Monitoring Terahertz Technology

(Under contract with Armasuisse #8003404787)

ARAMIS-Nr. R-3210/040-22

Report No. 2 (Q3 / 2008)

30.08.2008

Summary

This second report covers various aspects related to: attainable bandwidths in the terahertz regime, achievable transmission distances in air, dependences on atmospheric parameters, and used frequencies and interferences. We describe the attenuation of terahertz waves in the atmosphere due to water vapor. Frequency windows with minimum attenuation in the terahertz regime are identified. Stand-off scenarios for indoor and outdoor communication with terahertz are proposed. This scenarios will require definition of frequency window of operation for minimum attenuation, decision on the corresponding optical source with the appropriate signal to noise ratio and robustness for real world application.

Dr. Carolina Medrano

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0. Introduction

Communication at terahertz frequencies is becoming more and more attractive mainly because of the availability of the frequency band and the communications bandwidth. Other security applications of terahertz radiation makes use of the fact that this type of radiation penetrates clothing and other materials to provide images of hidden weapons, drugs or other objects. So far systems developed for this application do not offer a stand-off detection performance, this is mainly because water vapor in air absorbs THz radiation so strongly that most of this radiation never reaches the object to be imaged. There are however “windows” or frequency ranges, of the terahertz spectrum that do not absorb water very strongly. We describe the most critical aspects concerning systems for communication application in the terahertz range: sources, detection, attainable frequencies, transmission distances, attenuation of terahertz waves in the atmosphere and used frequencies and interferences.

1. Attainable Bandwidths

Communication with terahertz waves has an enormous potential within the information and communication technology. The realization of terahertz information and communication technology will enable high-performance (>1Terabit/sec) wireless connection for applications such as: a) communication in rural areas; b) communication between buildings during disasters; c) high vision data delivery in medicine; d) military; and e) media and entertainment. Table 1 presents an overview of the different methods to generate terahertz waves, frequency of operation, bandwidth and output power. Details on the performance of these devices were presented in the first report. All the listed devices operate at room temperature, and in spite of the significant progress achieved in the performance of quantum cascade lasers, their operation is still in the low temperature regime. All the electronic sources have characteristic broadbands below 12 GHz, which present an advantage for the application in communication. Their performance lies in the lower side of the terahertz range specifically below 800 GHz. They operate in a continuous wave mode, thereby making modulation schemes possible. Using UTC-PD operating in the 120-GHz-band, millimeter-wave wireless links have been developed and are currently being tested [1]. In order to cover higher terahertz frequencies in the terahertz gap, the use of novel materials with nonlinear optical techniques will be the focus of attention in the near future. Some research is going on in this field and the last row in table 1, shows what could be possible using this approach. A detailed evaluation of this approach will follow in the next report.

Devices	Frequency	Bandwidth	Output Power
QCL	1.38 THz (110K)	narrow	mW
Resonant Tunneling Diodes	> 1 THz	broadband	μW
UTC-PD	0.1 and 1 THz	broadband	μW
Gunn Diodes (InP)	0.422 THz	broadband	μW
Transistor (Intel)	1 .2 THz	broadband	μW
Tunnel Injection (GaN)	0.800 THz	broadband	mW
Nonlinear Optics (DAST)	**0.3 – 20 THz**	**< 100 GHz**	**μW**

Table 1. Terahertz sources, frequency of operation, bandwidth and output power.

For the establishment of a terahertz link, or communication with a terahertz carrier, or communication within few meters two important aspects have to be considered:

1) transmission of terahertz waves in air, 2) atmospheric dependences, and 3) realization of stand-off detection. These three aspects have to be considered in two main scenarios: indoor or outdoor communication. In outdoor communication detecting distances should be 100 meters or more, but the present technology concepts have to experience a dramatic improvement in order to make this a reality. More realistic with the present technologies detection of terahertz signals within distances from 1 to 10 meters should be possible, and electronic sources are rapidly advancing in this area operating at frequencies below 1 THz.

2. Transmission Distances in Air and Dependences on Atmospheric Parameters.

For communications with terahertz and other applications (military, security) that involve transmission in air, it is clear that not only the limited performance of sources and detectors but the strong water vapor absorption of terahertz waves, prevents their use in long range operation. For this applications stand-off detection or imaging at distances longer than 25 meters is essential. Therefore it is important to characterize the transmission distances and its relation with the terahertz frequency. Terahertz light is heavily absorbed by the atmosphere, and especially by water. Figure 1, shows this behavior in a logarithmic scale some attenuation values (in dB) from 10^7 Hz to 10^{16} Hz. In the terahertz gap (10^{11} – 10^{13} Hz) the attenuation is very high (>10 dB/m) making long distance atmospheric transmission very challenging, but possible for ~100 m [2].

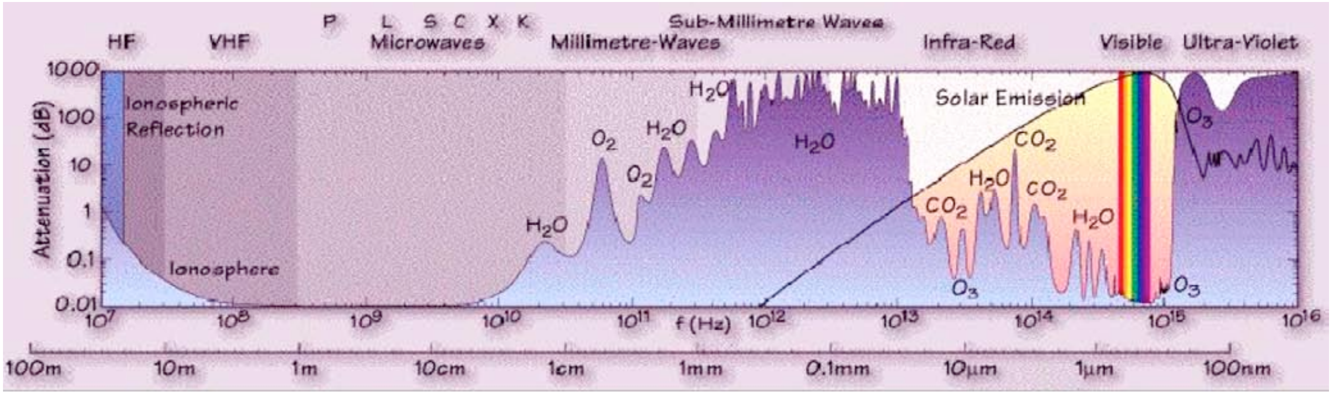

Figure 1. Attenuation of terahertz light in the atmosphere.

Although the strong water vapor absorption in the atmosphere prevents long range operation at sea level, there are several windows below 1 THz and above 10 THz. Figure 2 shows the absorption of a standard atmosphere over a 100 m path, with several important windows at terahertz frequencies below 2 THz [3].

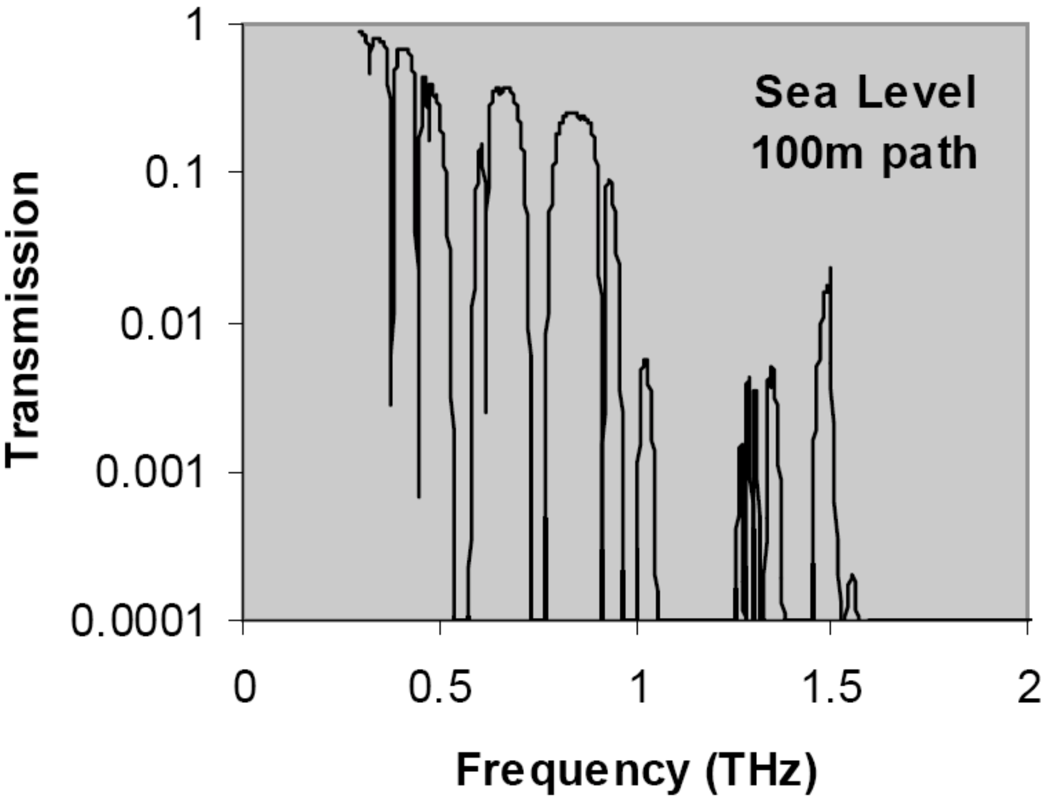

Figure 2. Terahertz transmission over 100 m at sea level. (US Standard atmosphere)

Water vapor is present in the troposphere up to 20 km altitude above sea level, and it is one of the main responsible of the spectral attenuation of signals crossing the atmosphere [4]. Water vapor decreases with altitude, so aircraft flying at 6'000 m and above can communicate over many kilometers in selected frequency ranges. Transmission from high-flying aircraft into space is also possible, either for communication or for long range sensing of space objects.

3. Transmitted power, Reachable Distances.

It is important to evaluate and analyze the output power level and frequency on the power received at the end of the stand-off regime. The transmitted power experiences an exponential decay through space. For a given minimum detectable power, the incremental distance Δl between the transmitter and the detector changes only logarithmically with the power available at the transmitter:

$$\Delta l = (10 \log N)/\alpha \tag{1}$$

where N is the N-fold increase in power and α is the atmospheric attenuation coefficient in dB/m. The frequency dependence of α is shown in figure 3. The attenuation changes rapidly and non-monotonically in the terahertz range, going from several dB/m over a span of ~0.1 THz [5]. The atmospheric path loss in dB/m, was measured by FTIR (dashed line) and calculated data from HITRAN 2004 [6]. Data correspond to a temperature of 296 K and 40% relative humidity for continuous frequency range of 1-5 THz.

Typical values of α at terahertz frequencies are 0.5 to 10 dB/m, for these values a tenfold increase in power yields diminishing increases in the range from 20 to 1 m. Because of the exponential decay, a small change in α will result in a significant change of the transmitted power over a long distance for example the relative transmitted power over 25 m is 0.32 % for α=1 dB/m, and for α =0.5 dB/m the relative transmitted power over 25 m is 5.6%. This simple but important analysis indicates that for long-range terahertz imaging, the frequency of the transmitter is much more important than its power, as long as adequate power levels (>10 mW) are available. For long range applications the atmospheric window with lower attenuation, will dictate the development of terahertz sources and detectors.

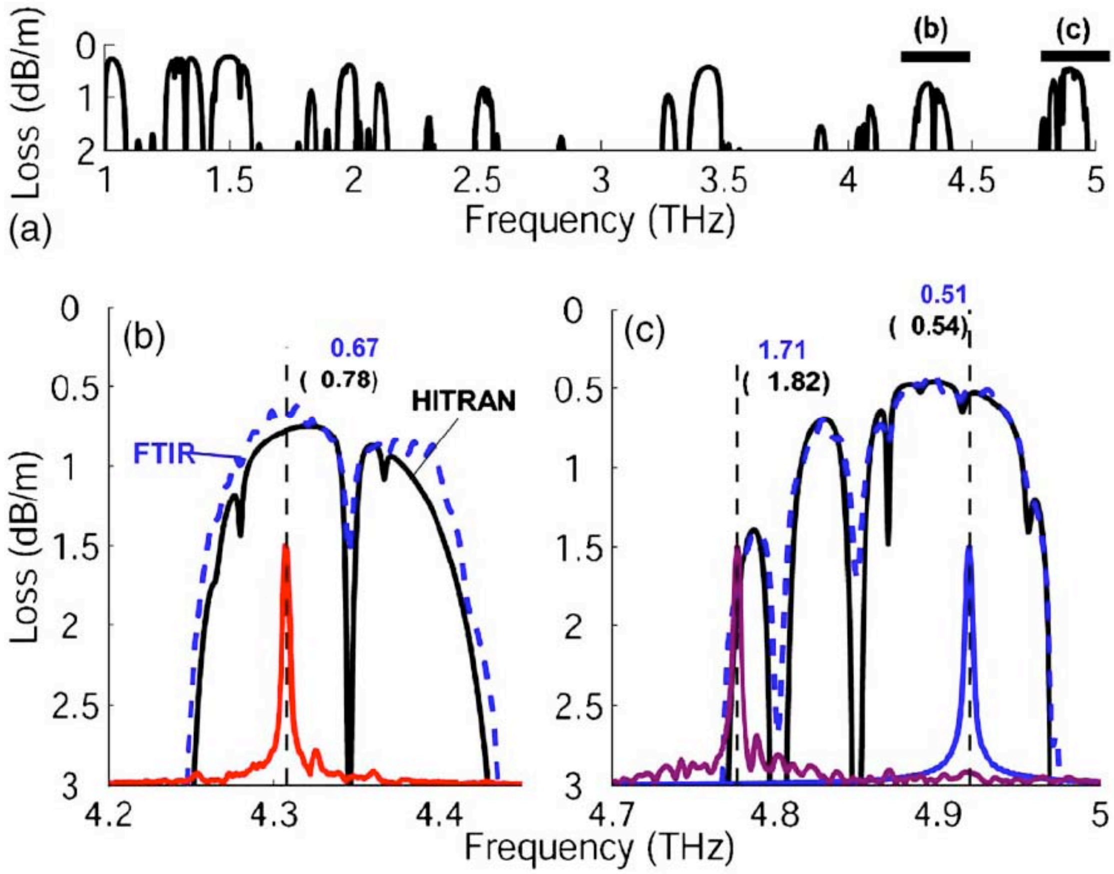

Figure 3. Atmospheric path loss in dB/m, measured by FTIR (dashed) and calculated from HITRAN 2004 (solid at 296 K and 40% relative humidity for continuous frequency range of 1-5 THz [part (a) calculation only] and 4.3 and 4.9 THz windows [parts (b) and (c). [5]

There will be more and more windows in the terahertz region where attenuation due to water vapor will not represent a problem for the transmission of the terahertz waves. Figure 4 shows the absorption coefficient in the terahertz region up to 30 THz. The attenuation is indicated in a logarithmic scale in dB/km [7].

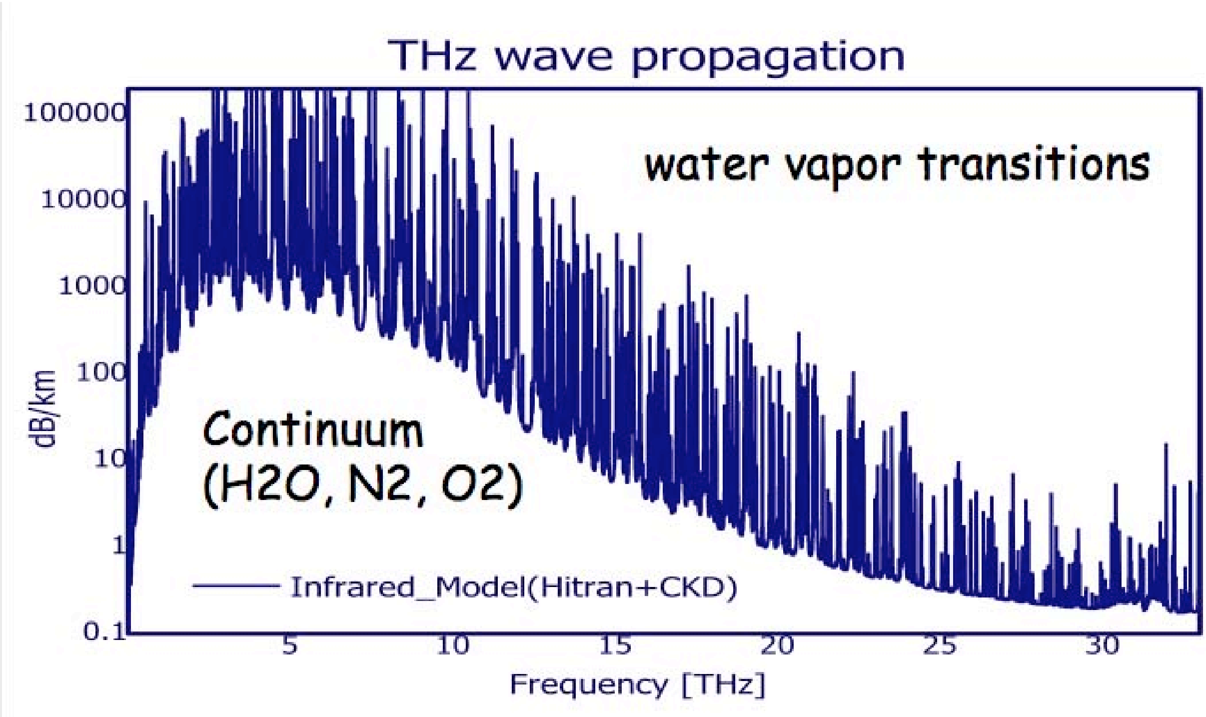

Figure 4. Absorption coefficient in the terahertz region.

The authors calculate the spectrum using data from HITRAN line catalog [6] and the Clough, Kneizys and Davies atmospheric continuum model. From this figure it is clear that for really long distance applications the development should point towards sources and generators at higher terahertz frequencies where the attenuation of the atmosphere is small. For these higher frequencies appropriate modulators should become available.

4. Usable Frequencies and Interferences.

All the information given above concerning attenuation values for free terahertz transmission mainly due to water vapor, sets important limits to the communication with terahertz waves. In the long term the realization of long distance communication in the terahertz region will be possible, but new technological concepts should be implemented towards the realization of the appropriate devices. Short range communication for maximum transmission distances of 50 m, should become a reality in the near future. Two main scenarios can be considered:

1) Outdoor communication with terahertz waves at short distances < 1, 20 and 50 m.
2) Indoor communication in a close environment.

For these two scenarios both electronic and optical solutions can be envisioned, operating at designated terahertz windows where the attenuation coming from absorption in water vapor is minimum. In table 2 we indicate some of the frequency windows where applications in short, or eventually long distance communications could be possible.

Frequency Window THz	Attenuation dB/m	System-Device
0–0.4	< 1	Electronic
0.7–0.8	<1	Electronic
1.4	<1	Optical
1.55–1.69	<1	Optical
1.8	<1	Optical
2.5 ± 0.3	<1	Optical
2.8 ± 0.3	<1	Optical
>3	(see figure 3)	Optical and QCL
> 15	(see figure 4)	Optical and QCL

Table 2. Frequency windows for terahertz-communication.

As previously mentioned in this report, electronic devices cover frequencies below 1 THz, they are constantly developing but they will not reach the larger regions of the spectrum above 3 THz where the attenuation is lower, in a short time from now. Optical approaches are covering frequency ranges from 1 THz and up. Although everything is in the research phase, the future looks more promising with optical approaches in the region above 1 THz.

In the near future indoor communication will develop faster, the problem of attenuation from water vapor can be limited choosing the proper frequency range. As for the detection method, it is possible to think on optical-based devices operating at frequencies above 1 THz [8].

Figure 5(a) shows a possible terahertz link scenario with a line-of-sight link between emitter and receiver.

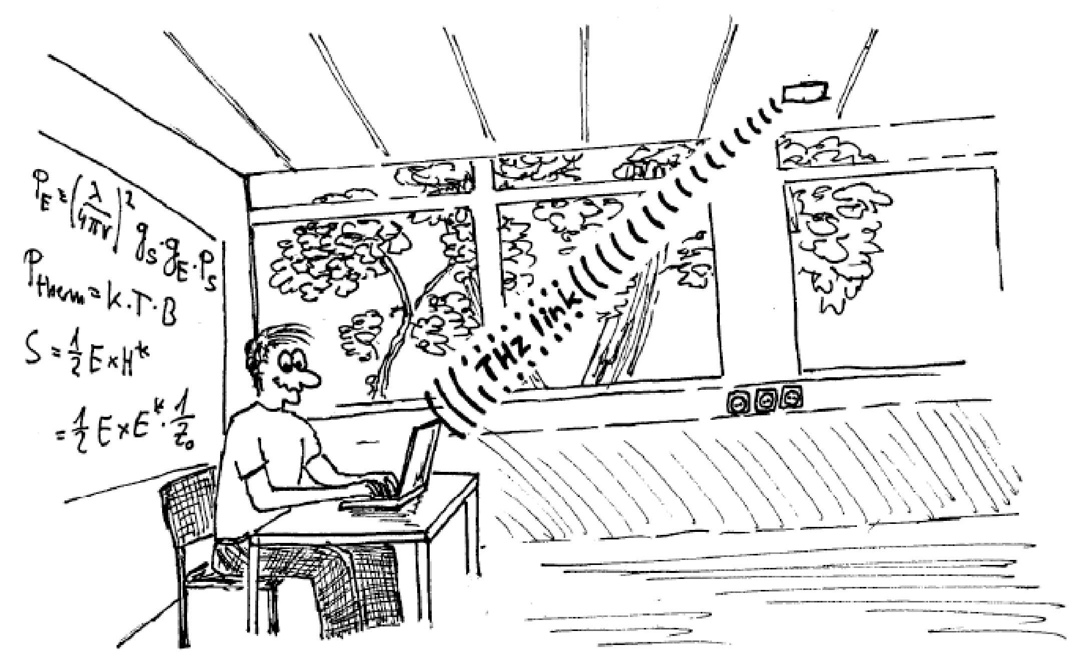

Figure 5(a). Indoor terahertz link scenario.

The link is broken is somebody steps into the terahertz beam, one solution is to use indirect non-line of sight paths as back up links. This solution involves reflections of the wall. This is illustrated in figure 5(b). Many of the materials that are transparent to terahertz waves like, carton, plastics, paper, will not represent a problem.

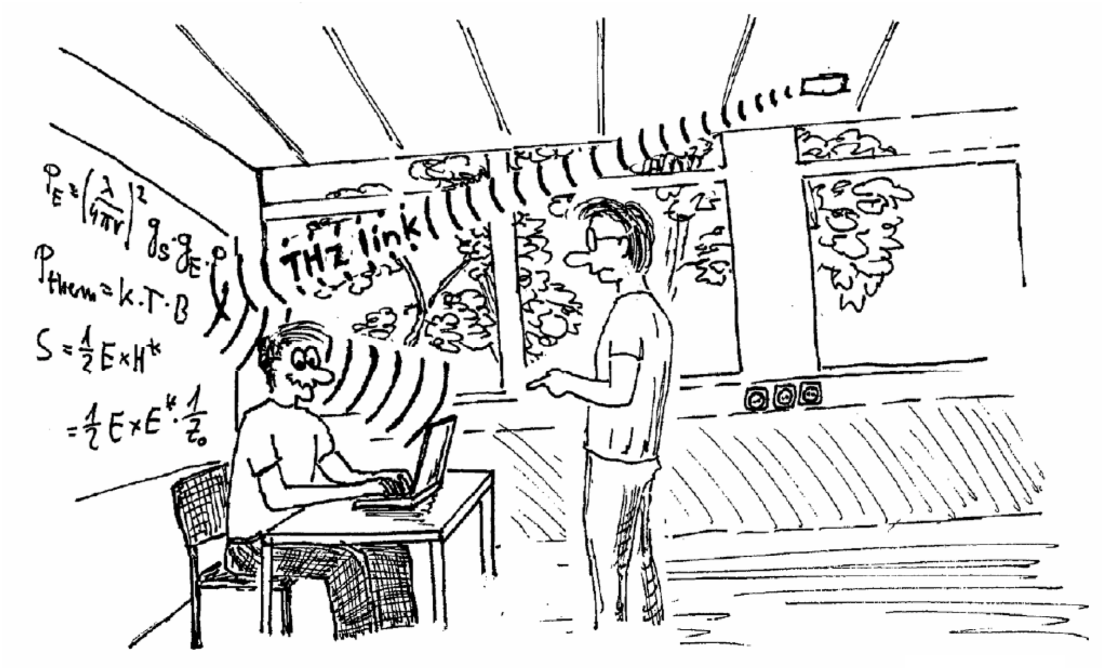

Figure 5(b). Indoor terahertz link scenario based on reflections from the walls to compensate for obstacles in the terahertz link.

New elements such as terahertz mirrors, modulators and waveguides have yet to be developed. On one side outdoor applications are forcing research towards longer terahertz frequencies where atmospheric attenuation is lower for the given frequency. On the other side, indoor communication in the terahertz frequency is pointing to enhance multiple reflections off the walls. Recently dielectric mirrors with reflection bands tailored to match the frequencies of the communication have been proposed [9]. The proposed materials are polymers most of which have refractive indices between 1.45 and 1.8. An omni-directional dielectric mirror should have an index step between two materials that is much higher than 1.8, therefore the authors propose the use of thin slices of high-resistive silicon and polypropylene layers. This idea has encouraged activities in order to characterize building materials [10]. Reflectivity of glass, plaster and wood was investigated in the frequency range below 300 GHz using a fiber coupled THz-TDS measurement setup. From the three mentioned materials, glass showed the highest reflection, and wood was the less reflective.

Other approaches include research for the fabrication of components such as plastic fiber and polycarbonate waveguides. Bare metal can transport THz pulses along its surface with virtually no dispersion and low attenuation [11].

5. Conclusions

In the last decade there has been a substantial research towards narrowing the terahertz gap. Research towards the best performance device in the terahertz frequency range is continuously growing. Both electronic devices as well as nonlinear-optics-based devices have experienced a dramatic improvement. Advances in electronics, laser technology and materials are accelerating this development. With this variety of technologies it is possible to generate output powers at µW or mW level at some regions of the terahertz gap. An important drawback in the communication with terahertz is the atmospheric attenuation of the terahertz waves, mainly due to water vapor. However there are frequency windows in the terahertz gap where the attenuation has tolerable limits for the implementation of communication with terahertz. Most of the electronic devices that are currently investigated operate at some of this frequency windows, but mainly in the gigahertz region. There are more windows with lower level of attenuation at frequencies above

1 THz and above 15 terahertz, where electronic sources are not adequated. Above 1 THz optical sources will provide the solution in a near future.

For the application of terahertz in communication two scenarios can be considered: short range <1m or long range>50 m. Long distance communication with terahertz will need some years to mature. Whereas indoor communication with terahertz may become a reality in the near future, either using “terahertz links”, or

involving reflection off the walls to avoid obstacles in the interrupted terahertz link. This solution is encouraging research in materials, so that the reflective properties of indoor interfaces can be improved.

The road map for the application of terahertz radiation in communication will start in a scenario involving indoor communication.

The most important aspects to identify to implement a terahertz system for indoor communication application are:

1) Minimum stand-off distances: more than 1 m, less than 30 m.
2) Decision on the frequency window above 1 THz for minimum attenuation of terahertz waves caused by relative humidity in air.
3) Decision on the adequate optical source, for best signal to noise ratio, modulation and robustness in a real world application. Possibilities of optical tunable sources should be investigated.
4) Implementation of a demonstrator.

6. References

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7. Abbreviations

BWO	Backward Wave Oscillator
dB	Decibel
DFG	Difference Frequency Generation
InGaAs	Indium Gallium Arsenide
IR	Infrared
InP	Indium Phosphide
InSb	Indium Antimonide
GaAs	Gallium Arsenide
GaSe	Gallium Selenide
GaP	Gallium Phosphide
LAN	Local Area Network
LTG	Low Temperature Grown
mW	milliwatt
MMIC	Microwave Monolithic Integrated Circuit
CdTe	Cadmium Telluride
DAST	4'-dimethylamino-N-methyl-4-stilbazolium tosylate
$LiNbO_3$	Lithium Niobate
GHz	Gigahertz
MeV	Mega electron Volts
OPO	Optical Parametric Oscillation
OR	Optical Rectification
pW	picoWatt
QCL	Quantum Cascade Laser
RF	Radio Frequency
THz	Terahertz
THz-TDS	Terahertz Time Domain Spectroscopy
TUNNET	Tunnel Injection Transit Time
UCT-PD	Unique Travelling Carrier Photo Diode
ZnTe	Zinc Telluride