Integrated Communications and Sensing in Terahertz Band: A Propagation Channel Perspective

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***Abstract*—The rise of new requirements for future wireless systems is leading to a convergence of communication systems toward very high carrier frequencies, wide bandwidth, and massive antenna arrays. Understanding the properties of terahertz (THz) electromagnetic waves is critical for integrated communication and sensing (ISAC) system development and optimization. Therefore, in this paper, we investigate the propagation channel parameters and the applicability of terahertz electromagnetic waves for integrated communications and sensing. In doing so, we explore the new challenges and differences that arise when moving from systems operating at frequencies below the terahertz frequency bands.**

***Index Terms*—terahertz - THz, THz frequency band, channel parameters, Integrated Communications and Sensing - ISAC, electromagnetic waves - EM waves, radio frequency (RF) sensing, THz channel modeling**

I. INTRODUCTION

The development of next-generation applications requires ubiquitous ultra-high data rates in various environments [1]. This can be achieved through improved spectral efficiency using advanced coding and modulation schemes, multiple antenna systems, and signal processing techniques, or by increasing the bandwidth of the communication. Due to the spectrum scarcity in the current operating frequency bands in and below mm-waves, the transmission rate above Tbps is difficult to achieve. Therefore, using higher, less occupied frequency bands can enable the required transmission rates. In this respect, the terahertz (THz) frequency band is considered a promising candidate and is expected to play a significant role in communication, sensing, imaging, and localization for 6G [2]. The THz communications apply the electromagnetic (EM) spectrum between 100 GHz up to 10 THz, with wavelengths from 3 mm to 0.03 mm [3]. THz radio waves have been traditionally applied in spectroscopy for sensing applications such as materials characterization, weather observation, and the study of astronomical objects, due to frequency-selective-material-dependent EM wave absorption in THz frequency bands. The THz radio waves find application also in imagining operating in the degraded visibility environment applications, due to their low absorption in foggy and smoked environments and as body scanners, due to their low penetration in the human and animal bodies. The measurement, modeling, and characterization of THz propagation channels [4] are imperative for designing wireless communication systems [5].

In the prospect of wireless communications, the THz frequency bands hold immense promise as they offer a wide variety of unallocated frequency bands that can overcome the spectrum scarcity and capability limits of current wireless technologies [6]. Higher carrier frequencies allow the use of wider bandwidths, which in the THz frequency bands become a magnitude greater than in the traditional wireless communication bands. Wide bandwidth can carry more information, achieving the desired goal of 1 Tbit/s link [7], which makes the THz radio waves capable of supporting ultra-high data rates and accommodating the ever-increasing demands for wireless connectivity. Wide bandwidth provides an option of implementing new and improved methods of sharing the bandwidth between users, which can increase the number of devices that can communicate simultaneously and/or improve the security (e.g. spread spectrum communication) and reliability (e.g. channel hopping) of wireless systems. THz radio waves retain significantly shorter wavelengths compared to lower frequency bands, allowing for the deployment of compact antenna arrays, facilitating the integration of multiple antennas into small devices. Consequently, THz communication systems can leverage beamforming techniques and spatial multiplexing to enhance signal quality and increase system capacity. The wide bandwidth, low communication latency, short wavelengths, high receiver sensitivity, and narrow-beam steering multiple antenna systems implemented in the THz communication systems open the possibility of using them for high resolution sensing and localization [8].

Since both sensing and communications rely on similar physical phenomena that share the same limited frequency spectrum, it is reasonable to develop systems with collaboration in mind to achieve mutual benefits [9]. Thus, a new approach for future networks is integrated sensing and communications (ISAC) design. Exploration of wireless links for sensing and communications will have beneficial effects on the energy consumption of end-user devices, EM pollution of the environment, spectrum reuse, beamforming performance [9],

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maintenance and cost, enable distributed sensing [10], improved surveillance and introduce anonymity in surveillance systems [8]. New technological advances in semiconductor technology that enable higher frequencies, advanced signal processing, directional antenna, massive antenna arrays, and a controllable radio propagation environment are making the integration of both technologies into a single system a promising and desirable feature [8]. The integration of two functionalities introduces challenges in propagation channel modeling for ISAC mainly related to changes in the physical environment (e.g., the position of scatterers, sensing targets, and radio nodes), the impact of the sensing target's features, interference between the two channels and shared sctterers [11]. Statistical, deterministic and hybrid channel modeling methodologies have been proposed. The combination of ISAC and THz technologies presents even more significant challenges for channel modeling. For instance, the impact of scattering and meteorological factors, should be considered [12]. For accurate channel modeling, the correlation between the communication and sensing channels can be beneficial [13]. An approach for considering the correlation due to the shared clusters is proposed and validated for heterogeneous vehicular ISAC channel model [14].

Understanding the properties of THz radio wave propagation is critical for system development and optimization of THz communication and sensing systems. While in radio frequency (RF) sensing systems, the interaction of the radio waves with a particular object is of the most importance, the impact of the whole environment on the radio wave propagation is essential in communication systems. In other words, classical sensing systems analyze the reflection, absorption, scattering, penetration, and diffraction of radio waves from an object of interest. In the design of wireless communication systems, we look at cumulative EM propagation parameters such as power delay spread, root mean square (RMS) delay spread, K-factor, cross-polarization, and angular spread. Path loss, atmosphere absorption, rain, and fog attenuation significantly degrade the performance of both systems. To integrate the sensing into the THz radio communication systems the radio wave propagation effects and their impact on the radio communication channel shall be analyzed.

The main contributions of the paper are:

- analysis of the propagation mechanisms in the THz frequency band and discussion on the applicability of the THz waves for ISAC,
- selection of radio channel parameters for ISAC in the THz frequency band and discussion on the impact of THz propagation mechanisms on the selected parameters,
- study and discussion of the implementation of the different ISAC system designs, namely communication-centric, sensing-centric and co-design, in the THz frequency band,
- analysis of the challenges and the related opportunities of using the THz waves for ISAC.

The paper is organized as follows. After this introduction, the THz EM propagation mechanisms are analyzed with their impact on sensing. Next, we looked at the THz radio channel parameters and their applicability in THz sensing. Section IV looks at the convergence of wireless communications and RF sensing. The challenges and related opportunities are discussed in Section V. The paper is finished with concluding remarks.

II. THz ELECTROMAGNETIC WAVE PROPAGATION MECHANISMS

Understanding radio wave propagation is crucial in the development of effective communication and sensing systems in terms of hardware, software, and protocols. Radio waves interact with objects in the environment and consequently propagate via different routes between transmitter (Tx) and receiver (Rx). The received signal thus contains information about the environment, which strongly depends on the frequency of the EM waves and the characteristics of the Tx and the Rx. While RF sensing exploits the interaction of EM waves with the environment, in communication systems, this interaction results in distortions of the received signal and it is not desirable. To understand the opportunities of ISAC at THz frequencies, we are going to survey the basic propagation mechanisms in THz frequencies and compare them to micro and millimeter waves in lower frequency bands.

A. Free Space Path Loss - FSPL

Free space path loss (FSPL) is defined as the attenuation of the radio wave propagating between Tx and Rx with the isotropic antennas in an environment without objects [15] and is described by the Friis transmission equation.

$$P_{Tx}(d) = P_{Tx}G_{Tx}G_{Rx}\left(\frac{c}{4\pi r f}\right)^2 = P_t\frac{1}{r^2}\frac{A_{Tx}}{\lambda}\frac{A_{Rx}}{\lambda} \quad (1)$$

where λ is the wavelength in meters, f is carrier frequency in Hz, c is the speed of light in m/s, r is the distance between Tx and Rx in meters, P_{Tx} transmit power, P_{Rx} received power, and G_{Tx} and G_{Rx} Tx and Rx antenna gains, respectively and A_{Tx} and A_{Rx} are antenna apertures at Tx and Rx respectively. The FSPL is sometimes known as spreading loss. The received power in a free space decreases with the square of the frequency f and distance r. To analyse the range of the systems operating in different frequency bands we studied the FSPL, plotted in Fig. 1 as a function of the frequency in the range from 1 GH to 3 THz and different distances between Tx and Rx (1 m, 10 m, 0.1 km, and 1 km) for isotropic and directional antennas. Assuming isotropic antennas at the Tx and Rx, equal transmit power at all frequencies, and equal Rx sensitivities, the range of the system operating at 1 GHz is 1000 times higher compared to the range of the system operating at 1 THz. According to these calculations, we can expect a 10, 100, and 1000 times lower range of THz wireless communication system, compared to mm-waves, cm-waves, and dm-waves, respectively.

Isotropic antennas with antenna gain $G = (4\pi A/\lambda^2)$ were considered in the left part of Eq. 1. Inserting the relation between aperture and gain into the FSPL equation yields the right part of Eq. 1, which reveals that by keeping the aperture/wavelength ratio constant the FSPL is independent of the frequency [16]. The horizontal line in Fig. 1 illustrates this, for A/λ equal to 10 m. For horn and parabolic antennas, the gain-aperture relation is specified as

$$A = \eta \frac{\pi d^2}{4}, \quad G = \eta \left(\frac{\pi d f}{c} \right)^2 \tag{2}$$

where η is aperture efficiency, which leads even to decreasing FSPL with the frequency.

With increasing frequency, the size of the antenna decreases, thus in THz communications, the physical size of antennas does not represent a serious problem. However, it is not possible to increase the effective aperture of the antenna by increasing its size because the aperture efficiency steadily decreases. Similar limitations apply to antenna arrays, where feed losses increase as the number of elements increases. In addition, there are practical difficulties and lossy characteristics that arise in the THz frequency bands due to the small spacing where the feeds cannot be physically sized down. Furthermore, the aperture of the omnidirectional antenna cannot be increased because it is already nearly the same as the isotropic antenna. Theoretically, the increased A_t/λ and A_r/λ would compensate for the path loss, but there are physical limitations. Therefore, highly directional antennas with high gains are needed at both ends to compensate for attenuation and decrease in output power with an inverse square proportional to frequency.

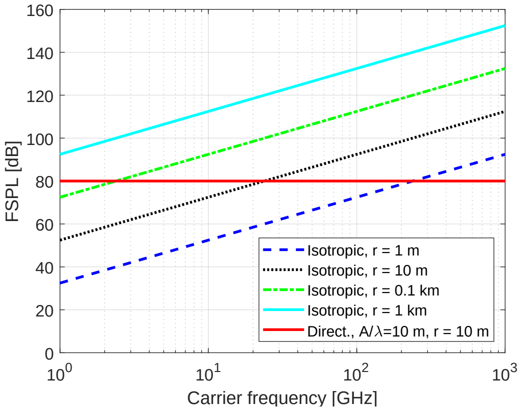

Fig. 1. Free space loss for 1 GHz – 3 THz.

B. *Path Loss - PL*

Path loss (PL) refers to the attenuation or reduction in the signal power due to propagation through the wireless channel between the Tx and the Rx. In addition to the severe PL due to the small wavelength and reduced antenna aperture, considered in FSPL analysis, the PL is affected by the environment i.e. obstacles between Tx and Rx, Tx and Rx height above the floor or earth. In empirical channel models, the environmental impact on the PL is represented as the path loss exponent, which describes the decrease of the received power by distance from the Tx. Path loss exponent in the FSPL model is equal to two, while for outdoor and indoor communications, the PL is obtained by measurement and varies between 1 and 4.

A PL modeling and analysis in the THz frequency band based on an extensive measurement campaign in the frequency range 220 - 330 GHz in an indoor short-range scenario is presented in [17]. The PL in indoor scenarios at 140 GHz and 220 GHz is studied in [18] based on the results from channel measurements in meeting and office rooms. Representative results of path loss exponents in the THz frequency band are discussed in [19]. No significant difference in terms of the PL exponent values between indoor and outdoor scenarios is noticed. The PL exponent values for the LOS are similar to the free space path loss due to a small diameter of the first Fresnel zone, while the values are larger for the reported NLOS cases.

The high PL expected in THz communications decreases the range of communication and sensing systems, but on the other hand, decreases the interference. The PL in the sensing system due to analysis of weak reflected signals seems to significantly decrease the range of sensing, and special attention has to be given to this problem.

C. *Atmospheric Attenuation*

The THz radio wave propagation is heavily affected by atmospheric absorption [20], due to EM excitation of air molecules to the higher energy states. Water vapors are the main propagation barrier. That is shown in the measurement campaigns [21], which agree with ITU-R P.676-12 model for the "Attenuation by atmospheric gases and related effects" [22] for frequencies below 1 THz. The frequency band below 1 THz is the most attractive since the attenuation above 1 THz considerably limits the range of the THz communications. The atmospheric attenuation based on [22] in dB/km is shown in Fig. 2, for the water vapor, oxygen, and cumulative attenuation.

Up to 300 GHz the attenuation is minimal and reaches only a fraction of dB/km. The main contribution to the atmosphere attenuation below 300 GHz is due to oxygen. As the frequency increases, the attenuation ranges up to 100 dB/km. Thus, on top of the free space attenuation of approximately 150 dB/km, the signal attenuates for 250 dB over a 1 km distance which is the main barrier for achieving long-range communications. In addition, high bandwidth of THz communications and sensings, the systems may exhibit the frequency selective attenuation, Fig. 2, achieving attenuation even over 10.000 dB/km. At the frequency band selection, these regions have to be strictly avoided. These large attenuation peaks at selective carrier frequencies emerge if the wavelength of THz radio waves approaches the dimensions of the oxygen and water molecules and the resonances are generated.

Temporal Broadening: The frequency-selective attenuation in the THz frequency band causes temporal broadening effects on transmitted signals, restricting the minimum spacing between consecutive pulses. In the THz frequency band, the broadening effects are much stronger compared to sub-THz frequencies due to the much higher level of frequency selectivity and wider bandwidth of communications. Furthermore, it increases with the communication distance. The NLOS propagation conditions, due to the longer path compared to LOS conditions are more affected [23]. Temporal broadening may cause serious limitation factors in the precision of sensing ISAC systems operating in the THz frequency bands.

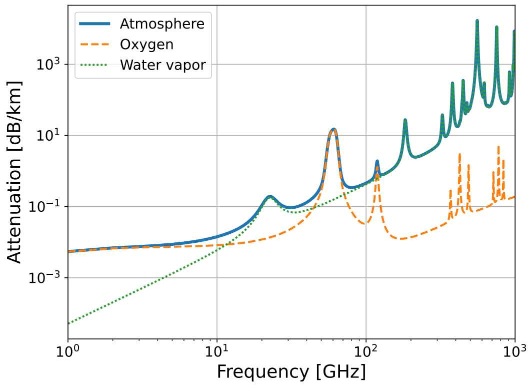

Fig. 2. Power attenuation in the atmosphere.

D. Rain and Fog Attenuation

THz radio wave propagation in an outdoor environment is affected by different weather or meteorological attenuation caused by aerial particulates including rain, clouds, and fog. Attenuation due to raindrops strongly increases with increasing frequency up to 100 GHz, while it becomes a constant function of the frequency due to particle scattering moves from Rayleigh to a more direct Mie scattering pattern (with a forward lobe which occurs when airborne particles are in the comparable size of the THz wavelength) [24]. These losses may not be significant yet still important in accurate channel characterization. To describe the rain attenuation in dB/km for the 1 GHz - 1 THz, ITU proposed P.838-3 raindrop attenuation model [25]. The different rain rates, namely light, moderate, heavy, and extreme, result in flat attenuation between 1 dB/km to 12 dB/km for THz frequency bands.

Attenuation in the outdoor environment can also be caused by fog and clouds. The phenomenon is described by ITU-R P.840-6 model [26] which assumes that the wave travels solely through a uniform fog or cloud environment. The losses are similar to losses caused by the rain and considerably smaller compared to the losses due to atmospheric absorption. They can be easily compensated since the attenuation at 100 GHz is around 5 dB/km which increases by about 15 dB/km in the range between 0.1 to 1 THz in the worst-case conditions i.e. in heavy fog/cloud conditions.

E. Vegetation Attenuation

Outdoors, THz radio waves are also significantly attenuated by vegetation, due to the scattering effects that reduce the strength of the received signal, especially under NLoS conditions. There is only one ITU model for calculating propagation losses due to vegetation [27]. It is valid for frequencies up to 60 GHz because of the lack of measurements at higher frequencies needed to develop a model for THz frequencies. To measure the water content on leaves, the time-domain spectroscopy technique can be used, and the measurements can be used to model the outdoor propagation channel [28].

F. Reflection and Diffuse Scattering

The EM wave reflects and scatters from the objects. The material EM properties and facet roughness impact the reflection and scattering. When the roughness of the surface is much smaller than the wavelength, specular reflection dominates. In this case, the reflectivity properties of the EM waves can be described by Fresnel equations [15]. Fresnel reflection coefficients Γ, describing the amount of reflecting energy from the surface, should be modified when the surface roughness becomes comparable to the signal wavelength, which is common at millimeter and submillimeter wavelengths, as [29]

$$\hat{\Gamma} = \rho_R \Gamma, \tag{3}$$

where ρ_R is Rayleigh roughness factor $\rho_R = e^{-g/2}$ with $g = (4\pi\sigma_h cos\theta_i/\lambda)/2$, λ is the wavelength and σ_h the RMS value of the roughness which increases with the increasing roughness of the surface.

At high frequencies, the surface roughness is more pronounced compared to the wavelength, resulting in non-specular reflections, also known as diffuse scattering, leading to a loss of intensity in the specular direction. This phenomenon poses a major computational challenge and can be solved using various approaches such as the small perturbation method [30], radar cross-section models [31], and the Kirchhoff approximation [32], or the integral equation model [33]. While these methods are valid for many indoor materials, for surfaces with sharp edges or rapid material discontinuities, heuristic solutions should be used, such as an effective roughness model (ER) [34]. The model defines the fraction of reflected power that is diffusely scattered from the surface by the diffuse scattering coefficient. Specular reflection and diffuse scattering are illustrated in Fig. 3.

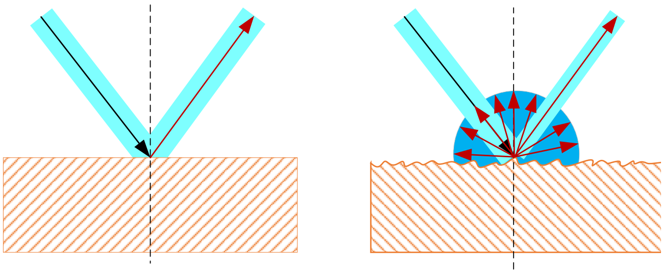

Fig. 3. Specular reflection and diffuse scattering.

Three widely known scattering models are commonly applied [34]. The Lambertian model assumes that the scattering radiation lobe has its maximum in the direction perpendicular to the wall. In the directive model, the scattering lobe is directed in the direction of specular reflection, while the backscattering model adds an additional term that accounts for backscattering phenomena.

At THz frequencies multi-layer reflections and reflections within inhomogeneous materials are present. These phenomena are more pronounced when the permittivity of the material (ϵ_r) is close to one, resulting in additional diffuse components. The size, shape, and refractive index of the surface also influence scattering. For accurate radio propagation prediction at THz frequencies, the power carried by scattered rays needs to be considered, especially in NLoS conditions where scattered rays may be dominant to support the communication link. Multi-layer reflection is depicted in Fig. 4.

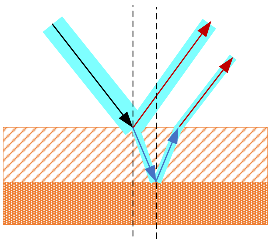

Fig. 4. Multi-layer reflection.

G. Diffraction

In addition to the influence of large objects and human blockage on the LoS path, small objects causing diffraction have to be considered as the predominant propagation mechanisms. Although the diffraction effect, which can be described by the Knife-edge diffraction and/or uniform theory of diffraction models, has a significant impact on signal propagation in frequency bands below 100 GHz, it is considerably reduced in THz frequency bands due to the high directivity and sharp shadows of various objects. Nevertheless, its impact must be considered as a form of multipath propagation that can contribute to the total received power and must be properly taken into account in channel modeling [35].

Recent work on measurements and modeling of diffraction phenomena at different frequencies (30 GHz, 140 GHz, and 300 GHz) confirms the existence of diffraction in the THz frequency band and shows that the diffraction effect becomes more dominant as frequencies increase from mmWave to THz frequencies [36] and must be carefully modeled. Extensive diffraction measurements at 60 GHz and 300 GHz and comparisons with theoretical models published in [37], [38], showed that the diffraction loss in the light shadow and light regions is almost independent of the material, while in the deep shadow regions, the loss is strongly dependent on the material.

H. Penetration and Transmission

In the THz frequency band, waves can penetrate through different non-conducting materials. The penetration is mainly limited by low transmit power and varies depending on material composition and thickness. Waves at these frequencies are noninvasive to the human body and are very susceptible to link blockage, which is the main problem with THz communication systems. In both indoor and outdoor environments, the influence of the penetration loss of different materials on THz radio waves is crucial. Measurements of the penetration loss of different materials at different frequencies show that the penetration loss increases with frequency [39]. For example, the average penetration loss for clear glass increases from 3.2 dB/cm to 12.3 dB/cm and 14 dB/cm at 28 GHz, 73 GHz, and 140 GHz, respectively. Similar results were obtained for drywall.

When the dielectric material is a mixture of different types and amounts of particles whose size is comparable to the wavelength, theoretical models that consider only surface scattering may not be accurate enough. The analytical approach based on Maxwell's equations is accurate but mathematically complicated and computationally intensive. In this respect new approaches have been developed, for example, studying volumetric inclusion and volume scattering caused by discrete particles in a homogeneous medium [40].

III. THZ RADIO CHANNEL PARAMETERS

To support the design, evaluation, and development of THz integrated communications and sensing solutions, the fundamental knowledge of the radio channel parameters is important. Thus, key parameters that describe radio channels and are important for the design and operation of communication systems are presented and their applicability to ISAC and localization is discussed. In communication systems, key parameters include path loss, fading characteristics, signal-to-noise ratio, delay spread, and Doppler frequency shift, influencing signal strength, coverage, data rate, and system performance. They are relevant for link budget calculations, design of diversity techniques and modulation schemes, estimation of interference levels, development of mitigation techniques, and design of equalization and time synchronization techniques.

Parameters such as power delay profile, K factor, coherence regions, delay spread, angular spread, and Doppler frequency shift are more relevant for localization and sensing. These parameters offer insights into multipath propagation, the propagation environment, and target localization. Power delay profile and angular spread are important for accurate multipath-rich environment sensing, particularly for determining arrival times and angles of multipath components. Further, polarization can also be a source of location information. Polarization changes during signal propagation in multipath environments can potentially provide object displacement and displacement rate information.

A. Power Delay Profile

The power delay profile (PDP) gives the distribution of signal power received over a multipath channel as a function of propagation delays [41]. It is an essential parameter for understanding the characteristics of multipath propagation and thus for the description of the environment. The wide bandwidth of the THz communication system enables high temporal resolution of the PDP and more information about the environment. On the other hand, directive antennas used for achieving high gains in THz communication systems cut off the multipath components and consequently reduce the information about the environment. The diffuse scattering at THz frequencies decreases the power of specular reflections, leading to the low power of multipath components at THz frequencies. The path length of the reflected EM waves is longer compared to the direct one, which introduces additional attenuation to reflected rays. The dispersion of the channel due to reflections can be characterized by the first and second central moment extracted from the PDP.

1) RMS Delay Spread: RMS delay spread is a derived parameter from PDP, the second moment of PDP, and the most widely used parameter to quantify the dispersion effect of the multipath channel. A larger RMS delay spread implies that the channel has a significant dispersion in propagation delays. The delay spread depends on the antenna beamwidth. The use of directional antennas results in a smaller delay spread due to the multipath components falling outside the antenna's main lobe. RMS delay spread is a derived parameter from the PDP and thus carries less information about the environment than the PDP. Due to the low spreading of the reflected EM waves at THz frequency bands, it is not applicable for environment sensing. However, it can be applied as a parameter for observing changes in the environment, for example, the presence of objects or persons.

2) Rician K Factor: The Rician K factor (KF) describes the strength of the LOS component compared to the reflected and scattered components in a wireless communication channel. The KF serves to assess the strength of the multipath effect and can be estimated from PDP calculating the ratio between the power of LOS components to all other components. The THz frequency band exhibits larger KFs than lower frequency bands due to the larger reflection and diffraction losses. A larger KF means that the LoS path dominates in the channel, indicating a weaker multi-path effect. Analysis of the measurements conducted between 130 and 140 GHz in an indoor environment suggests that a longer propagation distance, high reflection loss, and beam misalignment of the reflected multipath components cause a high KF value [42]. The reflections in enclosed indoor spaces are normally stronger than those in open outdoor environments, resulting in slightly smaller KF values. Extensive measurements at other frequencies are needed to conclude the trend of KF varying with frequencies.

B. Doppler Shift and Doppler Power Spectrum

The observed frequency f of EM waves changes with respect to the emitted frequency f_0 when there is a relative motion between the EM wave source v_{Tx} and Rx v_{Rx}:

$$f = \left(\frac{c_0 \pm v_{Rx}}{c_0 \pm v_{Tx}} \right) f_0 \tag{4}$$

The phenomenon is known as the Doppler shift, and it is widely applied in radars to detect the motion of an object. It is especially expressed at higher frequencies, as the Doppler shift becomes 10 times larger at 1 THz than that of 100 GHz [43]. THz radio waves thus enable the detection of micro-Doppler signatures [44], such as vibration and small movements of the target, empowering precise sensing applications. By contrast, severe Doppler effects at THz frequencies will greatly affect the communication systems [45], where the Doppler spectrum describes the spreading of an EM wave frequency due to the motion of the Tx and the Rx, and multipath propagation.

Doppler Spread: Doppler spread is the second moment of the Doppler spectrum. In channels with high Doppler spread the orthogonality of subcarriers can be disrupted, resulting in inter-carrier interference. One approach to alleviate the Doppler effect is to increase the spacing between subcarriers, but this may come at the cost of reduced accuracy in velocity estimation. This trade-off should be considered while designing an ISAC system.

C. Coherence Region

The coherence region in the temporal/frequency domain refers to a temporal/frequency interval in which the wireless channel exhibits similar characteristics. Outside the coherence region, the wireless channel characteristics can change significantly. The coherence region defines the coherence time and coherence bandwidth, which are related to Doppler spread and RMS delay spread, respectively.

The coherence time is a temporal measure of the channel's coherence. It is a statistical measure of the time duration over which the channel impulse response is time-invariant. Coherence time is the time-domain dual of Doppler spread. It is inversely related to the frequency of the wireless signal. Higher-frequency signals experience more rapid variations in the wireless channel, leading to shorter coherence times. In the THz frequency band, the coherence time is typically very short due to the extremely high frequency.

The coherence bandwidth is a measure of the channel's coherence in the frequency domain. It represents a range of frequencies over which the channel is considered flat and exhibits minimal or no frequency-selective fading. The delay spread of the wireless channel influences the coherence bandwidth. In particular, a larger delay spread results in a narrower coherence bandwidth.

The coherence region is usually calculated using empirical formulas. For instance, (i) the coherence time as a proportion to the reciprocal of the Doppler, and (ii) the coherence bandwidth as a proportion to the reciprocal of the delay spread. Analysis of the coherence time and bandwidth at 300 GHz is given at [46].

The low coherence time in wireless systems leads to a rapidly changing channel that affects both sensing and communication. In localization, the rapid channel changes result in faster location updates, which requires the acquisition of a sufficient number of samples within a time frame smaller than the coherence time. If the sampling frequency of the data remains constant, more samples can be acquired with a longer coherence time, which increases the accuracy of the distance/angle/shape determination. In communication, the coherence time determines the duration over which symbols or frames can be transmitted without distortion or fading. If the coherence time exceeds the symbol or frame duration, the channel is considered to have flat fading, which allows signal recovery by simple equalization. On the other hand, if the coherence time is shorter than the symbol or frame duration, frequency-selective fading occurs, which can lead to inter-symbol or inter-carrier interference.

Frequency-selective channel communication can be improved by using several pilot signals with different frequencies. Although this reduces the bandwidth available for communication resulting in a lower data rate, more reference points are available for channel estimation, which increases the accuracy of the channel calculation. Especially in communication systems using Orthogonal Frequency Division Multiplexing (OFDM) or similar multi-carrier modulation schemes, information about the channel state is crucial for equalization. Coherence time affects the frequency of channel evaluation and update rate. Shorter coherence times require more frequent estimates to ensure reliable communication. This has implications for adaptive modulation and coding schemes, as they can be employed more efficiently with accurate and timely channel state information.

D. RMS Angular Spread and Angular Spectrum

The angular spread is used to characterize the power dispersion of multipath components in the spatial domain. A small angular spread value indicates the received power comes from a narrow spatial region. The angular dispersion is due to the multipath components departing in different directions from the Tx, interacting with objects in the environment, and arriving at the Rx from different directions. The multipath rays arrive at the Rx from both the azimuth and the elevation planes and the angular spreads must be individually analyzed.

A commonly used definition of the RMS angular spread refers to the second central moment of the angular power spectrum, in analogy to the RMS delay spread. The angular spectrum refers to the spatial distribution of electromagnetic waves in terms of angles of arrivals. The angular spreads of arrival and departure in azimuth and elevation planes, i.e. azimuth spread of arrival (ASA), elevation spread of arrival (ESA), azimuth spread of departure (ASD), and elevation spread of departure (ESD) describe the angular dispersion.

A larger angular spread indicates a more dispersed or scattered channel. Conversely, a smaller angular spread implies a more directional channel. The angle information is especially valuable in the context of multi-antenna systems. The beamforming techniques and the relative locations between the Tx and Rx greatly influence the angular spreads [47]. The THz channel is sparse in the angular domain and exhibits a smaller angular spread than the mm-wave channel.

For similar heights of the Tx and the Rx, the elevation spreads are smaller than azimuth spreads. The contributions of the reflections from the floor and ceiling in indoor environments cause larger elevation spreads in indoor scenarios compared to outdoor scenarios, while the azimuth spreads are similar.

E. Cross Polarization Ratio

The cross-polarization ratio (XPR) quantifies the level of separation between polarizations in scenarios where the transmitting and receiving antennas have orthogonal polarizations. It quantifies the system's ability to discriminate between the desired polarization intended for transmission or reception and the undesired polarization that has to be rejected or minimized. The XPR is an essential parameter to assess the system's performance in managing signals with varying polarization and to examine the feasibility of polarization diversity.

The XPR in the THz frequency band is scarcely studied due to hardware limitations for performing the measurements. The trend in the variation of the XPR for different propagation environments and frequencies is not reported since extensive measurement campaigns are not conducted to provide a detailed analysis of the polarization. The available results are based on ray-tracing simulations. From the initial results provided by [48], [49] it can be observed that in the LOS case, the XPR values are larger than in NLOS cases due to the co-polarized direct path.

IV. CONVERGENCE OF WIRELESS COMMUNICATIONS AND SENSING IN THZ FREQUENCY BANDS

To show the integration of communication and sensing systems operating in THz frequency band opportunities, in addition to basic properties in THz radio wave propagation, knowledge about the main requirements and characteristics of both systems is a prerequisite. In this respect, we discuss the basic properties of communication and sensing systems and look at the system integration opportunities.

The main objective of communication systems is to transmit a message from one point, the Tx, to the remote point, the Rx, consequently at least two active devices are involved in communications. Communication signals are designed to carry as much information as possible. Communication signals can be very complicated to support different propagation environments, the characteristics of devices, and communication requirements. They are typically modulated to carry information, combined with non-modulated training signals. They can be discontinuous and fragmented over time, and frequency ranges. Although the communication signals can potentially be used for monitoring changes in the propagation environment, they are very different from conventional radar signals. Consequently, the sensing performance by using communication signals in general cannot be guaranteed [50].

A pulsed radar is recognized as a typical representative of radio frequency (RF) sensing systems, but RF sensing encompasses a wide range of applications, including spatial information sensing, RF spectrum sensing, signal identification, localization, positioning, and tracking.

According to the source of the observed signal RF sensing distinguishes passive and active sensing. The passive systems do not emit any RF signals but exploit already existing communication links for opportunistic sensing. By using radio waves reflected or scattered from the environment, an observer can extract the channel characteristics and use them for sensing. An example of a passive sensing system is to exploit beacon signals transmitted from the base stations or radio and TV broadcasting signals. Due to its scarce nature and the inability to control transmission, opportunistic passive sensing will almost always achieve lower performance than active radar systems [8]. Active systems, on the other hand, operate with their own source of RF signals. The classification of active RF sensing recognizes two approaches: if a target, that is being sensed, is equipped with a transceiver, then the sensing system is considered to be device-based; otherwise it is considered device-free. In addition, the sensing system can be described as bi-static, when the TX and the RX are positioned at different locations, and monostatic, when the TX and RX are co-located.

Even though the sensing and communication functions address completely different approaches to exploit EM waves, namely, radio waves convey information in communication systems, while in sensing systems, it is applied to illuminate the target, the same waveform can be applied as an illuminator to perform sensing and as an information carrier [50]. In this respect, the development of an ISAC system can follow one of three design paradigms [50]:

- communication-centric design,
- sensing-centric design, or
- co-design without an underlying system.

In the first two categories, realization focuses on how to achieve other functions based on the existing system with minimal effect on the primary system, while in the last category, a new system is developed from scratch, incorporating modern technologies and techniques.

A. Communication-centric ISAC System Design

In communication-centric ISAC systems, the communication system performance can be preserved. Since the main objective of communication systems is to convey messages, there are always at least two devices involved, so ISAC systems typically include bi-static sensing. In the device-based bi-static ISAC system, both Tx and Rx actively participate in the communication network, while one of the devices is also the target that is being sensed. The Rx can extract the characteristics of a wireless channel and use them for sensing purposes such as localization, distance and speed estimation, tracking, and so on. In the device-free bi-static ISAC system, the target to be sensed does not participate in the communication. Any type of radio link can be used to extract information about the surrounding environment and detect the changes in the wireless channel.

Communication-centric ISAC can be implemented as a monostatic and device-free sensing system, where the base station or access point is used for sensing while participating in the communication network. The resources in such systems are shared in either the time or frequency domain to achieve both sensing and communication functions. Device-free monostatic ISAC systems can also be built on top of the systems already developed. For example, in cellular networks, the base station can detect reflected and scattered radiation from the environment during communication and use it for device-free sensing.

The integration of the bi-static and monostatic sensing systems in the communication-centric ISAC system is shown in Fig. 5.

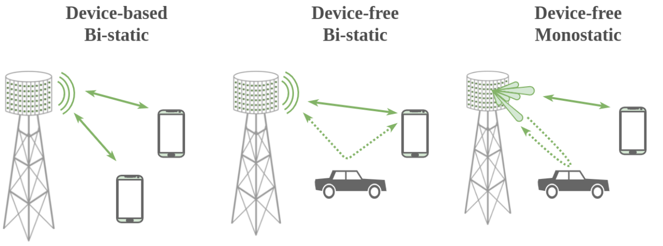

Fig. 5. Communication-centic ISAC system design.

Fig. 6 shows the communication and sensing applications for different frequency bands [51]. The main communication system applications foreseen for THz communications are extended reality and digital twins, while situation awareness and radar positioning are foreseen in sensing and localization applications. Situation awareness, looking at the changes in the environment using passive bi-static sensing seems a suitable topic for communication-centric ISAC systems, due to changes in the environment that can be detected from the radio signals.

B. Sensing-centric ISAC System Design

Conventional sensing systems, such as pulsed radar systems, emit short pulses of wide bandwidth followed by a silent period in which the echoes of the pulses are received and used for ranging. Continuous-wave radar systems, on the other hand, transmit waveforms at a specific frequency (usually chirp signals) while simultaneously scanning for reflected signals, which are used to determine the range or speed of the target. In both systems, the waveforms are usually unmodulated and designed for low-complexity hardware. To accomplish the sensing-centric design, the information can be embedded in the radar waveform [50]. As a result, radar systems typically cannot support very high data rate communications without significant changes to the waveforms and/or Rx structure. Sensing-centric design can be therefore used for an application not requiring high throughput, but providing high-accuracy sensing.

In this respect and taking foreseen applications at different frequency bands depicted in Fig. 6, the THz radars estimate the speed and position of vehicles, can include low data rate information to inform the target vehicle about its status and future activities, which is necessary information for the autonomous driving.

C. ISAC System Co-design

Although there is no clear boundary between the co-design category of technologies and systems and the previous two categories, the former have more freedom in terms of signal and system design and can be developed without being limited to existing communications or sensing systems. In this sense, communications and sensing functions can be designed and optimized taking into account the essential requirements for both, potentially allowing a better trade-off between the two functions [9]. The straightforward approach is to design a single waveform used both for radar and communication [8]. Some of the promising waveform designs are given and compared in [10]. The single waveform approach brings advantages such as more flexible and efficient use of spectrum, but the common waveform design is challenging since it must satisfy the requirements of both systems. In addition, suitable hardware architecture and improved sensing detection and estimation techniques are needed.

V. CHALLENGES AND RELATED OPPORTUNITIES

Due to the advantages brought by integration communication and sensing functions, the topic of ICAS has caught researchers' interests in the last decade [52]. A plethora of research has been done on research directions, operation constraints, and various implementations of an ICAS system with

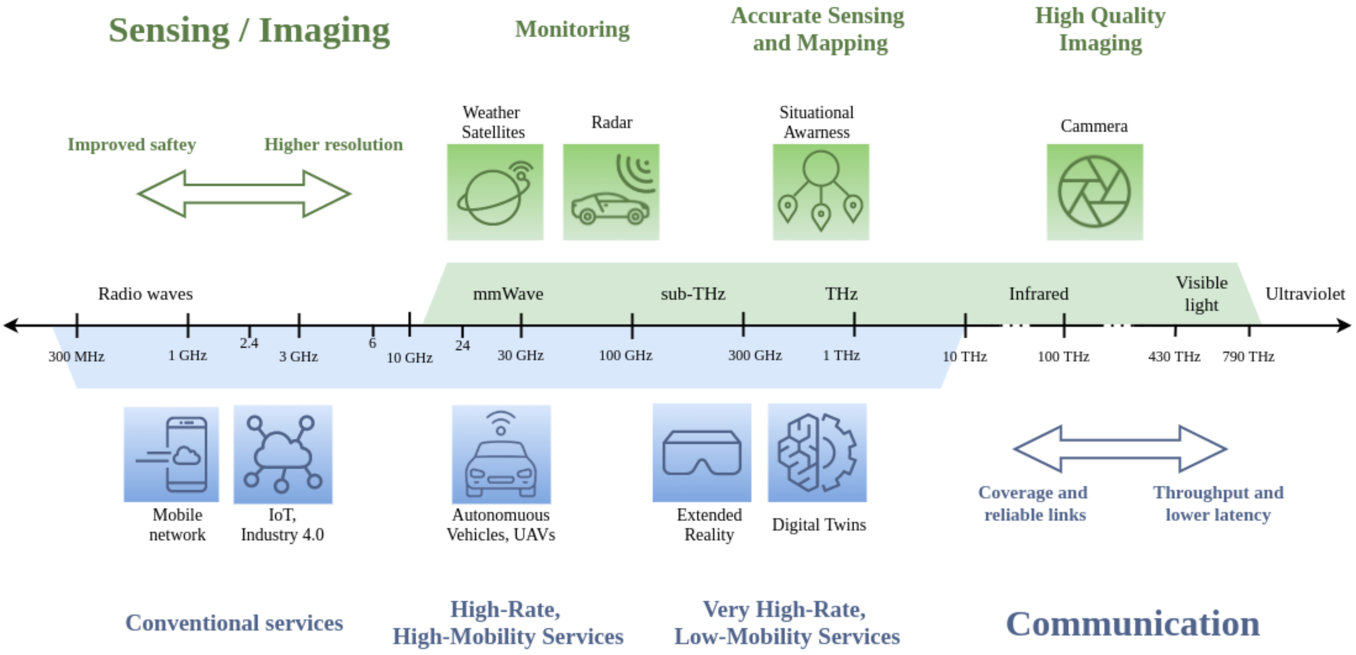

Fig. 6. Convergence of communications and sensing at THz frequencies.

frequencies below THz frequency bands. THz signals with frequencies above 100 GHz, on the other hand, interact with the environment differently and thus impose new challenges and opportunities. In general, THz radio waves have several advantages as well as challenges over lower-frequency waves for communications and sensing purposes, which are described in this section.

A. *Wide Bandwidth*

From an RF sensing and localization perspective, the transition to THz frequencies has several important advantages. The wide bandwidth and small wavelength of THz signals enable high-resolution and high-accuracy radar. Wider bandwidth allows a smaller time duration of the signals, which can be used to improve the time resolution and reduce the uncertainty of the signal, for example, while measuring the time of flight metric. In addition, with shorter pulse width or a sharper edge, wide bandwidth signals can excite more frequency components of the channel and reveal more details of the channel impulse response compared to narrowband signals. The radar range resolution (S) is proportional to the bandwidth (BW) of the transmitted pulse since the shorter pulses have the ability to distinguish between targets that are very close.

$$S \geq \frac{c_0}{2 \cdot BW} \tag{5}$$

Similarly, smaller wavelengths can distinguish smaller objects and their details, greatly improving the resolution of the radar system. Massive antenna arrays with high directivity will furthermore improve the localization performance, as a larger number of antennas enables better resolvability of angles.

B. *Interaction of the THz Radio Waves with Environment*

Furthermore, the utilization of THz radio waves presents exciting new prospects in the field of sensing. The way the THz radio waves interact with objects is related to the specific material composition. Depending on the material, THz radio waves can undergo complete reflection, absorption, or a combination of both phenomena. This unique characteristic unlocks a plethora of innovative applications, including imaging and spectroscopy. By scanning the response of a material across frequencies and plotting the measured spectrum, the EM signature of a material can be obtained.

C. *Propagation Losses*

The transmission of signals through the THz channel faces significant challenges due to path loss caused by spreading loss, molecular absorption, and potential blockage of the signal's path. While mmWave signals can penetrate certain obstacles like walls and human bodies, as depicted on Fig. 7, THz radio waves suffer from high attenuation and experience less diffraction when encountering common obstacles, severely limiting their ability to propagate through or around these objects. As a result, the line-of-sight path between an access point and user equipment can become obstructed, reducing the coverage distance of sensing and communication systems. For applications where a broad coverage area is required, such as outdoor localization or large-scale communication systems, signals with longer wavelengths are the more suitable choice. THz signals with short wavelengths are therefore considered for short-range applications, especially in indoor scenarios.

Since the multipath components experience significant attenuation due to longer propagation paths, the THz channel can be characterized as LoS dominant [53]. Moreover, the

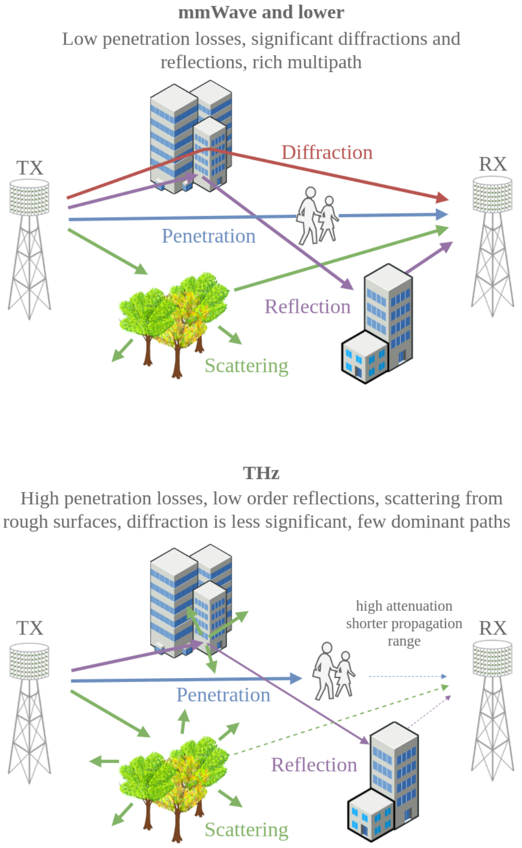

Fig. 7. Comparison of the propagation mechanisms in the THz and lower frequency bands.

increased scattering behavior of THz radio waves further diminishes the strength of reflected beams. Although challenging propagation environment for communication, the THz characteristics can be useful for radar applications and accurate localization systems, where the presence of a direct, unobstructed LoS path between the Tx and the target is essential.

1) THz Channel Frequency Selectivity: Unlike lower frequencies, THz radio waves possess enough energy to induce internal vibrations of the air molecules while propagating through the medium, which results in the absorption of the transmitted wave. The amount of absorbed energy is dependent on the wavelength, the environment (type of the molecule, their density, pressure, and temperature), and the distance between the Tx and Rx. Fig. 8 demonstrates that the absorption losses caused by the water vapor and oxygen molecules are not present at all frequencies, which can be used for different application scenarios. Large attenuation is present at the resonant frequencies of water vapors and oxygen molecules. The windows with low absorption losses can be used for medium-range ICAS systems, while frequencies with absorption spikes provide a unique opportunity to limit the ICAS system range, which can be useful for privacy aspects, or to remove the unwanted interference between two systems. In satellite communications, for example, the ionosphere presents a good filter to separate space systems from the ICAS systems at the ground of the earth. Given the temperature-dependent attenuation, measuring the attenuation values also allows the receiver to measure temperature changes and use this information to make adjustments to the receiver's temperature-sensitive components, ultimately improving the communication rate. It is worth noting that the attenuation of some parts of the spectrum is more sensitive to temperature changes than others, depending on which molecules dominate in those parts. Furthermore, the temperature effect is more pronounced with increasing distance between the receiver and transmitter.

2) Distance Depended Bandwidth: Molecular absorption and spreading losses are also strongly dependent on the distance of transmission. As a consequence, so is the used bandwidth. Fig. 9 depicts an example of how the bandwidth window shrinks with the increased distance, which must be taken into account while designing a THz ICAS system. In Fig. 9 we show an example of a low absorption window that lies between the peak values at 917 GHz and 970 GHz. The a) plot shows the absolute value of the channel response ($|H|$) and the b) plot shows the normalized channel response to provide an insightful comparison. It can be seen that the bandwidth window shrinks with increasing distance. Also, the effects of temperature variations on the bandwidth can be seen in the plot c), where the bandwidth window shrinks with increasing temperature. Less pronounced temperature variations can be seen at the resonant attenuation peak of 917 GHz than at the attenuation peak of 970 GHz.

Spreading losses and distance depend on bandwidth, however, provide new options to employ space-division multiple access. Depending on the communication distance, a specific power domain multiplexing can be used, since the received signal power at two devices separated by a certain distance is different, and can be therefore used for simultaneous communication with different devices. The authors in [54] mathematically proved and demonstrated, that with a properly designed hierarchical bandwidth modulation, the distance-dependent characteristics of the THz radio waves can be used, to increase the system capacity by spatially multiplexing the devices in the network.

D. Scattering

Another diminishing effect on THz signal strength, as well as its spatial and temporal characteristics, is signal scattering. THz radio waves are more susceptible to scattering than lower frequency waves because they have shorter wavelengths and interact more strongly with small particles and rough surfaces. The intense scattering nature of the THz radio waves on common objects (walls, furniture, etc.) and their reflected components can be exploited for novel methods of sensing. In [55], the authors presented how the diffused reflected components can be used for target sensing. Scattering and molecular absorption effects can also be used to image the internal structure and properties of materials and objects by measuring the scattered THz fields with different techniques, such as time-domain spectroscopy, frequency-domain spectroscopy, or holography [56].

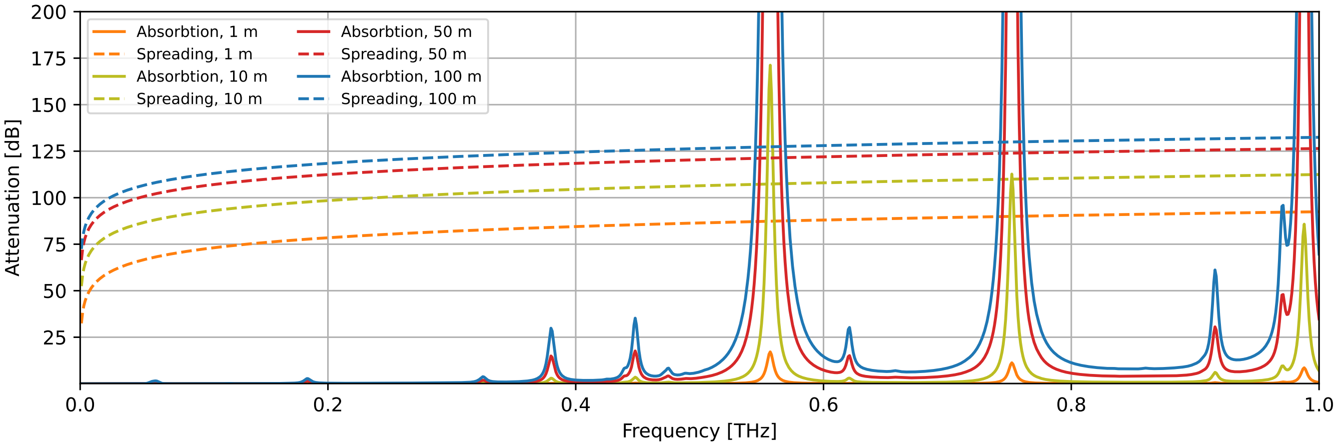

Fig. 8. Spreading loss (dashed lines) and molecular absorption loss (solid lines) for frequencies ranging from 0.1 to 1.0 THz and four different distances (1, 10, 50 and 100 m) [7].

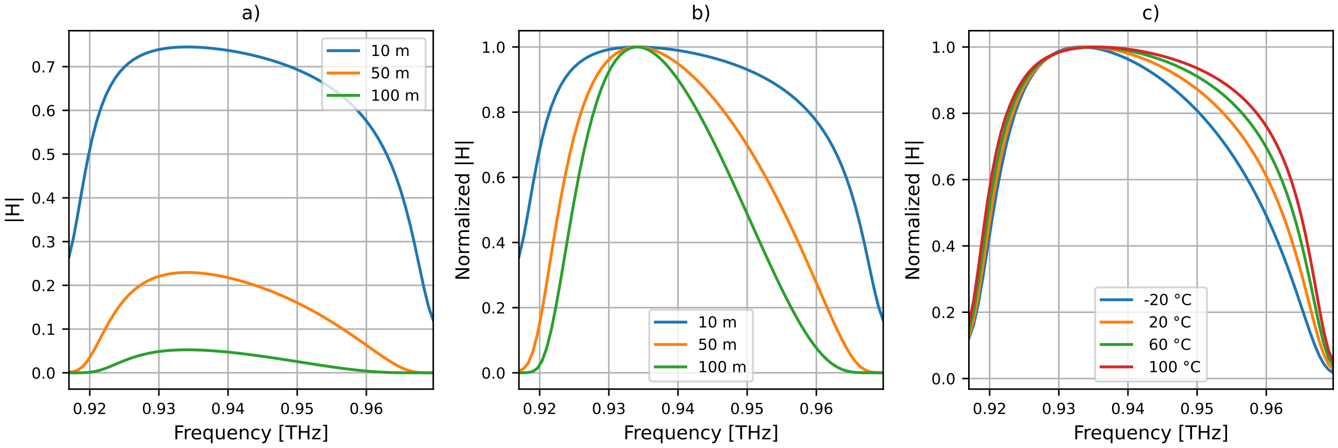

Fig. 9. Distance and temperature effect on bandwidth. a) bandwidth at 10 m, 50 m, and 100 m, b) normalized bandwidth at 10 m, 50 m, and 100 m, c) normalized bandwidth for a fixed distance of 20 m at -20 °C, 20 °C, 60 °C, and 100 °C.

E. Channel Sparsity

To compensate for the extremely high path loss effects of THz radio waves and increased noise caused by the wider bandwidth, the antenna gain must be very high to realize a reasonable signal-to-noise ratio (SNR), which implies narrow beams. A narrow beam is achieved with large antenna arrays, which focus transmitted energy in a desired direction. Antenna arrays can be realized with multiple antennas that are spatially arranged and electrically connected to form a single antenna.

For successful communication, the beam between the Tx and Rx must be aligned, which is a major challenge to achieve with highly directional and narrow beams. This challenge further emphasizes the importance of ICAS systems, as the localization function is necessary for optimal communication. To adjust the main lobe direction of the antenna and maximize the effective antenna gain, the Tx must know the position of the Rx, as depicted in Fig. 10. Due to the narrow beams, the initial search for the unknown position of a target object is time-consuming. Namely, the beam would have to scan the broad area before detecting an echo of the target. Omnidirectional antennas are not adequate, since the propagation losses of THz radio waves are high and their use would result in a very short sensing range.

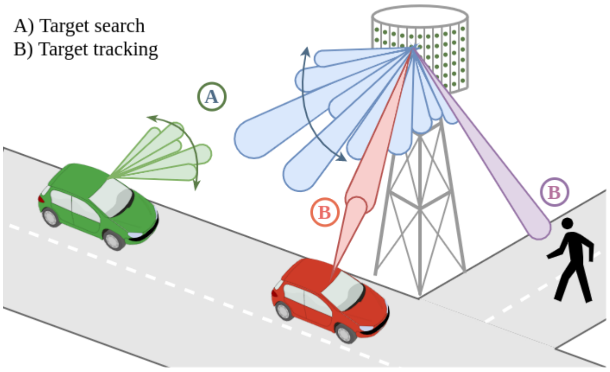

Fig. 10. Initial estimation and tracking of the target position using antenna arrays with narrow beams.

One approach to accelerate the first search for an object is presented in [57], where a two-step AoA estimation is proposed. In the first step, a low-frequency RF frontend is used for a quick and low-resolution angle estimation. Since the propagation loss at the lower frequency is significantly lower than at the THz frequencies, an omnidirectional antenna can quickly obtain the AoA estimate from a wide range. The estimated result is then used in the second step, where the high-resolution AoA estimation is achieved with the THz frequencies. In addition, THz radio waves are easily blocked or reflected by human movement and other obstacles, the channel characteristics vary over time and space, thus repeated sampling is required to maintain the true estimate.

Antenna arrays not only improve the spectral efficiency of communication systems [10] but also enhance the sensing performance of an ICAS system. The ability to generate very narrow beams is advantageous for sensing solutions to overcome the high scattering losses in the THz frequency band and reduce interference from reflected waves. The highly directional beams encounter fewer obstacles and interferences, resulting in reduced multipath effects and reduced delay spread of the propagation channel, improving the sensing accuracy. Although some of the additional available channel features are therefore lost, with fewer multipath components THz sensing and localization systems can achieve higher spatial resolution. Moreover, due to the beamforming, the THz channels are extremely sparse in the angular domain, and the number of resolvable angular paths of THz radio waves is significantly limited compared to lower frequency channels [58], [43].

Antenna arrays that form the beams can also be treated as a hardware resource. Drawing parallels with the video camera, an antenna array with a lot of antennas has a large number of ”pixels” for sensing. This allows radio devices to resolve numerous objects simultaneously and achieve sensing results with much better resolution [9]. On top of that, beamforming offers new prospects and solutions for ICAS, in view of using separate coexisting beams to perform sensing alongside communication. In [59] for example, a multibeam framework is proposed to simultaneously allow an antenna beam towards the user and a sensing beam to scan the environment. In [60], a multibeam ICAS system capable of detecting and localizing multiple targets is designed. The authors conclude that lower frequencies allow the detection of targets at longer ranges, but the accuracy of the system is lower due to the smaller number of antenna elements available.

F. Near Field Considerations

The Fraunhofer distance, denoted as r, represents the boundary between the near field and the far field regions. It can be expressed as:

$$r = \frac{2D^2}{\lambda}, \tag{6}$$

where D is the maximum physical dimension of the antenna and λ is the wavelength of the transmitted or received signal. While it is a reasonable assumption that a single antenna operating in the terahertz frequency range inherently operates in the far field due to the short wavelength and relatively small antenna size, this assumption becomes less straightforward when considering massive antenna arrays and MIMO designs. In the context of the THz frequency band, near-field propagation must be considered especially for antenna array applications such as beamforming and direction finding [61]. These methods often assume plane wave propagation, which is suitable for far-field operation, and neglect the curvature effects associated with spherical wave propagation from a point source, which are important in the near field.

When the sensing object is in the far field of the Tx, only directional information about the target is needed to steer the beam toward it. In contrast, for objects in the near field, it is essential to know both the direction and the distance of the target for the exact calculation of antenna excitation. Furthermore, the ability to generate a variety of beam shapes in the near field holds considerable potential for sensing and communication applications in various fields [62], [63]. This potential includes advantages such as utilizing multiple uncorrelated channels and overcoming problems related to blockage and interference mitigation.

VI. CONCLUSION

Path loss in the THz frequency band is severe due to the small wavelength and reduced antenna aperture, while there is no significant difference in terms of the path loss exponent values between indoor and outdoor scenarios. The THz frequency band exhibits a larger Rician K Factor than lower frequency bands. RMS delay spread decreases as the frequency increases. The delay spread increases with the propagation distance while typical delay spread values in outdoor THz scenarios are significantly larger than those in indoor scenarios. As the THz channel is sparse in the angular domain it exhibits a smaller angular spread than the mm-wave channel. In the THz frequency band, the coherence time is typically very short due to the extremely high frequency.

In addition to the advantages, such as the wide variety of unallocated frequency bands that can overcome the spectrum scarcity and capacity limitations of current wireless technologies, THz radio waves also bring new challenges and unanswered questions that need to be analyzed and resolved before applying them for communications and sensing. These include (i) propagation losses caused by spreading loss, molecular absorption, and potential blockage of the signal’s path, and (ii) channel sparsity, where as a compensation for the extremely high path loss effects of THz radio waves, and increased noise caused by the wider bandwidth, the antenna gain must be very high, which implies directional and narrow beams.

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