4-2 Power Measurement Emitted by UWB System in Time Domain

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ULTRA-wideband (UWB) technology is a wireless communications technology that transmits data with a low power-spectrum density with a bandwidth of several gigahertz. The U.S. Federal Communications Commission (FCC) approved the commercial implementation of UWB, within limits, in 2002. In ITU-R, Task Group 1/8 (TG1/8) was established to consider UWB standardization. TG1/8 was held six times from January, 2003 to October, 2005, and drew up drafts for new recommendation concerning the UWB characteristics, the impact to the other wireless communications, the spectrum management framework, and the measurement methods. The drafts will be published as new recommendations. Japanese administration had submitted 30 input documents through the entire meetings. The author delegated an expert to the TG1/8 except for the 1st meeting, and submitted seven contribution documents.

This paper describes the technical requirements and measurement methods of UWB system in FCC part 15 and in the drafts for new recommendations of ITU-R TG1/8. The paper also mentions a method of measuring the peak power-spectral density (PSD) of an ultra-wideband (UWB) transmitter in the time domain. The method uses a waveform reconstruction technique that enables an electric field to be reconstructed using a complex antenna factor of the receiving antenna and the waveform observed with an oscilloscope. In addition, the trends of UWB spectrum masks are shown.

Keywords
Ultra-Wideband wireless system, Measurement method, Time domain, ITU-R

1 Introduction

Ultra Wide Band (UWB) wireless systems collectively refer to wireless communications systems that transmit data using signals with a low power-spectrum density in a bandwidth of several gigahertz. Major UWB applications include short-range radar systems for automotive applications and the transmission of information between information devices in a range of several meters. Figure 1 shows an example. Here, personal computers (PCs) and digital appliances with built-in UWB devices are connected through a wireless link that transmits video signals at high transmission speeds of 100 Mbps to 480 Mbps. The maximum range of communication is approximately 10 m. Within this range, the UWB technique is intended to provide faster transmission rates and higher quality than conventional wireless LANs (Local Area Networks)[1][2]. In addition to the wireless USB application described above, researchers are also considering applying the UWB technique to sensor networks, which manage devices and monitor the environment using sensors equipped with communication functions, through installation of these sensors in electronic equipment and devices.

In 2002, the U.S. FCC[1] conditionally

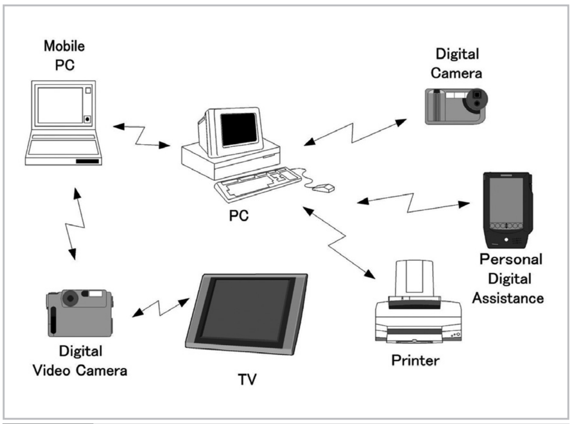

Fig.1 *Example of UWB applications*

approved the commercial implementation of UWB for license-free wireless stations. In the same year, the specifications concerning UWB were updated in FCC Part 15, which specifies regulations on the emission levels of high-frequency devices and radio-frequency devices for license-free radio stations, leading to the publication of the FCC 02-48[3]. In Europe, the CEPT[2] is examining standardization related to UWB wireless systems. In Japan, the Ministry of Internal Affairs and Communications assembled the UWB Wireless System Committee in April 2003 under the Working Group of the Information and Telecommunications Technology Council. The UWB Wireless System Committee is now investigating this standardization within Japan. Further, the ITU[3], one of the specialized United Nations (UN) agencies for telecommunications services, assembled Task Group 1/8 (TG1/8) from the SG1[4] meeting of the ITU-R (Radiocommunication Sector, one of the ITU sectors) in July 2002 to investigate UWB technology.

The TG1/8 held six meetings between January 2003 and October 2005. The TG1/8 consists of four Working Groups (WG): WG1, which investigates UWB system characteristics; WG2, which examines the impact on existing wireless communications services; WG3, which researches the spectrum management framework; and WG4, which studied measurement methods. WG1 was responsible for, among others, recommendations on the definitions of terms (including definition of UWB itself). WG2 was in charge of assessing the impact of UWB on existing wireless communications services, and its recommendations specify standards for shared use of UWB and other services. This group also submitted a draft report compiling studies on interference. WG3 put together a draft recommendation related to a spectrum management framework as a guide for administrative entities considering the introduction of UWB systems. WG4 investigated measurement methods and compiled a draft recommendation. These draft recommendations will be submitted to SG1. If approved, the documents will be subject to postal ballot by member nations, and if they obtain the specified minimum number of approving votes, these documents will be published as new recommendations.

Japanese representatives submitted 30 documents throughout the course of the meetings. Among these, 22 of the contributed documents are related to measurement methods (WG4). This author participated in all TG1/8 meetings except the first, and submitted seven documents on measurement methods[4]-[10].

This paper outlines the technical requirements and measurement methods for UWB systems according to the FCC and describes issues related to measurement methods as described in the new draft recommendations prepared in the ITU-R. The paper also discusses a method of measuring peak power-spectral density (PSD) in the time domain; the Communications System EMC Group submitted this method among its draft recommendation as a means of addressing the disadvantages of peak measurement under the FCC guidelines.

1 Federal Communications Commission
2 Conference of European Postal and Telecommunications
3 International Telecommunication Union
4 Study Group 1: Responsible for frequency management

2 Technical requirements and measurement methods under FCC guidelines

The specifications of FCC Part 15[11][12] classify UWB systems into three major categories: ground-penetrating radars and medical imaging systems, vehicular radar systems, and communications and measurement systems. Vehicular radar systems use sub-millimeter waves in the frequency range from 22 GHz to 29 GHz. Other systems use microwaves in the frequency range from 3.1 GHz to 10.6 GHz, in principle.

The FCC defines UWB wireless systems[5] as transmitters with a partial bandwidth of 500 MHz or greater or those with a fractional bandwidth that satisfy Equation (1).

$$\frac{2(f_H - f_L)}{(f_H + f_L)} \geq 0.20 \qquad (1)$$

Here, f_H and f_L are the upper and lower limits of the frequency, respectively. Frequency f_M is the frequency that yields the maximum radiation in this frequency range. Here, f_H and f_L are frequency values at levels 10 dB below f_M. If these technical requirements are satisfied, any system may be referred to as a UWB wireless system regardless of its modulation scheme—whether the system involves impulse radio, Direct Sequence Spread Spectrum (DS-SS), or Orthogonal Frequency Division Multiplexing (OFDM).

Figure 2 shows the spectral masks that specify the limits for communication and measurement UWB wireless systems classified by the FCC. For both indoor and outdoor (handheld) use, the limits are −41.3 dBm/MHz within the allowed frequency range (from 3.1 GHz to 10.6 GHz). Here, at the boundaries where the limit value changes stepwise, the system should satisfy the lower limit value. The specified UWB frequency band is broad, as shown in the figure, and overlaps those of existing services. As a dedicated band is unavailable, UWB systems use the same frequency range as existing systems.

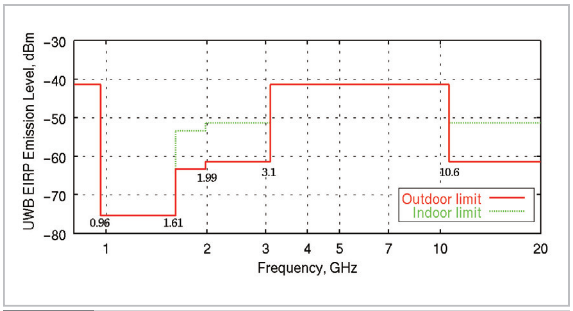

Fig.2 Spectral masks for UWB communication and measurement systems (red in the figure indicates values for outdoor use, and green indicates values for indoor use.)

These limits are values specified for a specific set of conditions: the mode of the device for measuring the spectrum (such as a spectrum analyzer) is set to Root Mean Square (RMS) detection, the Resolution Bandwidth (RBW) is set to 1 MHz, and the measured value is converted into Equivalent Isotropically Radiated Power (EIRP). If the distance is 3 m, the electric field expressed in dBμV/m is obtained by adding approximately 95.23 to the EIRP expressed in dBm.

In addition to the requirements described above, the spectral masks of a UWB communication and measurement system must also satisfy the limits shown in Tables 1 when the RBW of the measurement equipment is set to 1 kHz or greater.

Table 1 Additional limits for UWB wireless systems applied to indoor and outdoor use

Frequency range [MHz]	EIRP [dBm] (indoor)	EIRP[dBm] (outdoor)
1164-1240	-85.3	-85.3
1559-1610	-85.3	-85.3

FCC Part 15 specifies an EIRP value of 0 dBm as the limit for peak measurement with RBW equal to 50 MHz at the maximum radiation frequency f_M. However, few spectrum analyzers now commercially available satisfy the required RBW value of 50 MHz. Thus peak measurement must be performed with the available RBW and the obtained value must then be converted using the equation below. Otherwise, peak value must be measured with a different method altogether.

$$P_{\lim} = 20\log_{10}\left(\frac{B_{RBW}}{50}\right) \qquad (2)$$

Here, P_{lim} is the limit given in dBm after the conversion, and B_{RBW} is the RBW (in MHz) obtained in measurement. For example, assuming that peak measurement is conducted with RBW at 3 MHz, the obtained limit is −24.4 dBm. This conversion assumes an RBW at 3 MHz, a video bandwidth (VBW) of 3 MHz or greater, and a spectrum analyzer setting of "max-hold".

Frequencies at or below 960 MHz should be measured in accordance with CISPR16-1-1[13] using a Quasi-Peak (QP) detector. The value for RBW is also specified in CISPR16-1-1 for each frequency range. Frequencies at or above 960 MHz should be measured in RMS mode with RBW set to 1 MHz. Here, the boundary frequency is set to 960 MHz only in the U.S. Meanwhile, the CISPR specifies an upper limit for QP measurement of 1 GHz.

5 ITU-R draft recommendations also use the same definition.

3 ITU-R TG1/8 draft recommendation for measurement method

This section describes the main points of the draft recommendation[14] for the measurement method, as discussed in ITU-R TG1/8 WG4.

3.1 Average electric power measurement

Section **2.4** of the draft recommendation specifies measurement of average power radiated from UWB devices by one of the following three methods using a spectrum analyzer (including the EMI test receiver).

(1) With RMS detector
- RBW = 1 MHz, VBW = 1 MHz or greater (3 MHz recommended)
- Frequency span set to any value convenient for measurement (for example, 600 MHz for 600 measurement points).
- Integration time of 1 ms per measurement point

(2) In zero-span mode
- RBW = 1 MHz, VBW = 1 MHz or greater (3 MHz recommended)
- Zero-span, sample detector
- Sweep time set to 1 ms, single sweep
- The center frequency is varied by 1 MHz and average output is calculated using the following equation (where n is the number of measurement points and $P(i)$ is the measured power at each point)

$$P_A = 10\log_{10}\left(\frac{1}{n}\times\sum_{i=1}^{n}10^{\frac{P(i)}{10}}\right) \qquad (3)$$

(3) With integrated power
- RBW = 10 kHz, VBW = 30 kHz
- Frequency span of 1 MHz, sample detector, readout set in dBm
- Sweep time set to "auto"
- The center frequency is varied by 1 MHz and average output is calculated using the following equation (where S_P is the span and k is the coefficient for converting RBW to equivalent noise bandwidth)

$$P_A = 10\log_{10}\left(Sp\times\frac{\frac{1}{n}\times\sum_{i=1}^{n}10^{\frac{P(i)}{10}}}{RBW\times k}\right) \qquad (4)$$

3.2 Measurement of low-level power based on the radiometric technique

It is exceedingly difficult to measure extremely low (below-limit) power in the GPS band from 1 GHz to 2 GHz or in the sub-millimeter band using ordinary measurement techniques, since the signals are buried in the noise of the measurement equipment. Thus, a measurement method using a radiometer has been proposed, as shown in Fig. 3. This method first measures the thermal noise temperature of the wave absorber, which is then used as a reference value in subsequent measurements. The method then stipulates mea-

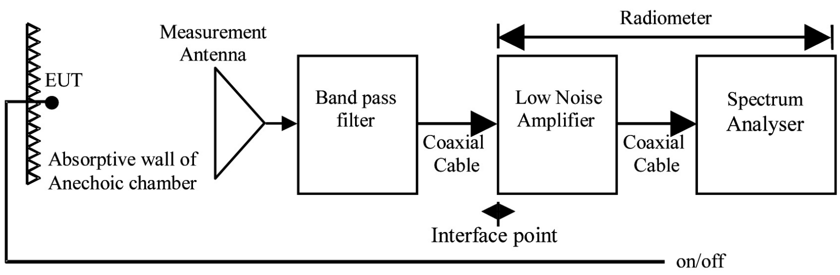

Fig.3 *Example of measurement equipment for the 1-GHz to 2-GHz range based on the radiometer method*[14]

surement of the noise temperature of the UWB transmitter and comparison of this value with the reference noise temperature, followed by determination of the extremely low power. This method enables measurement of any power above the thermal noise level.

3.3 Peak power measurement

The draft recommendation specifies measurement of peak power radiated from UWB devices using one of the following spectrum analyzer methods or using an oscilloscope (the latter method is described later).

(1) With the limit conversion formula from 50 MHz RBW to an arbitrary RBW

- RBW = 3 MHz (example), VBW = RBW or greater (3 times RBW recommended)
- Frequency span set to any value convenient for measurement
- Peak detector, max-hold
- Sweep time set to “auto”
- Limit: $L_{3\mathrm{MHz}} = L_{50\mathrm{MHz}} + 20\log_{10}(3/50) = L_{50\mathrm{MHz}} - 24.4$ dB

(2) With the limit conversion formula from 50 MHz RBW to an arbitrary RBW

- RBW = 3 MHz (example), VBW = RBW or greater (3 times RBW recommended)
- Zero-span, central frequency set to the maximum radiation frequency
- Sample detector
- Sweep time set to “auto”
- The complementary cumulative distribution function (CCDF) is measured and treated as Gaussian noise if this value is within ±2 dB of the Rayleigh distribution. In this case, the following equation is used for the limit conversion.
- Limit: $L_{3\mathrm{MHz}} = L_{50\mathrm{MHz}} + 10\log_{10}(3/50) = L_{50\mathrm{MHz}} - 12.2$ dB

3.4 Measurement in time domain

In the development stage of a UWB transmitter, the aim is to observe not only the spectrum of transmitted power but also the corresponding waveform. In such a case, an oscilloscope is generally used, as this device can perform measurements in the time domain. However, it should be noted that the waveform observed by an oscilloscope is not itself the electric field waveform.

Figure 4 shows an example of the equipment used to observe the waveform of the electric field of a UWB transmitter. The waveform $v_m(t)$ observed by the oscilloscope is the superposition of antenna output, $v_a(t)$, and the characteristics of the measurement equipment (including preamplifiers and cables), as illustrated in the figure above. To obtain the electric field waveform, one must remove the characteristics of the waveform measurement equipment and those of the antenna. Figure 5 shows the equivalent circuit for this waveform observation equipment. In this figure, $F_c(f)$ is the complex antenna factor[15], $S_a(f)$ is the S

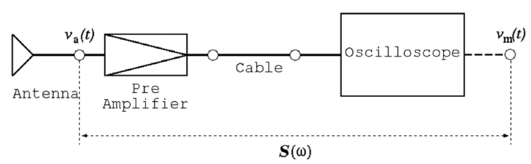

Fig.4 *Example of waveform observation equipment*

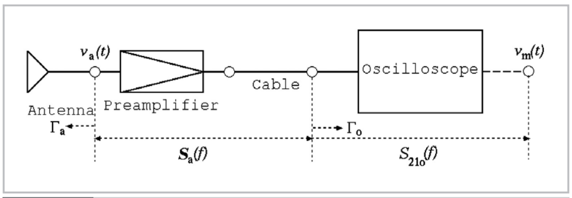

Fig.5 Equivalent circuit for waveform observation equipment

matrix of the preamplifier and cables, and $S_{21o}(f)$ is the frequency response characteristics of the oscilloscope. Γ_a and Γ_o represent the reflection coefficient at the antenna and at the input terminal of the oscilloscope, respectively. Thus, the electric field waveform $E(t)$ is expressed as the following equation[16].

$$E(t) = T_F^{-1}\left[\frac{(1-S_{11a}\Gamma_a)(1-S_{22a}\Gamma_o)}{S_{21a}S_{21o}}F_c(f)T_F[v_m(t)]\right] \quad (5)$$

Here, T_F indicates the Fourier transform, and T_F^{-1} indicates the inverse Fourier transform. The transmission coefficient from the output of the preamplifier to the input is usually negligibly small compared with the transmission coefficient (*i.e.*, the amplifier gain) from input to output, so this expression assumes that $S_{12a} = 0$.

Figure 6 shows an example of measurement equipment for measuring the waveform of the electric field emitted from an antenna excited by an impulse generator. The equipment includes a receiving antenna and an oscilloscope. This example shows the use of a double-ridged guided horn antenna, and the distance between the transmitting and the receiving antennae is set at 3 m. The impulse generator simulates the UWB signal based on the impulse radio system. Figure 7 shows the waveform observed by the oscilloscope. Figure 8 shows the electric field waveform reconstructed by applying Equation (5) to the oscilloscope waveform of Fig. 7 and the electric field waveform estimated from the output signal of the impulse generator and the characteristics of the transmitting antenna. This figure shows that the shapes and the peak values of the two waveforms agree well. The fall time of the peak is 45.0 ps for the reconstructed waveform and 50.0 ps for the estimated waveform, which shows that these waveforms also agree quantitatively. In the figure, the time display of the waveforms is deliberately shifted for comparison.

One can apply this method to obtain the

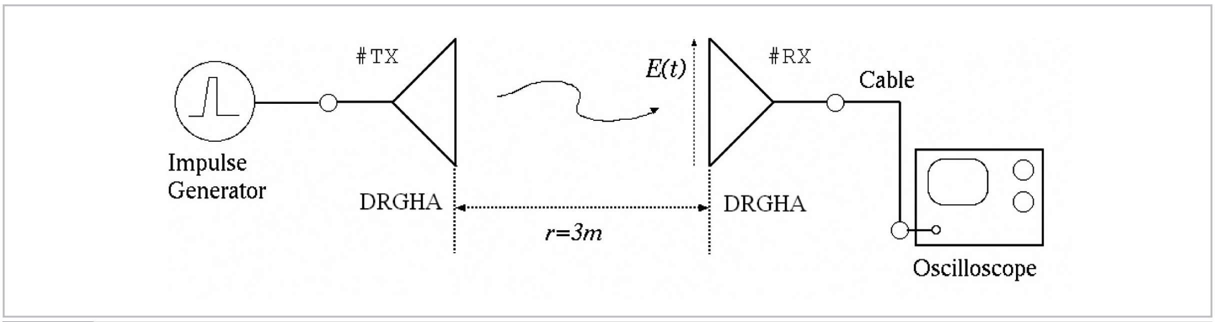

Fig.6 Example of UWB electric field waveform measurement equipment

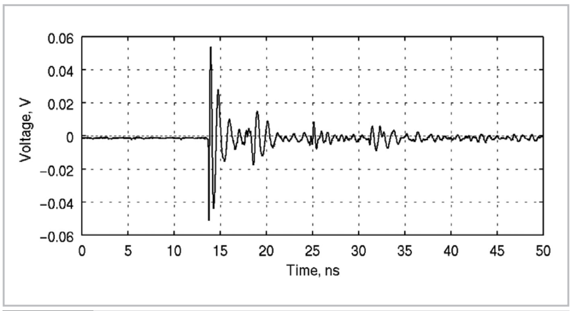

Fig.7 Waveform observed by oscilloscope

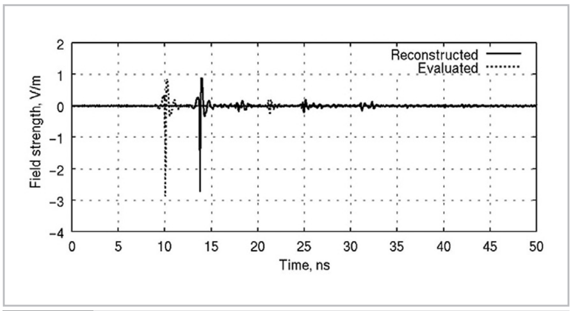

Fig.8 Reconstructed and estimated electric field waveforms

peak power at an RBW of 50 MHz. As discussed in the previous section, few spectrum analyzers support an RBW of 50 MHz, necessitating the use of a conversion formula such as that indicated in Equation (2). The conversion set forth in Equation (2) uses the same limits independent of the method. It is possible that for some methods the limits may be stricter than 0 dB/50 MHz. In particular, the Intermediate Frequency (IF) filter characteristics of a spectrum analyzer tend to deviate from the ideal when the RBW exceeds 3 MHz, so that one has no choice but to measure at RBW = 1 MHz or 3 MHz and then use the conversion formula. Thus, the best method is to measure the peak power at 50 MHz and thus to avoid the required use of the conversion formula.

On the other hand, measurement in the time domain is restricted by the upper frequency limit of the oscilloscope, which limits the measurement frequency range. Nevertheless, this measurement method is essentially applicable to all frequency bands. When reconstructing the electric waveform in Equation (5), the electric field waveform E_X, band-restricted by $X(f)$, can be obtained by multiplying the expression in Equation (5) by the ideal frequency response characteristics of the spectrum analyzer (or EMI test receiver); these characteristics are represented by the function $X(f)$, corresponding to the response characteristics of the IF filter. Generally, the IF filter of a spectrum analyzer is a Gaussian filter, so that one may treat $X(f)$ as a Gaussian function with a bandwidth of 50 MHz (−3 dB) to obtain peak power for an RBW of 50 MHz. Equation (2) gives the peak power with the value of E_X obtained here.

$$E_X(t) = T_F^{-1}\left[\frac{(1-S_{11a}\Gamma_a)(1-S_{22a}\Gamma_o)}{S_{21a}S_{21o}} F_c(f)X(f)T_F[v_m(t)]\right] \quad (6)$$

Here, we calculate the peak power of the above signal for the bandwidth of 50 MHz from Equation (6). We note that the maximum radiation frequency of this impulse signal is 5.8 GHz. In this case, the peak electric field strength $E_X(t)$ for the bandwidth of 50 MHz is calculated as 0.01683 V/m. Based on this value, the peak power is calculated as 85.0 μW (−10.7 dBm).

4 Investigation of spectral masks in Japan and Europe

Figure 9 shows temporary spectral masks in Europe (under the CEPT) and in Japan as of December 2005. The Japanese temporary spectral mask was developed based on an investigation conducted by the MMAC Promotion Council to examine shared use among UWB wireless systems and existing wireless services. This mask sets low limits for frequencies assigned to passive radio services, such as weather radar and airborne radar, and frequencies assigned to broadcasting services. Thus, the mask splits the frequency range into an upper and a lower range. For the lower range, the mask permits radiation of −41.3 dBm/MHz only for UWB systems equipped with features utilizing interference-reduction techniques. On the other hand, the European temporary mask is based on essentially the same concept as the Japanese mask, though with slightly different upper and lower frequency boundary values, reflecting the difference in the frequency assignments of the two regions. The European mask for the range of 4.2 GHz to 4.8 GHz permits radiation of −41.3 dBm/MHz, even for UWB systems without interference-reduction techniques, for a limited period (up to the year 2010).

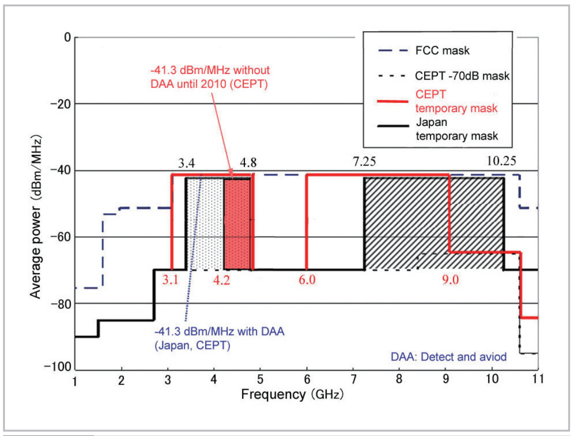

Fig.9 *Temporary masks in Europe and Japan (As of December 2005)* [17]

Here, the European mask specifies a frequency bandwidth of 1.7 GHz while the Japanese mask specifies a frequency bandwidth of 1.4 GHz. Assuming that the multiband OFDM of 500 MHz per band is used in the lower range, the European mask allows three bands for a single band group while the Japanese mask allows only two bands. Thus, future settings of this mask in Japan will need to take this issue into consideration, or, alternatively, the UWB system may be reconsidered.

In either case, Japan and Europe plan to assemble a set of technical requirements for UWB wireless systems—including spectral masks—in or around March 2006.

5 Conclusions

This paper presented an overview of the technical requirements of a UWB system under the FCC and discussed issues concerning measurement methods set forth in the draft recommendation compiled in the ITU-R. Further, this paper describes a measurement method in the time domain, which has been proposed as an alternative to the disadvantages of FCC peak measurement, with specific measurement examples. This report also addresses recent trends in the limits of UWB systems, both domestic and international.

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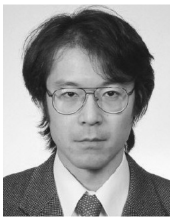

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