4 Investigation of EMC in Wireless Communication Systems

4-1 Electromagnetic Disturbance Measurement by Using Amplitude Probability Distribution for Protecting Digital Wireless Communication Systems

GOTOH Kaoru, ISHIGAMI Shinobu, MATSUMOTO Yasushi, SHINOZUKA Takashi, and YAMANAKA Yukio

Digital wireless communication services spread rapidly in recent decades, and RF disturbance emitted from electric devices has higher frequency and wider bandwidth because of large increasing in clock speed of recent electric devices. However, the disturbance measurement methods specified in the international special committee on radio interference (CISPR) is unable to follow such situation at the present.

Amplitude probability distribution (APD) measurement, which has been studied at CISPR as a new international standard, is known by the works of NICT that APD readings of disturbance correlate well with communication quality degradation of victim digital wireless communication systems. We report the latest findings in that studies and the situation of the international standardization, and their application.

Keywords
Disturbance measurement, Amplitude Probability Distribution, Bit error rate,
Microwave ovens, Internal interference noise

1 Introduction

It is widely known that the electromagnetic waves (referred to as “electromagnetic disturbance”) emitted from electric and electronic devices such as household electrical appliances interfere with other devices or broadcast and communications services in the surrounding area. Many countermeasures have been implemented for both the source and affected systems[1]. In view of the determination of restrictions on electromagnetic disturbance, the CISPR has established specifications for measuring equipment and legal limits of electromagnetic disturbance emitted by electric and electronic devices (See examples [2] and [3]). The electromagnetic disturbance measuring equipment specified by the CISPR features four detectors in the frequency ranges from 9 kHz to 1,000 MHz—specifically, peak, average, RMS (root mean square), and QP (quasi-peak) detectors. In particular, the characteristics of the QP detector are determined such that the indicated value of the electromagnetic disturbance measurement shows high correlation with the affection that electromagnetic disturbance can cause in AM radios. The QP detector is thus extremely effective in protecting analog broadcasts and communications. However, electric and electronic devices have recently become smaller and begun to employ higher speed digital components, causing electromagnetic disturbance in higher frequencies and wider bandwidth ranges. Further, we are seeing rapid growth in digital wireless communication and broadcast services that use frequency bands of 1 GHz or higher, which has led to new demands for the protection of digital systems. To protect digital wireless communication systems in these increasingly complex electromagnetic environments, it is urgent that we conduct studies on methods of measuring electromagnetic disturbance at or above 1 GHz, and establish a corresponding international standard.

Amplitude probability distribution (APD) measurement is a longstanding method of measuring impulse noise such as that caused by lightning. Despite its early implementation, the electromagnetic disturbance values obtained with this method continue to show a high correlation with degradation in performance of wireless communication services of the affected digital wireless communication systems, as NICT has demonstrated in past studies. More specifically, a report was issued on experiments conducted with the aim of regulating electromagnetic disturbance emitted by microwave ovens. This report presented experimental confirmation of the correlation between APD measurement for microwave ovens and the BER degradation characteristics of an affected PHS system[4]. Meanwhile, NICT has developed its own general-purpose APD measuring equipment (See example[5]).

Based on these experimental results and the demonstrated practicality of the measuring equipment, NICT proposed APD measurement to the CISPR as a candidate method for measuring electromagnetic disturbance at or above 1 GHz. APD measurement is now under deliberation for use in international standardization. The CISPR has completed voting and approval on the specifications of the APD measuring equipment by its member nations, and the specifications are now in the final stage of publication as an international standard[6]. In preparation for the proposal of APD measurement, NICT studied equations expressing the relationship between APD measurement of electromagnetic disturbance and BER degradation in affected systems and performed a number of verification experiments[7][8]. NICT also studied a method for regulating electromagnetic radiation disturbance from industrial, scientific, and medical (ISM) equipment using APD measurement[9] and investigated electromagnetic radiation disturbance limits. APD measurement has also gained attention in industry as well as in the field of international standardization, as seen in recent attempts to perform EMC evaluation of modules in electronic devices based on APD measurement. NICT is conducting the relevant technological development in collaboration with Taiyo Yuden Co., Ltd. [10]. This article provides an overview of APD measurement, discusses the correlation between the results of APD measurement of interfering disturbance and BER degradation of the affected systems, and describes examples of APD measurement applications, in that order.

2 Amplitude probability distribution measurement

Amplitude probability distribution (APD) is defined as the “probability of time that the amplitude of disturbance exceeds a specified level”. Figure 1 shows a diagram illustrating this concept. The vertical axis is the intensity of the disturbance envelope and the horizontal axis represents time. W_i indicates the range in which the disturbance envelope, $x(t)$, exceeds the threshold x_k. The variable n is the number of times that $x(t)$ exceeds x_k. T_0 is the total time of measurement. Here, the probability of time that $x(t)$ exceeds x_k is expressed as $APD(x_k)$ in the following equation:

$$APD(x_k) = \sum_{i=1}^{n(x_k)} W_i(x_i)/T_0 \tag{1}$$

The time probability distribution, $APD(x)$, with the threshold x as the variable, is generally referred to as the amplitude probability distribution. Figure 2 shows an example representation of this distribution. The horizontal axis is the intensity of the disturbance envelope taken as the threshold, and the vertical axis is the time probability as expressed by Equation (1). By definition, it is obvious that APD is expressed with the cumulative distribution, $F(x)$, of $x(t)$.

$$\begin{aligned} APD(x_i) &= \text{Prob}\left(x_i < x \le \infty\right) \\ &= 1 - \text{Prob}\left(-\infty < x \le x_i\right) \qquad (2) \\ &= 1 - F(x_i) \end{aligned}$$

The APD measuring equipment determines a value for the electromagnetic disturbance envelope using video output when the disturbance measuring equipment (generally an EMI receiver or a spectrum analyzer) is set at zero-span. The equipment measures APD in real time using a dedicated measurement unit equipped with an A/D converter and RAM. Figure 3 shows the external appearance of the prototype APD measuring equipment, and Fig. 4 shows its configuration. The specifications of the APD measuring equipment are indicated in [6]; this document will be published as a revised version of [1].

3 Relationship between APD of electromagnetic disturbance and BER degradation of affected systems

Figure 5 illustrates an overview of a case in which electromagnetic disturbance from electronic devices interferes with a digital wireless communication system. Let us consider an affected system based on the BPSK modulation scheme as an example. Figure 6 shows the relevant signal space. For example, Symbol (−1) corresponds to Signal point ($-\sqrt{E_b}$, 0), and Symbol (1) corresponds to Signal point ($+\sqrt{E_b}$,0). Here, E_b is the signal energy per bit. Figure 6 indicates a case in which

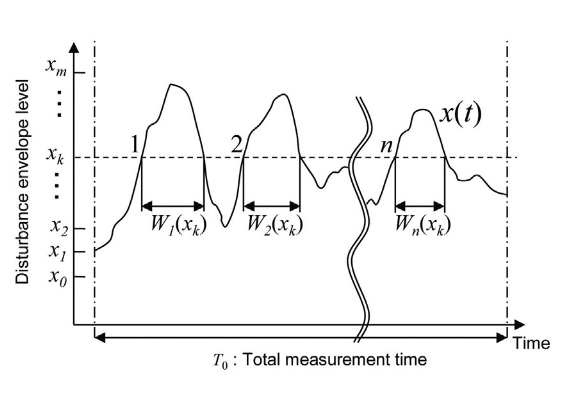

Fig.1 Overview of APD

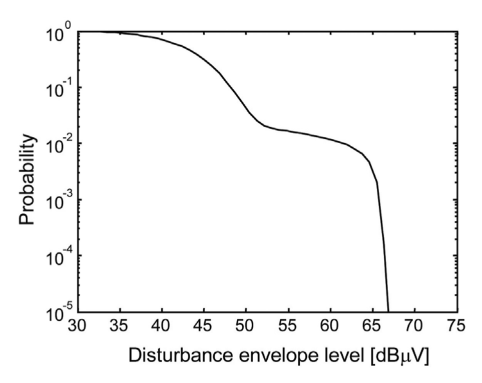

Fig.2 Example of amplitude probability distribution

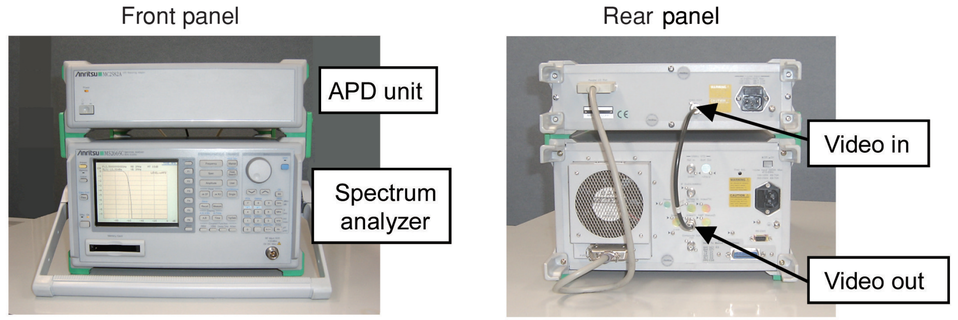

Fig.3 External appearance of APD measuring equipment

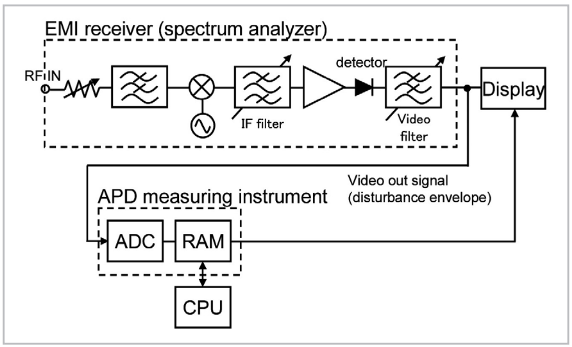

Fig.4 Configuration of APD measuring equipment

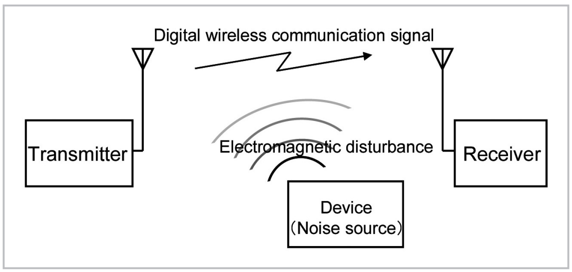

Fig.5 Electromagnetic disturbance emitted from electronic devices and the affected digital wireless communication system

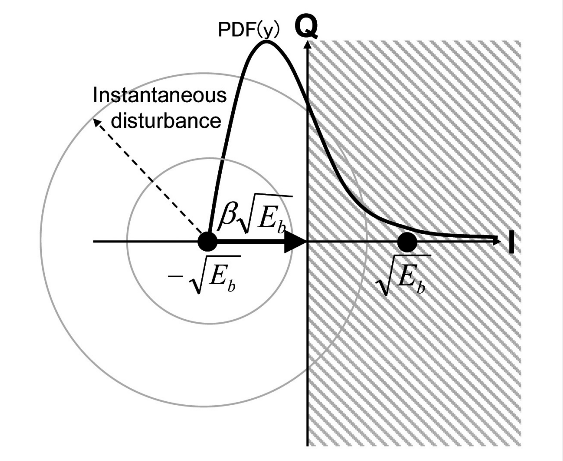

Fig.6 Disturbance in communication signal space (For BPSK)

electromagnetic disturbance interferes with a system when the system is receiving Symbol (−1). Now, let us assume the worst case. The phase of the electromagnetic disturbance upon determination of the symbol at matched filter output is considered to be oriented in the direction from the symbol being received to the symbol with the shortest signal distance (this orientation is the most frequent cause of errors), and the symbol is assumed to be incorrectly interpreted when the disturbance exceeds half of the minimum distance between the symbols; this distance is expressed as ($\beta\sqrt{E_b}$). Thus, the symbol error rate P_s agrees with the probability that the disturbance x_f at the matched filter output will exceed one-half of the minimum distance between the symbols:

$$P_s = \mathrm{Prob}\left(\beta\sqrt{E_b} < x_f\right) \tag{3a}$$

Here, β is 1/2 of the minimum distance between the symbols as normalized with $\sqrt{E_b}$. Next, the number of error bits per symbol is approximated as $1/P = \alpha$. Here, P is the number of bits transmitted per symbol.

$$BER = \alpha\,\mathrm{Prob}\left(\beta\sqrt{E_b} < x_f\right) \tag{3b}$$

Equation (3b) compares the signal and the disturbance at the matched filter output in units expressed as the square root of energy. On the other hand, the APD measuring equipment measures the amplitude of the disturbance at a filter output that features the same bandwidth as the matched filter, in the case of the APD measuring equipment the unit of measurement is amplitude expressed as the square root of electric power. Thus, the signal and disturbance amplitudes in Equation (3b) are multiplied by the bit rate, $R = 1/\alpha T_s$, to convert the physical quantities to the dimension of amplitude. Here, α is the inverse of the number of bits per symbol, and T_s is the symbol length.

$$\begin{aligned} BER &= \alpha\,\mathrm{Prob}\left(\beta\sqrt{E_b R} < x_f\sqrt{R}\right) \\ &= \alpha\,\mathrm{Prob}\left(\beta\sqrt{P_s} < x_f/\sqrt{\alpha T_s}\right) \\ &= \alpha\,\mathrm{Prob}\left(\sqrt{\alpha\beta^2}\sqrt{P_s} < \sqrt{x_f^{\,2}/T_s}\right) \end{aligned} \tag{3c}$$

Here, P_s is the signal power. The RMS signal amplitude, A, is $P_s^{1/2}$. In a direct sequence spread spectrum system with the spreading factor SF, the electromagnetic disturbance decreases to $1/SF$ times the original value in average in de-spreading process of the receiver. On the other hand, the RMS amplitude of band-limited disturbance x, which is quantified in APD measurement, is expressed as

$\sqrt{x_f^2/T_s}$. Thus, the relationship between the APD of the electromagnetic disturbance and the BER degradation of the affected digital wireless communication system is expressed as the following equation[7]:

$$\begin{aligned} BER &= \alpha\,\mathrm{Prob}\left(A\sqrt{\alpha\beta^2 \cdot SF} < x\right) \\ &= \alpha\,\mathrm{APD}\left(A\sqrt{\alpha\beta^2 \cdot SF}\right) \end{aligned} \qquad (3)$$

Here, the following assumptions must be satisfied for Equation (3) to hold.

(1) The phase of the electromagnetic disturbance takes the worst value so that the occurrence of a symbol error is most possible in the digital wireless communication system.

(2) The bandwidth of APD measuring receiver is equal to the signal bandwidth of the affected wireless system.

(3) The system noise level of the APD measuring equipment is equal to the system noise level of the receiver of the affected system.

(4) The receiver of the affected system employs coherent detection.

Figure 7 shows the configuration of an experiment to verify Equation (3). The electromagnetic disturbance is generated as a pulse modulation signal of the carrier frequency f_c = 2.1 GHz by a signal generator (SG2). The affected system is a W-CDMA system (carrier frequency: f_c = 2.1 GHz; SF = 4). The electromagnetic disturbance is added to the W-CDMA transmission signal generated by another signal generator (SG1). The signal subject to interference is analyzed with a vector signal analyzer (VSA) for modulation analysis (coherent detection) to obtain BER. On the other hand, the W-CDMA communication system is isolated when measuring the APD of the electromagnetic disturbance, and the electromagnetic disturbance signal is input into the spectrum analyzer for disturbance measurement. The system noise of the spectrum analyzer is adjusted in advance to equal the system noise of the VSA in BER measurement. The resolution bandwidth (RBW) of the spectrum analyzer for the disturbance measurement at 1 GHz or greater is specified as 1 MHz[1], so this value is used in this experiment. This means that assumption (2) stated above is not satisfied.

Figure 8 shows the results of APD measurement of electromagnetic disturbance. Figure 9 shows the results of BER degradation measurement of the affected W-CDMA system. The pulse width and the height of the electromagnetic disturbance is set at W_p =100 μs and A_p =55 dBμV, respectively, and the duty ratio is varied as 40% (open circle), 10% (inverse triangle), 4% (open triangle), 1% (open diamond), 0.4% (open square), and 0.1% (star). Figure 9 also shows the results of BER estimation as a solid line, as obtained from the results of APD measurement based on Equation (3). Considering that the estimation by

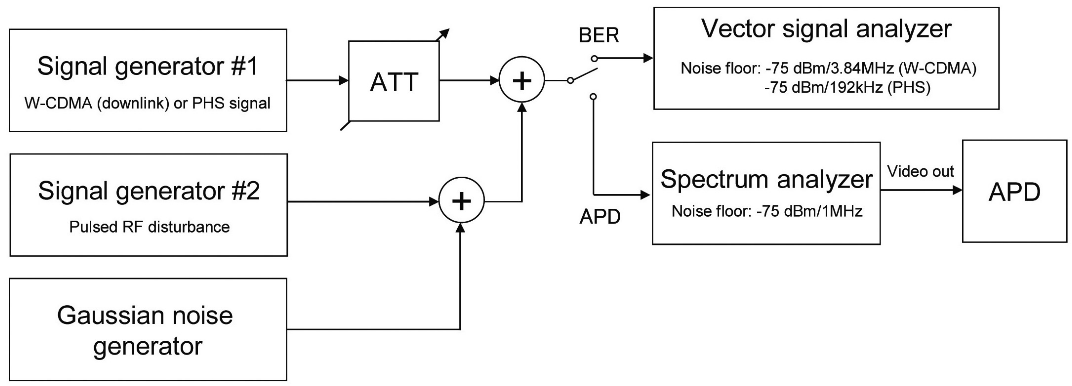

Fig.7 Configuration of the validation experiment for the theoretical correlation relationship between APD of the electromagnetic disturbance and BER degradation of the affected digital wireless communication system

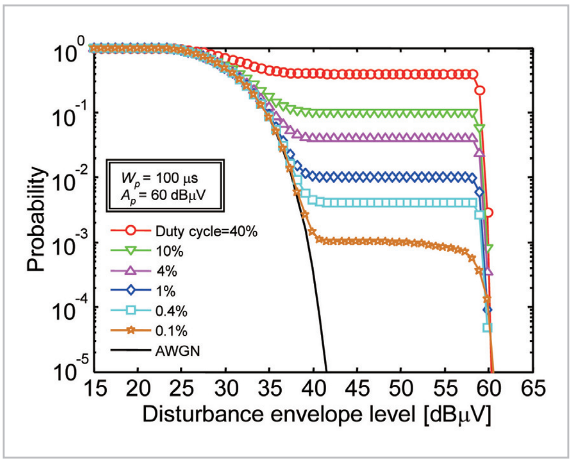

Fig.8 Results of APD measurement for electromagnetic disturbance (pulse modulated)

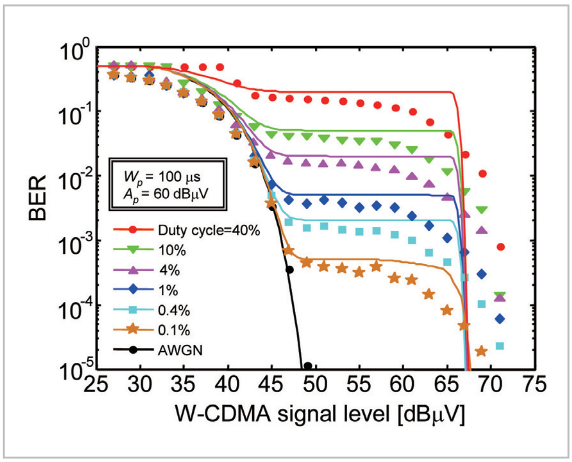

Fig.9 Results of BER degradation of the affected W-CDMA system and the estimated values

Equation (3) corresponds to worst-case conditions, the estimation of BER degradation based on APD measurement is adequate compared with the results of BER measurement. It is clear that Equation (3) uniquely correlates the results of APD measurement of the electromagnetic disturbance and BER degradation of the affected digital wireless communication system. For a more strict validation, one needs to perform experiments on communication methods other than W-CDMA systems and to use actual (not experimentally prepared) electromagnetic disturbance.

4 Application of APD (1)—Regulation of electromagnetic disturbance emitted from ISM equipment—

The previous section showed the correlation between APD measurement of electromagnetic disturbance and BER degradation of the affected system. As an application example of APD measurement based on the correlation characteristics, this section introduces the regulation of electromagnetic disturbance emitted from industrial, scientific, and medical (ISM) equipment.

CISPR11[3] specifies the method of measurement and the limits on electromagnetic disturbance emitted from ISM equipment. More specifically, the regulation stipulates peak measurement at RWB =1 MHz and VBW (video band width) of ≥1 MHz, and weighted measurement at RWB=1 MHz and VBW=10 Hz. This requirement specifies the limits for these quantities in each frequency band. Microwave ovens are the most common items of ISM equipment. The electromagnetic disturbance emitted from microwave ovens consists of irregular pulse noise, and peak measurement and weighting measurement alone cannot sufficiently describe the characteristics of such disturbance. For example, when the duty ratio of the measured signal is low, peak measurement overestimates the effects of the disturbance on the affected system. Weighted measurement, on the other hand, tends to underestimate these effects. Further, it is difficult to interpret the actual physical significance of the values obtained in weighted measurement, as these are represented as logarithmic means. These values also pose a problem in that they are significantly influenced by system noise in the disturbance measuring equipment.

On the other hand, APD measurement, which contains statistical amplitude information for electromagnetic disturbance and which is correlated with BER degradation of the affected system, is considered to be an effective measuring method in regulating electromagnetic disturbance from ISM equipment. The problem here lies in determining the limits of the electromagnetic disturbance from ISM equipment. There are two points of view on this matter. One involves establishing limits in view of protecting user equipment using digital wireless communication in the surrounding area, and the other views these limits in light of consistency with the limits of the current peak and weighted measurements. Here we consider the APD limits for ISM equipment from both of these points of view.

First, let us determine APD limits based on Equation (3) using the receiver sensitivity required for the user equipment of digital wireless communication services. Here we take user equipment for W-CDMA and PHS systems as examples. Table 1 shows the respective system specifications: parameters α and β and the receiver sensitivity required for the user equipment[11][12].

Table 1 *Specifications of W-CDMA and PHS*

	Modulation scheme	α	β	Transmission speed	Bandwidth	Antenna gain	Reference level	
W-CDMA Measurement channel	QPSK	0.5	1	12.2 kbps	3.84 MHz	0 dBi	BER < 10^{-3}	-106.7dBm /3.84MHz
PHS	π/4-shifted DQPSK	0.5	0.54	384 kbps	288 kHz	4 dBi	BER < 10^{-2}	16 dBμV

We can determine the degree of electromagnetic disturbance that satisfies the required sensitivity of the user equipment as a single point on the APD, based on the following equation derived from Equation (3).

$$\left[\text{Electric field strength, probability}\right]_{\text{APD\_required}} = \left[FL_s\sqrt{\alpha\beta^2 \cdot SF},\ \frac{BER_r}{\alpha}\right] \tag{4}$$

Here, F is the antenna factor, and L_s is the specified communication signal level for guaranteeing the required value of BER (BER_r). The solid stars in Fig. 10 indicate the points estimated from Equation (4) for the W-CDMA and PHS systems.

On the other hand, Table 2 shows the currently effective limits[3] in the frequency range of 1 GHz to 2.3 GHz, as an example.

Table 2 *Electromagnetic radiation disturbance limits for microwave ovens (1 GHz to 2.3 GHz, in the direction of maximum radiation, at 3 m)*

Peak measurement	92 dBμV/m
Weighted measurement	60 dBμV/m

The two dashed lines in Fig. 10 indicate these limits on APD. If the radiation from a microwave oven exceeds these limits (the grey zone in the figure), the microwave oven does not pass the conformance test.

The figure also indicates the results of APD measurement for six microwave ovens (distance: 3 m; bandwidth: 1 MHz) in solid lines with open symbols, and the results of APD measurement with the microwave ovens switched off are indicated by solid lines and closed symbols. All microwave ovens are confirmed to be below the currently effective limits. On the other hand, the points determined to satisfy the reference sensitivity requirements of the wireless user equipment (solid star) are extremely severe compared to actual radiation levels. These requirements demand levels of regulated disturbance lower than the system noise of the APD measuring equipment. However, it is necessary to establish a level margin due to the distance between the microwave oven and the user's wireless communication equipment and also due to the spatial and time densities of use. We plan to determine the final limits by taking into consideration the reference sensitivity of user equipment for major digital wireless communication services other than W-CDMA and PHS systems and to propose international standards accordingly.

5 Application of APD (2) — Evaluations of internal noise interference in user digital wireless communication equipment —

The discussion of APD measurement is not restricted to the matter of international standards; the industrial sector is also considering applying this method of measurement. NICT and Taiyo Yuden Co., Ltd. are working

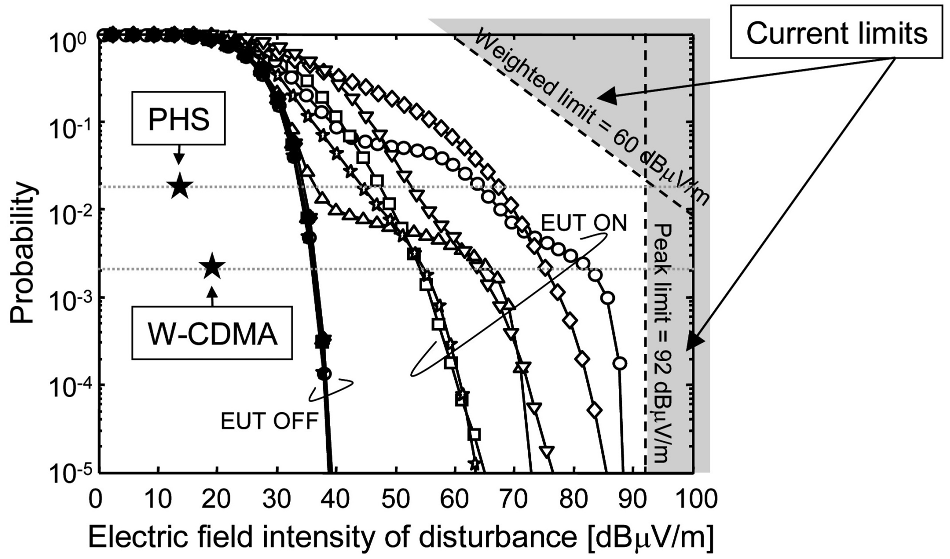

Fig.10 *Consideration of the APD limits of electromagnetic disturbance emitted from ISM equipment*

together on the development of an EMC evaluation method based on APD measurement for electronic components in user equipment. This represents a new approach to solving the problem of internal noise interference in user digital wireless communication equipment.

Internal noise interference is a phenomenon through which the electromagnetic disturbance generated in an electronic device causes degradation in its own performance. Generally, this consists primarily of conductive noise due to electromagnetic coupling between the noise source and the body of the user device or other internal circuits. However, in user wireless communication equipment, BER degradation may also occur due to radiation noise from the electronic components in the equipment itself, as the antenna near the noise source picks up this noise. To eliminate this type of problem, it is important to perform EMC evaluation for each electronic component constituting the digital wireless communication equipment. Such an evaluation is also industrially advantageous in that the manufacturers of the electronic components can guarantee the reliability of their products and distinguish differences in performance relative to the products of other manufacturers. However, the electromagnetic disturbance from electronic components generally consists of non-stationary noise at relatively low intensities. Thus, it is difficult to measure this noise, and an appropriate evaluation method has yet to be established. As it has already been confirmed that BER degradation can be estimated based on the results of APD measurement of external noise, it is expected that APD measurement will also prove effective in internal noise interference evaluation, including BER degradation evaluation for user equipment.

Figure 11 shows the two-dimensional distribution of radiation noise on the LCD control board in a personal digital cellular phone[13]. APD measurement was performed at each point within the two-dimensional space by moving a loop antenna on the board. The figure shows the levels of radiation noise with time probabilities of 10^{-2}, 10^{-3}, and 10^{-4}, as colored maps. The upper figure corresponds to the case in which the LCD displays a still image and the lower figure corresponds to the case in which the LCD is displaying a moving image. S-shaped noise distribution is clearly observed in the measurement with the moving picture display while it is only barely observed with the still image display. These measure-

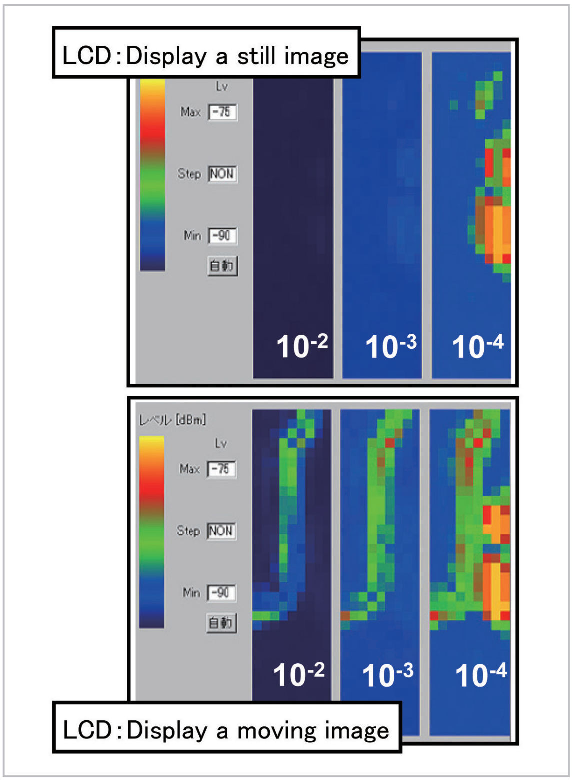

Fig.11 *Radiation noise distribution on the LCD control board in a personal digital cellular phone(Taiyo Yuden Co., Ltd.* [13] *)*

ments and visualization of the results allow us to identify the noise source and to study the conditions under which the noise is generated. These results are useful in designing internal circuits. In the future, we will study the degree of influence of the radiation noise from the electronic components in user equipment on the communication quality of the equipment. We will attempt to establish a method for evaluating the electronic components, which is directly linked to the effectiveness of EMC measures.

6 Conclusions

This article introduces recent research trends regarding APD measurement. The correlation between APD measurement and BER degradation of the affected digital wireless communication system is theoretically and experimentally demonstrated, and prototype measuring equipment is developed. It can be concluded that the APD measurement is an effective method of measuring electromagnetic disturbance in the age of digital wireless communications. The specifications of APD measuring equipment are already planned for issuance as an international standard. In the future, it will be necessary to establish a procedure for APD measurement and APD limits in the regulation of electromagnetic disturbance. Studies on industrial applications are also viewed as effective means of promoting further use of APD measurement.

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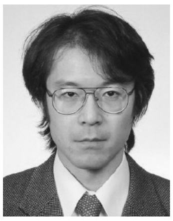

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