Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: Interference between THz Communications and Spaceborne Earth Exploration Services

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Abstract: Defined by the ITU radio regulations, spaceborne Earth exploration services operated in the THz frequency band must be precluded from any interference by active applications. THz communication systems operated outdoors may accidentally radiate in direction of the Earth exploration satellites. Critical scenarios have already been identified in doc. 15-12-0101-00-0thz. Now, the interference powers are modeled for the scenarios and transmit power constraints are derived under worst-case assumptions. Maximum distances achievable with these powers are estimated for several THz communication use cases.

Re: 15-12-0101-00-0thz-will-thz-communication-interfere-with-passive-remote-sensing.pdf

Purpose: Input for THz spectrum allocations and system design

Interference between THz Communications and Spaceborne Earth Exploration Services

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Outline

1. **Introduction**
2. Path Loss Measurements and Modeling
3. Interference Scenarios
4. Transmit Power Constraints
5. Interference Avoidance Concepts
6. Summary/Outlook

Introduction (1)

ITU Radio Regulations Footnote 5.565:

The frequency band 275-1000 GHz may be used by administrations for experimentation with, and development of, various active and passive services.

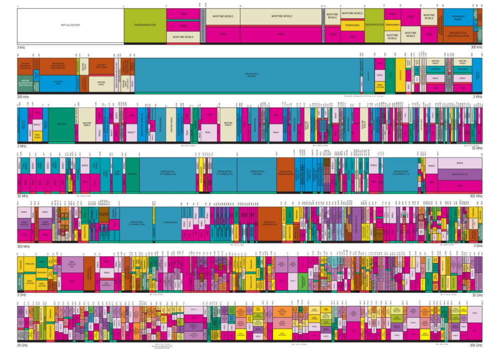
- Radio astronomy service: 275-323 GHz, 327-371 GHz, 388-424 GHz, [...]
- Earth exploration-satellite service and space research service 275-277 GHz, 294-306 GHz, 316-334 GHz, [...]

Administrations are urged to take all practicable steps to protect these passive services from harmful interference.

→ Two options for THz communications:

1. Operation in bands not of interest for radio astronomy/ Earth exploration
2. Coexistent spectrum usage

Introduction (2)



http://discovermagazine.com/2007/jun/tireless-wireless/allochrt_lg.jpgIssue

1. Operation in <u>uncritical bands only</u>
   - \+ No interference
   - \+ No power constraints
   - − Very small bandwidths (typically << 10 GHz)
   - − Widespread over the THz spectrum

→ No option for data rates >> 10 Gbit/s

2. <u>Coexistent spectrum usage</u> between THz communications and radio astronomy/Earth exploration
   - \+ Flexible spectrum usage
   - \+ Practically no bandwidth limitations
   - \+ Simultaneous operation of various systems
   - − Potential interference
   - − Power constraints

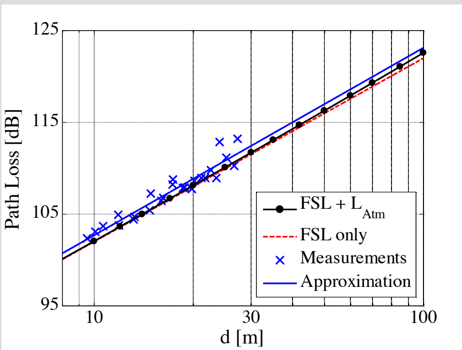
→ Interference studies inevitable

→ Possible **interference-free coexistence with radio astronomy already proven** (*IEEE doc. 802.15-15-10-0829-00-0thz*) ✔

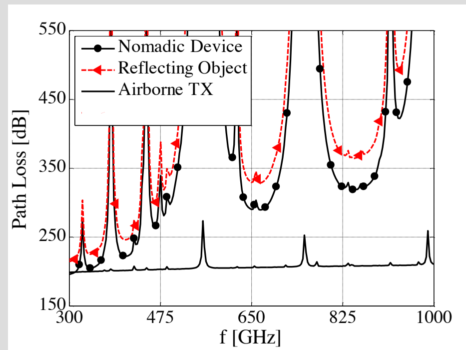
→ Interference with **Earth exploration**?

Methodology

1.) Path loss measurements

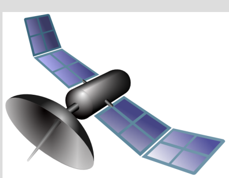


2.) Modeling of path losses from TX to satellite

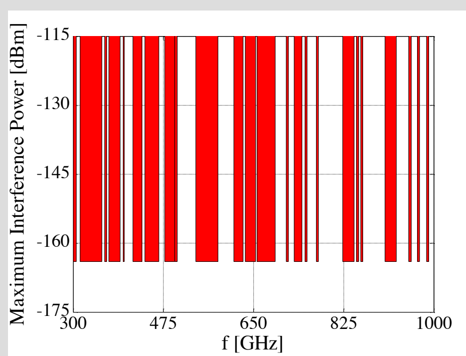


3.) Satellite data

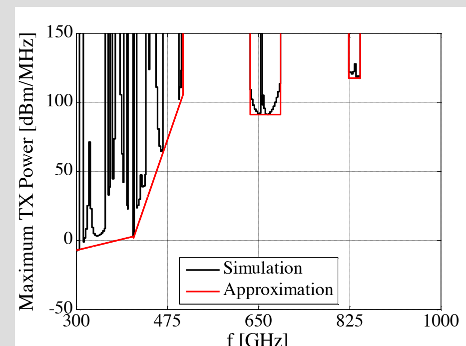
- Heigths
- Antennas
- Scanning modes
- Receiver sensitivities



4.) Allowed interference powers



5.) Transmit power limits for interference avoidance



Outline

1. Introduction
2. **Path Loss Measurements and Modeling**
   - **Path Loss Measurements**
   - **Atmospheric Attenuation**
3. Interference Scenarios
4. Transmit Power Constraints
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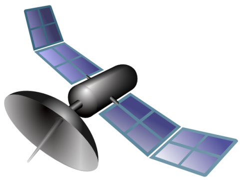
Path Loss Measurements (1)

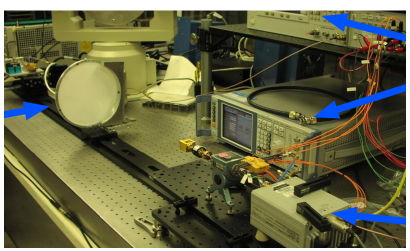
- Motivation: Path loss (PL) modeling required to estimate the interference power received at the satellite
- Problem: Satellite path cannot be measured directly



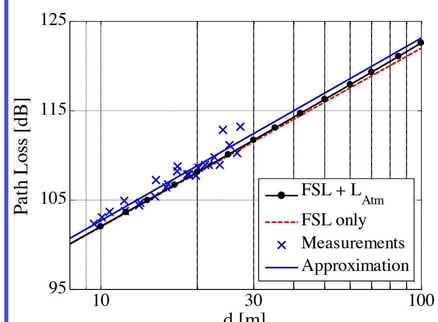
Path loss measurements → Valiation of path loss model → Application of model to long ranges

Several 100 km

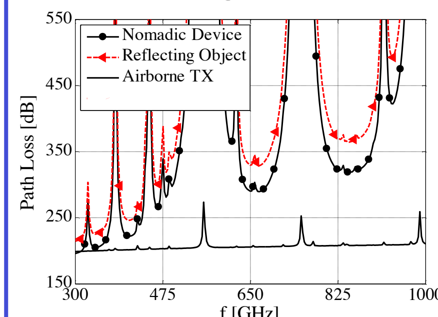
- PL measurements over short distances



- Measurements vs. simulations

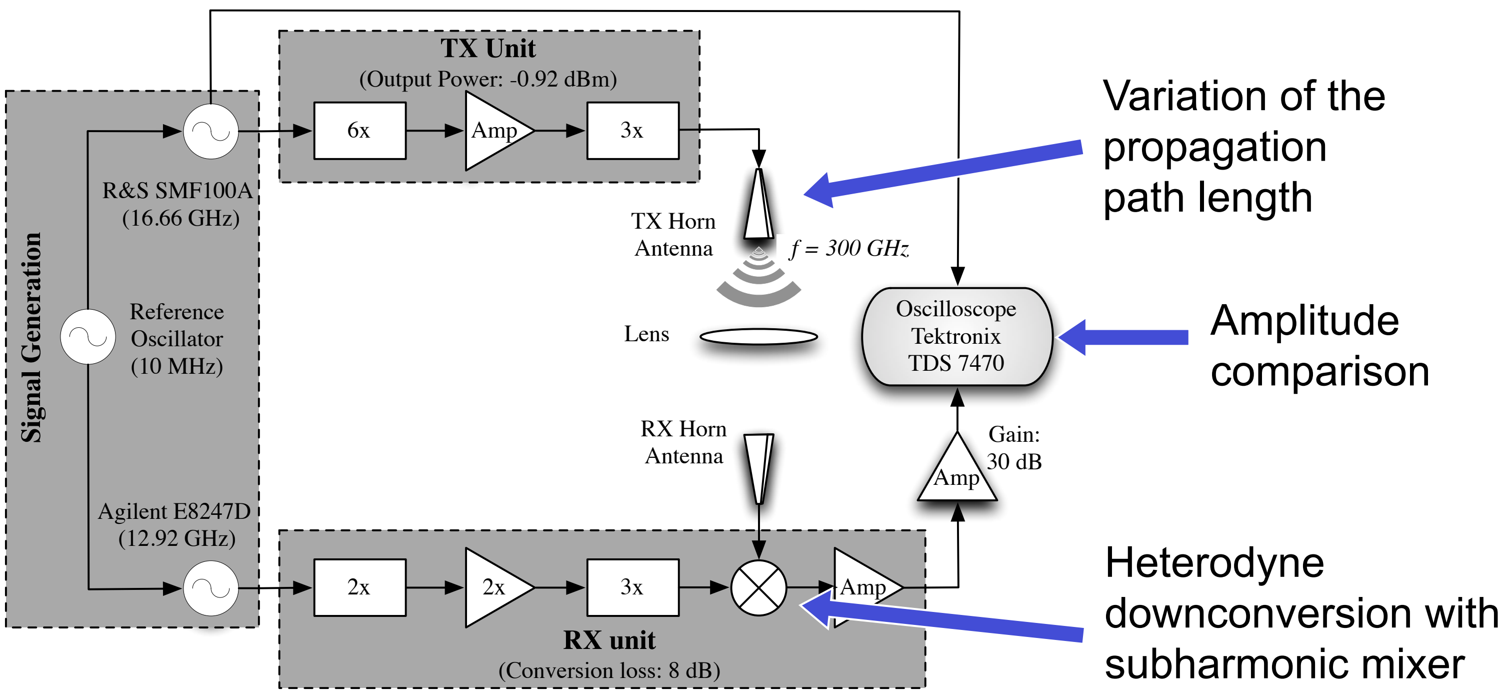


- Scenario path loss modeling



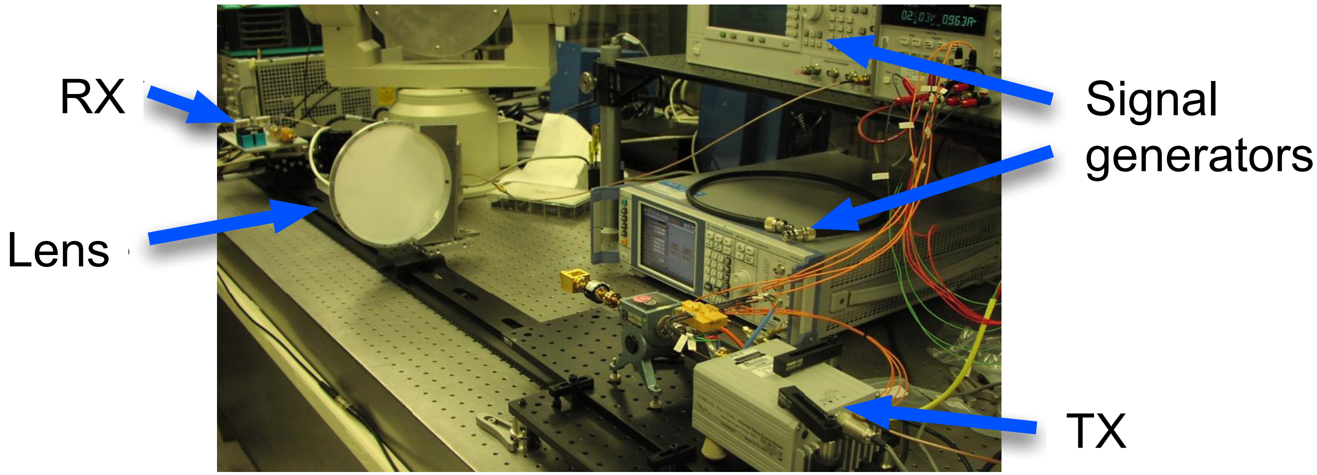
Path Loss Measurements (2)

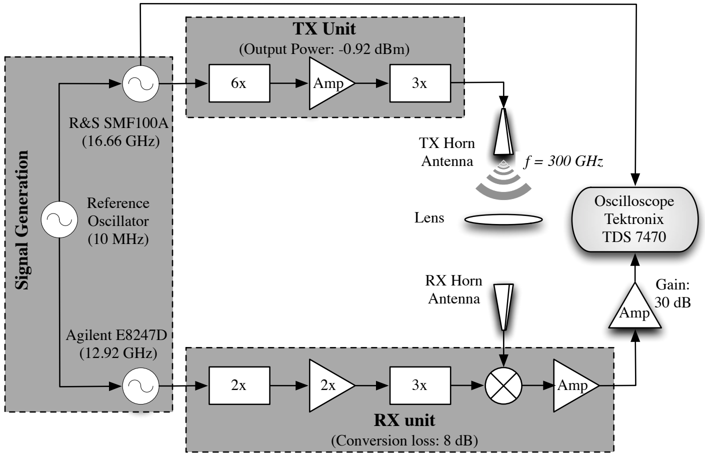
- Propagation loss measurements in cooperation with Northrop Grumman (contact: *Stephen Sarkozy*)
- Transmission of a continuous wave test signal at *f* = 300 GHz over a free space propagation path with variable length
- Comparison of the transmitted and received amplitude → path loss



Path Loss Measurements (3)

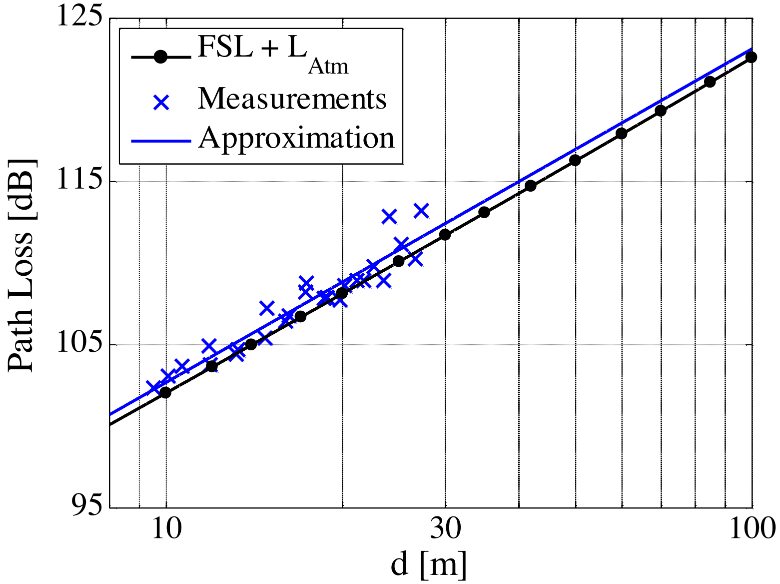
- Photo of the measurement setup:





Path Loss Measurements (4)

- Multiple measurement points at distances between 10 and 30 m
- Log-linear approximation of the measurements
- Modeling of the propagation path with the free space loss (FSL) + atmospheric attenuation L_{Atm}



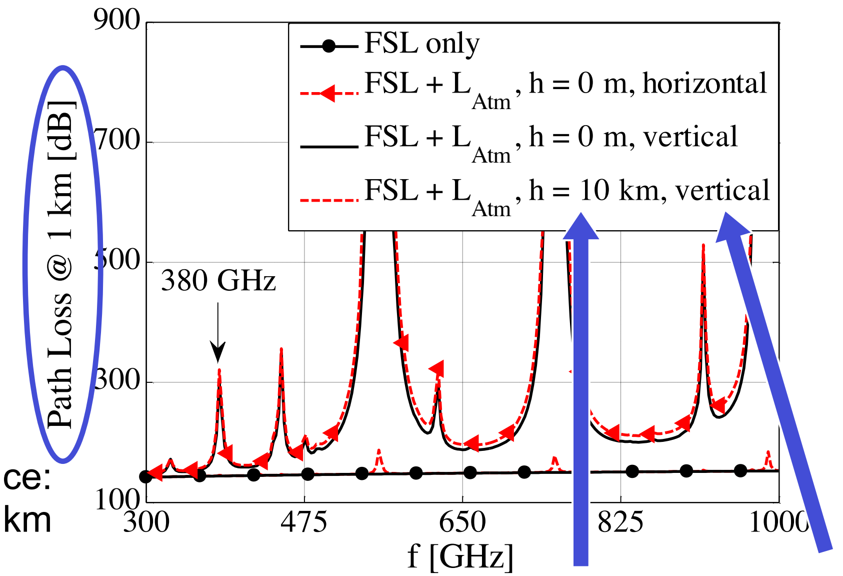
→ Very good agreement of measurements and simulations
→ Extrapolation of the modeled propagation loss possible

Atmospheric Attenuation (1)

- *So far*: One discrete frequency f = 300 GHz only
- Open aspects of the atmospheric attenuation:
  1. Frequency dependency?
  2. Transmitter orientation (horizontal vs. vertical)?
  3. Height dependency?

→ Application of the atmospheric modeling tool MODTRAN

Distance: 1km



Different TX heights

Different TX orientations

→ Highly attenuated frequency ranges with significant molecular absorption

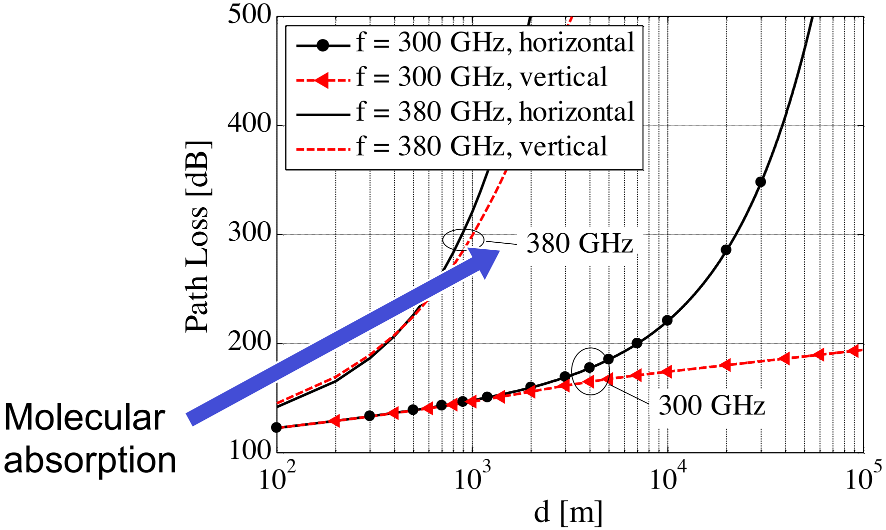
→ Slightly higher attenuation for horizontal TX orientation

→ Hardly any impact of the atmosphere at 10 km height

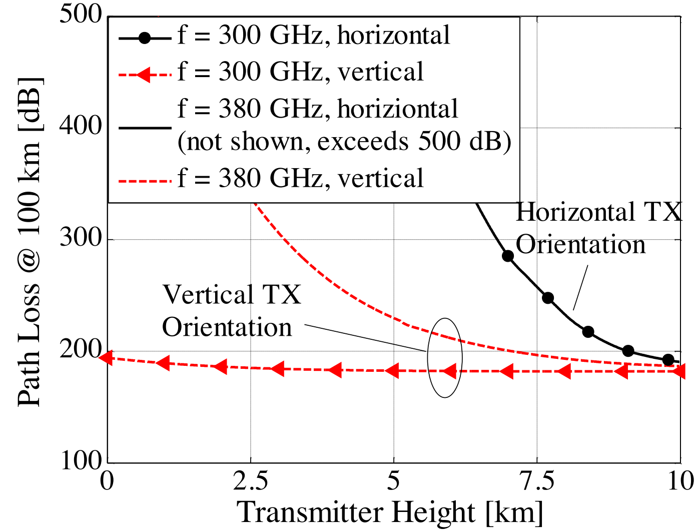
Atmospheric Attenuation (2)

- Idea: Identification of critical scenarios based on the path loss
- Illustration of the frequency, height and distance dependence:

TX on ground



Variation of TX height



→ Only atmospheric windows relevant on ground

→ Ground-based TX irrelevant in horizontal orientation

→ Airborne transmitter (h = 10 km) critical regardless of frequency and orientation

Outline

1. Introduction
2. Path Loss Measurements and Modeling
3. **Interference Scenarios**
   - **Critical Scenarios**
   - **Scenario Path Losses**
   - **Satellite Characteristics**
4. Transmit Power Constraints
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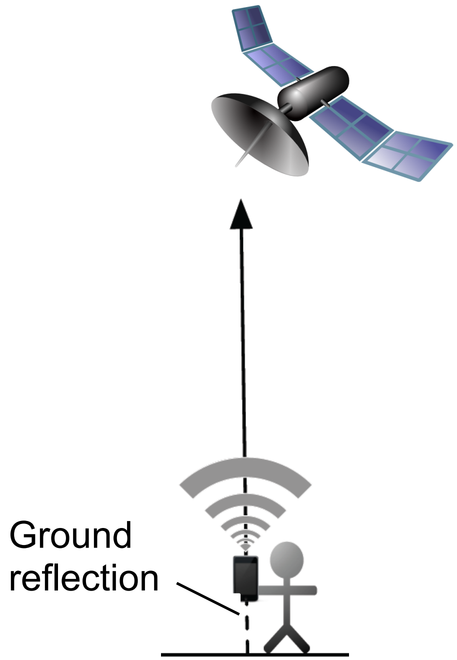
Critical Scenarios (1)

- Idea: Estimation of maximum occurring interference powers

→ Worst case assumptions throughout all scenarios

→ No additional attenuation due to weather impact

1. Nomadic devices operated outdoors in rural environment



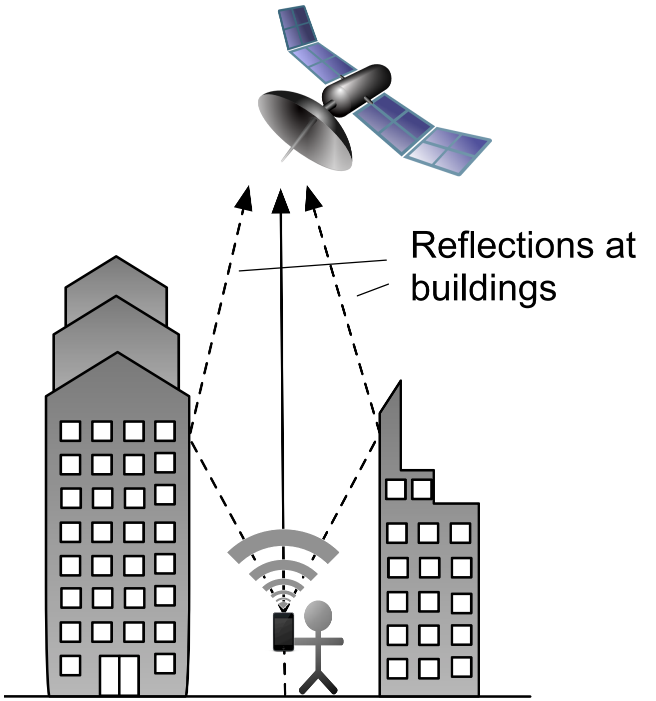
→ Nomadic TX is accidentally pointed in immediate skyward direction

→ Satellite passes over the TX, directly looking at the ground (0° zenith angle, shortest path)

→ A ground reflection may superimpose constructively with the direct path at the satellite

Critical Scenarios (2)

2. Nomadic devices operated outdoors in urban environment



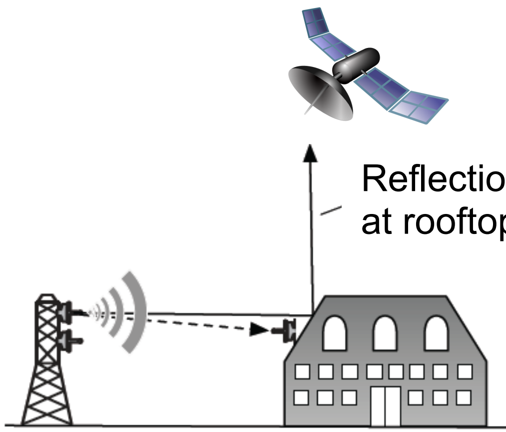
→ Similar conditions occur like in the rural setup
→ No objects shadow the direct ray path
→ Additionally, reflections from buildings around the TX may add up at the satellite

- Indoor-operated devices cannot become relevant due to transmission losses, if the introduced outdoor scenarios are uncritical

→ Indoor setups are implicitly covered by the outdoor scenarios

Critical Scenarios (3)

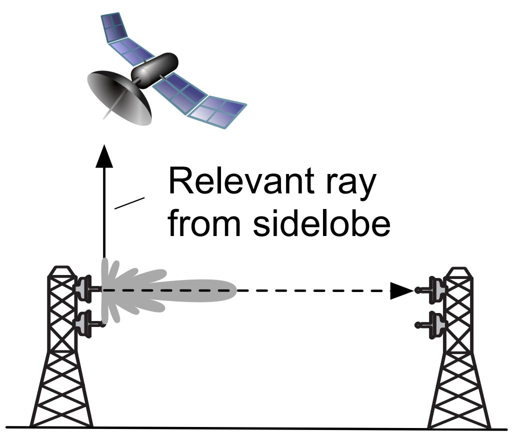
3. Fixed links with scattering objects close to direct ray path



→ Objects close to the direct ray path may scatter/reflect power in skyward direction

→ Unwanted scattering is thinkable *despite* highly directive antennas

4. Relevant emission from antenna sidelobes

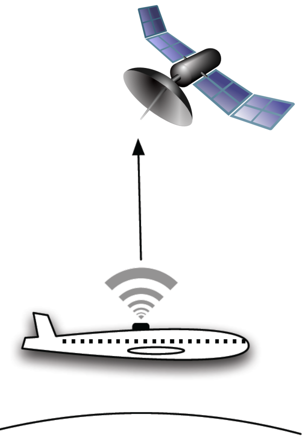


→ High sidelobe levels may cause non-negligible radiation in skyward direction

→ Fixed links become especially critical because of potentially high output powers

Critical Scenarios (4)

5. Airborne operated transmitters

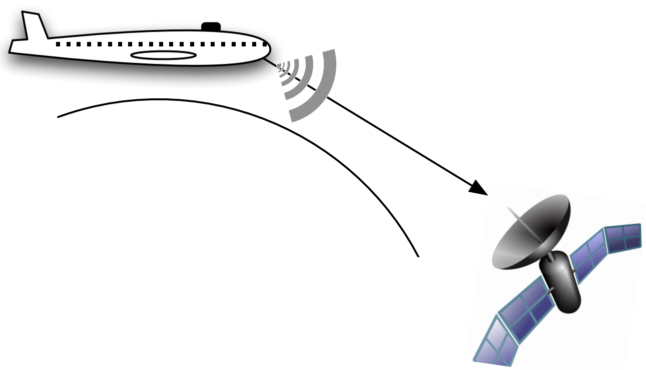


→ Radiation through the fuselage or windows is thinkable

→ Transmitted rays may not be attenuated like e.g. by composite fuselages

→ Hardly any atmospheric absorption occurs

6. Satellite in limb scanning mode

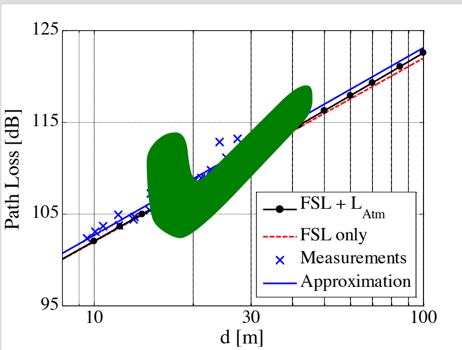


→ THz waves may be radiated in the immediate direction of the limb scanner

→ Ground-based transmitters do not become relevant due to the long horizontal path

Methodology

1.) Path loss measurements



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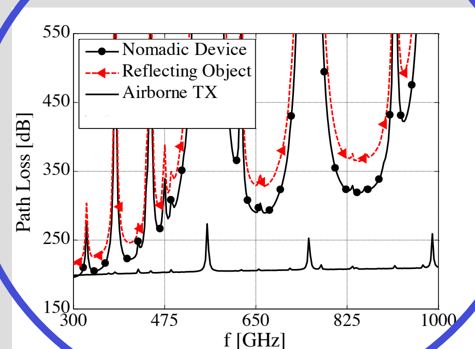
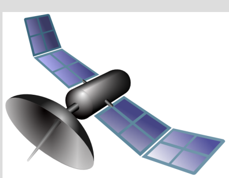
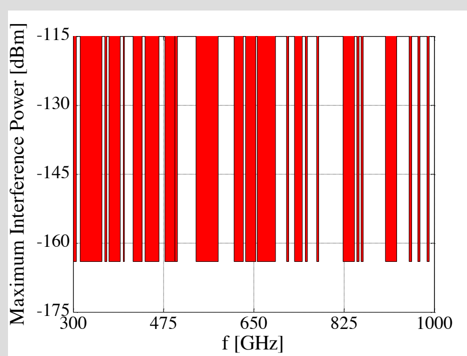


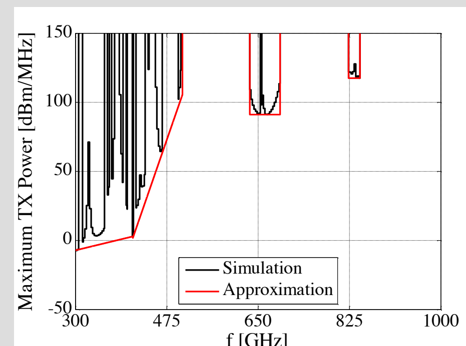
3.) Satellite data
- Heigths
- Antennas
- Scanning modes
- Receiver sensitivities



4.) Allowed interference powers

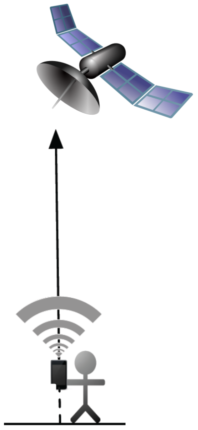


5.) Transmit power limits for interference avoidance



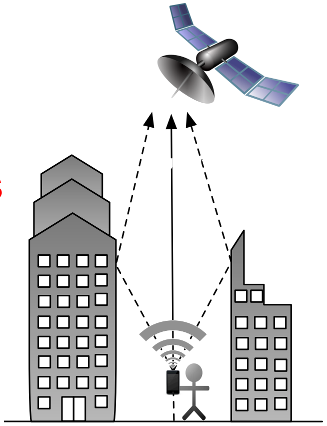
Scenario Path Losses (1)

1. Nomadic rural:
   1. Free space loss
   2. Vertical atmospheric path from ground to satellite
   3. <u>Worst case:</u> Constructive superposition of direct ray and ground reflection, ideal reflection factor r = 1



$$PL_1 = FSL + L_{Atm,vertical} - 6 \text{ dB}$$

2. Nomadic urban:
   1. Free space loss
   2. Vertical atmospheric path from ground to satellite
   3. <u>Worst case:</u> Direct ray, ground reflection and additional four rays from buildings around the TX, r = 1 (e.g. metal structures)

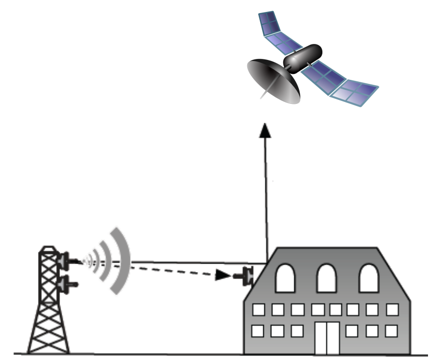


$$PL_2 = FSL + L_{Atm,vertical} - 15.56 \text{ dB}$$

Scenario Path Losses (2)

3. Fixed link (scattering object):
   1. Free space loss
   2. Horizontal atmospheric path from TX to scattering object (500 m assumed here)
   3. Vertical path from scattering object to satellite
   4. Worst case: Specular reflection with an ideal reflection factor of $r = 1$ (e.g. metalized glass)

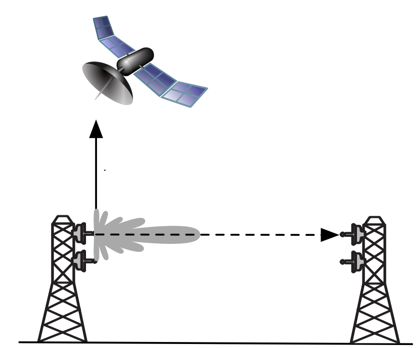
$$PL_3 = FSL + L_{Atm,horizontal} + L_{Atm,vertical}$$



4. Sidelobes:
   1. Free space loss
   2. Vertical atmospheric path from ground to satellite
   3. Worst case: High sidelobe level with respect to gain in main beam direction (40 dB sidelobe attenuation assumed here)

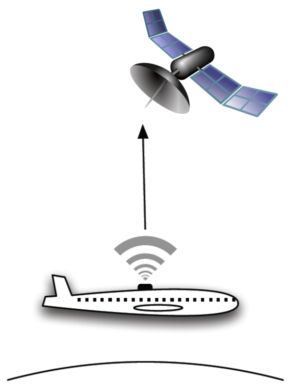
$$L_{Sidelobe} = (G_{TX} - G_{Sidelobe})$$

$$PL_4 = FSL + L_{Atm,vertical} + L_{Sidelobe}$$



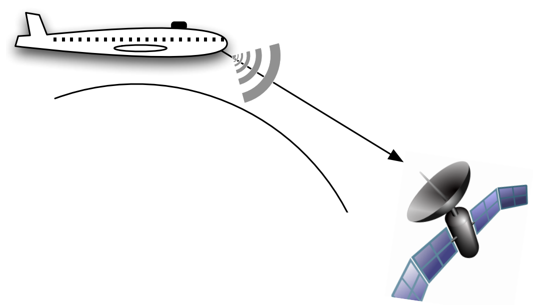
Scenario Path Losses (3)

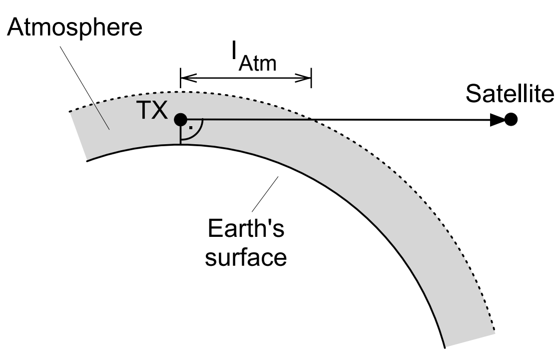
5. Airborne TX:
   1. Free space loss
   2. Vertical path from aircraft to satellite
   3. Worst case: No transmission attenuation by the fuselage (e.g. composite materials); outside mounted transmitters



$$PL_5 = FSL + L_{Atm,vertical}(h_{TX} = 10\ \mathrm{km})$$

6. Limb scanning (airborne TX):
   1. Free space loss
   2. Slanted atmospheric path from aircraft to satellite
   3. Worst case: Shortest occurring atmospheric path length

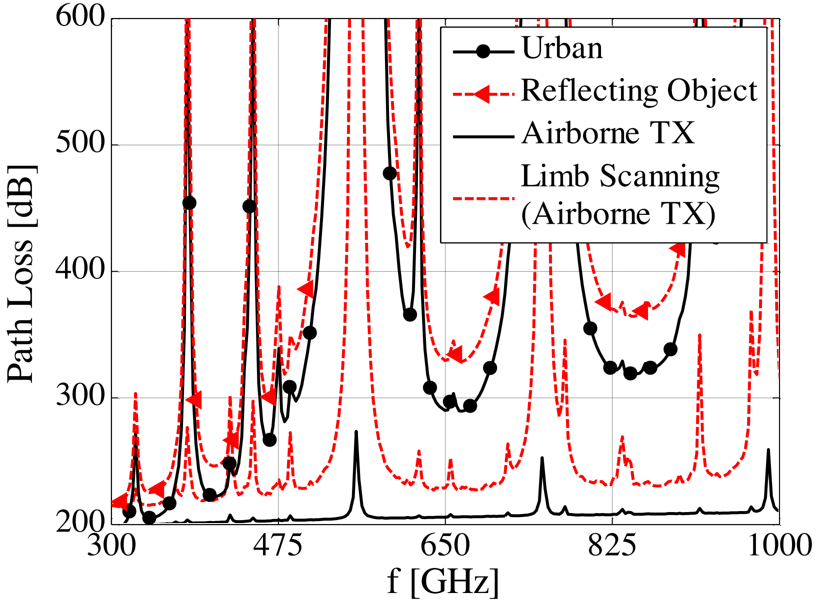




$$PL_6 = FSL + L_{Atm,slant}$$

Scenario Path Losses (4)

- Resulting path losses from TX to satellite (altitude 705 km):



f [GHz]	300	380	650	850
PL_1 [dB] Rural	205	>600	300	329
PL_2 [dB] Urban	196	>600	290	319
PL_3 [dB] Fixed	214	>600	330	365
PL_4 [dB] Sidelobe	251	>600	346	376
PL_5 [dB] Airborne	198	203	205	208
PL_6 [dB] Limb	214	276	228	232

→ Basis to determine the interference powers at the satellite

→ Most critical scenarios:

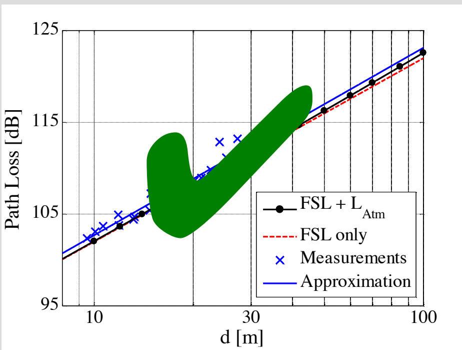
  → Atmospheric windows regardless of the setup

  → Airborne transmitters regardless of the frequency range

→ Which TX power is permitted at maximum?

Methodology

1.) Path loss measurements



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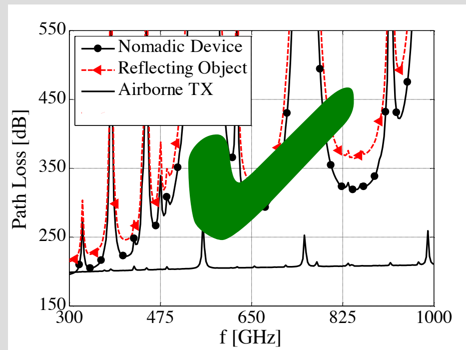

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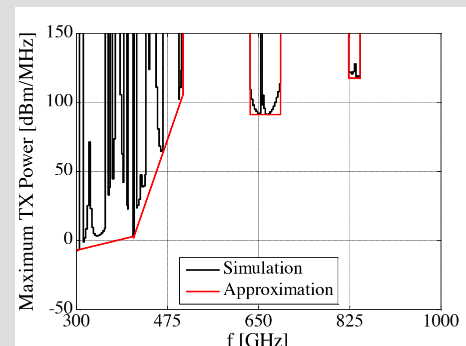

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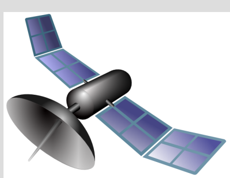

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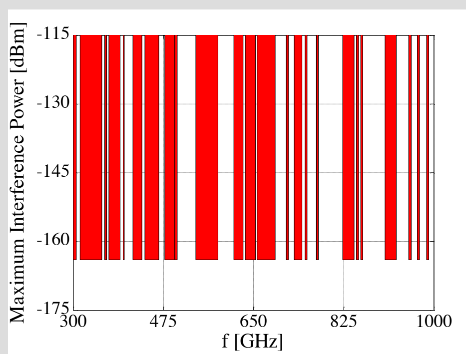
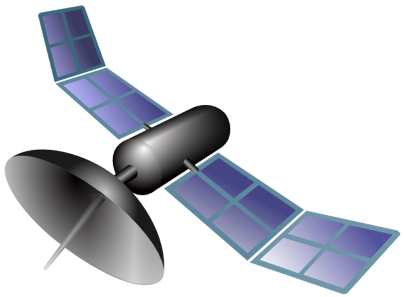


Satellite Characteristics (1)

- **Operational heights** of Earth exploration satellites: 705 – 850 km

→ Worst case: Shortest distance 705 km



- **Antenna gains**: Dish antennas with adjustable gain and HPBW via dish size; typically 40 – 60 dBi

$$G_{RX} \approx 10 \cdot \log_{10}\left(\frac{\alpha_{Dish}^2 d_{Dish}^2 f^2}{56.3}\right)$$

→ Worst case: Very high gain 60 dBi, 0.23° HPBW

Required dish sizes for 60 dBi gain

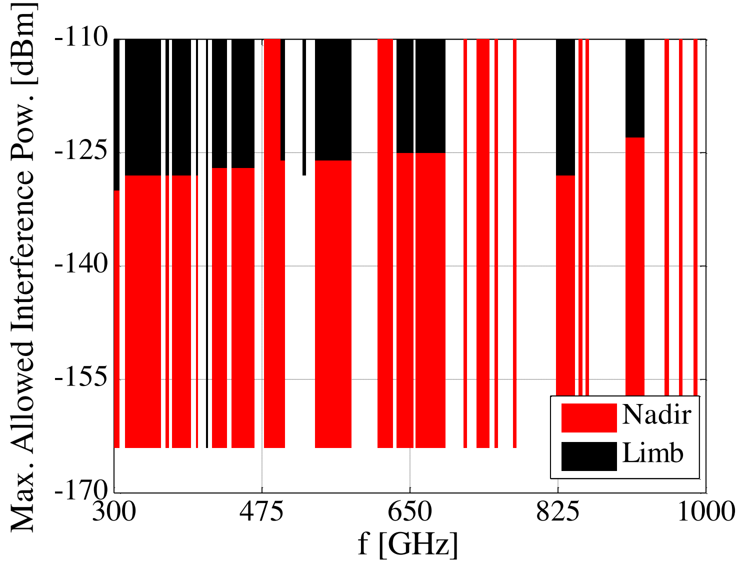
f [GHz]	300	400	500	750	1000
d_{Dish} [cm]	33.3	25	20	13.3	10

Satellite Characteristics (2)

- **Receiver sensitivities**:
  - Dependent on RX noise temperature and noise figure
  - Different for the two scanning modes nadir and limb

→ Maximum allowed interferences powers specified by ITU-R Report RS.1092-2 "*Interference Criteria for Satellite Passive Remote Sensing*" in accordance with actual RX sensitivities

Reference bandwidth:
3 MHz (nadir)
200 MHz (limb)



→ Very strict interference power constraints

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3. Interference Scenarios
4. **Transmit Power Constraints**
   - **Spectrum Masks**
   - **System Performance**
   - **Multiple Interfering Stations**
5. Interference Avoidance Concepts
6. Summary/Outlook

Methodology

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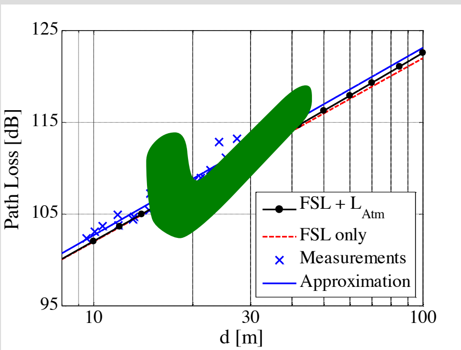

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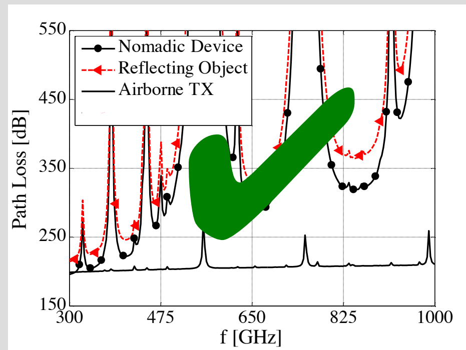

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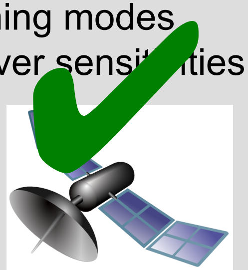
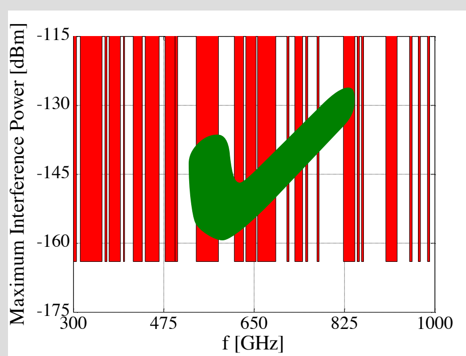
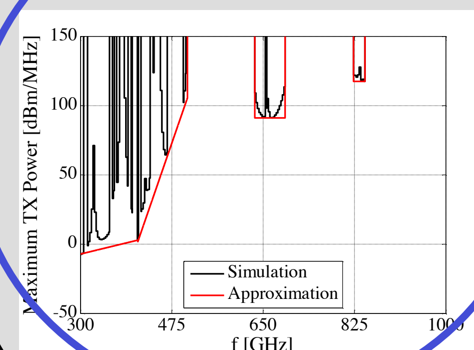


4.) Allowed interference powers



5.) Transmit power limits for interference avoidance

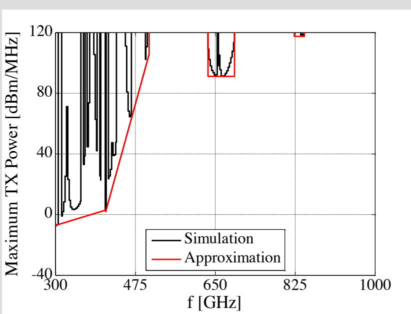


Spectrum Masks (1)

- **Maximum equivalent isotropically radiated power (EIRP)**:
  - Becomes scenario-specific through the path loss
  - Must respect the satellite antenna gain
  - Must not exceed the maximum allowed interference power

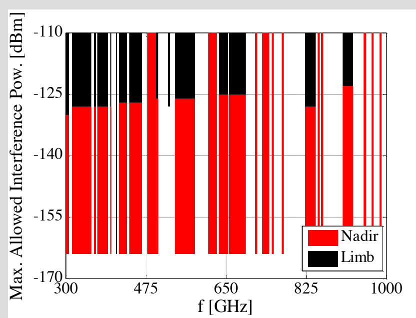
$$P_{TX,EIRP,max} \leq P_{int,max} + PL - G_{RX}$$

Transmit power masks



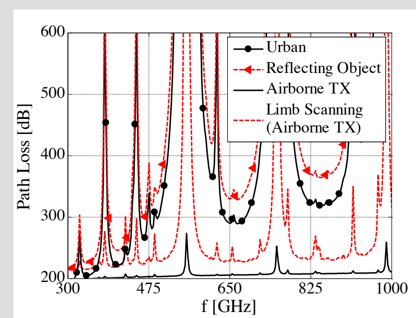
≤

Max. allowed interference



+

Path losses

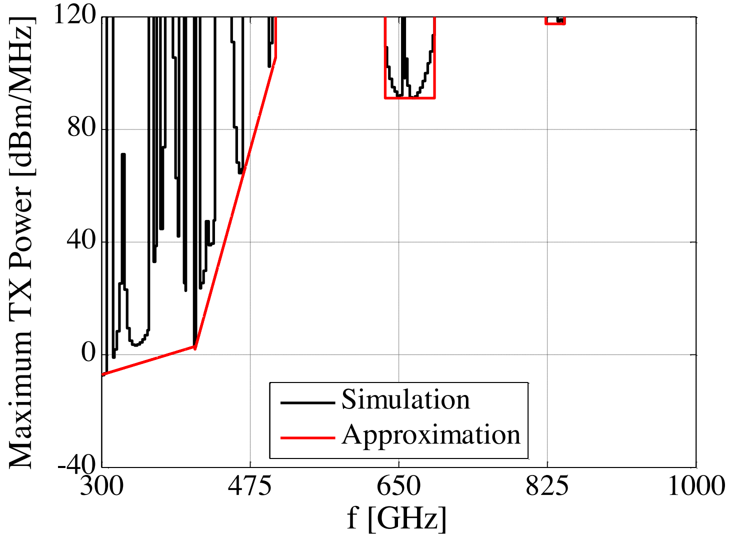


- 60 dBi

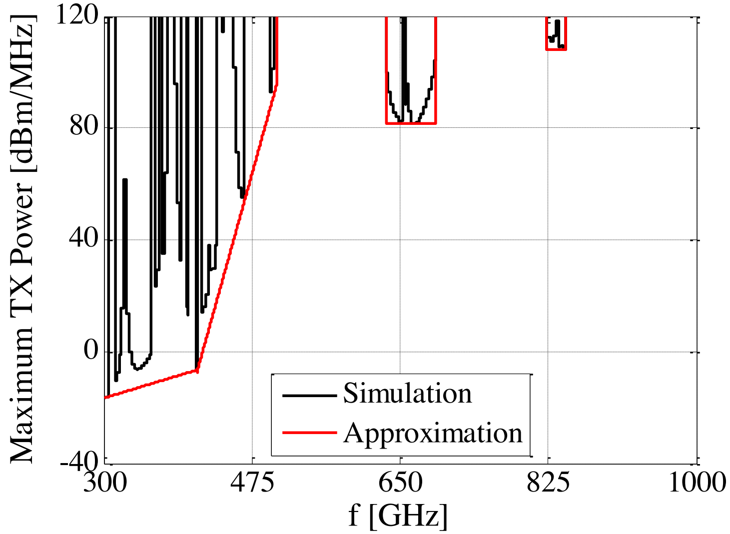
→ **No interference from TX, if power mask is complied with**

Spectrum Masks (2)

- Definition of transmit power spectrum masks
- Constraints for the isotropically radiated power spectral density:



1.) Nomadic device rural

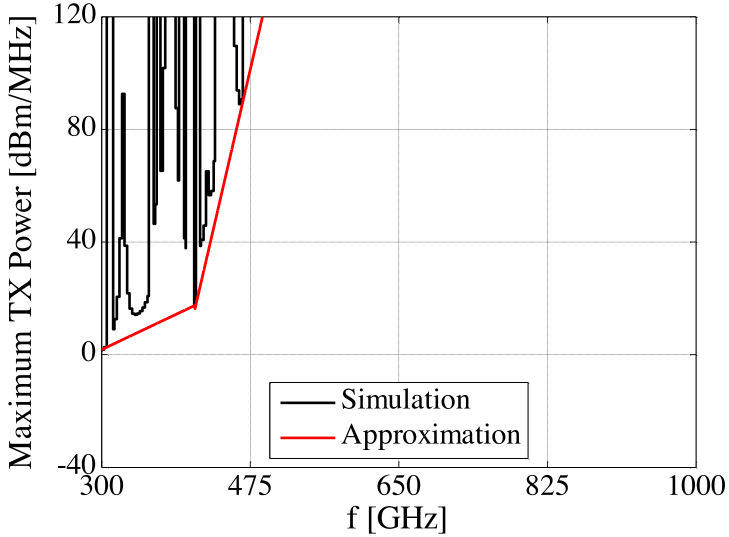


2.) Nomadic device urban

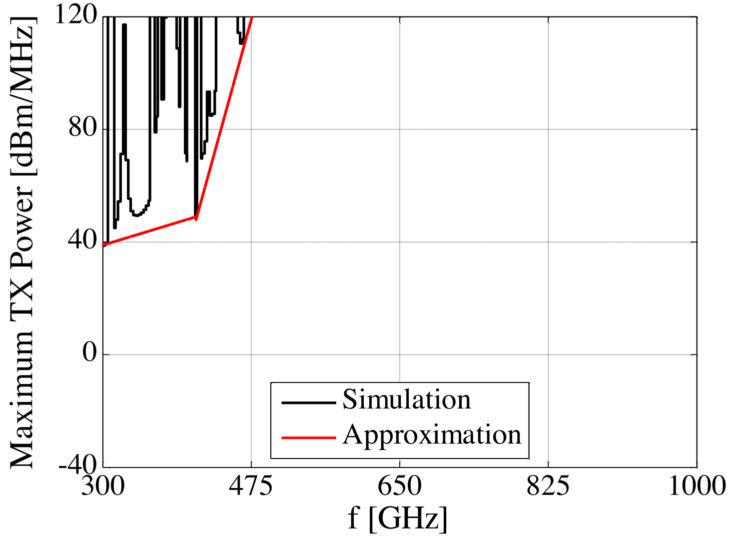
→ Simple approximation with line segments (line parameter sets given in [1])

→ Effective limitation to several 10 dBm EIRP for bandwidths of several 10 GHz

Spectrum Masks (3)



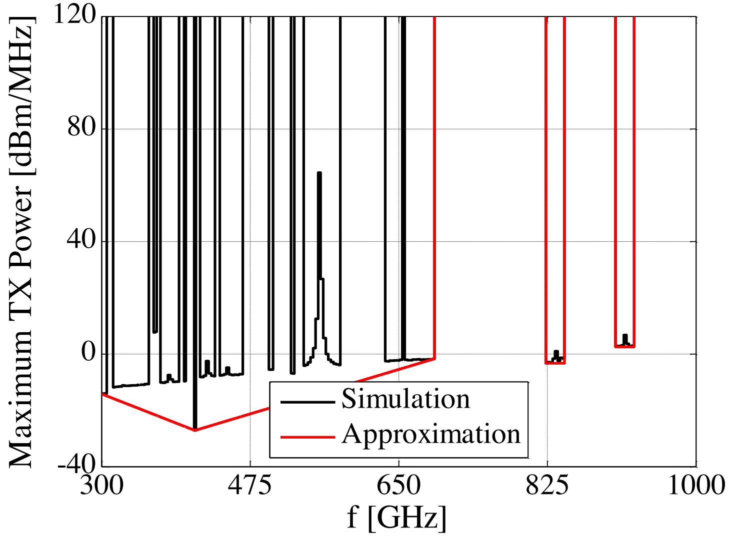
3.) Fixed links



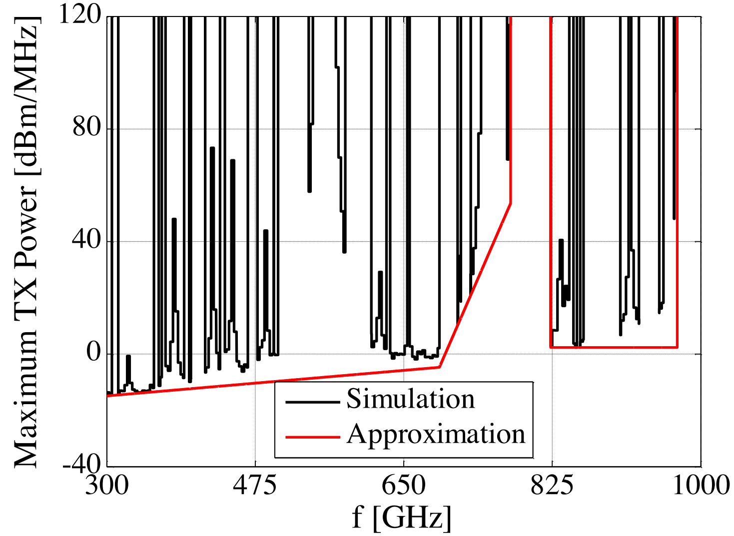
4.) Sidelobes

- → Fixed links far less critical than nomadic transmitter
- → Higher output powers and longer distances achievable
- → No significant limitation by sidelobes
- → Relevant constraints below 500 GHz only

Spectrum Masks (4)



5.) Airborne TX



6.) Limb scanning

→ Airborne transmitters most critical
→ Constraints in almost the entire THz range
→ Restriction to low powers and short ranges

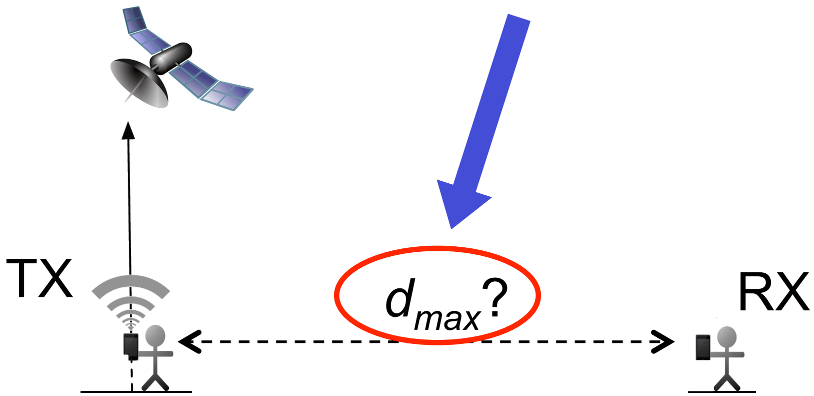
- Open aspect: Affection of the system performance by the power limitations?

System Performance (1)

- Hypothetical THz transceiver system for performance analysis:
  - Fixed maximum transmit power according to power masks
  - Receive antenna gain G_{RX} = 25 dBi (nomadic, airborne), 55 dBi (fixed links)
  - Noise figure NF = 5 dB
  - QPSK modulation with various data rates from 10 to 100 Gbit/s
  - White Gaussian noise N
  - Required SNR of 13.5 dB (corresponds to bit error rate of 10^{-6})

→ Which range is achievable despite the TX power limitations?

$$SNR_{min} = P_{TX,EIRP,max} - PL(d_{max}) + G_{RX} - N - NF$$



System Performance (2)

- Maximum EIRPs and achievable distances:

Very high powers allowed

		300 – 320 GHz		330 – 370 GHz		640 – 690 GHz	
	Data rate [Gbit/s]	10	40	20	80	50	100
1.) Rural	$P_{TX,EIRP,max}$ [dBm]	31.2	35.9	38.4	41.6	135.1	138.1
	d_{max} [m]	38	33	49	37	1115	1115
2.) Urban	$P_{TX,EIRP,max}$ [dBm]	21.7	26.3	28.8	32.1	125.5	128.5
	d_{max} [m]	13	12	18	13	964	964
3.) Fixed	$P_{TX,EIRP,max}$ [dBm]	40.9	44.8	50.3	52.1	164.8	167.8
	d_{max} [m]	964	867	840	710	2101	2101
4.) Sidelobe	$P_{TX,EIRP,max}$ [dBm]	77.2	81.9	84.4	87.6	181.1	184.1
	d_{max} [m]	3075	2986	2041	1937	2378	2378
5.) Airborne	$P_{TX,EIRP,max}$ [dBm]	20.5	26.5	17.6	23.6	39.9	40.6
	d_{max} [m]	12	12	6	6	20	16
6.) Limb	$P_{TX,EIRP,max}$ [dBm]	22.5	28.3	26.7	31.9	38.6	40.9
	d_{max} [m]	15	14	14	13	18	17

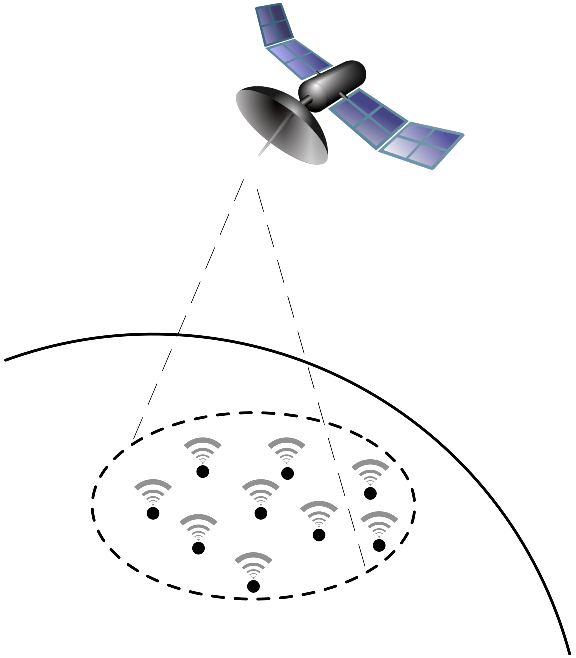
THz WLANs and WPANs possible

Fixed links realizable

Sidelobes uncritical

Airborne TXs limited to short ranges

Multiple Interfering Stations (1)



- *So far*: One transmitter only
- Illuminated area by satellite on ground within 3 dB half power beamwidth:

Gain	40 dBi	50 dBi	60 dBi
HPBW	2.29°	0.72°	0.23°
Area	627 km²	62 km²	6.3 km²

→ Simultaneous reception of signals from multiple stations

→ Superposition of interference powers

→ Preventive reduction of maximum allowed transmit power per station obligatory

- Interference margin:

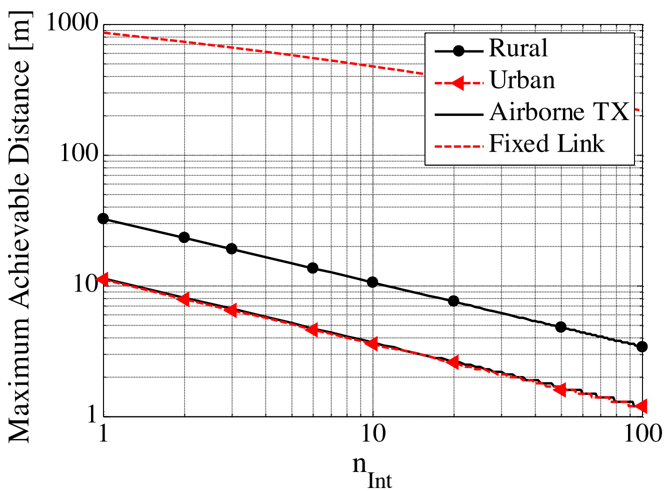
Number of expected simultaneous interferers

$$\widetilde{P}_{TX,EIRP,max} = P_{TX,EIRP,max} - 10 \cdot \log_{10}(n_{Int})$$

Multiple Interfering Stations (2)

Simultaneous interferers n_{int}	2	5	10	50	100
Interferer density [km^{-2}]	0.32	0.79	1.59	7.59	15.9
Average separation [km]	1.77	1.12	0.79	0.35	0.25
Required interference margin [dB]	3	7	10	17	20

- d_{max} *after* respecting interference margin (40 Gbit/s, 300 – 320 GHz):



Down to only several meters link coverage under adoption of interference margin

→ Significant performance impairments in case of multiple interferers
→ Active interference countermeasures necessary

Outline

1. Introduction
2. Path Loss Measurements and Modeling
3. Interference Scenarios
4. Transmit Power Constraints
5. **Interference Avoidance Concepts**
6. Summary/Outlook

Interference Avoidance Concepts (1)

- General idea: Prevention of relevant skyward radiation

→ Circumvention of transmit power constraints

→ Longer link distances, higher system performance

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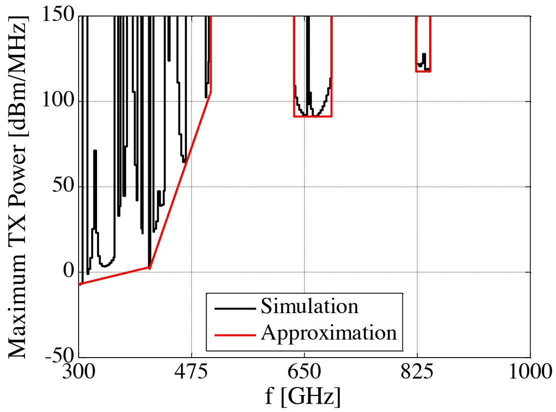
1. Transmit power masks
   - Limitation of TX powers
   - Unwanted performance impairments

→ No interference at any rate

2. Transmission in highly attenuated frequency ranges
   - Option for shorter distances only
   - Not applicable to airborne links (no significant atmospheric attenuation)

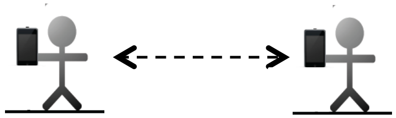
→ Virtually no power restrictions



Interference Avoidance Concepts (2)

3. Transmit power control with handshake
    - Negotiation of necessary link power
    - Power reduction
    - Relevant only if link operable below power limits

→ No contribution to relevant interference power

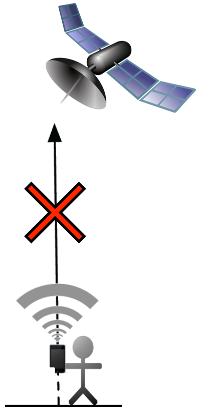


4. Electrically switchable/steerable antennas
    - Tracking of RX position
    - Regulation of beam direction

→ No skyward radiation

5. Automatic link deactivation (nomadic devices)
    - Orientation detection with gyrosensors
    - Consideration of satellite and device position (GPS and data bases)

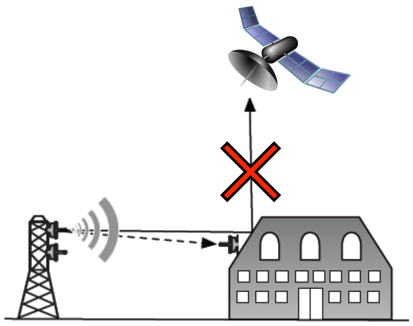
→ Power masks irrelevant



Interference Avoidance Concepts (3)

6. Environmental control (fixed link)
    - Careful TX/RX placement
    - Absorbing materials

→ No limitations, if reflections preventable



7. Environmental control (airborne TX)
    - Careful TX placement
    - Coatings with high transmission attenuations

→ Significantly higher TX powers possible

→ Harmful interference can be prevented at any rate
→ System performance impairments can be avoided with active interference countermeasures

Outline

1. Introduction
2. Path Loss Measurements and Modeling
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4. Transmit Power Constraints
5. Interference Avoidance Concepts
6. **Summary/Outlook**

Summary

- Coexistent THz spectrum usage between active and passive services is envisaged
- Remote sensing must be prevented from potential interference
- Critical scenarios are:
  - Outdoor-operated nomadic devices in rural or urban environments
  - Fixed links with scattering objects close to ray path or sidelobe emission
  - Airborne transmitters relevant for both nadir and limb scanning
- Multiple interferers can superimpose

- Power masks have been derived:

→ Worst case assumptions have been made

→ Relevant interference is possible

→ Significant output power constraints may apply

→ Simultaneous interference from multiple stations becomes critical

Outlook

- Interference from multiple stations has to be considered in detail
  - Stochastic position distributions
  - Random transmission times
  - Moving satellites

→ Probabilities for simultaneous interference?

→ Effect on transmit power constraints?

- Active interference countermeasures will have to be considered
  - Intelligent transceiver units
  - Transmission at frequencies with high atmospheric attenuation
  - Precise beamswitching/beamsteering
  - Careful TX/RX positioning
  - Absorbing materials

→ Interference-free conditions can be ensured

→ Transmit power and performance constraints can be avoided

References

[1] S. Priebe, D. M. Britz, M. Jacob, S. Sarkozy, K. M. K. H. Leong, J. E. Logan, B. S. Gorospe, T. Kürner: „Interference Investigations of Active Communications and Passive Earth Exploration Services in the THz Frequency Range“, accepted for publication in *IEEE Transactions on THz Science and Technology,* 14 pages, 2012

Technical Expectations Document (TED)

All information contained in this presentation is meant to be included in the technical expectations document 15-11-0745-05-0thz-thz-ig-technical-expectations-document-ted.doc.

Thank you for paying attention.

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