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Proposed New Cross Layer Protocol

Most of the cross-layer protocols in the literature rely on the signal to noise ratio calculations of the communication channel. However, there are other impairments, such as the ones coming from the radio front end, which can also impact the performance of communication link. In this chapter, the impact of such impairments is analyzed and a new cross layer protocol that takes advantage of this knowledge to improve the overall system performance has been proposed. Key thesis contributions discussed in this chapter are

• A methodology to combat the effects of two key impairments in wireless communication systems. These key impairments are gain imbalance and quadrature skew. State of the art focusses mainly on Additive White Gaussian Noise (AWGN) and theoretical discussions on RF front end impairments, such as quadrature skew. This thesis presents the hardware and software elements of an experimental system. Using this experimental setup, real-world effects of these impairments on an over-the-air link are presented. These experimental results are an important step in translating the innovations introduced in this thesis for industrial applications.

• Second key contribution in this thesis is the derivation of mathematical expressions for the two impairments, discussed earlier. These mathematical derivations allow measurement of these impairments at the radio front end in an efficient manner and minimizes the overhead associated with this additional step. This mathematical derivation makes it practical to implement the contributions of this thesis in real-world systems.

• Finally, a new cross layer protocol, which combats the effects of these radio front end impairments, is proposed. Experimental results are presented which demonstrate throughput improvements of 2x using this methodology, as opposed to a technique based purely on AWGN impairments. Results have been shown for m-ary PSK based systems.

3.1 Introduction

Cross layer design and optimisation techniques for wireless networks have been extensively studied in the literature. The underlying idea is to share information that is available at the PHY and the MAC layers with the higher layers to provide efficient methods for improving system performance. System performance can be measured using various metrics such as channel capacity, throughput, and energy consumption. Some of the work done in this area has been described in the earlier chapters.

This thesis derives inspiration from these techniques to propose a novel cross layer protocol with the objective of combating the impact of quadrature skew and gain imbalance and thus improving system performance. Section 3.2 describes the experimentation system that the thesis uses. Section 3.3 describes the various linear impairments introduced by the radio and provides a mathematical definition for the same. The section also demonstrates the impact of these impairments on BER, as observed on the experimentation system. Section 3.4 provides a mathematical derivation for measuring these impairments, as they are seen at the receiver. Section 3.5 describes the implementation of the proposed cross layer design optimization technique and presents cost benefit analysis of the same. This section also describes how the measured impairments can be shared with the PHY layer on the transmitter, through the proposed cross layer protocol, to improve system performance. The section also shows experimental validation of the proposed idea on real-world signals.

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3.2 Experimentation System

This thesis proposes a new cross layer protocol that combats the effects of radio's imperfections on BER and improves system performance. It proves the validity of the proposal by providing a mathematical derivation of the idea and implementing it on an experimentation system. This approach proves the implementation feasibility of the proposal and demonstrates performance benefits through results obtained from testing with real-world signals. The proposed solution will incur an overhead cost of performing measurements, generally not required by a receiver. However, it is shown that the benefits achieved by implementing the proposal far outweigh the overhead costs involved. To achieve all of these objectives, this thesis uses the experimentation system, as shown in Figure 3.1. This system contains a Laptop connected through an Ethernet cable to the National Instruments Universal Software Radio Peripheral (NI-USRP 2932). NI-USRP 2932 contains a tunable radio front end with frequencies from 400 MHz to 4,400 MHz. It offers support for 20 MHz baseband I/Q bandwidth and support for streaming data at a rate of 25 MS/s. NI-USRP 2932 has one transmit and one receive antenna. A custom communication scheme has been implemented using National Instruments LabVIEW software. The key parameters for this custom scheme are listed in Table 3.1.

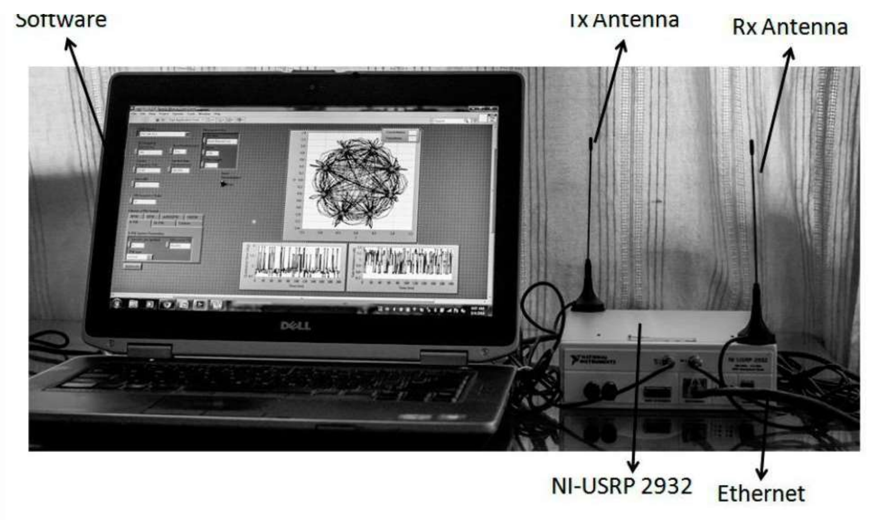

Figure 3.1: Experimentation System Setup to Measure the Impact of RF Front End Impairments on Bit Error Rate

Table 3.1: Key Parameters Used in the Experimentation System

Parameter	*Value*
Center Frequency	2400MHz
Modulation Scheme	M-ary Phase Shift Keying
M	256, 64, 16, 8, 4
Selection of M	Adaptive (based on BER measured at the receiver)
Pulse Shaping Filter	Root Raised Cosine
Pulse Shaping Parameter	0.5
Symbol Rate	1 MS/s

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A single carrier modulation scheme is chosen because of the simplicity involved in establishing the mathematical foundations of the proposal. The scope of future work in this area involves testing the proposal on single carrier frequency division multiple access (SC-FDMA) scheme used in long term evolution (LTE) uplink modulation and OFDM schemes used in IEEE 802.11ac WLAN standard. The key hardware and software components of the receiver are shown in Figure 3.2.

The amplifier block contains the low-noise amplifier and drive amplifier. The local oscillator block, which provides a continuous wave signal to the mixer, contains the phase locked loop (PLL) circuit and the voltage controlled oscillator (VCO). The mixer block performs the radio frequency (RF) to intermediate frequency downconversion. The analogue to digital converter (ADC) samples the IF signal and provides the digitised samples to the digital downconverter (DDC) which further downconverts the data to baseband samples. These baseband samples are referred to as in-phase (I) and quadrature-phase (Q) samples. These I/Q samples are provided as inputs, through an Ethernet port, to the receiver's software components, which are implemented on a general purpose processor. The block **`applyMatchedFilter`** applies a filter that matches the pulse-shaping filter applied on the transmit side. The block **`findSymbolTiming`** finds the optimal symbol timing of the matched signal by looking at maximum timing offsets of the overlapped symbols. The final block **`mapSymbolToBits`** maps the complex-valued symbols to bits br(t). The received bits br(t) are compared to the transmitted bit pattern to calculate the BER, which is an important figure of merit in link budget estimation. In this thesis, BER performance curves are presented as a function of Eb/No. A BER value of 1E-3 implies that 1 out of 1,000 transmitted bits are erroneous. AWGN with various Eb/No values is added in software and then the resulting signal is generated using the experimentation system as shown in Figure 3.3. In the rest of this thesis, this method is referred to as Scenario 1.

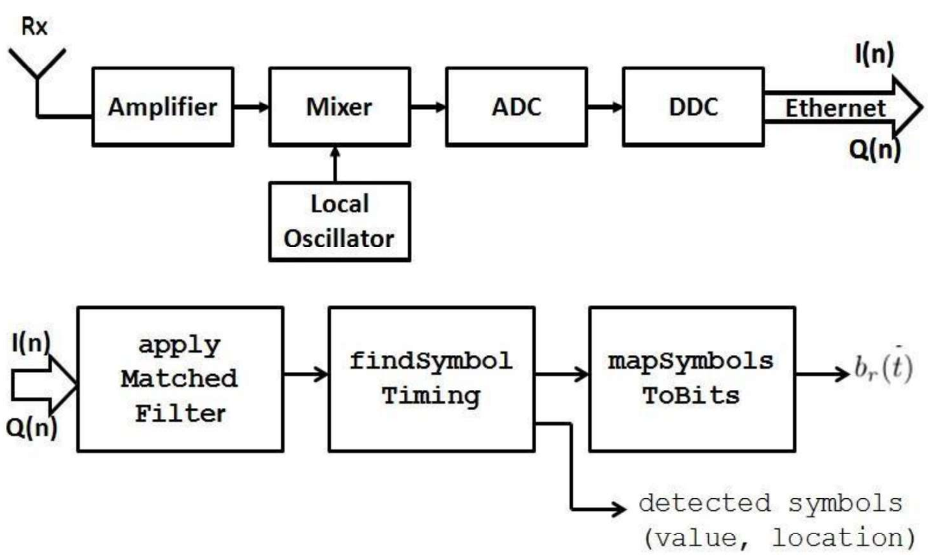

Figure 3.2: Key Hardware and Software Components of the Receiver, used for Scenario 1

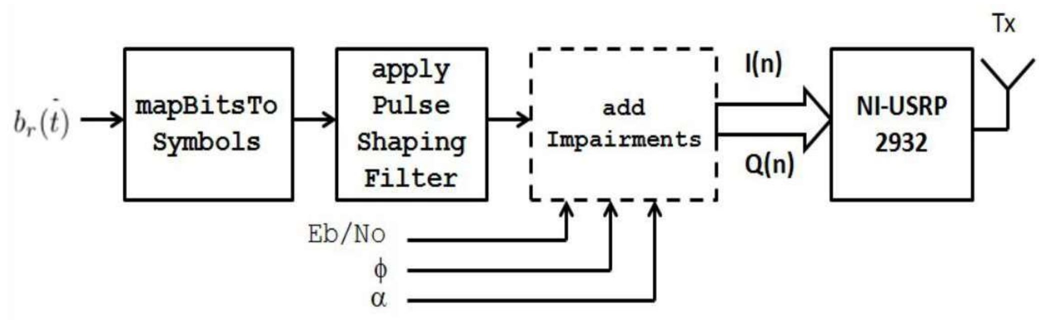

Figure 3.3: Key Building Blocks in the Transmitter Software: Dashed lines indicate a block that has been added as experimentation aid. Depicts Scenario 2, when all the three impairments are non-zero

The signal is captured by the receive antenna of the system and BER is calculated on the laptop. Figure 3.4 shows the BER performance curve as a function of Eb/No for 256-PSK, 64-PSK, 16-PSK, 8-PSK, and QPSK for Scenario 1. BER for a QPSK signal in an AWGN channel is given by the following closed form equation.

$$BER = \frac{1}{2}\, erfc\left(\sqrt{E_b/N_0}\right) \qquad (3.1)$$

where *erfc* is the complementary error function and describes the cumulative probability curve of a Gaussian distribution, as described by [Proakis *et al*, 1994]. Equation 3.1, plotted on a log-log scale, is shown by the plot labelled as QPSK (theory) in Figure 3.4. The close cross-correlation between the theoretical and experimental QPSK result validates the correctness of the software used in this thesis.

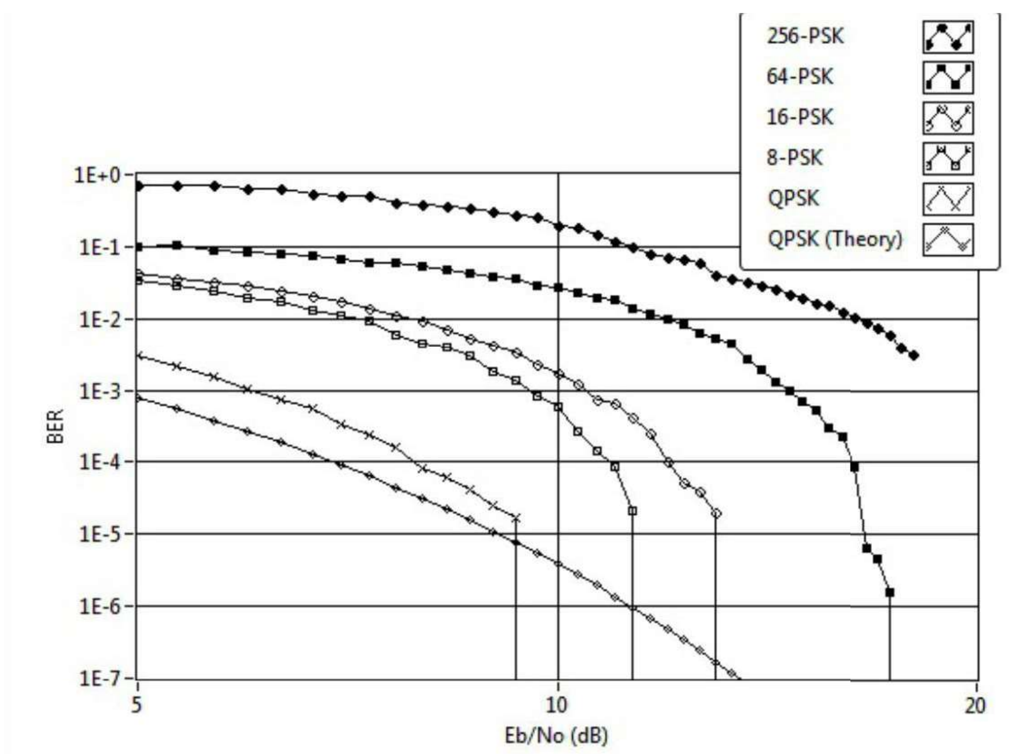

Figure 3.4: M-PSK BER Performance for Scenario 1, with AWGN Channel

Cross layer protocols that use the value of BER calculated at the receiver to adapt the index of a modulation scheme have been proposed by [Holland *et al*, 2001; Jamieson, 2008]. The hypothesis is that the impairments introduced by the radio also significantly impact BER and, if they are not properly accounted for, cross layer protocols would end up simplistically assuming that the drop in BER is only because of AWGN. This would cause the protocol to lower the modulation index (and effectively reduce throughput) whenever the BER criteria is not met. Experimental results that support this hypothesis are shown in Section 3.3.

3.3 Radio Front End Impairments

A typical transmitter's radio front end is shown in Figure 3.5. The radio front end consists of all the blocks needed to up-convert the baseband I/Q signals to radio frequencies. It contains digital to analogue converter (DAC), local oscillator (LO), filters, mixers, and combiners. Each of these components can act as a source of impairment and contribute to losses in the system [Cutler, 2002]. For example, the DAC may introduce loss in the system because of DC offset. An ideal LO generates a tone with an impulse as its frequency response. On the other hand, an imperfect LO may introduce loss in the system due to phase noise, which is caused by spreading of the tone energy into neighboring frequencies. The function of the phase shifter block is to produce a sinusoidal and a co-sinusoidal waveform from the reference signal provided by the local oscillator. These two signals must be exactly orthogonal to each other. If they are not, then the system may introduce losses due to impairments known as quadrature skew. Finally, the mixer may introduce system losses due to gain imbalance. Because an angular modulation scheme, M-PSK, is considered in this thesis, only the effects of quadrature skew and gain imbalance on the BER will be considered. This thesis assumes that the radio does not introduce any DC offset and that the receiver corrects for any frequency offset. It also assumes the local oscillator produces a sinusoidal signal with very low phase noise.

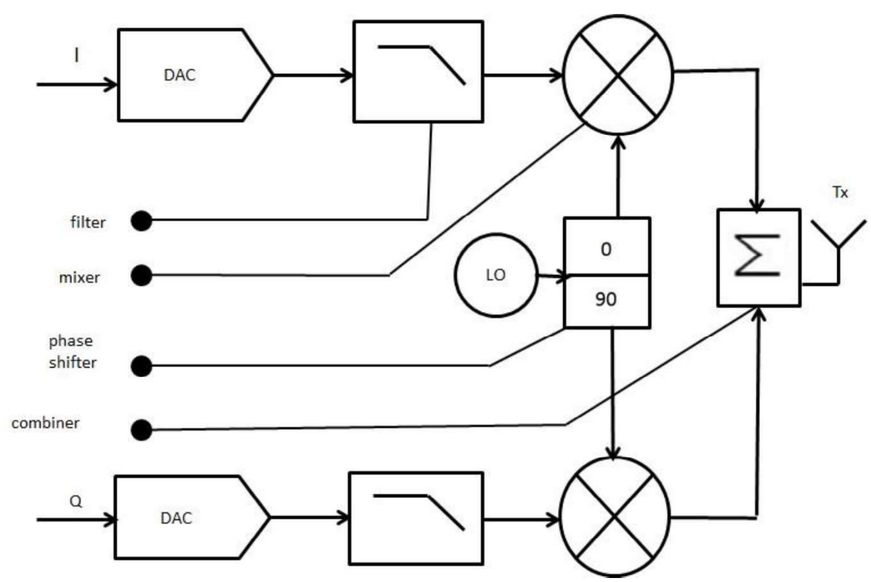

Figure 3.5: A Typical Transmitter's Radio Front End

Figure 3.6 shows the effects of quadrature skew and gain imbalance on the constellation of a QPSK signal.

Let α be the gain imbalance, in dB, introduced by the radio front end. Upon converting this value to linear scale, the gain imbalance β can be written as follows.

$$�= 10^{\frac{\alpha}{10}} \qquad (3.2)$$

Considering the effect of gain imbalance, the baseband signal can be denoted as follows.

$$�� = �(� +�\frac{i(t)}{\beta}, ���> 0 \qquad (3.3)$$

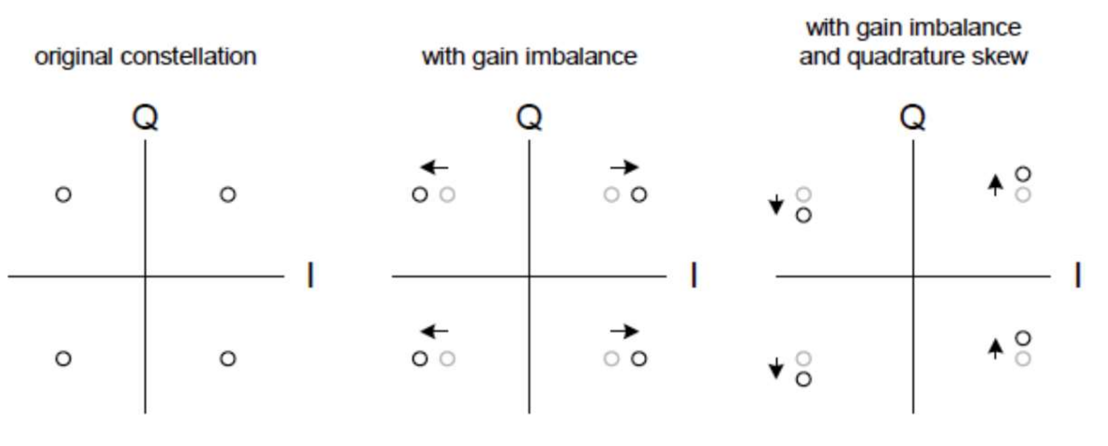

Figure 3.6: Effects of Gain Imbalance and Quadrature Skew on the Constellation of a QPSK Signal

$$�� = \frac{�(t)}{\beta} + ���, ��������� \qquad (3.4)$$

Let φ be the angle denoting the quadrature skew, in degrees, introduced by the transmitter. The effect of this quadrature skew on the baseband complex envelope waveform can be shown as follows.

$$�� = �(� + �(\sin(\emptyset)�(� + \cos(\emptyset)��) \qquad (3.5)$$

Since quadrature skew and gain imbalance are linear impairments, their effects are additive. After combining, the resulting baseband complex waveform can be written as

$$�� = �(� + �\frac{(\sin(\emptyset)�(t) + \cos(\emptyset)i(t))}{\beta}, ���> 0$$

(3.6)

$$�� = \frac{�(t)}{\beta} + �(\sin(\emptyset)�(� + \cos(\emptyset)��), ��������� \qquad (3.7)$$

Equations (3.2) through (3.7) show the mathematical definition of the gain imbalance and quadrature skew. Next step is to analyze the received signal in order to study the impact of these

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impairments on the BER. NI-USRP has a small value of residual (internal) quadrature skew and gain imbalance. To get a better control on the experiments, additional impairments have been

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added in the software, using the **addImpairments** block as shown in Figure 3.3. It should be noted that this block has been added only as an experimentation aid and that it is not part of a real-world transmitter. The overall impairments experienced by the receiver are the sum of these controlled impairments and the residual impairments of the NI-USRP. The BER performance curves for M-PSK with a quadrature skew of 5 degrees and gain imbalance of 1 dB is shown in Figure 3.7. For the rest of the thesis, this method will be referred to as Scenario 2.

Comparing Figure 3.7 with Figure 3.4, one can see that the BER performance degrades in the presence of quadrature skew and gain imbalance. To understand this in depth, three Eb/No data points are discussed in detail, as shown in Table 3.2. As described earlier, the communication system used in this thesis uses an adaptive modulation order selection technique based on the BER value measured at the receiver. If the BER value measured at the receiver falls below a threshold, the transmitter uses a lower order of modulation. Let us assume that this threshold value is set to 1E-2. For the first data point of 20 dB, the transmitter would select 256-PSK modulation scheme in case of Scenario 1 and 16-PSK in case of Scenario 2. This would effectively bring the throughput down from 8 Mb/s to 4 Mb/s. For the second data point of 10 dB, the transmitter would select 16-PSK as modulation scheme in case of Scenario 1 and QPSK in case of Scenario 2. In this case, the throughput value would be brought down from 4 Mb/s to 2 Mb/s. Finally, for the third data point of 5 dB, the modulation order would be adjusted from QPSK in case of Scenario 1 to BPSK in case of Scenario 2, thus effectively bringing the throughput down from 2 Mb/s to 1 Mb/s. In all these cases, the transmitter would assume that the lower value of BER measured at the receiver is due to excessive AWGN experienced by the channel, thus overlooking the real reason which, in this case, is the presence of quadrature skew and gain imbalance in the radio. To make things complex, these specifications may vary from radio to radio, even though they are all manufactured by the same vendor. Within a single manufacturing lot, changes in ambient temperature, humidity, and silicon fabric can result in variation of specifications. Taking this into account, BER is analyzed at a fixed value of Eb/No, for different values of quadrature skew and gain imbalance as shown in Figure 3.8. It shows that the BER performance degrades further as these impairments get more severe. It also demonstrates that the BER performance curve show a symmetric behaviour for quadrature skew values of positive and negative polarities.

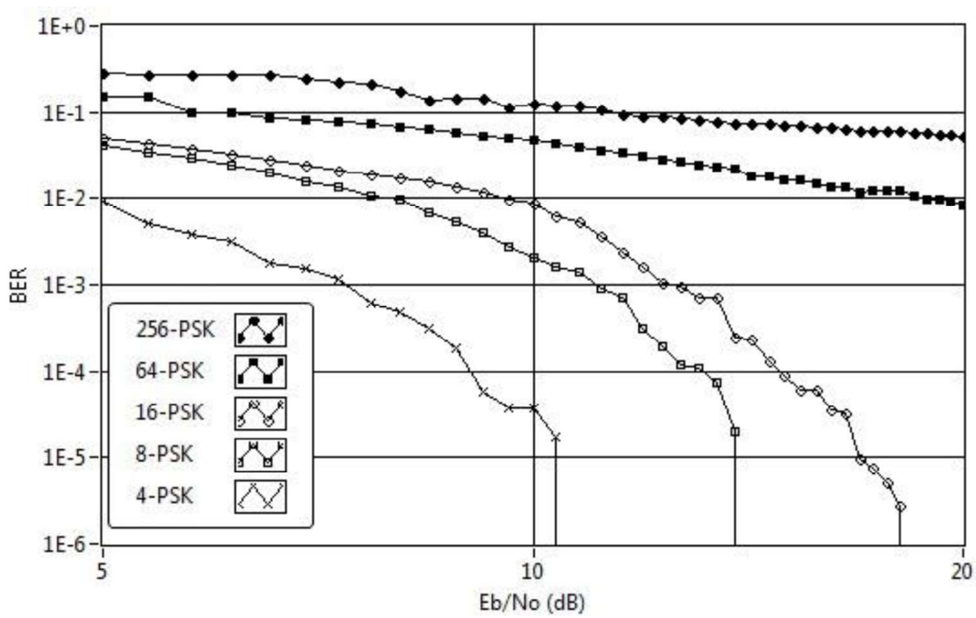

Figure 3.7: M-PSK BER Performance Curves for Scenario 2

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Table 3.2: Effects of Impairments on BER

Eb/No (dB)	*BER*	*Scenario 1*	*Scenario 2*
20	1E-2	256-PSK	16-PSK
10	1E-2	16-PSK	QPSK
5	1E-2	QPSK	BPSK

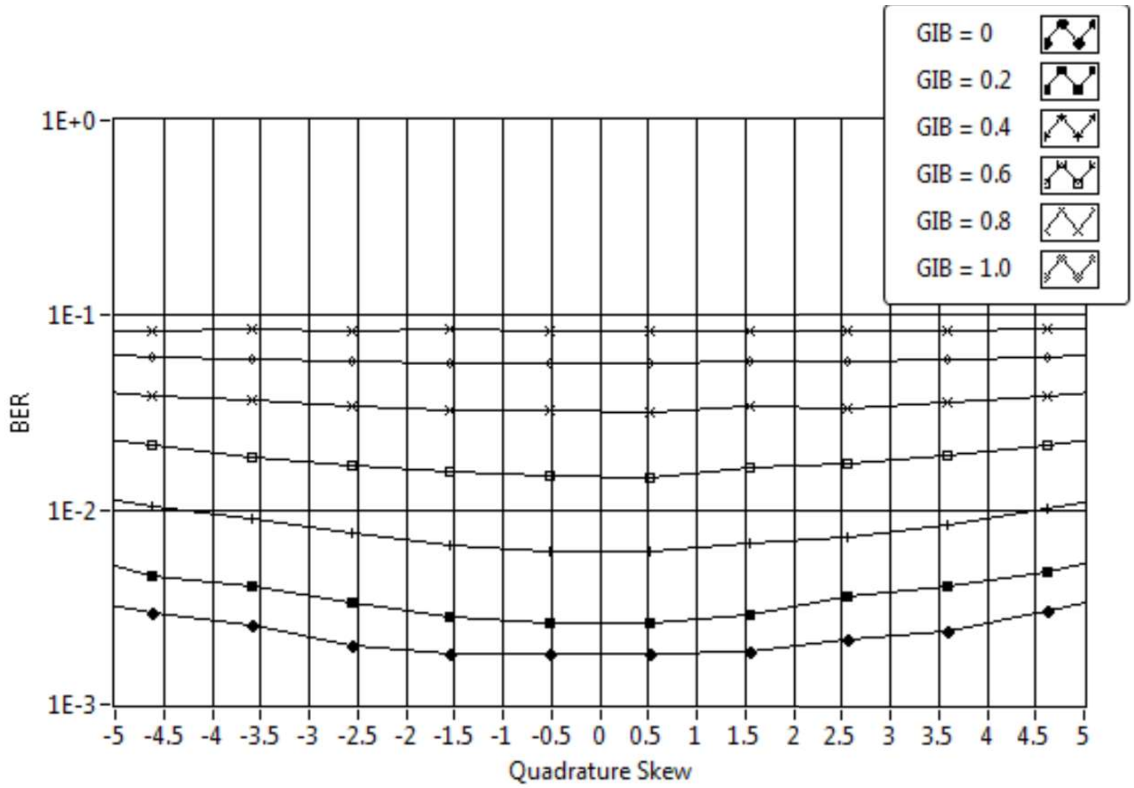

Figure 3.8: BER Performance Curves as a Function of Quadrature Skew and Gain Imbalance for Eb/No=10

Now that it has been shown how BER performance is influenced by these impairments, Section 3.4 will derive a closed form mathematical derivation for measuring these impairments and Section 3.5 will describe a cross layer protocol which uses the measured values to improve system performance.

3.4 Measuring Quadrature Skew and Gain Imbalance

Section 3.3 showed how the gain imbalance and quadrature skew values influence the BER performance for different modulation orders. In this section, a mathematical derivation is presented which shows how these impairments can be measured at the receiver. Let $\tilde{?}$ be the measured gain imbalance and ϕ be the measured quadrature skew. The algorithm described in this thesis for measuring quadrature skew and gain imbalance is independent of the modulation scheme and symbol map used for mapping the symbols to bits. The inputs to this generic algorithm are the detected symbol locations, after the frequency offsets, phase offsets, and DC offsets are removed. The algorithm measures the quantities of gain imbalance and quadrature skew simultaneously. This is because, given a signal that is impaired by both these phenomena, the value of one impairment cannot be determined without taking the other into consideration. By definition, quadrature skew is manifested by a shift of the Q-channel (positive in the right half plane and negative in the left-half plane) whereas the I-channel is unaffected. The first step in the measurement is to scale the incoming signal samples such that their I-channel values are equal to the I-channel values of the detected symbols. Since this algorithm assumes that all DC offsets have been removed and quadrature skew is defined such that the I-channel is unaffected, the only quantity that can still exist on the I-channel of the incoming signal, relative to the ideal symbols, is a non-unity gain, as shown in Figure 3.9.

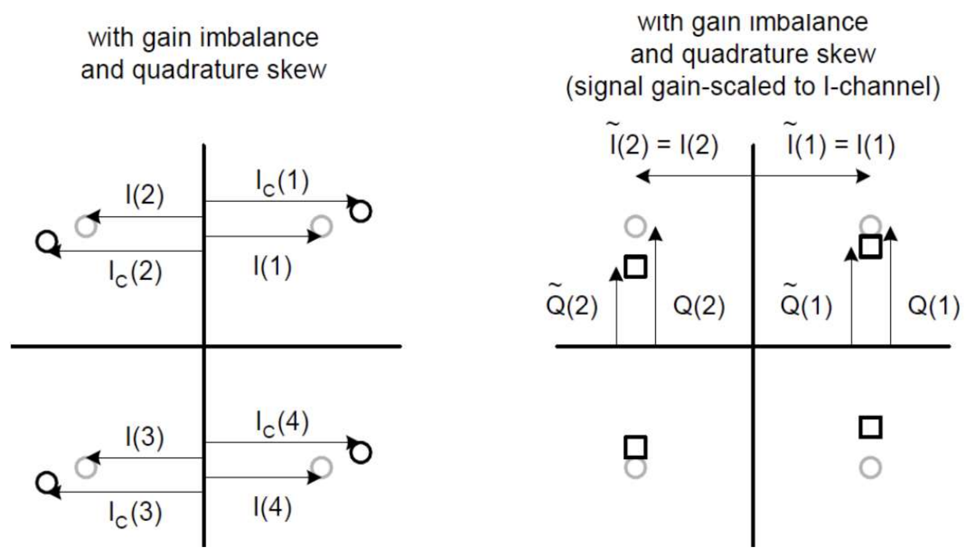

Figure 3.9: Explanation of Quadrature Skew and Gain Imbalance.

The scaling of the symbols is performed as per the following equation

$$\tilde{C}(n) = \tilde{I}(n) + j\tilde{Q}(n) = \frac{I_c(n) + jQ_c(n)}{G} = \frac{C(n)}{G} \qquad (3.8)$$

where $\tilde{C}(n)$ is the nth gain-scaled and corrected symbol, $C(n)$ is nth corrected symbol, and G [obtained as shown in Equation 3.9] is the gain of the I-channel of the corrected symbols relative to the I-channel magnitude of the detected symbols.

$$G = \frac{\sum_{n=0}^{N-1}\left[\frac{I(C(n))}{I(S(n))}\right]}{N} \qquad (3.9)$$

where S(n) is the nth detected symbol.

Since quadrature skew does not affect the I-channel and the gain-scaling performed in Equation 3.8, it ensures that the I-channel components of the incoming signal and the detected (ideal) symbols are equal. This implies that all impairments of the I-channel are now removed. However, the Q-channel of the gain-scaled corrected symbols still possesses gain imbalance and quadrature skew. The following equation accounts for the gain in the Q-channel

$$\tilde{S}(n) = \tilde{I}(n) + j\tilde{Q}(n) = \tilde{I}(n) + j\frac{Q(n)}{G_Q} \quad (3.10)$$

$$= \tilde{I}(n) + j\frac{\tilde{Q}(n)}{G_Q} = \tilde{I}(n) + j\tilde{Q}(n) G_X \quad (3.11)$$

where S(n) is the corrected symbols after correcting for I-channel gain and Q-channel gain, G_Q is the gain of the Q-channel of the corrected symbols relative to the Q-channel magnitude of the detected symbols, and G_X is gain imbalance. Inserting the signal definitions, given in equations (6) and (8), into the definition for quadrature skew, gives

$$I(n) + jQ(n) = I(n) + j[\sin(\phi) I(n) + \cos(\phi) Q(n)] \quad (3.12)$$

Setting the imaginary parts of Equation 3.11 and Equation 3.12 to be equal and solving for the skew angle φ

$$\phi = \sin^{-1}\left[\frac{\tilde{Q}(n) G_X}{\sqrt{I(n)^2+Q(n)^2}}\right] - \sin^{-1}\left[\frac{Q(n)}{\sqrt{I(n)^2+Q(n)^2}}\right] \quad (3.13)$$

Equation 3.13 represents the general equation for quadrature skew. The algorithm described in this thesis calculates quadrature skew from any one recovered (gain-scaled) symbol and its corresponding detected symbol. The quadrant within which the symbols lie is irrelevant. Even though the calculation in Equation 3.13 produces the same magnitude for φ regardless of the symbol quadrant being operated upon, it is important to realise that the sign of φ is inverted when performing the calculation on symbols in the left-half plane. The algorithm takes advantage of this property to speed up the calculation of these impairments. Using Equation 3.13 and the identity $\phi_1 = -\phi_2$, where ϕ_M is the calculated quadrature skew using the symbols in the M[th] quadrant, the following equation is obtained

$$\sin^{-1}\frac{\tilde{Q}_1 G_X}{\sqrt{I_1^2+Q_1^2}} - \sin^{-1}\frac{Q_1}{\sqrt{I_1^2+Q_1^2}} = \sin^{-1}\frac{Q_2}{\sqrt{I_2^2+Q_2^2}} - \sin^{-1}\frac{\tilde{Q}_2 G_X}{\sqrt{I_2^2+Q_2^2}} \quad (3.14)$$

where X_M is a given detected symbol component in quadrant M, $\tilde{X}_M$ is a given corrected symbol component X in quadrant M after its I-channel has been gain-scaled to that of its corresponding detected symbol, and GX is the gain imbalance. Let us define the following substitutions.

$$A = \sin^{-1}\left[\frac{Q_1}{\sqrt{I_1^2+Q_1^2}}\right] \quad (3.15)$$

$$B = \sin^{-1}\left[\frac{Q_2}{\sqrt{I_2^2+Q_2^2}}\right] \quad (3.16)$$

$$C = \frac{\tilde{Q}_1}{\sqrt{I_1^2+Q_1^2}} \quad (3.17)$$

$$D = \frac{\tilde{Q}_2}{\sqrt{I_2^2+Q_2^2}} \quad (3.18)$$

Substituting Equations 3.15 through Equations 3.18 into Equation 3.14 and rearranging, results in

$$\sin^{-1}(C G_X) + \sin^{-1}(D G_X) = A + B \quad (3.19)$$

Therefore,

cos(�sin(��) + �sin(��)) = cos(�+ � (3.20)

Using trigonometric identifies results in

cos(�sin(��) + �sin(��)) = cos(�+ � (3.21)

Let

�= cos(�+ � (3.22)

Substituting Equation 3.22 into Equation 3.21 and reducing trigonometric functions yields

√1 − �² �√1 − �²�² − ���= � (3.23)

Solving for gain imbalance yields

� = √((1−�²) / (�² +2���+�²)) (3.24)

Substituting Equation 3.15 through Equation 3.18 and Equation 3.22 into Equation 3.24, the gain imbalance, in terms of the I-channel gain-scaled corrected symbols and the group detected symbols, becomes

�= √((1−[cos �]²) / (�̃₁² / (√�₁² + �₁²)² + 2 �̃ �̃ / (√�₁² + �₁² √�₂² + �₁²) cos � + �̃₂² / (√�₂² + �₂²)²)) (3.25)

where

θ = �sin (� / √�₁² + �₁²) + �sin (� / √�₂² + �₂²) (3.26)

I/Q gain imbalance, in dB, is measured as 20 log(G_X). Quadrature skew, in degrees, can be calculated by substituting Equation 3.26 into Equation 3.13 and converting the result from radians to degrees. This concludes the mathematical derivation of how the quadrature skew and gain imbalance, as seen at the receiver, can be measured. Section 3.5 describes how this mathematical derivation is practically implemented on the experimentation system. Statistical properties of the measured values are described in detail. Next, a cross layer protocol that shares the measured values with the transmitter, which in turn uses them to compensate for the radio front end imperfections and improve system performance, is discussed.

3.5 Definition of Cross Layer Protocol

To implement the algorithm defined in Section 3.4, the receiver is modified as shown earlier in Figure 3.10. Figure 3.10 shows the modified receiver's block diagram after the addition of a new block, labelled as **`measureQS+GIB`**.

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It is self-evident that the addition of this new block increases the processing time of the receiver. In this section, the costs associated with this additional processing are studied. To do so, a parameter called cost factor ρ is defined, as shown in Equation (3.27) below

$$\rho = \frac{t_p}{t_c} \tag{3.27}$$

where t_p is the processing time of the measurement and t_c is its coherence time. Coherence time is defined as the time at which the cross-correlation statistics of the channel fall below 0.5, as described in [Rappaport, 1996]. The coherence time of an indoor wireless channel environment in a laboratory setup is approximately 200 ms [Mandke *et al*, 2007].

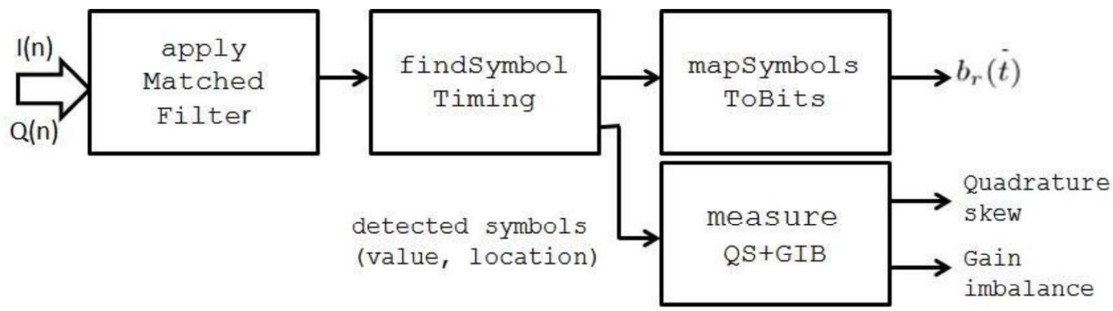

Figure 3.10: Modified Receiver Block Diagram: In order to measure quadrature skew and gain imbalance for the proposed cross layer design

The same concept is used to determine the coherence time of the gain imbalance and quadrature skew measurements. For the proposed idea to be practical to use, the first criteria is that the cost factor should be significantly less than 1. This implies that the processing time is orders of magnitude smaller than the coherence time of the measurement. The second criteria is that the processing time should be a constant and should not scale with the number of packets being received. Figure 3.11 shows the constellation diagram of the received 8-PSK modulated signal after the algorithm described in Section 3.4 was implemented in the measureQS+GIB block.

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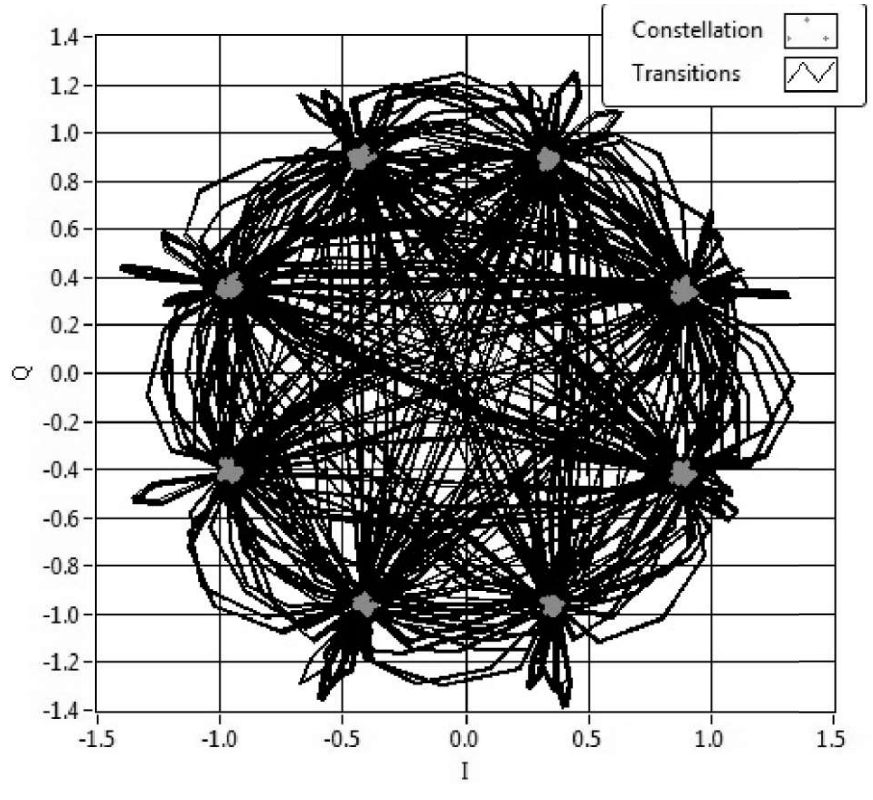

Figure 3.11: Constellation Graph of a 8-PSK Modulated Signal: where the blue circles show the received symbols and the black lines show transitions between the symbols

The processing time of the measureQS+GIB block, averaged over 1,000 trials, as a function of the number of packets, is shown in Figure 3.12. This shows that the processing time stays constant as the number of packets increases.

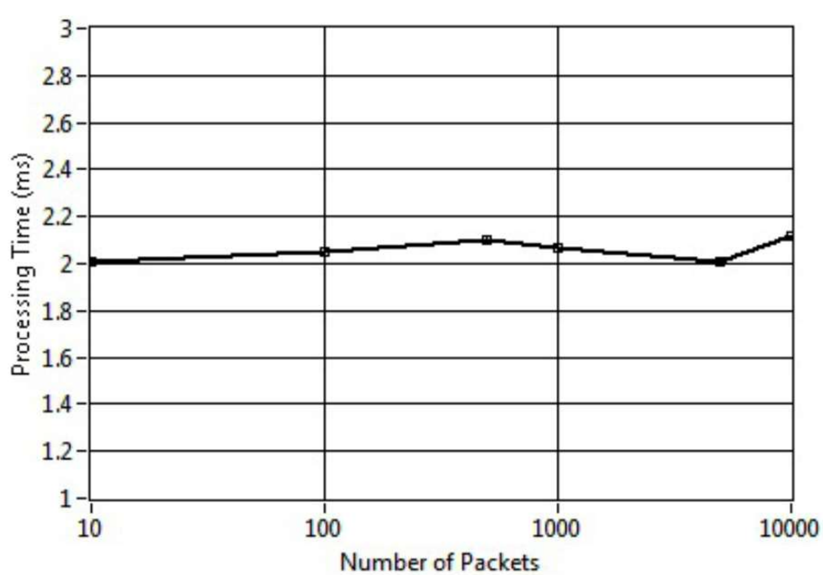

Figure 3.12: Processing Time for Additional Measurements as a Function of the Number of Packets

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Figure 3.13 and Figure 3.14 show the values of quadrature skew and gain imbalance measured over a certain period of time respectively.

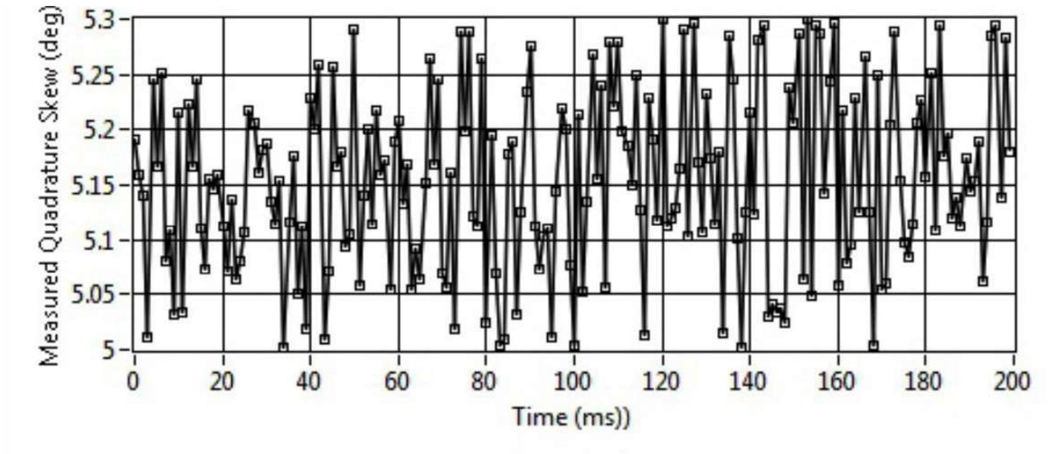

Figure 3.13: Values of Quadrature Skew Measured over a Certain Period of Time

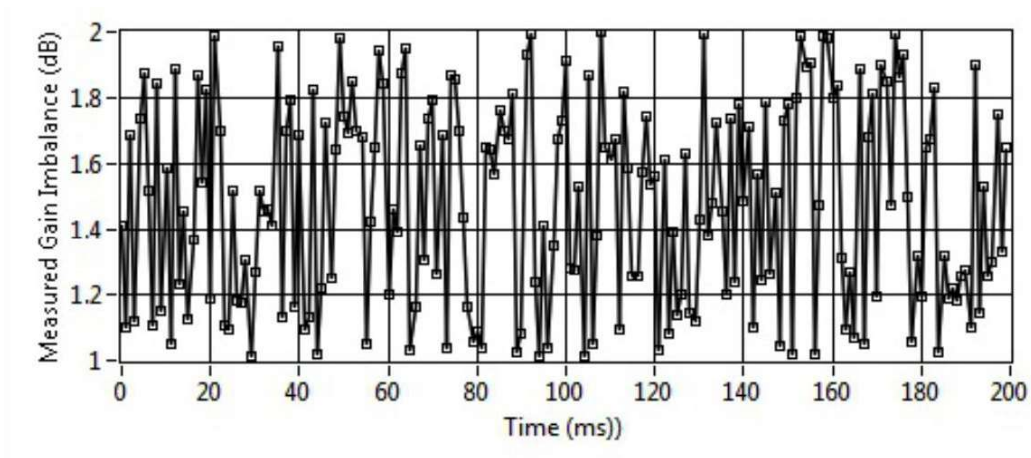

Figure 3.14: Values of Gain Imbalance Measured over a Certain Period of Time

These experiments show that the cross-correlation statistics of these measurements fall below 0.5 after a time period of 180 ms. Hence, the coherence time of these measurements has been set to 180 ms. Using these measured values of t_p and t_c in Equation 3.27, the cost factor ρ is calculated to be equal to 0.011, which is significantly less than 1. This shows that the proposed algorithm meets the criterion stated earlier and hence it is practical to use the **`measureQS+GIB`** block to measure the impairment values and report them back to the transmitter. The benefits achieved by making this measurement will far outweigh the associated costs. Next, a cross layer protocol is described that the receiver will use to share the measured values with the transmitter. Using the notation described in Section 2.1 earlier, the proposed cross layer protocol can be described by the following equations.

[[illegible] · [illegible]] → [[illegible] · [illegible]] · [[illegible]] (3.28)

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[[illegible] . [illegible]] → [[illegible] . [illegible]] · [[illegible]] (3.29)
[[illegible] . [illegible]] . [[illegible] = 0] → [[illegible] = 1] (3.30)

`measuredImpairments` is a two byte word as shown in Figure 3.15, where the lower 7 bits denote the measured gain imbalance, the upper 7 bits denote the measured quadrature skew, and the most significant two bits are reserved for future use.

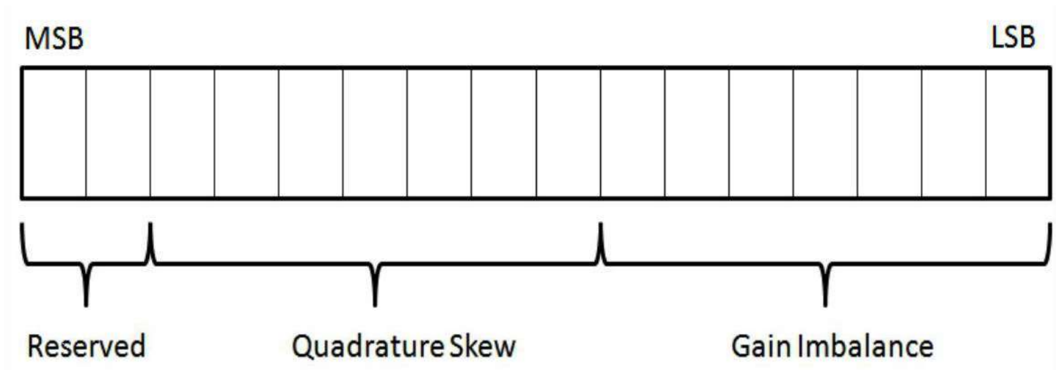

Figure 3.15: Definition of a New 16-Bit Frame: Includes two reserved bits, 7 bits for quadrature skew and 7 bits for gain imbalance

When the transmitter PHY receives the two-byte word from the receiver, it sends this information to the transmitter MAC. In turn, the transmitter MAC sets *icflag* equal to 1, which subsequently instructs the PHY layer to apply negative value of the measured gain imbalance and quadrature skew to the waveform that is being transmitted. This negates the effect of these impairments on the received signal. This change has been implemented on the experimentation system by modifying the transmitter as shown in Figure 3.16.

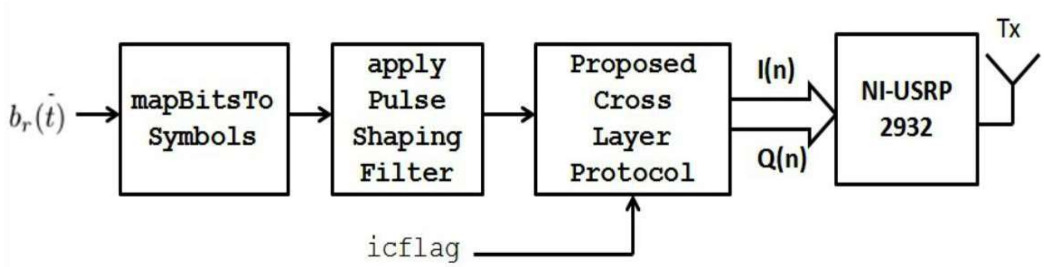

Figure 3.16: Block Diagram of Transmitter after Addition of New Block for Implementing Proposed Cross Layer Design Optimization

With this change in place, the BER versus Eb/No performance matches closely with the BER performance curves for Scenario 1 (with AWGN only), as shown in Figure 3.17 and Figure 3.18, for 8-PSK and 64-PSK respectively. The system performance improvements, in terms of throughput, resulting from the implementation of the proposed idea on cross layer design optimisation, are shown in Table 3.3.

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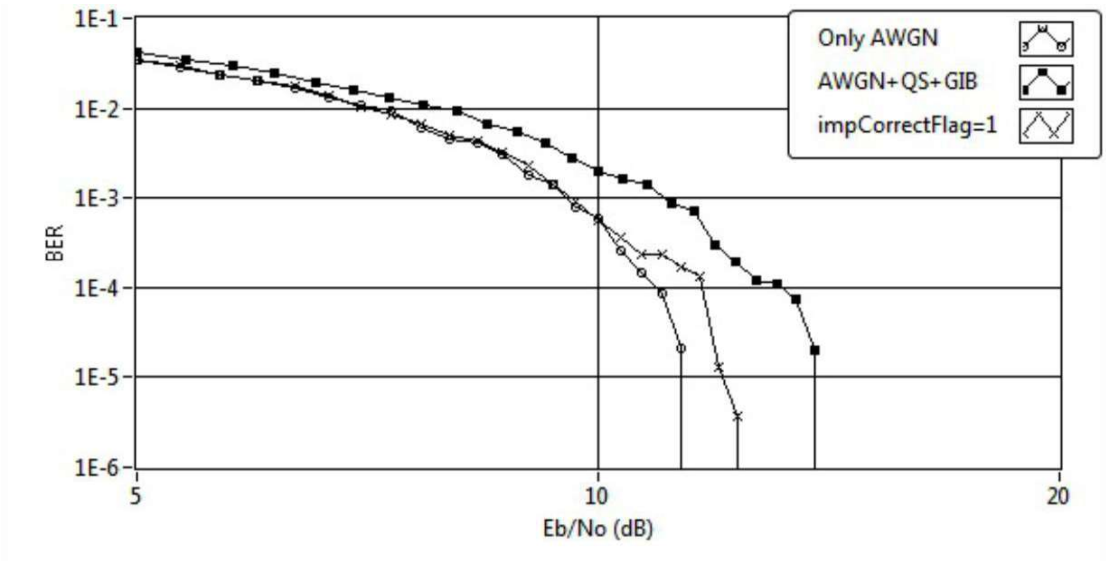

Figure 3.17: 8-PSK BER Performance Curve with icflag = 1

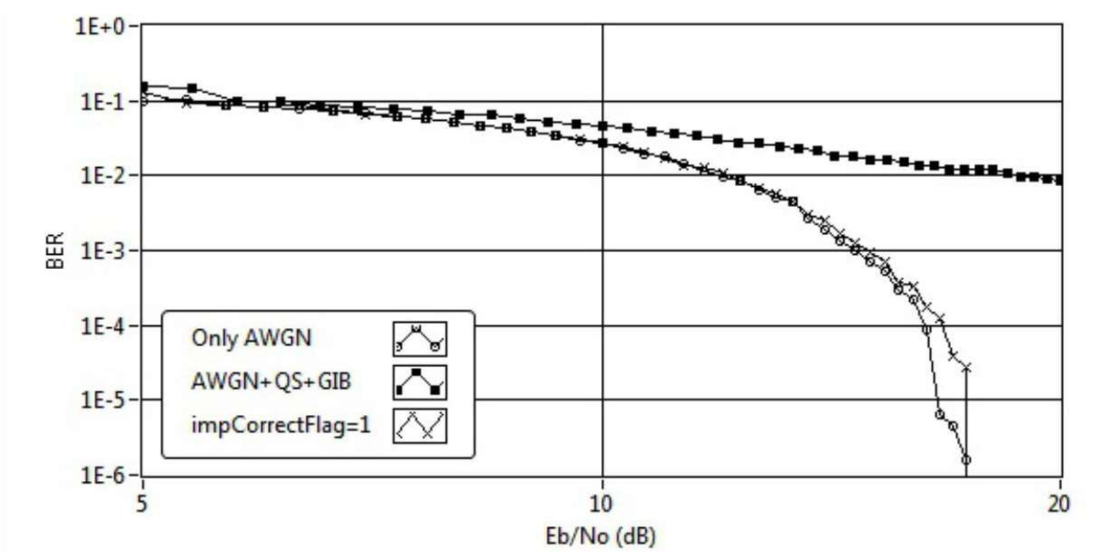

Figure 3.18: 64-PSK BER Performance Curve with icflag = 1

Table 3.3: Throughput Improvements with the Proposed Cross Layer Improvements

Eb/No	*Mb/s with icflag=0*	*Mb/s with icflag=1*
20	4	8
10	2	4
5	1	2

3.6 Summary

The impact of Eb/No of an AWGN channel on BER has been extensively studied in the literature through theoretical, simulation-based, and experimental results. However, this is not the only value that influences BER of a communication system. This chapter shows how linear impairments such as quadrature skew and gain imbalance also adversely impact the BER performance curve of an angular digital modulation scheme. This chapter shows how a communication scheme that selects the modulation order without taking these effects into account, can end up making sub-optimal choices. To mitigate this effect, this thesis presents a cross layer protocol in which the receiver measures these impairment values and shares this information with the transmitter. The transmitter, in turn, uses these values to negate the influence of these parameters on the received signal. This chapter presents a theoretical derivation of the impact of these impairments on the received signal and verifies the theoretical derivation with results obtained on a real-world experimentation system. This chapter then describes a technique to measure the gain imbalance and quadrature skew as seen at the physical layer of the receiver. This chapter also presents a cost-benefit analysis to demonstrate the practicality of the proposed idea. It is important to do such thorough cost benefit analysis of any proposed cross layer design protocol via clearly stated criteria.

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