Wireless Sensor Networks

1. Basics

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Organization

- Web page
  - http://cone.informatik.uni-freiburg.de/lehre/aktuell/wsn-ss16

- Forum
  - for discussions, remarks, critics, funnies, etc.

- Lecture
  - Lecturers:
    - Christian Schindelhauer (mostly)
    - Johannes Wendeberg (localization)
  - Monday, 14:15-16:00, room 101-01-009/013
  - Wednesday, 08:15-09:00, room 101-01-009/013

- Exercises
  - Tutors:
    - Amir Bannoura
    - Joan Bordoy
  - Wednesday, 09:15-20:00, room 101-01-009/013
  - starts 27.04.2016
Networks Types

- **Cellular networks**
  - one or more access stations
  - each access station covers a cell
  - e.g. mobile telephones, WLAN

- **Mobile ad hoc networks**
  - self-configuring network of mobile nodes
  - nodes serve as end-points or routers
  - without any dedicated infrastructure

- **Wireless sensor network**
  - connecting sensors and actuator units wireless communicating with one or more base stations
  - base station is more powerful than other nodes
Some Relevant Wireless Networks

- **GSM (Global System for Mobile Communications)**
  - GPRS (General Packet Radio Service)
  - EDGE (Enhanced Data Rates for GSM Evolution)
  - Smartphones, PDAs, Laptop/netbook, Tablets, Phablets

- **UMTS (Universal Mobile Telecommunications Systems)**
  - HSDPA (High Speed Downlink Packet Access)
  - 3rd generation mobile communication standard

- **LTE (Long Term Evolution)**
  - 4th generation standard

- **IEEE 802.11 a/b/g/n/ac – Wi-Fi (Wireless Fidelity)**
  - Wireless Local Area Network (WLAN)
  - computers, cameras, printers

- **Bluetooth (IEEE 802.15.1)**
  - several version, Bluetooth v4.0, Bluetooth low energy
Some Relevant Wireless Networks

- IEEE 802.15.4 + Zigbee
  - Wireless Personal Area Network (WPAN)
  - Wireless sensor networks
  - Zigbee Alliance
    - defined higher protocol layers
- DECT ULE (Digital Enhanced Cordless Telecommunications Ultra Low Energy)
  - adapted standard for cordless phones
- Low-Power Wide-Area Network (LPWAN)
  - LoRaWAN (Long Range Wide Area Network)
- Narrow-Band Internet of Things (NB-IOT)
  - narrowband radio technology specially designed for the Internet of Things (GSM/LTE)
- …
ISO/OSI Reference model

- **7. Application**
  - Data transmission, e-mail, terminal, remote login
- **6. Presentation**
  - System-dependent presentation of the data
- **5. Session**
  - start, end, restart
- **4. Transport**
  - Segmentation, congestion
- **3. Network**
  - Routing
- **2. Data Link**
  - Checksums, flow control
- **1. Physical**
  - Mechanics, electrics
## TCP/IP-Layer of the Internet

<table>
<thead>
<tr>
<th>Layer</th>
<th>Protocols/Protocols Stack</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application</td>
<td>Telnet, FTP, HTTP, SMTP (E-Mail), ...</td>
</tr>
<tr>
<td>Transport</td>
<td>TCP (Transmission Control Protocol)</td>
</tr>
<tr>
<td></td>
<td>UDP (User Datagram Protocol)</td>
</tr>
<tr>
<td>Network</td>
<td>IP (Internet Protocol)</td>
</tr>
<tr>
<td></td>
<td>+ ICMP (Internet Control Message Protocol)</td>
</tr>
<tr>
<td></td>
<td>+ IGMP (Internet Group Management Protocol)</td>
</tr>
<tr>
<td>Host-to-Network</td>
<td>LAN (e.g. Ethernet, 802.11n etc.)</td>
</tr>
</tbody>
</table>

CoNe Freiburg
Example: Routing between LANs

Stevens, TCP/IP Illustrated
Data/Packet Encapsulation

Stevens, TCP/IP Illustrated
Example Stacks

The Internet of Every Thing - steps toward sustainability CWSN Keynote, Sept. 26, 2011
Example Stacks

CTTC 2015 seminar by Prof. A.A. Economides
Moving particles with electric charge cause electromagnetic waves
- frequency $f$: number of oscillations per second
  - unit: Hertz
- wavelength $\lambda$: distance (in meters) between two wave maxima
- antennas can create and receive electromagnetic waves
- the transmission speed of electromagnetic waves in vacuum is constant
  - speed of light $c \approx 3 \cdot 10^8$ m/s

Relation between wavelength, frequency and speed of light:
\[
\lambda \cdot f = c
\]
Electromagnetic Spectrum

guided media

- twisted pair
- coaxial cable
- waveguide
- optical fibre

unguided media

- low frequency radio
- medium frequency
- high frequency
- micro wave
- infrared
- visible light
Bands

- LF  Low Frequency
- MF  Medium Frequency
- HF  High Frequency
- VHF Very High Frequency
- UHF Ultra High Frequency
- UV  Ultra Violet light
Bands for Wireless Networks

- VHF/UHF for mobile radio
  - antenna length
- SHF for point-to-point radio systems, satellite communication
- Wireless LAN: UHF to SHF
  - planned EHF
- Visible light
  - communication by laser
- Infrared
  - remote controls
  - LAN in closed rooms
Propagation Performance

- Straight-lined propagation in vacuum
- Received power decreases with $1/d^2$
  - in theory
  - in practice higher exponents up to 4 or 5
- Reduction because of
  - attenuation in air (in particular HF, VHF)
  - shadowing and mountain effect
  - reflection
  - diffusion at small obstacles
  - diffraction
Frequency Dependent Behavior

- VLF, LF, MF
  - follow the curvature of the earth (up to 1000 km for VLF)
  - permeate buildings

- HF, VHF
  - absorbed by the ground
  - reflected by the ionosphere 100-500 km height

- Over 100 MHz
  - straight-line propagation
  - marginal penetration of buildings
  - good focus

- Over 8 GHz absorption by rainfall
Problems

- **Multiple Path Fading**
  - Signal arrives at receiver on multiple paths because of reflection, diffusion, and diffraction
  - Signal time variation leads to interferences
    - decoding faults
    - attenuation

- **Mobility problems**
  - Fast fading
    - different transmission paths
    - different phasing
  - Slow fading
    - increase of distance between sender and receiver
Noise and Interference

- **Noise**
  - inaccuracies and heat development in electrical components
  - modeled by normal distribution

- **Interference from other transmitters**
  - in the same spectrum
  - or in neighbored spectrum
    - e.g. because of bad filters

- **Effect**
  - Signal is disrupted
Signal Interference Noise Ratio

- reception energy = transmission energy \cdot \text{path loss}
  - path loss \sim 1/d^\gamma
    - \gamma \in [2,5]
- Signal to Interference and Noise Ratio = \text{SINR}
  - S = (desired) Signal energy
  - I = energy of Interfering signals
  - N = Noise
- Necessary condition for reception
  \[ \text{SINR} = \frac{S}{I + N} \geq \text{Threshold} \]
Path Loss

- **Attenuation**
  - Received signal power depends on the distance $d$ between sender and receiver

- **Friis transmission equation**
  - distance: $R$
  - wavelength: $\lambda$
  - $P_r$: energy at receiver antenna
  - $P_t$: energy at sender antenna
  - $G_t$: sender antenna gain
  - $G_r$: receiver antenna gain

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

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

- **Measurements**
  - $\gamma$ path loss exponent
  - shadowing variance $\sigma^2$
  - reference path loss at 1m distance

<table>
<thead>
<tr>
<th>Location</th>
<th>Average of $\gamma$</th>
<th>Average of $\sigma^2$[dB]</th>
<th>Range of PL(1m)[dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engineering Building</td>
<td>1.9</td>
<td>5.7</td>
<td>[−50.5, −39.0]</td>
</tr>
<tr>
<td>Apartment Hallway</td>
<td>2.0</td>
<td>8.0</td>
<td>[−38.2, −35.0]</td>
</tr>
<tr>
<td>Parking Structure</td>
<td>3.0</td>
<td>7.9</td>
<td>[−36.0, −32.7]</td>
</tr>
<tr>
<td>One-sided Corridor</td>
<td>1.9</td>
<td>8.0</td>
<td>[−44.2, −33.5]</td>
</tr>
<tr>
<td>One-sided patio</td>
<td>3.2</td>
<td>3.7</td>
<td>[−39.0, −34.2]</td>
</tr>
<tr>
<td>Concrete canyon</td>
<td>2.7</td>
<td>10.2</td>
<td>[−48.7, −44.0]</td>
</tr>
<tr>
<td>Plant fence</td>
<td>4.9</td>
<td>9.4</td>
<td>[−38.2, −34.5]</td>
</tr>
<tr>
<td>Small boulders</td>
<td>3.5</td>
<td>12.8</td>
<td>[−41.5, −37.2]</td>
</tr>
<tr>
<td>Sandy flat beach</td>
<td>4.2</td>
<td>4.0</td>
<td>[−40.8, −37.5]</td>
</tr>
<tr>
<td>Dense bamboo</td>
<td>5.0</td>
<td>11.6</td>
<td>[−38.2, −35.2]</td>
</tr>
<tr>
<td>Dry tall underbrush</td>
<td>3.6</td>
<td>8.4</td>
<td>[−36.4, −33.2]</td>
</tr>
</tbody>
</table>

Structure of a *Broadband* Digital transmission

- MOdulation/DEModulation
  - Translation of the channel symbols by
    - amplitude modulation
    - phase modulation
    - frequency modulation
    - or a combination thereof
Computation of Fourier Coefficients

\[ f(x) = x, \text{ für } 0 < x < 2\pi \]

\[ f(x) = \pi - 2 \left( \frac{\sin x}{1} + \frac{\sin 2x}{2} + \frac{\sin 3x}{3} + \ldots \right) \]
Fourier Analysis for General Period

- Theorem of Fourier for period $T=1/f$:

  - The coefficients $c$, $a_n$, $b_n$ are then obtained as follows

    \[ g(t) = \frac{a_0}{2} + \sum_{k=1}^{\infty} a_k \cos(2\pi kft) + b_k \sin(2\pi kft) \]

    \[ a_k = \frac{2}{T} \int_{0}^{T} g(t) \cos(2\pi nft) dt \]

    \[ b_k = \frac{2}{T} \int_{0}^{T} g(t) \sin(2\pi nft) dt \]

- The sum of squares of the $k$-th terms is proportional to the energy consumed in this frequency:

  \[ (a_k)^2 + (b_k)^2 \]
How often do you measure?

- How many measurements are necessary to determine a Fourier transform to the k-th component, exactly?
- Nyquist-Shannon sampling theorem
  - To reconstruct a continuous band-limited signal with a maximum frequency \( f_{\text{max}} \) you need at least a sampling frequency of \( 2 f_{\text{max}} \).
Symbols and Bits

- For data transmission instead of bits can also be used symbols
  - E.g. 4 Symbols: A, B, C, D with
    - A = 00, B = 01, C = 10, D = 11

- Symbols
  - Measured in baud
  - Number of symbols per second

- Data rate
  - Measured in bits per second (bit / s)
  - Number of bits per second

- Example
  - 2400 bit/s modem is 600 baud (uses 16 symbols)
Broadband

- Idea
  - Focusing on the ideal frequency of the medium
  - Using a sine wave as the carrier wave signals

- A sine wave has no information
  - the sine curve continuously (modulated) changes for data transmission,
  - implies spectral widening (more frequencies in the Fourier analysis)

- The following parameters can be changed:
  - Amplitude $A$
  - Frequency $f=1/T$
  - Phase $\phi$

$$s(t) = A \sin(2\pi ft + \phi)$$
Amplitude Modulation

- The time-varying signal \( s(t) \) is encoded as the amplitude of a sine curve:
  \[
  f_A(t) = s(t) \sin(2\pi ft + \phi)
  \]

- Analog Signal
- Digital signal
  - amplitude keying
  - special case: symbols 0 or 1
    - on / off keying
The time-varying signal $s(t)$ is encoded in the frequency of the sine curve:

$$f_F(t) = a \sin(2\pi s(t)t + \phi)$$

- Analog signal
  - Frequency modulation (FM)
  - Continuous function in time

- Digital signal
  - Frequency Shift Keying (FSK)
  - E.g. frequencies as given by symbols
Phase Modulation

- The time-varying signal $s(t)$ is encoded in the phase of the sine curve:

$$f_P(t) = a \sin(2\pi ft + s(t))$$

- Analog signal
  - phase modulation (PM)
  - very unfavorable properties
  - es not used

- Digital signal
  - phase-shift keying (PSK)
  - e.g. given by symbols as phases
Digital and Analog signals in Comparison

For a station there are two options
- digital transmission
  • finite set of discrete signals
  • e.g. finite amount of voltage sizes / voltages
- analog transmission
  • Infinite (continuous) set of signals
  • E.g. Current or voltage signal corresponding to the wire

Advantage of digital signals:
- There is the possibility of receiving inaccuracies to repair and reconstruct the original signal
- Any errors that occur in the analog transmission may increase further
Phase Shift Keying (PSK)

- For phase signals $\phi_i(t)$

$$s_i(t) = \sqrt{\frac{2E}{T}} \cdot \sin(\omega_0 t + \phi_i(t))$$

- Example:
- Phase shifts can be detected by the receiver very well
- Encoding various symbols very simple
  - Using phase shift e.g. $\pi / 4$, $3/4\pi$, $5/4\pi$, $7/4\pi$
    - rarely: phase shift 0 (because of synchronization)
  - For four symbols, the data rate is twice as large as the symbol rate
- This method is called Quadrature Phase Shift Keying (QPSK)
Amplitude and Phase Modulation

- Amplitude and phase modulation can be successfully combined
  - Example: 16-QAM (Quadrature Amplitude Modulation)
    - uses 16 different combinations of phases and amplitudes for each symbol
    - Each symbol encodes four bits ($2^4 = 16$)
  - The data rate is four times as large as the symbol rate
Nyquist’s Theorem

Definition
- The band width $H$ is the maximum frequency in the Fourier decomposition

Assume
- The maximum frequency of the received signal is $f = H$ in the Fourier transform
  - (Complete absorption [infinite attenuation] all higher frequencies)
- The number of different symbols used is $V$
- No other interference, distortion or attenuation of

Nyquist theorem
- The maximum symbol rate is at most $2H$ baud.
- The maximum possible data rate is a bit more than $2 \log_2 H V / s.$
Do more symbols help?

- Nyquist's theorem states that could theoretically be increased data rate with the number of symbols used

Discussion:
- Nyquist's theorem provides a theoretical upper bound and no method of transmission
- In practice there are limitations in the accuracy
- Nyquist's theorem does not consider the problem of noise
The Theorem of Shannon

- Indeed, the influence of the noise is fundamental
  - Consider the relationship between transmission intensity $S$ to the strength of the noise $N$
  - The less noise the more signals can be better recognized

- Theorem of Shannon
  - The maximum possible data rate is $H \log_2(1 + S / N)$ bits/s
    - with bandwidth $H$
    - Signal strength $S$

- Attention
  - This is a theoretical upper bound
  - Existing codes do not reach this value
Bit Error Rate and SINR

- Higher SIR decreases Bit Error Rate (BER)
  - BER is the rate of faulty received bits
- Depends from the
  - signal strength
  - noise
  - bandwidth
  - encoding
- Relationship of BER and SINR
  - Example: 4 QAM, 16 QAM, 64 QAM, 256 QAM...