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

Submission Title: Preliminary Proposal for THz PHY in IEEE 802.15.3
Date Submitted: 21 July 2016
Source: Thomas Kürner, TU Braunschweig
Address Schleinitzstr. 22, D-38092 Braunschweig, Germany
Voice:+495313912416, FAX: +495313915192, E-Mail: kuerner@ifn.ing.tu-bs.de

Re: In response to TG3d 100 Gb/s Call for Proposals (15-15-0936-04-003d)

Abstract: TU Braunschweig / iBRoW Proposal for IEEE 802.15 TG3d
Purpose: To be considered in TG3d baseline document

Preliminary Proposal for a THz PHY in IEEE 802.15.3

List of Contributors

- Thomas Kürner (TU Braunschweig)
- Sebastian Rey (TU Braunschweig)
- Bile Peng (TU Braunschweig)
- Alexander Fricke (TU Braunschweig)
- Anthony Kelly (University of Glasgow)

This preliminary proposal is partially originating from the H2020-iBrow-project (www.ibrow-project.eu)

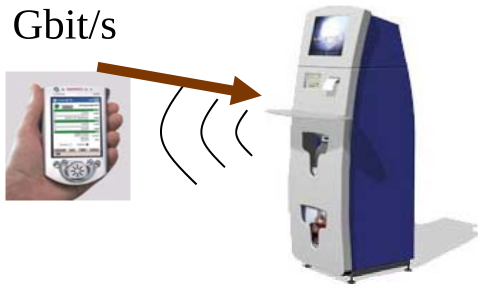
Outline

- Applications and Requirements for a 802.15.3d THz PHY
- Baseline for the preliminary proposal
- Channelization
- Modulation Schemes
- Forward Error Correction
- Data Rates and Link Budget

APPLICATIONS FOR A 802.15.3D THZ PHY

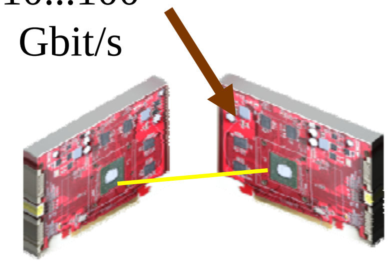
Applications for switched point-to-point links

10...100 Gbit/s



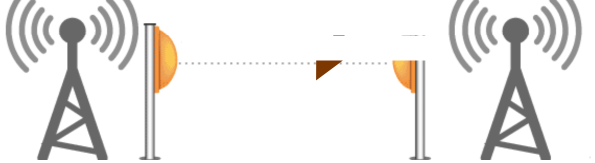
Kiosk downloads

10...100 Gbit/s



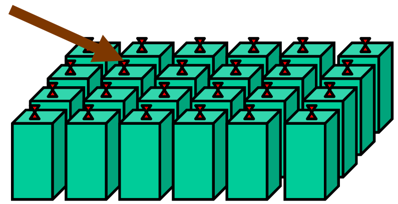
Intra-Device Communication

10..100 Gbit/s



Backhaul/Fronthaul links

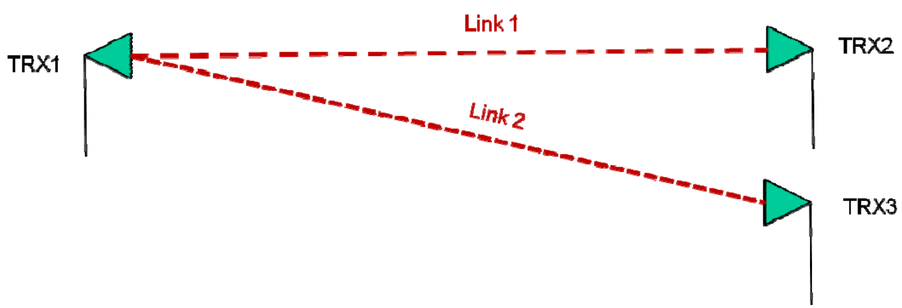
10...100 Gbit/s



Wireless Links in Data Centers

Common Characteristics of all four Applications

- It can be assumed that a-priori knowledge of the locations of Tx and Rx is available.
- As a consequence the efforts for device discovery and beam tracking may be reduced.
- Only two DEVs are involved in communications. However links may be switched between different DEVs



- The point-to-point nature with the application of highly directive antennas may yield less complex channels and less complex interference situations

BASELINE FOR THE PRELIMINARY PROPOSAL

Frequency Range and RF Channelization

- This proposal defines a PHY for the frequency range 252 – 325 GHz (called the ***THz PHY***)
- The links using the **THz PHY** are called ***THz links***
- The ***THz PHY*** may use larger bandwidth as used in the millimeter wave PHY defined in IEEE 802.15.3RevA. This will allow the use of less complex modulation schemes.
- Flexible bandwidths shall be achieved by channel bonding.

Features defined in IEEE P802.15.3e (HRCP)

- The applications Kiosk Downloading and Intra-Device Communications have some similarities to the applications currently considered in IEEE P802.15.3e
- Some features developed in IEEE P802.15.3e may also be applied in conjunction with the ***THz PHY***.
- The corresponding links will be called ***THz HRCP***
- This proposal also inherits the concept of ***pairnet*** as defined in IEEE P802.15.3e.
- For ***non-HRCP THz links*** the beacon may be not switched off after establishing the connection.

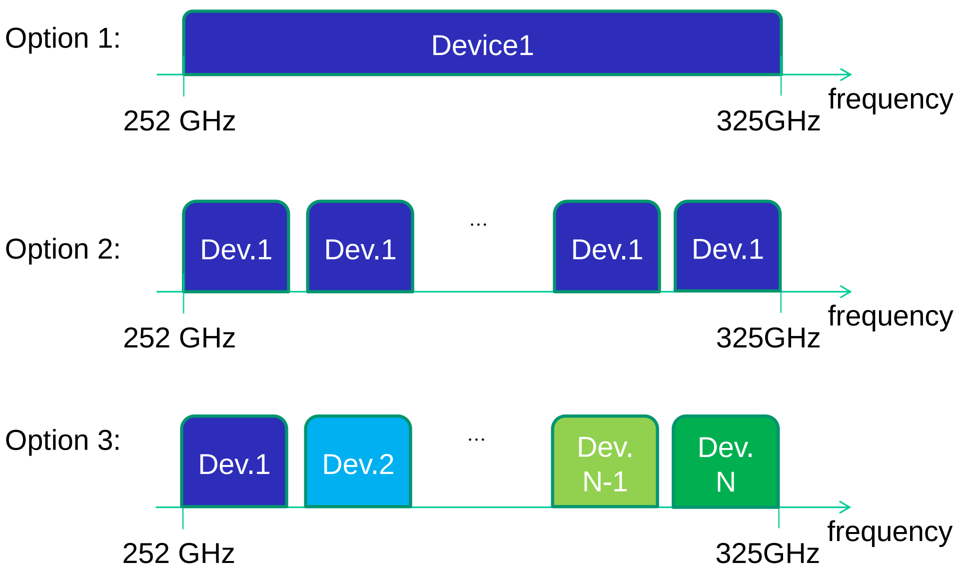
Modulation and Coding Schemes

- In order to enable the reuse of implementations based on IEEE P802.15.3RevA and IEEE P802.15.3e the modulation and coding schemes defined in the corresponding standards should be adopted as much as possible.
- However, other – more simple – coding schemes are defined in this proposal as well. This will be possible due to the less complex situation wrt channel properties and interference and will reduce complexity

CHANNELIZATION

Options for the utilisation of the spectrum

- In the TRD three principle options are provided for the utilization of the spectrum
- Due to the point-to-point nature of the applications considered in this project option 3 is not viable
- In order to achieve a better flexibility a variable bandwidth variant of option 2 is selected.



Source: IEEE 802.15 Doc Number 14/0309r20

Bandwidth of RF Channels

- In order to allow maximum compatibility with the channels defined in IEEE P802.15.3RevA and IEEE P802.15.3e RF channels are defined with bandwidths of multiples of 2.160 GHz
- The following bandwidths are possible for instances:

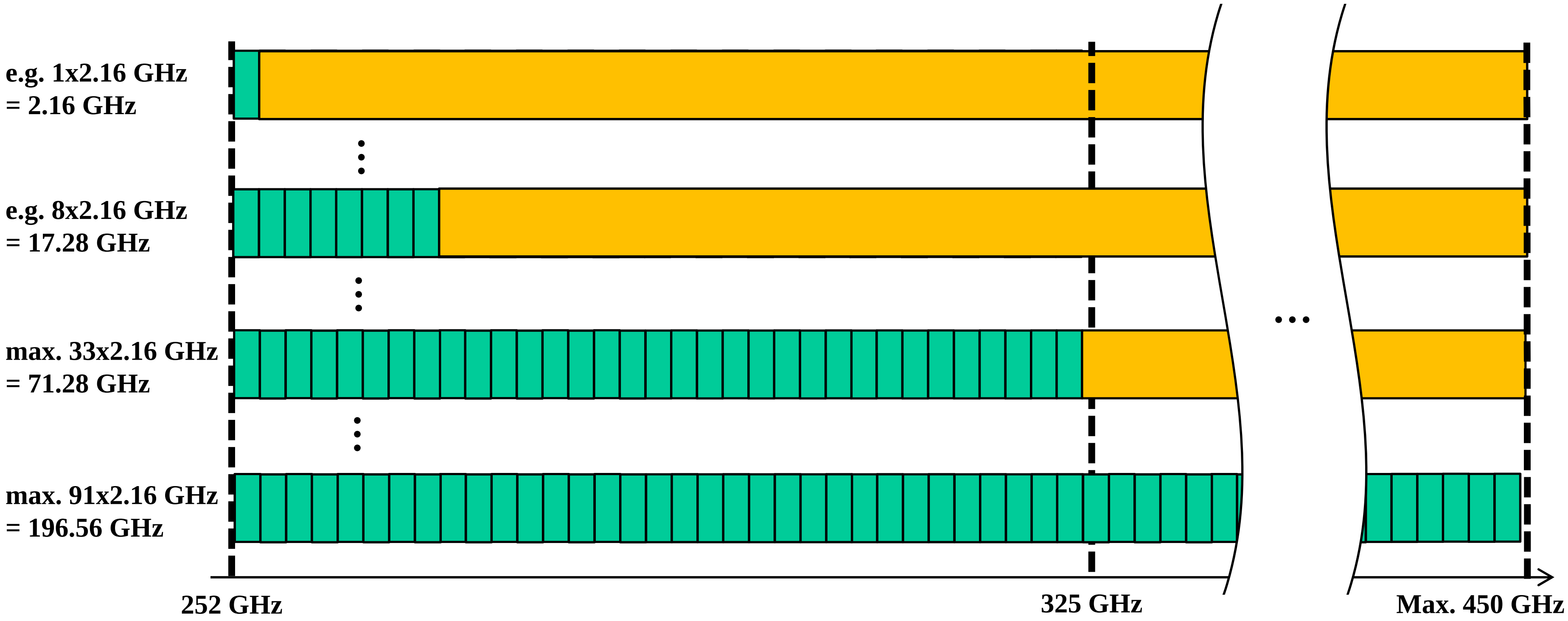
2.160 GHz	4.320 GHz
8.640 GHz	25.920 GHz
51.840 GHz	(103.680 GHz)*

* This is not supported by the current PAR, which covers a maximum bandwidth of 73 GHz only. However, this would allow to achieve a data rate of ~100 Gbps even with OOK

Reasoning for defining variable bandwidths

- Several Bandwidths allow for a flexible scaling of the data rate
- Highly compatible to existing standard with channel bonding
- Huge bandwidths allow for data rates of 50 to 100 Gbit/s even with OOK.

THz PHY Channelization



- **Flexible channelization based on multiples of 2.16 GHz for maximum compatibility**
- **resulting maximum bandwidth covered by PAR is 71.28 GHz**
- **resulting possible bandwidth according to WRC regulations is 196.56 GHz**

MODULATION SCHEMES

PHY Modes

- A compliant THz PHY shall implement at least one of the following PHY modes:

  a) Single carrier mode PHY

  – π/2-shift BPSK (required)
  – π/2-shift QPSK (required)
  – 8-PSK (optional)
  – 8-APSK (optional)
  – 16-QAM (optional)

  b) On-off keying mode PHY

Reasoning for Modulation Schemes of the SC mode PHY – 1 –

- π/2-shift BPSK
  - Compatible to existing standard
- π/2-shift QPSK
  - Reasonable data rate
  - Compatible to existing standard
  - 64 Gbit/s demonstrated e.g. in TERAPAN project (I. Kallfass *et al,* "Towards MMIC-Based 300GHz Indoor Wireless Communication Systems," *IEICE Trans. Electron,* vol. E98.C, no. 12, pp. 1081–1090, 2015.)

Reasoning for Modulation Schemes of the SC mode PHY – 2 –

- 8-PSK
  - Works for systems with limited linearity.
  - 30 Gbit/s demonstrated in Millilink project at 240 GHz (J. Antes *et al, Transmission of an 8-PSK modulated 30 Gbit/s signal using an MMIC-based 240 GHz wireless link*. IEEE MTT-S International Microwave Symposium Digest (IMS), 2013.)
- 8-APSK
  - Works for systems with limited linearity but in comparison is more robust to phase noise than 8-PSK.
- 16 QAM
  - 100 Gbit/s demonstrated at 240 GHz with an optical transmitter and an electronic receiver (S. Koenig *et al, 100 Gbit/s Wireless Link with mm-Wave Photonics*. Anaheim, California: Optical Society of America, 2013.)

Reasoning for OOK Phy

- Simple modulation scheme trades spectral efficiency for simplicity and therefore cost
- RTD based devices with integrated antennae are being developed in Japan, several European groups and in particular the I-BROW project
- Systems demonstrated up to and beyond 300GHz
- Potentially very low cost technology

OOK based RTD communications

- Oscillators up to 1.92 THz have been demonstrated. [T. Maekawa, H. Kanaya, S. Suzuki, and M. Asada, Appl. Phys. Express, 9, 024101 (2016).]
- Wireless data transmission of 30 Gb/s at 490 GHz. [N. Oshima, H. Hashimoto, D. Horikawa, S. Suzuki, and M. Asada, IEEE International Microwave Symposium,San Francisco, THIF2, May 2016.]
- Receiver functionality has been demonstrated at 300GHz. [T. Shiode, T. Mukai, M. Kawamura, and T. Nagatsuma, “Giga-bit wireless communication at 300 GHz using resonant tunneling diode detector,” in Proc. Asia-Pacific Microw. Conf. (APMC2011), pp. 1122-1125, Dec. 2011.]
- iBROW is developing systems for 10Gbit/s at 300GHz

FORWARD ERROR CORRECTION

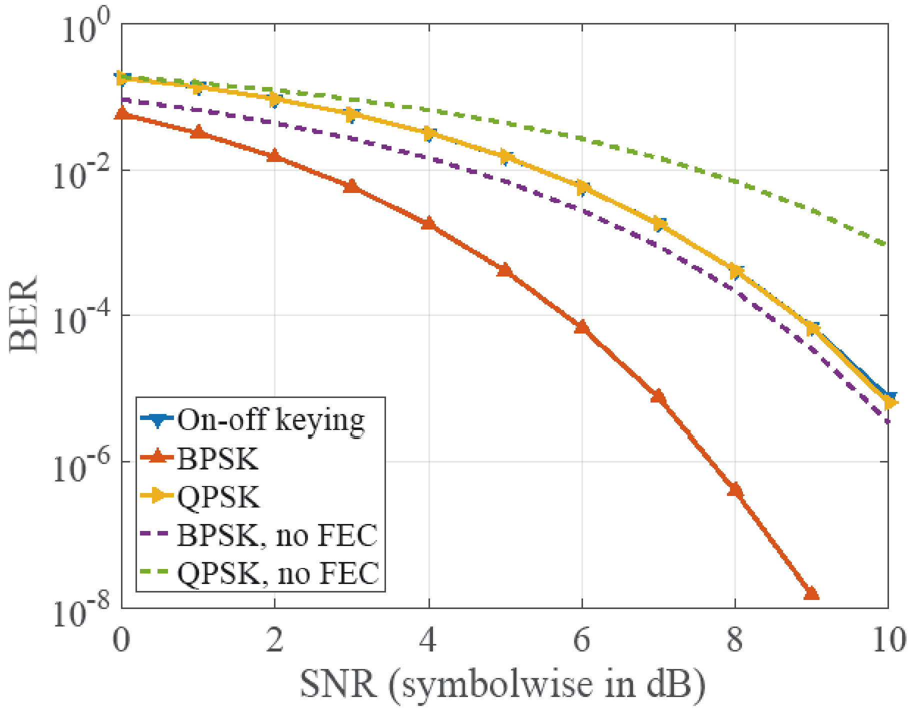
FEC defined in IEEE P802.15.3RevA and IEEE P802.15.3e

- The following FEC shall be reused*.
  - Rate 14/15 LDPC (1440,1344)
  - Rate 11/15 LDPC (1440,1056)
  - LDPC (672,336)
  - LDPC (672,504)
  - LDPC (672,588)
  - RS (255,239) in GF(2^8)

* In the full proposal a down-selection may be applied based on the results based on simulations using the TG3d channel models

Simpler FEC schemes

- Due to the extremely high data rate, a simpler FEC with less decoding complexity is of great advantage in hardware realization.
- The performance of a (7,4) Hamming code in an AWGN-channel is depicted in the figure on the right.
- See also: Doc. IEEE 802.15-13-0406-00



DATA RATES AND LINK BUDGET

					Data rate [Gb/s] w/o PW			Data rate [Gb/s] w/ PW		
MCS Identifier	**Modulation**	**Spectral Efficiency**	**FEC Type**	**FEC Rate**	**per Channel**	**max @ 325 GHz**	**max @ 450GHz**	**per Channel**	**max @ 325GHz**	**max @ 450GHz**
0	π/2-shift BPSK	1	LDPC (1440,1344)	14/15	1.6427	54.2080	**149.4827**	1.4373	47.4320	**130.7973**
1	π/2-shift BPSK	1	LDPC (1440,1056)	11/15	1.2907	42.5920	**117.4507**	1.1293	37.2680	**102.7693**
2	π/2-shift BPSK	1	LDPC (672,588)	7/8	1.5400	50.8200	**140.1400**	1.3475	44.4675	**122.6225**
3	π/2-shift BPSK	1	LDPC (672,504)	3/4	1.3200	43.5600	**120.1200**	1.1550	38.1150	**105.1050**
4	π/2-shift BPSK	1	LDPC (672,336)	1/2	0.8800	29.0400	80.0800	0.7700	25.4100	70.0700
5	π/2-shift BPSK	1	RS (255,239) in GF(28)	239/255	1.6496	54.4358	**150.1107**	1.4434	47.6313	**131.3469**
6	π/2-shift QPSK	2	LDPC (1440,1344)	14/15	3.2853	**108.4160**	**298.9653**	2.8747	94.8640	**261.5947**
7	π/2-shift QPSK	2	LDPC (1440,1056)	11/15	2.5813	85.1840	**234.9013**	2.2587	74.5360	**205.5387**
8	π/2-shift QPSK	2	LDPC (672,588)	7/8	3.0800	**101.6400**	**280.2800**	2.6950	88.9350	**245.2450**
9	π/2-shift QPSK	2	LDPC (672,504)	3/4	2.6400	87.1200	**240.2400**	2.3100	76.2300	**210.2100**
10	π/2-shift QPSK	2	LDPC (672,336)	1/2	1.7600	58.0800	**160.1600**	1.5400	50.8200	**140.1400**
11	π/2-shift QPSK	2	RS (255,239) in GF(28)	239/255	3.2991	**108.8715**	**300.2215**	2.8867	95.2626	**262.6938**
12	8-PSK	3	LDPC (1440,1344)	14/15	4.9280	**162.6240**	**448.4480**	4.3120	**142.2960**	**392.3920**
13	8-PSK	3	LDPC (1440,1056)	11/15	3.8720	**127.7760**	**352.3520**	3.3880	**111.8040**	**308.3080**
14	8-PSK	3	LDPC (672,588)	7/8	4.6200	**152.4600**	**420.4200**	4.0425	**133.4025**	**367.8675**
15	8-PSK	3	LDPC (672,504)	3/4	3.9600	**130.6800**	**360.3600**	3.4650	**114.3450**	**315.3150**
16	8-PSK	3	LDPC (672,336)	1/2	2.6400	87.1200	**240.2400**	2.3100	76.2300	**210.2100**
17	8-PSK	3	RS (255,239) in GF(28)	239/255	4.9487	**163.3073**	**450.3322**	4.3301	**142.8939**	**394.0407**
18	16-QAM	4	LDPC (1440,1344)	14/15	6.5707	**216.8320**	**597.9307**	5.7493	**189.7280**	**523.1893**
19	16-QAM	4	LDPC (1440,1056)	11/15	5.1627	**170.3680**	**469.8027**	4.5173	**149.0720**	**411.0773**
20	16-QAM	4	LDPC (672,588)	7/8	6.1600	**203.2800**	**560.5600**	5.3900	**177.8700**	**490.4900**
21	16-QAM	4	LDPC (672,504)	3/4	5.2800	**174.2400**	**480.4800**	4.6200	**152.4600**	**420.4200**
22	16-QAM	4	LDPC (672,336)	1/2	3.5200	**116.1600**	**320.3200**	3.0800	**101.6400**	**280.2800**
23	16-QAM	4	RS (255,239) in GF(28)	239/255	6.5983	**217.7431**	**600.4430**	5.7735	**190.5252**	**525.3876**

Data Rates for the more simpler Modulation and/or Coding Schemes

					Data rate [Gb/s] w/o PW			Data rate [Gb/s] w/ PW		
MCS Identifier	Modulation	Spectral Efficiency	FEC Type	FEC Rate	per Channel	max @ 325GHz	max @ 450GHz	per Channel	max @ 325GHz	max @ 450GHz
24	OOK	1	LDPC (1440,1344)	14/15	1,6427	54,2080	**149,4827**	1,4373	47,4320	**130,7973**
25	OOK	1	LDPC (1440,1056)	11/15	1,2907	42,5920	**117,4507**	1,1293	37,2680	**102,7693**
26	OOK	1	LDPC (672,588)	7/8	1,5400	50,8200	**140,1400**	1,3475	44,4675	**122,6225**
27	OOK	1	LDPC (672,504)	3/4	1,3200	43,5600	**120,1200**	1,1550	38,1150	**105,1050**
28	OOK	1	LDPC (672,336)	1/2	0,8800	29,0400	80,0800	0,7700	25,4100	70,0700
29	OOK	1	RS (255,239) in GF(28)	239/255	1,6496	54,4358	**150,1107**	1,4434	47,6313	**131,3469**
30	OOK	1	Hamming (7,4)	4/7	1,0057	33,1886	91,5200	0,8800	29,0400	80,0800
31	π/2-shift BPSK	1	Hamming (7,4)	4/7	1,0057	33,1886	91,5200	0,8800	29,0400	80,0800
32	π/2-shift QPSK	2	Hamming (7,4)	4/7	2,0114	66,3771	**183,0400**	1,7600	58,0800	**160,1600**
33	8-PSK	3	Hamming (7,4)	4/7	3,0171	99,5657	**274,5600**	2,6400	87,1200	**240,2400**
34	16-QAM	4	Hamming (7,4)	4/7	4,0229	**132,7543**	**366,0800**	3,5200	**116,1600**	**320,3200**

Link Budget – 1 –

- Based on:
  I. Kallfass *et al,* “Towards MMIC-Based 300GHz Indoor Wireless Communication Systems,” *IEICE Trans. Electron,* vol. E98.C, no. 12, pp. 1081–1090, 2015.
- Tx Power: -4.0 dBm
- (Bandwidth 64 GHz)
- Rx noise figure 6.7 dB

- Thermal noise for a bandwidth of 51.840 GHz:
  -66.9 dBm

Link Budget – 2 –

- Assuming:
  - Tx Power: -4.0 dBm
  - Bandwidth 50.84 GHz
  - Rx noise figure 6.7 dB

- For an SNR of 10 dB with only free space path loss:

Distance [m]	0.1	1	10	100	1,000
Required Gain per Antenna [dBi]	6.9	16.9	26.9	36.9	48.9

- Covers the whole range of applications with different antennas.