Wireless Communication 101 using LoRa

CCC u23 Long Range Wireless Networks

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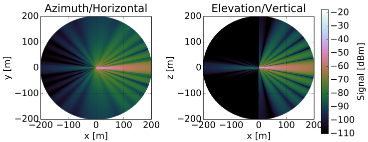
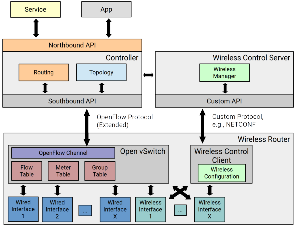
Whoami

- Researcher and PhD-Student at Hochschule Bonn-Rhein-Sieg, Sankt Augustin
- Research Topics:
  - Broadband internet connectivity for rural areas[1]
  - Long-Distance Wireless Networks and Directional Antennas
  - Propagation modeling
  - Software-Defined (Wireless) Networking
  - Low-Power Wide-Area Network (LPWAN)
  - Building automation
  - Crypto currency and Block chain





[1] Mainly Africa but Schwarzwald/Eifel/Sauerland is also ok.

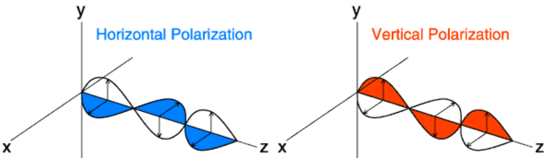
Will my Sensor work at a certain distance?!

Wireless communication.

Wireless communication

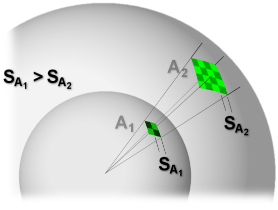
Wireless communication is the **transfer of information between two or more points**, that are not connected by an electrical conductor, using **modulated electromagnetic waves**.

- Important effects:
  - Free-Space Path Loss
  - Reflection
  - Diffraction
  - Earth curvature
  - Weather conditions



- Vertical: Electric field is $\perp$ to earth's surface.
- Horizontal: Electric field is $\parallel$ to earth's surface.

The FSPL equation

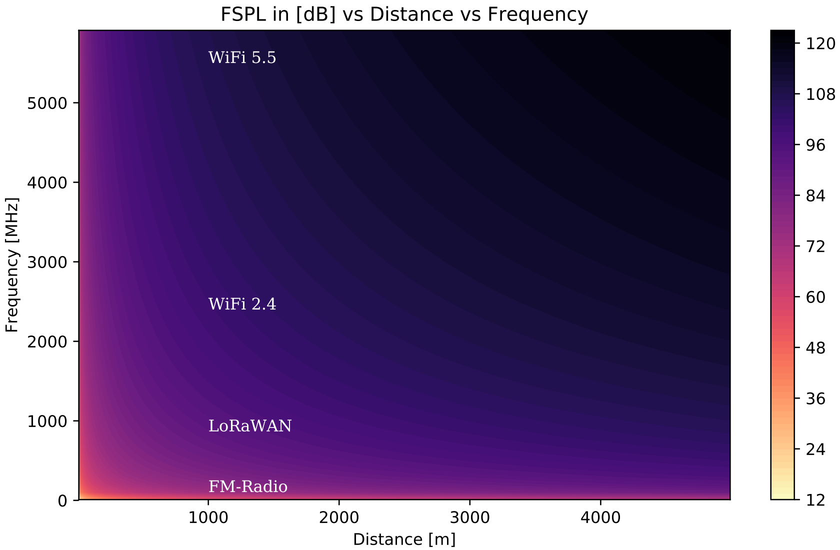


Free-Space Path Loss (FSPL)

The loss in signal strength of an electromagnetic wave that would result from a Line of Sight (LoS) path through free space (usually air), with **no** obstacles nearby to cause **reflection** or **diffraction**.

$$L_f[dB] = 20 * log_{10}(f_{MHz}) + 20 * log_{10}(d_{km}) + 32.4dB$$

Comparison of FSPL for different frequencies



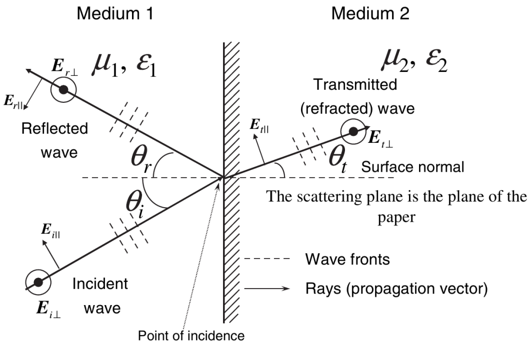
Ever wondered why lower frequencies are so expensive?

Reflection

Reflection

Reflection occurs when propagating electromagnet waves impinges upon an object which has very large dimensions when compared to the wavelength of the propagation wave [1].

- Two different things occur (depending on the reflection coefficient):
  - A certain amount of power is reflected. The phase sometimes changes.
  - A certain amount of power is refracted into the medium.



$$\theta_i = \theta_r$$

Snell's law of refraction:

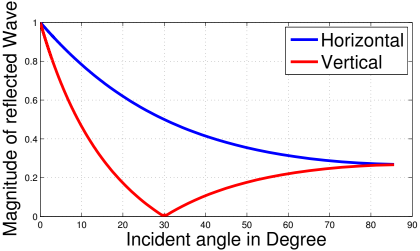
$$\frac{sin(\theta_i)}{sin(\theta_t)} = \frac{n_2}{n_1}$$

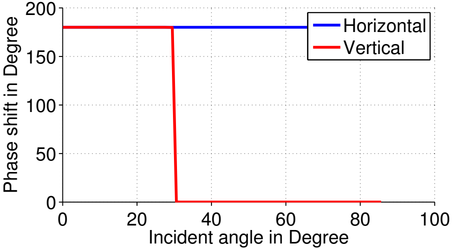
n: Refractive index

Reflection coefficent r

- The reflection coefficient is a complex number depended on [2]:
  - The polarization
  - The angle of incidents
  - Some medium characteristics (conductivity, ...)
  - The frequency

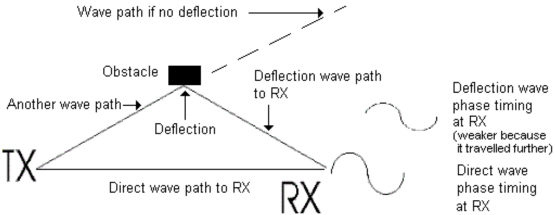
- The ITU-R [3] provides medium factors for different types of ground





Reflection with different incident angles at 5.5 GHz, dry ground

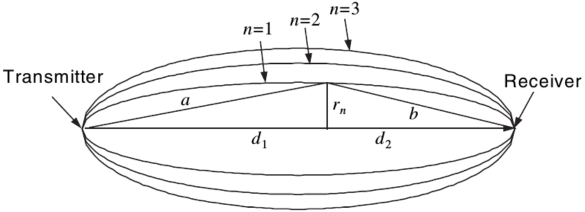
Fresnel-Zones: A simplification for reflection.



Secondary waves reflect on obstacles. Fresnel-Zones make it easy to calculate if they are in phase or out of phase at the receiver.

Fresnel-Zones

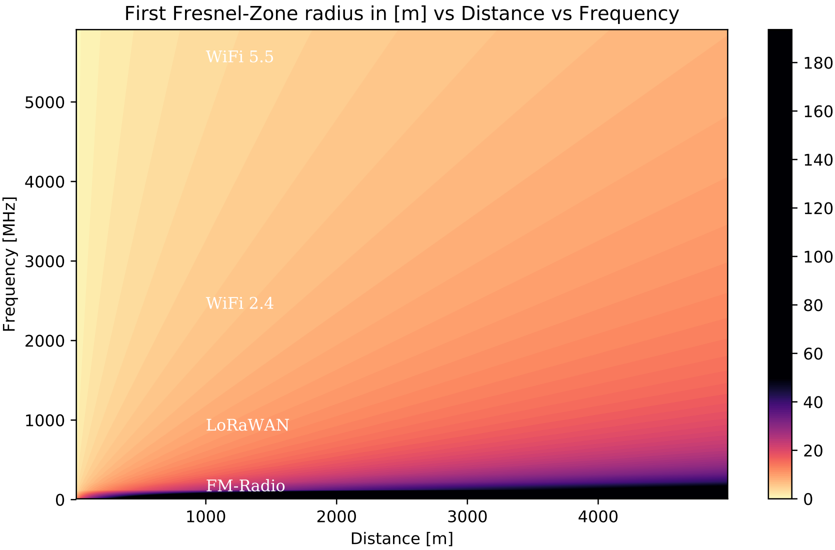
Fresnel-Zones are described as successive regions where secondary waves have a path length from the transmitter to receiver which are $n\lambda/2$ greater than the total path length of a LOS path [4].



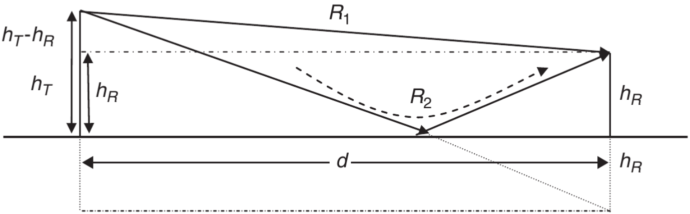
$$r_n = \sqrt{\frac{n \cdot \lambda \cdot d_1 \cdot d_2}{d_1 + d_2}}$$

! **Negative correlation** for frequency and diameter

Comparison of Fresnel zone radius



Two-Ray-Model: Assuming significant ground reflections



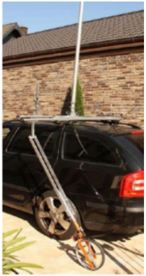
$$(R_2 - R_1) = \sqrt{(h_T + h_R)^2 + d^2} - \sqrt{(h_T - h_R)^2 + d^2} \approx \frac{2h_T h_R}{d}$$

$$A_{total} = A_{direct} + A_{reflected}$$

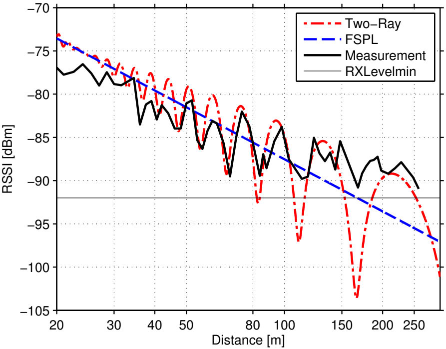
- under the assumption of small angles $r \approx -1$ (proof in the appendix)

$$\frac{P_R}{P_T} = 2 * (\frac{\lambda}{4\pi d})^2[1 - cos(\frac{2\pi f}{c}\frac{2h_T h_R}{d})]$$

Some Research: Verification of the Two-Ray-Model [5]



Omni-directional antennas mounted on the bottom of the outdoor-enclosures



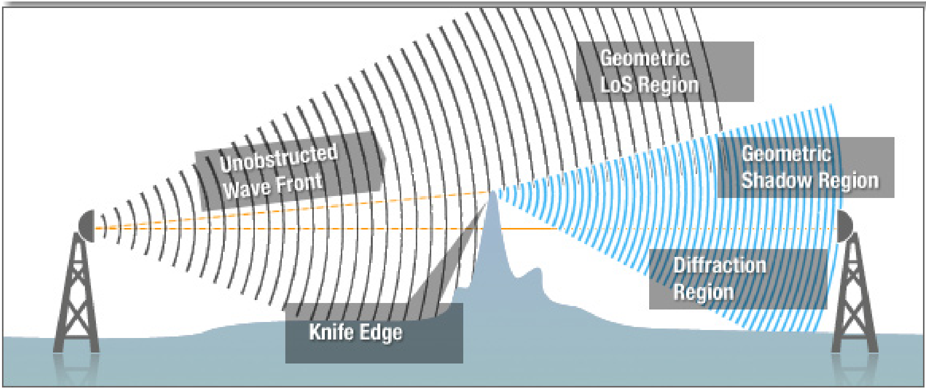
Results; Frequency: 5180. Polarization: Horizontal. Conductivity (δ): 0.125 S/m. Relative permittivity (ϵ_r): 5

- Omni: The Two-Ray-Model fits better than FSPL
- Directional: More complex due to antenna diagram

Diffraction: Shadowing by an object

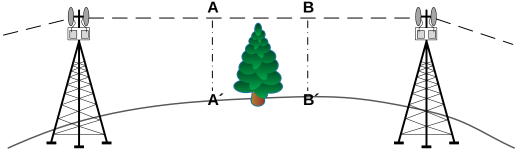
Diffraction

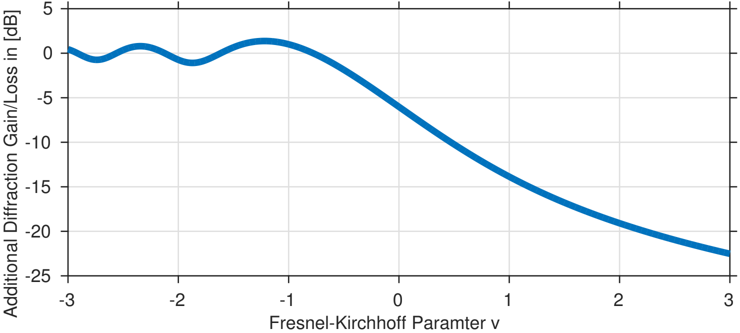
A radio wave that meets an obstacle has a natural tendency **to bend around the obstacle** (The Huygens - Fresnel-Principle). The bending, called diffraction, results in a change of direction of part of the wave energy from the normal line-of-sight path.



Diffraction: A simple example

$$v = h\sqrt{\frac{2 * (d_1 + d_2)}{\lambda * d_1 * d_2}}$$





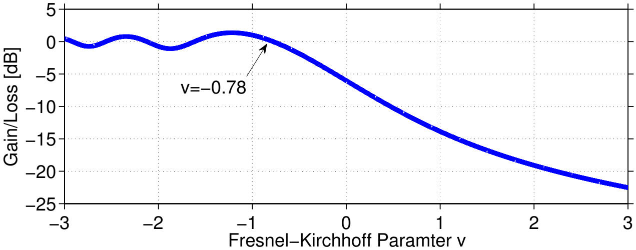
Fresnel-Zones: A simplification for diffraction

- **Rule of thumb: A link is free of diffraction if 55% of the first Fresnel-Zone are free of obstacles**
- Fresnel-Kirchoff Parameter different Fresnel-Zones:

$$v = h\sqrt{\frac{2*(d_1+d_2)}{\lambda*d_1*d_2}} = -\sqrt{\frac{n*\lambda*d_1*d_2}{d_1+d_2}} * \sqrt{\frac{2*(d_1+d_2)}{\lambda*d_1*d_2}} = -\sqrt{2n}$$

- Determine v for 55 % of the 1st Fresnel-Zone.

$$v = 0.55 * -\sqrt{(2*1)} = -0.78$$

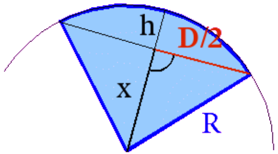


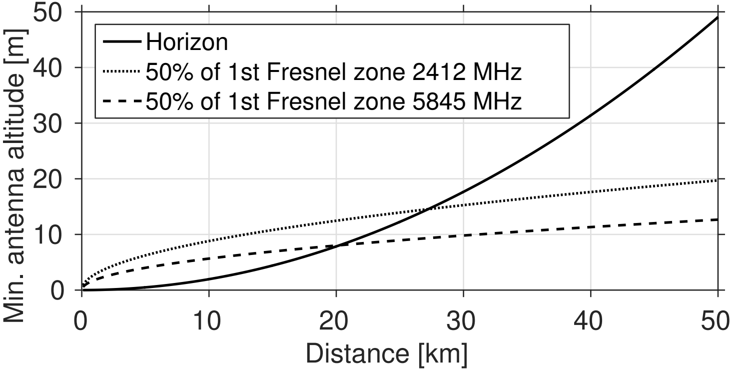
Additional influences: Earth Curvature

- The earth is not a flat surface but rather a sphere (surprise)
- The horizon influences the minimum antenna altitude

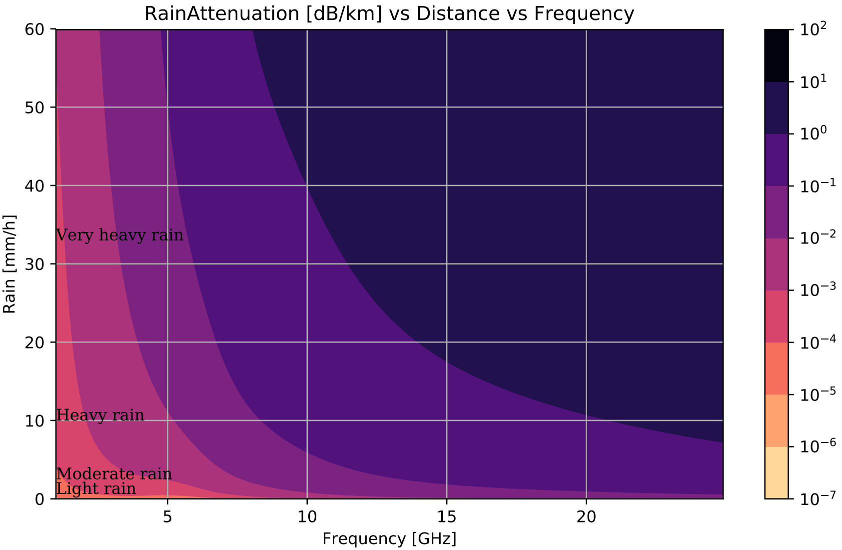
$$x = \sqrt{R_{Earth}^2 - (\frac{d}{2})^2}$$

$$h = R_{earth} - x$$





Additional influences: Weather conditions



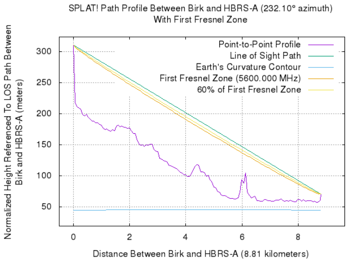
Building Attenuation - IMHO nearly unpredictable

	Main construction material	Isolation material	Windows	900 MHz			2100 MHz		
				5%	Average	95%	5%	Average	95%
House 1	Wood	Polyurethane (aluminum)	3-layered	12.0	13.3	18.8	22.0	24.0	28.0
House 2	Wood	Mineral wool	3-layered	4.7	5.2	6.8	7.0	8.9	9.5
House 3	Rock	Styrofoam	3-layered	14.0	14.3	15.8	16.8	20.5	21.4
House 4	Wood	Polyurethane (aluminum) (x2)	4-layered	16.3	17.6	18.0	22.3	23.8	26.6
House 5	Wood	Polyurethane (aluminum)	Wood panel	7.0	7.8	11.0	4.9	9.9	15.0
House 6	Wood	Mineral wool	3-layered	0.0	1.3	4.4	12.0	11.4	10.2
House 7	Wood	Glass wool	4-layered	1.0	3.2	5.5	4.7	9.1	8.3
House 8	Wood	Glass wool	3-layered	2.5	2.7	6.0	8.0	10.2	11.4
House 9	Masonry block	-	3-layered	15.2	15.5	15.0	18.7	19.5	21.2
House 10	Brick	Polyurethane (aluminum)	3-layered	19.2	21.4	23.0	25.3	24.9	26.1
House 11	Brick	Styrofoam	3-layered	18.8	17.9	16.8	22.9	19.0	16.7
House 12	Wood	Polyurethane (aluminum)	3-layered	11.0	12.9	16.0	18.9	20.9	21.1
House 13	Wood	Polyurethane (aluminum)	3-layered	8.5	9.2	11.0	16.6	12.5	9.3
House 14	Rock	-	3-layered	16.0	15.9	16.2	24.8	23.5	21.4
House 15	Wood	Mineral wool	3-layered	5.7	6.6	7.5	5.4	8.6	11.0

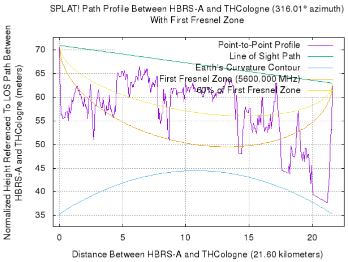
Source: [6]

- SPLAT (`http://www.qsl.net/kd2bd/splat.html`)
- Free Data from the Shuttle Radar Topography Mission (SRTM)

Point-To-Point Link examples

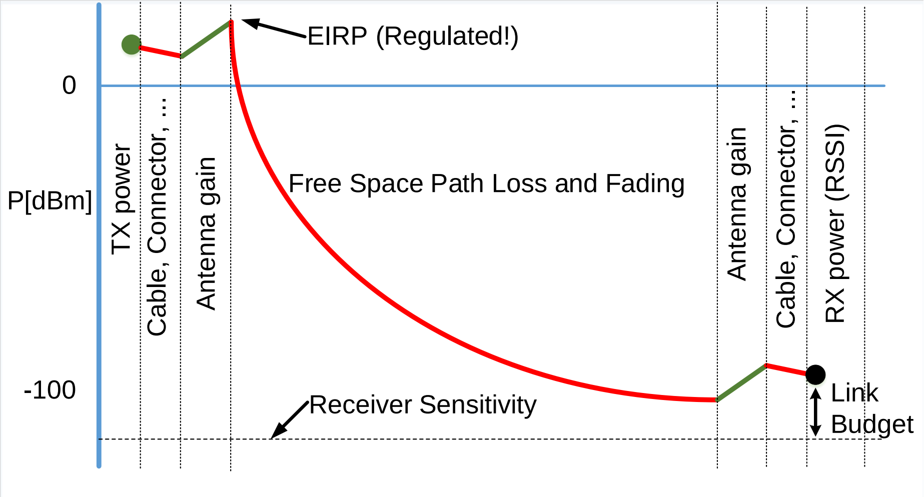


University of Applied sciences Bonn-Rhein-Sieg to Lohmar Birk 5 GHz



University of applied sciences Bonn-Rhein-Sieg to Technische Hochschule Cologne 5 GHz

Link Budget - Will I be able to receive something?



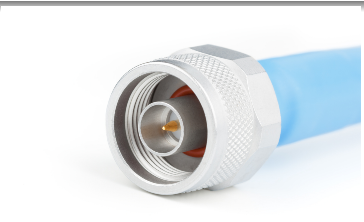
$$P_{RX} = P_{TX} - L_{C,TX} + G_{TX} - L_P(f,d) + G_{RX} - L_{C,RX} >> RXLevel_{min}$$

Cables and connectors

Cables = Attenuation

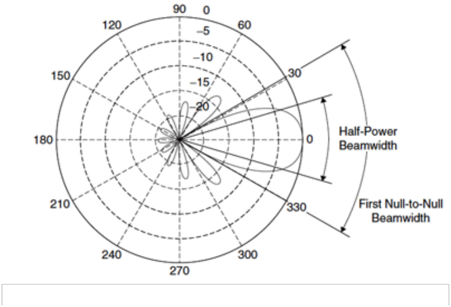
Cables and **connectors** operating at high frequencies lead to non-negligible attenuation.

- Important factors:
  - Price
  - Frequency: The higher the frequency the higher the attenuation
  - Length (keep as short as possible)



Frequency [GHz]	**1**	**1.5**	**2**	**2.5**	**3**	**4**	**5**	**6**
Aircell 7 [dB\100 m]	21,5	27,1	31,9	35,6	40,1	49,1	57	65
Satec RF-10 [dB\100 m]	12,3	15,3	18,0	20,6	/	27,3	/	/

Antennas



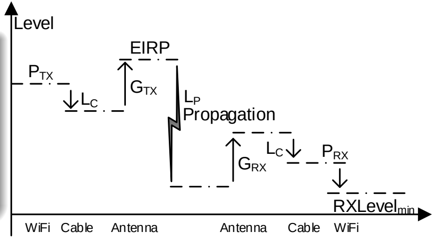
Important: Impedance, Polarization, Antenna Gain,3 dB Beamwidth

Example Antenna	Frequency [GHz]	Gain	beamwidth
0,868 GHz: WiMo	0,860-0.867	5 dBi	38°v;360°h
5 GHz: Grid	4,9 -6,0	30 dBi	5°v;6°h (3 dB)

Equivalent Isotropic Radiated Power

EIRP

Is the amount of power that a **theoretical isotropic antenna** (which evenly distributes power in all directions) would emit to produce the peak power density observed **in the direction of maximum antenna gain**.



Vfg 30/2014, geändert mit Vfg 36/2014, geändert mit Vfg 69/2014

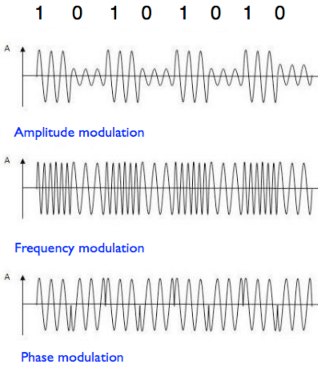
Allgemeinzuteilung von Frequenzen zur Nutzung durch Funkanwendungen mit geringer Reichweite für nicht näher spezifizierte Anwendungen; Non-specific Short Range Devices (SRD)

...

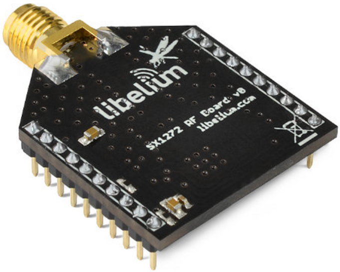
868,0 - 868,6	25 mW	Es sind Frequenzzugangs- und Störungsminderungstechniken einzusetzen, deren Leistung mindestens den Techniken entspricht, die in den gemäß Richtlinie 1999/5/EG bzw. des FTEG verabschiedeten harmonisierten Normen vorgesehen sind. Alternativ kann ein maximaler Arbeitszyklus[2)] von 1% verwendet werden.	Keine analogen Videoanwendungen

Transceiver and Modulation - General

- **Modulation**
  - Mapping of a digital signal (data) to an RF signal [7]
  - FM, AM, PM, and a combination of all.
- **Transceiver**
  - TXpower
  - $RXLevel_{min}$ = Sensitivity

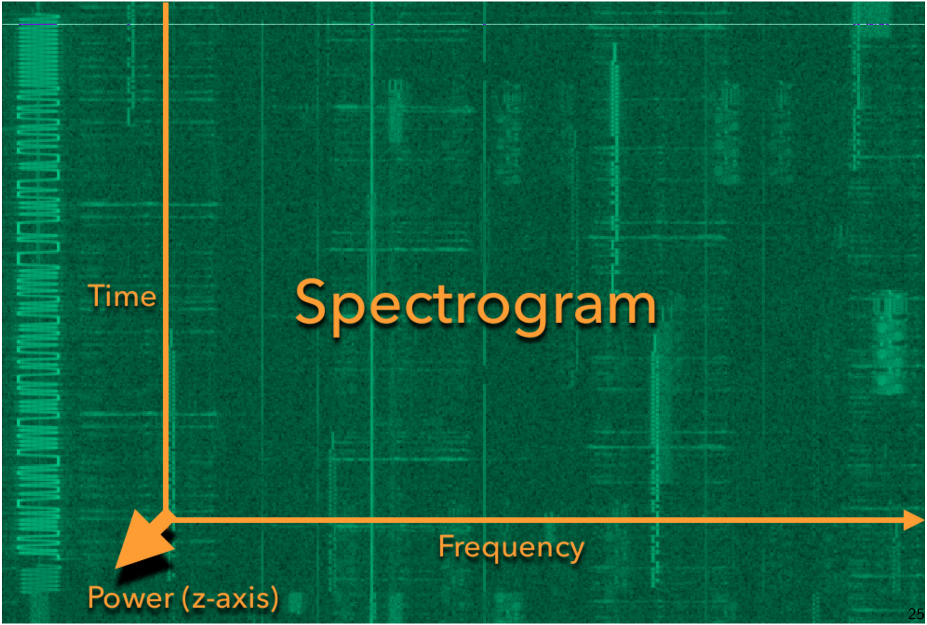


Modulations time domain [7]

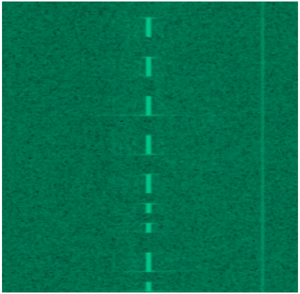


Semtech LoRa SX1272

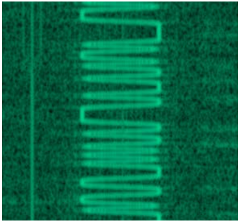
Spectrogram



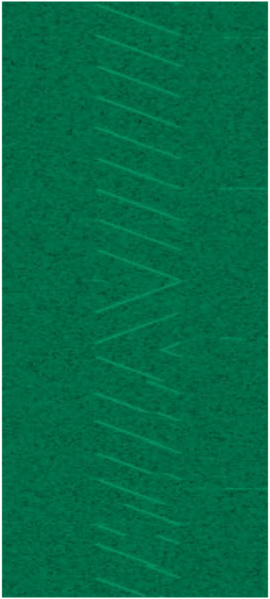
Different modulations examples



On-Off-Keying [7]



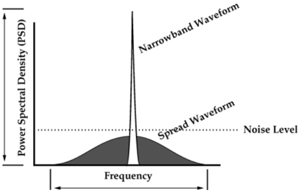
Frequency-Shift Keying [7]

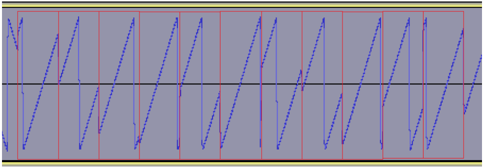


LoRa [7]

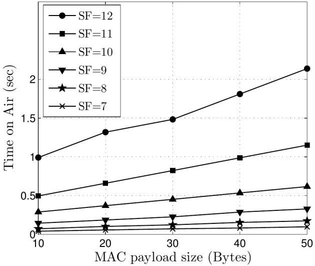
LoRa - **Chirp Spread Spectrum**

- Spread Spectrum is great for low SNR's $(\frac{S}{N})$
  - $C = B * log_2(1 + \frac{S}{N})$
- A chirp is a signal whose frequency increases or decreases over time
- Data is modulated on these chirps!
  - Bandwith: 125 kHz, 250 kHz, 500 kHz
  - Spreading Factor (SF): 7... 12 bits per symbol (symbol=chirp)
  - Duration of a symbol: $T_S = \frac{2^{SF}}{BW}$ [8]
  - Useful bit rate: $R_b = SF * \frac{BW}{2^{SF}} * CR$ [8]
  - Receiver sensitivity: $RXLevel_{min} = -174 + 10 * log_{10}(BW) + NF + SNR$





LoRa - Limitations



[9]

- Airtime in magnitude of SECONDS
- Duty cycle

#	Spreading factor	Channel width, kHz	Code rate	PHY bit rate, bps	RF sensitivity, dBm
0	12	125	4/6	250	-137
1	11	125	4/6	440	-136
2	10	125	4/5	980	-134
3	9	125	4/5	1760	-131
4	8	125	4/5	3125	-128
5	7	125	4/5	5470	-125
6	7	250	4/5	11000	-122

[10]

- SF: Trade throughput vs. range
- SF's are orthogonal
- BW: Trade throughput vs. range

LoRa link budget example

Spreading Factor	**12**	**9**	**7**
Transmitter:			
P_{TX} **[dBm]**	12	12	12
$L_{C,TX}$ **[dB]**	1	1	1
G_{TX} **[dBi]**	2	2	2
EIRP [dBm]	*14*	*14*	*14*
Receiver:			
G_{RX} **[dBi]**	1	1	1
$L_{C.RX}$ **[dB]**	1	1	1
$RXLevel_{min}$**[dBm] (125 kHz)**	-137	-131	-122
Path 15 km:			
FSPL [dB]	115	115	115
Link Budget:			
$RXLevel_{pred}$**[dBm]**	*-101*	*-101*	*-101*
Link Budget	***36***	***30***	***21***

Caution: Outdoor Free-Space $\neq$ Reality

Q&A

Thank your for your attention.
Are there any questions left?

- Feel free to drop me a mail or visit me at H-BRS (C162):
- michael.rademacher@h-brs.de
- More about our work:
- https://www.researchgate.net/profile/Michael_Rademacher
- Links:
- SPLAT: http://www.qsl.net/kd2bd/splat.html
- NASA-Data: https://e4ftl01.cr.usgs.gov/SRTM/SRTMGL1.003/2000.02.11/
- Lora-Talk: https://media.ccc.de/v/33c3-7945-decoding_the_lora_phy

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[3] ITU-R, “ELECTRICAL CHARACTERISTICS OF THE SURFACE OF THE EARTH,” *Recomm. ITU-R P.527-3*, vol. 1, pp. 1–5, 1992.

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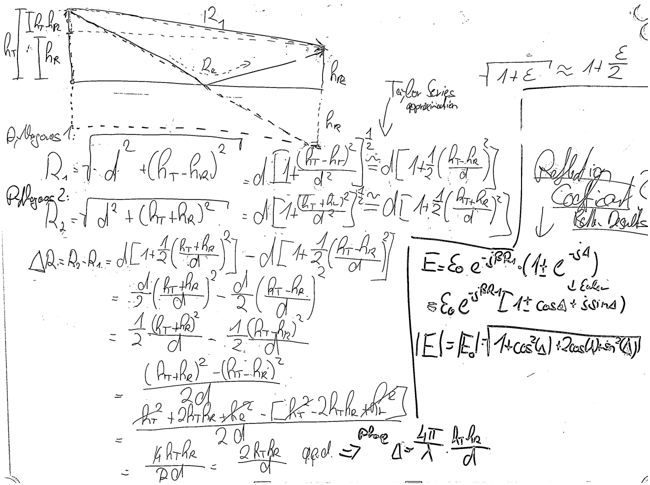
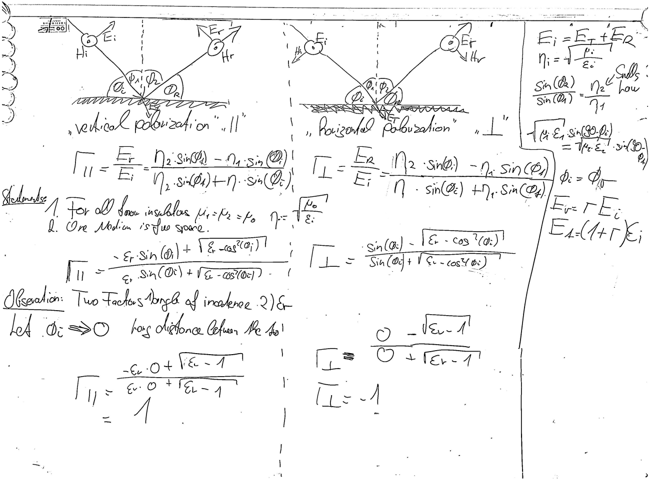
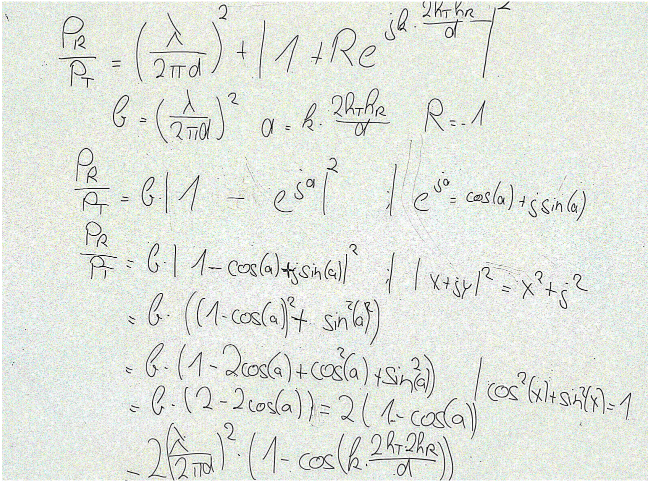


Path difference



„vertical polarization" „∥"
„horizontal polarization" „⊥"
$E_i = E_T + E_R$
$\eta_i = \sqrt{\frac{\mu_i}{\varepsilon_i}}$
Snells Law
$\frac{\sin(\phi_2)}{\sin(\phi_1)} = \frac{\eta_2}{\eta_1}$
$\phi_i = \phi_R$
$E_r = \Gamma E_i$
$E_t = (1+\Gamma) E_i$
$\Gamma_{\parallel} = \frac{E_r}{E_i} = \frac{\eta_2 \cdot \sin(\phi_t) - \eta_1 \cdot \sin(\phi_i)}{\eta_2 \cdot \sin(\phi_t) + \eta_1 \cdot \sin(\phi_i)}$
$\Gamma_{\perp} = \frac{E_R}{E_i} = \frac{\eta_2 \cdot \sin(\phi_i) - \eta_1 \cdot \sin(\phi_t)}{\eta_2 \cdot \sin(\phi_i) + \eta_1 \cdot \sin(\phi_t)}$
1. For all low insulators $\mu_1 = \mu_2 = \mu_0$ $\eta_i = \sqrt{\frac{\mu_0}{\varepsilon_i}}$
2. One Medium is free space.
$\Gamma_{\parallel} = \frac{-\varepsilon_r \sin(\phi_i) + \sqrt{\varepsilon_r - \cos^2(\phi_i)}}{\varepsilon_r \sin(\phi_i) + \sqrt{\varepsilon_r - \cos^2(\phi_i)}}$
$\Gamma_{\perp} = \frac{\sin(\phi_i) - \sqrt{\varepsilon_r - \cos^2(\phi_i)}}{\sin(\phi_i) + \sqrt{\varepsilon_r - \cos^2(\phi_i)}}$
Observation: Two Factors 1) angle of incidence 2) ε_r
Let $\phi_i \Rightarrow 0$
$\Gamma_{\parallel} = \frac{-\varepsilon_r \cdot 0 + \sqrt{\varepsilon_r - 1}}{\varepsilon_r \cdot 0 + \sqrt{\varepsilon_r - 1}} = 1$
$\Gamma_{\perp} = \frac{0 - \sqrt{\varepsilon_r - 1}}{0 + \sqrt{\varepsilon_r - 1}}$
$\Gamma_{\perp} = -1$

Constant R



$$\frac{P_R}{P_T} = \left(\frac{\lambda}{2\pi d}\right)^2 + \left|1 + Re^{jk\cdot\frac{2h_T h_R}{d}}\right|^2$$

$$G = \left(\frac{\lambda}{2\pi d}\right)^2 \quad a = k\cdot\frac{2h_T h_R}{d} \quad R = -1$$

$$\frac{P_R}{P_T} = G\cdot\left|1 - e^{ja}\right|^2 \quad \Big| \quad e^{ja} = \cos(a) + j\sin(a)$$

$$\frac{P_R}{P_T} = G\cdot\left|1 - \cos(a) + j\sin(a)\right|^2 \quad \Big| \quad |x + jy|^2 = x^2 + y^2$$

$$= G\cdot\left((1 - \cos(a))^2 + \sin^2(a)\right)$$

$$= G\cdot\left(1 - 2\cos(a) + \cos^2(a) + \sin^2(a)\right) \quad \Big| \quad \cos^2(x) + \sin^2(x) = 1$$

$$= G\cdot\left(2 - 2\cos(a)\right) = 2\left(1 - \cos(a)\right)$$

$$= 2\left(\frac{\lambda}{2\pi d}\right)^2\cdot\left(1 - \cos\left(k\cdot\frac{2h_T\cdot 2h_R}{d}\right)\right)$$

Two Ray Proof