

\[ \Psi(d) = N(\beta(d, \gamma), \sigma) \]
Channel Models

• Non-line-of-sight path
  • Amplitude of resulting signal has a Rayleigh distribution (Rayleigh fading)

• One dominant line-of-sight plus many indirect paths
  • Signal has a Rice distribution (Rice fading)
Channel Model for WSN

• Typical WSN properties
  • Low power communication
  • Small transmission range
  • Implies small delay spread (nanoseconds, compared to micro/milliseconds for symbol duration)
  • Frequency-non-selective fading, low to negligible inter-symbol interference
    • Coherence bandwidth often > 50 MHz
Channel Model for WSN

• Some example measurements
  • $\gamma$ path loss exponent
  • Shadowing variance $\sigma^2$

<table>
<thead>
<tr>
<th>environment</th>
<th>$\gamma$ (95% conf. bounds)</th>
<th>$\sigma$ (95% conf. bounds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>outdoor</td>
<td>4.7 (4.30 - 5.10)</td>
<td>4.6 (2.80 - 6.40)</td>
</tr>
<tr>
<td>indoor</td>
<td>3.0 (2.67 - 3.23)</td>
<td>3.8 (2.60 - 5.00)</td>
</tr>
</tbody>
</table>
Wireless channel models

An example: the wireless channel of wireless sensor networks
Channel Model for WSN

• Log-normal fading channel best characterizes WSN channels

\[ P_r(d) = P_t - PL(d_0) - 10\gamma \log \left( \frac{d}{d_0} \right) + X_\sigma \]

• Empirical evaluations for Mica2
Channel Model for WSN

- **PRR**: Packet reception rate \((1-p_b)^k\)
- **Transitional region for packet reception**
  - Not too good, not too bad
Channel Model for WSN

• PRR significantly varies in the transitional region
• Example: \(d = 20\text{m}\) \(\rightarrow \) PRR = \([0,1]\)

\[\rightarrow\text{We cannot operate solely in the connected region}\]

• Communication distance too short
Channel Model for WSN

Outdoor, PRR vs. Distance

Outdoor, PRR vs. Distance

$P_{out} = 5\text{dBm}$

$P_{out} = -7\text{dBm}$
Channel Model for WSN

Indoor, PRR vs. Distance, $P_{out} = 5\text{dBm}$

Indoor, PRR vs. Distance, $P_{out} = -7\text{dBm}$

Prof. Dr. Mesut Güneş • 3. Physical Layer
Channel Fading

- **Multipath effects**
  - Varies by position
  - Varies by frequency
  - Varies over time

- **Overcome with diversity**
  - Time diversity
    - Retransmission
  - Spatial diversity
    - Multiple antennas
  - Path diversity
    - Alternative receivers
  - Frequency diversity
    - Spreading, Multiple channels
Channel models

Digital
Channel Models: Digital

• Directly model the resulting bit error behavior ($p_b$)
• Each bit is erroneous with constant probability, independent of the other bits
  • Binary symmetric channel (BSC)

• Capture property of fading models that channel is in different states!

-> Markov models - states with different BERs
Channel Models: Digital

• Markov models -> states with different BERs
• Example: Gilbert-Elliot model with
  • bad state: high bit error rate
  • good state: low bit error rate

![Diagram]

$p_{gb}$
$p_{bg}$
$p_{gg}$
$p_{bb}$
## Popular wireless interfaces

<table>
<thead>
<tr>
<th>Radio</th>
<th>RFM TR1000</th>
<th>Infineon TDA5250</th>
<th>TI CC1000</th>
<th>TI CC2420</th>
<th>Zeevo ZV4002</th>
</tr>
</thead>
<tbody>
<tr>
<td>Platforms</td>
<td>WeC, Rene Dot, Mica</td>
<td>eyesIFX</td>
<td>Mica2Dot, Mica2 BTNode</td>
<td>MicaZ, TelosB SunSPOT, Imote2</td>
<td>Imote BTNode</td>
</tr>
<tr>
<td>Standard</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>IEEE 802.15.4</td>
<td>Bluetooth</td>
</tr>
<tr>
<td>Data Rate (kbps)</td>
<td>2.4-115.2</td>
<td>19.2</td>
<td>38.5</td>
<td>250</td>
<td>723.2</td>
</tr>
<tr>
<td>Modulation</td>
<td>OOK/ASK</td>
<td>ASK/FSK</td>
<td>FSK</td>
<td>OQPSK</td>
<td>FHSS-GFSK</td>
</tr>
<tr>
<td>Radio Frequency (MHz)</td>
<td>916</td>
<td>868</td>
<td>315/433/868/915</td>
<td>2.4GHz</td>
<td>2.4GHz</td>
</tr>
<tr>
<td>Supply Voltage (V)</td>
<td>2.7-3.5</td>
<td>2.1-5.5</td>
<td>2.1-3.6</td>
<td>2.1-3.6</td>
<td>0.85-3.3</td>
</tr>
<tr>
<td>TX Max (mA/dBm)</td>
<td>12 / -1</td>
<td>11.9 / 9</td>
<td>26.7 / 10</td>
<td>17.4 / 0</td>
<td>32 / 4</td>
</tr>
<tr>
<td>TX Min (mA/dBm)</td>
<td>N/A</td>
<td>4.9 / -22</td>
<td>5.3 / -20</td>
<td>8.5 / -25</td>
<td>N/A</td>
</tr>
<tr>
<td>RX (mA)</td>
<td>1.8-4.5</td>
<td>8.6-9.5</td>
<td>7.4-9.6</td>
<td>18.8</td>
<td>32</td>
</tr>
<tr>
<td>Sleep (µA)</td>
<td>5</td>
<td>9</td>
<td>0.2-1</td>
<td>0.02</td>
<td>3.3mA</td>
</tr>
<tr>
<td>Startup Time (ms)</td>
<td>12</td>
<td>0.77-1.43</td>
<td>1.5-5</td>
<td>0.3-0.6</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Summary

• Packet loss will always disturb communication
• Asymmetric links are common
• Link quality varies over time
• What is a good link metric?
Literature


