Overview of challenges in channel and propagation characterization beyond 100 GHz for wireless communication systems

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Abstract

This paper presents an overview of characterization aspects associated with the channel and propagation investigations in the frequency range between 100 GHz and 1000 GHz for future wireless multi-gigabit communication systems. While reviewing the state of the art, it summarizes key achievements and highlights possible further research directions together with their challenges.

1. Introduction

Based on the exponential growth of data rates achieved by wireless communication systems in the last three decades [1] one can conclude that in about 10 years from now data rates of about 15 Gbps will be needed. A possible application for such high data rates is the wireless extension of future fibre optic access networks. Obvious candidates to fulfill the huge spectrum demand for these systems are the mm and sub-mm wave systems. Especially beyond 300 GHz – in the so-called THz range – currently unregulated frequency bands are available. An overview of concepts and perspectives of THz communication systems also discussing the technological and propagation conditions can be found in [2]. A prerequisite for the development of these systems is the availability of propagation models for the corresponding frequency bands enabling the derivation of channel characteristics. Preferably, these should be analytical models, which are easily applicable in deterministic channel modeling, e.g. ray-tracing. Especially in the mm-wave range and in particular in the 60 GHz band, ray-tracing was demonstrated to provide channel simulation data that corresponded accurately with measurement results, see e.g. [13]. Apart from line-of-sight (LOS) free-space propagation, scattering and reflection are the most important propagation phenomena. For frequencies up to 60 GHz these phenomena have been widely studied, see e.g. [3]. However, only a few measurements at higher frequencies have been reported in the literature, see e.g. [4]. In the recent past, propagation studies at the Terahertz Communications Lab (TCL) at Braunschweig Technical University focused on modeling reflection and scattering processes in indoor environments based on measurements beyond 100 GHz [5-11]. In particular, electrical material parameters, i.e. refractive index and absorption coefficient of a range of common building materials are characterized. Furthermore, the properties of reflections from optically thick smooth materials, multiple reflections from multilayer or optically thin smooth materials and diffuse reflections from optically thick rough materials are treated. The investigated propagation models are employed in an integrated simulation environment together with hardware parameters and budget analysis to analyze the performance of future THz communications systems [18].

Reflection modeling, measurements and associated challenges as well as possible further developments are described in more detail in the following sections. Transmission and diffraction effects are also discussed. These phenomena form the core of THz propagation effects, and as such present constraints to the channel characterization.

2. Reflection measurements and modeling

A vector network analyzer based system with external upconverting mixer heads can be used to determine the reflection characteristics in the frequency range 70 GHz to 170 GHz [8], covering W- and D-bands. At the frequency of 300 GHz a standalone system [17] can be employed. For the frequency band 100 GHz to 1 THz the reflection measurements can be based on terahertz time-domain spectroscopy using a commercially available terahertz time-domain spectrometer [16]. Both optically thick and layered materials with smooth or rough surfaces can be measured.

In general, the problem of rough surface scattering can be solved with numerical simulation approaches that are based on integral or differential equation methods to solve the underlying Maxwell boundary value problem. However, numerical approaches are rather complex and usually time-intensive. Instead, under certain conditions analytical approximations can be used. Such algorithms are very robust, give physical insight into the problem and can be easily implemented in ray-tracing. The method which we presented in [5] is extended in order to model reflective properties of rough materials in the specular direction. The extension utilizes Kirchhoff theory of scattering from rough surfaces, which is implemented into the existing model by multiplication of the reflection coefficient derived from Fresnels equations with a Rayleigh roughness factor [7]. This factor can be calculated from measured surface roughness data of the investigated material. Example measurement and modeling results of the reflection coefficient at the frequency of 350 GHz are shown in Fig. 1 for three sample rough materials, including ingrain wallpaper and two samples of unpolished concrete plaster.

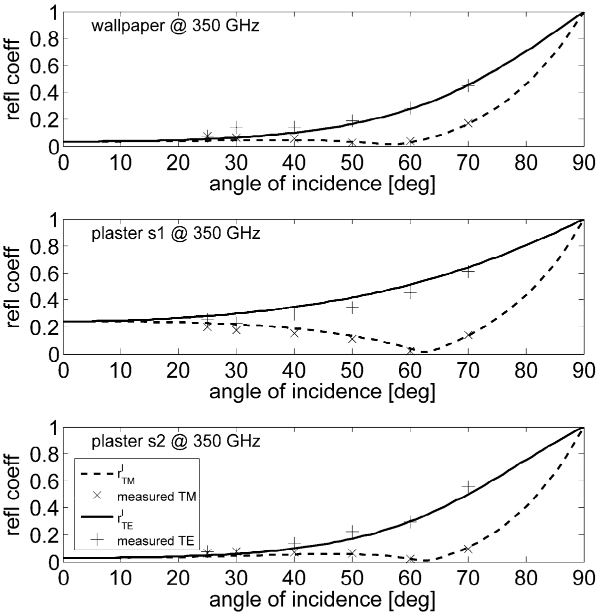

Fig. 1 Calculated magnitude of reflection coefficients and direct reflection measurements of wallpaper, and two plaster samples with different roughness at the frequency of 350 GHz of TE and TM polarized waves

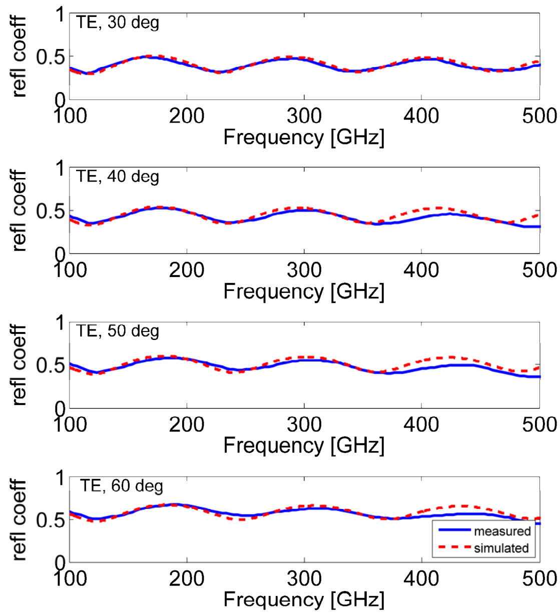

Fig. 2 Measured data and transfer matrix simulations of the frequency and angle dependent amplitude reflection coefficient of white paint on plaster for perpendicular polarization

If the surface reflection dominates the overall reflection coefficient of the investigated structure, classical Fresnels equations sufficiently describe the reflectivity in case of the smooth surface materials, while the Kirchhoff approach can be applied when the surface is rough. This is the case if the thickness of the obstacle is large compared to the wavelength and the material is absorbing strong enough, so that internally reflected waves are nearly completely attenuated when they reach the surface. However, in the presence of optically thin materials or layered stacks, multiple reflections must be included in the calculations. Frequency and angle dependence of the reflection coefficient can differ considerably from the ones of optically thick materials, due to constructive and destructive interference of reflected waves. The multiple reflections effect above 100 GHz can be modeled with the transfer matrix approach [9]. Example measurement and modeling results of the reflection coefficient for the frequencies between 100 GHz and 500 GHz are shown in Fig. 2 for a regips plaster sample covered with white paint.

3. Challenges of scattering and multiple-reflections characterization

In case of the modeling of scattering processes, the challenges mainly pertain to the limitations of the Kirchhoff approach. It can be applied at high frequencies, where the surface appears smooth on the scale of the wavelength. However, while providing physical insight into the problem of scattering and being easily implementable in deterministic propagation tools, the drawbacks of this method consist in its lack of precise characterization of the domain of validity. The main problem with the Kirchhoff model is that it ceases to be valid when shadowing is involved, i.e. when amplitude effects dominate over phase effects. Such a case might occur in practice in mobile communications and applies in particular to the angles of incidence, which are close to the grazing angle [14]. The limitations of analytical approaches are ultimately overcome only by numerical methods [15]. Especially in application areas for more complex scattering problems such as objects below the surface or rough layered media, numerical methods offer greater accuracy. Numerical approaches to problems of scattering can be classified into two categories, based either on integral equation or differential equation methods. The integral equation methods are especially suited for the solution of large, perfectly conducting or single dielectric surfaces without volume inhomogeneity. On the other hand, differential methods offer greater flexibility in modeling inhomogeneous materials, e.g. layered structures with rough surfaces.

For the multiple reflections modeling, the challenges are primarily associated with adequate characterization of the layered structures that might include rough interfaces. This problem is highlighted in Fig. 2, where a slight decrease in the measured reflectivity with increasing frequency compared to the simulations can be observed. Possibly, this can be explained by scattering due to slightly rough surfaces of the single layers. Kirchhoff scattering theory suggests increasing diffusive losses with increasing frequencies in specular direction as shown in [7]. The indicated problem could be likely solved by the modification of the transfer matrix method with the inclusion of rough surface scattering effects. This would also preserve the analytical approach, and hence would further render the method easily applicable to deterministic channel modeling.

4. Transmission and diffraction

In case of transmission through different materials, e.g. furniture or structural building objects, measured absorption coefficient can be employed to calculate the attenuation. The absorption levels are generally so high, that common indoor objects and structures can be considered opaque to the electromagnetic waves at THz frequencies [8]. For example, a 20 mm thick layer of HDF plate attenuates the power of a 300 GHz wave by around 45 dB, whereas a 30 mm thick plasterboard by 50 dB at normal incidence. Also, transmission through human bodies is associated with very high attenuation levels, which is due to the extremely high absorption of water. Water exhibits terahertz absorption with attenuation lengths on the order of tens of micrometers in the frequency range between 100 GHz and 3.72 THz. Hence, at these frequencies a human body is practically impenetrable to electromagnetic radiation [12]. Altogether, the levels of attenuation are high enough to neglect transmission as a relevant propagation mechanism in indoor environments at THz frequencies.

Diffraction can influence the received power in indoor environments, especially in areas that are heavily shadowed. However, as shown in [13] for the 60 GHz band, diffraction does not constitute a relevant propagation mechanism already at mm-waves. Hence, since diffraction losses increase with frequency, this mechanism can be neglected for propagation prediction in the THz range.

5. Conclusion

Due to the importance of reflected and scattered waves the application of a deterministic ray-tracing model to channel characterization at THz frequencies is the most appropriate choice. Since the wavelength is very small compared to the typical objects found in indoor environments the macroscopic description of the building structure has to be much more detailed as it is usually the case for lower frequencies, e.g. about 2 GHz. This means that objects like windows or furniture have to be included in the simulated scenario. Furthermore, also the microscopic structure of the reflecting or scattering surface cannot be neglected any more. For example, at plaster that appears as a flat surface at microwave bands, the surface roughness gains in importance at mm or sub-mm waves. Also the effect of multiple reflections cannot be neglected any more for layered media. Typical examples for multi-layer structures are double window panes or concrete wall covered with paint.

6. References

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