MODULATION AND CODING TECHNIQUES FOR HIGH CAPACITY COAXIAL CABLE AND SCM FIBER DIGITAL TV-HDTV DISTRIBUTION

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ABSTRACT

New emerging digital modulation-demodulation (modem) and coding techniques suitable for spectrally and power efficient digital TV and HDTV distribution systems over coaxial cable and subcarrier multiplexed (SCM) fiber optics systems are described. Efficient and robust modulators/demodulators (modems) combined with low redundancy forward error correction (FEC) - integrated circuits attain a spectral efficiency in the 2 b/s/Hz to 7 b/s/Hz range and a bit error rate (BER) in the 10^{-7} to 10^{-10} range. Recently developed VLSI-ASIC chips, having a universal QPSK-QAM-QPRS modem architecture combined with FEC-chips, operating up to 100 Mb/s, with a 3% to 10% redundancy will enable the transmission of 30 Mb/s rate (or even higher bit rate) digitized TV signals in one conventional analog TV band.

Requirements for FDM shared analog and digitized TV distribution systems are highlighted. The performance of a new class of QPRS filtered modems invented by the author is compared to conventional QPRS and QAM-8-PSK cable systems. The performance advantages of our new class of "above Nyquist rate" modems and of an operational SQPRS (staggered) QPRS system developed by Digital Radio Laboratories are highlighted.

1. MODEM AND CODED MODEM ARCHITECTURES FOR DIGITAL CABLE TELEVISION AND SCM FIBER OPTICS DISTRIBUTION

Numerous modulation/demodulation (modem) architectures have been implemented and considered for digital cable TV and subcarrier multiplexed (SCM) fiber optics digital TV distribution systems. From simple QPSK, 8-PSK to more advanced coded 64-QAM and even 1024-QAM cable systems have been designed and studied.

In general, the purpose of increasing the number of modulation states is to increase the spectral efficiency expressed in terms of b/s/Hz. For example, a theoretical QPSK system could transmit 12 Mb/s while a 16-QAM system 24 Mb/s in a 6 MHz wide video channel. The theoretical spectral efficiency and BER = f(C/N) performance of ideal coherent a = 0 filtered (raised-cosine-Nyquist filtered with a roll-off parameter of a = 0) uncoded modems is illustrated in Figure 3 and 4. The practical spectral efficiency is typically 5% to 50% below the theoretical values of QAM systems and is 4% to 30% above the "theoretical ISI-free" values for QPRS systems [1; 6; 11; 12; 13]. Steep filters, having an a = 0.1 to a = 0.2 and 60 dB out-of-band rejection have been used in several modem designs [1; 2] in order to approach the theoretical spectral efficiency limit of QAM, within 5%.

For example, in the **DigiCipher** radio broadcast system [J.A. Kraus, 18] trellis coded and Reed-Solomon FEC coded 16-QAM and 32-QAM a 19.51 Mb/s and a 24.39 Mb/s rate modulated signal is transmitted in bandwidth of 6 MHz. This corresponds to a 19.51 Mb/s: 6 MHz = 3.25 b/s/Hz (as compared to a theoretical uncoded of 4 b/s/Hz for a = 0, 16-QAM system.

For the DSC-HDTV (Digital Spectrum-Compatible High-Definition Television) system of **Zenith** [Luplow & Fockens, 8], the transmission of 11.1 Mb/s and of 21.0 Mb/s data (representing the digitized video, audio, ancillary data and error protection bits) 2-level VSB and 4-level VSB pilot aided methods are described [8]. The symbol rate is 10.76 M Symbols/second.

For the **ATVA-Progressive System**, a 19.43 Mb/s rate, 16-QAM system is described for the 6 MHz wide video channel [10].

For relatively lower data rate cable systems (1.544 Mb/s to 2.048 Mb/s) and hybrid FDM, analog video and digital data cable systems, more spectrally efficient modems have been implemented by our design teams including 256-

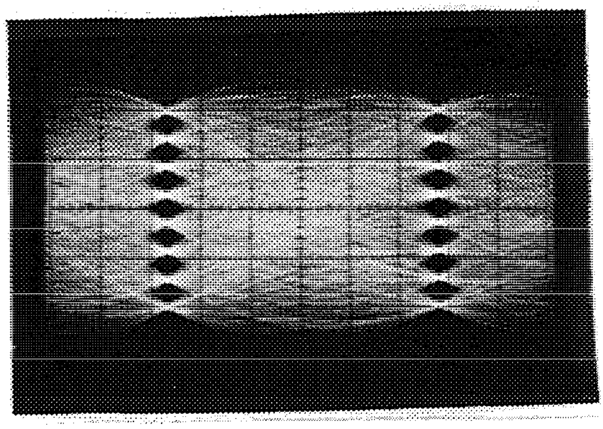

Fig. 1 Experimental 45M b/s coherently demodulated I-channel of a 64-QAM system with a = 0.1 filtering [1 and 2].

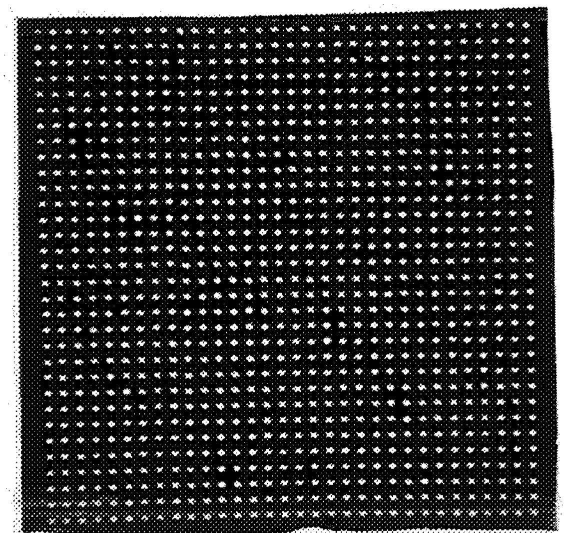

Fig. 2 Measured constellation of a 1024-QAM subsystem [1 and 2].

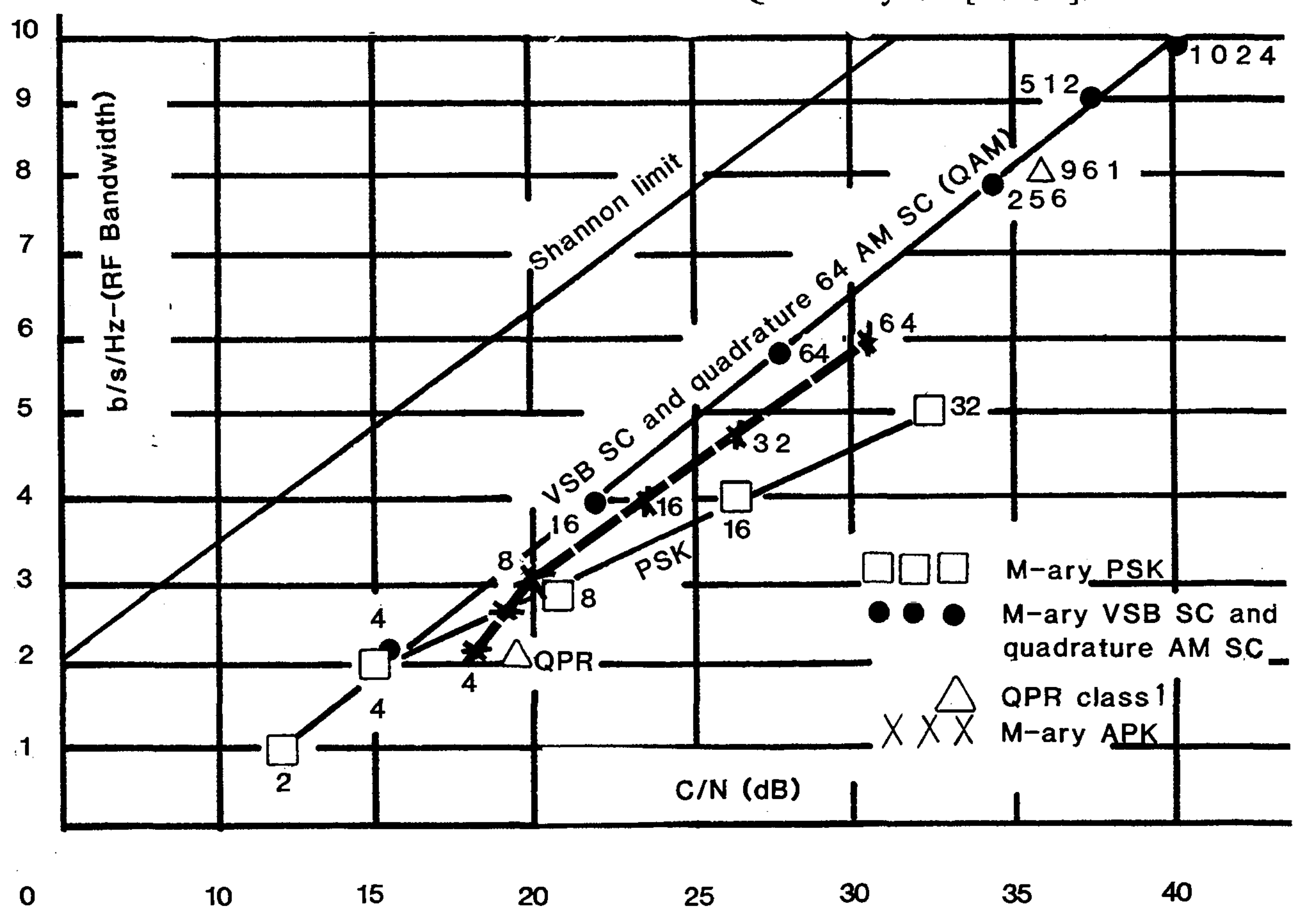

Fig. 3 Theoretical bit rate efficiency of uncoded-modulated coherent systems as a function of the available C/N at P(e) = 10^{-8}. The average C/N is specified in the double-sided Nyquist bandwidth which equals the symbol rate. Ideal a = 0 filtering has been assumed. Shannon limit is for coded-modulated systems [1 - 5].

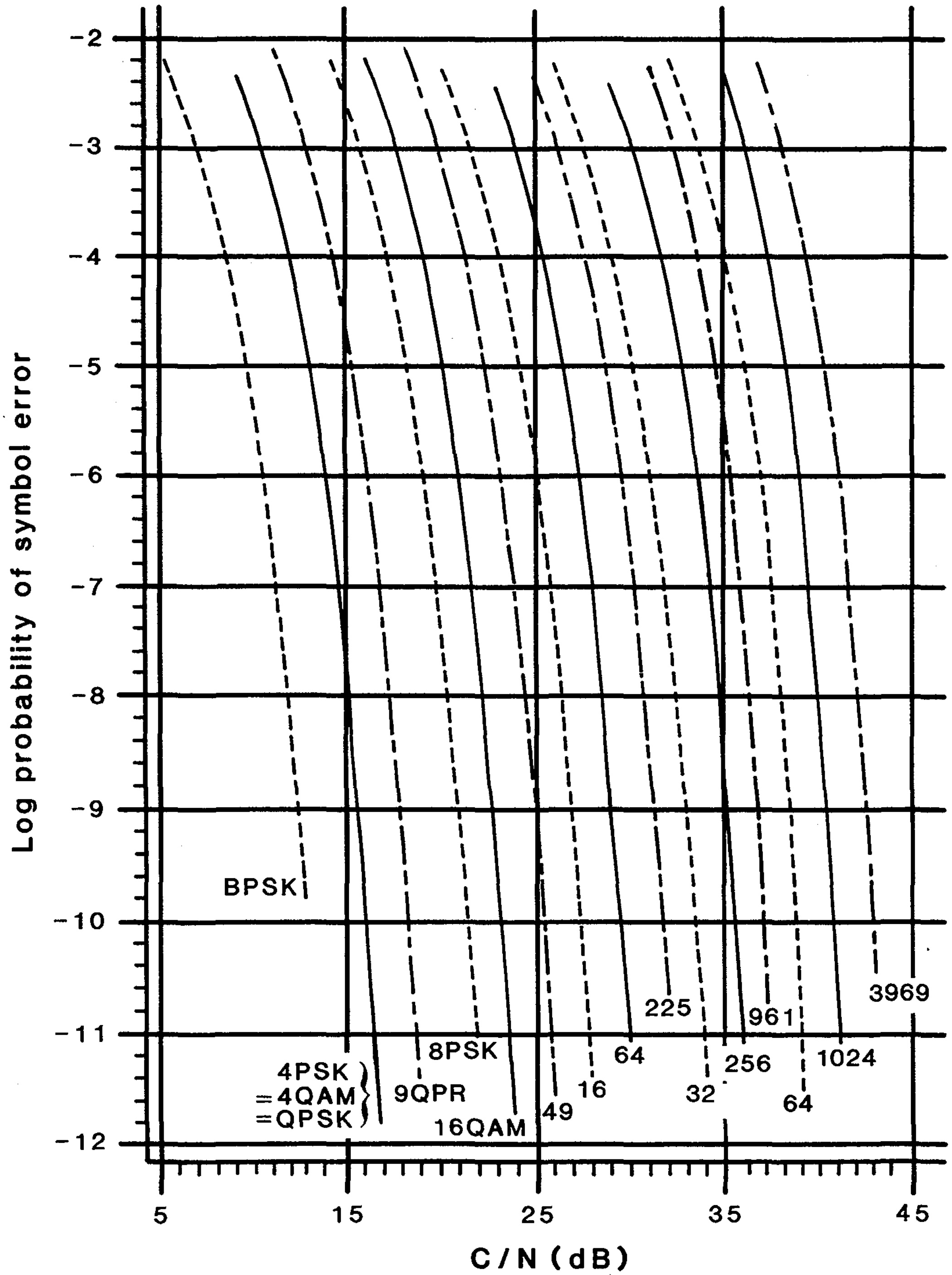

Fig. 4 Probability of error-theoretical performance curves of M-ary PSK, M-ary QAM and M-ary QPR modulation systems vs. the carrier-to-thermal noise ratio in dB. White Gaussian noise channel only - no phase noise. Double-sided Nyquist RF bandwidth equals the symbol rate bandwidth [1 - 5].

QAM modems which achieve a practical spectral efficiency of 6.66 b/s/Hz specified at the 60 dB out-of-band attenuation point [1; 2; 14]. A practical block and implementation diagram of an FEC-coded 256-QAM modem (could be extended to 1024-QAM) modem is illustrated in Figure 5. Even though our modem designs incorporate advanced baseband adaptive time equalizers (BATE) (fully digital), we found that the residual group delay, i.e., group delay and/or echo not equalized by the BATE and IF adaptive equalizer could significantly degrade the performance, as illustrated in Figure 6. We also found that by "staggering" or "offsetting" the 256-QAM or 1024-QAM systems, for short S-QAM we could reduce the sensitivity of the cable system to residual imperfections, see Figures 5 and 6. Experimental field data of one of our (2196, 2136)-BCH-FEC coded (2.7% redundancy) 256-QAM cable systems is illustrated in Figure 7 - Figure 9. For a BER = 10^{-6} our 256-QAM required a C/N = 32 dB and had a spectral efficiency of 6.66 b/s/Hz [2]. Extensive field experiments over LOS hybrid microwave and coaxial cable systems indicated that 99.875 percent or better EFS (error free second) performance could be obtained with these modems over regenerative spans exceeding 1000 km and excellent performance was also obtained on the cable system between Vancouver, Canada and Hawaii.

Probably one of the most spectrally efficient digital modulation cable systems studied so far has been the 1024-QAM system described by Feher in [2]. See the experimental constellation/hardware photograph of Figure 2. Evidently such an efficient system having the theoretical potential of **10 b/s/Hz** and practical potential of more than **9 b/s/Hz** requires an increased C/N requirement and very advanced complex equalization and interference (including echo) cancellation subsystems. For a 6 MHz video channel, a future 1024-QAM system could have the potential of 54 Mb/s. However, it could take some time prior to design completion and implementation of these types of systems.

Simpler, more robust modem architectures have also been considered for digital TV and digital audio cable distribution systems and for **SCM fiber optics** system applications [15-17]. A spectral efficiency in the 2 b/s/Hz to 3 b/s/Hz range has been found to be a good compromise for low C/N requirements, robust performance and low cost ASIC implementations.

Among the simplest and most robust digital modems are the BPSK, G-MSK and QPSK [1]. For a raw BER = 10^{-6} a low C/N in the range of 8 dB to 14 dB is sufficient. The spectral efficiency of these modems is less than 2 b/s/Hz, that is, these modem architectures are not suitable for spectrally efficient digital cable TV and digital audio cable distribution applications. Among the robust, i.e., low C/N operation, modems 8-PSK and staggered 9-state QPRS or S-QPRS are of significant interest. For coaxial cable and for SCM fiber optics systems [15], 8-PSK modems have been considered by several corporations. A brief comparative study of these techniques is highlighted in the next section.

2. COMPARISON OF 9-QPRS AND 8-PSK SYSTEMS: MULTIPLEXED DIGITAL AUDIO CABLE, TV AND SCM FIBER SYSTEMS

QPRS and S-QPRS systems offer several advantages over 8-PSK systems, including a 3 dB lower C/N requirement, simpler architecture, less sensitive to filter imperfections including group delay or cable roll-off, and more robust performance in a phase noise dominated channel. The 3 dB lower C/N could be potentially even further reduced, i.e., to a lower C/N with non-redundant QPRS error correction and/or Viterbi decoding.

The 8-PSK system has 3 b/s/Hz theoretical spectral efficiency, while the Nyquist rate for 9-QPRS is 2 b/s/Hz. However, as highlighted in our publications and patent [1; 12-14], we note that the practical spectral efficiency of 8-PSK systems is in the 2.5 b/s/Hz range with more complex filters - leading to significant system sensitivities. The practical spectral efficiency of the 9-QPRS system is in the 2.2 b/s/Hz to 2.6 b/s/Hz range. It has been proven by numerous organizations (since Dr. Lender's discovery around 1960) that it is feasible to transmit with simple/robust hardware significantly above the Nyquist binary rate with 3-level partial response (PR) signals - which are the baseband part of 9-QPRS modems. See Lender's chapter in [4].

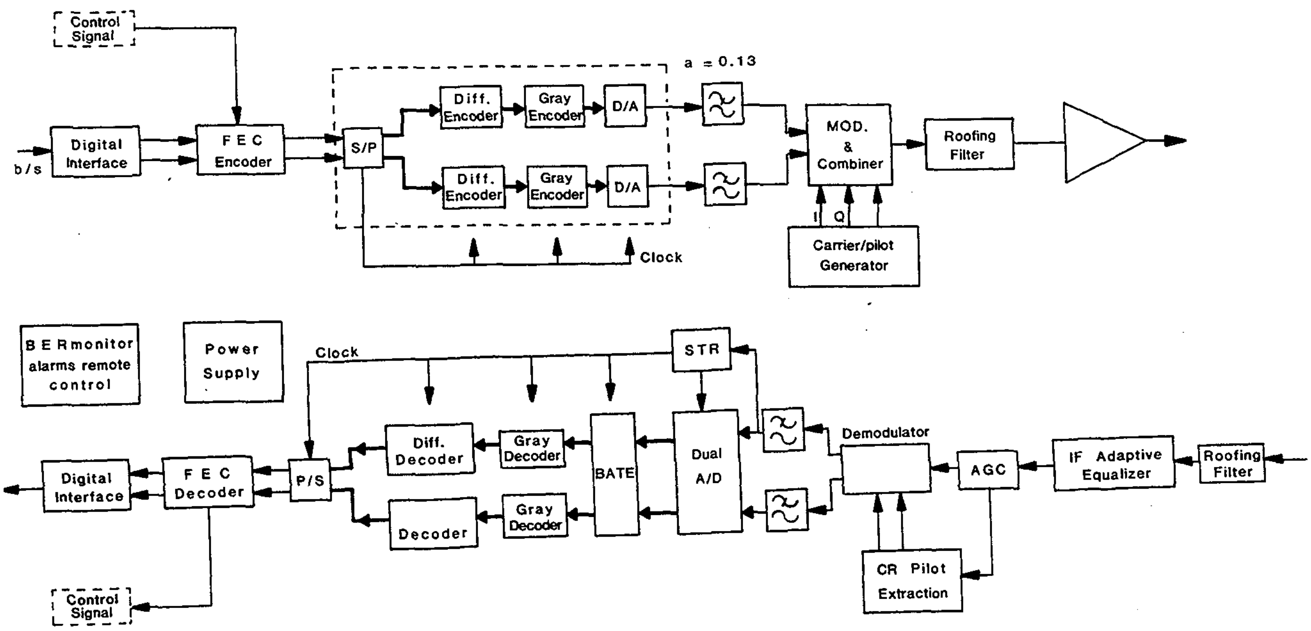

Fig. 5 Block diagram of FEC-Coded QAM and QPRS systems including baseband adaptive time equalizers (BATE).

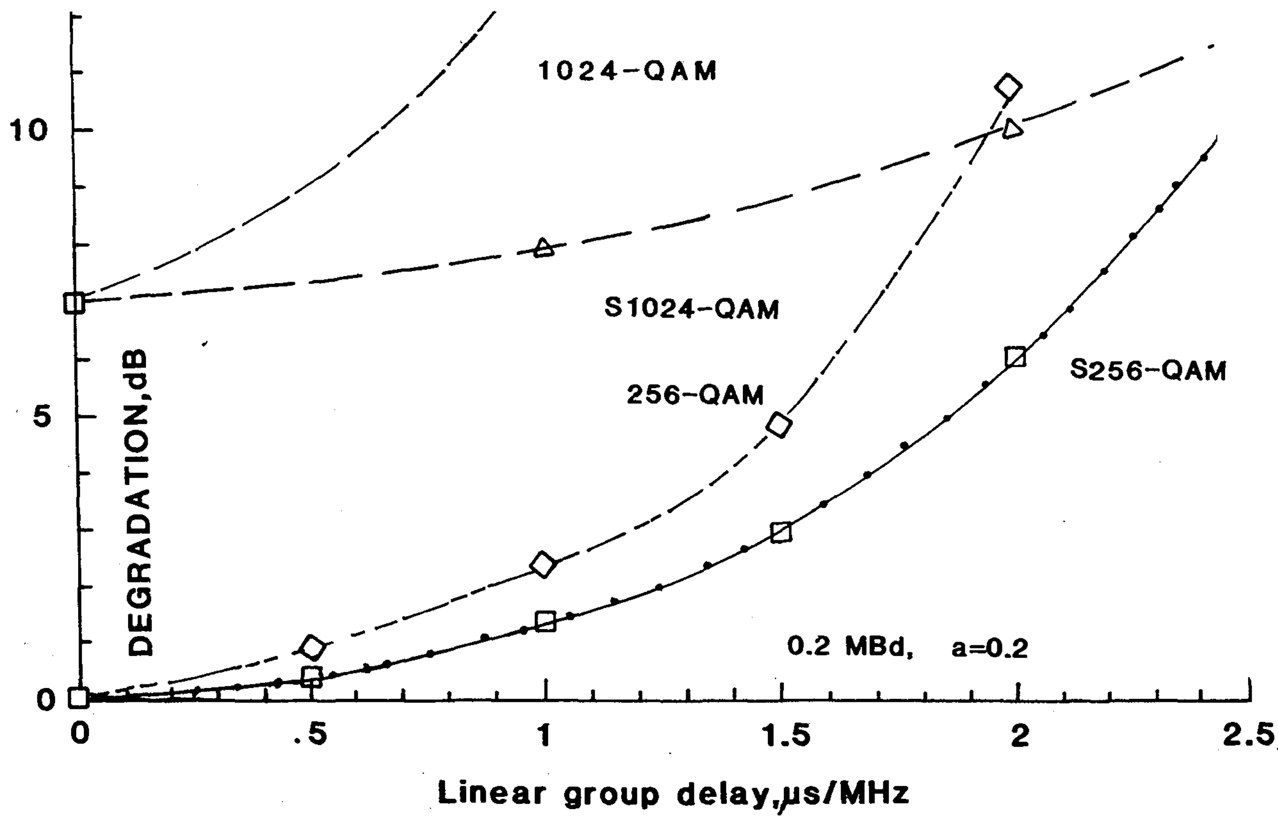

Fig. 6 Performance degradation at BER = 10^{-6} of conventional QAM and of staggered QAM, i.e., SQAM due to residual (unequalized) linear group delay distortions of a cable TV system. These normalized curves are for a scaled-down 0.2 M Baud system [1 and 2].

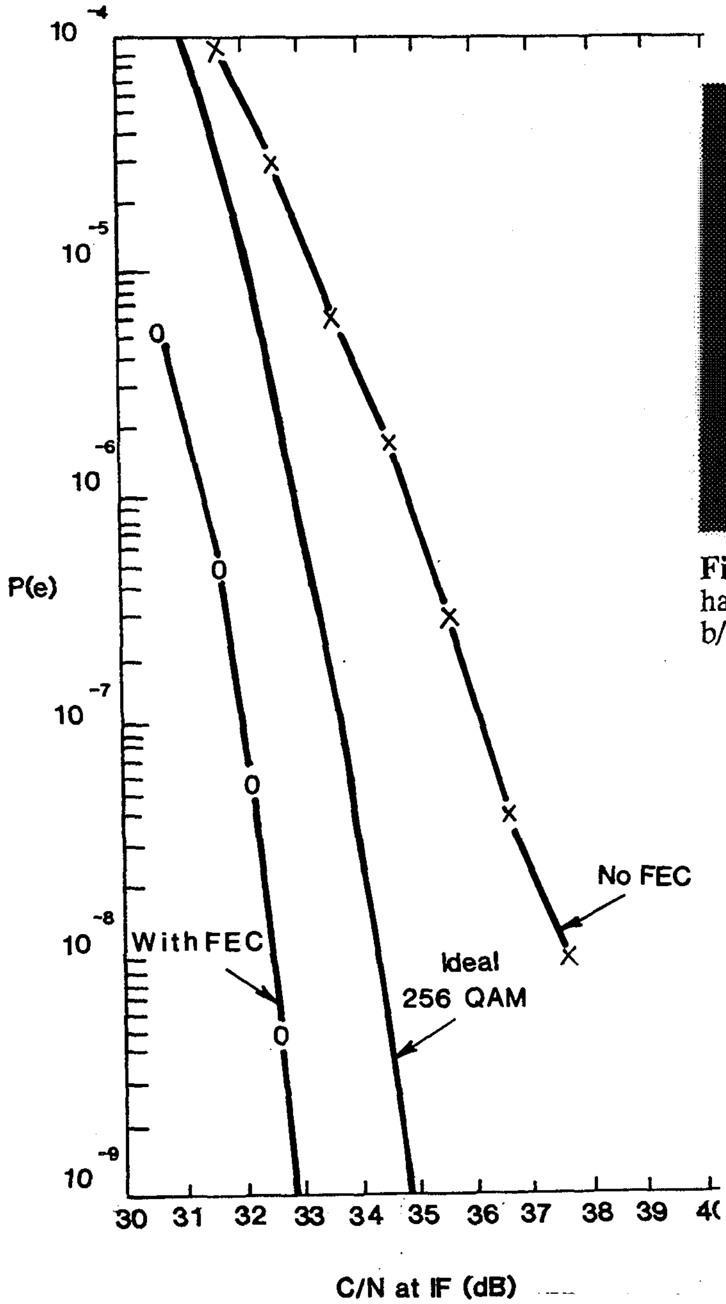

Fig. 7 Experimental 256-QAM-FEC coded performance in cable systems and LOS microwave systems, measured by the author [1 and 2].

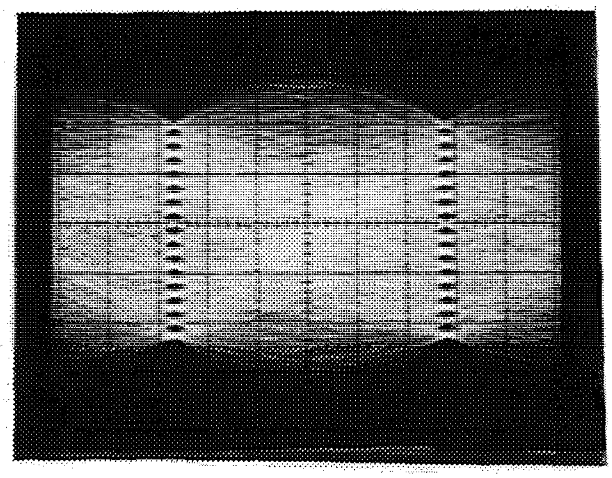

Fig. 8 256-QAM experimental eye diagram having a practical spectral efficiency of 6.66 b/s/Hz.

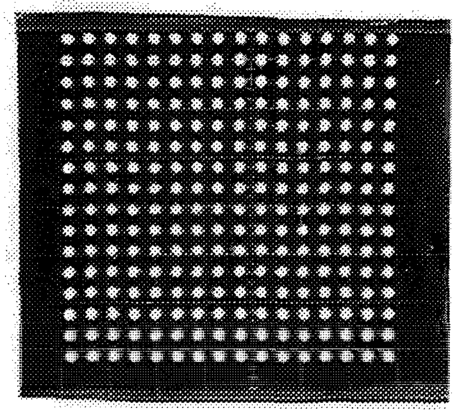

Fig. 9 Constellation of a 256-QAM digitally equalized cable system tested between Vancouver (Canada) and Hawaii [2].

The theoretical BER = P(e) = f(C/N) advantage of 9-QPRS systems as compared to 8-PSK is illustrated in Figure 4 and Table 1.

Table 1 Reduced C/N requirement of 9-QPR as compared to 8-PSK in AWGN systems. The 9-QPR system is about 3 dB more robust than the 8-PSK system.

	9-QPR	8-PSK
10^{-4}	13.5 dB	16.5dB
10^{-6}	16 dB	19 dB
10^{-8}	17.5 dB	20.5 dB

The practical efficiency of 8-PSK is in the 2.5 b/s/Hz to 3 b/s/Hz range if an out-of-band rejection of 20 dB to 30 dB is sufficient. For cable TV applications, we assume that an integrated our-of-band spectral rejection of about 60 dB is required, thus the practical efficiency of 8-PSK is assumed to be less than 2.5 b/s/Hz.

An additional advantage of 9-QPRS systems (as compared to 8-PSK) is that they are approximately 3 dB more robust to **phase noise** [1; 14]. For example, at BER = 10^{-6} the integrated phase noise requirement is (C/N_p) = 23 dB for a 2 dB degradation in case of 8-PSK, while it is only 20 dB in case of 9-QPRS. thus the 9-QPRS has an additional 3 dB phase noise advantage.

Increased capacity-improved performance QPRS systems, i.e., $3 \times 3 = 9$ state; $7 \times 7 = 49$-QPRS and even $15 \times 15 = 225$-QPRS systems can be designed by using a new invention (see [13], patent by Feher et al.). The advantage of the patented QPRS are illustrated in Figs. 14 and 15. A capacity increase of 8% without increasing the number of states and thus the C/N requirement is attained in the experimental results of Fig. 15.

3. DRL'S NEW SQPRS MULTIPLEXED DIGITAL AUDIO CABLE BROADCAST SYSTEM

Staggered 9-QPRS or S-QPRS systems have additional advantages as compared to conventional QPRS. In references [1; 11; 12], it is demonstrated that staggering reduces the peak-factor and the potential intermodulation problems and leads to simpler, better performance coherent demodulator design. In Figure 10, the constellation diagram of a 9-state SQPR digital cable system is presented, courtesy of Digital Radio Laboratories (DRL), Carson, CA. The DRL modem, 9-SQPR is the **'industry first'** operational staggered QPRS cable system implemented in ASIC, see Figure 11. The 9-QPR modem is currently in operation, see Figure 12. The DRL digital audio system carries 18.56 Mb/s data, i.e., two 9.28 Mb/s in two 4 MHz SAW filtered channels. Exceptionally high fidelity MUX (multiplexed) digital audio channels and commercial free music and audio is distributed to cable broadcast systems and directly into homes.

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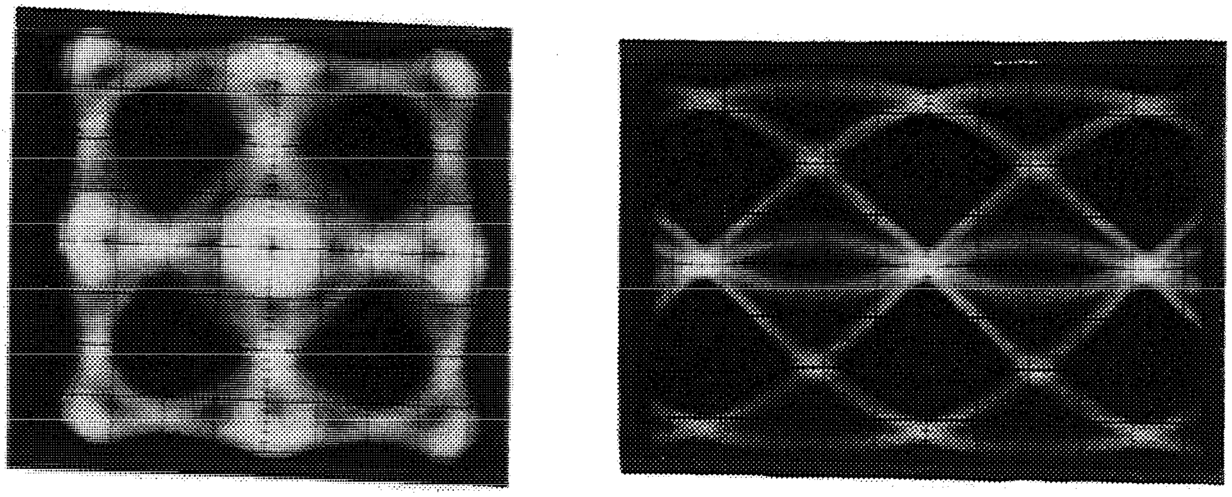

Fig. 10 Constellation and eye diagram of a SQPR digital cable system operated at an 9.28 Mb/s rate. Courtesy of Digital Radio Laboratories, Carson, CA [6].

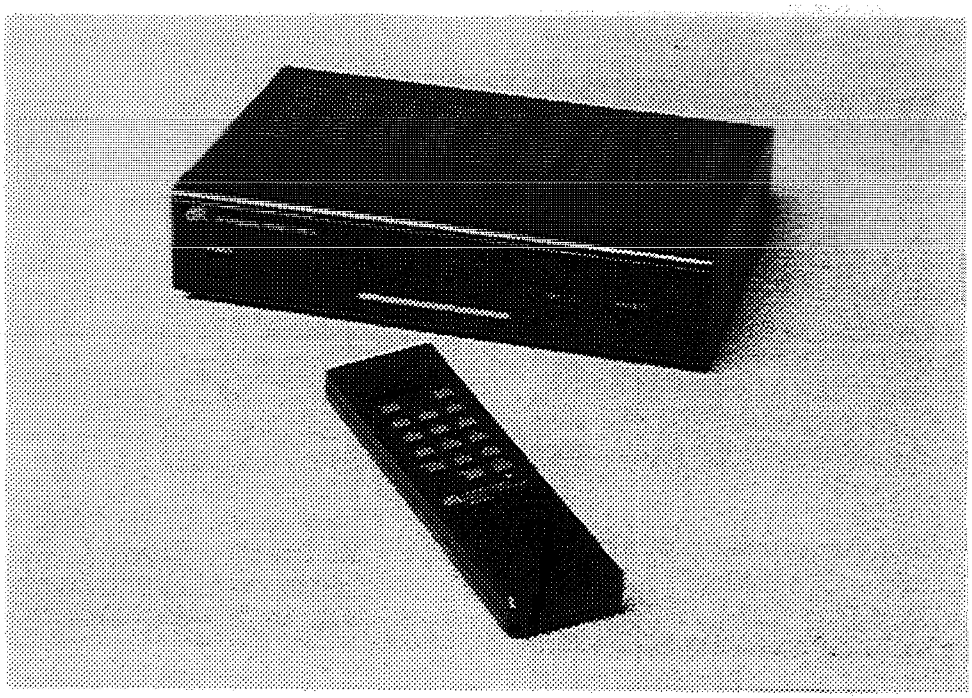

Fig. 11 Cable TV - digital audio receivers for Digital Planet and other highest quality audio receivers. ASIC implementations by Digital Radio Laboratories of Carson, CA led to a compact size, versatility and low-cost original-proprietary SQPR systems design [6].

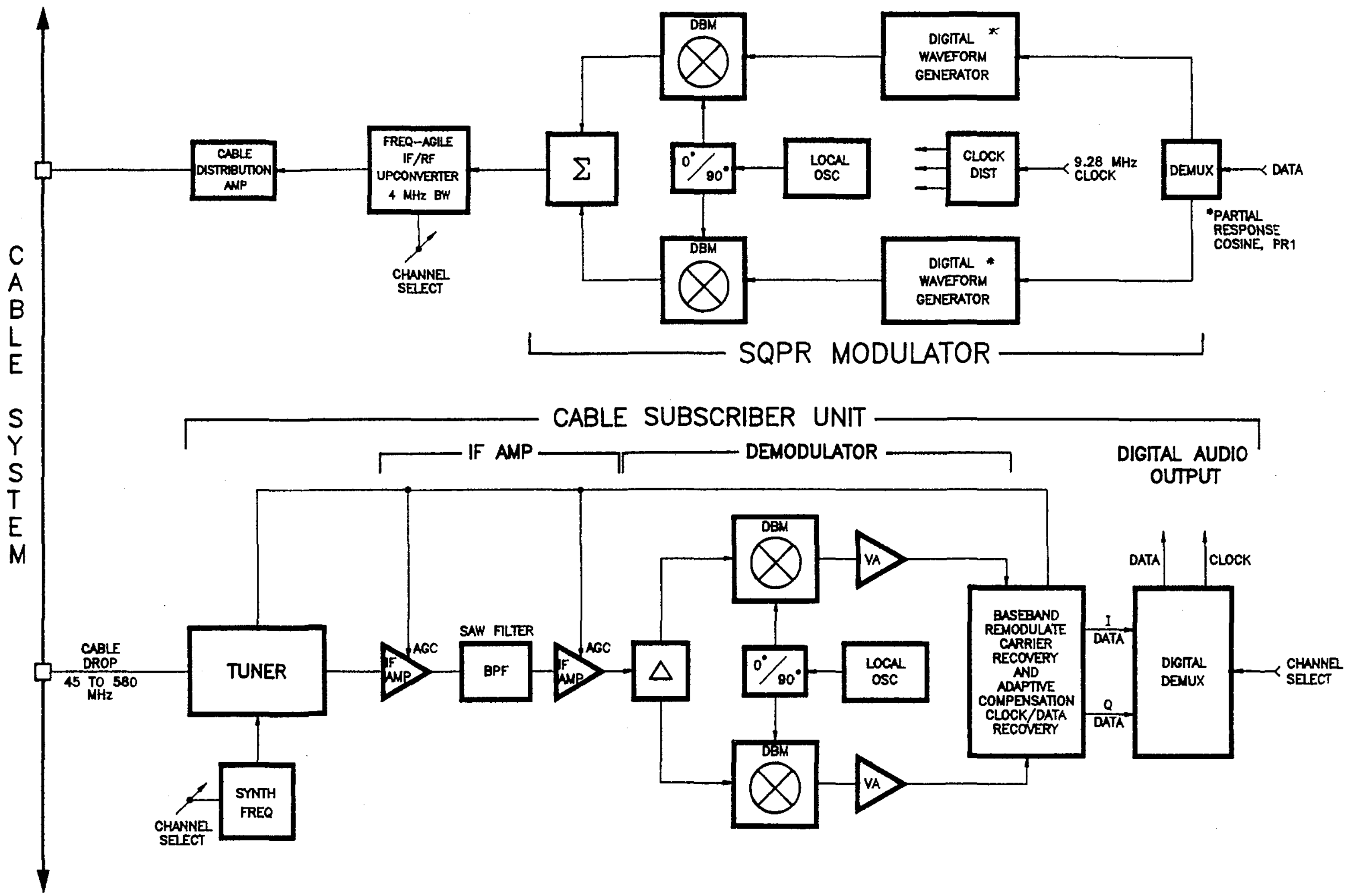

Fig. 12 Digital Audio Cable System of Digital Radio Laboratories (DRL), Carson, CA. This original ASIC implemented staggered SQPRS already operational cable system outperforms conventional 8-PSK systems, see Table I and [6].

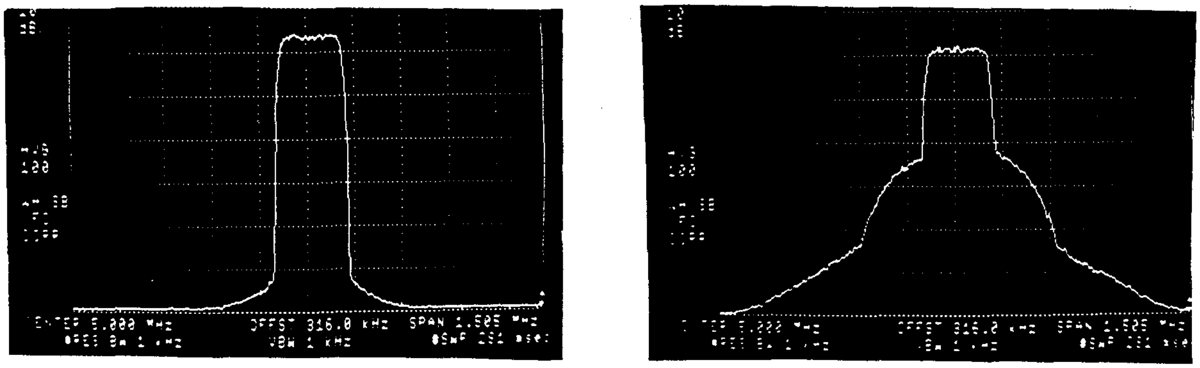

Fig. 13 Spectrum of a 64-QAM linearly and nonlinearly amplified (NLA) system. Spectral regrowth and interference into adjacent TV channels [7 and 11].

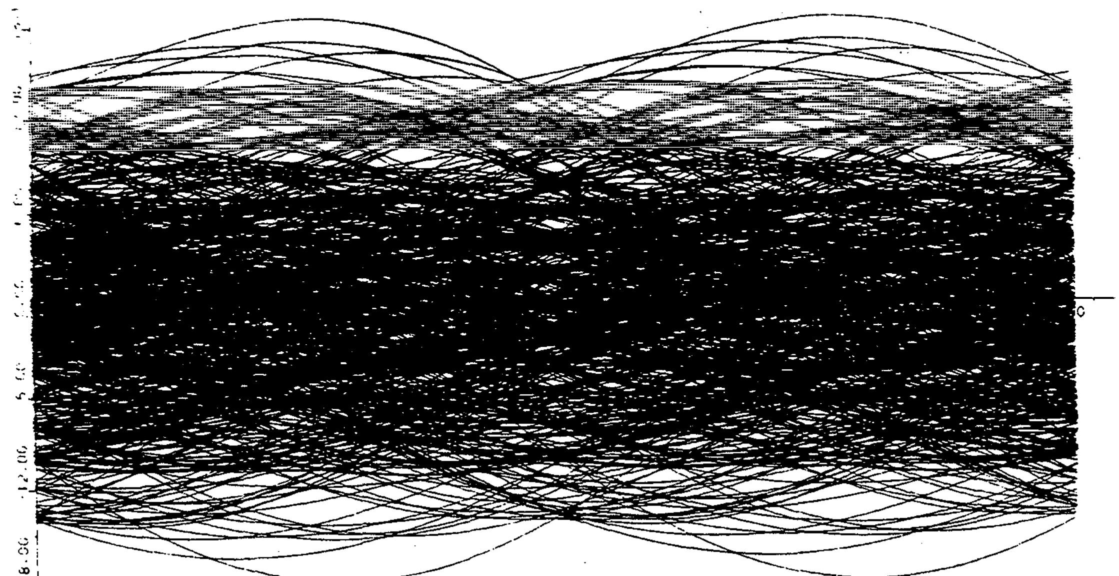

Fig. 14 Conventional 225-QPRS (15 × 15 baseband) operated at 4% above the Nyquist rate with 6.24 b/s/Hz-computer simulation [1; 12; 13] leads to closed eye diagrams.

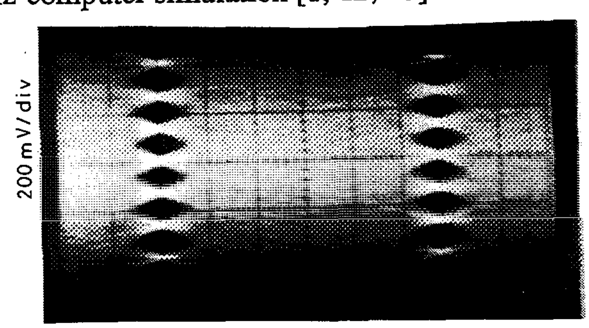

Fig. 15 New 49-QPR and other QPR filter methods, see Feher et al. Patent [13], enable transmission above the Nyquist rate. In this hardware experiment, instead of 4 b/s/Hz we had 4.32 b/s/Hz (an 8% increase and "open eye diagrams" [1; 4; 11; 12; 13].

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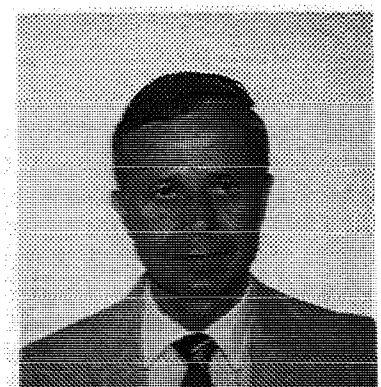

RESUME OF DR. K FEHER

Kamilo Feher, Professor of Electrical and Computer Engineering, University of California, Davis, and Director, Consulting Group, DIGCOM, Inc., has 26 years of industrial and academic R&D, teaching, management, and consulting experience. He has been Consultant to U.S., Canadian, and to many overseas corporations and to governments and has presented numerous short courses. He is known as a very productive world class systems and design research engineer, consultant and a dynamic, enthusiastic instructor. He has 6 U.S. and international patents. He has coauthored more than 260 original research papers and is the author of five books: Advanced Digital Communications: Systems and Signal Processing Techniques (Englewood Cliffs, NJ: Prentice-Hall, 1987); K. Feher and Engineers of Hewlett

Packard: Telecommunications Measurements, Analysis and Instrumentation (Englewood Cliffs, NJ: Prentice-Hall, 1987); Digital Communications: Satellite Earth Station Engineering (Englewood Cliffs, NJ: Prentice-Hall, 1983); Digital Communications: Microwave Applications (Englewood Cliffs, NJ: Prentice-Hall, 1981); and Digital Modulations Techniques in an Interference Environment, (Gainesville, VA: Don White Consultants, 1977). He supervises large digital communications (university and industry based) research teams. His inventions are used by internationally acclaimed major corporations throughout the world. His major discoveries of emerging digital cellular and mobile radio (modulation-demodulation) communications and digital satellite mobile/braodcasting systems are expected to make significant contributions to the ultimate objective of communications - to enable anyone to communicate instantly with anyone else from anywhere.

For his contribution to digital communications research and development (as a professor at the University of Ottawa, Canada), Dr. Feher was awarded the Steacie Memorial Fellowship in 1981, the most prestigious award of the Natural Sciences and Engineering Research Council of Canada (NSERC), the "Engineering Medal, Ontario, Canada", 1989, and elected Fellow of the IEEE. While at UC Davis he received the 1991 S. Helt Memorial Award for contributing an "outstanding series of papers to the *IEEE Transactions on Broadcasting*". He is very active in advanced technology transfer from university to industry.

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