TIWSNE – Wireless Sensor Networks and Electronics – (Q4)

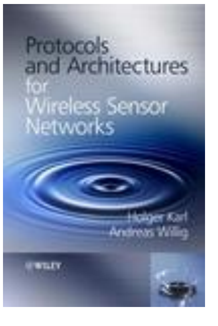
Physical Layer - WSN

John Rohde

(Email: jr@ase.au.dk)

Lecture plan of Today

Karl et al., Chapter 4 (85-109):

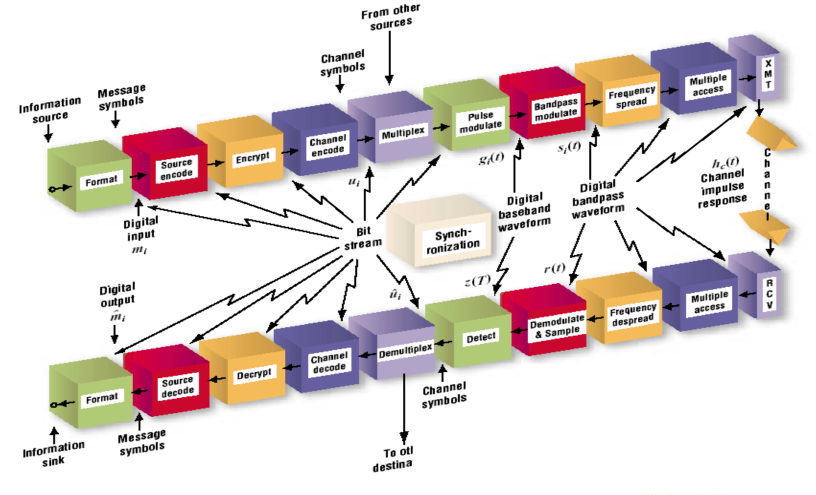


- Topics:
  - *Frequency bands*
  - Modulation
  - Signal distortion – wireless channels
  - From waves to bits
  - Channel models
  - Transceiver design

Goals of this Lecture

- Understand peculiarities of wireless communication
  - "Wireless channel" as an abstraction of these properties – e.g., bit error patterns
  - Focus is on radio communication
- Impact of different factors on communication performance
  - Frequency band, transmission power, modulation scheme, etc.
  - Some brief remarks on transceiver design
- Understanding of energy consumption in radio communication
- Difference between WSNs and other high-end wireless systems

Transceiver Block Structure



OSI Reference Model

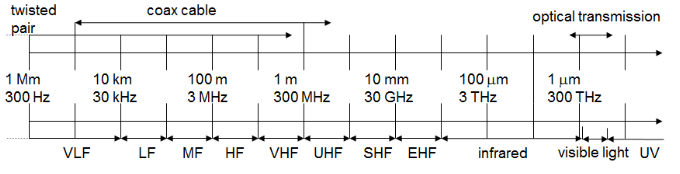
7	Application	Network Processes to Applications
6	Presentation	Data Representation
5	Session	Interhost Communication
4	Transport	End-to-end Connections
3	Network	Address and Best Path
2	Data Link	Access to Media
1	Physical	Binary Transmission
	Medium	Transfer of Signals

Overview

- ***Frequency bands***
- Modulation
- Signal distortion – wireless channels
- From waves to bits
- Channel models
- Transceiver design

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, …)



- VLF = Very Low Frequency
- LF = Low Frequency
- MF = Medium Frequency
- HF = High Frequency
- VHF = Very High Frequency

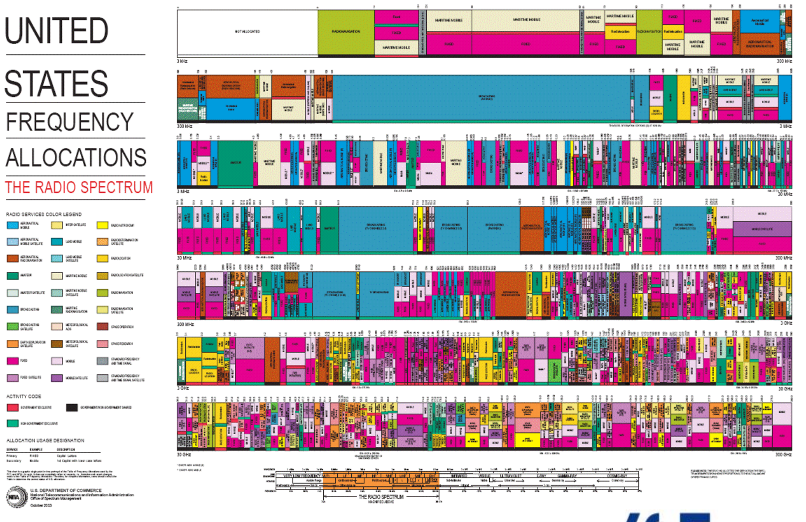
UHF = Ultra High Frequency
SHF = Super High Frequency
EHF = Extra High Frequency
UV = Ultraviolet Light

Frequency Allocation

- Some frequencies are allocated to specific uses:
  - Cellular phones, analog television/radio broadcasting, DVB-T, radar, emergency services, radio astronomy…
- Particularly interesting: License-free ISM/SRD bands ("Industrial, Scientific, Medical / Short Range Device")

Some typical ISM bands	
Frequency	Comment
13,553-13,567 MHz	
26,957 – 27,283 MHz	
40,66 – 40,70 MHz	
433 – 464 MHz	Europe
863,000-868,600 MHz 868,700-869,200 MHz 869,400-869,650 MHz 869,700-870,000 MHz	Europe
900 – 928 MHz	America
2,4 – 2,5 GHz	WLAN/WPAN
5,725 – 5,875 GHz	SRD
24 – 24,25 GHz	

Example: US frequency allocation



Example: 2.4 GHz world-wide regulations

2.4 GHz operating frequency range and operating channels

Lower Limit	Upper limit	Regulatory range	Geography
2.402 GHz	2.480 GHz	2.400–2.4835 GHz	China
2.402 GHz	2.480 GHz	2.400–2.4835 GHz	North America
2.402 GHz	2.480 GHz	2.400–2.4835 GHz	Europe[a]
2.473 GHz	2.495 GHz	2.471–2.497 GHz	Japan
2.447 GHz	2.473 GHz	2.445–2.475 GHz	Spain
2.448 GHz	2.482 GHz	2.4465–2.4835 GHz	France
NOTE—The frequency ranges in this table are subject to the geographic-specific regulatory authorities.			

[a]Excluding Spain and France.

Minimum	Hopping set	Geography
75	79	China
75	79	North America
20	79	Europe[a]
N/A	23	Japan
20	27	Spain
20	35	France
NOTE—The number of required hopping channels is subject to the geographic-specific regulatory authorities.		

[a]Excluding Spain and France.

Example: Rules & Regulations - 5,725 – 5,875 GHz

DK - Radiogrænseflade 00 032

Lovtidende A

2010 **Udgivet den 16. oktober 2010**

12. oktober 2010. Nr. 1176.

Bekendtgørelse om Dansk radiogrænseflade nr. 00 032 for laveffekts radioanlæg med integreret eller dedikeret antenne beregnet til telemetri, fjernstyringsformål, alarmering, tale og dataoverførsel i visse frekvensbånd mellem 6 MHz og 246 GHz[1)]

I medfør af § 9 i lov om radio- og teleterminaludstyr og elektromagnetiske forhold, jf. lovbekendtgørelse nr. 823 af 3. juli 2007, fastsættes:

§ 1. For laveffekts radioanlæg med integreret eller dedikeret antenne beregnet til telemetri, fjernstyringsformål, alarmering, tale og dataoverførsel i visse frekvensbånd mellem 6 MHz og 246 GHz gælder følgende danske radiogrænseflade, jf. bilag 1: Dansk radiogrænseflade nr. 00 032 for laveffekts radioanlæg med integreret eller dedikeret antenne beregnet til telemetri, fjernstyringsformål, alarmering, tale og dataoverførsel i visse frekvensbånd mellem 6 MHz og 246 GHz.

§ 2. Bekendtgørelsen træder i kraft den 1. november 2010.

IT- og Telestyrelsen, den 12. oktober 2010

JØRGEN ABILD ANDERSEN

/ Per V. Christensen

Example: Rules & Regulations - 5,725 – 5,875 GHz

Frekvenstildelinger, sendeeffekter, tilladelsesforhold m.v.

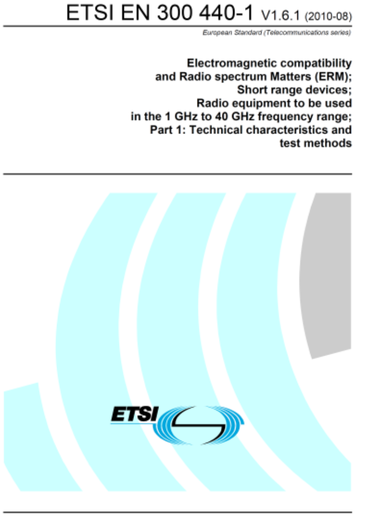
Nr.	Parameter	Beskrivelse			Status
1	Tjeneste ifølge ITU's Radioreglement	Mobil tjeneste.			N
2	Anvendelse	Telemetri, fjernstyringsformål, alarmering, tale og dataoverførsel.			N
3	Tilladte frekvensbånd	Bånd a	6,765-6,795 MHz		N
		Bånd b	13,553-13,567 MHz		
		Bånd c	26,957-27,283 MHz		
		Bånd d	40,660-40,700 MHz		
		Bånd e	49,500-50,000 MHz		
		Bånd f	138,200-138,450 MHz		
		Bånd g	138,650 MHz		
		Bånd h1/h2	433,050-434,040 MHz		
		Bånd i1/i2/i3	434,040-434,790 MHz		
		Bånd j	863,000-865,000 MHz		
		Bånd k	865,000-868,000 MHz		
		Bånd l	868,000-868,600 MHz		
		Bånd m	868,700-869,200 MHz		
		Bånd n1/n2	869,400-869,650 MHz		
		Bånd o1/o2	869,700-870,000 MHz		
		Bånd p	2400,0 MHz-2483,5 MHz		
		Bånd q	5725 MHz-5875 MHz		
		Bånd r	24,00-24,25 GHz		
		Bånd s	61,0-61,5 GHz		
		Bånd t	122-123 GHz		
		Bånd u	244-246 GHz		
4	Maksimalt tilladte sendeeffekter	Bånd a	42 dBμA/m		N
		Bånd b	42 dBμA/m		
		Bånd c	42 dBμA/m svarende til 10 mW e.r.p.		
		Bånd d	10 mW e.r.p.		
		Bånd e	1 mW e.r.p.		
		Bånd f	10 mW e.r.p.		
		Bånd g	500 mW e.r.p.		
		Bånd h1	1 mW e.r.p. og -13 dBm/10 kHz effekttæthed for modulationsbåndbredder større end 250 kHz		
		Bånd h2	10 mW e.r.p.		
		Bånd i1	1 mW e.r.p. og -13 dBm/10 kHz effekttæthed for modulationsbåndbredder større end 250 kHz		
		Bånd i2	10 mW e.r.p.		
		Bånd i3	10 mW e.r.p.		
		Bånd j	25 mW e.r.p.		
		Bånd k	25 mW e.r.p.		
		Bånd l	25 mW e.r.p.		
		Bånd m	25 mW e.r.p.		
		Bånd n1	500 mW e.r.p.		
		Bånd n2	25 mW e.r.p.		
		Bånd o1	5 mW e.r.p.		
		Bånd o2	25 mW e.r.p.		
		Bånd p	10 mW e.i.r.p.		
		Bånd q	25 mW e.i.r.p.		
		Bånd r	100 mW e.i.r.p.		
		Bånd s	100 mW e.i.r.p.		
		Bånd t	100 mW e.i.r.p.		
		Bånd u	100 mW e.i.r.p.		
5	Duty cycle og brugsrestriktioner		**Duty cycle**	**Brugsrestriktioner**	
		Bånd a	Ingen krav		
		Bånd b	Ingen krav		
		Bånd c	Ingen krav	Note 1)	
		Bånd d	Ingen krav	Note 1)	
		Bånd e	Ingen krav		
		Bånd f	≤ 1 %		
		Bånd g	Ingen krav, max. båndbredde på 25 kHz	Må alene anvendes til sporing af stjålne genstande.	
		Bånd h1	Note 2)	Note 3)	
		Bånd h2	≤ 10 %	Note 4)	
		Bånd i1	Note 2)	Note 3)	
		Bånd i2	≤ 10 %	Note 4)	
		Bånd i3	≤ 100 % ved kanalafstand op til 25 kHz. Note 2)	Note 3)	
		Bånd j	Note 5) eller ≤ 0,1 %	Note 4)	
		Bånd k	Note 5) eller ≤ 1 %	Note 4)	
		Bånd l	Note 5) eller ≤ 1 %	Note 6)	
		Bånd m	Note 5) eller ≤ 0,1 %	Note 6)	
		Bånd n1	Note 5) eller ≤ 10 % Der skal være en kanalafstand på 25 kHz, medmindre hele båndet anvendes som en samlet kanal til højhastighedstransmission af data	Note 6)	
		Bånd n2	Note 5) eller ≤ 0,1 %	Note 4)	
		Bånd o1	Note 2)	Note 3)	
		Bånd o2	Note 5) eller ≤ 1 %	Note 4)	
		Bånd p	Ingen krav	Ingen	

Example: Rules & Regulations - 5,725 – 5,875 GHz

		Bånd q — Ingen krav — Ingen Bånd r — Ingen krav — Ingen Bånd s — Ingen krav — Ingen Bånd t — Ingen krav — Ingen Bånd u — Ingen krav — Ingen Note 1) Ingen videoapplikationer Note 2) Taleapplikationer tilladt med avancerede afhjælpningsteknikker Note 3) Ingen audio- og videoapplikationer Note 4) Ingen andre analoge audioapplikationer end tale. Ingen analoge videoapplikationer Note 5) Der skal benyttes teknikker for tilgang til radiofrekvenser og afhjælpning over for interferens, der giver mindst samme ydelse som de teknikker, der er beskrevet i harmoniserede standarder, som er vedtaget i henhold til direktiv 1999/5/EF Note 6) Ingen analoge videoapplikationer	
6	Tilladelsesforhold	Kan anvendes uden individuel tilladelse til frekvensanvendelse.	N
7	Harmoniseret standard	EN 300 220. EN 300 330. EN 300 440.	I
8	Internationale forpligtelser	ERC/REC 70-03. Kommissionens beslutning 2006/771/EF, senest ændret ved afgørelse 2010/368/EU.	I
9	Notifikations nr.	2010/390/DK.	I

N = Normativ
I = Informativ

ETS EN 300 440 applies !!



Example: Rules & Regulations - 5,725 – 5,875 GHz

Table 1: Short Range Devices within the 1 GHz to 40 GHz frequency band

	Frequency Bands	Applications	Notes
Transmit and Receive	2 400 MHz to 2 483,5 MHz	Generic use	
Transmit and Receive	2 400 MHz to 2 483,5 MHz	Detection, movement and alert applications	
Transmit and Receive	(a) 2 446 MHz to 2 454 MHz	RFID	See annex C of EN 300 440-1 [1]
Transmit and Receive	(b) 2 446 MHz to 2 454 MHz	RFID	See annex C of EN 300 440-1 [1]
Transmit and Receive	5 725 MHz to 5 875 MHz	Generic use	
Transmit and Receive	9 200 MHz to 9 500 MHz	Radiodetermination: radar, detection, movement and alert applications	
Transmit and Receive	9 500 MHz to 9 975 MHz	Radiodetermination: radar, detection, movement and alert applications	
Transmit and Receive	10,5 GHz to 10,6 GHz	Radiodetermination: radar, detection, movement and alert applications	
Transmit and Receive	13,4 GHz to 14,0 GHz	Radiodetermination: radar, detection, movement and alert applications	
Transmit and Receive	17,1 GHz to 17,3 GHz	Radiodetermination: GBSAR detection, movement and alert applications	See annex E of EN 300 440-1 [1]
Transmit and Receive	24,00 GHz to 24,25 GHz	Generic use and for Radiodetermination: radar, detection, movement and alert applications	
NOTE: (a) and (b) refer to two different operational restrictions for different power levels in the same frequency band.			

Table 4: Maximum radiated peak power (e.i.r.p.)

Frequency Bands	Power	Application	Notes
2 400 MHz to 2 483,5 MHz	10 mW e.i.r.p.	Generic use	
2 400 MHz to 2 483,5 MHz	25 mW e.i.r.p.	Detection, movement and alert applications	
(a) 2 446 MHz to 2 454 MHz	500 mW e.i.r.p.	RFID	See also table 6 and annex C
(b) 2 446 MHz to 2 454 MHz	4 W e.i.r.p.	RFID	See also table 6 and annex C
5 725 MHz to 5 875 MHz	25 mW e.i.r.p.	Generic use	
9 200 MHz to 9 500 MHz	25 mW e.i.r.p.	Radiodetermination: radar, detection, movement and alert applications	
9 500 MHz to 9 975 MHz	25 mW e.i.r.p.	Radiodetermination: Radar, detection, movement and alert applications	
10,5 GHz to 10,6 GHz	500 mW e.i.r.p.	Radiodetermination: Radar, detection, movement and alert applications	
13,4 GHz to 14,0 GHz	25 mW e.i.r.p.	Radiodetermination: Radar, detection, movement and alert applications	
17,1 GHz to 17,3 GHz	400 mW e.i.r.p.	Radiodetermination: GBSAR detection, movement and alert applications	See annex E
24,00 GHz to 24,25 GHz	100 mW e.i.r.p.	Generic use and Radiodetermination: radar, detection, movement and alert applications	

5.4.1.2 Extreme temperature ranges

For tests at extreme temperatures, measurements shall be made in accordance with the procedures specified in clause 5.4.1.1, at the upper and lower temperatures of one of the following ranges, either:

a) the temperature range as declared by the provider; or

b) one of the following specified temperature ranges:

- Temperature category I (General): -20 °C to +55 °C;
- Temperature category II (Portable): -10 °C to +55 °C;
- Temperature category III (Equipment for normal indoor use): 5 °C to +35 °C.

5.4.2 Extreme test source voltages

5.4.2.1 Mains voltage

The extreme test voltages for equipment to be connected to an ac mains source shall be the nominal mains voltage ±10 %. For equipment that operates over a range of mains voltages clause 5.4.2.4 applies.

6.1.1 Normal test signals for data

Where the equipment has an external connection for general data modulation, the normal test signals are specified as follows:

D-M2: a test signal representing a pseudo-random bit sequence of at least 511 bits in accordance with ITU-T Recommendation O.153 [3]. This sequence shall be continuously repeated. If the sequence cannot be continuously repeated, the actual method used shall be stated in the test report.

D-M3: a test signal shall be agreed between the test laboratory and the provider in case selective messages are used and are generated or decoded within the equipment.
The agreed test signal may be formatted and may contain error detection and correction.

Table 5: Spurious emissions

Frequency ranges / State	47 MHz to 74 MHz 87,5 MHz to 108 MHz 174 MHz to 230 MHz 470 MHz to 862 MHz	Other frequencies ≤ 1 000 MHz	Frequencies > 1 000 MHz
Operating	4 nW	250 nW	1 µW
Standby	2 nW	2 nW	20 nW

Overview

- Frequency bands
- ***Modulation***
- Signal distortion – wireless channels
- From waves to bits
- Channel models
- Transceiver design

Goals of Modulation – Engineering a Comm. System

We would like to:

- increase the bit rate as much as possible
- increase the spectral efficiency as much as possible
- increase the power efficiency as much as possible
- minimize the cost/power implementation

Transmitting Data Using Radio Waves

- Basic task : Transmit can send a radio wave, receive can detect whether such a wave is present and also its parameters
- Parameters of a wave = cosine function:

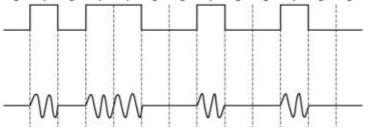
$$\boxed{s(t) = A(t)\cos\left(2\pi f(t) + \theta(t) + \phi\right)}$$

Parameters: amplitude A(t), frequency f(t), phase ϕ(t)

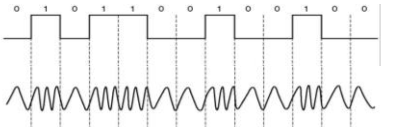
- Manipulating these three parameters allows the sender to express data; receiver reconstructs data from signal
- Simplification: Receiver “sees” the same signal that the sender generated – not true, see later!

Modulation (keying!)

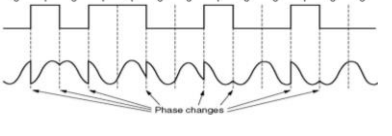
- Use data to modify the amplitude of a carrier frequency !
  Amplitude Shift Keying



- Use data to modify the ***frequency*** of a carrier frequency !
  Frequency Shift Keying



- Use data to modify the ***phase*** of a carrier frequency !
  Phase Shift Keying



Receiver: Demodulation

- The receiver looks at the received wave form and matches it with the data bit that caused the transmitter to generate this wave form
  - Necessary: one-to-one mapping between data and wave form
  - Because of channel imperfections, this is the optimum strategy for digital signals, but does not apply to analog signals
- List of challenges:
  - Carrier synchronization: frequency can vary between sender and receiver (accuracy/stability - ppm, temp. drift, aging, …)
  - Bit synchronization (actually: symbol 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!

Overview

- Frequency bands
- Modulation
- ***Signal distortion – wireless channels***
- From waves to bits
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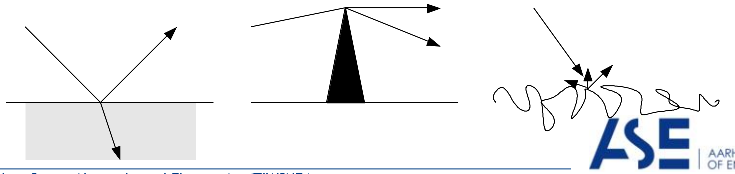
Transmitted Signal <> Received Signal !

- Wireless transmission ***distorts*** any transmitted signal
  - Received <> transmitted signal; results in ***uncertainty at receiver*** about which bit sequence originally caused the transmitted signal
  - Abstraction: ***Wireless channel*** describes these distortion effects
- Sources of distortion
  - Attenuation – energy is distributed to larger areas with increasing distance
  - Reflection/refraction – bounce of a surface; enter material
  - Diffraction – start “new wave” from a sharp edge
  - Scattering – multiple reflections at rough/"bend" surfaces
  - Doppler fading – shift in frequencies (loss of center)



Attenuation Results in <u>Path Loss</u>

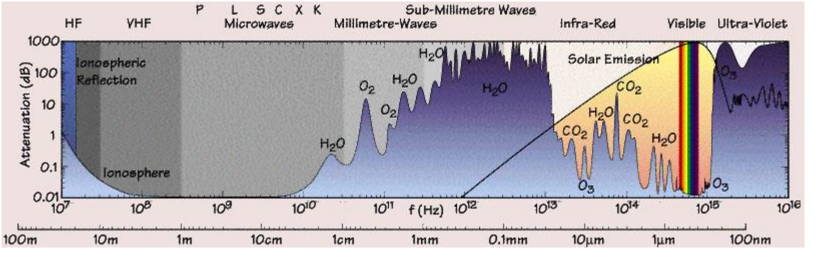
- Effect of attenuation: received signal strength is a function of the distance *d* between sender and transmitter
- Captured by ***Friis free-space equation***
  - Describes signal strength at distance d relative to some reference distance $d_0 < d$ for which strength is known

$$
\begin{aligned}
P_{\text{recv}}(d) &= \frac{P_{\text{tx}} \cdot G_t \cdot G_r \cdot \lambda^2}{(4\pi)^2 \cdot d^2 \cdot L} \\
&= \frac{P_{\text{tx}} \cdot G_t \cdot G_r \cdot \lambda^2}{(4\pi)^2 \cdot d_0^2 \cdot L} \cdot \left(\frac{d_0}{d}\right)^2 = P_{\text{recv}}(d_0) \cdot \left(\frac{d_0}{d}\right)^2
\end{aligned}
$$

  - d_0 is ***far-field distance***, depends on antenna technology

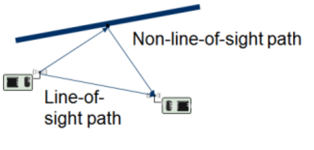
Atmospheric attenuation vs frequency

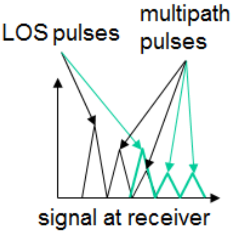
- Attenuation depends on the used frequency
- Can result in a ***frequency-selective channel***
  - If bandwidth spans frequency ranges with different attenuation properties



Distortion Effects: Non-line-of-sight paths

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



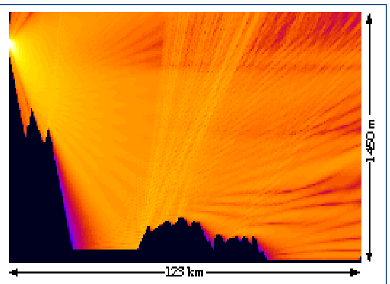


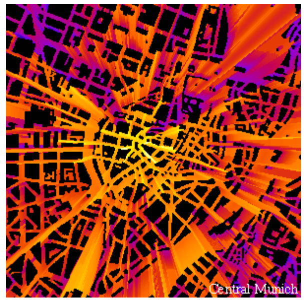
- Different paths have different lengths = propagation time
  - Results in ***delay spread*** of the wireless channel
  - Closely related to frequency-selective fading properties of the channel
  - With movement: ***slow/fast fading***

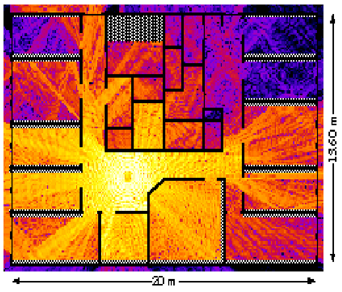
Wireless Signal Strengths in a Multi-path Environment

Simulation Models:

- Brighter color = stronger signal
- Obviously, simple (quadratic) free space attenuation formula is not sufficient to capture these effects







Generalizing the Attenuation Formula

- To take into account stronger attenuation than only caused by distance (e.g., walls, …), use a larger exponent $\gamma > 2$
  - γ is the ***path-loss exponent***

$$P_{\mathrm{recv}}(d) = P_{\mathrm{recv}}(d_0) \cdot \left(\frac{d_0}{d}\right)^{\gamma}$$

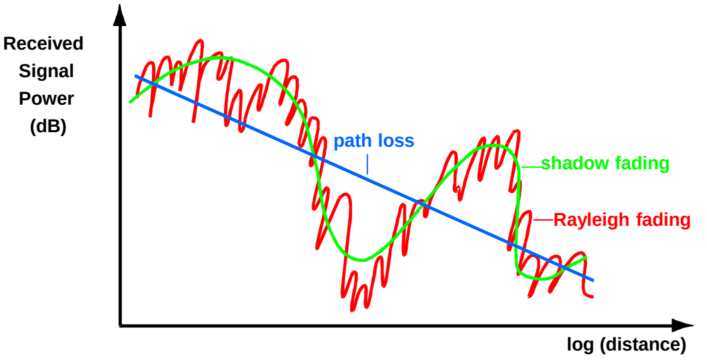
  - Rewrite in logarithmic form (in dB):

$$\mathrm{PL}(d)[\mathrm{dB}] = \mathrm{PL}(d_0)[\mathrm{dB}] + 10\gamma \log_{10}\left(\frac{d}{d_0}\right)$$

- Take obstacles into account by a random variation
  - Add a Gaussian random variable with 0 mean, variance σ^2 to dB representation
  - Equivalent to multiplying with a lognormal distributed r.v. in metric units ! ***lognormal fading***

$$\mathrm{PL}(d)[\mathrm{dB}] = \mathrm{PL}(d_0)[\mathrm{dB}] + 10\gamma \log_{10}\left(\frac{d}{d_0}\right) + X_{\sigma}[\mathrm{dB}]$$

Real Life RSSI - Path Loss and fading



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Received Signal Strength Indicator (RSSI) in TELOSB Sensor Nodes !

- RF chip:
  - CC2420 is a true single-chip 2.4 GHz IEEE 802.15.4 compliant RF transceiver, designed for low power and low voltage wireless applications

From DATASHEET:

- CC2420 has a built-in RSSI providing a digital value that can be read from the 8 bit RSSI.RSSI_VAL register.
- The RSSI value is always averaged over 8 symbol periods (128 µs).
- QUALITY control: The RSSI_VALID status bit indicates when the RSSI value is valid, meaning that the receiver has been enabled for at least 8 symbol periods.

TEXAS INSTRUMENTS

Accuracy?

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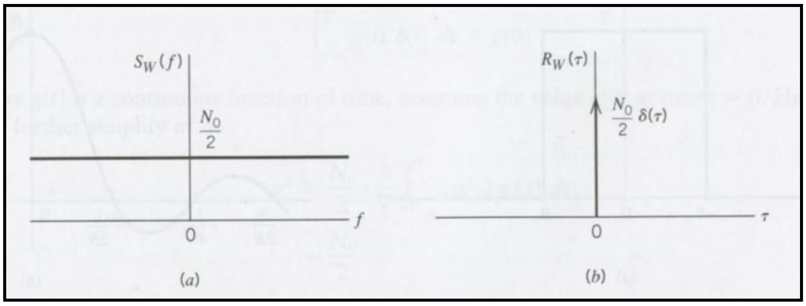
Overview

- Frequency bands
- Modulation
- Signal distortion – wireless channels
- ***From waves to bits***
- Channel models
- Transceiver design

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
    - Typical model: an additive Gaussian variable, mean 0, no correlation in time (see next slide)
  - ***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
- Effect: Received signal is distorted by channel, corrupted by noise and interference
  - What is the result on the received bits?

Additive White Gaussian Noise (AWGN)



Symbols and Bit Errors

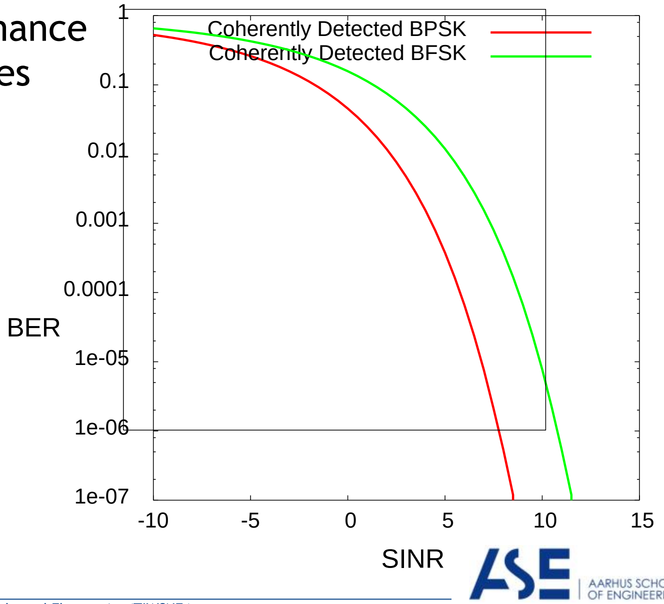
- Extracting symbols out of a distorted/corrupted wave form is fraught with errors
  - Depends essentially on strength of the received signal compared to the corruption
  - Captured by ***signal to noise and interference ratio (SINR)***

$$\boxed{\text{SINR} = 10\log_{10}\left(\frac{P_{\text{recv}}}{N_0 + \sum_{i=1}^{k} I_i}\right)}$$

- SINR allows to compute ***bit error rate*** (***BER***) for a given modulation
  - Also depends on data rate (# bits/symbol) of modulation
  - E.g., for simple DPSK, data rate corresponding to bandwidth:

$$\text{BER}(\text{SINR}) = 0.5e^{-\frac{E_b}{N_0}}$$
$$E_b/N_0 = \text{SINR}\cdot\frac{1}{R}$$

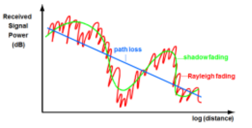
Performance Examples



Overview

- Frequency bands
- Modulation
- Signal distortion – wireless channels
- From waves to bits
- ***Channel models***
- Transceiver design

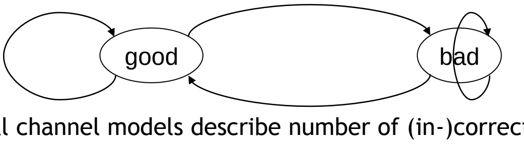
Channel Models – Analog



- How to stochastically capture the behavior of a wireless channel
  - Main options: model the SNR or directly the bit errors
- Signal models
  - Simplest model: assume transmission power and attenuation are constant, noise an uncorrelated Gaussian variable
    - ***Additive White Gaussian Noise*** model, results in constant SNR
  - Situation with no line-of-sight path, but many indirect paths: 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 Models – Digital

- Directly model the resulting bit error behavior
  - Each bit is erroneous with constant probability, independent of the other bits !
    binary symmetric channel (BSC)
  - Capture fading models' property that channel be in different states ! Markov models – states with different BERs
    - Example: Gilbert-Elliot model with “bad” and “good” channel states and high/low bit error rates



  - Fractal channel models describe number of (in-)correct bits in a row by a heavy-tailed distribution

WSN-specific Channel Models

- Typical WSN properties
  - Small transmission range
  - Implies small delay spread (nanoseconds, compared to micro/milliseconds for symbol duration)

    Frequency-non-selective fading, low to negligible ISI
- Some example measurements
  - γ path loss exponent
  - Shadowing variance σ^2
  - Reference path loss at 1 m

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

Wireless Channel Quality – Summary

- Wireless channels are substantially worse than wired channels
  - In throughput, bit error characteristics, energy consumption, …
  - Security?
- Wireless channels are extremely diverse
  - There is no such thing as THE typical wireless channel
- Various schemes for quality improvement exist
  - Some of them geared towards high-performance wireless communication – not necessarily suitable for WSN, ok for MANET, cellular etc.
    - Diversity, equalization, MIMO…
  - Some of them general-purpose (ARQ, FEC)
  - Energy issues need to be taken into account!

Overview

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Some transceiver front-end design considerations

- Strive for good power efficiency at low transmission power
  - Some amplifiers are optimized for efficiency at high output power
  - To radiate 1 mW, typical designs need 30-100 mW to operate the transmitter
    - WSN nodes: 20 mW (mica motes)
  - Receiver can use as much or more power as transmitter at these power levels

    ! Sleep state is important
- Startup energy/time penalty can be high
  - Examples take 0.5 ms and ¼ 60 mW to wake up
- Exploit communication/computation tradeoffs
  - Might payoff to invest in rather complicated coding/compression schemes

Choice of Modulation

- One exemplary design point: which modulation to use?
  - Consider: required data rate, available symbol rate, implementation complexity, required BER, channel characteristics, …
  - Tradeoffs: the faster one sends, the longer one can sleep
    - Power consumption can depend on modulation scheme
  - Tradeoffs: symbol rate (high?) versus data rate (low)
    - Use m-ary transmission to get a transmission over with ASAP
    - But: startup costs can easily void any time saving effects
- Adapt modulation choice to operation conditions
  - E.g. introduce dynamic voltage scaling - ***Dynamic Modulation Scaling***

Summary

- Wireless radio communication introduces many uncertainties into a communication system
- Handling the unavoidable errors will be a major challenge for the communication protocols
- Dealing with limited bandwidth in an energy-efficient manner is the main challenge !
- MANET/Cellular and WSN are pretty similar here
  - Main differences are in required data rates and resulting transceiver complexities (higher bandwidth, spread spectrum techniques)