FDTD Analysis of Digitally-modulated Electromagnetic Wave Propagation in Human Head

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Abstract— Numerical analysis has been performed regarding the propagation and scattering of digitally modulated electromagnetic waves in human head. It is found that waveform distortion and noises are caused unsystematically by the interaction between the wide frequency components of the digital signals and the complicated dielectric structure of the human head. It is also found that pulse shaping to the digital base-band waveform, which limits the band width of the digital signals, reduces the noise in the waveform.

1. INTRODUCTION

Wireless digital communication systems prevail rapidly in our life environment. The influence of the electromagnetic wave to the human body has been carefully evaluated so that they will not impair human health [1, 2]. However, there still exist a number of uncertainties in accessing the influence quantitatively, in particular, inside the complicated dielectric structure of the human bodies. The digitally-modulated electromagnetic waves have a distinctive feature compared to the continuous harmonic waves; e.g. the widely used phase shift keying (PSK) signals have a sudden phase shift, which typically results in a wide frequency spectrum of the transmitted signals.

In this paper, an interaction is investigated numerically between the digitally-modulated electromagnetic waves and the human head in which the distribution of the dielectric permittivity is complicated and even considered random from the electromagnetic point of view. We analize the influence of the phase-shifting modulation, without the loss of generality, associated with the typical binary phase shift keying (BPSK). Other phase-shift schemes such as the quaternary phase shift keying (QPSK) and its modifications basically have the same principle of the phase shifting, thus can be treated in the same context. Although specific communication systems that comprise sophisticated waveform shaping techniques are not considered, the influence of basic waveform shaping effects is investigated using simple trapezoidal digital waveforms. Other modulation techniques such as the frequency shift keying (FSK) and the minimum shift keying (MSK) will be our future topic of research.

Our analysis has been performed with the finite-difference time-domain (FDTD) method. The numerical human phantom used in our analysis was developed in the National Institute of Information and Communications Technology (NICT), Japan, by the nuclear magnetic resonance computer tomography (NMR-CT) of actual human bodies [3], and is anatomically accurate. The measured tissue properties [4] have been modeled in the FDTD method as multi-pole Debye media [5]. Our FDTD code has a capability of dealing with the frequency dependent permittivity and conductivity of 50 different tissues over a frequency range as wide as 1 MHz to 20 GHz [6]. To the best of authors' knowledge, such a numerical analysis has not been performed elsewhere including the geometrical and the material complexity at the same time. This paper attempts to elucidate the behavior of the digitally-modulated electromagnetic waves in the human head.

2. RANDOM NATURE OF THE ELECTRICAL PROPERTY OF HUMAN HEAD

The configuration of the head model is shown in Fig. 1, which has been implemented in our FDTD analysis. The size of the FDTD analysis space is 320 mm in x, 300 mm in y, and 310 mm in z-direction, in which the head model is situated; the height is 270 mm from the neck to the top of the head. The FDTD space is terminated by the PML absorbing boundary conditions, and 20 mm air spaces are inserted both under and over the head model. The whole region is discretized with $\Delta = 1$ mm Yee cell cubes, while the spatial resolution of the head model is 2 mm cube. The electromagnetic wave is illuminated from the front of the face as a plane wave with E_z polarization. The maximum instantaneous field strength is $E_0 = 27.4$ V/m, which makes the time-averaged illumination intensity $\bar{P}_0 = 1$ W/m^2.

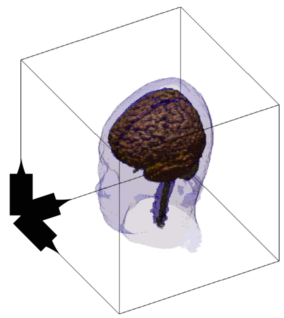

Figure 1: Configuration of the male human head model analyzed in this paper. The shape of the cerebrospinal system is emphasized, while other organs, bones and fluid are all included in the model.

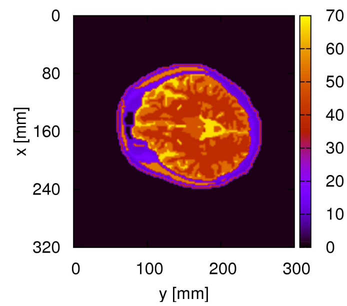

Figure 2: Distribution of the relative dielectric permittivity ε'_r (color bar) of the male human head model at 2000 MHz on a horizontal cross section 100 mm down from the top of the head.

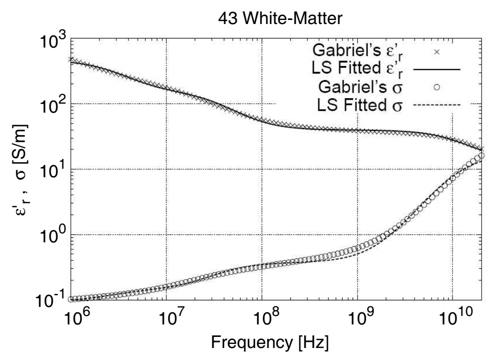

Figure 3: Frequency dependency of the dielectric permittivity ε_r and conductivity σ of white matter for the head model. Gabriel's original experimental data [4] and their fit by Debye dispersion [6] are shown.

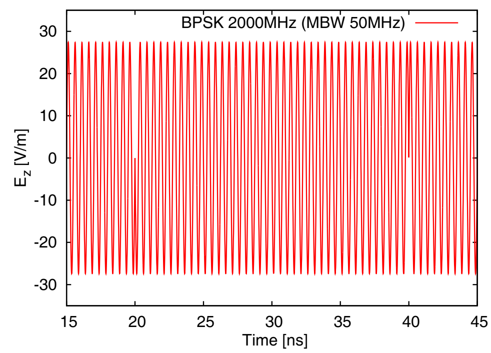

Figure 4: Input BPSK time data for 2000 MHz carrier wave and 50 MHz MBW with no pulse shaping.

The human head has a complicated dielectric structure as shown in the cross section of Fig. 2, regarded even as random electromagnetic media. For example, the skull consists of bone cortical, of which complex relative permittivity at 1 GHz is $\dot{\varepsilon}_r \equiv \varepsilon'_r - i\varepsilon''_r = 12 - i2.7$; the brain consists of white matter ($\dot{\varepsilon}_r = 39 - i11$), gray matter ($\dot{\varepsilon}_r = 52 - i18$), cerebrospinal fluid ($\dot{\varepsilon}_r = 68 - i43$) and so on, which all intricately intermingle.

The human tissues also have frequency dispersion in the permittivity, which varies significantly in the microwave frequency range of our interest. The frequency dependencies of the 50 kinds of the human tissues are modeled by the multi-pole Debye functions [6], which have been implemented into the FDTD method for the effective frequency range from 1 MHz to 20 GHz. An example of the white matter as a part of the brain is shown in Fig. 3; the real part of the relative permittivity decreases by an order of magnitude and the conductivity σ, which relates to the imaginary part of the permittivity by $\varepsilon''_r = \sigma/(\omega\varepsilon_0)$ with ω the angular frequency and ε_0 the permittivity of vacuum, increases by two orders of magnitudes in this frequency range. The strong frequency dispersion, common to the most human tissues, leads to random scattering and propagation of electromagnetic waves in human body, particularly inside the human head as is expected from the layered shell structure of skin, skull and fluid.

3. NUMERICAL ANALYSIS OF DIGITAL ELECTROMAGNETIC WAVE PROPAGATION IN HUMAN HEAD

A plane wave was illuminated with the BPSK time signal from the front of the face at the carrier frequency of 2000 MHz. The digital signals shift the phase every 40, 20, 10 and 5 periods of the carrier wave, i.e., the modulation band width (MBW) of 50 MHz, 100 MHz, 200 MHz and 400 MHz were tested to study their effects to the digital signal propagation. The input BPSK time signal for 50 MHz MBW is plotted in Fig. 4, where the sudden phase shifting is observed at time 20 ns and 40 ns. The resulting time signals and the Fourier spectra observed at the center of the head are plotted in Fig. 5 for the BPSK without pulse shaping, and in Fig. 6 for the BPSK with a trapezoidal pulse shaping.

For the results shown in Fig. 5(a), large noise-like spikes appear at the instant when the BPSK signal switches the phase. The noise has its peak height nearly three times as large as the CW part of the signal. Comparison to the results of other MBWs in Fig. 5(b) shows that the noise waveform is independent of the MBW. This is because the noise is associated with the sudden phase change

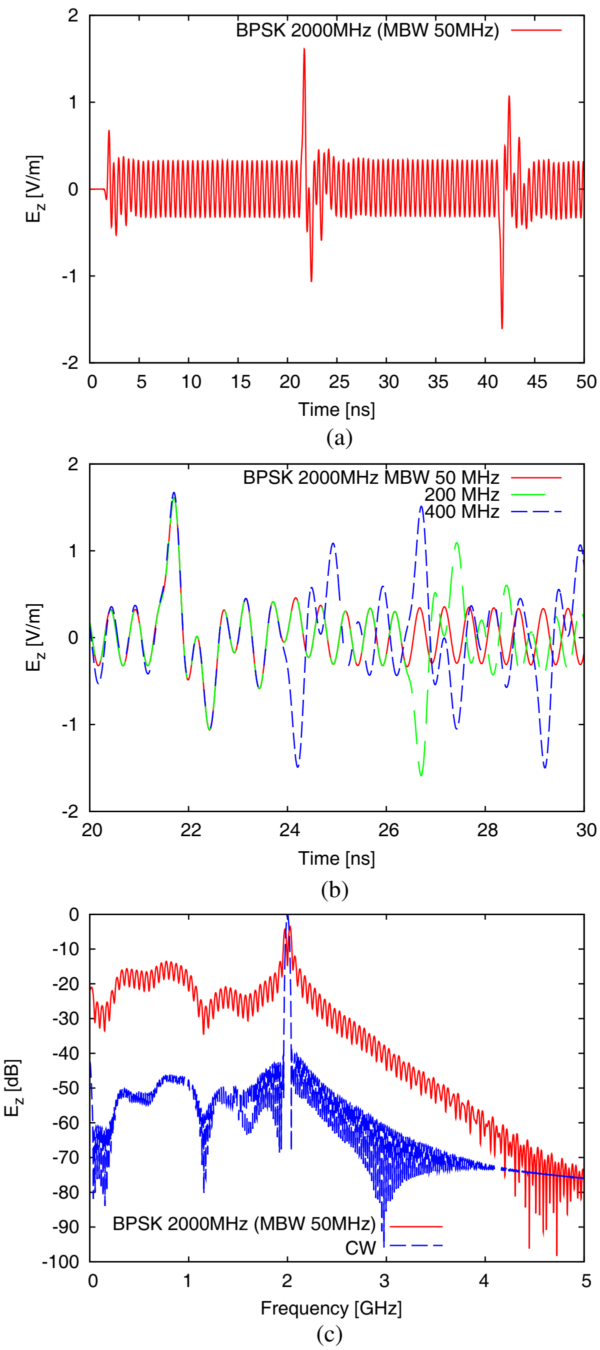

Figure 5: Time data and Fourier spectrum for 2000 MHz wave observed at the center of the male head without pulse shaping. (a) Time data inside the human head. (b) Expanded waveform of (a) for the comparison of spike noise for various MBWs. (c) Normalized fourier spectrum of (a).

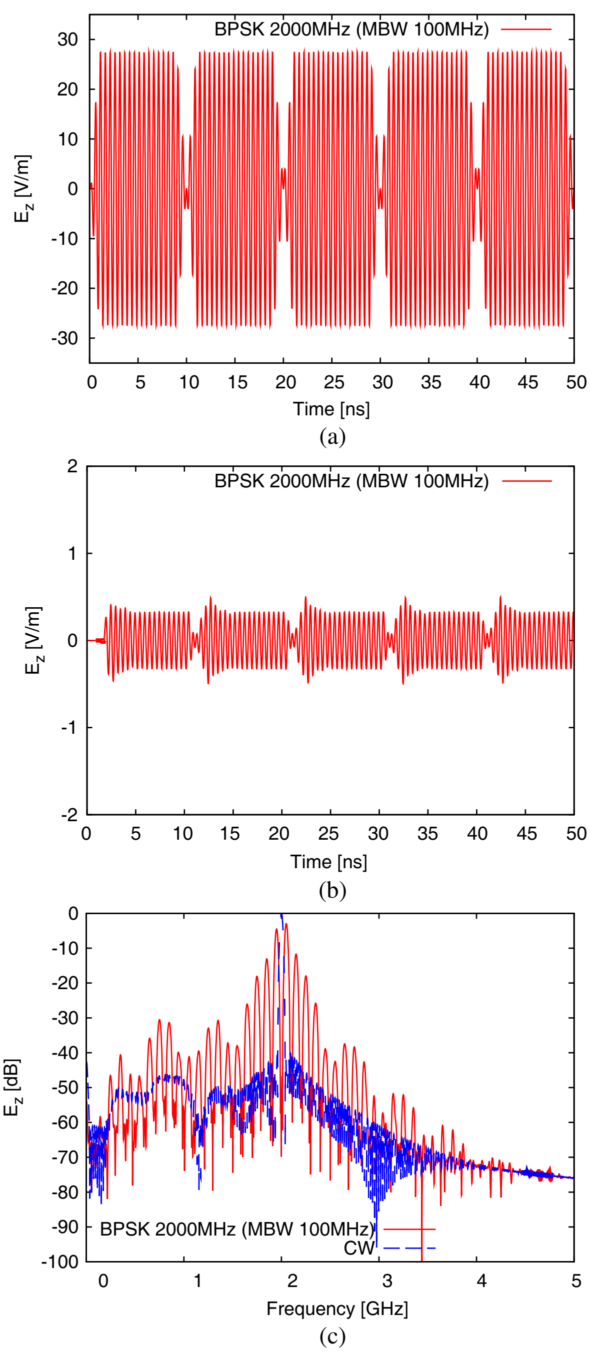

Figure 6: Time data and Fourier spectrum for 2000 MHz wave observed at the center of the male head with trapezoidal pulse shaping. (a) Input BPSK time data processed with trapezoidal pulse shaping. (b) Time data inside the human head. (c) Normalized Fourier spectrum of (b).

of the digital modulation. The reason for it is also seen in their spectrum in Fig. 5(c); the spectrum widely spreads over approximately 5 GHz range and interacts with the frequency dispersion of the human tissues, typically varies over an order of magnitude in the same frequency range as seen in Fig. 3. Our preliminary analysis showed that a number of high-order resonances occur in the human head over the frequency range from approximately 300 MHz to 2000 MHz due to the round shape of the head (not shown in this paper). It is also presumed that the noise is enhanced as the frequency components happen to come closer to those resonances.

The input signal is then modulated with a digital base-band signal having a trapezoidal waveform. The resulting BPSK signal exhibits gradual phase shifting as shown in Fig. 6(a). The signal observed at the center of the head is shown in Fig. 6(b). Obviously, the spike noise at the time of phase shift has decreased significantly. The Fourier spectrum in Fig. 6(c) shows a limited bandwidth of the digital signal after pulse shaping. More practical pulse shaping techniques such as the raised-cosine filter will have the same effect.

It has been also observed in our additional analyses, using a female head model and similar models reduced in size as infants (not shown), that the head, with its round shape, tends to focus the electromagnetic wave onto the center region of the head. The focal point is not obvious due to the complicated distribution of the human tissues, but strongly depends on the individual configuration of the head, brain, and skull, as well as the frequency, the location, and the polarization of the illuminating source. The signal is not always but occasionally enhanced as in Fig. 6. Such randomness may well cause individual variation in their permissible level against electromagnetic exposure.

4. CONCLUSIONS

Scattering and propagation of electromagnetic waves in the human head have been investigated for the wireless digital signals using the numerical human phantom and the frequency dispersion tissue models. It has been observed that the BPSK signal without pulse shaping exhibits large noise-like signals, which is reduced significantly when the digital signal is processed with a pulse shaping technique. Such enhanced scattering of digital waves has been observed randomly in the human head models under various conditions, which may cause a certain level of individual variation in the perceptiveness to electromagnetic exposure.

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