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The Implementation of Group Delay Equalizer and Its Performance Evaluation for Point-to-Point Digital Radio Relay System

Kyoung-Whoan Suh

Abstract

The implementation of IF group delay equalizer and its performance are presented for radio relay system applications, and measured results are in good agreement with the simulated ones based upon analytical formulations. For waveguide filter of 40 MHz channel spacing, equalized delay accuracy of about +/− 2.0 nsec can be obtained only by constructing 4 stage delay circuits, which provides good performance in system BER curves compared with no filter case, and the difference is less than 1.0 dB at 10^{-12} BER. So this scheme with simple hardware design can be used for correcting the distorted group delays mainly caused by waveguide filters. To evaluate the designed group delay equalizer, various simulated and experimental results are shown here in conjunction with STM-1 signal of co-channel 64-QAM digital radio relay system.

Ⅰ. INTRODUCTION

With the help of state-of-the-art microwave technology, modern digital radio relay system(DRRS) has adopted the co-channel dual polarization technique. It utilizes two orthogonal polarizations with the same RF carrier for a given frequency band so as to obtain spectral efficiency as maximum as possible. So it provides a couple of transmission capacities compared with a conventional DRRS using an alternative frequency allocation. Moreover, such a technique is usually operated with 64- or 128-quadrature amplitude modulation(QAM) scheme [1]~[3] because of cost effectiveness in terms of channel bandwidth and transmission capacity. It implies that 64- or 128-QAM gives the same transmission capacity of 2×STM-1 signals per 40 or 30 MHz channel spacing, respectively.

When designing such a highly spectral efficiency DRRS, one should take into account the channel countermeasure technique for distorted signal waveforms[4]~[6]. They include not only a time-variant response caused by multi-path propagation, but also a static or time-invariant one like group delay distortion resulting from channel filter. For the dynamic channel variation called a frequency selective fading, it can be alleviated by using digitally adaptive time and frequency domain equalizers[7]~[9]. As for the frequency domain equalizer called a slope equalizer, it has only a function of making the distorted or sloped spectrum flat throughout the channel, but it does not cause the group delay itself. On the other hand, for the static channel distortion such as non-flattened group delay, it can be also removed by analog or digital group delay equalizer(GDE)[10],[11]. In consequence, it has been reported that if the system can not combat distorted signals properly, quality of service can not meet the objectives recommended by ITU-T G. 862[12].

In general, imagining a signal as a composite of

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components at difference frequencies, differential delay results in components arriving at the output at different times, causing distortion. Most of the non-flattened group delays stem from waveguide filters in the channel branching network(CBN). CBN is used for separating each channel signal from received antenna signals or vice versa, and it consists of circulators, waveguide filters and adapters. Since waveguide filter inherently produces non-flattened group delay within channel bandwidth, it brings about degraded system performance, and what is still worse, co-channel DRRS is more seriously affected due to the narrow co-channel separation and high level modems. However, this effect can be compensated by means of GDE, making the overall group delay response of each channel as flat as possible.

In this paper, in order to analyze the comprehensive GDE solutions in terms of an analytical formulation, design and synthesis, and system BER performance compared with the previous result[10], an analog group delay equalizer is suggested for DRRS applications, and the synthesis of the second-order all-pass filter and its insertion loss caused by delay circuit are also described for the practical design. The designed GDE provides a simple hardware, easy tune, and good performance even for large group delay over channel bandwidth. To evaluate the performance of GDE, a variety of results based upon simulation and experiment are shown here for STM-1 signal with co-channel 64-QAM DRRS[3].

Ⅱ. ANALYTICAL FORMULATION

2-1 Channel Group Delay

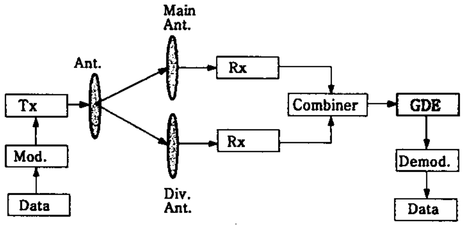

Fig. 1. Simplified digital radio relay system with space diversity.

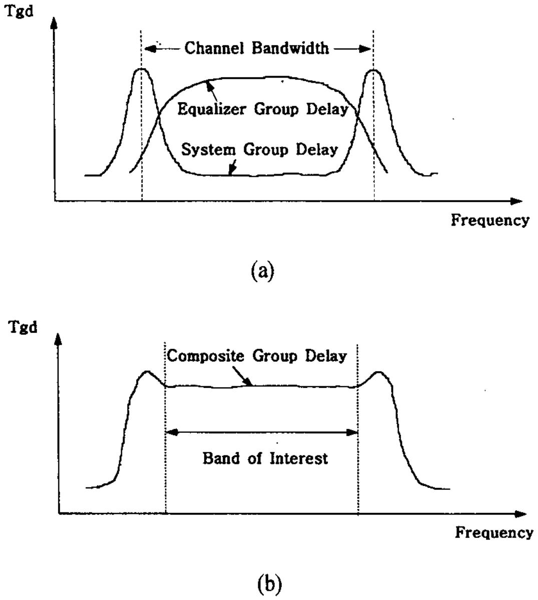

Fig. 2. Concept of group delay equalization.
(a) System and equalizer group delays,
(b) Composite group delay.

Fig. 1 shows a simplified block diagram of DRRS including group delay equalizer(GDE) in the receiver part. STM-1(155.520Mbps) signal of electrical or optical interface is input to the modulator which centers an IF signal at 70 or 140 MHz, and the modulated signal is connected to the transmitter followed by channel branching filter, orthomode transducer, and antenna. On the other hand, the received signals from main and diversity antennas are fed into main and diversity receivers, respectively and both signals are added by IF-combiner[13],[14]. Then the combined signal becomes an input of the demodulator, but the non-flattened group delays in the channel are corrected by GDE.

As the waveguide filter usually does, the group delay response shown in Fig. 2(a) indicates the maximum value at channel edges and reveals the minimum one at center. To make the group delay as flat as possible, two steps are generally performed as depicted in Fig. 2(a). First, measure a total group delay response from transmitter to receiver. Second, implement a desired group delay equalizer providing the inverse characteristic of system group delay as close as possible. Therefore the resultant output of GDE can be obtained like Fig. 2(b) with flat group delay over in-band. In consequence, the group delay equalization is to flatten the distorted group delay over in-band or symbol rate depending upon modulation scheme and input data rate. Even though the group delay deviation becomes larger and larger as frequency goes away from center to edge, but its effect on system performance may be negligible so long as non-flattened group delay lies in the out-of-symbol rate. So GDE should be carefully made such that it provides a complementary group delay with a shape inverted with respect to system delay response for symbol rate region.

2-2 Group Delay Equalizer

Fig. 3 shows a block diagram of GDE, which consists of 3 parts such as group delay equalizer, amplitude equalizer, and level detector. The non-flattened group delay in each channel can be corrected by the second-order all-pass filter called GDE[15]. To equalize the non-flattened group delay without amplitude variation, GDE should maintain an all-pass response with respect to the amplitude throughout the in-band, and it may take several stages of the second-order all-pass filter. Then the overall group delays are constructed by simply accumulating each stage group delay response. After all, it is possible to get the required group delay characteristic without any amplitude distortions. However, in fact, the group delay circuit usually causes some undesirable distortions such as gain ripple and power loss. In order to counteract those effects, it should also keep a function of amplitude equalization.

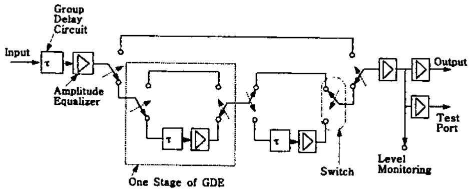

Fig. 3. Structure of group dalay equalizer.

The transfer function of the second-order all-pass filter, $T(s)$ is given by[15]

$$T(s) = k - \frac{2k\frac{\omega_r}{Q}s}{s^2 + \frac{\omega_r}{Q}s + \omega_r^2} \tag{1}$$

where ω_r and Q denote the pole resonance frequency and quality factor, respectively and k is constant. To find the group delay the phase shift β is written as

$$\beta(\omega) = -2\ \tan^{-1}\left(\frac{\frac{\omega_r}{Q}\omega}{\omega_r^2 - \omega^2}\right) \tag{2}$$

and derivative Eq. (2) to angular frequency gives the group delay equalization as

$$T_{gd}(\omega) = -\frac{d\beta}{d\omega} = \frac{2Q\,\omega_r(\omega^2 + \omega_r^2)}{Q^2(\omega^2 - \omega_r^2)^2 + \omega^2\omega_r^2}\,. \tag{3}$$

From Eq. (3) one may find the maximum and DC values are given as

$$T_{gd,\max} = \frac{4Q}{\omega_r}\,, \tag{4}$$

$$T_{gd}(\omega = 0) = \frac{2}{Q\,\omega_r}\,. \tag{5}$$

Eq.(1) may be realized with a variety of configurations based upon either passive or active all-pass filter. The passive type can be implemented with inductors, capacitors, and transformers, and the active one with operational amplifiers. However,

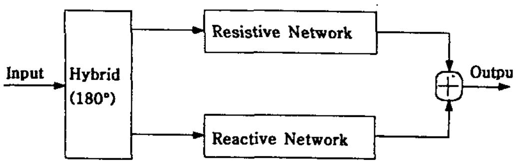

Fig. 4. Simplified block diagram of group delay equalizer.

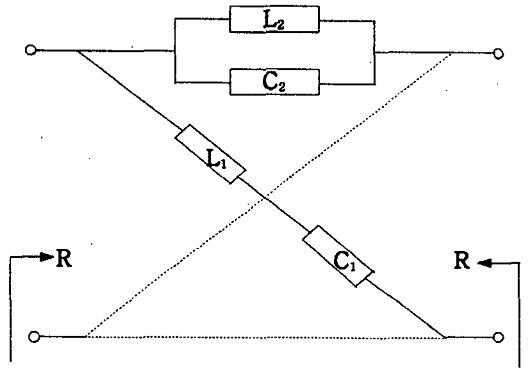

Fig. 5. Second-order constant resistance circuit.

operational amplifiers usually give some restrictions imposed by components limiting the operating frequency as well as demanding the amplitude equalizer. On the other hand, from Eq.(1) one may consider a new passive type of second-order all-pass filter. The first term in the right side is constant, so this may be regarded as the response of the resistive network, and the second term is the reactive network. Therefore, Fig. 4 shows the simplified block diagram of proposed analog GDE, which makes the simple hardware and easy tune for large variation of group delay.

Ⅲ. CIRCUIT DESIGN AND ANALYSIS

3-1 The second-order constant resistance circuit

Consider the second-order constant resistance circuit shown in Fig. 5, which is all-pass network passing all frequencies(true for high Q components) and has parabolic delay with a shape inverted with respect to the delay response of filters. Therefore, it is useful for compensating the distorted delay of filters. Fig. 5 consists of two L-C resonance circuits with series and parallel types, respectively and transfer function is given by

$$T(s)=\frac{s^2-\frac{1}{\sqrt{L_1C_2}}s+\frac{1}{L_1C_1}}{s^2+\frac{1}{\sqrt{L_1C_2}}s+\frac{1}{L_1C_1}}. \qquad (6)$$

Then the quality factor, resonance frequency, and constant resistance are also written as

$$Q=\omega_r\sqrt{L_1C_2}, \qquad (7)$$

$$\omega_r^2=\frac{1}{L_1C_1}=\frac{1}{L_2C_2}, \qquad (8)$$

$$R^2=\frac{L_2}{C_1}=\frac{L_1}{C_2}. \qquad (9)$$

3-2 Circuit Transformation

Let's transform Fig. 5 into the equivalent circuit for the quality factor Q with greater than 1 or less. Even though there are several alternative all-pass structures, two equivalent circuits has been considered in terms of simplicity. In case of Q>1, Fig. 5 may be equivalent to Fig. 6 and its parameters are related as

$$L_a=\frac{2R}{\omega_rQ}=2L_2, \qquad (10)$$

$$L_b=\frac{QR}{2\omega_r}=\frac{1}{2}L_1, \qquad (11)$$

$$C_a=\frac{Q}{\omega_rR}=C_2, \qquad (12)$$

$$C_b=\frac{2Q}{\omega_r(Q^2-1)R}=\frac{2C_2C_1}{C_2-C_1}. \qquad (13)$$

In the similar way, the equivalent circuit for Q<1 can be shown in Fig. 7 and its parameters are also given by

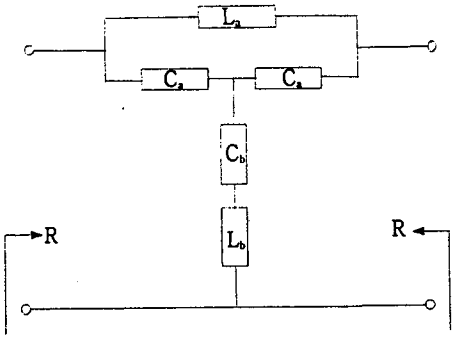

Fig. 6. Equivalent circuit of Fig. 5 for Q>1.

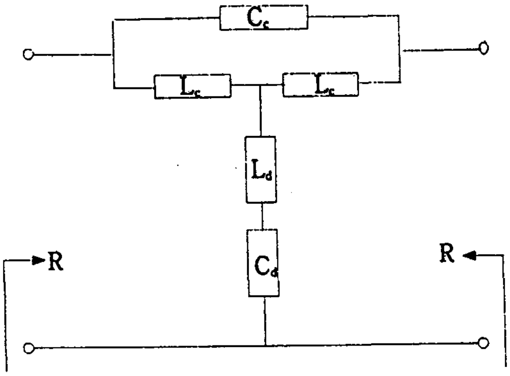

Fig. 7. Equivalent circuit of Fig. 5 for Q<1.

$$L_c = L_2, \tag{14}$$

$$L_d = \frac{1}{2} L_1, \tag{15}$$

$$C_c = \frac{1}{2} C_2, \tag{16}$$

$$C_d = 2 C_1. \tag{17}$$

Now let's consider how many stages should be taken for correcting a given non-flattened group delay. It depends on three factors such as system group delay response, in-band bandwidth, and equalizing accuracy degree. In general, a rough approximation for stage number, N is given by[10]

$$N = 2 \times \triangle_{BW} \times \triangle_{\tau} + 1 \tag{18}$$

where $\triangle_{BW}$ is the bandwidth of the interest in Hz and $\triangle_{\tau}$ is the non-flattened group delay over $\triangle_{BW}$ in second.

Table. 1. Specifications of designed GDE for transmitting STM-1 signal with 64-QAM modulation.

Items	Specifications
Input IF Frequency	70 MHz
Input Bandwidth	40 MHz
Input Power Level	-10 dBm
Output Power Level	-10 dBm ± 1dB
Input Impedence	50 ohm
Output Impedence	50 ohm
Input Return Loss	>20 dB
Output Return Loss	>20 dB
Amplitude Deviation	<+/-0.25 dB @ BW=32 MHz
Delay Deviation	<+/-2.5 nsec @ BW=28 MHz
Operation Temperature	0~50℃
Supply Voltage	$\pm 5V_{dc}$

GDE specifications we are considering are listed in Table 1, which is aimed at the distorted group delay of 64-QAM DRRS with 40 MHz channel spacing. Then this system can transmit STM-1 signal without quality degradation, which is valid only for the static distortion. Assuming that one uses higher modulation schemes like 128- or 256-QAM/TCM, the parameters such as channel spacing, amplitude and delay deviations listed in Table 1 may be changed. This means that the tolerance limits are more stringent.

Ⅳ. SIMULATED AND EXPERIMENTAL RESULTS

4-1 Simulated Results

To see how the group delay characteristics vary

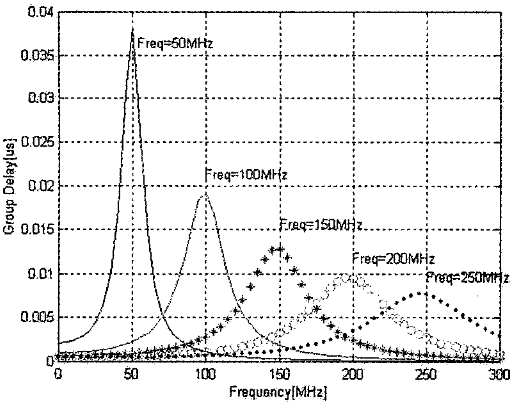

Fig. 8. Simulated results of group delay circuit as a function of resonance frequency.

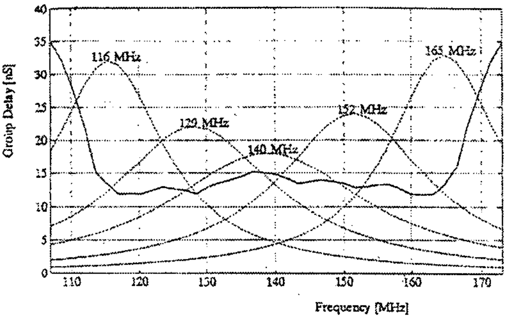

Fig. 9. Simulated results of GDE for distorted delay.

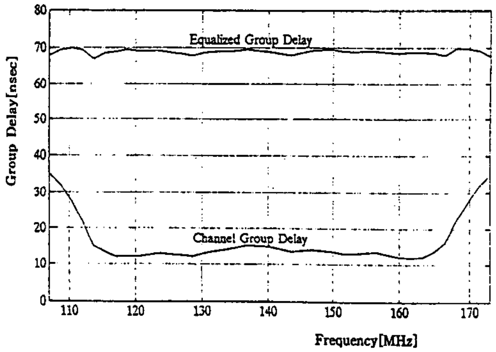

Fig. 10. Equalized group delay response for Fig. 9.

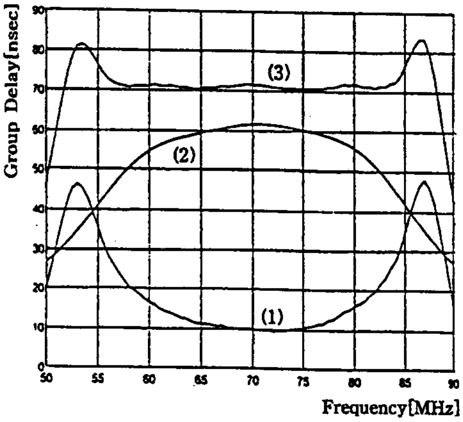

Fig. 11. Simulated group delay for DRRS channel.

from the resonance frequency, Fig. 8 presents several delay responses for Q=3. As the resonance frequency becomes larger and larger, the maximum group delay is smaller and smaller. For 80 MHz channel spacing and its waveguide filter combined with 64-QAM DRRS transmitting 2×STM-1 signals, Fig. 9 depicts the actual channel group delay noted by bold line and 5 group delay responses of which resonance frequencies are 116, 129, 140, 152, and 165 MHz, where a simulation tool of MDS is used to obtain the desired delay curves. By summing those 5 responses, the resultant group delay response can be obtained like Fig. 10, which is nearly flat enough toaccept +/− 2.5 nsec tolerance. Therefore, if channel delay characteristics are known, one may choose an optimum combination between quality factor Q and resonance frequency, which makes the flattened group delays.

As another simulation for 40 MHz channel spacing of 64-QAM DRRS, Fig.11 shows three kinds of the group delay characteristics such as waveguide filter, designed GDE, and combined GDE noted by (1), (2), and (3), respectively. It is shown that the combined group delay curve, (3) is a sum of (1) and (2). Since the group delay deviation usually permits less than +/− 2.5 nsec over 27 MHz symbol rate, the result is fairly good and acceptable, As mentioned before, even though the group delay deviation is getting larger at channel edges, but its effect is negligible because of out-of-symbol rate

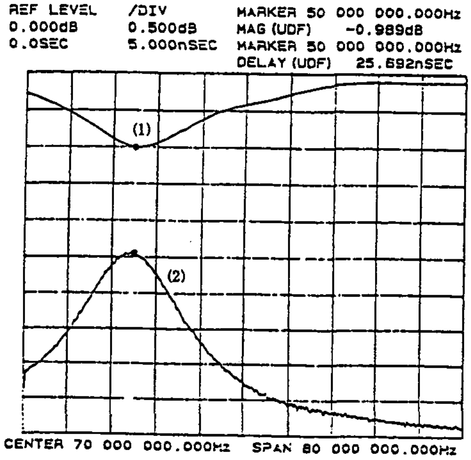

Fig. 12. Amplitude and delay responses of group delay circuit.

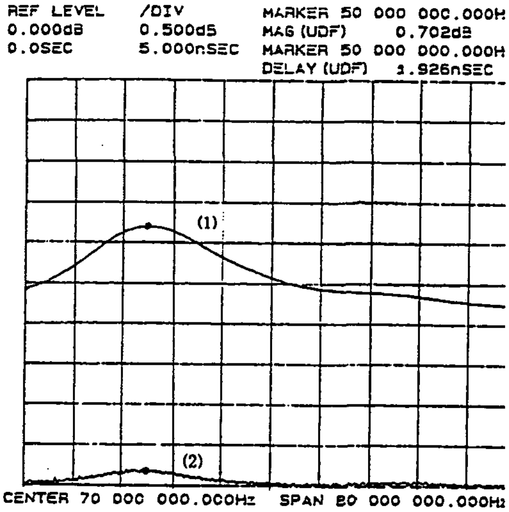

Fig. 13. Amplitude and delay response of amplitude equalizer circuit.

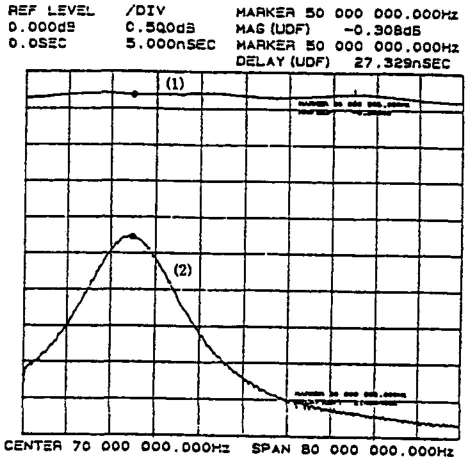

Fig. 14. Amplitude and delay response of GDE.

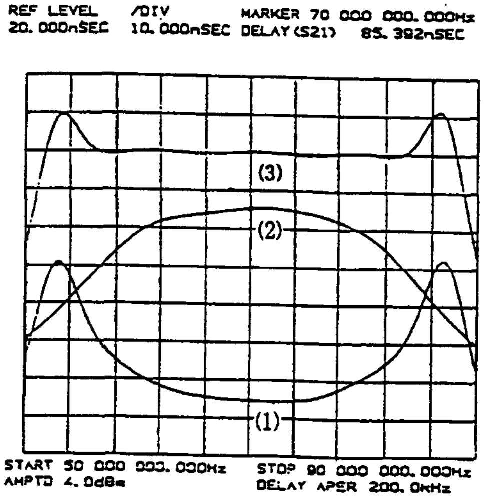

Fig. 15. Measured group delay for Fig. 11.

region.

4-2 Experimental Results

First, let's consider the group delay circuit in view of how the group delay and its amplitude are actually related. For instance, if one designs a single stage of group delay circuit at 50 MHz resonance frequency, Fig. 12 shows its measured amplitude and delay responses noted by (1) and (2), respectively. Although the delay at the resonance frequency gives about 25.7 nsec, the amplitude response is not flat but distorted. This is not what we are trying to get due to amplitude change, which results from the insertion loss of the second order all-pass filter. Hence, in order to correct amplitude distortion, one can design the amplitude equalizer, which is only one stage amplifier with resistors, inductors, and capacitors, and the desired amplitude curve can be easily constructed by trimming those parameters combined with the network analyzer. So curves (1) and (2) in Fig. 13 illustrate the amplitude and delay responses of the designed amplitude equalizer. The amplitude curve (1) at 50 MHz gives about 0.7 dB and its maximum delay is about 1.9 nsec. Consequently, one may obtain the combined result like Fig. 14 from two results above. The amplitude deviation of curve (1) gives about +/- 0.1 dB which is nearly constant, and the group delay curve (2) shows the maximum delay of about 27.3 nsec, which was changed in small.

Second, Fig. 15 depicts three measured group delay responses such as waveguide filter, implemented GDE, and combined GDE marked by (1), (2), and (3), respectively. Curve (1) means the total channel delay from modulator to demodulator including transceiver and channel branching network, and also in order to make inverted version of curve (1), GDE with curve (2) was designed and implemented. So GDE output, which means the overall response denoted by (3), shows good performance compared with simulated result of Fig. 11. Fig. 16 shows the photograph of implemented GDE and slope equalizer, respectively, where GDE indicates the lower half part of 2-layered PCB with 15cm × 15 cm.

Third, in order to check how group delay affects the signal in time domain and why GDE should be adopted for high capacity co-channel DRRS, for instance, eye patterns were measured under STM-1 input signal of 64-QAM with 27 MHz symbol rate. Fig. 17 presents the measured eye diagrams without GDE, not showing eye openings due to the distorted group delay. From Fig. 18, however, eye openings with some clearance could be seen if only GDE like Fig. 15 is installed in the receiver.

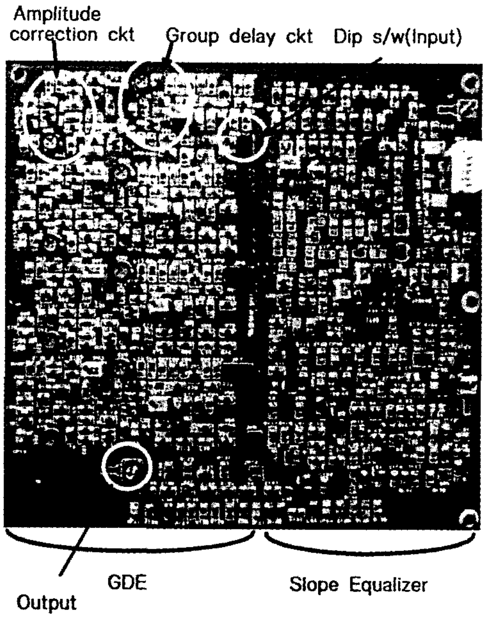

Fig. 16. Photograph of the implemented GDE.

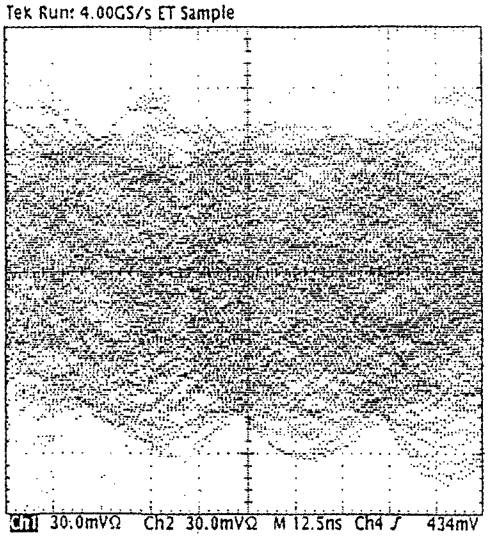

Fig. 17. Eye diagrams of 64-QAM signal without GDE.

Finally, to show the system performance combined with GDE, two BER curves are compared in Fig. 19. They are measured in RF including transceiver. One is tested without channel branching filters and with GDE-off state. The other is performed for channel branching filters with 40 MHz spacing and GDE-on state. Even if the relative group delay distortion caused by transceiver filters is not

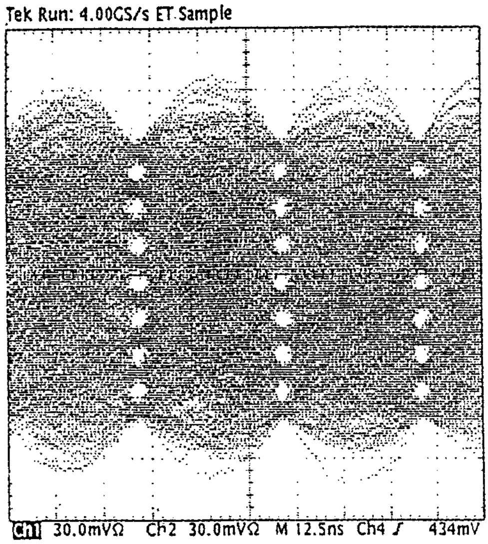

Fig. 18. Eye diagrams for Fig. 17 with GDE.

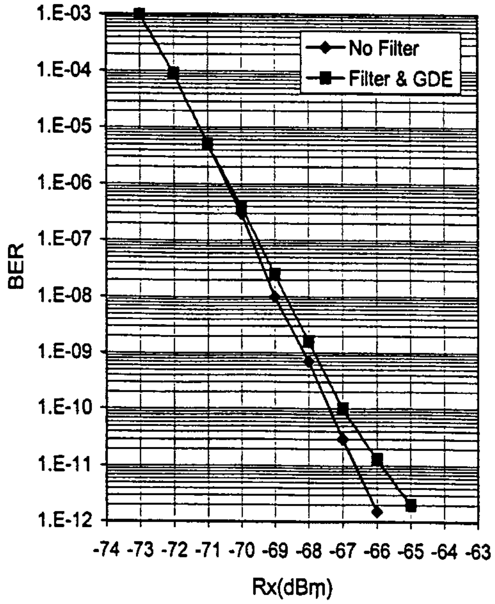

Fig. 19. BER curves with/without branching filters and GDE.

more than 40 nsec from channel center to the Nyquist frequency of 13.5MHz, there is nearly no difference between two curves, and it should be noted that this result is remarkable.

V. CONCLUSIONS

In this paper, the implementation of GDE and its performance has been examined for STM-1 signal of co-channel 64-QAM DRRS, and measured results have also been in good agreement with simulated ones based upon analytical formulations. For waveguide filter of 40 MHz channel spacing, the proposed scheme has confirmed equalized delay accuracy of less than +/− 2.0 nsec only by constructing 4 stage delay circuits, and with the help of this result, the difference in system curves gives about 1.0dB at 10^{-12} BER, which is negligible compared with no filter case.

The proposed GDE provides some features in terms of simple hardware, easy tune, and good performance and it can be used for equalizing distorted group delays caused by waveguide filters. In addition, if it is combined with digital filter in the modulator, which is capable of flattening the group delay with symmetrical form to the channel center, the number of GDE stage can be greatly reduced by three or four by paying small cost for hardware complexity.

Furthermore, this scheme is also applicable to the modern co-channel 128-QAM DRRS with 30 MHz channel spacing, and the result may be expected as good as 40 MHz channel spacing case. However, since the channel spacing is only 30% wider than the Nyquist bandwidth of the transmitted spectrum, GDE is mandatory and carefully designed, and this will be discussed for further work.

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REFERENCES

[1] W. Bourdon, W. Geidel, G. Lange, and J. G. Neideck, "A new generation of SDH radio relay system for $1 \times 155/2 \times 155/4 \times 1555$ Mbit/s," *Proc. 3rd ECRR*, pp. 56-63, 1991.

[2] G. Sebald, G. Filiberti, R. Schmidmaier, and S. Bianchi, "A STM-1 XPIC-Modem for 28/30 MHz co-channel applications," *Proc. 5th ECRR*, pp. 265-271, 1996.

[3] K. W. Suh, "Implementation of co-channel radio relay system and its performance evaluation with synchronous digital hierarchy," *Journal of the Institute of Electronics Engineers of Korea*, vol. 35-D, no. 11, pp.1046-1058, Nov., 1998.

[4] W. D. Rummler, "A new selective fading model: application to propagation data," *The Bell System Technical Journal*, vol. 58, pp. 1037-1071, May-June, 1979.

[5] A. A. R. Townsend, *Digital line-of-sight radio links*: a handbook Prentice-Hall, International (UK), Chapter 8, 1988.

[6] K. Feher, *Digital communication: microwave applications*, Prentice-Hall, Englewood Cliffs, N. J., Chapter 5, 1981.

[7] K. W. Suh, C. Y. Park, and D. Y. Lee, "Implementation of a single multi-task chip; ATDE, XPIC, and DF applicable to multi-level QAM digital radio system," *Proc. IEEE Globecom*, pp. 1463-1467, Nov., 1995.

[8] G. Y. Hur, K. W. Suh et al., "A study on DSE combined with 13-tap ATDE and 64-QAM for SDH microwave digital radio system," *Proc. KITE Conference*, vol. 16, no. 2, pp. 48-51, Nov., 1993.

[9] O. P. Hong, J. S. Yun, H. T. Ha, J. H. Lee, and K. W. Suh, "Design and implementation of adaptive slope equalizer in digital microwave radio system transmitting STM-1," *Proc. KITE Conference*, vol. 21, no. 1, pp. 431-433, May, 1998.

[10] J. S. Yun, D. W. Lee, and K. W. Suh, "Implementation of group delay equalizer and its effect on performance of co-channel digital radio relay system," Proc. 1995. *Asia Pacific Microwave Conference*, pp. 844-847, Oct., 1995

[11] S. Bianchi and R. Schmidmaier, "A digital group delay equalizer for high capacity SDH radio applications," *Proc. 6th ECRR*, pp. 278-282, 1998.

[12] J. Meyer, "Implications of draft new ITU-T recommendation G.826 on digital radio-relay system," *Proc. 4th ECRR*, pp. 21-28, 1993.

[13] A. Richgni and T. Testi, "IF combining techniques for space diversity analog and digital radio system," *Proc. IEEE ICC*, pp.4B.6.1-4B. 6.5, 1982.

[14] K. W. Suh, Improvement of IF in-phase combiner for space diversity technique of digital radio relay system, *Journal of the Institute of Electronics Engineers of Korea*, vol. 36-D, no. 4, pp. 296-305, April, 1999.

[15] A. B. Williams and F. J. Taylor, *Electronic filter design handbook*, Mcgraw-Hill Company, 1988.

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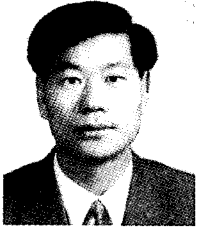

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