Wideband and Ultra-Wideband Channel Measurement and Modeling for Broadband Wireless Systems

Jun-ichi TAKADA
Department of International Development Engineering
Graduate School of Science and Engineering
Tokyo Institute of Technology
Meguro-ku, Tokyo 152-8552, JAPAN
Phone/Fax: +81-3-5734-3282, E-mail: takada@ide.titech.ac.jp

Abstract
The spatial domain information of the propagation is extremely important to take into account the antenna systems in the wireless broadband systems. This paper describes the concept and the modeling of the double-directional spatio-temporal channel for wideband and ultra-wideband wireless systems. The research activities toward the establishment of the channel model in Tokyo Tech are also described.

Keywords: propagation channel, double-directional channel, channel sounding, ultra-wideband.

1. Introduction
According to the increasing demand of the high speed wireless systems, a lot of new technologies to enhance the data rate and the error performance have been proposed. Wireless channels are composed of antennas and propagation paths and they suffer from multipath and co-channel interferences. Multiple antenna systems such as a smart antenna and a MIMO transmission technology are utilizing the spatial domain diversity of the channels. The former technology is oriented to suppress the interference signal as well as to combine the desired signal to improve the transmission quality. The latter technology is oriented to increase the channel capacity by virtually establishing the parallel spatial channels. Their performances are very sensitive to the channel characteristics, and it is very important to establish the versatile channel models. Before the spatial domain has been focused, the fading fluctuation and the delay spread are modeled only in the temporal domain. But these models are just the projection of the spatio-temporal channel model to the time domain, and are not directly applicable to those techniques utilizing spatial domain. Many efforts have been made to establish the spatial or spatio-temporal channel models[1], [2], the standard models that are accepted among everyone do not exist. The continuing comprehensive studies are therefore very important. The first half of this paper presents the concept of wideband double-directional channel, as well as the activities of the simulation, the measurement, and the modeling in Tokyo Tech.

On the other hand, an ultra-wideband (UWB) radio is now considered as a completely alternative approach to achieve the very high speed wireless link, especially for the personal area network within the distance of a few meters. It is a kind of a spread-spectrum system, but the spreading bandwidth is so wide (typically more than 500 MHz) and the spectral density is so low that it can share the same frequency band with other conventional radio systems. Although the line-of-sight path is usually dominant, the anti-multipath technique such as rake receiver can be applied. The standard channel model established in IEEE 802.15 TG3a[3], it is just a classical time-domain model and the antennas are not separated by the spatial channels. Moreover, the distortion of the waveform due to the antennas is not negligible. It is, therefore, necessary to distinguish the antennas and the spatial propagation paths to realize the versatile channel models. In the latter half of this paper, the measurement approaches of the antenna and the double-directional propagation paths for UWB systems in Tokyo Tech are described.

2. Wideband Channel
2.1. Concept of Channel Modeling
To separate the effects of antennas and propagation in the wireless channel, the vector complex antenna directivity and the double-directional ray response are separately considered in this paper. Figure 1 shows the schematic view of the antennas and the ray paths. The channel response can be written
in the form of

\[
(\text{Channel Response}) = \sum_{\text{rays}} (\text{Rx antenna directivity}) 
\cdot (\text{ray response}) \cdot (\text{Tx antenna directivity}),
\]

where antenna directivity is expressed as a vector (polarization) complex directivity including phase rotation due to position offset, and the ray response is expressed as a dyadic (vector vs. vector) complex path gain between Tx and Rx origins.

By using the matrix form, the array antenna directivity can be expressed in the equivalent complex baseband as

\[
\mathbf{E}(\Omega) = \begin{bmatrix}
  e_{\phi_1}(\Omega) & e_{\phi_2}(\Omega) \\
  e_{\phi_2}(\Omega) & e_{\phi_2}(\Omega) \\
  \vdots & \vdots \\
  e_{\phi_M}(\Omega) & e_{\phi_M}(\Omega)
\end{bmatrix} \begin{bmatrix}
  \hat{\theta}(\Omega) \\
  \hat{\phi}(\Omega)
\end{bmatrix}, \quad (2)
\]

where \( \Omega = (\theta, \varphi) \). Even in the wideband system, the frequency characteristics of the antenna can be usually negligible small compared with those of the propagation channel, so that \( \mathbf{E}(\Omega) \) is assumed not to be a function of the frequency.

In the same way, the propagation ray paths model can be expressed as

\[
\mathbf{F}(t, \tau, \Omega_R, \Omega_T) = \sum_{l=1}^{L} 
\begin{bmatrix}
  \hat{\theta}_R(\Omega_{Rl}) \\
  \hat{\phi}_R(\Omega_{Rl})
\end{bmatrix}^T 
\begin{bmatrix}
  \gamma^\theta_l \\
  \gamma^\phi_l
\end{bmatrix} 
\begin{bmatrix}
  \hat{\theta}_T(\Omega_{Tl}) \\
  \hat{\phi}_T(\Omega_{Tl})
\end{bmatrix} 
\cdot \delta(\Omega_T - \Omega_{Rl}) \cdot \delta(\Omega_T - \Omega_{Tl}) 
\cdot \delta(t - \tau_l) \cdot \exp(j2\pi f_d t) 
\cdot \exp(-j\mathbf{k}(\Omega_{Rl}) \cdot \mathbf{v}_R t) \cdot \exp(+j\mathbf{k}(\Omega_{Tl}) \cdot \mathbf{v}_T t). \quad (3)
\]

where \( t \) and \( \tau \) indicate the transmitter and the receiver, respectively, \( f_d \) is the Doppler frequency due to motion of scatterer, \( \mathbf{k}(\Omega) \) is the wavenumber vector directed to \( \Omega \), and \( \mathbf{v} \) is the moving velocity of the antenna. Even in the wideband system, the frequency characteristics of the path gain can be usually negligibly small compared within the bandwidth. Therefore, only the time delay due to the propagation path is taken into account.

By using the antenna and the ray-response of the propagation environment, the MIMO channel response model can be expressed as

\[
\mathbf{H}(t, \tau) = 
\int_{\Omega^T} \int_{\Omega^R} \mathbf{E}(\Omega_R) \cdot \mathbf{F}(t, \tau, \Omega_R, \Omega_T) \cdot \mathbf{E}^H(\Omega_T) 
\cdot d\Omega_R d\Omega_T \quad (4)
\]

Note that the antenna response is deterministic and unchanged, while the propagation response dynamically changes in various manners. The microscopic change is due to the Doppler shift which is expressed in the last two exponentials. As far as the matrix composed of \( \gamma^\beta_l \) is unchanged, the channel can be assumed to be wide-sense stationary. This is often termed by the short-term fading. On the other hand, more macroscopic change is due to the birth and the death of the ray, i.e. the matrix composed of \( \gamma^\beta_l \) is gradually changing according to the change of the surrounding environment. This is often termed by the long-term fading or the shadowing.

### 2.2. Double-Directional Wideband Channel Sounding

The measurement of the ray-response (3) in the real environment is called the double-directional channel sounding. The instrument is called the channel sounder. At least two commercial products are known to measure the double-directional channel response\([4],[5]\). Both channel sounders have the following common features:

1. Single Tx/Rx architecture is deployed for the reduction of hardware complexity and the ease of the calibration. Antennas are switched at both Tx and Rx sides (time division multiplex). Therefore, the real-time measurement is not possible. Usually, the data processing is done after coming back from the field campaign.

2. Superresolution algorithms are used to extract the ray parameters, such as directions of departure and arrival, time delay of arrival, and signal magnitude. Now, space-alternating generalized expectation maximization (SAGE) algorithm and its modification are commonly used\([6],[7]\). It is based on the maximum likelihood estimate, and there is no restriction about the waveform or the array geometry. Contrary to subspace-based methods such as MUSIC and ESPRIT, SAGE utilizes the transmit waveform, and therefore, the preprocessing for the suppression of the coherence is not required.

Alternatively, we have been developing a real-time MIMO channel sounder which utilizes the following new technologies\([8],[9]\):

1. MIMO Tx/Rx architecture is deployed. Each Tx transmits the multitone signal with slight offset of the frequency. At Rx side, Tx signals can be separated in the frequency domain. As well, a novel comprehensive calibration system has been proposed to eliminate the deviation of multiple Tx/Rx. The measurement time is drastically reduced since no antenna switching is required.

2. Instead of SAGE, multi-dimensional unitary ESPRIT combined with the spatial smoothing technique has been deployed. It is advantageous that ESPRIT...
directly outputs the estimated parameters, in contrast to SAGE or MUSIC in which the spectral search is necessary. Real-time implementation of the ESPRIT is possible.

Now we are in the process to get the radio license at 5 GHz band.

2.3. Ray-Tracing Simulation

The propagation prediction by using ray-optical approaches is getting very popular, and many researchers implemented their own ray-tracing tools. In many cases, however, the validation of the simulation by comparing with the field test results had been very difficult as the sounding data were not usually available.

We have also implemented several different ray-tracing simulators. One is 2D-3D hybrid approach for the microcellular environment[10], [11], [12]. Figures 2 show the concept of 2D-3D hybrid method. Since the antennas at both ends are below the rooftop level, and the propagation over the rooftop is negligible. Therefore, ray-launching is executed in horizontal plane to consider the specular reflection and the edge diffraction. In the ray-launching method, a lot of rays are launched from the source point toward all the directions. When a ray is arrival to a surface of some specific building, it is reflected according to the reflection law. When it is arrival to an edge of some building, the edge is considered as a new secondary source to launch the ray again toward all the directions. At the receiving point, a capture circle is considered to check the arrival of the ray, since the rays are discretize in the angular domain. Therefore, the size of the circle is varying according to the length of the ray. After the determination of 2D rays, 3D ray-path formulation is done by considering the height of the buildings and checking the existence of reflection/diffraction points on the surfaces of the buildings. The ground reflection can also be considered by taking the image of Tx point with respect to the ground. Some ray acceleration techniques are used, such as back-face culling and volume bounding. In the present implementation, Fresnel reflection coefficient and Lubbers' empirically corrected UTD diffraction coefficient are used.

To validate the simulator, we have made several field tests. Among them, we compare the azimuth-delay spectrum obtained by the simulation and the wideband sounder measurement with a directional antenna in a microcellular environment in the residential area in Yokosuka[13]. Figure 3 shows the map of the test site. It is a residential area with wooden houses and concrete walls. The specification of the sounder is shown in Table I. It is not a super resolution sounder, but a standard PN correlation type sounder connected to a rotating parabolic antenna.

![Concept of 2D-3D hybrid ray-tracing](image)

**Fig. 2.** Concept of 2D-3D hybrid ray-tracing.

![Map of the test site](image)

**Fig. 3.** Map of the test site; Yokosuka Highland, Japan.

Figures 4 and 5 compares the azimuth-delay spectra obtained by the field test and the simulation, respectively. Both results are in agreement with respect to the dominant signals, but some non-specular components are observed only in experiment. Therefore, the simulator can accurately predict the strong arrival waves. Contrary, the signals with long delay are difficult to predict, as the simulator only considers the specular reflection. Some diffuse effects shall be integrated in near future[14].

3. Ultra-Wideband Channel

To consider the ultra-wideband (UWB) channels, the frequency characteristics of the antennas as well as the scattering process can not be assumed as constant over the bandwidth. Additional discussion is

| TABLE I |
|-----|-----|
|**Frequency** | 8.45 GHz |
|**Bandwidth** | 100 MHz |
|**Delay Resolution** | 20 ns |
|**TX Antenna** | Vertical halfwave dipole |
|**RX Antenna** | V-pol 50 cm parabola |
|**Beamwidth** | 4° |
2.1. Extension of Channel Model to UWB

The concept of the channel model, which consists of the antennas and the propagation as presented in Eq. (1), is valid. However, in the UWB systems some extensions are necessary to consider the frequency characteristics of the antennas and the propagation loss.

The antenna directivity (2) can be extended to

\[
\mathbf{E}(f, \Omega) = \begin{bmatrix}
\varepsilon_{\theta 1}(f, \Omega) & e_{\varphi 1}(f, \Omega) \\
\varepsilon_{\theta 2}(f, \Omega) & e_{\varphi 2}(f, \Omega) \\
\vdots & \vdots \\
e_{\theta M}(f, \Omega) & e_{\varphi M}(f, \Omega)
\end{bmatrix}
\begin{bmatrix}
\hat{\theta}(\Omega) \\
\hat{\varphi}(\Omega)
\end{bmatrix}.
\]

(5)

On the other hand, the ray path propagation (3) shall be more carefully treated, as the delay time \( \tau \) is the Fourier pair of \( f \). Therefore, the Fourier transform of Eq. (3) shall be considered as

\[
\mathbf{F}(t, f, \Omega_R, \Omega_T) = \sum_{l=1}^{L} \left[ \begin{array}{c}
\hat{\theta}_R(\Omega_R) \\
\hat{\varphi}_R(\Omega_R)
\end{array} \right]^T \begin{bmatrix}
\gamma_{\theta \theta}(f) & \gamma_{\theta \varphi}(f) \\
\gamma_{\varphi \theta}(f) & \gamma_{\varphi \varphi}(f)
\end{bmatrix} \begin{bmatrix}
\hat{\theta}_T(\Omega_T) \\
\hat{\varphi}_T(\Omega_T)
\end{bmatrix}
\cdot \delta(\Omega_R - \Omega_T) \delta(\Omega_T - \Omega_T) \exp(-j2\pi f \tau) \\
\cdot \exp(j2\pi f \mathbf{d}_R \cdot \mathbf{v}_R t) \\
\cdot \exp\left(-\frac{2\pi f}{c} \mathbf{r}_R \cdot \mathbf{v}_R t\right) \exp\left(j\frac{2\pi f}{c} \mathbf{r}_T \cdot \mathbf{v}_T t\right).
\]

(6)

It is noted that \( \gamma_{\alpha \beta}(f) \) includes the frequency dispersion effect which may result in the time dispersion as well.

2.2. Antenna as a Part of UWB Channel

Figure 6 shows the electric field directivity of the dipole antenna. It is clear that radiation pattern changes according to the frequency. The frequency transfer function of this antenna toward \( \theta = 90^\circ \) and \( \theta = 60^\circ \) are compared in Figs. 7 and 8. It is clear from these figures that the directive transfer function may vary very drastically even for a same antenna.

Although it is easy get the directive transfer function of the antenna via the numerical simulation, it is more difficult via the measurements. By now we consider two alternative measurement methods. One method[15] is just to use two identical antennas to point in the same directions to each other. The antenna transfer function is just a square root of the measure transfer function divided by the free space transfer function. Another way is the use of complex 3-antenna method[16]. It measures the complex antenna factor which can be easily transformed into the antenna transfer function.

2.3. Double-Directional Ultra Wideband Channel Sounding

It is not so complicated to extend the double-directional channel sounding to apply for the UWB. From Eq. (6), it is easily understood that the directions of departure and arrival, as well as the delay time of arrival are constant for each of the ray paths over the UWB frequency. However, the complex amplitude of the ray, i.e. \( \gamma_{\alpha \beta}(f) \), is a function of the frequency. Therefore, instead of estimating a single complex amplitude, the amplitudes of subbands are estimated separately. In this manner, we extended the SAGE algorithm for UWB sounding[17].
Figure 7 shows the measurement setup. Due to the limitation of the facility, the single-directional measurement was done by neglecting the directivity of the fixed Tx antenna. A measurement test has been done in an empty room shown in Fig. 10 together with the ray paths estimated by the sounding. The measurement parameters are listed in Table II. The rays estimated by the sounding can be well described by the specular reflections. By now, we still have some error in the amplitude estimation, and some improvement is necessary.

4. Conclusion

This paper presented our approaches for wideband and UWB channel measurement and modeling approaches. The most important point of our approaches is that the antennas and the propagation paths shall be separately modeled. For this purpose, antenna models shall be described by the polarized directive transfer function of all over the surface. Propagation models shall be described by the sum of ray paths. Each ray path has the double-directional information, i.e., directions of departure and arrival, as well as the delay time of arrival, and the dyadic path gain that expresses the polarization-dependent attenuation and depolarization.

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References

### TABLE II
Measurement parameters for UWB channel sounding.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>$3.1 \text{ [GHz]} \sim 10.6 \text{ [GHz]}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>The number of samples in frequency domain</td>
<td>751 points ($\Delta f = 10$ [MHz])</td>
</tr>
<tr>
<td>Bandwidth of each subband</td>
<td>$100$ [MHz]</td>
</tr>
<tr>
<td>The number of samples in spatial domain</td>
<td>$10 \times 10$ in horizontal plane with interval of $4.8$ [cm] (less than half wavelength of $3.1$ [GHz])</td>
</tr>
<tr>
<td>Estimated components</td>
<td>Azimuth $\phi$, elevation $\theta$, time delay $\tau$, complex amplitudes at all the subbands</td>
</tr>
<tr>
<td>Antennas</td>
<td>Biconical antennas</td>
</tr>
<tr>
<td>Polarization of the wave</td>
<td>Vertical–Vertical</td>
</tr>
</tbody>
</table>


Jun-ichi TAKADA was born in Tokyo, Japan, in 1964. He received B.E., M.E. and D.E. degrees from Tokyo Institute of Technology in 1987, 1989, and 1992, respectively. From 1992 to 1994, he has been a Research Associate at Chiba University, Japan. From 1994, he has been an Associate Professor of International Cooperation Center for Science and Technology (INCOCSAT), Tokyo Institute of Technology, Japan. There, he served as a coordinator of Core University Academic Cooperation Program sponsored by Japan Society for Promotion of Science (JSPS) for six years to establish and accelerate the research cooperation with South East Asian Universities including Thailand. From 1997 he also participated in the project of Research Center for Communication and Information Technologies (ReCCIT), King Mongkut’s Institute of Technology Ladkrabang, which was sponsored by Japan International Cooperation Agency (JICA) as a short-term expert. He has visited Thailand more than thirty-five times. From 2001, he has been with the Department of International Development Engineering, Tokyo Institute of Technology, as an Associate Professor, where he tries to transfer his experiences on the academic cooperation to the students. His current research interests are wireless channel characterization and modeling, ultra-wideband radio, and applied radio instrumentation and measurements. He is a member of IEEE, IEICE Japan, and ECTI Thailand. His group is participating in COST 273 “Towards Mobile Broadband Multimedia Communications,” a cooperation program sponsored by European Union.