

January 2017 doc.: IEEE 802. 15-17-0039-02-003d-summary-of-results-from-link-level-simulations

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

Submission Title: Summary of Results from TG3d Link Level Simulations

Date Submitted: 16 January 2017

Source: Thomas Kürner, TU Braunschweig

E-Mail: kuerner@ifn.ing.tu-bs.de

Re: n/a

Abstract: This document provides a summary of results from TG3d link level simulations. The results are intended to be included in the draft standard IEEE 802.15.3d or for validation the technical requirements of the standard

Purpose: Discussion document for the TG 3d

Notice: This document has been prepared to assist the IEEE P802.15. It is offered as a basis for discussion and is not binding on the contributing individual(s) or organization(s). The material in this document is subject to change in form and content after further study. The contributor(s) reserve(s) the right to add, amend or withdraw material contained herein.

Release: The contributor acknowledges and accepts that this contribution becomes the property of IEEE and may be made publicly available by P802.15.

Summary of Results from TG3d Link Level Simulations

Thomas Kürner
TU Braunschweig

Outline

- Basis for the calculations
- Deriving maximum EVM at the transmitter
- Required Receiver Sensitivity
- Achieved maximum link distances

Basis for the calculations

- The following calculations are based on the results from doc. 16/0746r7 “Preliminary Performance of FEC schemes in-TG3d channels”, where required minimum SNR values have been derived using the TG3d channel models:

<https://mentor.ieee.org/802.15/dcn/16/15-16-0746-07-003d-preliminary-performance-of-fec-schemes-in-tg3d-channels.pdf>

EVM

- The draft standard requires numbers for the maximum Error Vector Magnitude (EVM), that shall be measured at a compliant the transmitter
- In the following table it has been assumed that the EVM at the transmitter should be at least correspond to the minimum required SNR for an AWGN channel.

Suggestion for Table 11b-13 Maximum EVM

MCS Identifier	Modulation	FEC Rate	Max. EVM [dB]
0	BPSK	11/15	-3
1	BPSK	14/15	-6
2	QPSK	11/15	-6
3	QPSK	14/15	-9
4	8-PSK	11/15	-11
5	8-PSK	14/15	-14
6	8-APSK	11/15	-11
7	8-APSK	14/15	-14
8	16QAM	11/15	- 13
9	16-QAM	14/15	- 16
10	64-QAM	11/15	- 18
11	64-QAM	14/15	- 22

Receiver Sensitivity

- The receiver sensitivity has to be calculated for each of the defined eight bandwidths.
- A noise figure of 8 dB is assumed for the receiver
- The minimum SNR assumed is the value derived from the simulations of the AWGN channel increased by 3 dB.
- The increase of 3dB is required in order to take into account the additional noise originating from variations of the signal due to the EVM at the transmitter. It is assumed that the noise at the receiver and the EVM at the transmitter are uncorrelated.

Suggestion for Table 11b-14 Reference Sensitivity Levels for MCS for the THz-SC PHY

MCS Identifier	Modulation	FEC Rate	Receiver Sensitivity [dBm] depending on the bandwidth							
			2.16 GHz	4.32 GHz	8.64 GHz	12.96 GHz	17.28 GHz	25.92 GHz	51.84 GHz	69.12 GHz
0	BPSK	11/15	-67	-64	-61	-59	-58	-56	-53	-52
1	BPSK	14/15	-63	-60	-57	-55	-54	-52	-49	-48
2	QPSK	11/15	-64	-61	-58	-56	-55	-53	-50	-49
3	QPSK	14/15	-60	-57	-54	-52	-51	-49	-46	-45
4	8-PSK	11/15	-59	-56	-53	-51	-50	-48	-45	-44
5	8-PSK	14/15	-57	-54	-51	-49	-48	-46	-43	-42
6	8-APSK	11/15	-59	-56	-53	-51	-50	-48	-45	-44
7	8-APSK	14/15	-57	-54	-51	-49	-48	-46	-43	-42
8	16-QAM	11/15	-57	-54	-51	-49	-48	-46	-43	-42
9	16-QAM	14/15	-53	-50	-47	-45	-44	-42	-39	-38
10	64-QAM	11/15	-52	-49	-46	-44	-43	-41	-38	-36
11	64-QAM	14/15	-47	-44	-41	-40	-38	-36	-33	-32

Suggestion for Table 11b-19 Reference Sensitivity Levels for MCS for the THz-OOK PHY

MCS Identifier	Modulation	FEC Rate	Receiver Sensitivity [dBm] depending on the bandwidth							
			2.16 GHz	4.32 GHz	8.64 GHz	12.96 GHz	17.28 GHz	25.92 GHz	51.84 GHz	69.12 GHz
0	OOK	224/240	-62	-59	-56	-54	-53	-51	-48	-47
1	OOK	11/15	-67	-64	-61	-59	-58	-56	-53	-52
2	OOK	14/15	-63	-60	-57	-55	-54	-52	-49	-48

Maximum Achievable Link Distances

- In the following exemplary maximum achievable link distances are calculated based on
 - receiver sensitivity levels for the corresponding channel model
 - sets of Tx output power (P_{Tx}); antenna gain at the transmitter (G_{Tx}) and antenna gain at the receiver (G_{Rx})
 - free-space propagation loss at a carrier frequency of 300 GHz

Link Distance for the AWGN Channel

P_TX=5 dBm*; G_Tx=40 dB; G_Rx=40 dB

*This set-up is equivalent to a scenario with P_Tx=30dBm and 25 dB atmospheric attenuation due to weather conditions

MCS Identifier	Modulation	FEC Rate	Maximum Link Distance in m							
			2.16 GHz	4.32 GHz	8.64 GHz	12.96 GHz	17.28 GHz	25.92 GHz	51.84 GHz	69.12 GHz
0	BPSK	11/15	3005	2125	1502	1227	1062	867	613	531
1	BPSK	14/15	2050	1450	1025	837	725	592	418	362
2	QPSK	11/15	2134	1509	1067	871	755	616	436	377
3	QPSK	14/15	1441	1019	721	588	510	416	294	255
4	8-PSK	11/15	1213	858	606	495	429	350	248	214
5	8-PSK	14/15	970	686	485	396	343	280	198	171
6	8-APSK	11/15	1213	858	606	495	429	350	248	214
7	8-APSK	14/15	972	687	486	397	344	281	198	172
8	16-QAM	11/15	961	680	481	392	340	277	196	170
9	16-QAM	14/15	648	458	324	264	229	187	132	114
10	64-QAM	11/15	534	377	267	218	189	154	109	94
11	64-QAM	14/15	327	231	163	133	116	94	67	58
0	OOK	224/240	846	691	598	488	345	299	846	691
1	OOK	11/15	1528	1248	1081	882	624	540	1528	1248
2	OOK	14/15	1014	828	717	586	414	359	1014	828

at least 100 Gbit/s achieved by this mode

Link Distance for the AWGN Channel

P_TX=0 dBm; G_Tx=18 dB; G_Rx=18 dB

MCS Identifier	Modulation	FEC Rate	Maximum Link Distance in m							
			2.16 GHz	4.32 GHz	8.64 GHz	12.96 GHz	17.28 GHz	25.92 GHz	51.84 GHz	69.12 GHz
0	BPSK	11/15	10,66	7,54	5,33	4,35	3,77	3,08	2,18	1,88
1	BPSK	14/15	7,27	5,14	3,64	2,97	2,57	2,10	1,48	1,29
2	QPSK	11/15	7,57	5,35	3,79	3,09	2,68	2,19	1,55	1,34
3	QPSK	14/15	5,11	3,62	2,56	2,09	1,81	1,48	1,04	0,90
4	8-PSK	11/15	4,30	3,04	2,15	1,76	1,52	1,24	0,88	0,76
5	8-PSK	14/15	3,44	2,43	1,72	1,41	1,22	0,99	0,70	0,61
6	8-APSK	11/15	4,30	3,04	2,15	1,76	1,52	1,24	0,88	0,76
7	8-APSK	14/15	3,45	2,44	1,72	1,41	1,22	1,00	0,70	0,61
8	16-QAM	11/15	3,41	2,41	1,71	1,39	1,21	0,98	0,70	0,60
9	16-QAM	14/15	2,30	1,62	1,15	0,94	0,81	0,66	0,47	0,41
10	64-QAM	11/15	1,89	1,34	0,95	0,77	0,67	0,55	0,39	0,33
11	64-QAM	14/15	1,16	0,82	0,58	0,47	0,41	0,33	0,24	0,20
0	OOK	224/240	6,00	4,24	3,00	2,45	2,12	1,73	1,23	1,06
1	OOK	11/15	10,85	7,67	5,42	4,43	3,83	3,13	2,21	1,92
2	OOK	14/15	7,20	5,09	3,60	2,94	2,55	2,08	1,47	1,27

at least 100 Gbit/s achieved by this mode

Link Distance for the AWGN Channel

P_TX=0 dBm; G_Tx=6 dB; G_Rx=6 dB

MCS Identifier	Modulation	FEC Rate	Maximum Link Distance in m							
			2.16 GHz	4.32 GHz	8.64 GHz	12.96 GHz	17.28 GHz	25.92 GHz	51.84 GHz	69.12 GHz
0	BPSK	11/15	0,67	0,48	0,34	0,27	0,24	0,19	0,14	0,12
1	BPSK	14/15	0,46	0,32	0,23	0,19	0,16	0,13	0,09	0,08
2	QPSK	11/15	0,48	0,34	0,24	0,20	0,17	0,14	0,10	0,08
3	QPSK	14/15	0,32	0,23	0,16	0,13	0,11	0,09	0,07	0,06
4	8-PSK	11/15	0,27	0,19	0,14	0,11	0,10	0,08	0,06	0,05
5	8-PSK	14/15	0,22	0,15	0,11	0,09	0,08	0,06	0,04	0,04
6	8-APSK	11/15	0,27	0,19	0,14	0,11	0,10	0,08	0,06	0,05
7	8-APSK	14/15	0,22	0,15	0,11	0,09	0,08	0,06	0,04	0,04
8	16-QAM	11/15	0,22	0,15	0,11	0,09	0,08	0,06	0,04	0,04
9	16-QAM	14/15	0,14	0,10	0,07	0,06	0,05	0,04	0,03	0,03
10	64-QAM	11/15	0,12	0,08	0,06	0,05	0,04	0,03	0,02	0,02
11	64-QAM	14/15	0,07	0,05	0,04	0,03	0,03	0,02	0,01	0,01
0	OOK	224/240	0,38	0,27	0,19	0,15	0,13	0,11	0,08	0,07
1	OOK	11/15	0,68	0,48	0,34	0,28	0,24	0,20	0,14	0,12
2	OOK	14/15	0,45	0,32	0,23	0,19	0,16	0,13	0,09	0,08

at least 100 Gbit/s achieved by this mode

Link Distance for the Intra-Device Channel

P_TX=0 dBm; G_Tx=6 dB; G_Rx=6 dB

MCS Identifier	Modulation	FEC Rate	Maximum Link Distance in m							
			2.16 GHz	4.32 GHz	8.64 GHz	12.96 GHz	17.28 GHz	25.92 GHz	51.84 GHz	69.12 GHz
0	BPSK	11/15	0,65	0,46	0,33	0,27	0,23	0,19	0,13	0,12
1	BPSK	14/15	0,42	0,30	0,21	0,17	0,15	0,12	0,09	0,07
2	QPSK	11/15	0,42	0,30	0,21	0,17	0,15	0,12	0,09	0,07
3	QPSK	14/15	0,28	0,20	0,14	0,12	0,10	0,08	0,06	0,05
4	8-PSK	11/15	0,24	0,17	0,12	0,10	0,08	0,07	0,05	0,04
5	8-PSK	14/15	0,15	0,10	0,07	0,06	0,05	0,04	0,03	0,03
6	8-APSK	11/15	0,26	0,18	0,13	0,11	0,09	0,07	0,05	0,05
7	8-APSK	14/15	0,16	0,12	0,08	0,07	0,06	0,05	0,03	0,03
8	16-QAM	11/15	0,16	0,11	0,08	0,07	0,06	0,05	0,03	0,03
9	16-QAM	14/15	0,07	0,05	0,04	0,03	0,03	0,02	0,02	0,01
10	64-QAM	11/15	0,02	0,01	0,01	0,01	0,01	0,00	0,00	0,00
11	64-QAM	14/15	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
0	OOK	224/240	0,38	0,27	0,19	0,15	0,13	0,11	0,08	0,07
1	OOK	11/15	0,68	0,48	0,34	0,28	0,24	0,20	0,14	0,12
2	OOK	14/15	0,45	0,32	0,23	0,19	0,16	0,13	0,09	0,08

at least 100 Gbit/s achieved by this mode

Link Distance for the Intra-Device Channel

P_TX=0 dBm; G_Tx=18 dB; G_Rx=18 dB

MCS Identifier	Modulation	FEC Rate	Maximum Link Distance in m							
			2.16 GHz	4.32 GHz	8.64 GHz	12.96 GHz	17.28 GHz	25.92 GHz	51.84 GHz	69.12 GHz
0	BPSK	11/15	10,57	7,47	5,28	4,31	3,74	3,05	2,16	1,87
1	BPSK	14/15	7,17	5,07	3,58	2,93	2,53	2,07	1,46	1,27
2	QPSK	11/15	7,57	5,36	3,79	3,09	2,68	2,19	1,55	1,34
3	QPSK	14/15	4,64	3,28	2,32	1,90	1,64	1,34	0,95	0,82
4	8-PSK	11/15	4,30	3,04	2,15	1,76	1,52	1,24	0,88	0,76
5	8-PSK	14/15	2,72	1,93	1,36	1,11	0,96	0,79	0,56	0,48
6	8-APSK	11/15	4,24	3,00	2,12	1,73	1,50	1,23	0,87	0,75
7	8-APSK	14/15	2,97	2,10	1,48	1,21	1,05	0,86	0,61	0,52
8	16-QAM	11/15	2,99	2,12	1,50	1,22	1,06	0,86	0,61	0,53
9	16-QAM	14/15	1,78	1,26	0,89	0,73	0,63	0,52	0,36	0,32
10	64-QAM	11/15	0,74	0,52	0,37	0,30	0,26	0,21	0,15	0,13
11	64-QAM	14/15	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
0	OOK	224/240	6,00	4,24	3,00	2,45	2,12	1,73	1,23	1,06
1	OOK	11/15	10,85	7,67	5,42	4,43	3,83	3,13	2,21	1,92
2	OOK	14/15	7,20	5,09	3,60	2,94	2,55	2,08	1,47	1,27

at least 100 Gbit/s achieved by this mode

Link Distance for the CP Channel

P_TX=0 dBm; G_Tx=12 dB; G_Rx=12 dB

MCS Identifier	Modulation	FEC Rate	Maximum Link Distance in m							
			2.16 GHz	4.32 GHz	8.64 GHz	12.96 GHz	17.28 GHz	25.92 GHz	51.84 GHz	69.12 GHz
0	BPSK	11/15	2,64	1,87	1,32	1,08	0,93	0,76	0,54	0,47
1	BPSK	14/15	1,81	1,28	0,91	0,74	0,64	0,52	0,37	0,32
2	QPSK	11/15	1,90	1,35	0,95	0,78	0,67	0,55	0,39	0,34
3	QPSK	14/15	1,20	0,85	0,60	0,49	0,42	0,35	0,24	0,21
4	8-PSK	11/15	1,08	0,76	0,54	0,44	0,38	0,31	0,22	0,19
5	8-PSK	14/15	0,73	0,52	0,37	0,30	0,26	0,21	0,15	0,13
6	8-APSK	11/15	0,93	0,66	0,46	0,38	0,33	0,27	0,19	0,16
7	8-APSK	14/15	0,77	0,54	0,38	0,31	0,27	0,22	0,16	0,14
8	16-QAM	11/15	0,84	0,59	0,42	0,34	0,30	0,24	0,17	0,15
9	16-QAM	14/15	0,25	0,18	0,13	0,10	0,09	0,07	0,05	0,04
10	64-QAM	11/15	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
11	64-QAM	14/15	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
0	OOK	224/240	1,51	1,07	0,75	0,62	0,53	0,44	0,31	0,27
1	OOK	11/15	2,72	1,93	1,36	1,11	0,96	0,79	0,56	0,48
2	OOK	14/15	1,81	1,28	0,90	0,74	0,64	0,52	0,37	0,32

at least 100 Gbit/s achieved by this mode

Link Distance for the CP Channel

P_TX=0 dBm; G_Tx=24 dB; G_Rx=12 dB

MCS Identifier	Modulation	FEC Rate	Maximum Link Distance in m							
			2.16 GHz	4.32 GHz	8.64 GHz	12.96 GHz	17.28 GHz	25.92 GHz	51.84 GHz	69.12 GHz
0	BPSK	11/15	10,66	7,54	5,33	4,35	3,77	3,08	2,18	1,88
1	BPSK	14/15	7,25	5,13	3,63	2,96	2,56	2,09	1,48	1,28
2	QPSK	11/15	7,57	5,35	3,79	3,09	2,68	2,19	1,55	1,34
3	QPSK	14/15	4,83	3,41	2,41	1,97	1,71	1,39	0,99	0,85
4	8-PSK	11/15	4,23	2,99	2,12	1,73	1,50	1,22	0,86	0,75
5	8-PSK	14/15	2,85	2,01	1,42	1,16	1,01	0,82	0,58	0,50
6	8-APSK	11/15	4,25	3,01	2,13	1,74	1,50	1,23	0,87	0,75
7	8-APSK	14/15	3,00	2,12	1,50	1,22	1,06	0,87	0,61	0,53
8	16-QAM	11/15	2,77	1,96	1,38	1,13	0,98	0,80	0,56	0,49
9	16-QAM	14/15	1,73	1,22	0,86	0,71	0,61	0,50	0,35	0,31
10	64-QAM	11/15	0,93	0,66	0,46	0,38	0,33	0,27	0,19	0,16
11	64-QAM	14/15	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
0	OOK	224/240	6,00	4,24	3,00	2,45	2,12	1,73	1,23	1,06
1	OOK	11/15	10,85	7,67	5,42	4,43	3,83	3,13	2,21	1,92
2	OOK	14/15	7,20	5,09	3,60	2,94	2,55	2,08	1,47	1,27

at least 100 Gbit/s achieved by this mode

Link Distance for the Data Center Channel

$P_{TX}=10$ dBm; $G_{Tx}=6$ dB; $G_{Rx}=6$ dB

MCS Identifier	Modulation	FEC Rate	Maximum Link Distance in m							
			2.16 GHz	4.32 GHz	8.64 GHz	12.96 GHz	17.28 GHz	25.92 GHz	51.84 GHz	69.12 GHz
0	BPSK	11/15	1,84	1,30	0,92	0,75	0,65	0,53	0,38	0,33
1	BPSK	14/15	1,31	0,93	0,65	0,53	0,46	0,38	0,27	0,23
2	QPSK	11/15	1,38	0,97	0,69	0,56	0,49	0,40	0,28	0,24
3	QPSK	14/15	0,82	0,58	0,41	0,34	0,29	0,24	0,17	0,15
4	8-PSK	11/15	0,54	0,38	0,27	0,22	0,19	0,16	0,11	0,10
5	8-PSK	14/15	0,28	0,20	0,14	0,12	0,10	0,08	0,06	0,05
6	8-APSK	11/15	0,66	0,47	0,33	0,27	0,23	0,19	0,14	0,12
7	8-APSK	14/15	0,25	0,17	0,12	0,10	0,09	0,07	0,05	0,04
8	16-QAM	11/15	0,45	0,32	0,22	0,18	0,16	0,13	0,09	0,08
9	16-QAM	14/15	0,02	0,02	0,01	0,01	0,01	0,01	0,00	0,00
10	64-QAM	11/15	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
11	64-QAM	14/15	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
0	OOK	224/240	1,20	0,85	0,60	0,49	0,42	0,35	0,24	0,21
1	OOK	11/15	2,16	1,53	1,08	0,88	0,77	0,62	0,44	0,38
2	OOK	14/15	1,44	1,02	0,72	0,59	0,51	0,41	0,29	0,25

at least 100 Gbit/s achieved by this mode

Link Distance for the Data Center Channel

$P_{TX}=10$ dBm; $G_{Tx}=18$ dB; $G_{Rx}=18$ dB

MCS Identifier	Modulation	FEC Rate	Maximum Link Distance in m							
			2.16 GHz	4.32 GHz	8.64 GHz	12.96 GHz	17.28 GHz	25.92 GHz	51.84 GHz	69.12 GHz
0	BPSK	11/15	33	23	16	13	12	10	7	6
1	BPSK	14/15	21	15	11	9	8	6	4	4
2	QPSK	11/15	24	17	12	10	8	7	5	4
3	QPSK	14/15	15	11	8	6	5	4	3	3
4	8-PSK	11/15	13	9	6	5	5	4	3	2
5	8-PSK	14/15	8	6	4	3	3	2	2	1
6	8-APSK	11/15	13	9	7	5	5	4	3	2
7	8-APSK	14/15	8	6	4	3	3	2	2	1
8	16-QAM	11/15	9	7	5	4	3	3	2	2
9	16-QAM	14/15	4	3	2	2	1	1	1	1
10	64-QAM	11/15	3	2	1	1	1	1	1	0
11	64-QAM	14/15	0	0	0	0	0	0	0	0
0	OOK	224/240	19	13	9	8	7	5	4	3
1	OOK	11/15	34	24	17	14	12	10	7	6
2	OOK	14/15	23	16	11	9	8	7	5	4

at least 100 Gbit/s achieved by this mode

Link Distance for the Data Center Channel*

P_TX=10 dBm; G_Tx=30dB; G_Rx=30 dB

*based on simulations with channel impulse responses derived for G_Tx=18 dB and G_Rx=18 dB;
the achievable distances can be considered as a lower bound for G-Tx=30 dB and G_Rx=30 dB

MCS Identifier	Modulation	FEC Rate	Maximum Link Distance in m							
			2.16 GHz	4.32 GHz	8.64 GHz	12.96 GHz	17.28 GHz	25.92 GHz	51.84 GHz	69.12 GHz
0	BPSK	11/15	522	369	261	213	185	151	107	92
1	BPSK	14/15	337	239	169	138	119	97	69	60
2	QPSK	11/15	376	266	188	154	133	109	77	67
3	QPSK	14/15	240	169	120	98	85	69	49	42
4	8-PSK	11/15	205	145	103	84	73	59	42	36
5	8-PSK	14/15	132	93	66	54	47	38	27	23
6	8-APSK	11/15	210	149	105	86	74	61	43	37
7	8-APSK	14/15	131	93	66	54	46	38	27	23
8	16-QAM	11/15	148	104	74	60	52	43	30	26
9	16-QAM	14/15	66	47	33	27	23	19	13	12
10	64-QAM	11/15	40	28	20	16	14	12	8	7
11	64-QAM	14/15	522	369	261	213	185	151	107	92
0	OOK	224/240	301	213	150	123	106	87	61	53
1	OOK	11/15	544	384	272	222	192	157	111	96
2	OOK	14/15	361	255	180	147	128	104	74	64

at least 100 Gbit/s achieved by this mode

Link Distance for the Data Center Channel*

P_{Tx}=10 dBm; G_{Tx}=30dB; G_{Rx}=30 dB

*based on simulations with the AWGN channel; these distances can be considered as an upper bound for a channel model, that could be derived G_{Tx}=30 dB and G_{Rx}=30 dB

MCS Identifier	Modulation	FEC Rate	Maximum Link Distance in m							
			2.16 GHz	4.32 GHz	8.64 GHz	12.96 GHz	17.28 GHz	25.92 GHz	51.84 GHz	69.12 GHz
0	BPSK	11/15	534	378	267	218	189	154	109	94
1	BPSK	14/15	365	258	182	149	129	105	74	64
2	QPSK	11/15	380	268	190	155	134	110	77	67
3	QPSK	14/15	256	181	128	105	91	74	52	45
4	8-PSK	11/15	216	152	108	88	76	62	44	38
5	8-PSK	14/15	172	122	86	70	61	50	35	30
6	8-APSK	11/15	216	152	108	88	76	62	44	38
7	8-APSK	14/15	173	122	86	71	61	50	35	31
8	16-QAM	11/15	171	121	85	70	60	49	35	30
9	16-QAM	14/15	115	81	58	47	41	33	24	20
10	64-QAM	11/15	95	67	47	39	34	27	19	17
11	64-QAM	14/15	58	41	29	24	21	17	12	10
0	OOK	224/240	301	213	150	123	106	87	61	53
1	OOK	11/15	544	384	272	222	192	157	111	96
2	OOK	14/15	361	255	180	147	128	104	74	64

at least 100 Gbit/s achieved by this mode

Conclusions on achievable link distances

- For the close-proximity and intra-device use cases the achievable distances derived from simulations using corresponding channel models are within the requirements for these applications if a transmitter with an output power of 0 dBm is used.
- For the backhaul/fronthaul application, where the AWGN channel model is applicable, a few 100 meters required a Tx power of around 30 dBm* in order to account for additional atmospheric attenuation of around 25 dB
- For the data center application antenna gains with around 30 dB at both ends of the link are required to fulfill the requirements, if a transmitter with an output power of 10 dBm is used.

30 dBm output power is feasible using traveling wave tube amplifiers, see e. g M. Yoshida, J. Kobayashi, Y. Fujishita, N. Masuda, N. Sekine, A. Kanno, N. Yamamoto, I. Hosako, “Development Activity of Terahertz Amplifiers with FWG-TWTs”, 17th IEEE International Vacuum Electronics Conference (IVEC 2016), Monterey (2016).