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Title	**A Brief Examination of CQPSK for CPE PHY Modulation**
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Source	Eric Jacobsen Intel 5000 W. Chandler Blvd. CH7-410 Chandler, AZ 85226 Voice: (480)554-6078 Fax: (480)552-0771 mailto:eric.a.jacobsen@intel.com
Re:	This paper is in response to the Call for Evaluations and Improvements for 802.16.1 for Session #6 as contained in Published Document IEEE 802.16-00/07. This paper refers to CQPSK modulation as presented in IEEE 802.16.1pp-00/09a and proposed in IEEE 802.16.1pp-00/09. This method is proposed as the modulation scheme for the return channel.
Abstract	The CQPSK modulation scheme is evaluated for fundamental channel performance. Simulation results are compared for CQPSK and GMSK, which is a very similar method in common use. Power efficiency is evaluated relative to theoretical limits, and spectral efficiency is compared between the two schemes and QPSK.
Purpose	Third party evaluation to aid in assessment of 802.16 PHY proposals.
Notice	
Release	
IEEE Patent Policy	

A Brief Examination of CQPSK for CPE PHY Modulation

Eric Jacobsen
Intel

Introduction

CQPSK has been proposed as the modulation scheme for the return channel considered by the 802.16 Working Group [2]. This paper offers an evaluation of the fundamental characteristics of CQPSK in order to provide the Working Group with additional data for discussion and selection of a PHY standard.

The most fundamental performance criteria for modulation schemes are power efficiency and spectral efficiency. One of the desirable characteristics of CQPSK is the constant-envelope behavior that allows the use of saturated (Class-C) amplifiers or linear amplifiers run with minimal backoff. A similar modulation scheme in common use, GMSK, also enjoys constant-envelope behavior as well as reasonable power and spectral efficiency for network applications. Comparison of CQPSK with GMSK offers a useful evaluation especially considering that the only essential difference between the schemes is the phase filter in the modulator. Simulation results for power efficiency are included for CQPSK and GMSK with respect to theoretical performance, and spectral occupancy is compared between the two schemes.

Constant Envelope Phase Modulation

A simple method of phase modulating a constant-envelope signal utilizes a VCO as the modulator. Since the VCO's output amplitude is independent of the input signal, it can easily be kept constant in order to utilize efficient High Power Amplifier (HPA) technologies in the implementation. Generally this is done at some expense to spectral efficiency. Certain phase-filtering schemes allow reclamation of some spectral efficiency with arguably the most common being GMSK. CQPSK utilizes a slightly different phase filter to provide an alternative compromise to GMSK.

Figure 1 shows the basic block diagram of a phase-filtered VCO modulation system. The modulating bit stream is fed serially into the phase filter, which smoothes or shapes the transitions. The VCO input is essentially a phase argument, so the response of the filter provides smoothing in the phase modulation realized in the VCO.

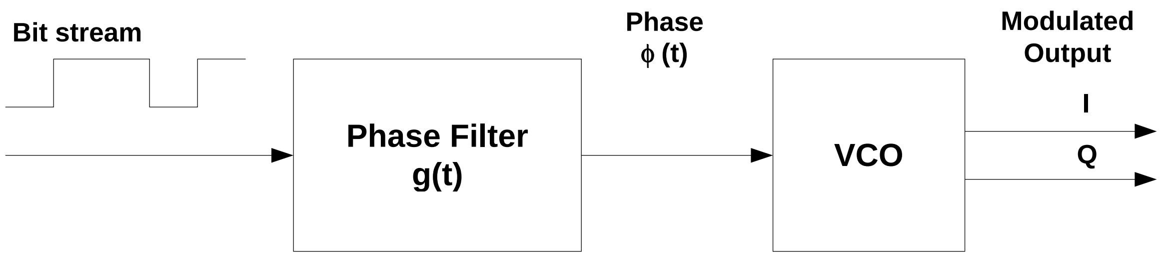

Figure 1. Basic Phase Modulator with Phase Filter.

For GMSK the filter response is a gaussian shape, the width of which allows selection of a compromise between spectral efficiency (i.e., sidelobe response) and power efficiency. As the time-domain width of the response is increased, Inter-Symbol-Interference (ISI) is also increased which provides a sidelobe reduction at the expense of power efficiency. Many GMSK systems (e.g., GSM) utilize a pulse width with a time-bandwidth product of BT = 0.3 which provides reasonable spectral behavior at a cost of ~1dB in power efficiency.

The phase filter for CQPSK is expressed in Equations 1 and 2 as indicated in [1]. This phase filter has some interesting properties in that it provides a five-level modulated phase input to the VCO due to ISI in the phase domain. Figure 2 shows a diagram of the output of the phase filter for a GMSK system with BT = 0.3, and Figure 3 shows the output of the phase filter for CQPSK. The GMSK system provides two-level modulation in the phase domain with noticeable ISI, while the CQPSK system provides five distinct phase transition levels due to the built-in ISI generated in Equation 2.

$$g_0(t) = \sin\left(\frac{\pi\cdot t}{T}\right)\cdot\left(\frac{1}{\pi\cdot t} - \frac{2 - \frac{2\cdot\pi\cdot t}{T}\cdot\cot\left(\frac{\pi\cdot t}{T}\right) - \frac{\pi^2\cdot t^2}{T^2}}{\frac{24\cdot\pi\cdot t^3}{T^2}}\right)$$

Equation 1.

$$g(t) = \frac{1}{8}\cdot g_0(t-T) + \frac{1}{4}\cdot g_0(t) + \frac{1}{8}\cdot g_0(t+T)$$

Equation 2.

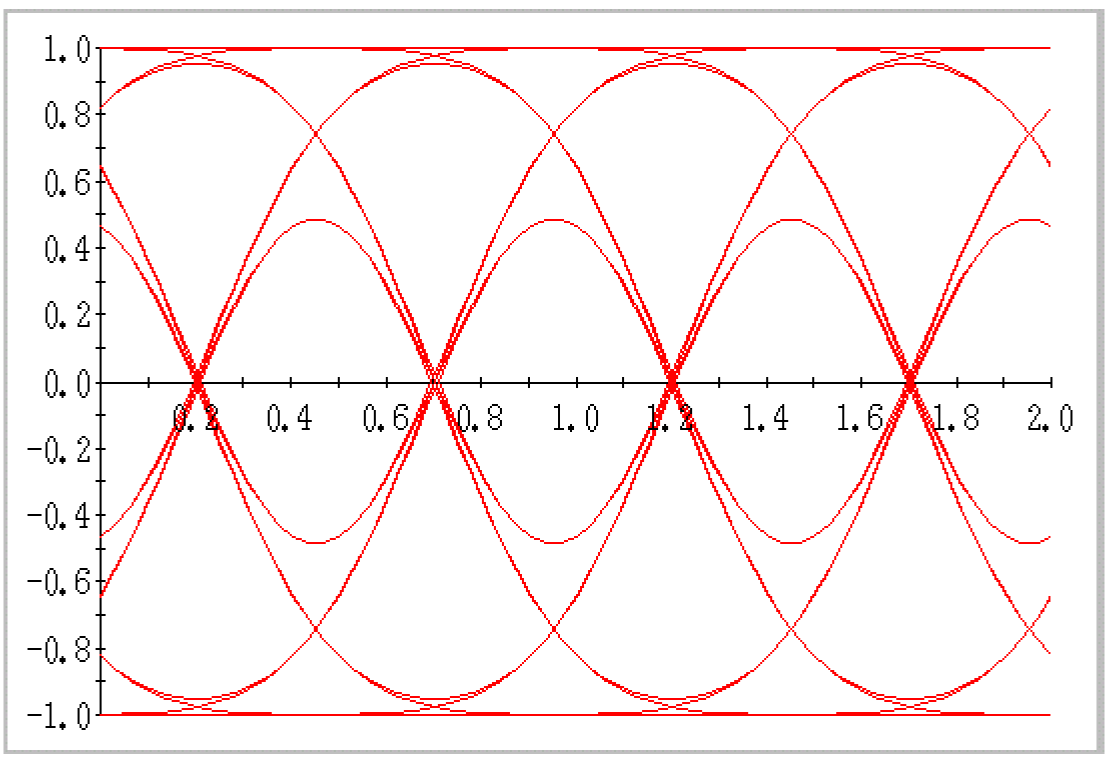

Figure 2. Four symbols of GMSK gaussian filtered phase, BT=0.3. Note the significant ISI.

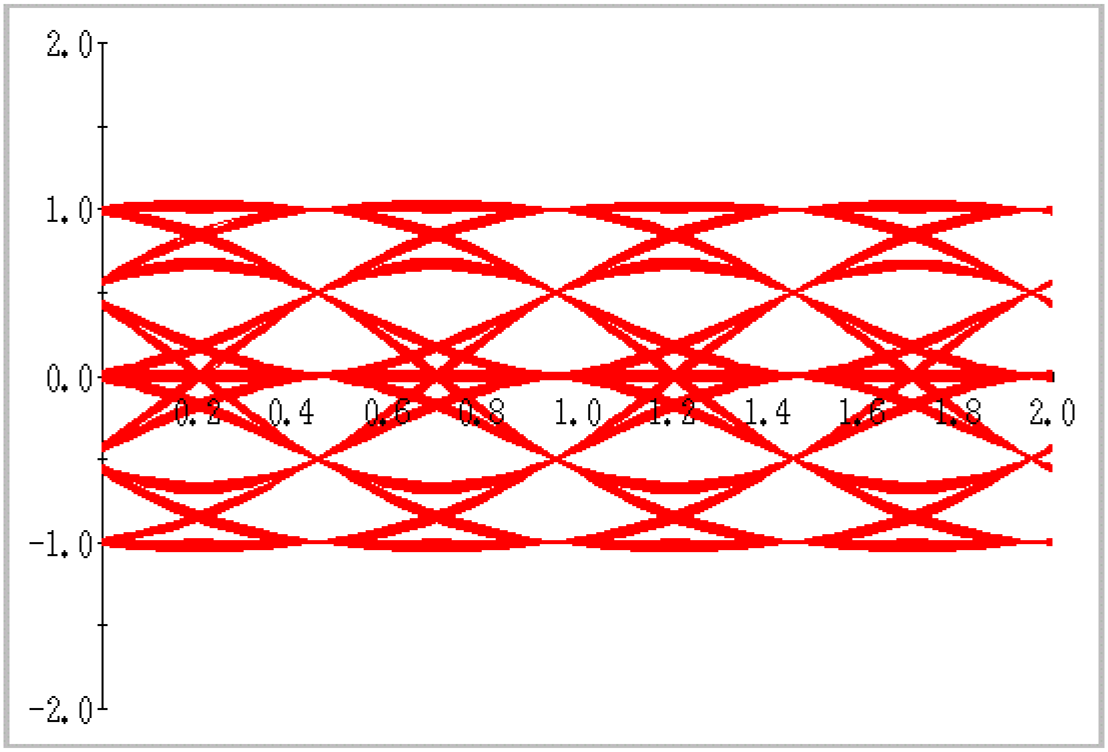

Figure 3. Four symbols of CQPSK filtered phase.
Eye patterns are discernable and the five possible phase transitions are visible as well.

Simulation and Results

Simulations were performed using SPW (aka Cierto) from Cadence Design Systems. Phase modulator models were constructed using appropriate phase filters with VCO models. GMSK and CQPSK are similar at the modulator output to OQPSK, and an OQPSK demodulator can be used to recover each with no loss of performance. The demodulator simulation models for GMSK and CQPSK were identical, utilizing Raised-Cosine Nyquist filters with 40% excess bandwidth. Raised-Cosine receive filters are used (as opposed to Root-Raised-Cosine) since they provide good frequency selection and do not contribute additional ISI in the receiver. A block diagram of the simulation demodulator model is shown in Figure 4.

The modulated spectra of GMSK with BT = 0.3 (i.e., the GSM case) and CQPSK are shown in Figure 5. The spectral shapes of the two methods are very similar to within ~1.25 symbol rates of the channel center. With BT = 0.3, GMSK exhibits noticeable sidelobes at ~-37dBc while CQPSK continues to decay monotonically. Adjusting the gaussian phase filter to BT = 0.22 reduces the GMSK sidelobes seen in Figure 5 with an expected reduction in power efficiency. Figure 6 shows the modulated spectra of GMSK with BT = 0.22 and CQPSK, and it is seen that the spectra are essentially the same for this case.

Power efficiency performance results are represented in the BER plot shown in Figure 7. The simulations executed estimate performance for fully coherent demodulation in AWGN with no implementation loss. Theoretical performance for coherent demodulation of QPSK is shown in the solid red line, while simulation results for GMSK with BT = 0.3 are shown in the dotted line. Simulation results for GMSK with BT = 0.22 are indicated with the dash-dot line, and CQPSK is represented in the dashed line. The GMSK performance shows the expected ~1dB loss from theoretical with BT = 0.3, while the CQPSK system suffers an additional ~2.5dB loss in power efficiency. Performance for GMSK with BT = 0.22 is approximately 1dB better than CQPSK with essentially the same spectral characteristics.

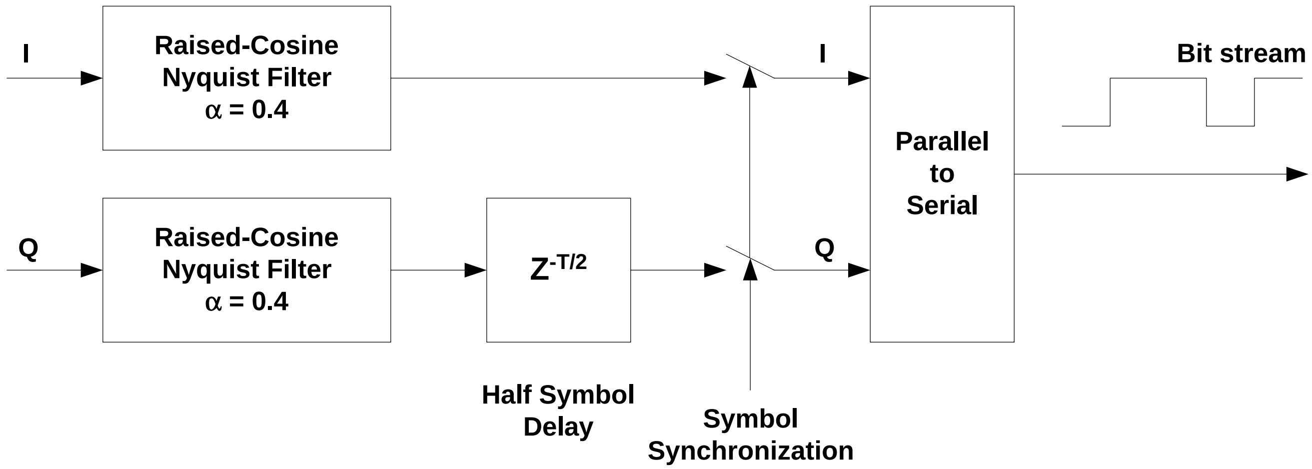

Figure 4. Block diagram of simulation demodulator model.

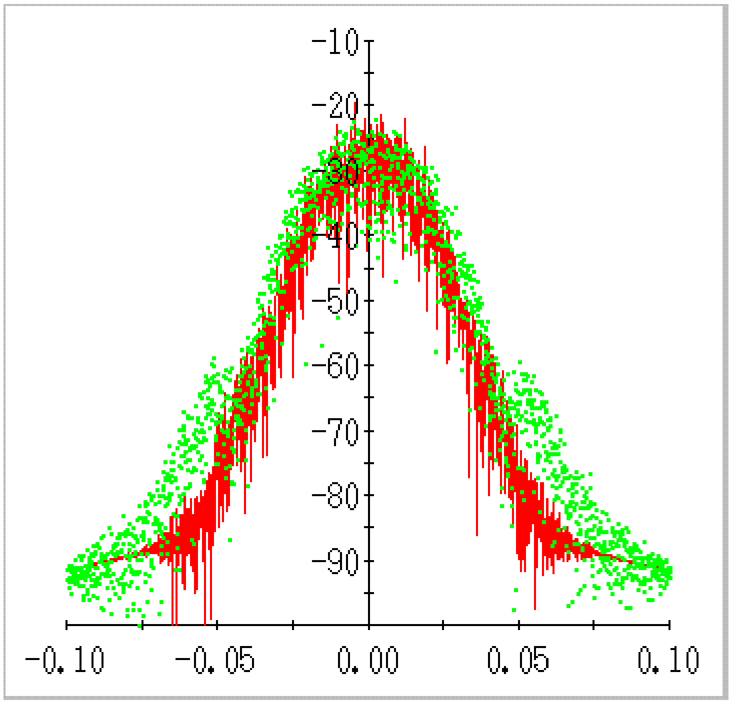

Figure 5. The modulated spectra of GMSK with BT = 0.3 and CQPSK overlaid for comparison. The GMSK signal is represented with green points, while the CQPSK signal is indicated by the red lines. Since the modulated symbols are each 32 samples long in the simulation, the symbol rate range is +/-0.015625 in the horizontal scale.

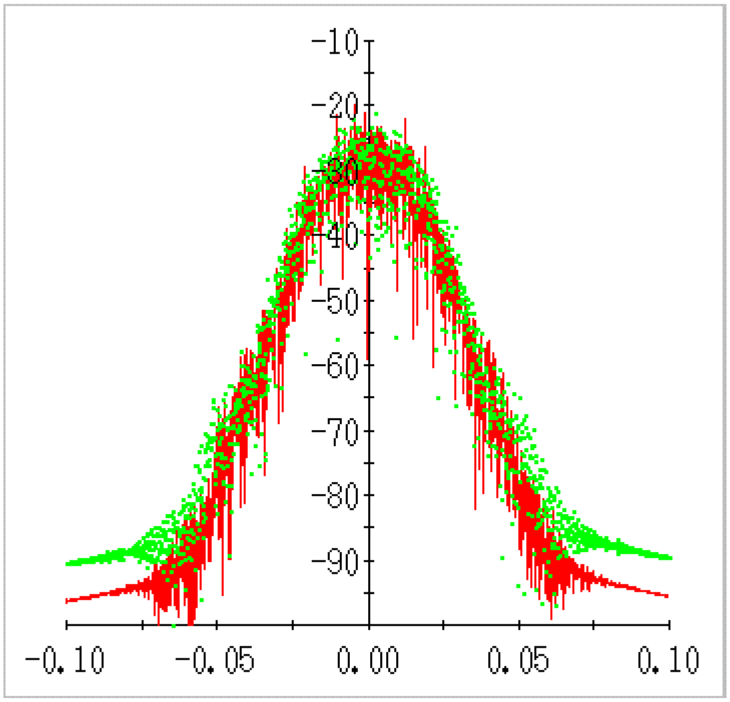

Figure 6. The modulated spectra of GMSK with BT = 0.22 and CQPSK overlaid for comparison. The GMSK signal is represented with green points, while the CPQSK signal is indicated by the red lines. Spectral occupancy of the two modulations is essentially the same.

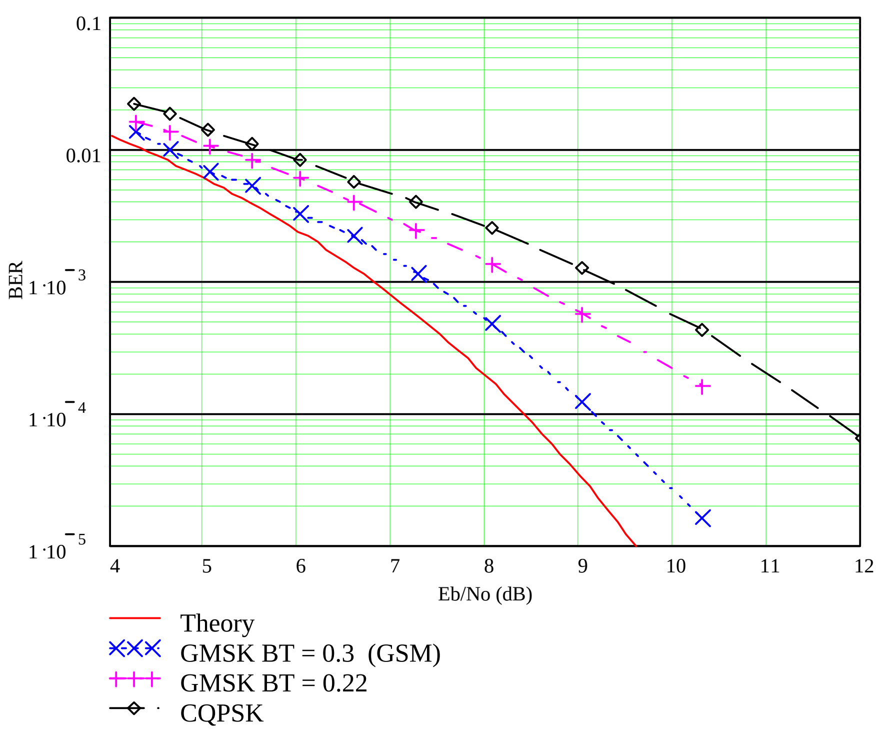

Figure 7. BER for coherent reception of GMSK and CQPSK in AWGN.

An intuitive explanation for the additional loss experienced with CQPSK can be seen in Figures 8 and 9. Figure 8 shows the received constellation for GMSK with BT = 0.3, and the four constellation points are spread due to the ISI introduced by the gaussian phase filter. Figure 9 shows the received constellation for CQPSK, and it is readily apparent that the constellation points are spread by an increased amount of ISI. Figure 10 and 11 show eye diagrams of GMSK and CQPSK, respectively, at the modulator output. The additional ISI exhibited in the CQPSK modulation is apparent.

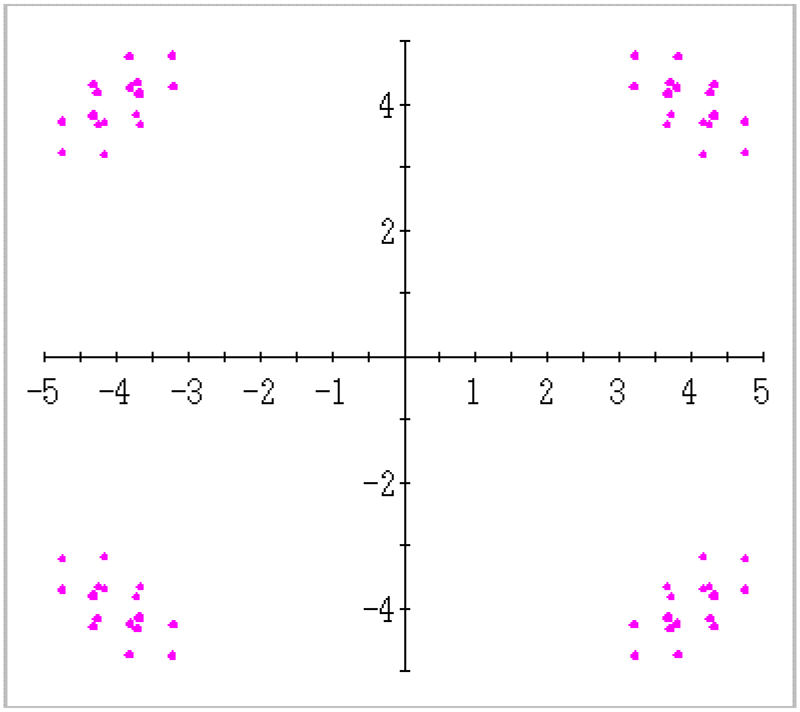

Figure 8. GMSK receive constellation for BT = 0.3. The ISI due to the gaussian phase filter spreads the four constellation points.

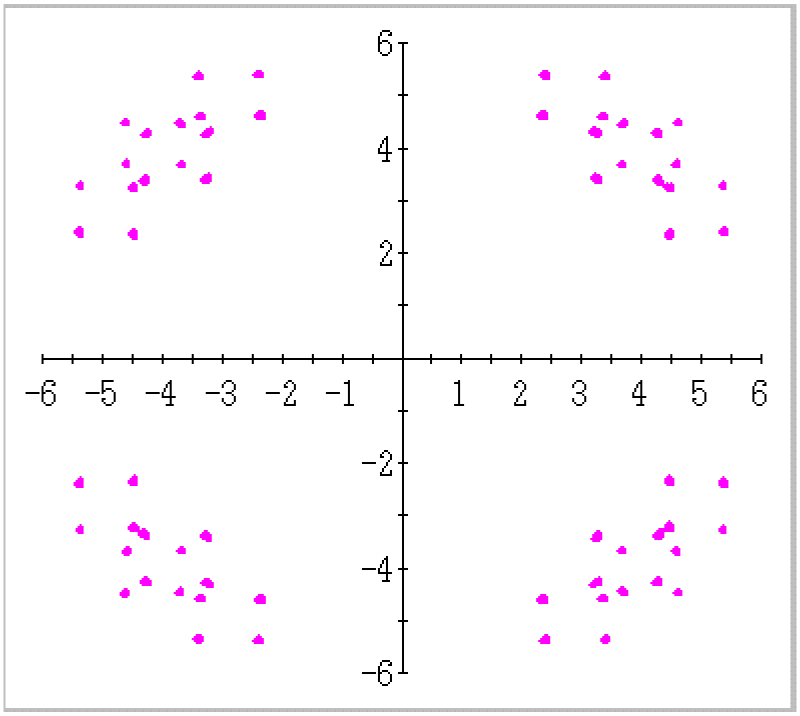

Figure 9. CQPSK receive constellation. The wide spreading of the constellation points indicates the presence of significant ISI.

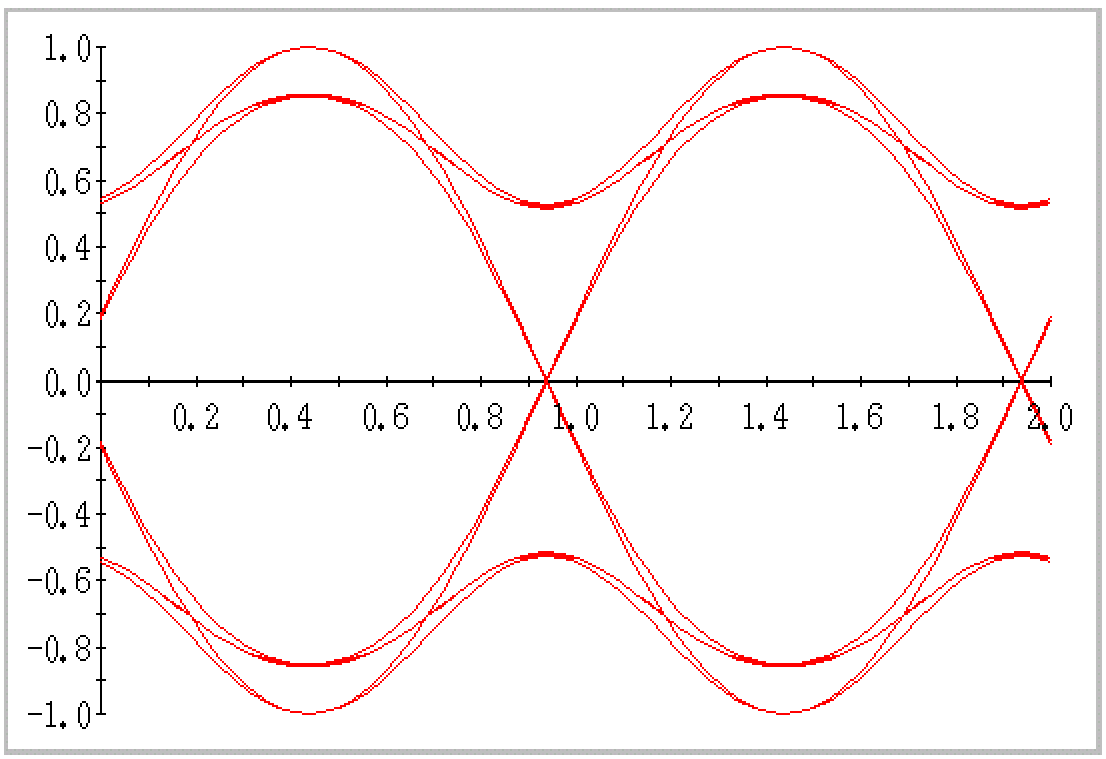

Figure 10. Modulator Eye Diagram for GMSK with BT = 0.3. The ISI is exhibited in the additional level in the peak region.

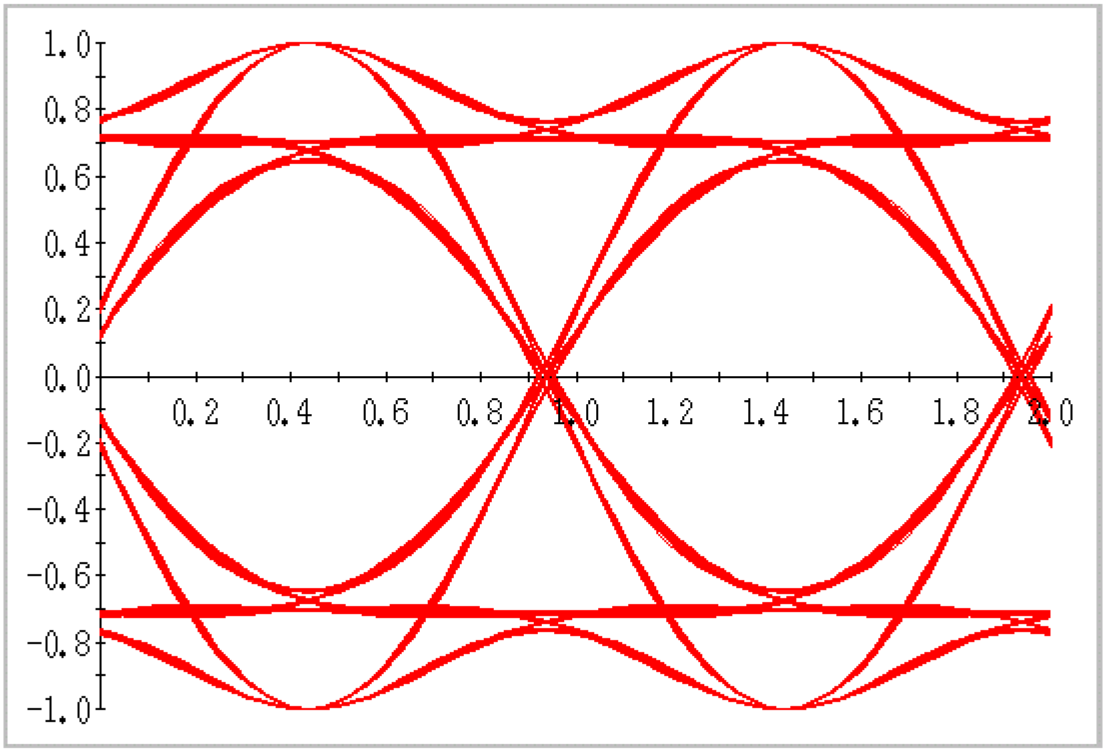

Figure 11. Modulator Eye Diagram for CQPSK. The additional ISI in comparison to the GMSK signal is clear.

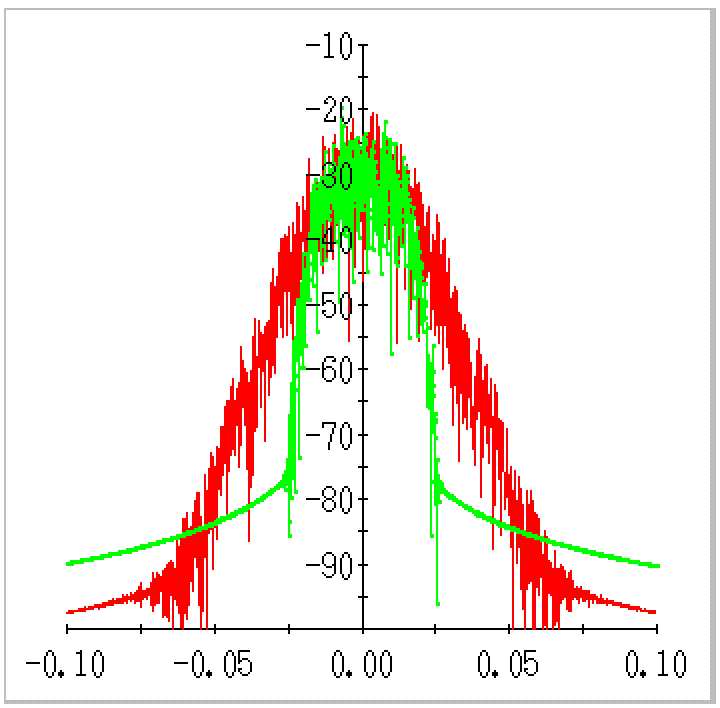

Figure 12. The modulated spectra of QPSK and CQPSK overlaid for comparison. The QPSK signal is represented by the green lines while CQPSK is indicated by the red lines. The QPSK signal was filtered with a 40% Root-Raised-Cosine Nyquist transmit filter. QPSK provides much better spectral efficiency as long as the power amplification provided by the HPA is highly linear.

Discussion and Conclusions

The proposed CQPSK modulation scheme is very similar in style and implementation to GMSK so comparison with GMSK seems to be a suitable benchmark. Simulations indicate that GMSK with BT = 0.22 provides ~1dB improvement in power efficiency over CQPSK with essentially the same spectral characteristics. The similarity of the two modulation methods suggests that expected performance in multipath interference, ACI, CCI, etc., impairments would be very similar if not identical. Modulators using a phase-filter and VCO architecture are identical for the two schemes with the exception of the phase-filter response. A digital phase-filter with programmable coefficients could easily be made to handle either scheme, or even different BT parameters for GMSK, and the demodulators are identical for all of the considered cases.

Evaluation of the return channel modulation scheme must take into account the size and configuration of the expected HPA in the CPE, since it has significant impact on CPE cost as well as network spectral efficiency in the return channel spectrum. Figure 12 shows the modulated spectra of QPSK/OQPSK and CQPSK revealing the relative spectral inefficiency of CQPSK. This improved spectral efficiency in QPSK requires linear amplification in the HPA, which increases the cost and power consumption of the CPE. The use of linear amplification may also simplify implementation of network power control since a remote link to the ODU is not needed to adjust the CPE output power.

It may be desirable to allow adaptive modulation in the return channel to allow systems to take advantage of high link margins in nodes near the base station. In such cases the CPE could back off the output power with a linear HPA to the point where QPSK or OQPSK could be used in a narrower return channel than required for GMSK or CQPSK. This would require an adaptable modulator that could select between the GMSK VCO model and a more traditional quadrature modulator architecture. It is very difficult to implement GMSK or CQPSK in a traditional quadrature modulation architecture since the ISI introduced by the phase filter is essentially cross-channel interference between the I and Q channels.

Given the similarity of CQPSK and GMSK modulation methods and the apparent superiority of GMSK in power efficiency, it is difficult to make a case for selection of CQPSK for the return channel modulation when there appears to be superior alternatives. Unless there are other unstated advantages of CQPSK it does not seem to represent the best available option for the return channel modulation. It may be prudent to consider more spectrally efficient methods such as QPSK or OQPSK if practical given CPE terminal cost considerations.

References:

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[2] J. Klein, L. Lindh, C. Eklund, et al, "PHY Layer Proposal for BWA," Document #802.16.1pc-00/09, Presented at 802.16 Session #5, Richardson, TX, Jan. 12, 2000.

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[4] Sklar, B., *Digital Communications: Fundamentals and Applications*, Englewood Cliffs, NJ: Prentice-Hall, 1988.