Memoirs of the Faculty of Engineering, Okayama University, Vol.37, No.1, pp.51-62, November 2002

Pulse Timing Control of Multiple Signal Interconnections for Reduction of EMI

Akihiro NAMBA[1), *], Yoshitaka TOYOTA[2)], Osami WADA[1)] and Ryuji KOGA[1)]

[1)] Graduate School of Natural Science and Technology, Okayama University
[2)] Departement of Communication Network Engineering, Okayama University
3-1-1 Tsushima-naka, Okayama 700-8530, Japan

(Received October 7, 2002)

This paper presents pulse timing control method to reduce electromagnetic emission from multiple signal interconnections. Pulse timing control gives intentional skew between signals. Higher order harmonics are canceled because of the difference of the phase between the signals. Using this property, pulse timing control can reduce the EMI in wide frequency range. In this paper, we show that radiated electromagnetic field from multiple signal lines reduces its intensity to the same level of the field from one line by using pulse timing control. The result of measurement shows that EMI from four differential transmission lines can be reduced more than 9 dB in the 200 MHz to 800 MHz frequency range.

1 INTRODUCTION

The operation speed of an electric device is rising increasingly by progress of technology. The high frequency ingredient contained in the signal on a print circuit board or a cables, connected between equipments, is also increasing. In connection with the rise of such signal frequency, the level of electromagnetic interference (EMI) generated by an electric device also increases, and the bandwidth also spreads out.

In order to increase data transmission rate, many parallel signal lines may be used. In this paper, authors introduce the pulse timing control method. This is a method of reducing EMI radiated from the parallel signal system which is performing synchronous operation. Pulse timing control is the method of canceling the higher order harmonics ingredient of EMI by giving a skew between channels, and EMI decreases.

The spread spectrum clock generation (SSCG) is used as a method of reducing EMI by modulating the timing of a signal. SSCG is the method of extending the energy of a signal to wider frequency range than an EMI receiver's bandwidth by modulating a clock signal, and reducing EMI [1, 2]. However, since SSCG gives a jitter to the clock used as a timing standard, it may have a bad influence on synchronous operation [3]. Moreover, SSCG modulates a clock signal, and is only reducing the spectrum level, and the radiation itself is not reduced in essence. On the other hand, pulse timing control cancels

*E-mail namba@dev.cne.okayama-u.ac.jp

actual electromagnetic field and reduces EMI by the phase difference between channels. Moreover, if skew compensation is performed just before a receiving IC, it does not have any bad influence on synchronous operation.

This paper shows the basic principle of the EMI reduction. Skew is given between parallel signals at regular intervals as the simplest example of pulse timing control. The experimental result of the far field cancellation is demonstrated using an interconnection of printed circuit boards with four differential lines. When skew of 1ns was given and pulse timing control was performed between channels, EMI was reduced by 9 dB or more in the 200 to 800 MHz frequency range. Moreover, the design parameters of skew needed for the pulse timing control are formulated, and it is shown that the determination of the frequency range and the amount of EMI reduction is possible with the design parameters.

2 THE BASIC PRINCIPLE OF PULSE TIMING CONTROL

Pulse timing control utilizes a skew between channels, and reduce EMI by canceling higher order harmonic fields from multiple signal lines which have phase differences due to the given skew.

Hereafter, the pulse timing control performed to two lines or to many lines are explained. Although actual EMI is composition of the electromagnetic wave generated from each channel, if the transmission characteristics and radiation property of each channel are assumed to be equal to each other in a linear system, EMI is proportional to the superposition of voltage of all the transmission lines. Then, summation of the voltage waveforms of all channels is considered as a measure of EMI in the following discussion.

2.1 Harmonics Cancellation for Two Lines

As shown in Fig. 1, two waveforms $v_1(t)$,$v_2(t)$ with skew between channels are considered. These waveforms are presupposed that they are the same in waveform except for the skew existing between channels; i.e. $v_2(t) = v_1(t - t_s)$. Then, if the two waveforms are added, the result will be written as the following formula:

$$\begin{aligned} v_{\mathrm{add}}(t) &= v_1(t) + v_2(t) \\ &= v_1 * \{\delta(t) + \delta(t - t_s)\} \end{aligned} \qquad (1)$$

where $*$ is the convolution operator. $\delta(t)$ and $\delta(t - t_s)$ are the impulses showing the timing of start raising. The added waveform is expressed by a convolution of a basic waveform $v_1(t)$ and a impulse sequence $\delta(t) + \delta(t - t_s)$.

By carrying out the Fourier transformation of equation (1), the Fourier integration of $v_{\mathrm{add}}(t)$ is represented as follows:

$$V_{\mathrm{add}}(f) = V_1(f)\{1 + \mathrm{e}^{-\mathrm{j}2\pi f t_s}\}, \qquad (2)$$

where $V_{\mathrm{add}}(f)$ and $V_1(f)$ are the Fourier integration of $v_{\mathrm{add}}(t)$ and $v_1(t)$, respectively. An absolute value of $\exp(-\mathrm{j}2\pi f t_s)$ is 1 and a phase changes with frequency f and skew t_s. Thus, at the following frequency where $\exp(-\mathrm{j}2\pi f t_s) = -1$, or

$$f = (2m + 1)/2t_s, \qquad (3)$$

it is set to $V_{\mathrm{add}}(f) = 0$. And at the following frequency where $\exp(-\mathrm{j}2\pi f t_s) = 1$, or

$$f = m/t_s, \qquad (4)$$

it is set to $V_{\mathrm{add}}(f) = 2V_1(f)$, where $m = 0, 1, \cdots$. When the skew between channels is zero (i.e.

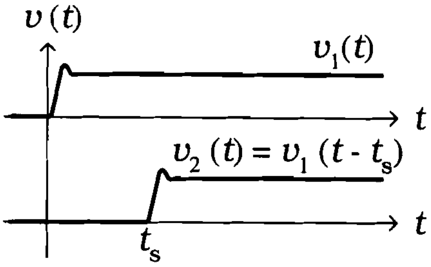


Figure 1: Waveforms with skew between channels (2 lines).

$t_s = 0$), $V_{add}(f)$ is not dependent on frequency and is always $2V_1(f)$. These mean the following thing. A higher order frequency ingredient is cancelled at the frequency where the phase difference between channels is in opposite phase, and the ingredient doubles its amplitude at the frequency where the phase is in the same.

Fig. 2 illustrates the spectrum $V_{add}(f)$ of the addition waveform when being referred to as $V_1(f) = 1$V and skew $t_s = 0$ ns, 1 ns. The solid line represents the spectrum when 1 ns skew is given to the signal, and the broken line represents the spectrum when no skew is given to the signal. When no skew is given, the spectrum is not dependent on frequency and is always 6 dBV(2 V). However, by giving 1ns skew, the spectrum of an addition waveform becomes zero at 500 MHz because of the opposite phase between signals.

When a skew is given to two lines, the large reduction effect appears only near the frequency of $1/2t_s$. Fig. 2 shows that the frequency range where the reduction by the skew is larger than 6 dB is from 333 MHz to 666 MHz, and the width is as narrow as 333 MHz. In the following section, a method that the spectrum of a superposed waveform is reduced over wide bandwidth is examined by giving various skews between lines.

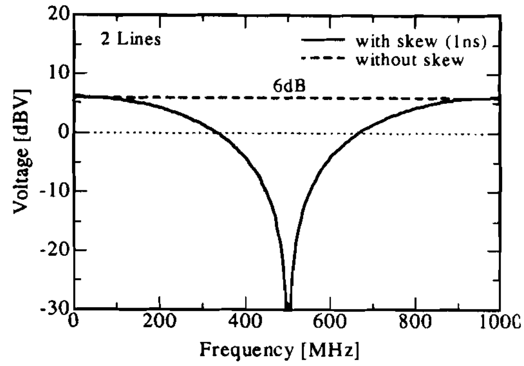


Figure 2: The synthetic voltage spectrum of 2 lines.

2.2 Harmonics Cancellation for Many Lines

The signals of n channels as shown in Fig. 3 are considered, and the skew to the channel 1 of the channel i is set to t_{si}. It is assumed that the waveform of each channel is the same waveform except for the skew. That is, the voltage waveform of the channel i is $v_i(t) = v_1(t - t_{si})$. If the total $v_{add}(t)$ of all the channels is considered, the added voltage waveform $v_{add}(t)$ can be expressed as follows by the convolution of $v_1(t)$ and $\sum_{i=1}^{n} \delta(t - t_{si})$,

$$v_{add}(t) = \sum_{i=1}^{n} v_i(t) = v_1(t) * \sum_{i=1}^{n} \delta(t - t_{si}). \quad (5)$$

The skews between neighbering channels are given at equal intervals. The skew t_{si} of the channel i is written as $t_{si} = (i-1)t_s$, and the Fourier integration $V_{add}(f)$ of $v_{add}(t)$ can be written as follows:

$$V_{add}(f) = V_1(f) \sum_{i=0}^{n-1} (e^{-j2\pi f t_s})^i. \quad (6)$$

Since the above equation is the sum of the geometric series having the first term $V_1(f)$ and

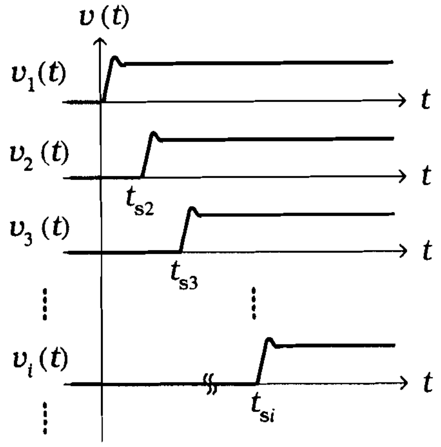


Figure 3: The waveform with skew between channels (many lines).

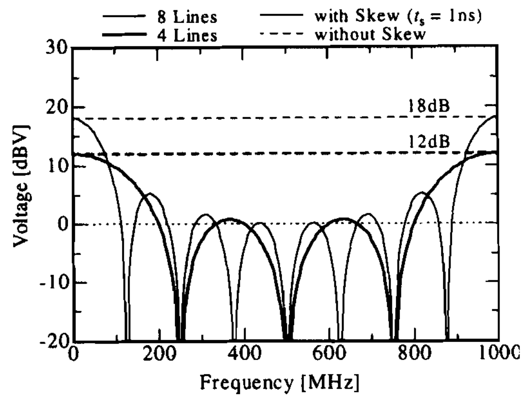


Figure 4: The synthetic voltage spectrum of many lines.

the common ratio $\exp(-j2\pi f t_s)$, it can be transformed as follows:

$$V_{add}(f) = V_1(f)\frac{1-e^{-j2\pi f n t_s}}{1-e^{-j2\pi f t_s}}, \qquad (7)$$

where $\exp(-j2\pi f t_s) \neq 1$, that is $f t_s \neq m$, $(m = 0, 1, \cdots)$. When $f t_s = m$, $V_{add}(f) = nV_1(f)$.

An equation (7) is transformed as follows:

$$V_{add}(f) \;=\; V_1(f)e^{-j\pi f(n-1)t_s}\frac{\sin \pi f n t_s}{\sin \pi f t_s}. \qquad (8)$$

The absolute value of the spectrum of the added waveform can be expressed by two sinusoidal functions as the following equation:

$$|V_{add}(f)| = |V_1(f)|\left|\frac{\sin \pi f n t_s}{\sin \pi f t_s}\right|. \qquad (9)$$

The absolute value of the voltage spectrum is shown in Fig. 4 when substituting $V_1(f) = 1$ V, $n = 4$ or 8, and $t_s = 1$ ns in the equation (9). When no skew is given between channels, the voltage spectrum becomes constant and is n times larger than the spectrum of a channel 1. Thus, the level is 4 V(12 dBV) in the case of 4 lines, and the level is 8 V(18 dBV) in the case of 8 lines. On the other hand, when the skew of 1ns is given, the reduction effect of 10 dB or larger appears in the wide band from 200 MHz to 800 MHz. Near 500 MHz where the reduction effect is the largest, the total voltage spectrum intensity is about 1V(0 dBV), and this intensity is equal to the voltage spectrum intensity driven only by one line.

Then the amount of reduction of the added voltage spectrum by giving skew is described. Since the added voltage spectrum is $nV_1(f)$ when no skew is given between channels, the amount of reduction of the voltage spectrum by giving skew is defined as the following:

$$\begin{aligned} R(f) &= -20\log\frac{|V_{add}(f)|}{n|V_1(f)|} \\ &= 20\log\left|\frac{n\sin \pi f t_s}{\sin \pi f n t_s}\right| \ [\text{dB}], \end{aligned} \qquad (10)$$

where $R(f)$ is the amount of reduction. The equation (10) is valid when $f t_s \neq m$, $(m = 0, 1, \cdots)$. In the case of $f t_s = m$, $R(f)$ is set to be 0 dB.

The amount of reduction of the total spectrum by applying the pulse timing control is illustrated in Fig. 5. It is calculated with equation (10) for skew $t_s = 1$ ns, the number of lines

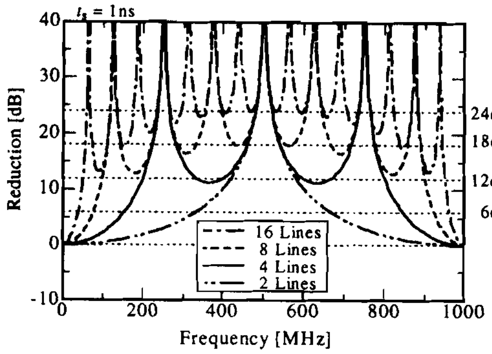


Figure 5: The amount of reduction of a synthetic voltage spectrum.

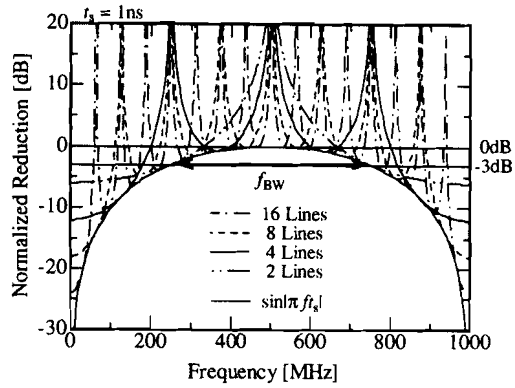


Figure 6: The amount of normalization reduction of a synthetic voltage spectrum.

n = 2, 4, 8, or 16. Fig. 5 shows that the reduction effect is getting larger when the number of lines increases, and the effective frequency range is also getting wider.

In this section we explain the principle of the pulse timing control by considering the spectrum of total voltage. EMI generated from many lines can be explained similarly. The pulse timing control is the method to reduce EMI using the property that the spectrum of composed waveform is cancelled due to the skew in wide frequency range.

3 The design parameters for pulse timing control

In this section we consider the frequency bandwidth of the reduction effect, which is one of the design parameters when pulse timing control is applied to the system.

The equation (10), which describes the amount of reduction of the voltage spectrum by pulse timing control, is transformed to the following expression,

$$R(f) = 20\log n + 20\log|\sin\pi f t_s| - 20\log|\sin\pi f n t_s| \text{ [dB]}. \quad (11)$$

Since $0 \leq |\sin\pi f t_s| \leq 1$ and $0 \leq |\sin\pi f n t_s| \leq 1$, the second and the third terms are evaluated to be $20\log|\sin\pi f t_s| \leq 0$ and $20\log|\sin\pi f n t_s| \leq 0$. Moreover, $20\log|\sin\pi f t_s|$ and $20\log|\sin\pi f n t_s|$ change their values periodically with frequency f from $-\infty$ to 0 at intervals of the frequency of $1/t_s$ and $1/nt_s$, respectively. Therefore, outline of the amount of reduction is expressed by the first and the second terms in the right side of equation (11), and the third term expresses the repetition for every frequency interval $1/nt_s$. Moreover, it is shown that the amount of the maximum reduction is $20\log n$[dB], and the total voltage spectrum is set to $1/n$ by performing pulse timing control. That is to say, the total voltage spectrum falls to the spectrum level for one line.

The amount of reduction of the voltage spectrum is normalized with the value of the maximum reduction $20\log n$, and is shown in Fig. 6, where t_s = 1 ns and $n = 2, 4, 8, 16$. The thin solid line in Fig. 6 shows the calculation result of $\sin|\pi f t_s|$. Fig. 6 shows that the envelope of the amount of normalized reduction is $\sin|\pi f t_s|$ and the envelope is not a function of the number of lines n. The bandwidth f_{BW} is defined as the

Table 1: The design parameters of pulse timing control.

center frequency f_c	$(2m+1)/2t_s$
-3 dB bandwidth f_{BW}	$1/2t_s$
-3 dB Reduction frequency range	$1/4f_s \sim 3/4f_s$
maximum reduction	$20\log n$[dB]

frequency range in which the reduction falls by 3 dB from the maximum of an envelope $\sin|\pi f t_s|$. And the center frequency f_c is defined as the frequency at which an envelope $\sin|\pi f t_s|$ has the maximum value. The bandwidth f_{BW} and the center frequency f_c are as follows, respectively

$$f_{BW} = \frac{1}{2t_s} = \frac{1}{2} f_s, \quad (12)$$

$$f_c = \frac{2m+1}{2t_s} = \left(m + \frac{1}{2}\right) f_s, \quad (13)$$

where f_s is the frequency decided by skew t_s, i.e. f_s is $f_s = 1/t_s$, $(m = 0, 1, \cdots)$. The frequency range in which the amount of reduction becomes more than $20\log n - 3$[dB] is $(m+1/4)f_s$ to $(m+3/4)f_s$.

The center frequency, the bandwidth, the reduction frequency range, and the amount of the maximum reduction are collectively shown in the table 1. These parameters are the design indices of the pulse timing control. What is necessary is just to decide skew t_s from the design parameters shown in the table 1, and all the characteristics of the pulse timing control is determined.

In this section, we have considered the case when the skew between channels was given at equal intervals. The frequency range in which the large reduction effect appears is comparatively narrow, because the amount of reduction is expressed by the sinusoidal function when a skew is given at equal intervals. It is expected that larger reduction effect may be acquired in wider frequency range by optimizing the skew given to each channel.

4 MEASUREMENT RESULT OF FAR ELECTRIC FIELD

4.1 Measurement Settings

Far electric field measurement of the four differential interconnection lines with PCBs shown in Fig. 7 was performed. This system consists of a transmitting board and a receiving board which are double-sided boards, and un-shield twisted pair (UTP) cable (category 5; characteristic impedance:100Ω) with a length of 1m connecting these boards. As shown in Fig. 8, the terminal load of each differential line is 100Ω(= 50Ω × 2) resistance, mounted on the receiving board. In addition, the ground plane of the receiving board is not connected to the system ground.

Far electric field measurement was performed in a semi-anechoic chamber at Okayama University. As shown in Fig. 9, EUT was positioned horizontally at 1 m height from the floor, and the receiving antenna was located at the horizontal distance of 3 m from the EUT, and at the height of 1 m or 3 m. The transmitting board was driven with a data generator installed under the ground floor as shown in Fig. 10, and the far electric field was measured when setting up skew t_s between channels of 0 ns, 0.85 ns and 1 ns. The specifications of the generator are shown in Table 2, and conditions of far electric field measurement are shown in Table 3.

4.2 Input Voltage

Far electric field measurement was performed with the two boards system connected with four differential lines. In the ideal differential signal-

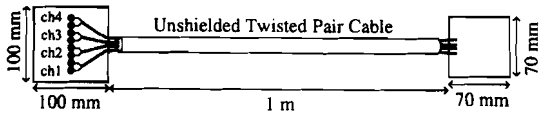


Figure 7: Four differential interconnection lines with PCBs (two double-sided boards;the back sides are whole GND planes).

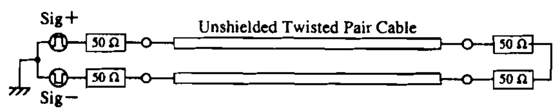


Figure 8: The equivalent circuit of the differential line.

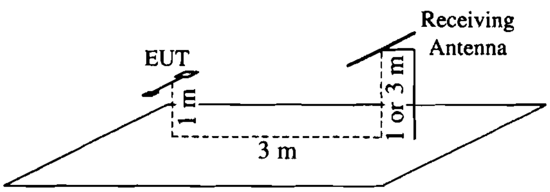


Figure 9: The location of EUT and the antenna in the far electric field measurement.

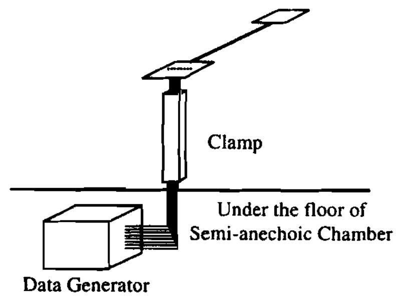


Figure 10: Connection of the generator and the board.

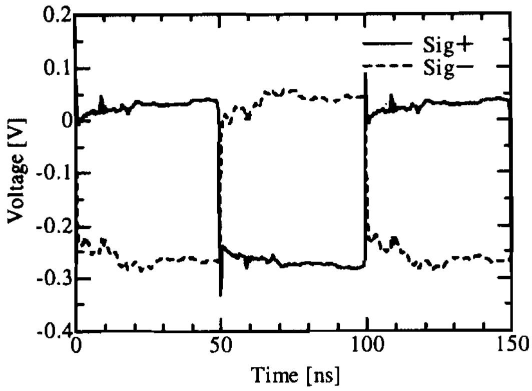
ing system, EMI generated from a differential line is small. However, in an actual differential signaling system, common mode current is generated on the differential line due to asymmetry of a drive circuit or a line, therefore, EMI increases. In order to simulate the asymmetry of these differential transmission systems, common mode current was generated by giving skew of 0.3 ns between signal + and signal − of each differential line in the measurement as shown in Fig. 11. The common mode emission radiated from the four differential lines was reduced by pulse timing control, and it tried to decrease EMI.

4.3 Mesuerment Results

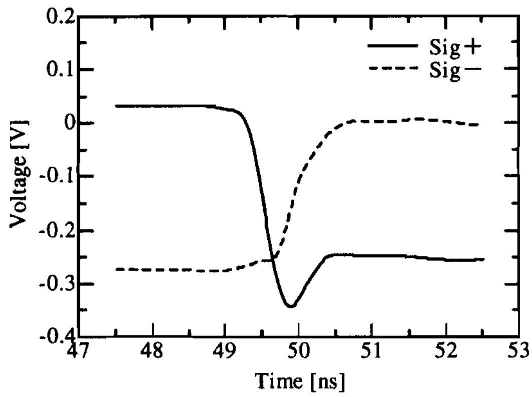
The measurement result with the receiving antenna at the height of 1 m is shown in Fig. 12, and the measurement result with the antenna height of 3 m is shown in Fig. 13. Each figure (a) shows the far electric field intensity for different skew, and each figure (b) shows the amount of reduction of the far electric field intensity compared to the level at zero skew. The comparison of measurement results and calculation results are shown in Fig. 14; Fig. 14 (a) is a result for $t_s = 0.85$ ns of skew, and Fig. 14 (b) is a result for $t_s = 1$ ns.

Fig. 12 and Fig. 13 show that the far electric field spectrum from 200 MHz to 800 MHz is reduced by 5 dB to 10 dB when the skew between channels is given. Although the amount of reduction is small near the frequencies of 250 MHz, 490 MHz, and 770 MHz, it is because the level of a far electric field is low even when the skews is zero, and the dynamic ranges of the measurement is not enough in such frequency range and the amount of reduction is not measured correctly.

Fig. 12 shows the measurement result with a receiving antenna of 1 m height, and Fig. 13 shows the result with the antenna of 3 m height. Since the interference of a direct wave and a floor reflection wave changes with antenna height, the profile of a far electric field spectrum shown in Fig. 12(a) and Fig. 13(a) also changes with antenna height. However, Fig. 14 shows that if the



(a)



(b)

Figure 11: Input Voltage waveform. (a) The whole. (b) The scaled-up.

given skew is the same, it is not concerned with antenna height but the amount of reduction is equal. This means the following result. The common mode current which flows on the cable, which is a source of radiation, was reduced by giving a skew.

Fig. 14 shows that the measurement and calculation results of the amount of reduction are well in agreement except for the frequencies at which far electric field intensity has dips. Although the calculated value of the amount of the maximum reduction is 12 dB, the measurement result of the amount of reduction is 10 dB. In calculation the assumption that the signal of four lines is completely the same is used. Actual difference in the real signals may be the reason why the calculated reduction is larger than the measured reduction.

Table 2: Specification of the generator

Data Generator	Hewlett Packard 81200 front-end : HP E4843A
Output Signal	frequency : 10 MHz Clock Voltage : −0.15 V ~ 0.15 V raising/falling time : 350 ps (20-80 %)

Next, the design parameters shown in table 1 are considered. The frequency range in which the reduction is larger than 9 dB is calculated from table 1. The range is from 250 MHz to 750 MHz when skew of 1ns is given, and the range is from 294 MHz to 940 MHz when skew of 0.85 ns is given. Since these frequency ranges are calculated by the envelope of reduction, the actual ranges are wider than calculated ranges. Fig. 14 shows that the actual range is from 200 MHz to 800 MHz when the skew of 1ns is given, and the actual range is from 230 MHz to 940 MHz when the skew of 0.85 ns is given. And the total EMI level in the frequency range is only 3 dB higher than the level for one line. From the above discussion, the optimum skew can be determined by using a design parameters shown in table 1.

5 CONCLUSION

In this paper, the pulse timing control is proposed to reduce radiated EMI from many parallel lines over a wide frequency range, and the following effects are demonstrated.

- The total EMI can be reduced to the same level as emission from a single line.

Table 3: The conditions of far electric field measurement

Spectrum Analyzer	Hewlett Packard E7403A
Biconical antenna	Schwarzbeck VHA 9103 20-370 MHz
Logperiodic antenna	Schwarzbeck UHALP 9108 A1 250-1000 MHz
Attenuator	Agilent Technologies 8491B 6 dB
Pre-amplifier	Hewlett Packard 8447F
Clamp	Lüthi FTC 40X15E
Board installation position	height:1 m, horizontal
Horizontal distance	3 m
Antenna height	1 m, 3 m
Measured polarization	horizontally polarization

- The amount of reduction is more than $20 \log n - 3$[dB] at the frequency range of $0.25f_s$ to $0.75f_s$, where n is the number of the lines. For example, the reduction is 9 dB for $n = 4$, and is 15 dB for $n = 8$.

The reduction effect is verified experimentally, when the skew for 1ns was given to four lines; the reduction effect was 9 dB or larger in 200 MHz to 800 MHz.

Pulse timing control is the technique of reducing EMI by giving a skew between channels. If a skew compensation circuit is inserted in a receiving system, although propagation delay will increase of several ns, the circuit design which does not affect synchronous timing operation becomes possible. In unidirectcional data communications system, it is a very effective EMI reduction method.

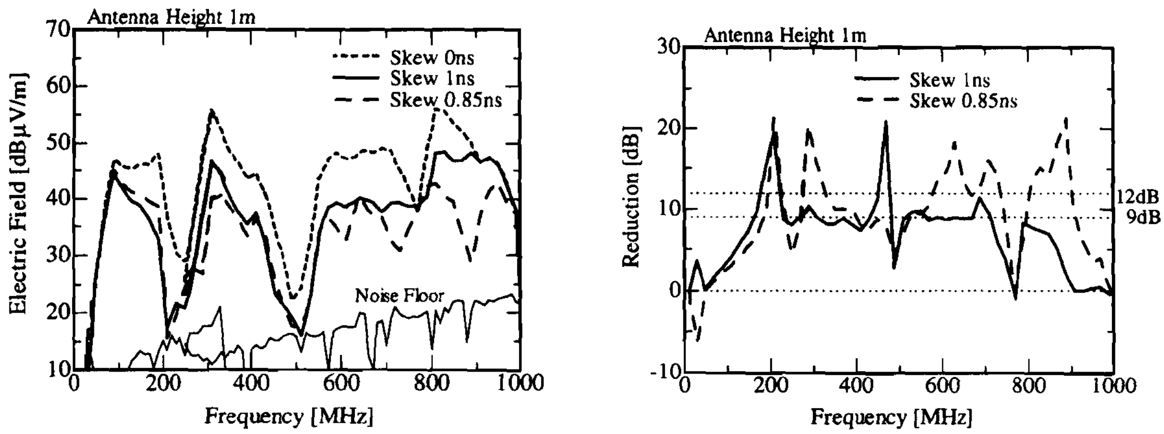
This research is supported by the Japan Society for the Promotion of Science, Research for the Future Program "Reduction of Electromagnetic Noise Levels".

REFERENCES

[1] K. B. Hardin, J. T. Fossler, D. R. Bush : Proc. of the 1994 IEEE Int. Symp. on Electromagnetic Compatibility, (1994), 227-231.

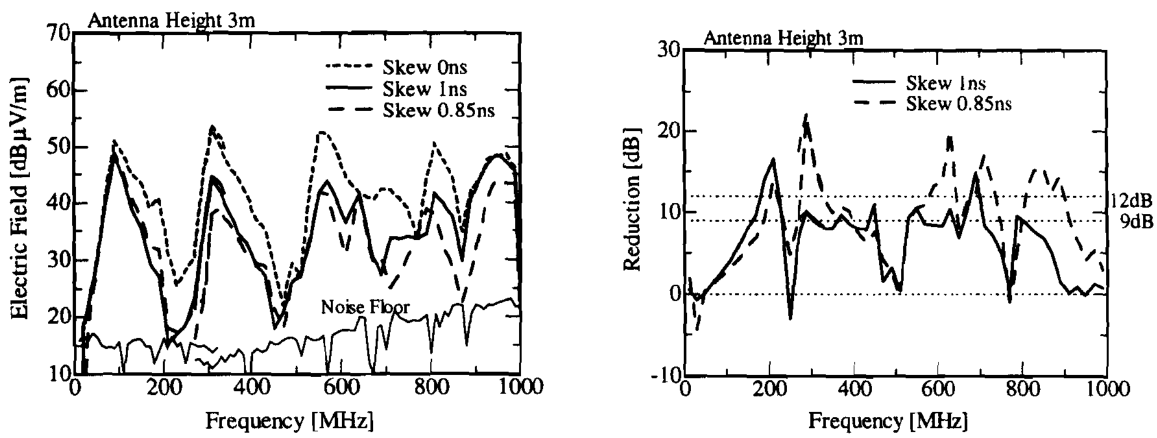
[2] Hung-Wei Chen, Jiin-Chuan Wu : IEICE Trans. Electron. vol.E84-C, no.12 (2001), 1959-1966.

[3] K. B. Hardin, J. T. Fossler, A. L. Cable, M. J. Pulley, Proc. of the 1997 IEEE Int. Symp. on Electromagnetic Compatibility, (1997), 302-307.



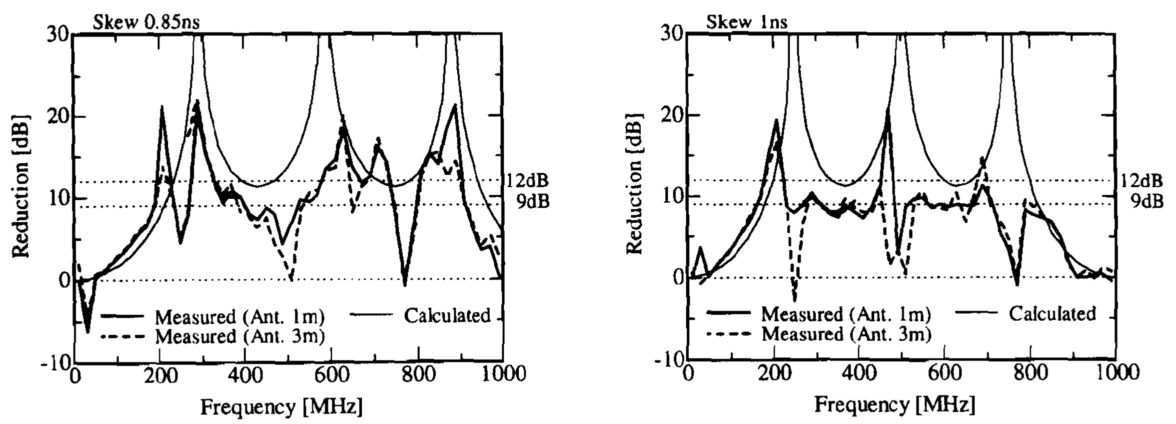
(a) (b)

Figure 12: The measurement results of far electric field at an antenna height of 1 m. (a) The spectrum of electric field. (b) The amount of reduction.



(a) (b)

Figure 13: The measurement results of far electric field at an antenna height of 3 m. (a) The spectrum of electric field. (b) The amount of reduction.



(a) (b)

Figure 14: The measurement and calculation result of the amount of far electric field reduction (a) skew 0.85 ns and (b) skew 1 ns.