THz Radio Communication: Link Budget Analysis Towards 6G

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***Abstract*—How well do upper millimeter-wave and terahertz frequency bands enable wireless communications? In this work, we approximate the current and estimate the future communication potential with emphasis on antenna and radio frequency hardware technologies, and radio propagation challenges. This is done by performing link budget evaluations with justified estimates of link budget calculus terms, such as the achievable or required noise figure, transmit power, and antenna gain. Estimates are based on current enabling technologies and needs to advance those. In RF viewpoint the bottlenecks are in generating sufficiently high transmit power and low noise with the support of very high antenna gains. As an example, we discuss opportunities around 300 GHz frequency. Challenges to support 100 Gb/s bit rate at 30 GHz bandwidth on 10-meter link distance is analyzed for different kind of devices.**

***Index Terms*—THz communication, link budget, link distance, RF performance**

I. INTRODUCTION

Trend in evolution of wireless communications systems is towards higher data rates, system capacities, system bandwidths, and operation frequencies. 5G is the first generation of mobile communication systems that supports millimeter wave band transmission for high speed wireless data transfer. It provides transmission rates on the order of several gigabits per second (Gbps) utilizing wide transmission bandwidths up to a few hundred megahertz (MHz). The next generation, 6G wireless communication systems, are foreseen to expand operations to upper mm-wave (mmW) band (100–300 GHz) and terahertz (THz) band (300–3000 GHz) frequencies. Future 6G systems will target to peak data rates up to terabit per second (Tbps) with low latency in transmission [1]. Significantly larger transmission bandwidths are needed compared to what 5G systems and spectrum allocations below 100 GHz can provide.

International Telecommunication Union (ITU) and most national regulators have listed spectrum allocations up to 275 GHz. In ITU region 1, including Europe, a total of 81 GHz spectrum is allocated for fixed/mobile communications in frequency range 100–275 GHz, with 23 GHz of that allocation being in frequency range 252–275 GHz [2]. World Radiocommunication Conference 2019 (WRC-19) identified 137 GHz of spectrum in the band 275–450 GHz for land mobile and fixed service without any specific conditions to protect passive services, e.g., Earth exploration-satellite service (EESS), operating in THz frequencies [3]. Thus, a total of 160 GHz spectrum is available for fixed/mobile communications in frequency range 250–450 GHz.

A fixed point-to-point link or an indoor system operating in upper mmW or terahertz band assumes usually line-of-sight (LOS) connection between transmitter and receiver. Attenuation of the radio signal in atmospheric propagation in LOS condition depends on free space path loss (Friis' formula), molecular absorption, and specific attenuation due to rain. Friis' transmission formula indicates that doubling the frequency quadruples the free space path loss that is due to reduced antenna element aperture as a function of frequency. In addition, molecular absorption spectral lines start impacting link budgets around 60 GHz (oxygen) and above 300 GHz (water). Rain attenuation is highly time and location dependent, but its impact must be included as a margin in long distance link designs.

Upper mmW and THz band antenna elements are typically tightly integrated with radio transceiver solution enabling the circuit or module level integration due to their small physical size. However, decreased antenna dimensions cause disadvantageous characteristics in the wave propagation. As the effective wave capturing area is smaller, the antenna element and thus received power reduces following the Friis' equation. THz antenna solutions must overcome this

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fundamental challenge by increasing the size of the antenna aperture using, e.g., lenses or phased arrays. In transmission and reception, large antenna aperture enables high directivity and gain to compensate free space propagation losses.

Convenient way to implement large size (and gain) antennas, e.g., for backhaul links is to use reflector-type dish antennas or dielectric collimating lens antennas. Lens is a specially shaped piece of dielectric material that focuses the field radiated by an antenna. Effectively a lens, as a component of antenna system, increases aperture of the antenna, providing higher gain and narrower antenna beam. Phased array as an alternative approach has been widely adopted at lower mmW region, e.g., 28 GHz in 5G [4]. However, doubling the frequency quadruples the number of antennas for the same aperture. Moving from 28 GHz to 200-300 GHz range a reasonable 32 element array scales up to the range of 2000 antennas and parallel transmit and receive RF paths. Such complexity is difficult to manage, and power consumption will limit strongly the practical implementation. Therefore, current 5G solutions are not easily scalable to 300 GHz range.

Another fundamental physical constraint for 6G systems comes from the limited performance of electrical circuit technologies when approaching THz region. Radio transceiver solutions for current 4G and 5G mobile terminals are mainly implemented with complementary metal oxide semiconductor (CMOS) integrated circuit (IC) technology due to favorable cost, modularity and high level of integration. However, even today mobile terminal power amplifiers (PAs) are using either III-V technology, such as gallium arsenide (GaAs) or indium phosphide (InP), or silicon germanium (SiGe) heterojunction bipolar transistor (HBT) to overcome the limitation of the CMOS to generate enough radio frequency power efficiently at frequencies below 6 GHz. Also, the base station radios are utilizing other III-V technologies in the power amplifiers and low noise amplifiers (LNAs) to complement CMOS radio transceiver solutions to improve the radio performance. However, big and bulky discrete PA and LNA components are not anymore feasible solutions with small antennas even at lower mmW region. Highly integrated CMOS or SiGe HBT mmW transceivers need to be adopted as IC solutions with integrated PAs and LNAs next to the antennas minimizing form factor and any RF loss degrading the performance in phased arrays. Future 6G frequencies at 100GHz and above will have also major challenge due to the available transistor speed (like f_{max} i.e. maximum frequency to achieve power gain) especially in silicon-based technologies such as CMOS and SiGe HBT. Approaching the boundary leads to exponential degradation in gain and output power as well as increased noise. Practical boundary to implement amplifiers is up to half of the f_{max}. A recent example demonstrates RF transceiver operation up to 240GHz range using SiGe HBT technology with $f_{max} \approx 500$GHz [5]. Even in this case performance is compromised compared to the capabilities of the same technology at frequencies below 100 GHz. In addition to thermal noise and output power limiting performance in absolute scale i.e. range, other non-idealities, like phase noise relative to signal level and bandwidth will have impact on applicable modulations by limiting maximum achievable signal-to-noise ratio (SNR). This is also highly dependent on applicable waveform, e.g., single carrier vs. orthogonal frequency division multiplexing (OFDM).

This paper discusses on key technology options in highly abstracted manner but keeping the most essential performance bottlenecks included. These are based on state-of-the-art technology boundaries in anticipated 6G link scenarios. Only a few early prototypes exist for short range links capable of operating at data rates close to 100 Gbps. New technologies may not quickly fill the gap between preferred and realistic performances. Therefore, it is of essence to study critical performance boundaries and build bridge from technologies to realistic communications concepts. For example, link budget analysis of fixed wireless links in [6] concludes that high bit rate connection over 1 km distance is possible but requires very high gains for the transmit and receive antennas. Is this scenario realistic to scale up for mass markets and what are technologies that can make it? These are key questions for 6G community in coming years. To boost the technology advancement, IEEE 802.15.3d has specified a physical layer for High Data Rate Wireless Multi-Media Networks operating in frequency range 252–325 GHz with eight different channel bandwidths from 2.16 GHz up to 69.12 GHz [7].

In this paper, we focus in 300 GHz band operation in the link budget analysis and extend the consideration into small form factor devices. Carrier frequencies up to 300 GHz are potential operation frequencies for the first 6G systems in THz band. In the following sections, we will consider various aspects in link budget analysis for THz band communication systems. Practical antenna and radio frequency hardware capabilities for fixed outdoor and low mobility indoor communication systems operating at 300 GHz frequency are discussed and appropriate values selected for the link budget calculations. The link performance is analyzed with respect to achievable link distance with target system bandwidth and bit rate.

II. LINK BUDGET EVALUATION METHOD

The major challenges on realistic link budget and sufficient range determination on upper mmW band is to consider present and future performance of key enabling technologies. A simple link budget evaluation model for the requirement analysis of THz communication systems is adopted. It is intended to assess potential *link distances*, *system bandwidths*, *bit rates* and a support for mobility with respect to THz band transceiver technology capabilities and physical characteristics, like free space loss and molecular absorption, of the propagation medium to give comprehensive view on challenges and opportunities. A radio communication system model showing key transceiver parameters which affect to achievable link distance is given in Fig. 1. Power amplifier (PA) and low noise amplifier (LNA) present here the performance of the whole RF transmitter and receiver, respectively while digital signal processing (DSP) abstracts the modem processing to a single SNR number for simplicity.

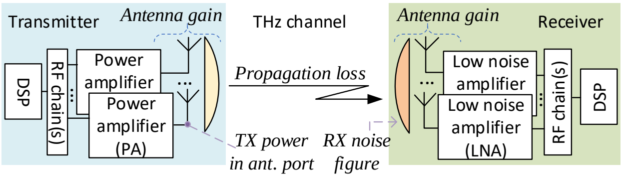

Figure 1. Radio communication system model

Inter-dependencies of various system parameters are illustrated in Fig. 2. A target bit rate can be realized with certain bandwidth and *modulation/coding* combinations. To match the target bit rate with the selected bandwidth we consider the single carrier modulation with M-ary phase-shift keying (M-PSK) or M-ary quadrature amplitude modulation (M-QAM) and a simple repetition code with selected *code rate*. The selected modulation/coding combination requires a certain system SNR, *Target SNR*, for reaching the bit rate target. This is compared to achievable SNR at the reception, *Rx SNR*, which is specified by the *noise power*, *propagation loss*, *antenna gains*, and the transmit signal *(Tx) power*. The achievable Rx SNR includes all effects of transceiver RF implementation including data converters.

The maximum Tx power may be limited by regulations or by available component technologies. The former is often the case at lower frequencies and the latter at higher frequencies, where the capability to generate transmitted power and to achieve low noise are strictly bounded by speed of semiconductor technologies. Maximum frequency to achieve voltage or power gain i.e. f_T or f_{max} set strict physical limits for communication capabilities. Those are further lowered by parasitic effects in the semiconductors and interconnections between circuits. Here, in *Tx power* value, we include an estimate of achievable output for PA with selected technology examples and public analysis operating in upper mmW band. That is complemented with signal waveform dependent crest factor to model the backoff of the PA, and other RF transmitter chain impairments are included to a fixed 'post-PA' loss factor. The Rx RF chain impairments are included in the receiver *noise figure* (NF). System bandwidth, together with the NF, determine the total noise power level in the input of the Rx antenna.

The overall propagation loss is combination of the free space path loss, clutter loss, and atmospheric attenuation. These are all essentially dependent of the link distance. Furthermore, we assume that it is possible to arrange a direct LOS connection from transmitter to receiver. Transmitter and receiver antennas are modelled either with antenna element and lens or antenna array gains. The antenna gain affects also the *beam width*, which has impact on the supported mobility in highly directive communication systems.

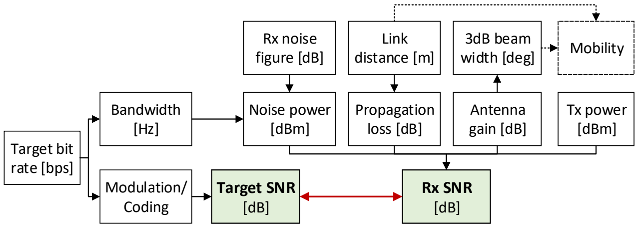

Figure 2. Inter-dependencies of selected RF system parameters.

A. *Target bit rate and bandwidth*

Potential use cases for THz band communications include wireless backhauling/fronthauling, close proximity communication systems, wireless links between servers inside a data center, and very high data rate connections needed for future 6G indoor services. Bit rate requirement may vary from 10 to 100 Gbps and even up to 1 Tbps with holographic type communications [1,7]. For the link budget calculations, we select primary link design parameters as follows: carrier frequency is 300 GHz, system bandwidth 30 GHz, and target bit rate 100 Gbps. As the outcome of the analysis, we will determine the achievable link distance with given parameters. LOS model is mostly used as other scenarios lead easily to highly limited link ranges that are impractical in the field. However, for other channel non-idealities like beam misalignment or reflections a parameter describing link margin could be adopted to evaluate more challenging propagation scenarios. Unfortunately, based on the analysis it will be shown later that when extremely high data rates, bandwidths and carrier frequencies needed simultaneously the link budget will not allow similar margins that are anticipated in current cellular or local area communications below 6 GHz or not even below 100 GHz.

B. *Transmit power and noise figure*

One of the most critical parameters for the THz radio performance is the available RF power from the PA. Upper THz frequencies are using photonic based technologies to generate RF power while lower frequencies are relying on silicon or III-V based technologies such as gallium nitride (GaN) or InP that enable small size PA development of THz frequency base station and mobile terminals. For compact, cost efficient and large-scale integration of mmW transceivers silicon-based technologies (SiGe HBT, CMOS or CMOS silicon on insulator (SOI)) are the viable solutions especially for mass markets.

A survey for different semiconductor technologies to generate RF power over wide range of frequencies is conducted in [8] indicating a strong dependence between the achievable saturated output power, operation frequency, and used semiconductor technology. As a summary, the achievable saturated radio frequency power decreases when operational frequency increases regardless of the used IC technology due to transistor speed limitations. For the link budget analysis, we choose two presentative values for the maximum saturated power of the PA, namely +5 dBm and +13 dBm. The first value represents the state-of-the-art performance based on SiGe HBT and CMOS PAs at 200–250 GHz based on reported values in [5,8], while the latter value is for PA solution based on III-V technology at 300 GHz as reported in [8].

Also, noise figure of the receiver, is a technology dependent parameter that is a function of frequency and f_T [9]. The reported noise figures of upper mmW band receivers or LNAs are in the range of 10–15 dB and the noise performance is limited by the used IC technology [5, 10]. These NF values are higher than NFs of current 5G receivers due to carrier frequency. We selected three NF values 10 dB, 12 dB and 15 dB for our analyses to present expected NF performances of different kind of THz receivers. The two first values are for III-V technologies for larger devices considering the best LNA and leaving some margin for the contributions elsewhere in the receiver. However, tightly integrated, silicon based phased arrays can’t be expected to achieve better than 15dB noise figure

C. *Antenna gain*

In general, the only way to achieve high gain THz antenna is to increase the antenna aperture. Cassegrain reflector antenna has a large aperture and high gain (55 dBi) but is not cost-effective or easily integrated [11]. State-of-the-art solution at 300 GHz is to integrate dielectric lens to the system package, which typically means an antenna arrangement of one fixed beam. Practical gain values depend on the size, shape, and the dielectric properties of the lens, and are in the order of 20 – 30 dBi [12]. Switched beam antennas at lower mmW bands (75 GHz) are achieved by integrating several antenna elements to a single lens. At mmW bands, phased antenna arrays have been found feasible in commercial 5G solutions.

When considering feasible antenna system for THz communication, the challenge is related to the beam steering capability. Lens antennas are fixed beam solutions by nature, which means that only one transceiver contributes to the communication to a single direction. This limitation is valid for a switched beam antenna in case of multiple antennas and transceivers integrated to a single lens. Further, the shape of one radiation beam is fixed, and thus geometrical coverage of one antenna element in high gain lens antenna is limited. Alternatively, large coverage is possible by using several antenna elements and beams simultaneously. Advantages of integrated lens antennas include efficient utilization of whole antenna aperture, stable radiation pattern over broad operation band and cost-effectiveness.

Phased antenna array has better beam steering capability. Practically, one active phased array can generate multiple simultaneous beams but leads to more complex RF front-end implementation. Challenges might arise from the element spacing when antennas are smaller than other integrated circuit components. Also, hundreds or thousands antenna elements require substantial number of transceiver chains which can increase implementation costs and will lead to challenges in the power consumption and thus also temperature control.

The proper antenna strategy for THz communication depends on the beam steering requirements. For a fixed link, the integrated lens antenna is a convenient solution. Switched beam lens antenna enables one or several simultaneous beams and could be optimum for low mobility applications. Phased arrays might show their advantage in case of moderate gain and high mobility communication applications. Trade-off between gain and mobility may lead to antenna system solutions including a combination of different basic high-gain antenna types.

For the link budget analysis, we select three type of antennas. Small lens antenna is realistic for local, low mobility indoor devices and large Cassegrain antenna for backhaul links. Mobile device and base station equipped with antenna arrays are included in the analysis to evaluate mobility aspects. Antenna gains 23–26 dBi represent calculated gains for small lens antennas with a diameter of 8–11 mm operating at 300 GHz. Antenna gain 55 dBi is a reported value for Cassegrain antenna operating at 275 GHz [11]. Gain for the antenna array depends on array size, element gain and efficiency and is calculated as 17.1 dBi and 29.1 dBi for the 32 and 512 element arrays in mobile device and base station, respectively.

III. RESULTS

Link budget calculations are conducted for short ranges up to ~10m using two different symmetric and static parameter sets for links (Links 1 and 2) and one mobile scenario (Link 3) including asymmetry in uplink and downlink directions. In addition, one fixed backhaul scenario for long range is calculated in Table I. Link 1 has small form factor devices at both ends such as access point or small portable device with a small lens antenna and silicon-based solution in the transceiver. Link 2 has small base station, front haul or laptop kind of devices with lens antennas and III-V technologies adopted in the transceiver to achieve better performance. Link 3 represents conventional mobile use scenario with asymmetric link consisting of mobile equipment implemented using silicon-based technologies while a small base station has better performance assuming adoption of III-V components as PAs and LNAs for performance and a large phased array. The base station is probably the most complex and challenging scenario for implementation as realizing poorly scalable III-V components as part of a 512-element array might not be practical. At least that scenario is significantly more complex and requires exceptional advances in mass market capable technologies with shorter range compared to state-of-the-art 5G mmW links. In backhaul scenario, it is possible to use the best performing technologies as antenna provides huge gain and link is fixed. These four link scenarios address comprehensively key reasons on the technology impact with associated cost and complexity for links ranging from centimeters up to kilometers.

Finally, also phase noise should be considered as it is often dominant factor especially in high-order modulations requiring SNR of 30dB or even more. Here, waveform selection makes a big difference. In OFDM based systems phase noise is multiplied around each sub-carrier in down and up conversion, spreading the oscillator power all over the band. However, in single carrier modulations phase noise is strongly attenuated in phase locked loops (PLL) around RF oscillators and therefore filtering impact will relax the requirement. Unfortunately, due to transistor speed limitations multiplication of the lower frequency PLL signal is the only option to up or down convert the signal leading to higher noise. In addition, multiplication of wideband noise from PLL, that is typically at much lower level than close-in phase noise but still significant, will also migrate on the wideband channel [13]. This is partially unsolved issue. Therefore, both clock and PLL quality and proper waveform selection require careful attention in research towards 6G.

Target SNR to Rx SNR comparison in Table I indicates that the target link distance of 10 m is achievable in link scenarios 2 and 3 but not with 1. In link 3 scenario, the achievable link distance is asymmetric in favor of downlink direction mainly due to larger amount of PAs in the base station transmitter. The target link distance of 1000 m for backhaul link can be well achieved with the determined transceiver parameters. Note, that parameter *PA output power* is saturated Tx power in Table I. Effective isotropic radiated power (EIRP) takes into account antenna element, lens and array gains and indicates the total power transmitted towards the main lobe. Modulation dependent back-off factor and post-PA loss, in total estimated as 3.6 dB for 16-QAM signal, are included in EIRP, as well.

Table I: Link budget calculation

Parameter	**Unit**	**Link 1**	**Link 2**	**Link 3-UL**	**Link 3- DL**	**Backhaul**
Frequency	GHz	300				
Wavelength	m	1.0E-3				
Link distance	m	10				1000
Signal bandwidth	GHz	30				
Target bit rate	Gbps	100				
Modulation order	b/sym	4				
Code rate		0.8				
Target SNR	dB	16.7				
Free space path loss	dB	102.0				142.0
Atm. attenuation	dB	0.0				3.0
Tot. propagation loss	dB	102.0				145.0
Antenna type		lens	lens	Ph. array	Ph. array	lens
# of TX antennas		1	1	32	512	1
# of RX antennas		1	1	512	32	1
Antenna gain Tx	dBi	23.0	26.0	17.1	29.1	55.0
Antenna gain Rx	dBi	23.0	26.0	29.1	17.1	55.0
-3 dB beam width	deg	14.4	10.2	28.5	7.1	0.4
PA output power	dBm	5.0	13.0	5.0	13.0	13.0
EIRP of TX	dBm	24.4	35.4	33.6	65.6	64.4
Rx power	dBm	-54.6	-40.7	-39.4	-19.4	-25.5
Noise power	dBm	-69.2				
Rx noise figure	dB	15	10	12	15	10
Total noise power	dBm	-54.2	-59.2	-57.2	-54.2	-59.2
Rx SNR	dB	-0.5	18.5	17.7	34.8	33.7
Rx SNR–target SNR	dB	**-17.2**	**1.8**	**1.0**	**18.1**	**17.0**

To enhance the analysis, achievable link distances for all link scenarios with different target bit rates are shown in Fig. 3. Seven different M-PSK/M-QAM waveforms (M=4,8,16,32,64,128,256) are used to cover the bit rate range from zero to 240 Gbps with the fixed signal bandwidth of 30 GHz. Backhaul is evaluated both with and without 20 mm/h rain. Heavy rain of 20 mm/h rate induces attenuation of 10.7 dB/km at 300 GHz [14]. Evidently, outdoor links are vulnerable to weather conditions which raises a challenge in THz band system design. As a note, we have assumed LOS connection and a perfect alignment between transceivers. If we add, e.g., 6 dB link margin, the achievable range would reduce to half. The 6 dB margin could correspond to a reflection from a reasonably good reflecting surface or half power beam misalignment at both ends of the link.

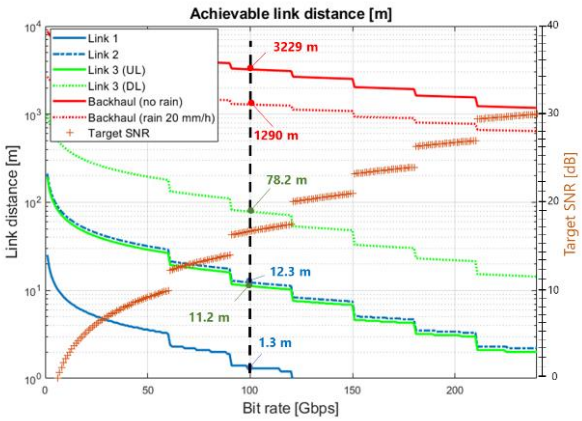

Figure 3. Achievable link distances and the target SNR at 300 GHz carrier frequency

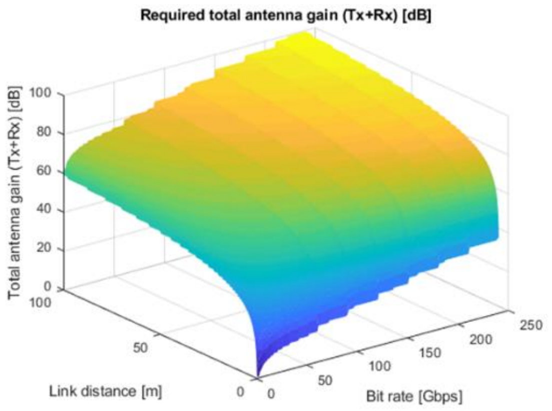

Figure 4. Required total antenna gain vs link distance with device targeted for link scenario 1

Figure 4 presents the total antenna gain (Tx + Rx) requirement as a function of link distance and bit rate with the selected system parameters. Bit rate of 100 Gbps is achievable with link distances 6.5 m and 61 m, if the total antenna gain shared between transmitter and receiver is 60 dBi and 80 dBi, respectively.

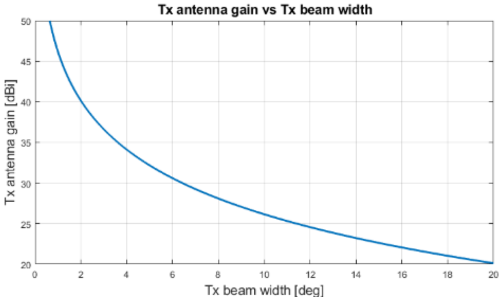

Figure 5. Half power beam width vs antenna gain

Antenna gain has an approximate relation to the half power (-3 dB) beam width. It is inversely proportional to the square-root-value of antenna gain (in linear unit). This approximation assumes rotationally symmetric antenna pattern. Figure 5 shows calculated half power beam width as a function of antenna gain. The support for mobility from beam tracking point of view can be speculated based on link distances and half power beam widths. For example, with link budget parametrization for Link 2 the Tx antenna gain is 26 dBi, corresponding to beam width of 10.2°. The half power area illuminated by such a beam is about 3.6 m wide at 10 m distance. Thus, a mobile transceiver would require new beam allocation approximately every 3.6 m. With backhaul transceiver parameters the beam width is 0.4°, which would make beam alignment extremely difficult and mobility practically impossible.

IV. CONCLUSION

We have evaluated communication link distances for links implemented with different technologies and complexity at 300 GHz looking towards anticipated 6G use scenarios. Communications with high bit rates and bandwidths is feasible only for short range with transceivers having a small form factor including antennas. Achievable link distance with target bit rate of 100 Gbps was limited to 1.3–12.3 m in such scenarios. Then with very large gain antennas in point-to-point outdoor links, distances can be extended significantly, i.e., above 3km for backhaul applications. Furthermore, in long range outdoor links the impact of rain attenuation is considerable and heavy rain may halve the distance. Another challenge is implementation of phased arrays and misalignment of narrow pencil beams both in mobile and static scenarios.

The coverage is dominated by Tx power generation capability, receiver noise and used antenna gains at both link ends. Very high propagation loss inherent to THz frequencies must be compensated mainly by high gain antennas, since the RF power generation has a decreasing trend as function of frequency due to semiconductor technologies. Performance of transceivers using silicon technologies should approach current III-V state-of-the-art performance in performance, and architectural innovations. That may facilitate higher performance also in smaller devices and at lower cost.

Directivity of high gain antennas leads to narrow beam width. Even moderate mobility becomes challenging and would require both adaptive antenna solutions, like switched beam lens antennas, and sophisticated beam acquisition and tracking protocols. Long range links seem to be feasible only for fixed transceivers with very high antenna gains, since antennas are large and their beams are extremely narrow, e.g., 0.4°. However, narrow beams and high propagation losses relieve the network planning in the traditional interference handling point of view.

On the other hand, wide signal bandwidths introduce new interference scenarios. The RF carrier to carrier interference may not be critical problem, but legacy cellular systems at lower frequencies may influence the communication due to electromagnetic compatibility (EMC) reasons since, in our example, the baseband signal bandwidth goes up to 30 GHz. It is evident that transition from lower mmW region to THz will not come without need of major technological breakthroughs at different areas from electronics to algorithms. It is of utmost importance evaluate these opportunities holistically and realistically when concepting communications towards 6G.

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