High-Capacity Coherent DCIs using PolMuxed Carrier and LO-Less Receiver

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Abstract—A PAM4 based direct detection system has been standardized for short-distance data center interconnects because of its simple architecture. Performance of the PAM4 systems is limited for high dispersion values or demands complicated signal processing for further increase in data rates. A polarization multiplexed carrier based self-homodyne (PMC-SH) link with adaptive polarization control is a practical approach with an laser oscillator (LO)-less and carrier phase recovery (CPR)-free coherent receiver that can replace PAM4 links for achieving high data rates. We analytically find that PMC-SH scheme results in a significantly better BER for a given transmission rate or can achieve doubling of the data rate for given bandwidth of electronics and laser power (when compared with PAM4). Practical implementation of the proposed system with adaptive polarization control is also discussed. Presented theoretical framework highlights the advantages of such self-homodyne systems over PAM4 based systems in terms of SNR requirements and capacity.

Index Terms—PAM4 links, data center interconnects, self-homodyne system, polarization multiplexed carrier.

I. INTRODUCTION

DATA center applications are dominated by short distance optical links as intra data center links cover 71.6% of the total applications [1]. Although coherent links with the employment of spectrum efficient techniques like quadrature phase shift keying (QPSK) and quadrature amplitude modulation (QAM) are the first choice for long haul communications, need of power consuming digital signal processing with analog to digital converters make them unsuitable for short distances. A pulse amplitude modulation (PAM) based direct detection system is being used and is widely chosen because of simple hardware and lower power requirements [2] for such data center interconnects (DCI). As the traffic demands are projected to reach 20.6 ZB per year by 2021 as per Cisco forecast [1], the PAM4 adaptability for this future need is a major concern now [3]–[6]. Use of the commercial PAM modules for such high data rates is being discussed in demonstrations for DCI applications [7], [8]. In parallel, implementation of the coherent techniques using remote modulation and self-homodyne (SH) scheme using duplex fiber have also been demonstrated [9], [10]. However, none of the above propositions assures reduction in the signal processing complexity for controlling the power requirements at data centers. For reducing the power consumption and cost, analog domain signal processing has been proposed for coherent receivers [11]–[13]. Presented work investigates an SH scheme to replace the PAM4 links with the aim of further increasing capacity using analog signal processing based receivers.

An SH system is a reduced complexity coherent receiver in which the carrier related processing at the receiver is not required as the carrier is sent along with the modulated signal. The SH systems offer many advantages: i) A simple coherent receiver (without local oscillator) and similar receiver electronics is required (without carrier phase noise/carrier phase recovery and correction algorithms that are required in conventional coherent systems). It simplifies electronic signal processing and makes it comparable to the PAM4 links and is feasible for analog domain processing for further power reduction; ii) Phase noise cancellation results in line width tolerance, thus reducing the cost of an expensive laser at transmitter (which is a stringent requirement in conventional coherent systems) [13], [16]; iii) Opens up a way to increase data rates further by employing spectrally efficient techniques like 16 QAM and 64 QAM [17], [18]. A polarization multiplexed carrier based self-homodyne (PMC-SH) system does not require switches or converters (as required in other SH schemes [19], [20]) that can limit the performance at high speed. Implementation of the PMC-SH systems have been experimentally demonstrated before [15], [17], [18], [21], [22]. However practical implementation of this technique in DCIs is constrained by the need of continuous polarization control for adequately separating the carrier and the modulated signal at the receiver.

The adaptive polarization control for the PMC-SH links can be achieved with an electrically controlled polarization controller (EPC) by minimizing power in one of the polarization at reception [23]. Silicon photonics based polarization controllers (PCs) are also being proposed for other applications that can be implemented for PMC-SH systems further [24]. Experimental demonstration of a practical PMC-SH system (which uses adaptive polarization control) has been presented in our other work for 64 Gb/s SH-16 QAM system [25].

In this work, the performance of the PMC-SH links and the PAM4 links respectively is evaluated and compared based on the statistical framework considering all the practical factors like insertion loss and receiver noise. An optimum (Best) case of PAM4 with non uniform levels for shot noise limited receiver is considered. The practical implementation of PMC-SH links is discussed and adaptive PC requirements are also included in the power modeling of the PMC-SH links.

This paper is organized as follows: Section II describes system details with applied polarization control method. Section III discusses the detailed statistical framework. Section IV presents the results.
presents the comparison graphs, followed by Section V which includes conclusion and future work directions.

II. PROPOSED SYSTEM AND ITS PRACTICAL IMPLEMENTATION

A PMC-SH system block diagram is presented in Fig.1 with the consideration of its practical implementation with continuous polarization control. Self-homodyning is achieved in this system by using polarization diversity for sending the carrier along with the modulated signal. At the transmitter end, one of the polarization of the laser output is modulated and combined with the other polarization (unmodulated carrier to be used as LO at the receiver). At the receiver end, due to polarization impairments, the modulated signal is mixed with the carrier and the carrier is mixed with the modulated signal. This is the result of random fluctuations in state of polarization by the channel. Adaptive polarization control is required for maintaining the linear state of polarization continuously for the proper separation of two polarization without any cross polarization mixing. Polarization mode dispersion effect is not very significant for the short distance DCIs, so and an EPC with a simple circuitry is able to attain desired state of polarization.

For such SH systems, minimization of power in one polarization is able to achieve linear state of polarization as discussed in [23]. An electrically controlled PC can be used to maintain minimum power in one polarization by changing its angles based on the control inputs. The control inputs are provided by a control circuit with gradient decent algorithm. Gradient descent algorithm results in control signals towards minimizing the feedback signal. For providing electrical feedback, some fraction (≈10%) of one polarization power is converted into electrical feedback signal by a photo detector (PD). This control loop successfully separates the carrier and the modulated signal as presented in the snapshots of the simulations for the optical spectrum’s of both polarizations (before and after EPC) in Fig.1. Simulations were performed in VPItransmissionmaker for 50 Gb/s SH-QPSK system with 20 km fiber. Details of the simulations are available in our previous work [23].

Separated carrier is used as an LO for the coherent receiver front end for the reception of the modulated signal. Receiver front end consists of an optical hybrid and PDs providing electrical I and Q signals. A receiver front end with a monitoring PD can be used to avoid external PD for the feed back that simplifies implementation. Received I and Q signals are applied to signal processor that can be analog processing based equalizer as no complicated processing is required. Equalization is only needed for the dispersion compensation as there is no need for carrier related processing. Practical implementation of this system has been demonstrated by performing experiments for 64 Gb/s SH-16QAM system with EPC and key results (received signal and equalized signal) are shown in Fig.1. Details of the experimental setup and results are available in our other submitted work [25]. These experiments validate the practicality of the SH systems in terms of implementation and demands further evaluation in terms of signal to noise ration (SNR) and capacity for short reach links.

III. STATISTICAL FRAMEWORK

For evaluating the performance of the PMC-SH links in comparison to the PAM4 links, expressions for the probability of error P(E) have been derived in terms of laser power and baud rate. The PAM4 link is compared with the PMC-SH-QPSK link (offering same bit rate as PAM4) and with PMC-SH-16QAM link (offering double bit rate than PAM4).

Systems have been modeled with the consideration of insertion losses of all the components and for both types of receivers (thermal noise limited and shot noise limited). Note that Q is denoting mathematical Q function in the following analysis.

A. PAM4 links

PAM4 system has a simple direct detection receiver as shown in Fig.2 and the received power is effected by the modulator insertion loss and fiber attenuation. General expression for P(E) is detailed in Appendix A in the form of considered amplitude levels $a_1, a_2, a_3, a_4$ for four possible symbols with variances $\sigma_1, \sigma_2, \sigma_3, \sigma_4$ respectively. Optimum spacing
between levels for PAM4 is used for the comparison analysis. In the case of thermal noise limited receiver, expression for signal power to noise power (SNR) is:

\[
SNR = \left( \frac{RP_t}{ak_m t} \right)^2 \left( \frac{n_t \Delta f}{(ak_m t)^2 n_t^2 \Delta f} \right)
\]

(1)

where \( P_t \) is transmitter laser power, \( R \) is responsivity, \( k_m t \) is the insertion loss of intensity modulator, \( n_t \) is thermal noise power spectral density, and \( \Delta f \) is the receiver bandwidth. Average power for non-uniformly spaced PAM4 scheme is:

\[
P_a = \left(0 + \frac{1}{81} + \frac{16}{81} + 1\right)P_t = 0.302P_t.
\]

(2)

By considering average power in (1), effective SNR for the case of thermal noise limited receiver is:

\[
SNR_{PAM4nt} = \left( \frac{0.302RP_t}{ak_m t} \right)^2 \left( \frac{n_t \Delta f}{(ak_m t)^2 n_t^2 \Delta f} \right).
\]

BER can be calculated by putting value of SNR\(_{PAM4nt}\) in [15] and the resulting expression is:

\[
BER_{PAM4nt} = \frac{3}{4} \left[ Q \left( \frac{1}{3} \sqrt{\frac{(0.302RP_t)^2}{(ak_m t)^2 n_t^2 \Delta f}} \right) \right].
\]

(3)

Expression for signal power to noise power considering only shot noise is:

\[
SNR = \frac{RP_t}{2q\Delta f \left( \frac{RP_t}{ak_m t} \right)} = \frac{RP_t}{2aq\Delta f k_m t},
\]

(4)

where \( q \) is electron charge. By considering average power in (2), effective SNR for the case of shot noise limited receiver is:

\[
SNR_{PAM4ns} = \frac{0.302RP_t}{2aq\Delta f k_m t},
\]

(5)

BER can be calculated by putting the value of SNR\(_{PAM4ns}\) in [15] and resulting expression is:

\[
BER_{PAM4ns} = \frac{3}{4} \left[ Q \left( \frac{1}{3} \sqrt{\frac{0.151RP_t}{aq\Delta f k_m t}} \right) \right].
\]

(6)

**B. PMC-SH-QPSK links**

Block diagram of a PMC-SH-QPSK system along with the power modeling at every stage in terms of laser power is shown in Fig.3. Received power is effected by modulator insertion loss and fiber attenuation with additional insertion losses by PBS, PBC and PC. At the reception, after separation of both polarization by PC, the carrier and the modulated signal is applied to an optical hybrid. The outputs of optical hybrid is applied to PDs for converting optical signals into I and Q electrical signals. Suppose X polarization is carrying the modulated signal (\( \sqrt{Ps} e^{i(\omega_c t + \theta_m)} \)) and Y polarization is carrying the carrier signal (\( \sqrt{PC} e^{i\omega_c t} \)), where modulated signal power \( Ps = P_t/(2ak_p k_0^2 k_{m2}) \), carrier power \( PC = P_t/(2ak_p k_0^2) \), \( k_0 \) is insertion loss of PBS/PBC, \( k_p \) is insertion loss of polarization controller, \( a \) is the attenuation due to fiber channel, \( k_{m2} \) is the insertion loss of MZM QPSK modulator and \( \theta_m \) is carrier phase according to the modulating signal. The output current from a balanced PD stage can be evaluated as:

\[
i_1 = R \left[ Ps + PC + 2\sqrt{PsPC} \cos \theta_m \right],
\]

\[
i_2 = R \left[ Ps + PC - 2\sqrt{PsPC} \cos \theta_m \right],
\]

\[
i_1 - i_2 = 4R\sqrt{PsPC} \cos \theta_m.
\]

Correspondingly noise components are:

\[
\sigma^2_{s1} = 2q\Delta f R \left( Ps + PC + 2\sqrt{PsPC} \cos \theta_m \right) + n_t^2 \Delta f,
\]

\[
\sigma^2_{s2} = 2q\Delta f R \left( Ps + PC - 2\sqrt{PsPC} \cos \theta_m \right) + n_t^2 \Delta f,
\]

\[
\sigma^2 = \sigma^2_{s1} + \sigma^2_{s2} = 4q\Delta f R(PS + PC) + 2n_t^2 \Delta f.
\]

SNR for this system is:

\[
SNR = \left( \frac{i_1 - i_2}{\sigma^2} \right) = \left( \frac{4R\sqrt{PsPC} \cos \theta_m}{4q\Delta f R(PS + PC) + 2n_t^2 \Delta f} \right).
\]

The modulus value of \( \cos \theta_m \) can be taken as \( 1/\sqrt{2} \) as all symbols are containing angles multiple of 45°. In this case average power for all symbols is equal to one symbol so effective SNR is same as calculated SNR. Further by putting the expressions of \( Ps \) and \( PC \) in (III-B) and after simplifying, expression for SNR\(_{SH-QPSK}\) reduces to:

\[
\frac{R^2P_t^2}{q\Delta fRP_t(ak_p k_0^2)(1 + k_{m2}) + (ak_p k_0^2)^2 k_{m2} n_t^2 \Delta f}.
\]

Note that both noise (thermal and shot noise) has been added in the above expression. BER can be calculated by putting the value of SNR\(_{SH-QPSK}\) in [16]. For the case of shot noise limited receiver limited receiving expression for BER\(_{SH-QPSKs}\) is:

\[
BER_{SH-QPSKs} = Q \left( \frac{RP_t}{q\Delta f(ak_p k_0^2)(1 + k_{m2})} \right) - \frac{1}{2} Q^2 \left( \frac{RP_t}{q\Delta f(ak_p k_0^2)(1 + k_{m2})} \right),
\]

(8)

For the case of thermal noise limited receiver resulting expression for BER\(_{SH-QPSK}\) is:

\[
BER_{SH-QPSK} = Q \left( \frac{RP_t}{(ak_p k_0^2)^2 k_{m2} n_t^2 \Delta f} \right) - \frac{1}{2} Q^2 \left( \frac{RP_t}{(ak_p k_0^2)^2 k_{m2} n_t^2 \Delta f} \right).
\]

(9)

**C. PMC-SH-16 QAM links**

Links based on 16 QAM technique offer double data rate as compared to PAM4 and PMC-SH-QPSK links. Block diagram for a PMC-SH-16 QAM link is same as a PMC-SH-QPSK system in terms of power modeling. Main difference is the value of insertion loss of the modulator (that is \( \approx 3 \text{dB} \) more in practical system as compared to QPSK modulator) and average power per symbol. General expressions for (E) of 16 QAM links with standard uniformly spaced levels are discussed in Appendix C. Average power for the standard (uniformly spaced) 16 QAM as displayed in Fig.11 can be calculated as:
\[ \Delta f = 0.55P_t \]

**SNR\textsubscript{SH-16QAM}** with the consideration of average power 0.55\(P_t\) can be written as with the reference of (7):

\[ R^2(0.55P_t)^2 \]

\[ 0.55q\Delta f R P_t (1 + k_{m3}) \]

\[ + (ak_p k_b^3)^2 k_{m3} n t^2 \Delta f \]

where \( k_{m3} \) is the modulator insertion loss for 16 QAM modulation. BER\textsubscript{SH-16QAM} can be calculated by putting the value of SNR\textsubscript{SH-16QAM} in (17). Resulting expression for BER\textsubscript{SH-16QAM} in the case of shot noise limited receiver is:

\[ BER\textsubscript{SH-16QAM} = \frac{3}{4} Q \left( \frac{1}{3} \right) \sqrt{\frac{0.55P_t R}{q\Delta f (ak_p k_b^3)(1 + k_{m3})}} \]

\[ - \frac{9}{16} Q^2 \left( \frac{1}{3} \right) \sqrt{\frac{0.55R P_t}{q\Delta f (ak_p k_b^3)(1 + k_{m3})}} \].

Resulting expression for BER\textsubscript{SH-QPSK} in the case of thermal noise limited receiver is:

\[ BER\textsubscript{SH-QPSK} = \frac{3}{4} Q \left( \frac{1}{3} \right) \sqrt{\frac{R^2(0.55P_t)^2}{(ak_p k_b^3)^2 k_{m3} n t^2 \Delta f}} \]

\[ - \frac{9}{16} Q^2 \left( \frac{1}{3} \right) \sqrt{\frac{R^2(0.55P_t)^2}{(ak_p k_b^3)^2 k_{m3} n t^2 \Delta f}} \]. (12)

**IV. PERFORMANCE EVALUATION: PAM4 VS PMC-SH SYSTEMS**

**A. Performance comparison for PAM4, QPSK and 16 QAM techniques**

In the context of optical system, graphs are plotted between SNR and BER to understand at the SNR requirement for same BER. Expressions presented in (14), (15), (16) and (17) are plotted between SNR and BER for PAM4, QPSK and 16QAM systems (with out consideration of average power per symbols and system losses) respectively. For PAM4 and 16QAM, both cases (uniformly spaced and optimally spaced level) are covered as P(E) changes with the change in Euclidean distance. Graph shown in Fig. 6 indicates that QPSK technique has lowest SNR requirement and 16QAM also doesn’t have much SNR difference for same performance with the outcome of double bit rate.

**B. Performance comparison for PAM4, PMC-SH-QPSK and PMC-SH-16 QAM links with respect to Laser power**

Optical power required for the same performance is observed in this section. Practical values have been considered for all the parameters (values are indicated the caption of the graph).

1) **Thermal noise limited receiver:** Expressions presented in (8), (9) and (10) are plotted between Laser power and BER for PAM4, SH-QPSK and SH-16 QAM systems (with consideration of average power per symbol and system losses) respectively. Multilevel techniques (PAM4 and 16 QAM) are considered with uniformally spaced levels. By varying laser power, BER is plotted for all three systems in following graphs with and without fiber as presented in Fig 5.

2) **Shot noise limited receiver:** For this case, PAM4 is considered with optimally spaced levels. Although 16 QAM is considered with both uniformly spaced and optimally spaced levels. So PMC-SH-16 QAM with standard levels value also
can be closely compared with optimal PAM4 links. Graph shown in Fig. 6 is plotted between Laser power vs BER using the expressions presented in (6), (9), and (11). Observations from Fig. 6 are: A PMC-SH-QPSK clearly needs very less laser power as compared to other systems for the same performance, and A PMC-SH-16 QAM system with standard uniform level spacing is very close to PAM4 (with optimum levels) and also offering double data rate.

C. Performance comparison for PAM4 and SH-16 QAM links with increasing Baud rate

Expressions in (3), (12) for thermal noise limited receiver and expressions in (6), (11) for shot noise limited receiver are plotted (by keeping receiver bandwidth $\Delta f = 0.7$ B, where B is baud rate) between baud rate and BER for PAM4 and SH-16 QAM systems (with consideration of average power per symbol and system losses). Graphs presented in Figs. 8 and 7 indicates PMC-SH-16 QAM system can provide double capacity with comparable performance with increasing baud rate. Laser power is kept constant for these plots.

V. CONCLUSION

A PMC-SH-QPSK system outperforms over PAM4 link in every aspect (SNR and required laser power) with offering same bit rate. Performance of a PMC-SH-16 QAM system is comparable (as case of optimally spaced levels are considered is considered for PAM4) as compared to PAM4 link. This analysis strengthen the employment of PMC-SH links in place of PAM4 links for DCIs.

APPENDIX A

PROBABILITY OF ERROR FOR PAM4 LINKS

For considering the effects of non uniform spacing between PAM4 levels and threshold levels to compensate the variance of signal dependent noise, a general constellation as shown in Fig. 9 is considered. It has four symbols having amplitude levels $a_1, a_2, a_3, a_4$ with noise variance $\sigma_1, \sigma_2, \sigma_3, \sigma_4$ and having decision threshold of $\lambda_1, \lambda_2, \lambda_3$. Probability of error can be calculated as:

$$P(E) = p(a_1)P(E|a_1) + p(a_2)P(E|a_2) + p(a_3)P(E|a_3) + p(a_4)P(E|a_4),$$

By assuming equally probable symbols, above expression reduces to:

$$P(E) = \frac{1}{4} [P(E|a_1) + P(E|a_2) + P(E|a_3) + P(E|a_4)],$$

Probability of error for symbol $a_1$ can be calculated in terms of probability of correct detection as:

$$P(E|a_1) = 1 - P(C|a_1).$$
Symbol \( a_1 \) is correctly detected if received symbol lies in the decision area of \( a_1 \) as indicated in Fig. 9. Probability for error of symbol \( a_1 \) can be calculated as:

\[
P(C|a_1) = \int_{-\infty}^{\lambda_1} \frac{1}{\sqrt{2\pi}\sigma_1^2} e^{-\left(\frac{r-a_1}{\sigma_1}\right)^2} dr
\]

\[
= 1 - Q \left( \frac{\lambda_1 - a_1}{\sigma_1} \right)
\]

\[
P(E|a_1) = Q \left( \frac{\lambda_1 - a_1}{\sigma_1} \right).
\]

Similarly as per decision area, probability of error for symbol \( a_4 \) is:

\[
P(E|a_4) = Q \left( \frac{a_4 - \lambda_1}{\sigma_4} \right).
\]

Probability for correct detection of symbol \( a_2 \) can be calculated as:

\[
P(C|a_2) = \int_{\lambda_1}^{\lambda_2} \frac{1}{\sqrt{2\pi}\sigma_2^2} e^{-\left(\frac{r-a_2}{\sigma_2}\right)^2} dr
\]

So by solving above expression in terms of \( Q \),

\[
P(E|a_2) = Q \left( \frac{a_2 - \lambda_1}{\sigma_2} \right) + Q \left( \frac{\lambda_2 - a_2}{\sigma_2} \right).
\]

Similarly for probability of error for symbol \( a_3 \) is:

\[
P(E|a_3) = Q \left( \frac{a_3 - \lambda_2}{\sigma_3} \right) + Q \left( \frac{\lambda_3 - a_3}{\sigma_3} \right).
\]

Total probability of error is:

\[
P(E) = \frac{1}{4} Q \left( \frac{\lambda_1 - a_1}{\sigma_1} \right) + \frac{1}{4} Q \left( \frac{a_2 - \lambda_1}{\sigma_2} \right) + \frac{1}{4} Q \left( \frac{\lambda_2 - a_2}{\sigma_2} \right) + \frac{1}{4} Q \left( \frac{a_3 - \lambda_2}{\sigma_3} \right) + \frac{1}{4} Q \left( \frac{\lambda_3 - a_3}{\sigma_3} \right) + \frac{1}{4} Q \left( \frac{a_4 - \lambda_3}{\sigma_4} \right).
\]

Correspondingly, bit error rate (BER) is (If gray coding is used):

\[
BER = \frac{1}{4\log_2 M} P(E).
\]

**A. With uniformly spaced levels**

In this case, equal spacing for levels can be considered as thermal noise is not signal dependent. Hence \( a_1 = 0, a_2 = \frac{1}{2}a, a_3 = \frac{1}{2}a, a_4 = a \) have been considered for four amplitude levels with same variance for all symbols \( \sigma_1 = \sigma_2 = \sigma_3 = \sigma_4 = \sigma_t \). Here \( \sigma_t \) is the variance representing the thermal noise. Accordingly, threshold levels are \( \lambda_1 = \frac{1}{2}a, \lambda_2 = \frac{1}{2}a, \lambda_3 = \frac{3}{2}a \) as per maximum likelihood criteria. By putting all the values in (13), BER can be calculated as:

\[
BER_{PAM4u} = \frac{3}{4} \left[ Q \left( \frac{a}{2\sigma_t} \right) \right] = \frac{3}{4} \left[ Q \left( \frac{1}{6\sqrt{SNR}} \right) \right].
\]

**B. With optimum spaced levels**

Shot noise is a signal dependent noise, non uniform spacing is being used in practical systems to obtain optimum performance [27]. For attaining constant \( Q \) parameter for all the symbols, \( a_1 = 0, a_2 = \frac{1}{2}a, a_3 = \frac{2}{3}a, a_4 = a \) have been considered. According to the signal values, variance \( \sigma_2 = \frac{1}{4}\sigma_s \) and \( \sigma_3 = \frac{2}{3}\sigma_s \) is considered for analysis, where \( \sigma_s \) is constant part of variance of shot noise \( \sigma_s \). In this case for confirming same \( Q \) parameter for all symbols, thresholds are calculated as mentioned in [28]

\[
\lambda_2 = \frac{\sigma_2a_3 + \sigma_3a_2}{\sigma_2 + \sigma_3} = \frac{2}{9}a, \quad \lambda_3 = \frac{\sigma_3a_4 + \sigma_4a_3}{\sigma_3 + \sigma_4} = \frac{2}{3}a,
\]

Q parameters for adjacent symbols \( a_3 \) and \( a_4 \) and for adjacent symbols \( a_3 \) and \( a_2 \) are:

\[
Q = \frac{I_4 - I_3}{\sigma_4 + \sigma_3} = \frac{a}{3\sigma}, \quad Q = \frac{I_3 - I_2}{\sigma_3 + \sigma_2} = \frac{a}{3\sigma}.
\]

By putting this same \( Q \) values in (13), BER can be calculated for PAM4 systems with optimum (non-uniformly) spaced levels as:

\[
BER_{PAM4u} = \frac{3}{4} \left[ Q \left( \frac{a}{3\sigma} \right) \right] = \frac{3}{4} \left[ Q \left( \frac{1}{3\sqrt{SNR}} \right) \right].
\]

**APPENDIX B**

**PROBABILITY OF ERROR FOR QPSK LINKS**

Symbols are considered as per the given constellation diagram in Fig. 10 for QPSK links. Probability of error can be calculated for this techniques also as: By assuming equally probable symbols, above expression reduces to:

\[
P(E) = \frac{1}{4} \left[ P(E|a_1) + P(E|a_2) + P(E|a_3) + P(E|a_4) \right],
\]

For QPSK symbols, probability of error is same for all the symbols because of same decision area. So total probability of error can be \( P(E) = P(E|a_1) \). QPSK signal is two dimensional so two received parameters \( r_1 \) and \( r_2 \) are considered. These two dimensions are basis functions that are orthonormal. Probability of error for symbol \( a_1 \) can be calculated in terms of probability of correct detection \( P(C|a_1) \) as:

\[
P(E) = \int_0^\infty \frac{1}{\sqrt{2\pi}\sigma^2} e^{-\frac{(r_1-a_1)^2}{2\sigma^2}} dr_1 \int_0^\infty \frac{1}{\sqrt{2\pi}\sigma^2} e^{-\frac{(r_2-a_2)^2}{2\sigma^2}} dr_2
\]

\[
= Q \left( \frac{a}{\sigma} \right) Q \left( \frac{-a}{\sigma} \right).
\]

Fig. 10: QPSK constellation diagram.
So probability of error is

\[ P(E) = P(E|a_1) = 1 - P(C|a_1) = 2Q \left( \frac{a}{\sigma} \right) - Q^2 \left( \frac{a}{\sigma} \right). \]

Correspondingly,

\[ BER_{QPSK} = Q \left( \frac{a}{\sigma} \right) - \frac{1}{2} Q^2 \left( \frac{a}{\sigma} \right) = Q \left( \sqrt{\text{SNR}} \right) - \frac{1}{2} Q^2 \left( \sqrt{\text{SNR}} \right). \]

(16)

**APPENDIX C**

**PROBABILITY OF ERROR FOR 16 QAM LINKS**

QAM is the combination of phase and amplitude modulation. Average power is not same for each symbol so two cases (shot noise limited and thermal noise limited system) are considered for this technique as done for PAM4. This scheme doubles the data rate as compare to PAM4 and QPSK technique based systems. Signal constellation diagram (in Fig. [11]) represents the amplitude levels and decision area considered for this case. A signal independent noise is considered with constant noise variance \( \sigma \) for all symbols. Symbols having same decision area have similar probability of error. If equally probable symbols are assumed then probability of error is

\[ P(E) = \frac{1}{16} \left[ 8P_1 + 4P_2 + 4P_3 \right] = \frac{P_1}{2} + \frac{P_2}{4} + \frac{P_3}{4}, \]

where \( P_1 = P(E|a_1), P_2 = P(E|a_2) \) and \( P_3 = P(E|a_3) \). Firstly \( P(C|a_1) \) can be calculated as:

\[ = \int_0^{2\pi} \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(r_1)^2}{2\sigma^2}} dr_1 \int_0^{2\pi} \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(r_2)^2}{2\sigma^2}} dr_2, \]

\[ = \left[ 1 - 2Q \left( \frac{a}{3\sigma} \right) \right] \left[ 1 - Q \left( \frac{a}{3\sigma} \right) \right], \]

so,

\[ P(E|a_1) = P_1 = 1 - P(C|a_1) = 3Q \left( \frac{a}{3\sigma} \right) - Q^2 \left( \frac{a}{3\sigma} \right). \]

Similarly for \( P_2, P(C|a_2) \) can be calculated as:

\[ = \int_0^{2\pi} \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(r_1)^2}{2\sigma^2}} dr_1 \int_0^{2\pi} \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(r_2)^2}{2\sigma^2}} dr_2, \]

\[ = \left[ 2 - 2Q \left( \frac{a}{3\sigma} \right) \right]^2, \]

so,

\[ P(E|a_2) = P_2 = 4Q \left( \frac{a}{3\sigma} \right) - 4Q^2 \left( \frac{a}{3\sigma} \right). \]

For \( P_3, P(C|a_3) \) can be calculated as following:

\[ = \int_0^{2\pi} \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(r_1)^2}{2\sigma^2}} dr_1 \int_0^{2\pi} \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(r_2)^2}{2\sigma^2}} dr_2, \]

\[ = \left[ 1 - Q \left( \frac{a}{3\sigma} \right) \right]^2, \]

so,

\[ P(E|a_3) = P_3 = 2Q \left( \frac{a}{3\sigma} \right) - Q^2 \left( \frac{a}{3\sigma} \right). \]

Total probability of error is:

\[ P(E) = 3Q \left( \frac{a}{3\sigma} \right) - \frac{9}{4} Q^2 \left( \frac{a}{3\sigma} \right). \]

Correspondingly, BER is (If gray coding is used, BER=SER/\log_2 M [26]):

\[ BER_{16QAM} = \frac{3}{4} Q \left( \frac{a}{3\sigma} \right) - \frac{9}{16} Q^2 \left( \frac{a}{3\sigma} \right). \]

(17)

**ACKNOWLEDGMENT**

The authors would like to thank Meity for funding the project.

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