A Study on Channel Model for THz Band

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Abstract - **Impulse response of the terahertz band (0.1–10 THz) for wireless nanosensor networks is considered. For wireless communication analysis and modeling, the impulse response is very important. In the earlier works, the impulse response has been derived from the transmittance by assuming a linear phase shift. However, the linear phase shift only leads to a symmetric impulse response before and after the LoS propagation delay. Physically, it is impossible for a signal to arrive before the LoS propagation delay since this violates causality. In this paper, a phase shift function leading to an impulse response satisfying causality is derived. The validity of the derived model is shown by comparison between measurements and results predicted by the theory.**

Index Terms — **Causal impulse response, channel model, molecular absorption, nanodevice communication, terahertz band**

1. Introduction

There are several visioned applications for nanodevices, such as health monitoring and haptic interface [1]. Electromagnetic (EM) communication in THz band has been proposed to enable device-to-device communication in the wireless nanosensor networks (WNSNs) [1]. In contrast to the ultra high frequency (UHF) band, the effect of the molecular absorption needs to be considered in the THz band. The molecular absorption and its effect on the transmittance of the channel have been studied. The transmittance is telling the fraction of the radiation capable of propagating through the channel. To develop wireless communication techniques for WNSNs, an impulse response of the THz band is required. One reasonable approach to obtain an impulse response ($h_{\text{linear, c}}$) is to use the transmittance which only has an amplitude information but no phase information. In [2], a linear phase shift only was added to the transmittance and the impulse response was obtained by inverse Fourier transform (IFT). However, the impulse response based on the linear phase shift does not satisfy causality. In this paper, we derive a time domain channel model, i.e., the impulse response, from the transmittance in the case of free space propagation with the spreading loss and the molecular absorption. We show the validity of the derived impulse response based on a comparison with the experimental data.

2. System model

We consider a free space channel model in a line-of-sight (LoS) path between a transmitter and a receiver. In addition to the channel, transmitting and receiving antennas are employed in the system.

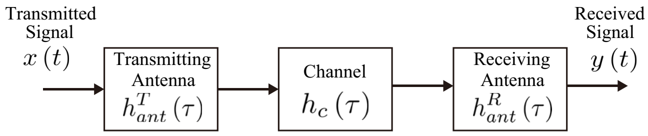

Fig. 1. The system model in time domain.

(1) Transmittance

A spreading loss and the molecular absorption loss are considered in the channel model. The molecular absorption loss is frequency selective due to discrete absorption. At the distance z between the transmitter and receiver, the transmittance $|H_c(f, z)|^2$ is [2]

$$|H_{\mathrm{c}}(f,z)|^2 = \frac{P(f,z)}{P(f,z=0)} = \frac{\exp(-k_a(f)z)}{4\pi z^2}, \quad (1)$$

where $P(f, z = 0)$ and $P(f, z)$ represent the transmitted signal power and the received signal power respectively and $H_c(f, z)$ is the frequency response for the channel. f and $k_a(f)$ are the frequency and the absorption coefficient respectively. We utilize the *am* model to calculate the absorption coefficient [2].

(2) System model in time domain

We assume three effects of the propagation due to the channel in the THz band and the antennas in both transmission and reception. Thus we model the system model for the THz band as Fig. 1.

The received signal $y(t)$ at time t can be obtained by a convolution between transmitted signal $x(t)$ and the system impulse response, $h(\tau, z)$, as

$$y(t) = \int_{-\infty}^{\infty} h(\tau, z)\, x(t-\tau)\, d\tau. \quad (2)$$

The system impulse response $h(\tau, z)$ takes account into the channel and the antennas in transmission and reception, so $h(\tau, z)$ is defined as

$$h(\tau) = h^{\mathrm{T}}_{\mathrm{ant}}(\tau, z) * h_{\mathrm{c}}(\tau, z) * h^{\mathrm{R}}_{\mathrm{ant}}(\tau, z) \quad (3)$$

where * represents convolution integral. $h_c(\tau, z)$, $h^{\mathrm{T}}_{\mathrm{ant}}(\tau)$ and $h^{\mathrm{R}}_{\mathrm{ant}}(\tau)$ are channel impulse response and antenna impulse response in transmission and reception, respectively. The antenna impulse response in transmission and reception are derived from the first time derivative of the current density [3].

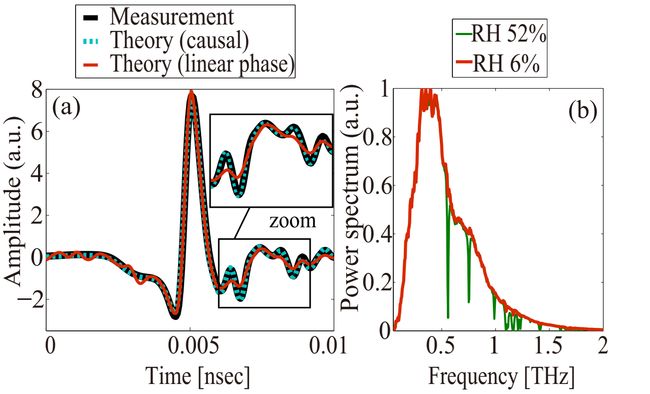

Fig. 2. Comparison between the measurement result in RH=52% and the calculation result. (a) Received pulse in time domain (b) Transmitted and received power spectrum.

3. Causal channel impulse response

The causal channel impulse response satisfies

$$h_{\text{causal, c}}(\tau,z)=\begin{cases}h_{\text{causal, c}}(\tau,z) & \tau\geq 0\\ 0 & \tau<0.\end{cases} \tag{4}$$

The frequency response of $h_{\text{causal, c}}(\tau, z)$ is given by

$$H_{\text{c}}(f,z)=\int_0^{\infty}h_{\text{causal, c}}(\tau,z)e^{-j2\pi f\tau}d\tau, \tag{5}$$

Let exp[- $\alpha(f, z)$] and $\theta(f, z)$ denote the amplitude and phase components of $H_{\text{c}}(f, z)$, respectively, i.e.,exp[- $\alpha(f, z)$]= $|H_{\text{c}}(f, z)|=|H(f, z)|$ and $\theta(f, z)=\arg(H_{\text{c}}(f, z))$. Then $H_{\text{c}}(f, z)$ is given by

$$H_{\text{c}}(f,z)=\exp[-\alpha(f,z)+j\theta(f,z)] \tag{6}$$

Since the impulse response $h_{\text{causal, c}}(\tau, z)$ satisfies causality, $\alpha(f, z)$ and $\theta(f, z)$ are Hilbert transform pairs. Therefore, $\theta(f, z)$ is given by

$$\theta(f,z)=\frac{1}{\pi}\text{PV}\int_{-\infty}^{\infty}\frac{\alpha(f',z)}{f-f'}df', \tag{7}$$

where PV represents Cauchy principal value. Given $|H_{\text{c}}(f, z)|$, $H_{\text{c}}(f, z)$ is available based on (6)-(7). Finally, the causal impulse response is given by

$$h_{\text{causal, c}}(\tau,z)=\int_{-\infty}^{\infty}H_{\text{c}}(f,z)e^{j2\pi f\tau}df, \tag{8}$$

4. Numerical and experimental results

In this section, we show the validity of the causal impulse response by using comparison between measurement and theoretical pulse. The parameters are as follows: distance z=62.5 cm, pressure p=1015.9 hPa, temperature T=295.15 K. The measurements of received pulses were conducted with the terahertz time domain spectroscopy (THz-TDS) technique with Teravil / EKSPLA T-spec spectrometer. There are two measurements, one in 52% relative humidity and one in 6% relative humidity. The received pulse with RH=6% is used as a transmitted signal $x(t)$ since there is only little molecular absorption. The analytically obtained received pulse is obtained by the transmitted signal and the theoretical impulse responses ($h_{\text{causal, c}}$, $h_{\text{linear, c}}$). The antenna impulse responses are obtained similarly as in [3].

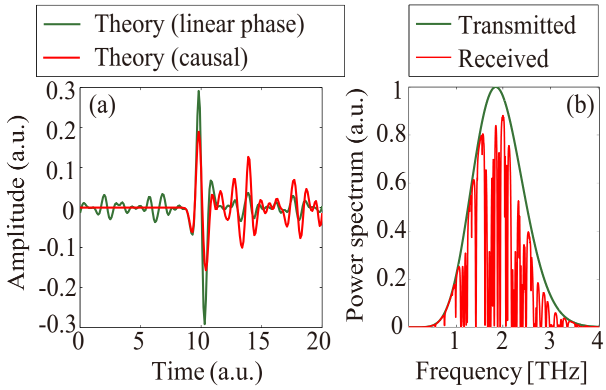

Fig. 3. Comparison between the linear phase shift result and the causal impulse response result in RH = 52%. The dipole length 1 μm and diameter 0.23nm. (a) Received pulse in time domain (b) Transmitted power spectrum and received power spectrum.

The comparison received pulses are shown in Fig. 2 (a), where RH=52% is assumed. The analytically obtained pulse from $h_{\text{causal, c}}$ agrees with the received pulse from measurement data very well. Although the difference between analytically obtained received pulse from $h_{\text{linear, c}}$ and measurement result is slightly large, the difference is not very significant. The reason for this is that frequency response does not have much frequency selectivity which can be seen in Fig. 2 (b), where the power spectrum at RH=6% and RH=52% correspond to transmitted and received power spectrum, respectively.

We compare the received theoretical pulses provided by $h_{\text{causal, c}}$ and $h_{\text{linear, c}}$ in Fig. 3. In this comparison, we assume that short dipole antenna is utilized in both transmission and reception [3]. We can see the frequency selectivity of the channel in Fig. 3 (b). Fig. 3 (a) shows the analytically obtained received pulses based on $h_{\text{causal, c}}$ and $h_{\text{linear, c}}$. Due to frequency selectivity, the difference between $h_{\text{causal, c}}$ and $h_{\text{linear, c}}$ is now significant.

5. Conclusion

This paper introduced a causal time domain channel model for the THz band. We employed the Hilbert transform to obtain the phase component from a transmittance which only contains the amplitude component. Experimental measurements showed the validity of the proposed method.

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