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Optical Channelizer Evaluation Using Empirical Data and Simulation

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OPTICAL CHANNELIZER EVALUATION USING EMPIRICAL DATA AND SIMULATION

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Abstract

Westinghouse Electric Corporation Communication Division under NASA contract NAS3-25865 developed a proof-of-concept (POC) multichannel demultiplexer implemented as an acousto-optic radiofrequency (RF) spectrum analyzer. A detailed analysis of the experimental results indicate that the expected degradation caused by the acousto-optical channelizer is approximately 2.0-dB degradation at 10^{-5} bit-error-rate (BER) and 3.0-dB degradation at 10^{-8} BER. This degradation may be quite acceptable when considering the excellent volume, mass, and power characteristics of acousto-optical channelizing relative to other technologies. In addition, system performance can be greatly improved by using digital pulse shaping in the modem and increasing the channel spacing from 40 to 45 kHz for 64-kbps quadrature phase-shift keying (QPSK) modulation.

Westinghouse Acousto-Optic Channelizer

Westinghouse Electric Corporation Communication Division under NASA contract NAS3-25865 developed a proof-of-concept (POC) multichannel demultiplexer implemented as an acousto-optic radiofrequency (RF) spectrum analyzer that demonstrated the capability of demultiplexing 1000 low data rate frequency-division, multiple-access (FDMA) uplinks.[1] The multichannel demultiplexer was implemented as an acousto-optic RF spectrum analyzer utilizing heterodyne detection with a modulated reference. Demodulation was performed using a commercial demodulator. A photo-detector was placed at the focal point of the channel of interest and the signal fed into the commercial demodulator to fully characterize the effect that the optical demultiplexer has on a modulated signal such as quadrature phase-shift keying (QPSK).

The acousto-optic spectrum analyzer (Fig. 1) is based on the Bragg interaction between light and sound in a crystal material. An ultrasonic acoustic wave is impressed on the crystal. A portion of a laser beam passing through the Bragg cell is diffracted at an angle proportional to the RF applied to the acoustic transducer. The diffracted beam is amplitude modulated and frequency and phase shifted by the Bragg interaction with the intensity proportional to the power of the applied RF signal. For heterodyne detection with a modulate reference, the output of the signal at the photo-detector is at a common intermediate frequency (IF) and proportional to the amplitude of the communication signal. Thus, the multichannel demultiplexer (MCD) performs both the demultiplexing and downconversion of the composite RF signal.

The acousto-optic channelizer was designed to allow 64 kbps of offset quadrature phase-shift keying (OQPSK) modulated information to be frequency stacked with 40-kHz channel spacing. The modem filters that were initially specified and simulated by Westinghouse were 6-pole, 16-kHz Butterworth filters. These modem filters are far from an optimal choice for bandwidth and power efficient modulation. In addition, because of technical difficulties at the onset of the contract that strained available funds, NASA and Westinghouse decided to allow testing with a government-supplied modem, Comstream CM421. This modem is capable of generating uncoded 64-kbps QPSK modulation signals at a 70-MHz IF within a 50-kHz bandwidth. Both NASA and Westinghouse were unable to obtain detailed information on the internal data filters used in the modem. However, NASA subsequently learned that the data filter for the 64-kbps QPSK mode is a 16-kHz equalized 6-pole, Butterworth filter (6-pole, Butterworth filter at one-half the symbol rate). Thus, the overall Westinghouse testing utilized suboptimal filtering and mismatch between the commercially available modem and the optical channelizer. Figure 2 shows the basic test setup of BER testing. Only one adjacent channel was implemented for adjacent channel testing.

Westinghouse Experimental Results

The Westinghouse measured experimental results are shown in figure 3. Because of the mismatch between the Comstream modem and the optical channelizer, a series of BER measurements were taken to establish a baseline BER curve with which optical channelizer effects could be compared. The first measurement established the modem back-to-back performance. This curve shows approximately 1.75-dB degradation from theory and 1.25-dB worse performance than specified by the modem manufacturer. This may be the result of miscalibration. The second curve includes the 16-kHz transmit filter between the modulator and demodulator and no adjacent channels. An additional 4-dB degradation results from this filter mismatch. The 3 additional curves have the optical channelizer inserted between the 16-kHz transmit filter and the demodulator. The channelizer degrades the system performance by an additional 2 to 2.5 dB as indicated by the BER curves for no adjacent channel interference and for equal power adjacent channels. The flair of the BER curve for a channel with 8-dB fade relative to the adjacent channels indicates that the combination of the spatial filter (channel filter) and the receive filter in the demodulator cannot overcome the amount of adjacent channel energy received by the desired channel.

Acousto-optical Channelizer Characterization

The Westinghouse measured gain characteristics of the channelizer are shown in figure 4. These data were obtained by varying the frequency across a channel and measuring the output spectral power off a spectrum analyzer display. This measurement technique does not allow phase or group delay data to be obtained.

The optical channelizer was recharacterized to obtain gain and group delay information that could then be used in simulation of the communication system. Because a frequency downconversion process occurs within the optical channelizer, an amplitude modulation (AM) envelope modulation technique was employed whereby the group delay measurement is obtained from the modulation envelope rather than the RF carrier.[2-4]

The group delay is calculated as $T_d = \phi_e / (360° \times f_m)$ where T_d is the group delay, ϕ_e is the envelope phase shift and f_m is the amplitude modulation frequency. Because the bandwidth resolution using this technique is $2f_m$, a tradeoff is required between bandwidth resolution and phase resolution. Increasing the AM frequency, f_m, increases the resolution of the phase measurement at the expense of bandwidth resolution.

The AM envelope modulation technique has many sources for measurement errors: detector delay variation versus power level, incidental phase modulation produced by the amplitude modulation, RF source phase noise, and impedance mismatch. The individual error components produced by these sources are generally in the tens of nanoseconds. The error source of greatest concern for our purposes is caused by the detector delay variation versus power. Fortunately, we desire the greatest accuracy over the center of the channel where the gain is maximum and gives minimum measurement error. When the channel is attenuated because of the filtering, the group delay is of little concern.

For this communication system, the symbol rate is 32 kHz giving a symbol time of 31.75 µs. A 1- to 2-µs accuracy is sufficient and is readily obtainable over the main lobe of the filter.

The gain-phase measurement test setup is shown in figure 5. A synthesized signal generator is used to create a 1-kHz, 50-percent AM signal at the RF output that is input to the optical channelizer. The signal generator also provides the 1-kHz reference that is used as the reference channel input to the gain-phase meter. The output of the optical channelizer photodyode is amplified, filtered, and input to the gain-phase meter for comparison with the reference input. A dc output voltage from the gain-phase meter proportional to the gain or phase is input to a digital multimeter. A LabView (National Instruments) program was written to step the signal generator through the desired frequencies, record the voltmeter readings, and store these measurements for further analysis. The relative gain and group delay characteristics are easily calculated from these data.

Figure 6 shows a typical gain and group delay plot. The channel in this plot is centered at 67.700 MHz. Figure 7 shows the repeatability of the gain and group delay measurements. Three separate gain and phase plots for the same channel centered at 78.000 MHz are overlaid. Figure 8 is a histogram of 1 frequency point measured 1000 times. The mean, mode, and standard deviation of the 1000 points are - 1.01757°, -1.01868°, and 0.001483°, respectively.

Acousto-optical Channelizer Modeling

The acousto-optic channel filter was modeled in Signal Processing Workstation (SPW) (Alta Group, Cadence, Inc.) using the arbitrary frequency domain group delay filter block and empirical data that Westinghouse and NASA compiled. Three filters were modeled for use in the communication system simulations: the Westinghouse channel filter with group delay set to zero across all frequencies, the 66.700-MHz, NASA-measured channel filter with the appropriated group delay values included, and the 66.700-MHz, NASA-measured channel filter with the group delay set to zero across all frequencies (Fig. 9). The 66.700-MHz channel was chosen because it matched the basic amplitude and group delay characteristics of all other channels measured around 70.000 ± 10.000 MHz. Setting the group delay to zero in the 66.700 MHz filter allowed a comparison of the same gain-shaped filter with and without group delay effects.

Simulation Results

To understand the difference in degradation caused by the channelizer and that caused by the modulation filtering and filter mismatches of the experimental setup, a system simulation was performed for QPSK modulation through the channelizer using SPW. The basic SPW simulation configuration is shown in figure 10. Three modulators are stacked side by side with the middle modulator at baseband and the two adjacent channels spaced at +/- the channel width (40 kHz for most tests). The adjacent channels are multiplied by a gain factor to either amplify or attenuate these channels. For –100 dB gain, the adjacent channels are basically nonexistent. Positive gain values simulate a fade condition on the middle channel measured for BER performance. Tests were performed with and without the acousto-optical channelizer filter present.

Figure 11 shows the QPSK modulator configuration. Random data are created independently for the in-phase and quadrature channels and passed through the baseband transmit filter. The in-phase and quadrature channels are combined into a complex representation and then shifted in frequency.

The demodulator is shown in figure 12. The receive filters are identical the transmit filters in the modulator. The impulse train creates a pulse every eight samples as the modem is configured to operated on eight samples per symbol. The delay unit is adjusted to obtain the optimal sample period.

Because of the tremendous speed advantage over Monte-Carlo techniques, BER calculations were obtained using a semi-analytical technique. Energy per bit/ normalized noise power (Eb/No) values can be obtained in a few minutes rather than hours or days for BER values of 10^{-6} or greater. This technique may be applied to linear systems with noise that can be characterized as average white Gaussian noise (AWGN). The general concept for this semi-analytical technique is to analyze the eye diagram out of the sample and hold circuitry following the demodulator receive filter. The Gaussian noise characteristics for a given Eb/No are calculated and averaged for each point in the eye diagram at the optimal sampling frequency.[5]

The simulation blocks were implemented such that three different baseband filter types could be inserted into the modem system. The three filters used were a 16-kHz, 6-pole, unequalized Butterworth filter; a 16-kHz, 6-pole, equalized Butterworth filter; and a 40-percent square root raised cosine (RRC) filter. The filter response, group delay, and optimally sampled eye diagrams at the demodulator without the acousto-optical channelizing filter present are shown in figures 13, 14, and 15 for each filter type. Figure 16 shows the result of adding the acousto-optic channelizing filter between the modulators and demodulator. These eye diagrams are taken with no adjacent channels.

Figures 17, 18(a), and 18(b) show eye diagrams out of the modulator with a 40-percent RRC transmit filter and the spectral response of the signal at the input and output of the channelizer filter for various adjacent channel interference levels. These diagrams clearly show the signal degradation caused by the channelizer filter and the adjacent channels. The eye diagrams indicate that there should be little variation in performance for no adjacent channel and when adjacent channels are of equal power to the desired channel. However, the eye diagrams indicate that the system begins to degrade when the desired channel experiences a 5-dB fade and has unacceptable performance at a 10-dB fade. The BER curves in figure 19 validate this. Note the system performance is nearly identical for equal power adjacent channels at 40-kHz spacing and a 10-dB faded channel at 45-kHz spacing. Thus, system performance can be greatly improved by increasing the channel separation and allowing the optical channelizer to simply perform the spatial channel separation function whereas the transmit/receive filter pair performs the match filtering function.

The BER curves in figure 20 show the results of adding the acousto-optic channelizing filter between the modulator and demodulator for various transmit/receive filters with no adjacent channels present and with equal power adjacent channels. The results indicate that the channelizing filter adds approximately 2.0-dB degradation at 10^{-5} BER and 3.0-dB degradation at 10^{-8} BER for each of the modem filters. In addition, little degradation occurs for equal power adjacent channels.

The BER curve in figure 21 shows that channelizer degradation obtained from the simulation results of the NASA-measured optical channelizer and the Westinghouse experimental results closely match. For clarity, only the 16-kHz unequalized low-pass transmit/receive filter simulations are shown.

The BER curve in figure 22 shows that the degradation caused by the small amount of group delay variation is insignificant. Thus, the amplitude distortion caused by the channelizer is the major source of system degradation.

Concluding Remarks

The results of this study indicate that digital pulse shaping should be used in the modem and that the expected degradation caused by the acousto-optical channelizer is approximately 2.0-dB degradation at 10^{-5} BER and 3.0-dB degradation at 10^{-8} BER. This degradation may be quite acceptable when considering the excellent volume, mass, and power characteristics of the acousto-optical channelizing relative to other technologies. In addition, increasing the channel spacing from 40 to 45 kHz will enable very good system performance during channel fading of greater than 10 dB.

References

1. Abromovitz, I.J.; Flechsig, D.E.; and Matteis, R.M.: Advanced Technology for a Satellite Multichannel Demultiplexer / Demodulator, NASA CP-194435, January 1994.
2. Chodora, J.: Group Delay Characterization of Frequency Converters, Microwave Journal, September 1995, pp. 102-116.
3. Kerczewski, R.J.: A Study of the Effect of Group Delay Distortion on an SMSK Satellite Communications Channel, NASA TM–89835, April 1987.
4. Hewlett Packard Model 3575A Gain-Phase Meter Operating and Service Manual, Manual Part Number 03575-90002, August 1987.
5. Communication Library Reference - for SPW - The DSP Framework, Comdisco Systems, Inc, July, 1993.

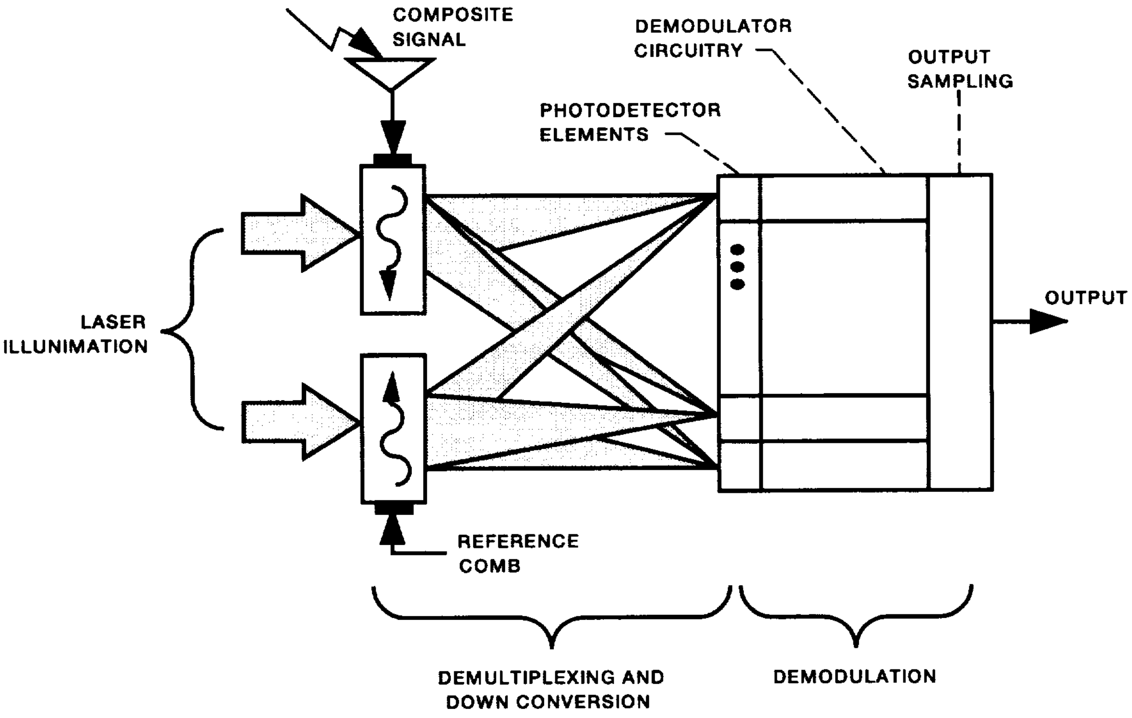


Fig. 1—MCDD POC model for heterodyne detection with a modulated reference.

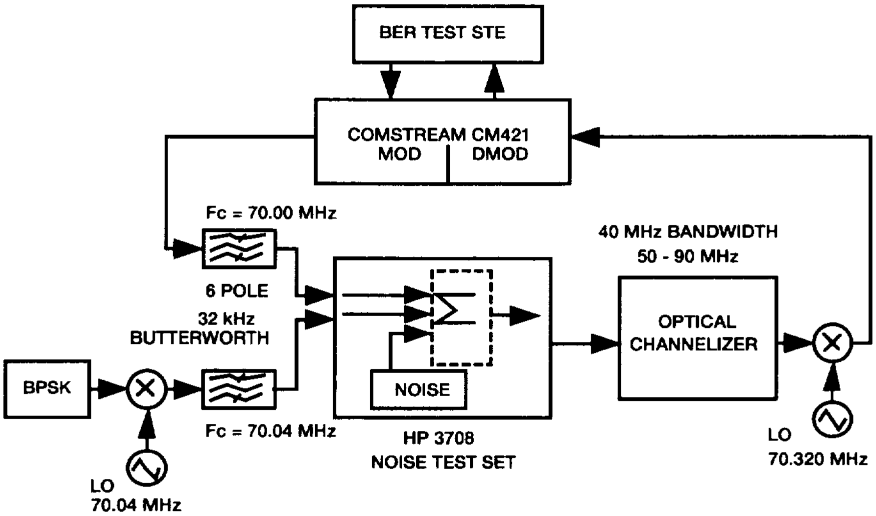


Fig. 2—Single channel BER test setup with adjacent channel loading.

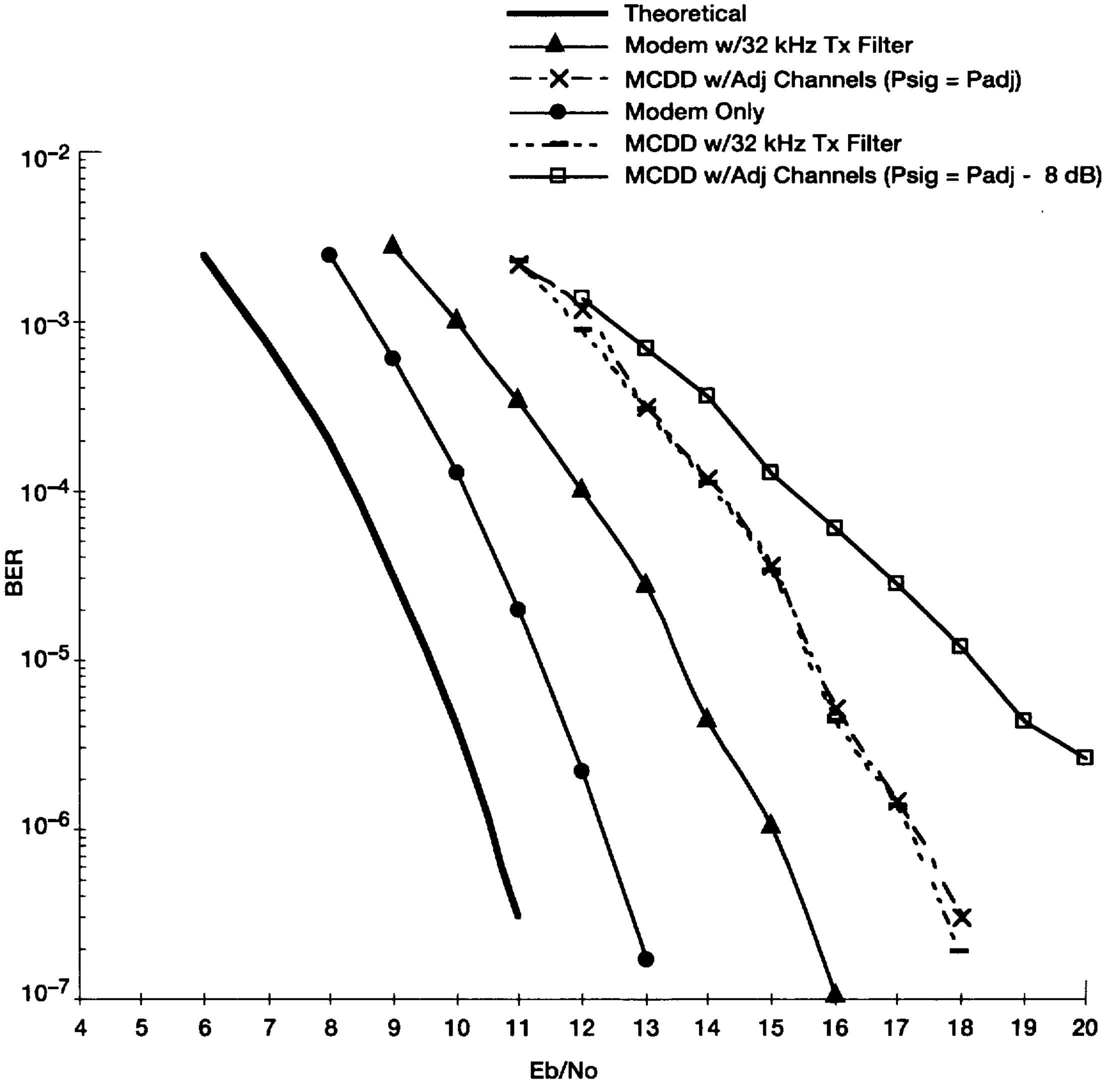


Fig. 3—Westinghouse-measured experimental results.

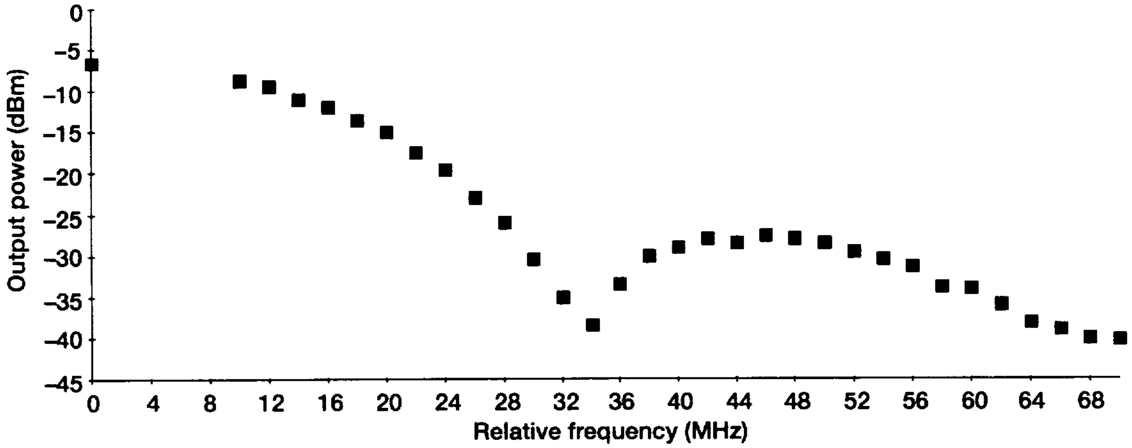


Fig. 4—Westinghouse-measured channel filter gain.

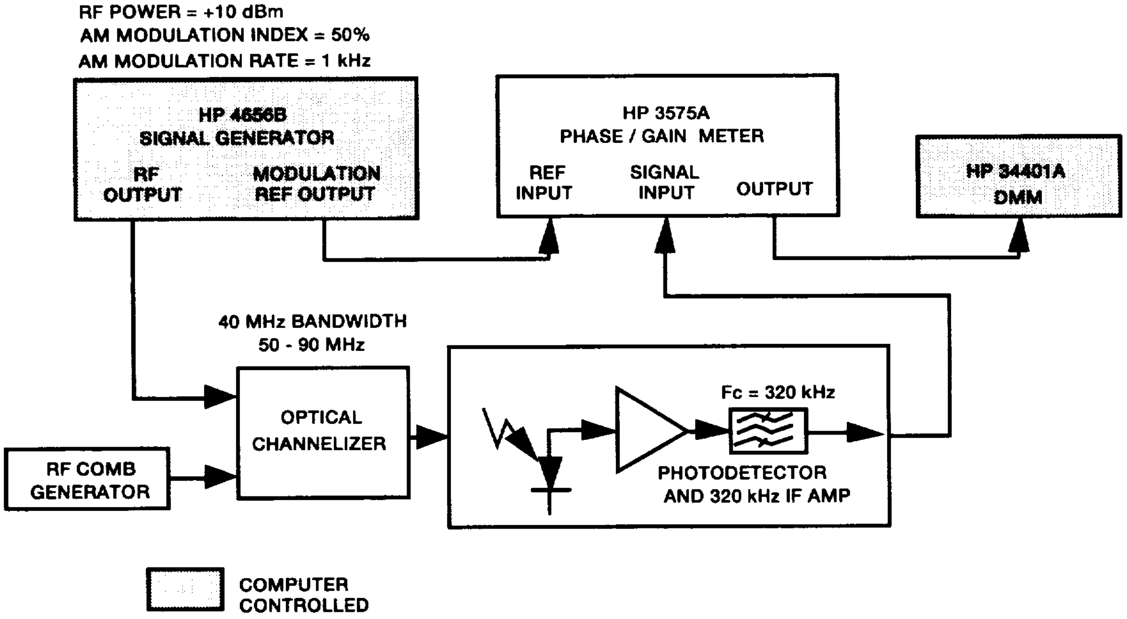


Fig. 5—Gain-phase measurement test setup.

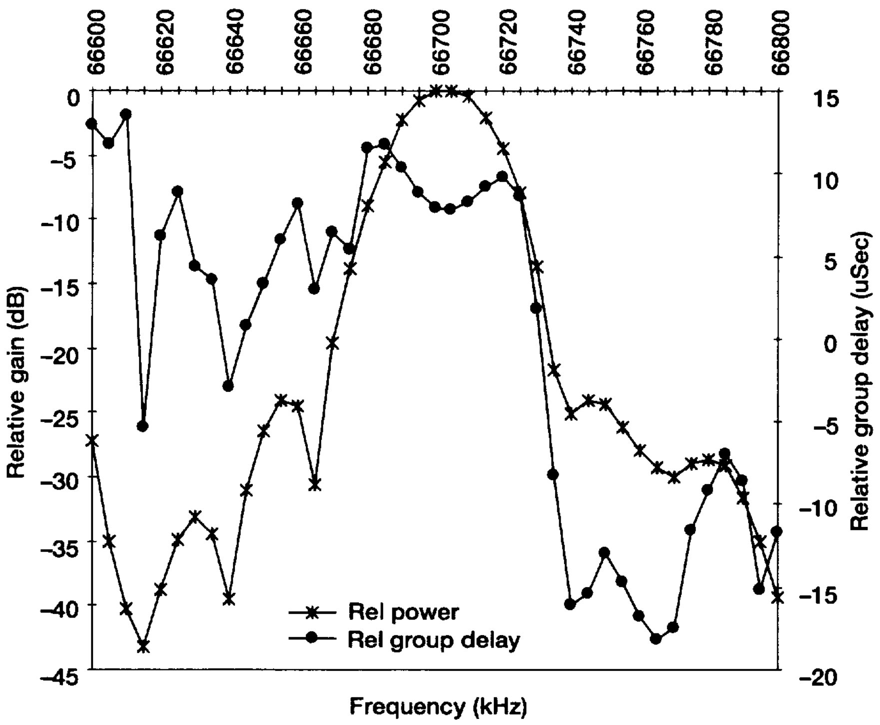


Fig. 6—Gain and group delay versus frequency.

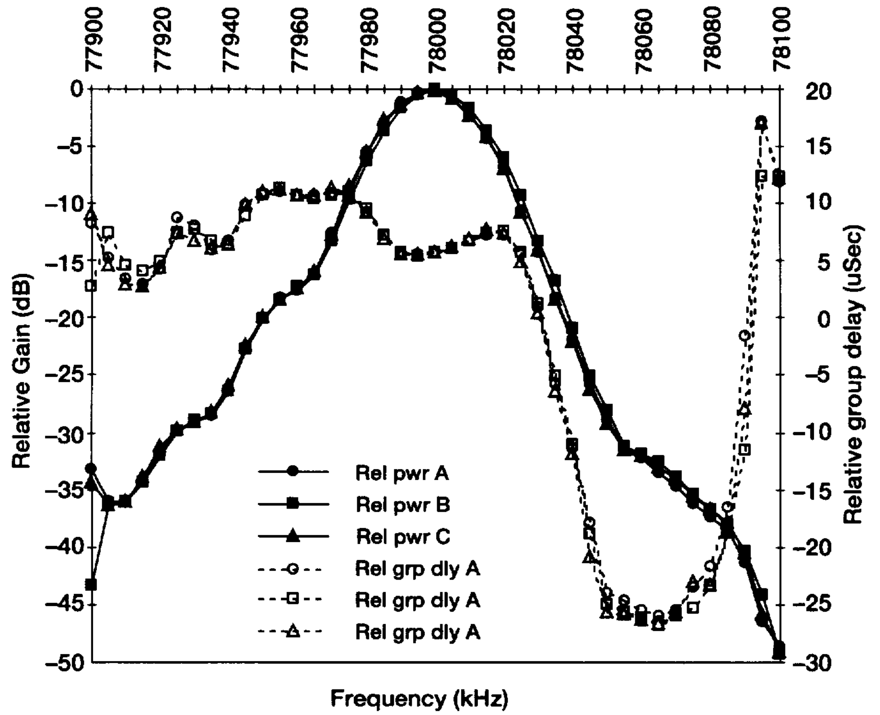


Fig. 7—Repeatability of measurements for gain and group delay.

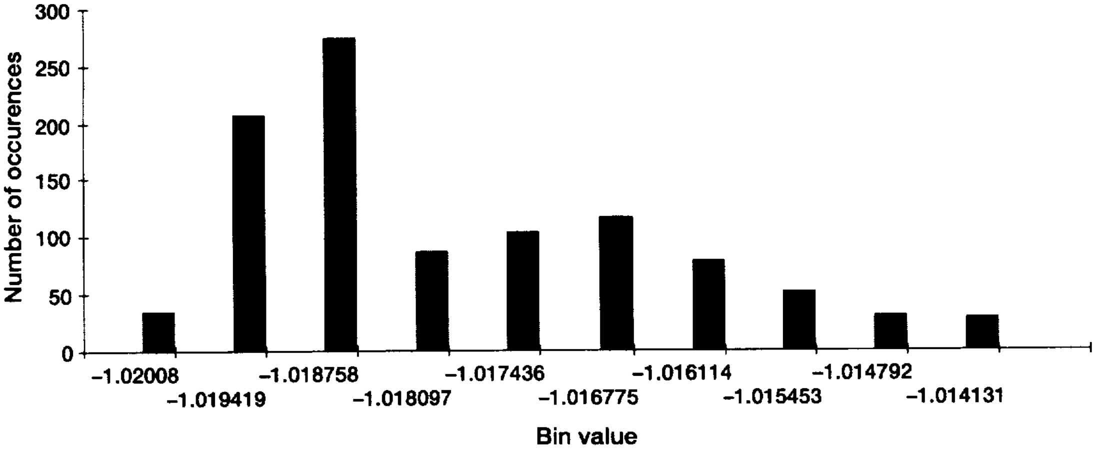
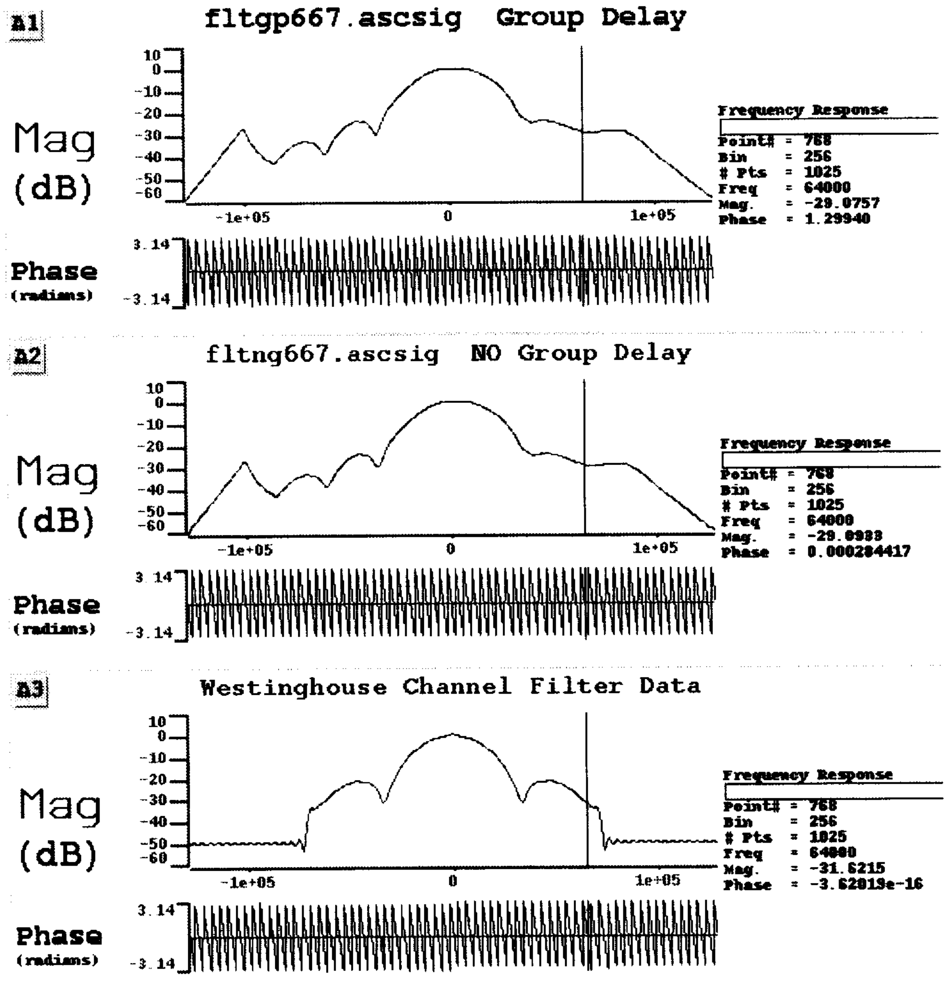


Fig. 8—Histogram of phase



```
Frequency Response
Point# = 768
Bin    = 256
# Pts  = 1025
Freq   = 64000
Mag.   = -29.0757
Phase  = 1.29940
```

```
Frequency Response
Point# = 768
Bin    = 256
# Pts  = 1025
Freq   = 64000
Mag.   = -29.0988
Phase  = 0.000284417
```

```
Frequency Response
Point# = 768
Bin    = 256
# Pts  = 1025
Freq   = 64000
Mag.   = -31.6215
Phase  = -3.62019e-16
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Fig. 9—Channelizer filter models.

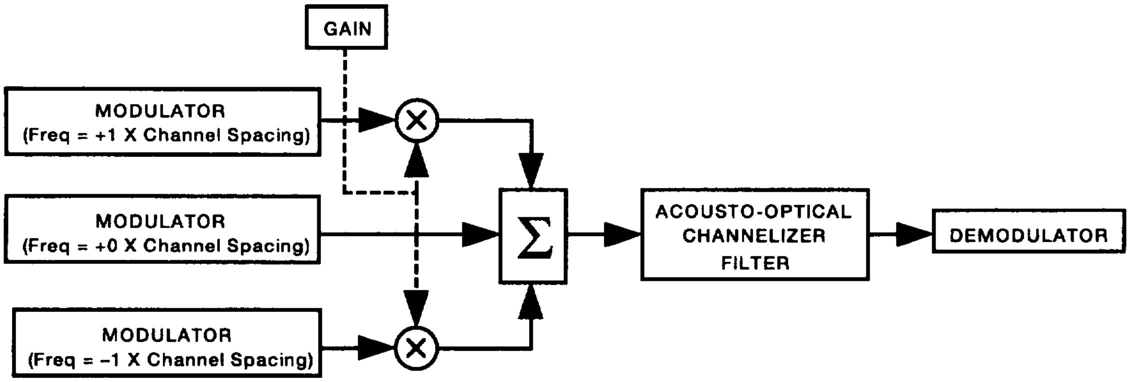

Fig. 10—SPW simulation.

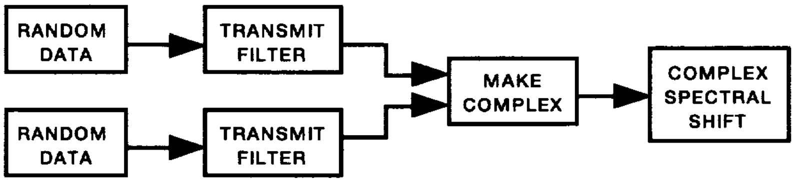

Fig. 11—QPSK modulator.

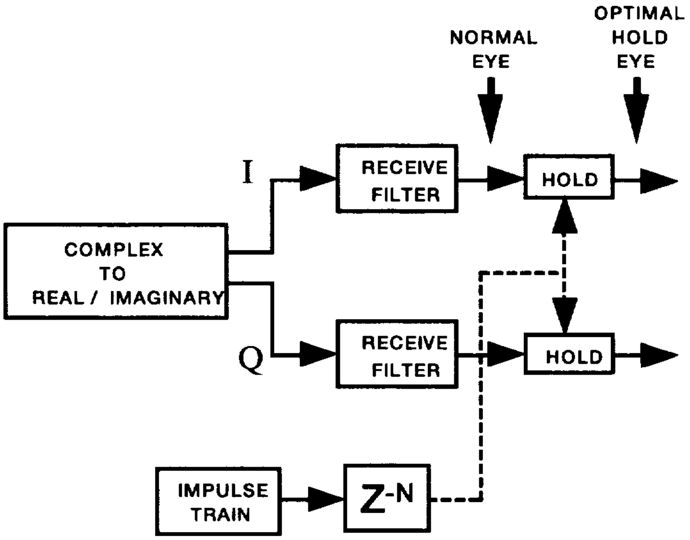

Fig. 12—SPW QPSK demodulator.

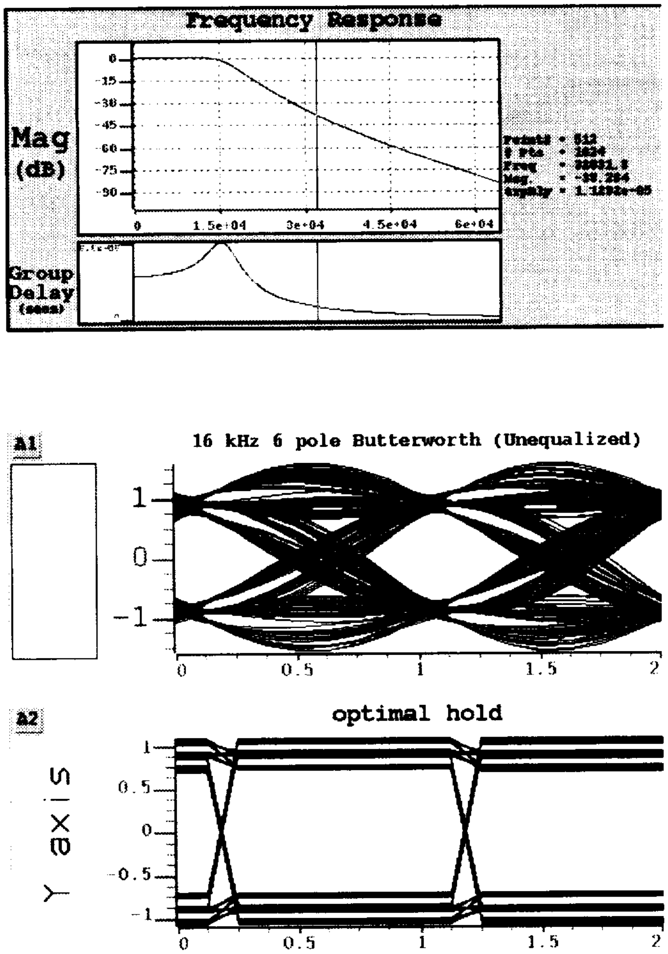

Fig. 13—16-kHz 6-pole unequalized Butterworth filter.

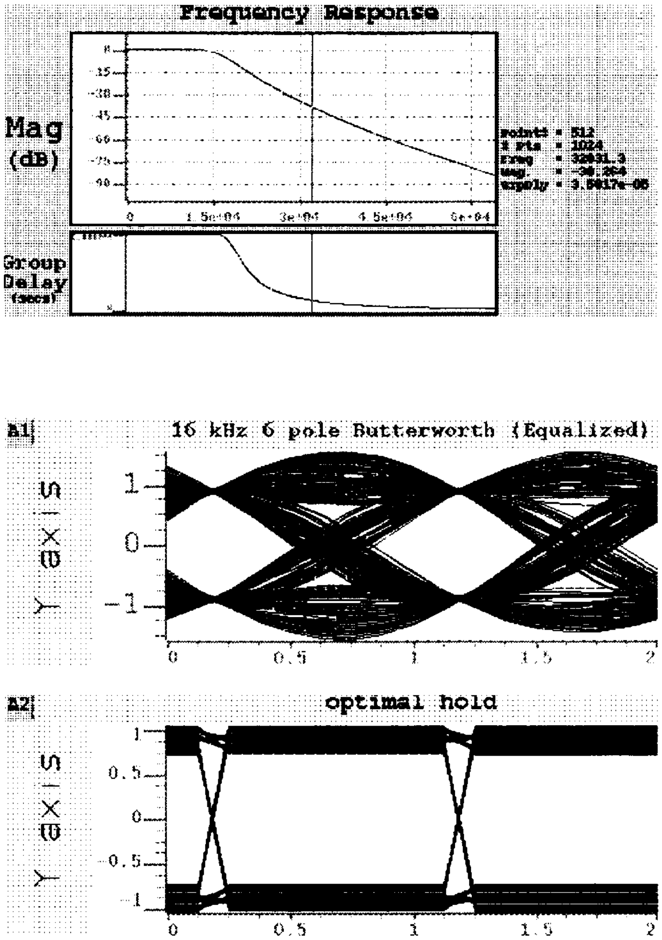

Fig. 14—16-kHz 6-pole equalized Butterworth filter.

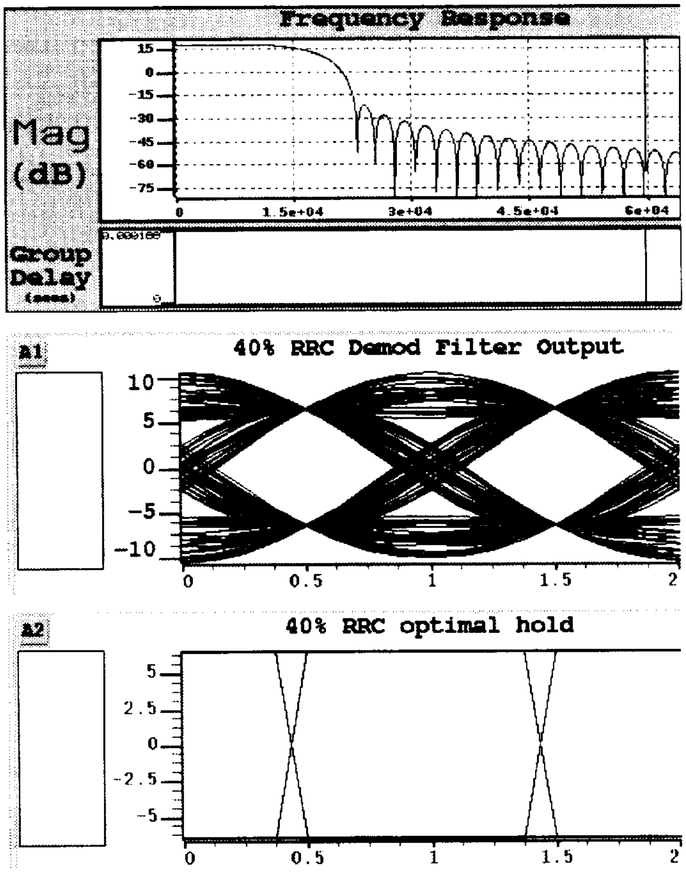

Fig. 15—Forty-percent square root raised cosine (RRC) filter.

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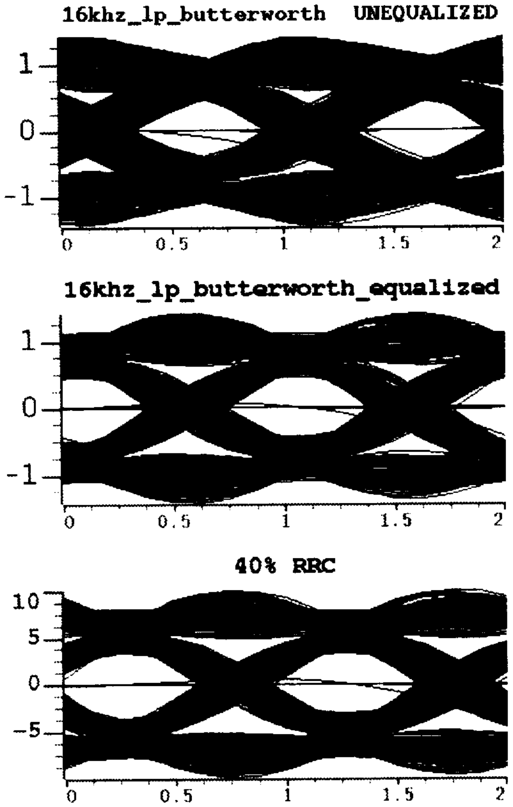
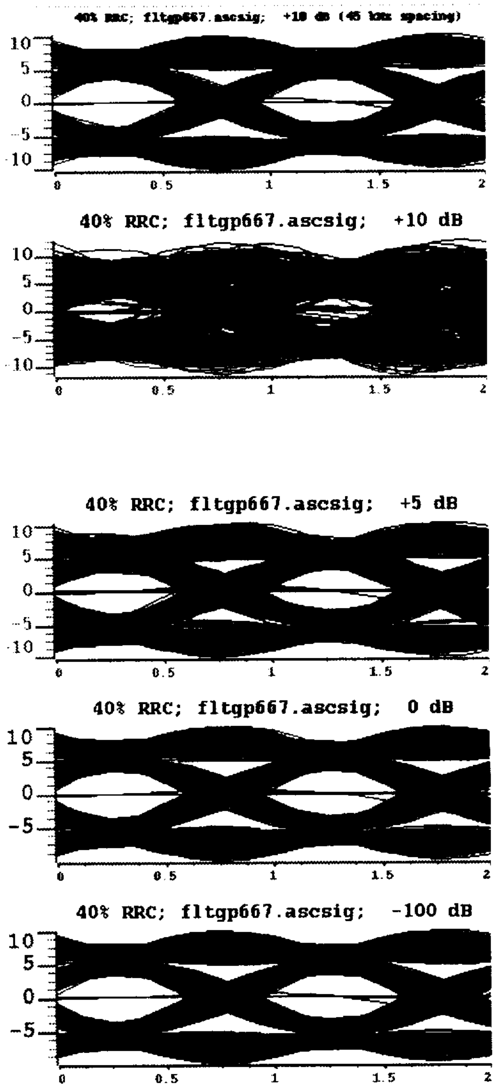

16khz_1p_butterworth UNEQUALIZED

16khz_1p_butterworth_equalized

40% RRC

Fig. 16—Eye diagrams out of receive filter with optical channelizer (fltgp 667) in-line.


40% RRC; fltgp667.ascsig; +10 dB (45 kHz spacing)

40% RRC; fltgp667.ascsig; +10 dB

40% RRC; fltgp667.ascsig; +5 dB

40% RRC; fltgp667.ascsig; 0 dB

40% RRC; fltgp667.ascsig; -100 dB

Fig. 17—Forty-percent RRC receive filter output eye diagrams.