Basic considerations on Terahertz communication systems

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- Objective of this presentation to understand
  - physical limits in terms of capacity and range
  - impact on application scenarios
  - under constraints of radiation limits
  - but idealized conditions

Outline

- Potential technical KPIs
- Frequency bands
- Radiation limits
- Propagation conditions
- Link capacity versus range
- Coherence time
- Means for range extension by keeping radiation limits
- Remote sensing applications based on active Radar concepts
- Conclusion

Examples of technical KPIs for future systems

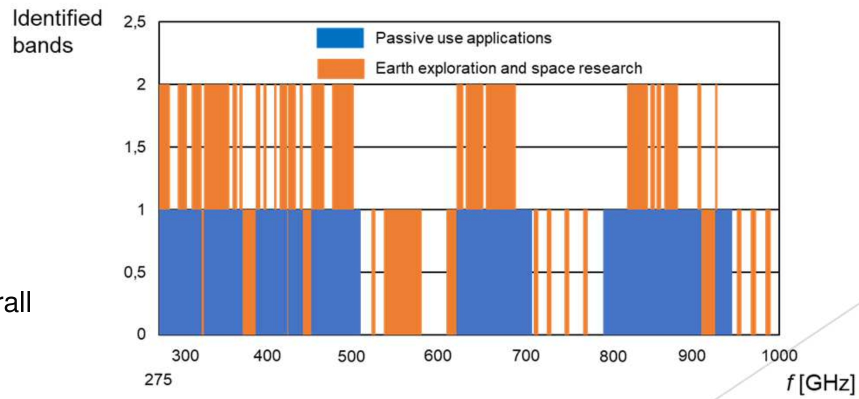
Target KPI	5G NR	5G NR SEVO	5G NR MEVO	5G NR LEVO
Spectrum	< 52.6 GHz	< 250 GHz	< 500 GHz	< 1000 GHz
Bandwidth	< 0.5 GHz	< 2.5 GHz	< 5 GHz	< 10 GHz
Peak Data Rate	DL: > 20 Gbps UL: > 10 Gbps	DL: > 100 Gbps UL: > 50 Gbps	DL: > 200 Gbps UL: > 100 Gbps	DL: > 400 Gbps UL: > 200 Gbps
User Data Rate	DL: > 100 Mbps UL: > 50 Mbps	DL: > 500 Mbps UL: > 250 Mbps	DL: > 1 Gbps UL: > 0.5 Gbps	DL:> 2 Gbps UL: > 1 Gbps
Peak Spectral Efficiency	DL: > 30 bps/Hz UL: > 15 bps/Hz	DL: > 40 bps/Hz UL: > 20 bps/Hz	DL: > 50 bps/Hz UL: > 25 bps/Hz	DL: > 60 bps/Hz UL: > 30 bps/Hz
Density	> 1 device/sqm	> 1.3 device/sqm	> 1.7 device/sqm	> 2 device/sqm
Area Traffic Capacity	> 10 Mbps/sqm	> 50 Mbps/sqm	> 100 Mbps/sqm	> 200 Mbps/sqm
Reliability	URLLC: > $1 - 10^{-5}$	> $1 - 10^{-6}$	> $1 - 10^{-8}$	> $1 - 10^{-9}$
U-Plane Latency	URLLC: < 1 ms	< 0.5 ms	< 0.2 ms	< 0.1 ms
C-Plane Latency	< 20 ms	< 10 ms	< 4 ms	< 2 ms
Net. Energy Efficiency	Qualitative	> 30 % gain	> 70 % gain	> 100% gain
Term. Energy Efficiency	Qualitative	> 30 % gain	> 70 % gain	> 100% gain
Mobility	< 500 Km/h	< 500 Km/h	< 500 Km/h	< 1000 Km/h
Positioning accuracy	NA (< 1 m)	< 30 cm	< 10 cm	< 1 cm

Source: EMPOWER project: HORIZON 2020 ICT, Deliverable 2.2: First Technology roadmap for advanced wireless. https://www.advancedwireless.eu/wp-content/uploads/Deliverables/EMPOWER_deliverable_D2_2_final.pdf.

Potential frequency bands

102	–	105 GHz
105	–	109.5 GHz
111.8	–	114.25 GHz
122.25	–	123 GHz
130	–	134 GHz
141	–	148.5 GHz
151.5	–	155.5 GHz
155.5	–	158.5 GHz
158.5	–	164 GHz
167	–	174.5 GHz
174.5	–	174.8 GHz
191.8	–	200 GHz
209	–	217 GHz
217	–	226 GHz
231.5	–	232 GHz
232	–	235 GHz
238	–	240 GHz
240	–	241 GHz
252	–	265 GHz
265	–	275 GHz

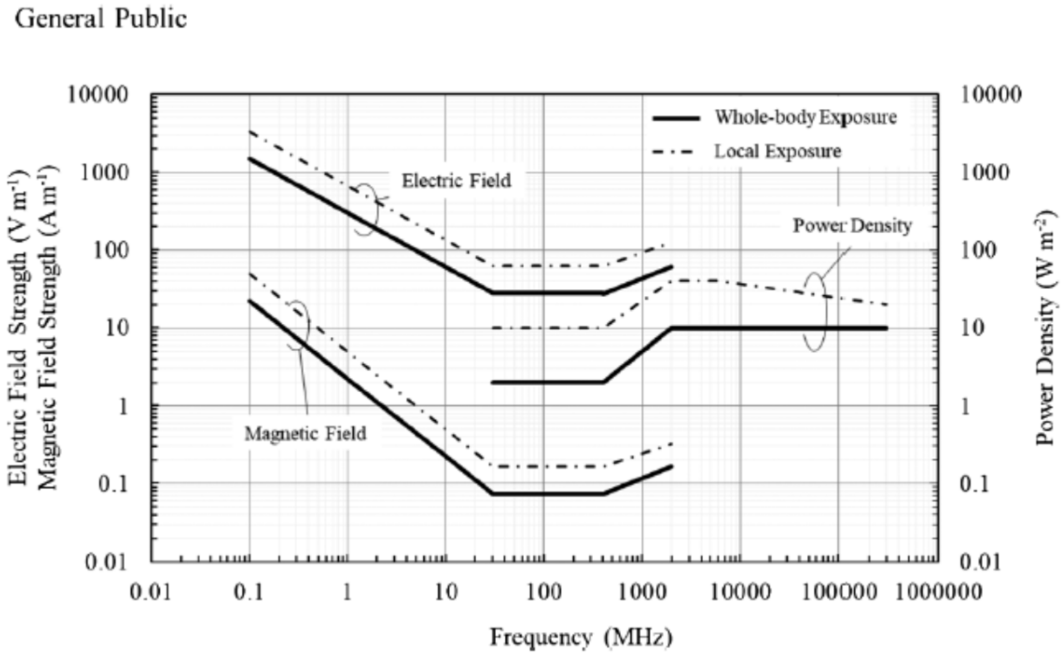
- However, opening for several bands for fixed and land mobile service applications in addendum to footnote 5.564A in WRC 2019 Final Acts
  - No specific conditions
    - 275 – 296 GHz
    - 306 – 313 GHz
    - 318 – 333 GHz (atmospheric absorption peak at 324 GHz)
  - Specific conditions to protect earth exploration satellites (passive service)
    - 296 – 306 GHz
    - 313 – 318 GHz
    - 333 – 356 GHz
- In footnote 5.565 many bands up to 1000 GHz allocated to
  - Radio astronomy
  - Earth exploration satellite service (passive) and space research (passive)



- Mobile allocation besides other allocations in ITU Radio Regulation 2016
- Changes in ITU WRC 2019
  - Loss of mobile allocation
  - Kept mobile allocation, but change in overall allocation (Fixed, Radio astronomy)
  - and above up to 3000 GHz no allocation anymore

Source: ITU: Radio Regulations 2016, Vol. I to Vol. IV. https://www.itu.int/en/history/Pages/RadioRegulationsA.aspx?reg=1.43.
ITU: World Radiocommunication Conference 2019 (WRC-19) Final Acts. 28 October – 22 November Sharm El-Sheikh, Egypt, 2020, https://www.itu.int/dms_pub/itu-r/opb/act/R-ACT-WRC.14-2019-PDF-E.pdf.

Radiation limits
Such limits are provided up to 300 GHz



- Reference levels for time averaged general public exposures of ≥ 6 min, to electromagnetic fields from 100 kHz to 300 GHz (unperturbed rms values; see Tables 5 and 6 for full specification) [ICNIRP] in 2020
- Values for local exposure only 3 to 6 dB higher than for full body exposure
  - 3 dB: $r/r_0 = 1.41$ $3\,dB = 20 \cdot \log(r/r_0)$
  - 6 dB: $r/r_0 = 2$ $6\,dB = 20 \cdot \log(r/r_0)$

Sources: ICNIRP: ICNIRP Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz). ICNIRP publication 2020.

ICNIRP: ICNIRP Guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to 300 GHz). ICNIRP publication 1998

European Commission: Council Recommendation of 12 July 1999 on the limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 GHz). (1999/519/EC), July 30, 1999, https://op.europa.eu/en/publication-detail/-/publication/9509b04f-1df0-4221-bfa2-c7af77975556/language-en.

NISV: Verordnung zum Schutz vor schädlichen Wirkungen nichtionisierender Strahlung bei der Anwendung am Menschen (NiSV). 2020, https://www.buzer.de/NiSV.htm.

Radiation density
EIRP is relevant parameter

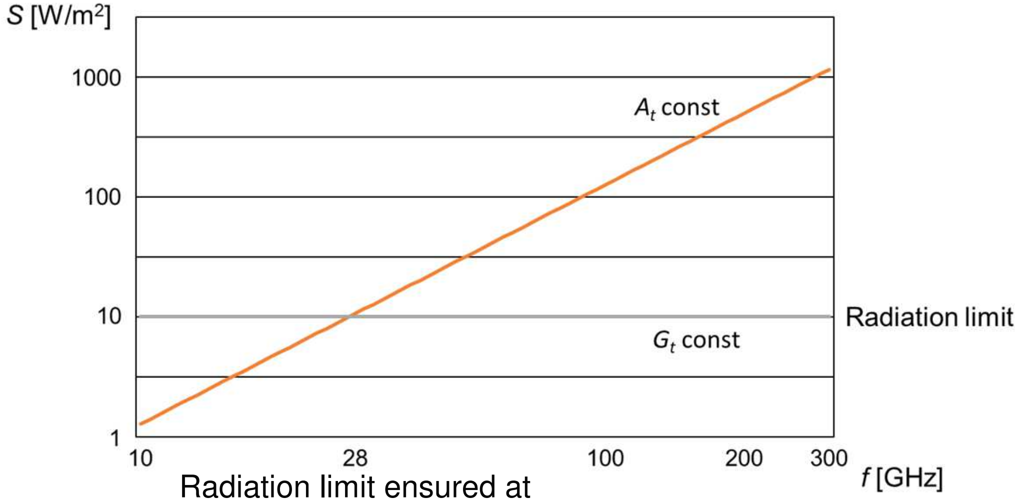
- *EIRP*

$$EIRP = P_t \cdot G_t$$

- Radiation density *S*

$$S = \frac{EIRP}{4 \cdot \pi \cdot r^2} = \frac{P_t \cdot G_t}{4 \cdot \pi \cdot r^2} \quad \text{with} \quad S_{max} \leq 10 \, {}^{W}\!/_{m^2} = 1 \, {}^{mW}\!/_{cm^2}$$

- Assumed reference distance
  - end devices used very closely by humans: $r_{min,\, d} = 0.1$ m
  - access points or base stations: $r_{min,\, BS} = 1.0$ m



Radiation limit ensured at 28 GHz (5G)

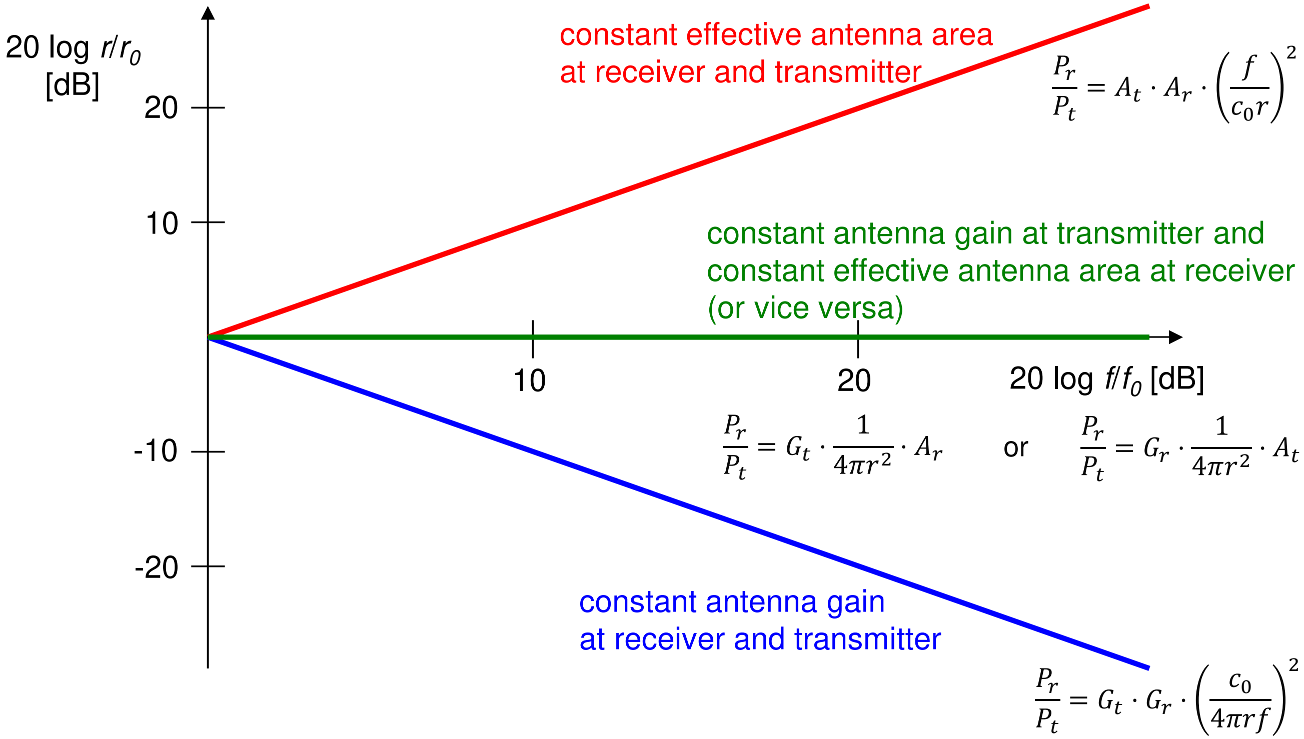
- In the approach to keep effective area *A* constant
  - receiver benefits from increased antenna gain with increased frequency
  - but for transmitter the transmit power P_t needs to be adapted to keep radiation density *S* within allowed limits
- *EIRP* needs to be constant versus frequency

Three cases of antenna configurations

Keeping either antenna gain or effective antenna area constant versus frequency

- Friis formula between receive and transmit power (assumption: free-space propagation)

$$\frac{P_r}{P_t} = G_t \cdot \frac{1}{4\pi r^2} \cdot A_r = G_t \cdot G_r \cdot \left(\frac{\lambda_0}{4\pi r}\right)^2 = G_t \cdot G_r \cdot \left(\frac{c_0}{4\pi r f}\right)^2 \quad \text{and} \quad A = G \frac{c_0{}^2}{4\pi \cdot f^2}$$

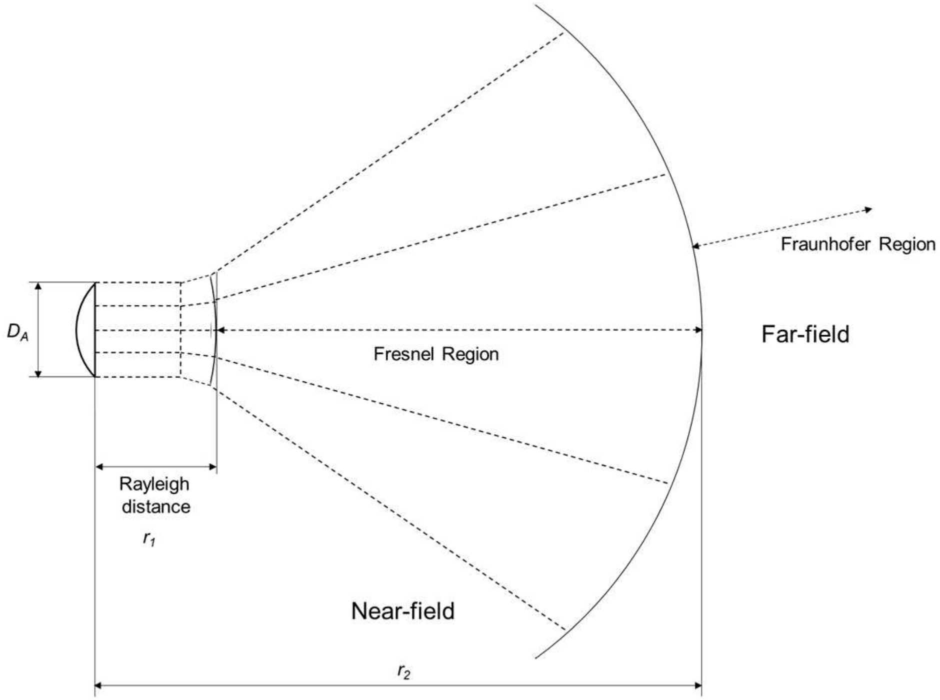


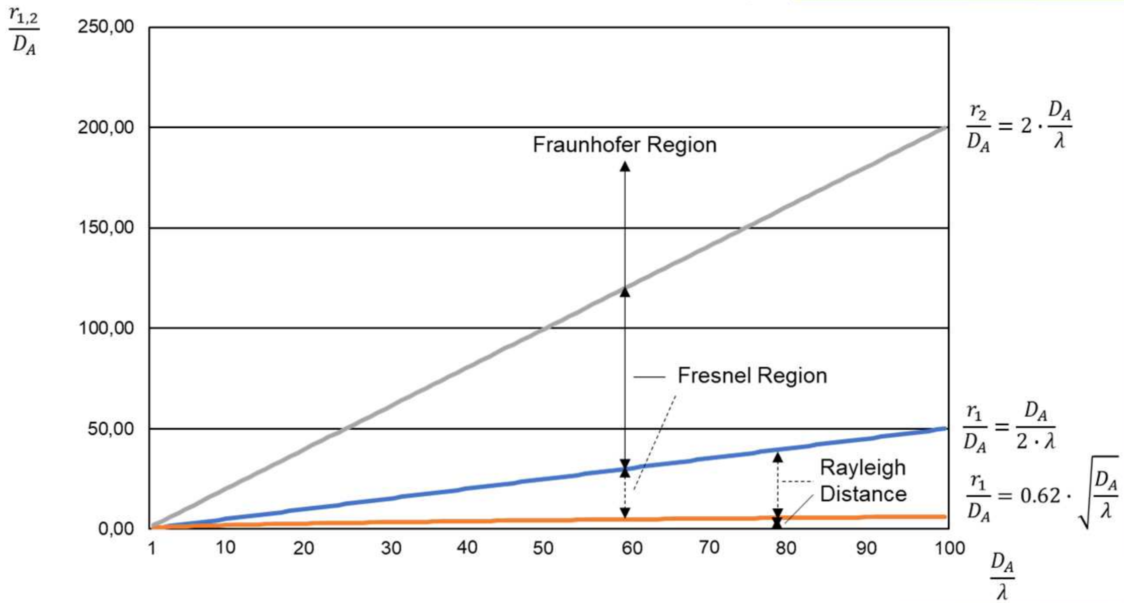
- Technically, increased propagation loss can be mitigated by appropriate antenna concepts
- Antennas may be used for the transmit and receive direction

Source: Rappaport, T.S., Xing, Y., Kanhere, O., Ju, S., Madanayake, A., Mandal, S., Alkhateeb, A., and G.C. Trichopoulos: Wireless Communications and Applications Above 100 GHz: Opportunities and Challenges for 6G and Beyond. IEEE Access, Vol.7, 2019, pp. 7829, https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8732419.

Near field versus far field

Low range results often in near field propagation conditions





- With increasing frequency far field region is growing

- Massive MIMO requires bigger antenna arrays
- System often operated under near field conditions, where far field antenna patterns do not apply
- What is the impact on MIMO algorithms?

Source: Zinke, O. and H. Brunswig: Lehrbuch der Hochfrequenztechnik. Vol. I, Springer-Verlag, Berlin, Heidelberg, New York, 2nd Edition, 1973.

Path-loss models

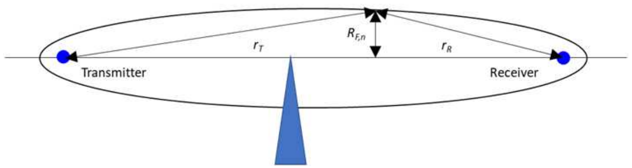
- General path-loss model

$$L_{ln}(r) = \overline{L_{ln}(r_0)} + 10 \cdot n \cdot \log\left(\frac{r}{r_0}\right) + X_\sigma \quad \text{[dB]}$$

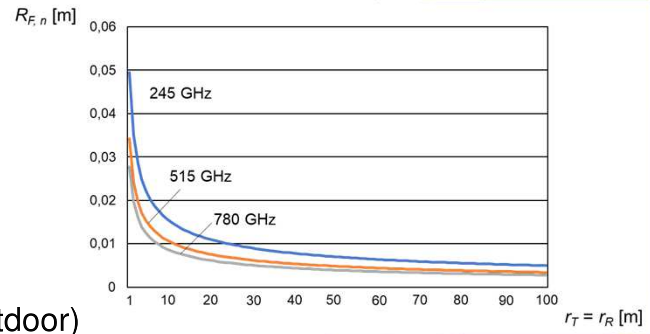
- With respect to high path-loss only deployment scenarios with free space propagation (n = 2) assumed
- X_σ zero mean Gaussian process in [dB] to describe random shadow fading
- Short-term fading (mainly Rice fading in this case) not considered, this would require additional margins
- Free-space propagation

$$L_{p,FS} = \left(\frac{c_0}{4\pi r f}\right)^2 \qquad \text{or} \qquad L_{p,FS} = 32.44 + 20 \cdot \log f + 20 \cdot \log r \quad [dB]$$

- First Fresnel-zone very narrow in Terahertz domain



$$R_{F,n} = \sqrt{n \cdot \lambda \cdot \frac{r_T + r_R}{r_T \cdot r_R}}$$

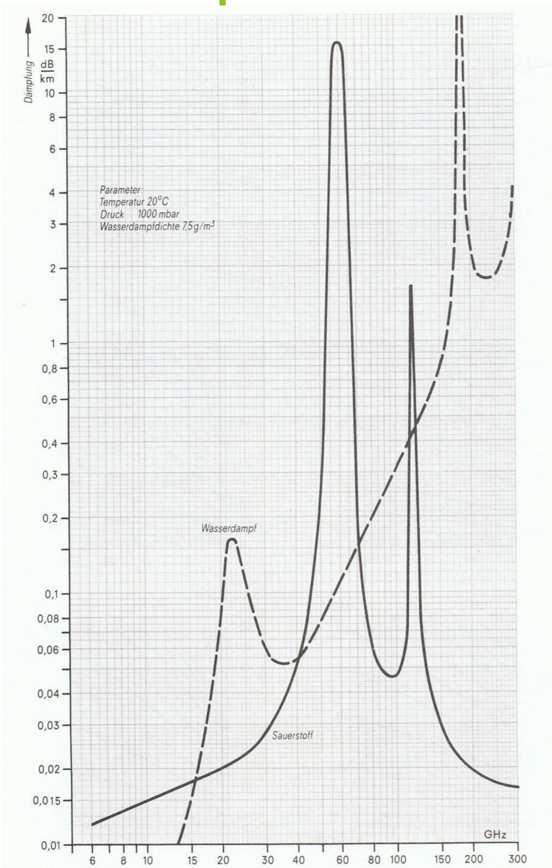


- Additional attenuation components to be considered in Terahertz domain
  - atmospheric path-loss due to water vapor, oxygen, other gases L_{at} (indoor and outdoor)
  - rain (and mist and fog) attenuation L_r (outdoor) and
  - foliage attenuation L_{fol} (outdoor)
  - wall penetration due to high path-loss not considered

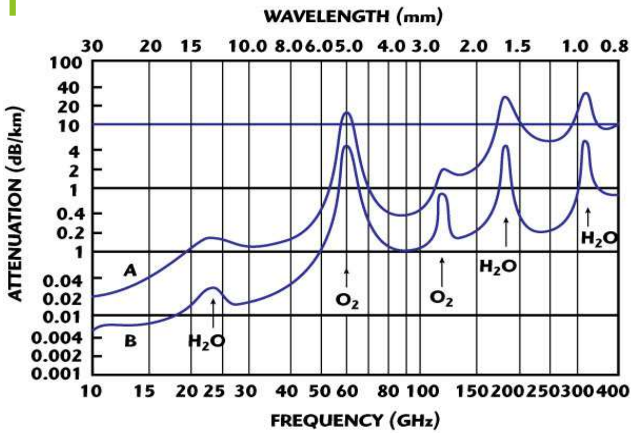
$$L_{p,total,outdoor}(f,r) = L_{p,FS}(f,r) + \frac{L_{at}(f, r_0 = 1km)}{1km} \cdot r + L_r(f,r) + L_{fol}(f,r) \text{ [dB]}$$

Source: Rappaport T.S.: Wireless Communications - Principles & Practice. New Jersey: Prentice Hall 1996.

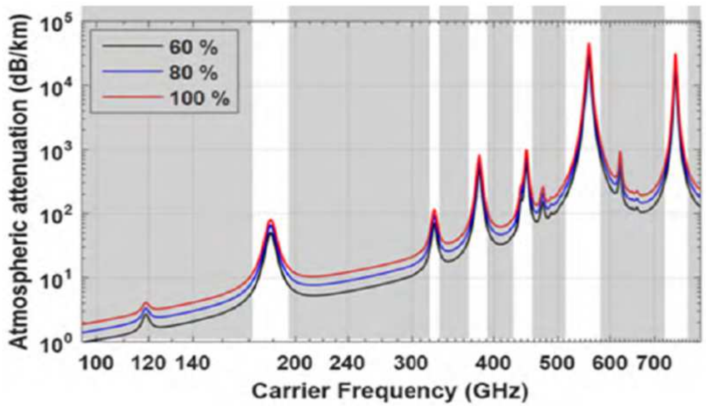
Atmospheric attenuation



Bildanlage 16
Absorption durch Wasserdampf und Sauerstoff in der Normalatmosphäre



Average atmospheric absorption of MMWs: (A) Sea Level: T = 20°C, P = 760mm, H_2O = 7.5 g/m³ (B) 4 km altitude: T = 0°C H_2O = 1 g/m³

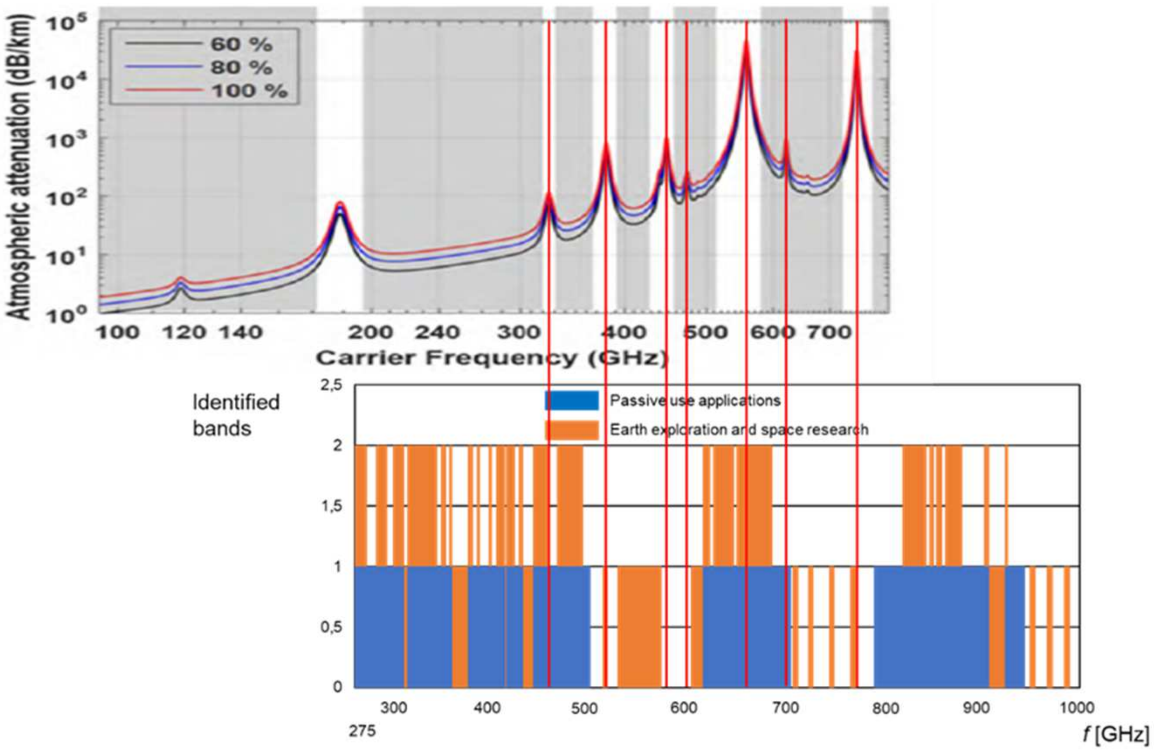


Source: Brodhage, H. and W. Hormuth: Planung und Berechnung von Richtfunkverbindungen. 10th updated edition, Siemens AG, Berlin – Munich, 1977.

Atmospheric attenuation https://www.google.de/search?q=atmospheric+attenuation&tbm=isch&imgil=_7j3UAzMc8V24M%253A%253BxavIlyPM90TYtM%253Bhttp%25253A%25252F%25252Fpropagation.ece.gatech.edu%25252FECE6390%25252Fproject%25252FFall2012%25252FTeam09%25252FTeam9GeoSatTech_website_FINAL%25252FSatCom%2525252520website%25252FatmosphericAttenuation.html&source=iu&pf=m&fir=_7j3UAzMc8V24M%253A%252CxavIlyPM90TYtM%252C_&usg=__Mg-xPyoRjlv0FLIIGW36BAnbW9k%3D&biw=1325&bih=731&ved=0ahUKEwi5-47n0sLVAhUgS48KHZz6DV0QyjcINA&ei=lhCHWbnYO6CWvQSc9bfoBQ#imgrc=h7rXWaRh3pkrGM:&spf=1502023840468.

Rappaport, T.S., Xing, Y., Kanhere, O., Ju, S., Madanayake, A., Mandal, S., Alkhateeb, A., and G.C. Trichopoulos: Wireless Communications and Applications Above 100 GHz: Opportunities and Challenges for 6G and Beyond. IEEE Access, Vol.7, 2019, pp. 7829, https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8732419.

Atmospheric attenuation in relation to frequency spectrum



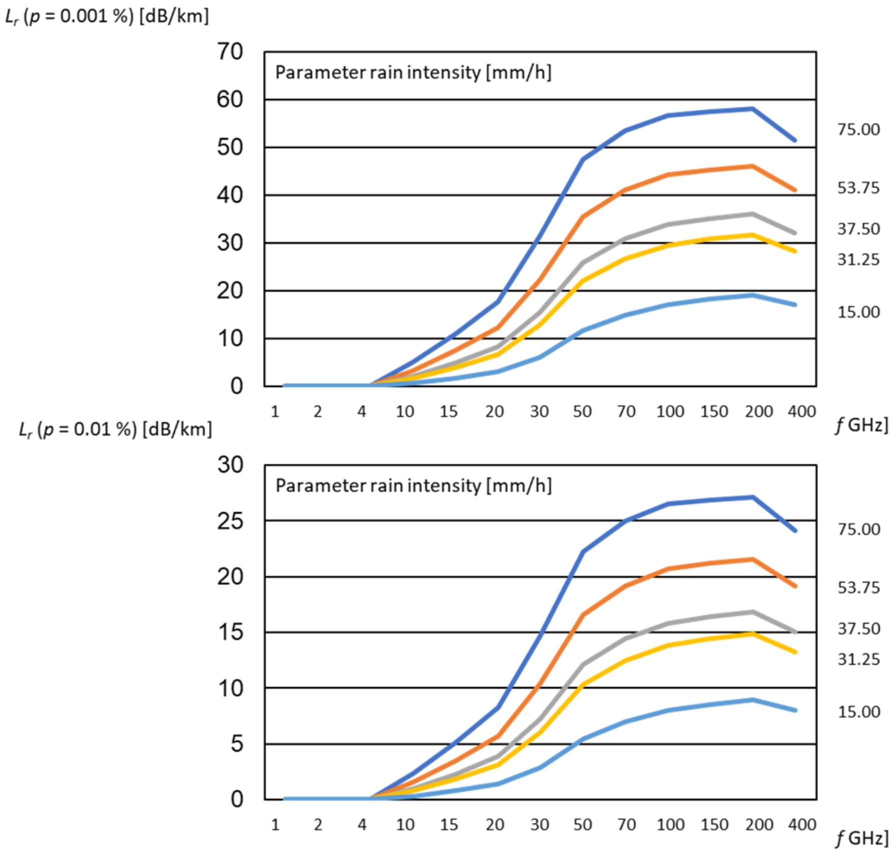
- Not allocated frequency bands are somehow correlated with absorption peaks

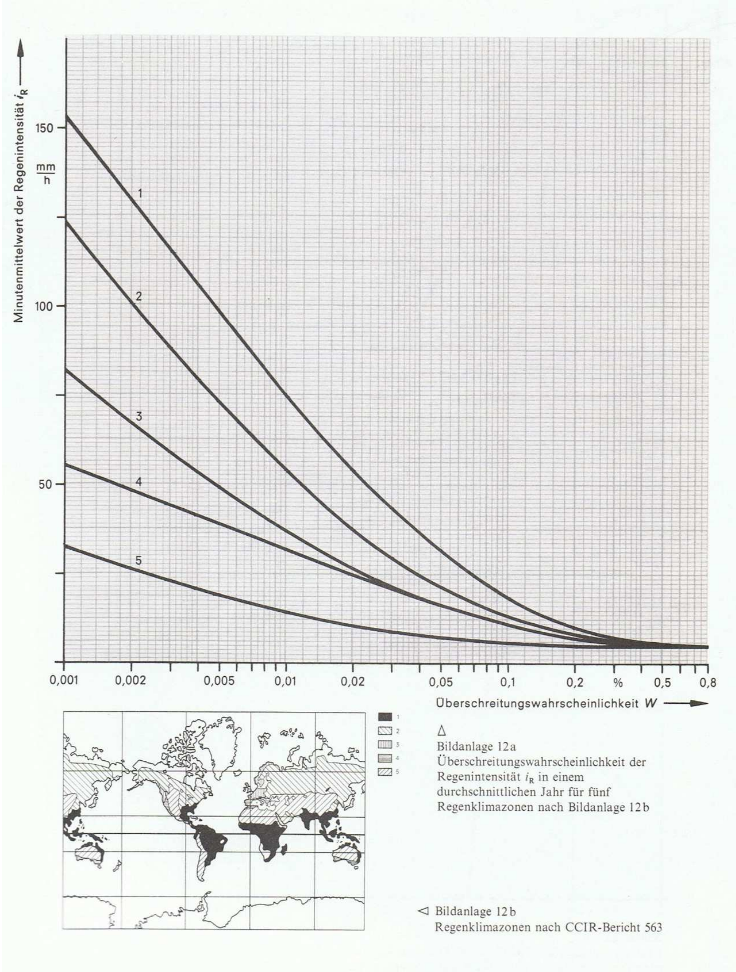
Source: Rappaport, T.S., Xing, Y., Kanhere, O., Ju, S., Madanayake, A., Mandal, S., Alkhateeb, A., and G.C. Trichopoulos: Wireless Communications and Applications Above 100 GHz: Opportunities and Challenges for 6G and Beyond. IEEE Access, Vol.7, 2019, pp. 7829, https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8732419.

ITU: Radio Regulations 2016, Vol. I to Vol. IV. https://www.itu.int/en/history/Pages/RadioRegulationsA.aspx?reg=1.43.

ITU: World Radiocommunication Conference 2019 (WRC-19) Final Acts. 28 October – 22 November Sharm El-Sheikh, Egypt, 2020, https://www.itu.int/dms_pub/itu-r/opb/act/R-ACT-WRC.14-2019-PDF-E.pdf.

Rain attenuation





- Maximum attenuation at around 200 GHz

Source: Brodhage, H. and W. Hormuth: Planung und Berechnung von Richtfunkverbindungen. 10th updated edition, Siemens AG, Berlin – Munich, 1977.

Recommendations and Reports of the CCIR: XVIth Plenary Assembly, Dubrovnik 1986, Vol. V: Propagation in Non-Ionized Media, Report 338-5, Propagation Data and Prediction Methods Required for Line-of Sight Radio Relay Systems, ITU, Geneva 1986.

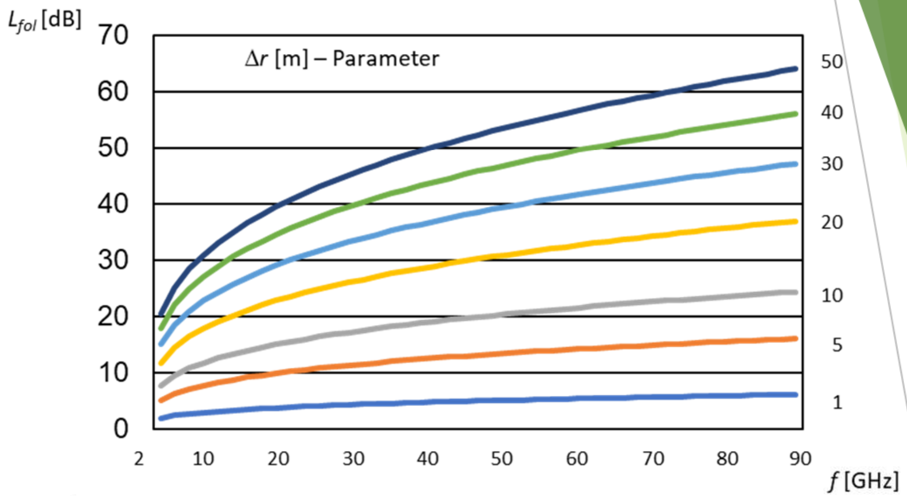
ITU-CCIR: CCIR Rep. 721-1, Recommendations and Reports of the CCIR, 1982, XV Plenary Assembly, Geneva 1982, Vol. 5.

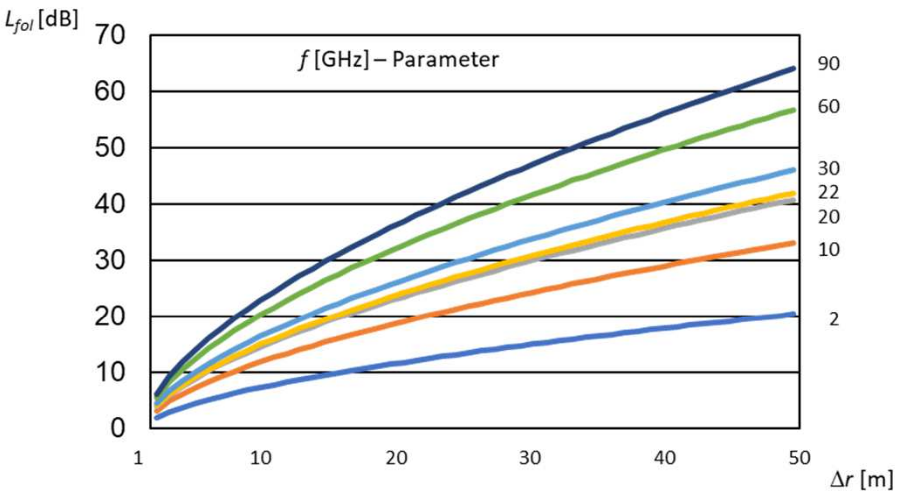
Jung, V. and H.-J. Warnecke: Handbuch für die Telekommunikation. Springer Verlag, Berlin, second edition, 2002.

Foliage attenuation

$$L_{fol} = 0.2 \cdot f^{0.3} \cdot \Delta r^{0.6} \quad [\mathrm{dB}]$$

- Where
  - f frequency in [MHz]
  - Δr depth of transversing foliage in [m]
  - and applied for Δr < 400 m
- Model is limited to f < 90 GHz





- Foliage deployment are avoided in the following due to high additional attenuation

Source: Federal Communications Commission: Millimeter Wave Propagation: Spectrum Management Implications. Office of Engineering and Technology, New Technology Development Division, Bulletin Number 70, July 1997.

Link capacity versus range

- Investigation at Shannon limit as best-case example

$$P_{r,min} = EIRP + G_r - L_p - L_{at} \cdot r - L_r \cdot r - M_{real} = \frac{S}{N} + N_0 + 10 \cdot \log W\Big|_{Hz} + F \quad [\text{dBm}]$$

- With increased bandwidth W compared to a reference bandwidth W_0 the link-budget is reduced by

$$\Delta L = 10 \cdot \log\left(\frac{W}{W_0}\right) \quad [\text{dB}]$$

$$C_{max} = W \cdot \log_2\left(1 + \frac{P_{r,min}{'}}{W \cdot N_0{'} \cdot F{'}}\right)$$

$$= W \cdot \log_2\left(1 + \frac{P_t{'} \cdot G_{t'} \cdot G_r{'}}{W \cdot N_0{'} \cdot F'} \cdot \left(\frac{1}{4 \cdot \pi \cdot r} \cdot \frac{c_0}{f}\right)^2 \cdot \left(L_{at,1km}{'} \cdot L_{r,1km}{'}\right)^r \cdot M_{real}{'}\right)$$

$$= W \cdot \log_2\left(1 + \frac{EIRP_{max}{'} \cdot G_r{'}}{W \cdot N_0{'} \cdot F{'}} \cdot \left(\frac{1}{4 \cdot \pi \cdot r} \cdot \frac{c_0}{f}\right)^2 \cdot \left(L_{at,1km}{'} \cdot L_{r,1km}{'}\right)^r \cdot M_{real}{'}\right) \; *$$

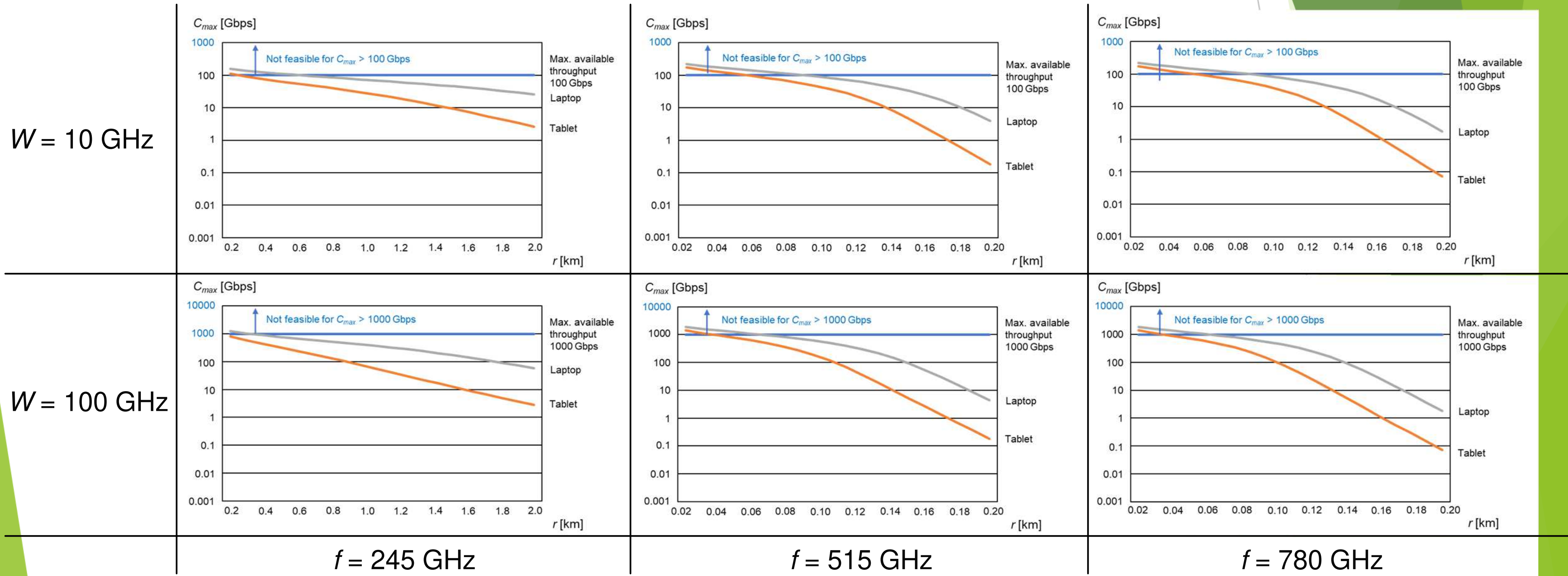
* x' means value in linear domain

- Selected parameters

Parameter		Values and comments		
f [GHz]		245	515	780
G_r [dB]	Downlink: Tablet, laptop, d_a = 0.02 m	34.2	40.7	44.3
	(d_a = 0.1 m)	(48.2)	(54.6)	(58.3)
	Uplink: Base station, d_a = 0.3 m	57.7	64.5	67.8
$EIRP$ [dBm]	Downlink	51 dBm ≙ 125.7 W		
	Uplink	31 dBm ≙ 1.257 W		
L_{at} [dB/km]	15 g/m³ water vapor density (245 GHz) 80 % humidity (515 GHz and 780 GHz)	6.3 to 10 8 average	240	260
L_r [dB/km]	Region 1	58.11	51.57	51.57
	Region 3	36.06	31.10	31.10
	Region 5	19.19	17.18	17.18
M_{eral} [dB]		2	2	2
N_0 [dBm/Hz]	290 K noise temperature	-174	-174	-174
F [dB]		2 to 5	2 to 5	2 to 5
W [GHz]	Parameter within the following limits	0 to 140 max 1 GHz 10 GHz 100 GHz 140 GHz	0 to 109 max 1 GHz 10 GHz 100 GHz 109 GHz	0 to 150 max 1 GHz 10 GHz 100 GHz 150 GHz

Downlink indoor capacity versus range

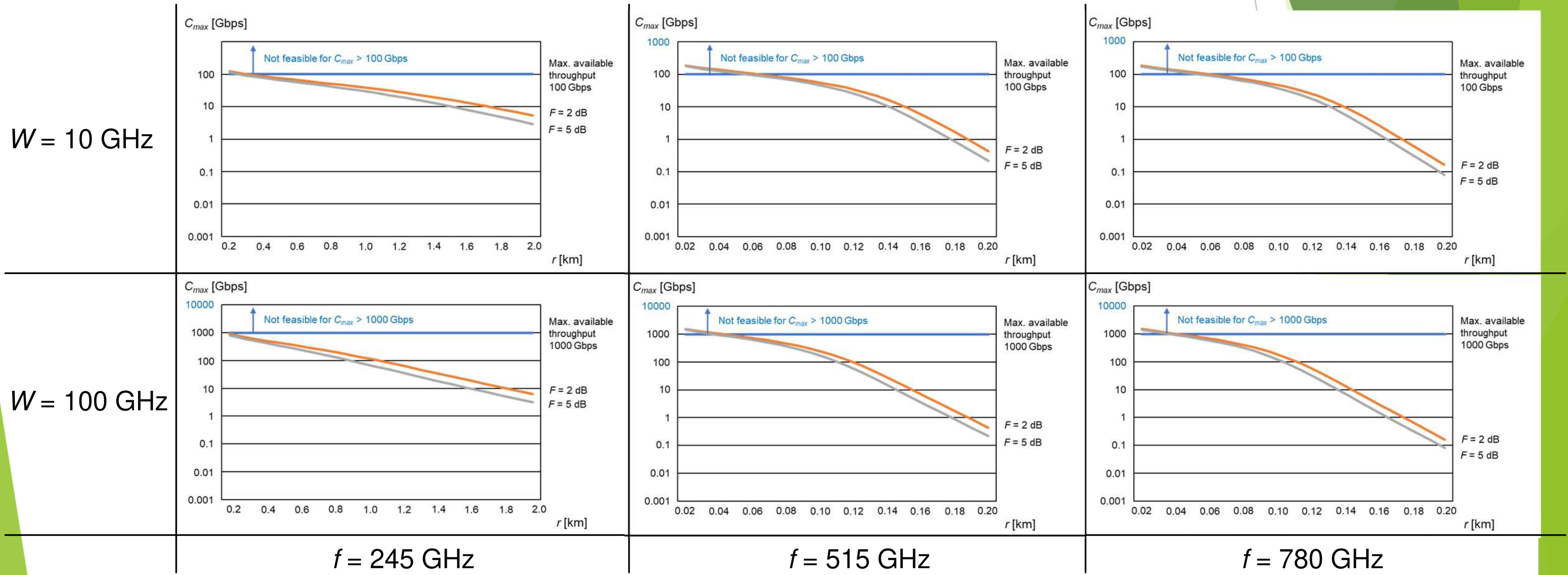
- Atmospheric attenuation for higher vapor density (15 g/m^3), tablets and laptops, F = 2 dB



- Practical modulation scheme limited to spectral efficiency of 10 bit/s/Hz

Uplink indoor capacity versus range

- Atmospheric attenuation for higher vapor density (15 g/m^3), base stations, F = 2 and 5 dB



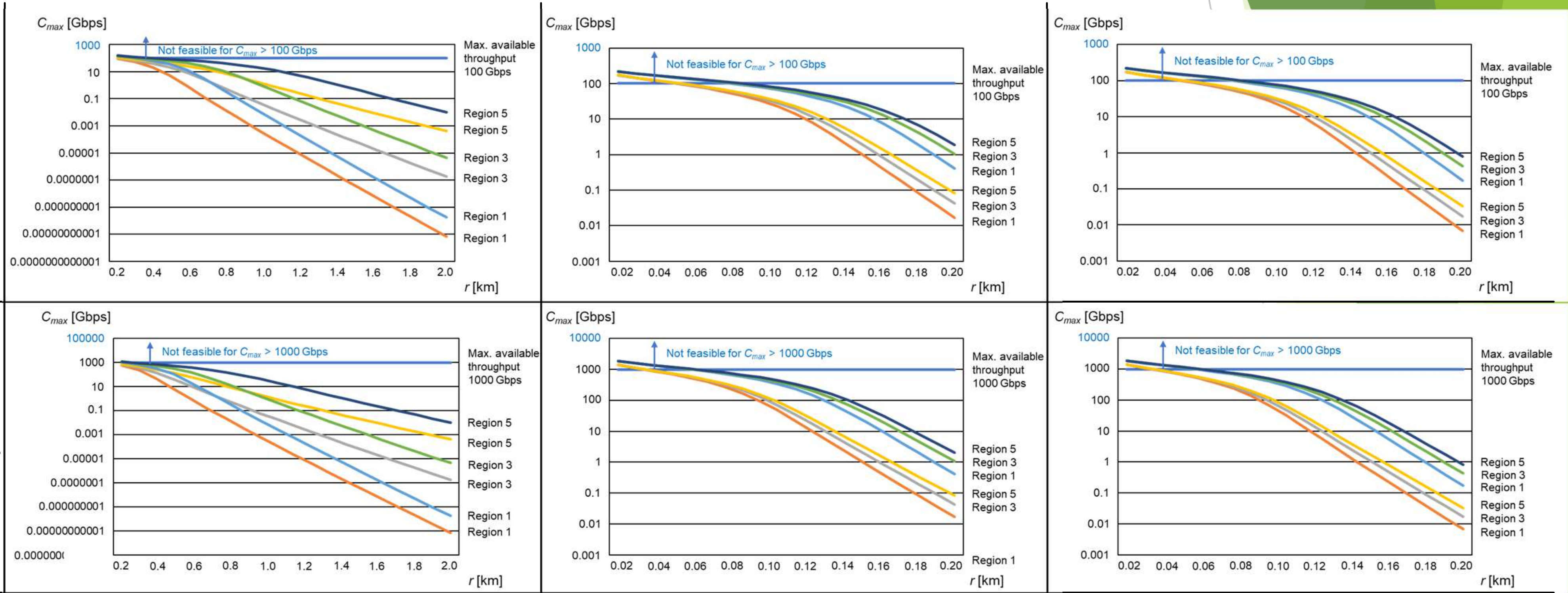
- Practical modulation scheme limited to spectral efficiency of 10 bit/s/Hz

Downlink outdoor capacity versus range

- Atmospheric attenuation for higher vapor density (15 g/m^3), rain attenuation for Regions 1, 3 and 5 (ρ = 0.001 %), tablets and laptops, F = 2 dB

W = 10 GHz

W = 100 GHz

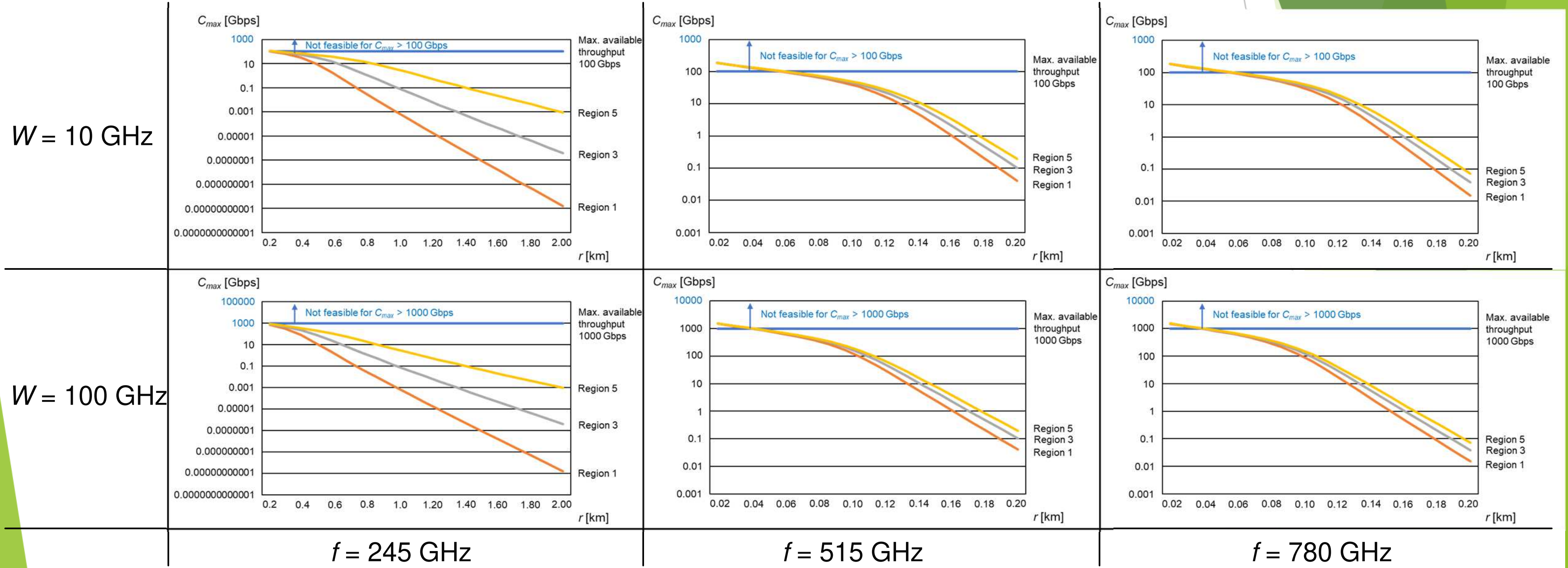


f = 245 GHz | f = 515 GHz | f = 780 GHz

- Practical modulation scheme limited to spectral efficiency of 10 bit/s/Hz

Uplink outdoor capacity versus range

- Atmospheric attenuation for higher vapor density (15 g/m^3), rain attenuation for Regions 1, 3 and 5 (ρ = 0.001 %), base stations, F = 2 and 5 dB



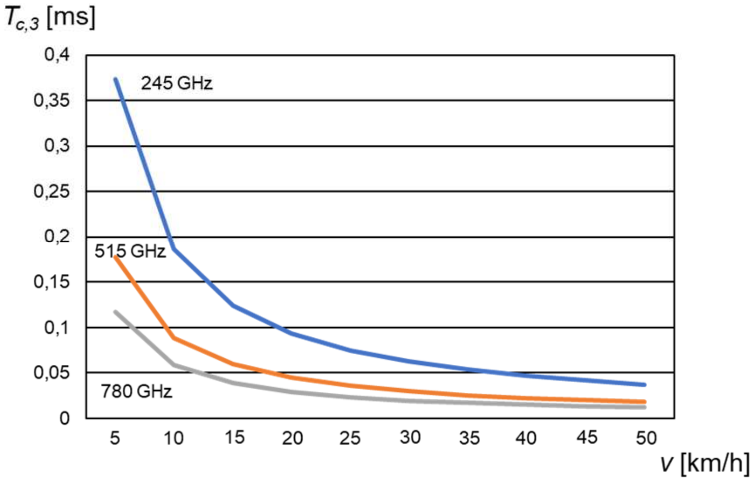
- Practical modulation scheme limited to spectral efficiency of 10 bit/s/Hz

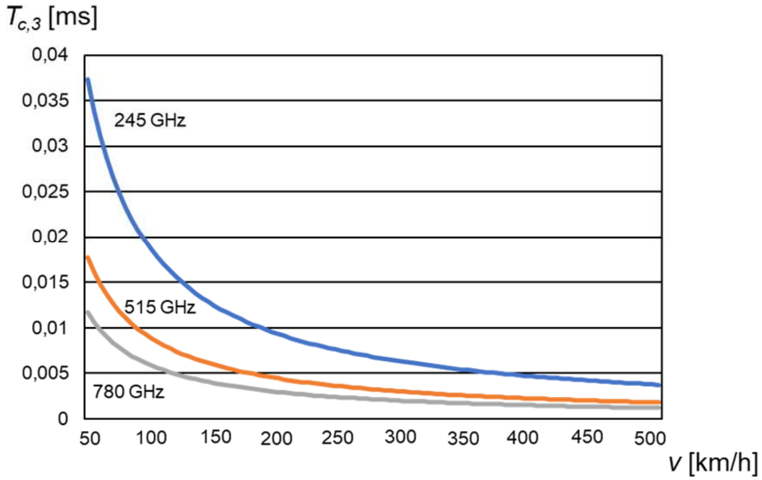
Coherence time

- Different definitions of coherence time

$$T_c \approx \frac{1}{f_{d,max}} \qquad T_{c,1} \approx \frac{1}{D_s} \qquad T_{c,2} \approx \frac{9}{16 \cdot \pi \cdot f_{d,max}} = \frac{1}{5.59 \cdot f_{d,max}} \qquad T_{c,3} \approx \sqrt{\frac{9}{16 \cdot \pi \cdot f_{d,max}{}^2}} = \frac{3}{4 \cdot \sqrt{\pi} \cdot f_{d,max}} = \frac{1}{2.36 \cdot f_{d,max}} \qquad T_{c,4} \approx \frac{1}{4 \cdot D_s}$$

- Evaluation for $T_{c,3}$



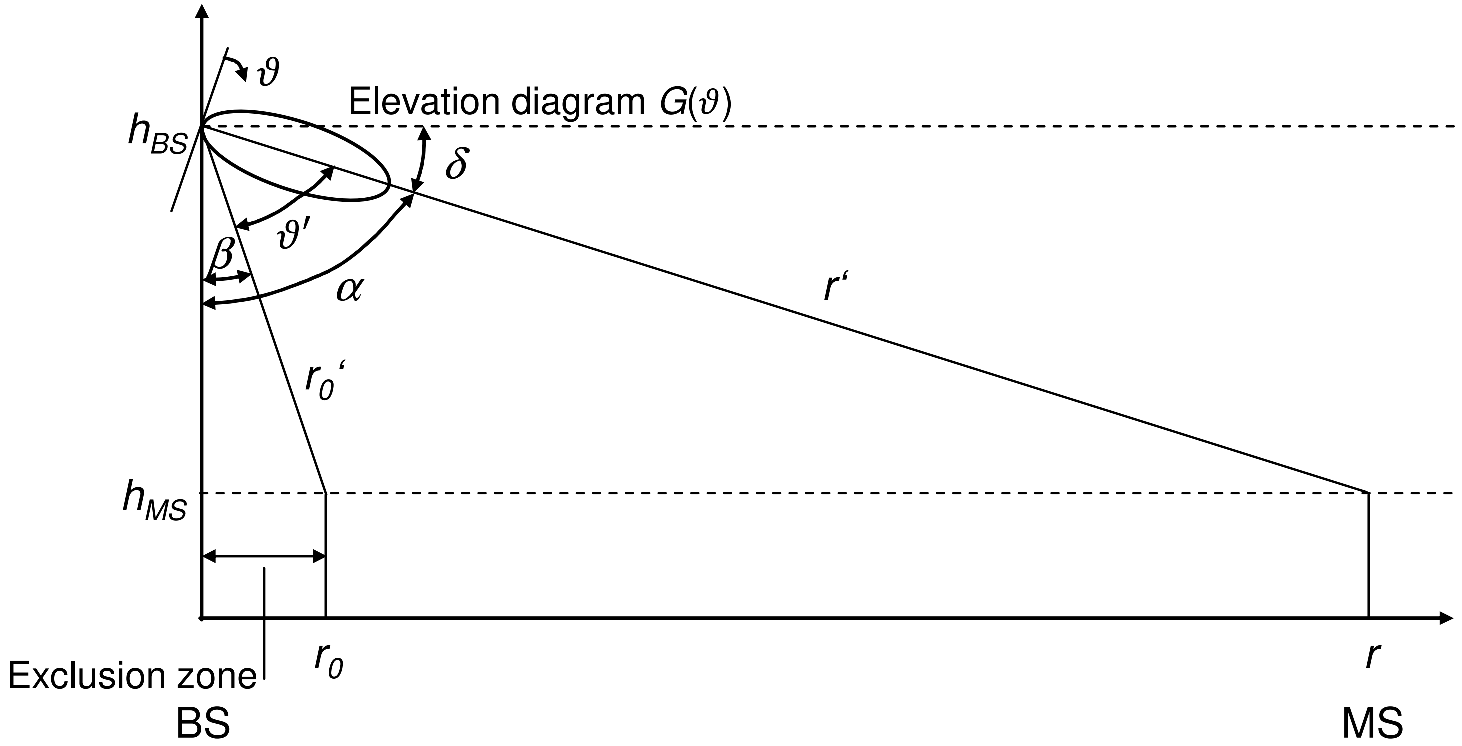


- Coherence time is very short, which requires very fast channel estimation and adaptation

Source: Rappaport T.S.: Wireless Communications - Principles & Practice. New Jersey: Prentice Hall 1996.
Tse, D. and P. Viswanath: Fundamentals of Wireless Communication. Cambridge University Press, Cambridge, 2005.
Steele, R.: Mobile radio communications. Pentech Press Publishers, London and IEEE Press, New York, 1994.

Means for range extension by keeping radiation limits

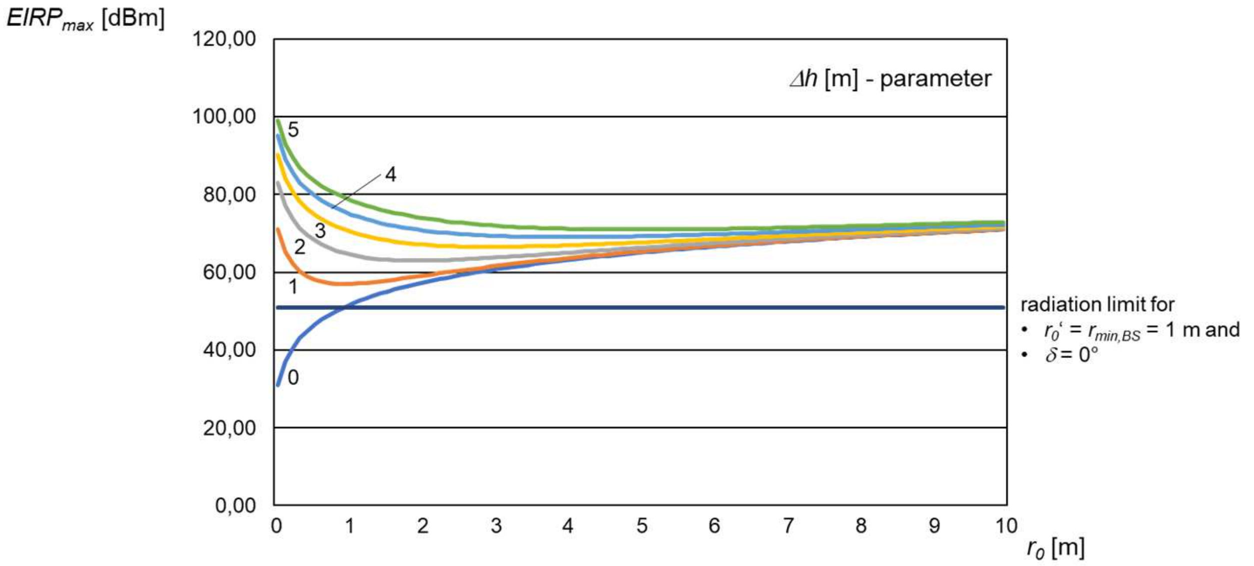
- Propagation scenario with increased base station antenna height $\Delta h = h_{BS} - h_{MS}$



- Elevation antenna diagram $G(\vartheta)$ considered
- This allows to increase maximum allowed $EIRP_{max}$ and thereby propagation range r towards cell edge

Means for range extension by keeping radiation limits

- Maximum allowed $EIRP_{max}$ versus distance r_0 between base station location and location of human
- Assumptions
  - Transmit antenna elevation diagram corresponds to Hertz dipole $sin^2(\vartheta)$ (simplification)
  - Downtilt angle $\delta = 0°$



- Minimum at $r_0 = \Delta h$ provides maximum allowed $EIRP_{max}(\Delta h) = 10\,\frac{\mathrm{W}}{\mathrm{m}^2} \cdot 16 \cdot \pi \cdot \Delta h^2$
- $EIRP_{max}$ allows to avoid exclusion zone with $r_0 = 0$

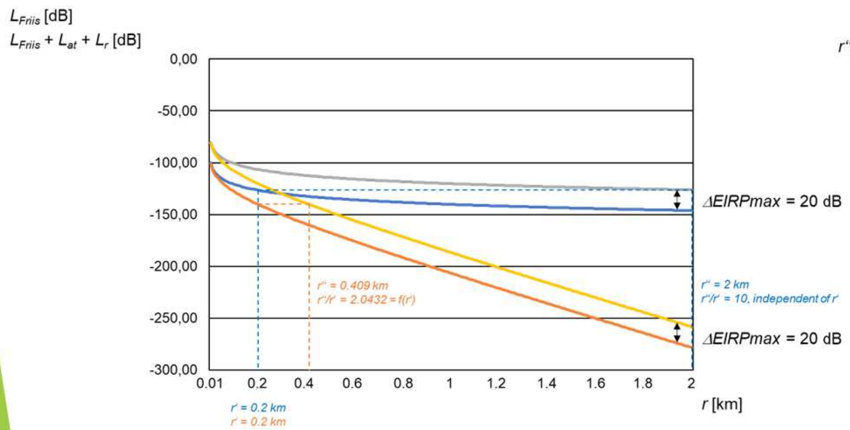
Means for range extension by keeping radiation limits

- For Friis formula of free-space propagation without additional attenuation components (atmosphere, rain) relative range extension *r“/r‘* independent of range *r‘*

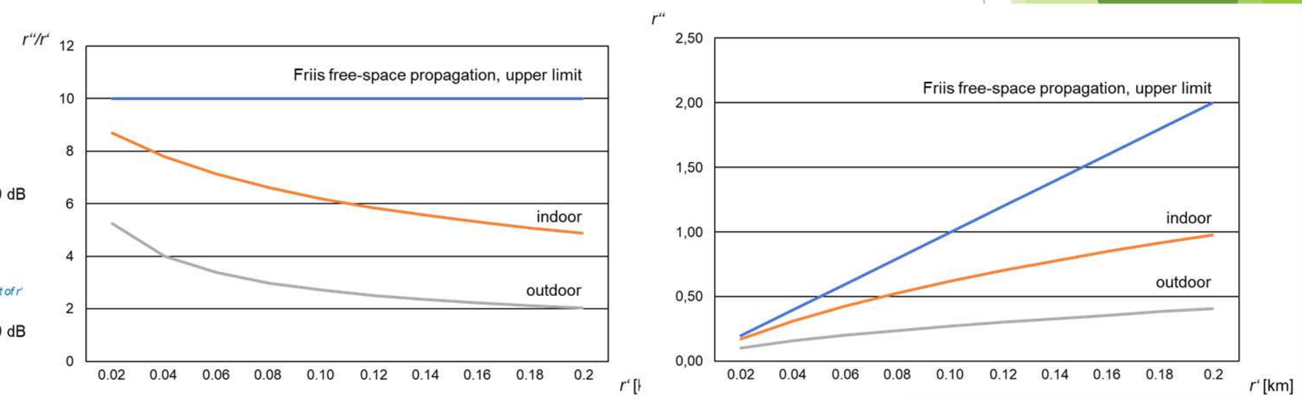
$$\frac{r''}{r'} = \frac{2 \cdot \Delta h}{r_{min,BS}}$$

- For additional attenuation components (atmosphere, rain) relative range extension *r“/r‘* is decreasing with range *r‘*, *r“/r‘* follows from zero search of

$$0 = \mathrm{r}' \cdot \left(\frac{L_r(f, r_0' = 1km)}{1km} + \frac{L_{at}(f, r_0' = 1km)}{1km} \right) \cdot \left(\frac{r''}{r'} - 1 \right) + \Delta EIRP_{max} - 10 \cdot \log \left(\frac{r''}{r'} \right)^2$$



Outdoor including free-space, atmospheric and rain attenuation



Indoor and outdoor including free-space, atmospheric and rain attenuation compared to upper limit of free-space only

Remote sensing applications based on active Radar concepts

- Sensing is based on Radar concepts
- Radar equation applies with Radar cross section σ depending on illuminated object (free space)

$$\frac{P_r}{P_t} = G_t \cdot \frac{1}{4\pi r^2} \cdot \sigma \cdot \frac{1}{4\pi r^2} \cdot A_r = {G_t}^2 \cdot \frac{{c_0}^2}{(4\pi)^3 \cdot r^4 \cdot f^2} \cdot \sigma$$

- Even under free-space propagation conditions without additional attenuation (atmosphere, rain) the effective path-loss is increasing with r^4
- Significant impact on achievable range r for higher frequencies, where atmospheric and rain attenuation are significant

$$\frac{P_r}{P_t} = G_t \cdot \frac{1}{4\pi r^2} \cdot (L_{at} \cdot L_r)^r \cdot \sigma \cdot \frac{1}{4\pi r^2} \cdot (L_{at} \cdot L_r)^r \cdot A_r = {G_t}^2 \cdot \frac{{c_0}^2}{(4\pi)^3 \cdot r^4 \cdot f^2} \cdot \sigma \cdot (L_{at} \cdot L_r)^{2r}$$

- Applications are limited to short range

Source: Meinke/Gundlach: Taschenbach der Hochfrequenztechnik. Berlin: Springer-Verlag 1986.

Conclusion

- Terahertz systems considered as part of beyond 5G / 6G systems
- Currently challenging technical requirements discussed in terms of carrier frequency, bandwidth and throughput
- Opportunity to identify significantly wider contiguous frequency bands in future WRCs in discussion with other service communities (radio astronomy, earth exploration satellites)
- In case of humans are involved in use cases and applications radiation limits to be respected
- Due to short range and high transmit antenna gain Terahertz systems mainly operated under near field conditions
- Path-loss significantly affected by
  - free space propagation (first Fresnel zone free of obstacles)
  - atmospheric attenuation
  - rain attenuation
  - foliage loss (should be avoided in deployments)
  - wall penetration loss scenarios not considered, because communication basically impossible
- Much better performance in terms of capacity versus range for indoor scenarios due to rain in outdoor
- Atmospheric attenuation can only be avoided in vacuum, e.g., inter-satellite links
- Higher base station antenna locations can increase range to a certain extend in downlink
- **In summary:**
  - Significant range limitations need to be considered for definition of use cases and applications especially for high throughput systems and where radiation limits to secure humans must be respected
  - For backhaul and fronthaul systems less stringent requirement on radiation limits, if no humans involved
  - Terahertz systems as cable replacements in data centers
  - Inter-satellite links in vacuum provides good propagation conditions