3. Receiver Optimization in the Presence of Rayleigh Noise

Detection in the presence of noise is a fundamental topic in communications theory. Regardless of the noise source, engineers are constantly faced with filtering tradeoffs associated with the careful balancing of desirable noise cancellation and unwanted filter-induced signal distortions. The exact filter bandwidth and shape which optimizes this tradeoff can be a complex issue as many factors must be considered including modulation format, demodulation/detection algorithm, and type(s) of noise present in the system [1, 2]. Ultimately, the goal of such optimizations is to achieve the highest signal fidelity by maximizing the SNR.

In fiber optic communication systems, ASE is often the dominant noise source limiting reach and reception. For this reason, ASE's impact on optimal reception is a well studied topic in both IM-DD and coherent optical systems [3-8]. By contrast, little (if any) research has investigated the impact RB has on the design of optical receivers. Considering the importance of IB links, Raman amplified links and PONs in future optical systems, it is appropriate to investigate how optimally designed optical receiver can maximize the SNR in the presence of both coherent and incoherent RB noise. This chapter represents the first rigorous study to elucidate the various tradeoffs associated with receiver design in the presence of RB noise. Two scenarios will be examined: links corrupted by coherent RB noise and links corrupted by incoherent RB noise. It will be demonstrated that the design rules governing optimal receiver design will contrast greatly depending on which type of RB is present. For coherent RB limited links, it is found that little improvement can be attained via receiver optimization. This is attributed to the inability to filter coherent RB noise since it is spectrally overlapped with the signal. For incoherent RB limited links, it is found that ideal receiver filtering tends to optimize for unconventionally narrow optical filters (i.e. narrower than would be typically used to optimize in the ASE limit). Ultimately, the highest SE in an IB link is achieved by implementing very narrow optical filtering in order to sacrifice additional ISI distortions in favor of substantially higher RB reduction.

3.1 Receiver Model

3.1.1 Preamplified Reception with ASE, RB and Electrical Noise

A central conclusion of Chapter 2 was that the accurate modeling of heavily filtered UDWDM channels corrupted by RB noise entails the use of exact RB PSDs and filtering effects. As a result, the numerical model will be used throughout this chapter for its ability to incorporate exact RB PSDs, realistic filter shapes and filter distortion effects. While the general approach to solving (2.4-2.8) is the same, several changes are noted.

A detailed schematic of the preamplified receiver structure under investigation is shown in Fig. 3.1. As before, back-to-back performance will be assumed in order to eliminate complexities associated with propagation dispersion and nonlinearity.

The preamplified receiver in Fig. 3.1 is straightforward: a PRBS modulated signal, $e_{sig}(t)$, is first corrupted by some amount of additive RB noise. The $OSNR_{RB}$ is given by

$$OSNR_{RB} = \frac{P_{ave}}{P_{RB}} = \frac{\overline{\left\langle \left| e_{sig}(t) \right|^2 \right\rangle}}{P_{RB}}. \tag{3.1}$$

and the term in <> denotes time averaging of the signal *intensity*. Both the signal and RB are amplified by a lumped amplifier with gain, G. Additive ASE from the amplifier is added to the signal and RB using the relations

$$\begin{aligned} OSNR_{ASE} &= \frac{P_{ave}}{B_{RBW} N_{ASE}} \\ &= \frac{GP_{ave}}{h\nu GFB_{RBW}} \\ &= \frac{n_{ph} h\nu R}{h\nu FB_{RBW}} \\ &= \frac{n_{ph} R}{FB_{RBW}} \end{aligned} \tag{3.2}$$

B_{RBW} is the resolution bandwidth of the $OSNR_{ASE}$ measurement, N_{ASE} is the spectral density of the ASE, F is the amplifier noise figure, R is the data rate and n_{ph} is the number of photons per bit—the significance of the number of photons per bit will be discussed shortly. It has been assumed in (3.2) that the input $OSNR_{ASE}$ is much larger than the output $OSNR_{ASE}$.[1]

The preamplified signal and RB and the additive ASE are optically filtered, thus simulating the effect of optical demultiplexing. Again, it is assumed that the optical filter has a 1st order Gaussian filter shape. The optically filtered fields are then

[1] See Appendix III for more details regarding this approximation.

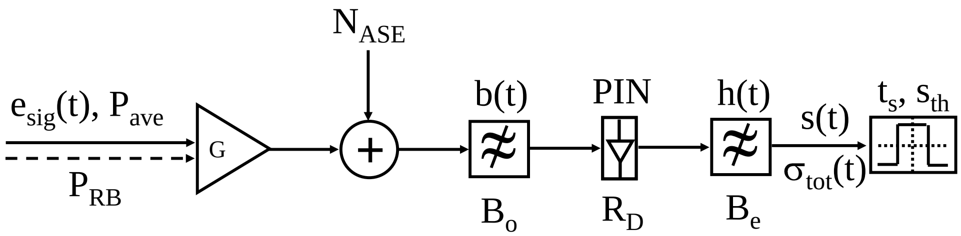

Fig. 3.1. Schematic diagram of the preamplified receiver model. Additional mathematical descriptions of the various parameters can be found in Chapter 2. In this study, G = 27 dB and NF = 3 dB (ideal amplification).

detected with a PIN photodetector with responsivity, $R_{D.}$ The detected photocurrent is further corrupted by electrical noise and is then electrically filtered by the low pass receiver characteristics as described by (2.27). The total electrical noise—given by (2.11)—stems from the amplification of thermal noise and dark current and is calculated with NEP = $30 \cdot 10^{-9}$ mW/√Hz, which is consistent with the Agilent 11982A Lightwave Receiver used in the experiments of Chapter 2 [9]. 40 Gb/s data rates are assumed throughout this chapter. The filtered signal and noise are then passed to the decision circuit which samples the waveform once every bit period and the sampled result is then compared to a fixed decision threshold, s_{th}. Samples above s_{th} are detected as marks whiles samples below s_{th} are detected as spaces. The total BER is given by calculation of (2.28).

3.1.2 Figure of Merit: Quantum Limited Sensitivity

In contrast with Chapter 2, which was concerned with solving the numerical model for a specific set of experimentally determined values, this chapter seeks to develop a framework which allows comparison of noise performance in a variety of circumstances. For this reason, the performance calculations in this chapter are quoted as sensitivity penalties relative to the ASE quantum limit (QL_{ASE}). The QL_{ASE} is the ASE-dominated sensitivity limit, quoted in photons/bit, which identifies the required signal strength into the receiver to achieve a BER of 10^{-9}, assuming a matched electrical filter and ideal 3 dB noise figure [10]. For NRZ and RZ formats, n_{QL} is 38 photons/bit [11]. For DB, n_{QL} is 32.4 photons/bit [12]. Interestingly, DB has a theoretically better fundamental sensitivity.

In reality, performance will never be totally ASE dominated (electrical noise will always persist to some extent), nor will matched filtering be achieved (typical electrical response is a Bessel filter), thus it is illuminating to quote performance in terms of QL penalty

$$QL(dB) = 10\log\left(\frac{n_{actual}}{n_{QL}}\right). \tag{3.3}$$

where n_{actual} is the calculated signal strength (in photons/bit) necessary to achieve a BER of 10^{-9}. The QL penalty is convenient because it is, under normal circumstances, bit rate independent.[2] Also, it provides a means of comparison between the various modulation and noise types. It should be noted that no current derivation exists which calculates the fundamental QL for RB-limited reception. Therefore, all penalties will be relative to the ASE-limited QL.

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[2] If electrical noise is included in the calculation, QL is not *exactly* bit rate independent since electrical noise is proportional to B_e. However, for the cases considered, electrical noise is several orders of magnitude smaller than the signal dependent noise contributions. The bit rate would have to exceed several hundred Gb/s for this statement to require modification.

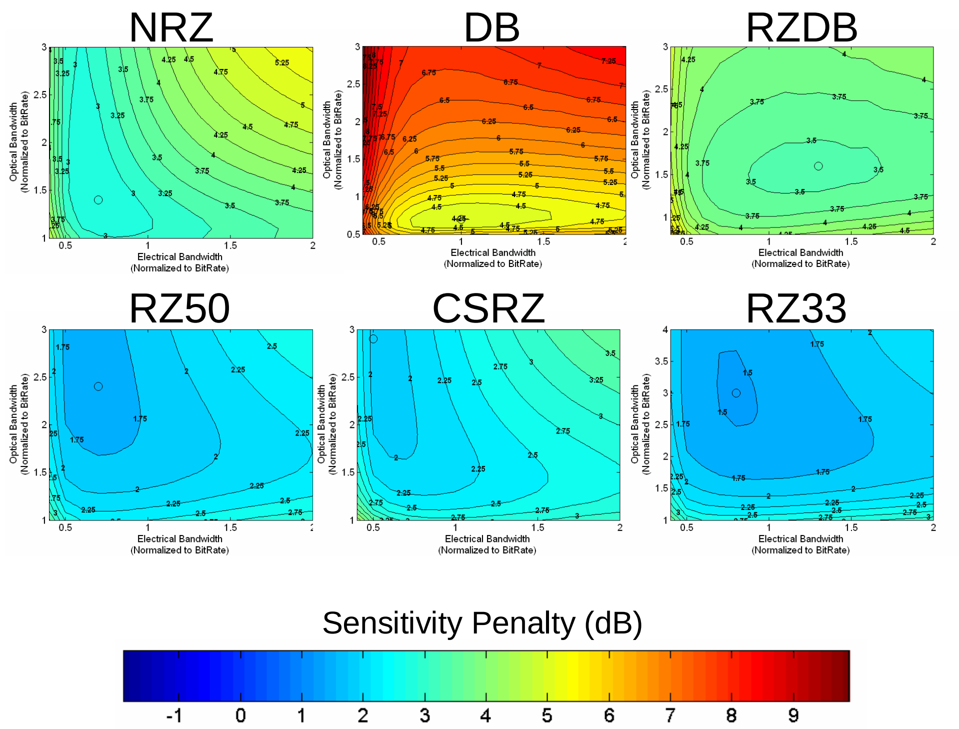

Fig. 3.2. ASE-limited contour plots of constant QL to attain BER=10^{-9}. Optimal B_o/B_e combinations designated by circles.

3.2 ASE Dominated Performance

In order to evaluate the accuracy of the numerical model, ASE-limited performance was first calculated and compared to previously published results [7, 13] The first goal is to determine the proper optical and electrical filter bandwidths for each individual modulation format. The results are described in the contour plots in Fig. 3.2. The contour plots give the contours of constant QL penalty as a function of both electrical (x-axis) and optical (y-axis) 3 dB filter bandwidth. As before, the electrical filtering is modeled by a 4th order Bessel filter impulse response.

The results indicate that each modulation format has a distinct optimal combination of B_o and B_e. The circles in the contour plots show the numerically

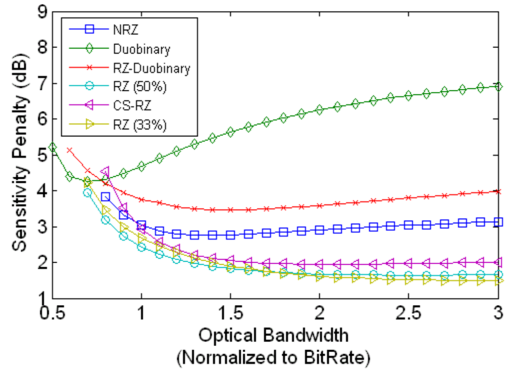

Fig. 3.3. QL sensitivity penalty to achieve BER=10^{-9} for fixed electrical bandwidth. B_e = 0.7*R for NRZ and RZ formats and B_e = 1*R for DB formats. With the exception of DB, performance is fairly flat beyond B_o = 1.5*R.

determined optimal points of operation in ASE-limited systems. In general, wider modulation formats like RZ50 and RZ33 optimize for larger optical filters (>2.4*R). NRZ is found to optimize with a B_o of about 1.4*R and a B_e of 0.7*R. These values are in close agreement with previous results [7, 13] and validate the accuracy and precision of the numerical modeling technique.

It is interesting to note the filtering performance of DB and RZ-DB modulation. As it is clearly shown in the contours, DB modulation optimizes for narrower optical filters and slightly wider electrical filters. This trend has been previously reported in [13-15] and is related to the complex ISI interaction of DB pulses. The benefits of DB come from the fact that neighboring marks destructively interfere such that larger optical filtering is preferred. Thus, DB tends to optimize with a B_o of 0.7*R. Additionally, since the phase information of the DB waveform is lost upon square-law detection, the contours indicate that slightly wider B_e is preferred. This would indicate that when designing optimal DB receivers, optically induced ISI is more desirable than electrically induced ISI.

To limit the cost and complexity of the electronics, B_e will be between 0.5 and 1*R. Therefore, Fig. 3.3 plots the QL penalty as a function of B_o for fixed B_e. For NRZ and RZ formats, B_e is fixed at 0.7*R as is consistent with optimal values in Fig. 3.2. For DB, B_e is fixed at 1*R since DB tends to optimize for slightly larger B_e. A primary conclusion of Fig. 3.3 is that, with the exception of DB, all formats are weakly dependent on B_o when $B_o > 1.5*R$. This would indicate that there is some flexibility when designing optimal receivers degraded by ASE noise. Moreover, unless DB is being implemented, the exact choice of B_o is largely unaffected by modulation format. This fact is especially true for the RZ formats which have flat QL penalty curves extending beyond 3*R.

3.3 Coherent RB Dominated Performance

3.3.1 Coherent RB Limits

Having established the baseline ASE-limited results, it is now possible to contrast RB-limited performance. Results for coherent RB noise performance in the absence of ASE and electrical noise are shown in Fig. 3.4. Several interesting features are noted. First, in all cases, performance optimizes for $B_e > 2*R$. This is explained on account of the fact that electrical filtering will not reduce appreciable amounts of coherent RB beat noise since the signal and noise field perfectly overlap in the frequency domain. Therefore, optimal performance is attained for very large electrical bandwidth since this minimizes electrically induced ISI. Of course, this is an

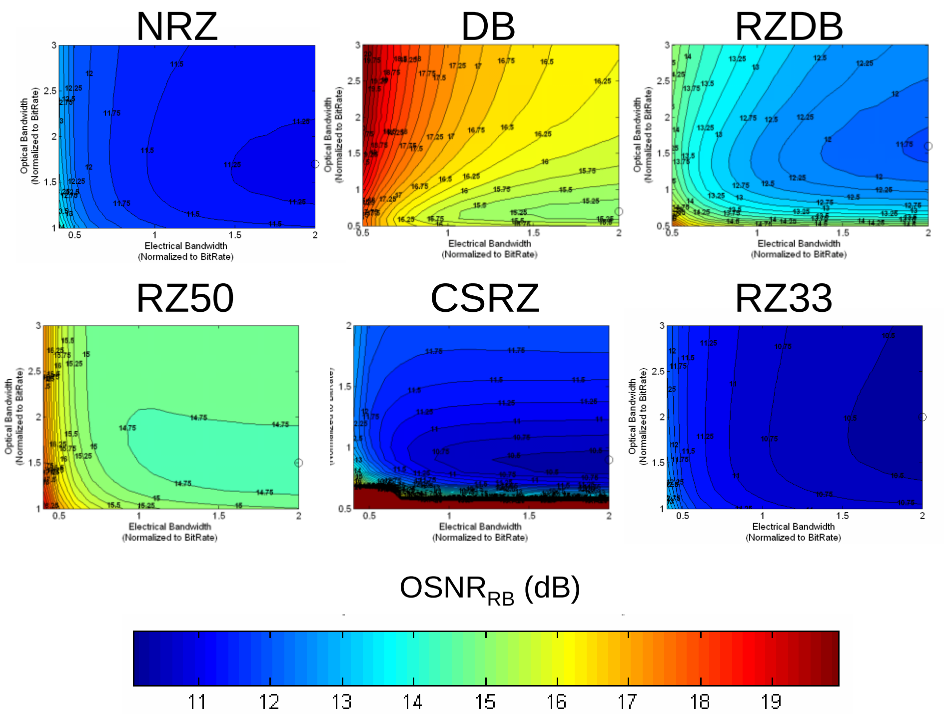

Fig. 3.4. Coherent RB-limited contour plots of constant QL to attain BER=10^{-9}. Optimal B_o/B_e combinations designated by circles. Values quoted in absolute $OSNR_{RB}$ (dB) required to maintain BER = 10^{-9}.

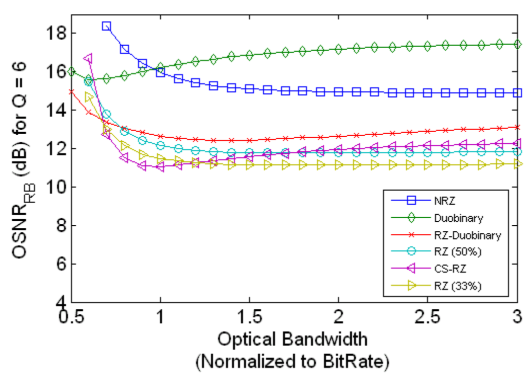

Fig. 3.5. Required $OSNR_{RB}$ to achieve BER=10^{-9} for fixed electrical bandwidth. B_e = 0.7*R for NRZ and RZ formats and B_e = 1*R for DB formats. With the exception of DB, performance is fairly flat beyond B_o = 1.5*R.

unrealistic solution since electrical noise will place on upper bound high frequency cutoff according to (2.11).

Fig. 3.5 plots the required $OSNR_{RB}$ as a function of B_o for B_e of 0.7*R for NRZ and RZ and 1*R for DB. Results show that, with the exception of DB and CSRZ, optical filtering cannot remove appreciable amounts of coherent RB noise meaning that it is most desirable to minimize optically induced ISI by implementing very large optical filters. The reason is the same as before in that no noise reduction is achieved through filtering of the perfectly overlapped signal and RB. Interestingly, DB again optimizes at B_o=0.7*R meaning that the optical ISI effect has a greater influence on signaling performance when compared to the impact of RB. Also, CSRZ minimizes around 1*R in the presence of coherent RB. This is explained by the fact that CSRZ has strong +/-R/2 harmonic components. Hence, additional ISI penalties from excessive optical filtering are preferred in order to reduce the strong +/-R/2 beating terms of CSRZ.

3.3.2 ASE and Coherent RB

The previous results for coherent ASE were obtained in the absence of ASE and electrical noise. Realistic results for the ASE-limited sensitivity in the presence of RB (20 dB crosstalk level) are shown in Fig. 3.6. Results for the optimal optical bandwidth for fixed electrical filters are shown in 3.7. As would be expected, the inclusion of coherent RB causes additional QL penalties. Moreover, optimal values for B_o and B_e change.

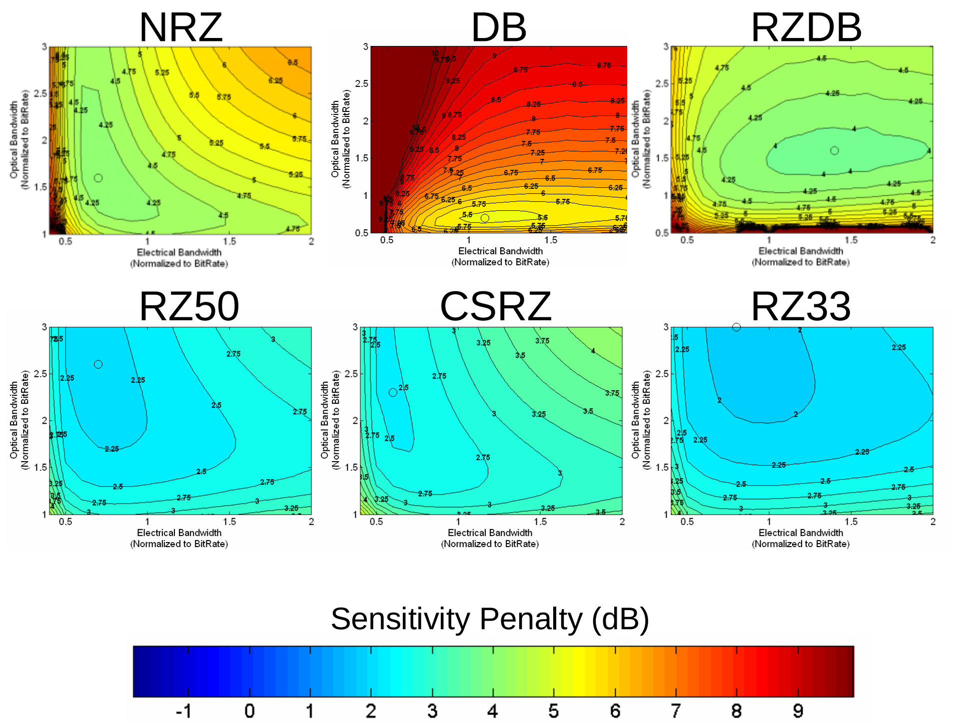

Fig. 3.6. ASE-limited contour plots of constant QL to attain BER=10^{-9} in the presence of 20 dB of RB crosstalk (i.e. $OSNR_{RB}$ = 20 dB into preamplifier). Optimal B_o/B_e combinations designated by circles.

While differences exist between the contour plots of Fig. 3.2 and Fig. 3.6 and the fixed B_e plots of Fig. 3.3 and Fig. 3.7, the most relevant question relates to whether or not the presence of coherent RB noise changes the optimal receiver characteristics. In order to study this, Fig. 3.8 shows how B_o changes as a function of $OSNR_{RB}$ for fixed B_e. Fig. 3.8a indicates that large swings in optimal B_o occur as the $OSNR_{RB}$ increases above 20 dB. For NRZ, the trend is towards large optical filter bandwidths while the opposite is true RZ formats. These trends exemplify the intricate balance between noise reduction and filter induced ISI for the various modulation formats. Again, DB is largely independent of RB noise level since its performance is

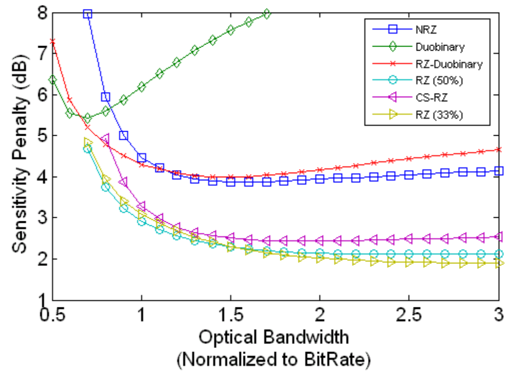

Fig. 3.7. QL sensitivity penalty to achieve BER=10^{-9} in the presence of 20 dB of RB crosstalk for fixed electrical bandwidth. B_e = 0.7*R for NRZ and RZ formats and B_e = 1*R for DB formats.

determined by the optically induced ISI effects. Fig. 3.8b shows that large penalties are suffered when the $OSNR_{RB}$ is larger than about 20 dB. To quantify this effect, Fig. 3.8c shows the relative excess QL penalty compared to the case of no RB. Results indicate that NRZ and DB suffer greater than 1 dB excess penalty for $OSNR_{RB}$ levels above about 20 dB. All RZ formats have slightly better RB immunity with 1 dB excess penalties occurring around 16-17 dB.

Interestingly, the large optimization variations witnessed in Fig. 3.8 overstate the importance of receiver optimization as shown in Fig. 3.9. Here, a comparison is made between the optimal receiver values as determined in Fig. 3.8 with the ASE-limited optimal values as determined by Fig. 3.3. Despite the seemingly large differences between optimal B_o values, Fig. 3.9 shows that there is little difference between ASE-optimized and ASE-with-coherent-RB-optimized receiver performance. With the exception of CSRZ subject to extremely high RB levels (< 15 dB $OSNR_{RB}$),

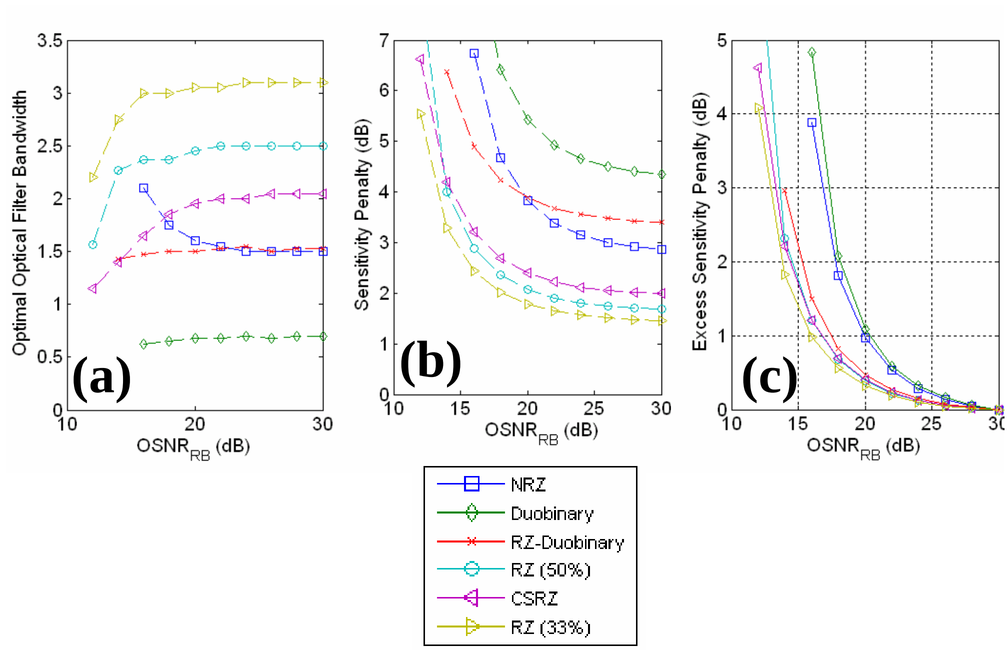

Fig. 3.8. QL performance under optimal receiver condition as a function of coherent RB level. (a) Optimal optical filter bandwidth. (b) Absolute QL penalty. (b) Excess QL penalty relative to case without RB crosstalk.

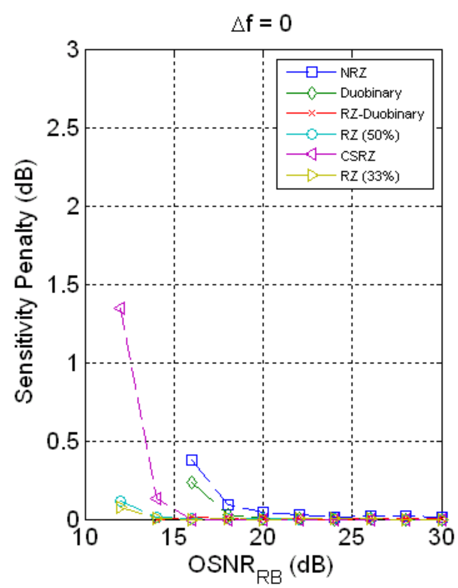

Fig. 3.9. Excess penalty for using ASE-limited optical receiver as a function of coherent RB level. The penalty for using an ASE-optimized receiver is minimal.

there is less than 0.4 dB of excess penalty for using a simple, ASE-limited receiver. Thus, even if it is erroneously assumed that coherent RB is negligible and that ASE is the only significant noise process, no excess penalties from the improper choice of receiver filter will be sustained. The fact that this is the case is not surprising: Fig. 3.5 and Fig. 3.7 each indicate that coherent RB QL sensitivity penalty is only weakly coupled to optical filter bandwidth as illustrated by the flatness of the curves beyond 1.5*R. Hence, while it is possible to calculate exact optimal receiver characteristics, Fig. 3.9 demonstrates that even large deviations do not result in appreciable link budget loss. Therefore, the primary conclusion of this section is that *coherent RB noise has a negligible effect on the optimal design of preamplified receiver low pass characteristics*.

3.4 Incoherent RB Dominated Performance

3.4.1 Incoherent RB: 0.8 bits/s/Hz Spectral Efficiency

Intuitively, it makes sense that receiver filtering has little to no net impact on coherent RB reduction since the signal and noise occupy the same frequency space. Conversely, it would seem that in the case of IB links with incoherent RB that some amount of filtering may be beneficial. This section studies how incoherent RB impacts optimal receiver design.

As a test case, an IB link is numerically modeled which has an aggregate SE of 0.8 bits/s/Hz. This corresponds, for example, to an IB topology which contains 40 Gb/s channels with unidirectional channel spacing of 100 GHz. Therefore, the two adjacent RB channels are separated by +/- 50 GHz (i.e. 1.25*R). From the previous

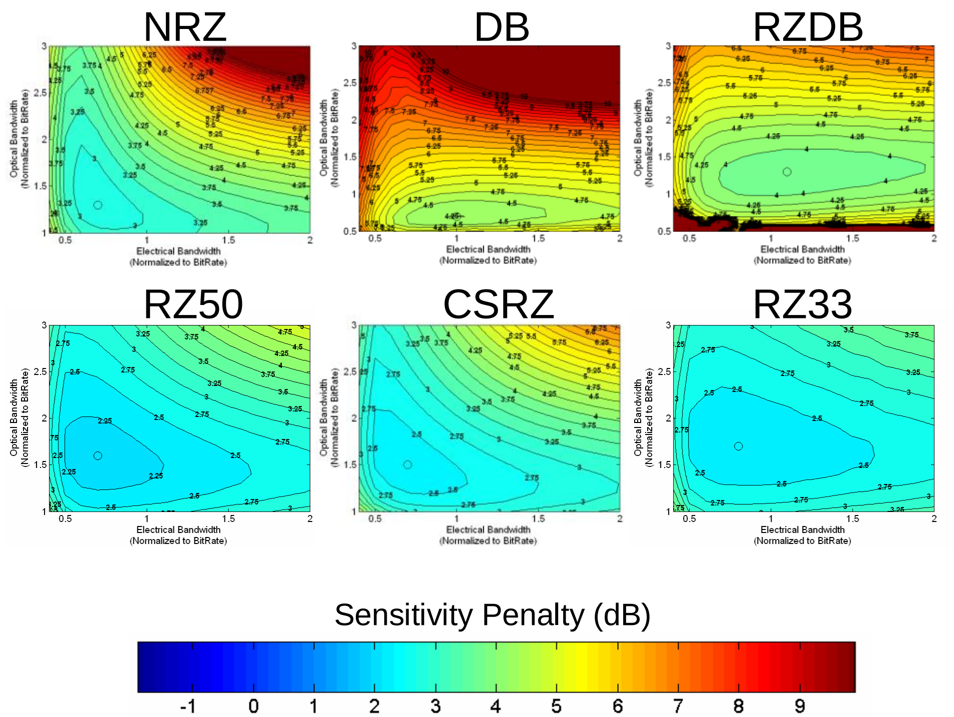

Fig. 3.10. QL sensitivity penalty to achieve BER=10^{-9} in the presence of 20 dB of RB crosstalk for fixed electrical bandwidth. B_e = 0.7*R for NRZ and RZ formats and B_e = 1*R for DB formats.

chapter, it was determined that channel spacing greater than R improves the RB sensitivity by as much as 10 dB. These experimentally measured improvements do not account for the fact that the optical filter may further improve RB immunity.

The QL sensitivity penalty for an IB link with ASE, electrical noise and 10 dB $OSNR_{RB}$ is shown in Fig. 3.10. In analyzing the results, it is clear that a 0.8 bit/s/Hz spectral efficiency IB link optimizes for unconventionally narrow optical filter bandwidths. For example, RZ50 has an ASE-limited optimal optical bandwidth of 2.4*R. In the IB topology calculated here, the optimal optical bandwidth reduces to 1.55*R.

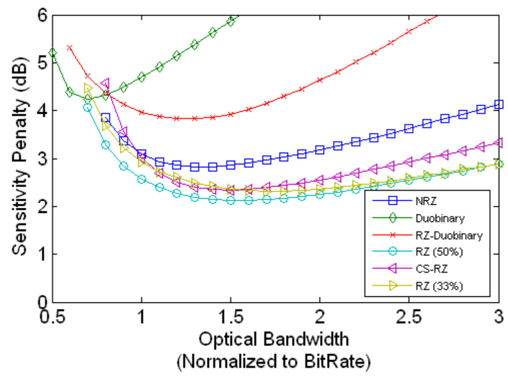

Fig. 3.11. QL sensitivity penalty to achieve BER=10^{-9} in the presence of 20 dB of RB crosstalk for fixed electrical bandwidth. B_e = 0.7*R for NRZ and RZ formats and B_e = 1*R for DB formats.

The importance of using narrow optical filtering is further demonstrated in Fig. 3.11. When the electrical filter is fixed to 0.7*R (or 1*R for DB formats), a clear minimum emerges which yields the smallest attainable QL penalty. Whereas the fixed B_e curves in the previous section tended to flatten after B_o > 1.5*R, the optimal filter bandwidths for the IB link optimize at specific values. Beyond these optimal values, performance degrades because a larger amount of incoherent RB passes unmitigated to the photodetector. Interestingly, optimal values for B_e remain in the region between 0.5 and 1*R indicating that exactly the same receiver electronics can be used without incurring additional penalties. Overall, the results of Fig. 3.10 and Fig. 3.11 demonstrate the vital importance of well designed demultiplexers in IB links. With the exception of DB (which again optimized for a B_o = 0.7*R), trading optical filter induced ISI is preferred over passing undue amount of adjacent channel crosstalk.

3.4.2 Spectral Efficiency Considerations

The impact of incoherent RB for different spectral efficiencies is now discussed. Results shown in this section are for optimally determined optical filter values, fixed B_e, and $OSNR_{RB}$ of 10 dB. Fig. 3.12a shows the ultimate spectral efficiencies possible for all modulation formats considered. As was mentioned previously, optimal filter bandwidths tend to be narrower than ASE-limited links. Fig. 3.12 shows that these optimal values vary significantly as a function of channel spacing. The trend is clear: the wider the modulation format, the larger the change in optimal B_o value. For example, the widest format, RZ33, which has an ASE-optimized B_o of about 3.1*R, narrows to about 1.4*R when the channel spacing is R. DB, on the other hand, maintains a nearly constant B_o, regardless of channel spacing. This indicates that DB is almost totally immune to incoherent RB in IB links and may be the best choice of modulation format for these purposes.

However, when one considers the absolute QL penalty of the various formats, the best choice of modulation format corresponds to the required spectral occupancy. In general, wider modulation formats tend to have better *absolute QL penalty* while narrower formats tend to have the smallest *excess QL sensitivity penalty*. Fig. 3.12b and Fig. 3.12c illustrate this point. By plotting the optimal QL penalty as a function of channel spacing, it is clear from Fig. 3.12b that RZ formats are far superior to NRZ and DB, especially for SE less than 1 bit/s/Hz. Alternatively, Fig. 3.12c plots the excess sensitivity penalty caused by incoherent RB relative to the ASE-limited penalty (i.e. the QL limit as $\Delta f \rightarrow \infty$). This plot indicates the 1 dB power penalty incurred by

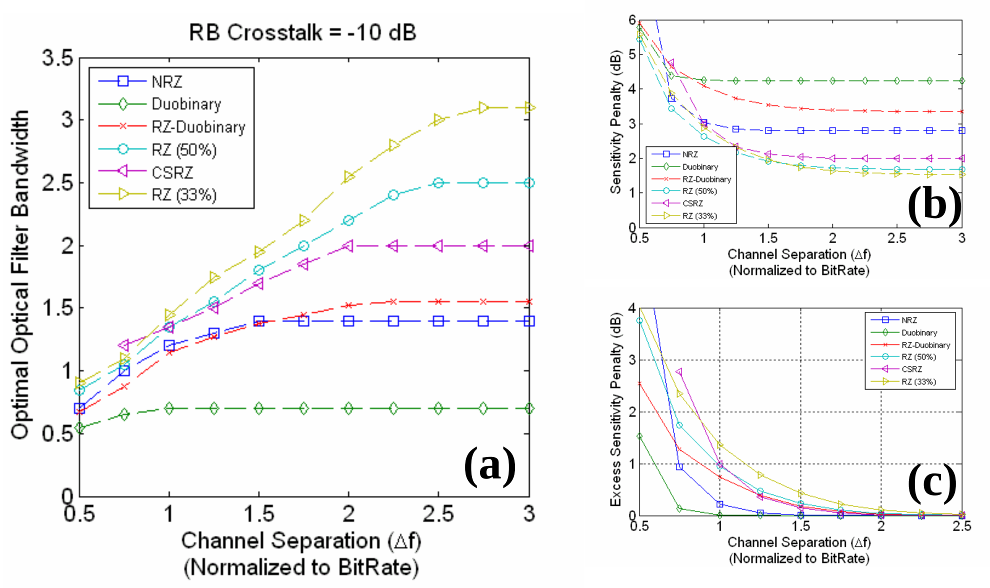

Fig. 3.12. QL performance under optimal receiver condition as a function of channel separation between signal and RB. (a) Optimal optical filter bandwidth. (b) Absolute QL penalty. (b) Excess QL penalty relative to case without RB crosstalk.

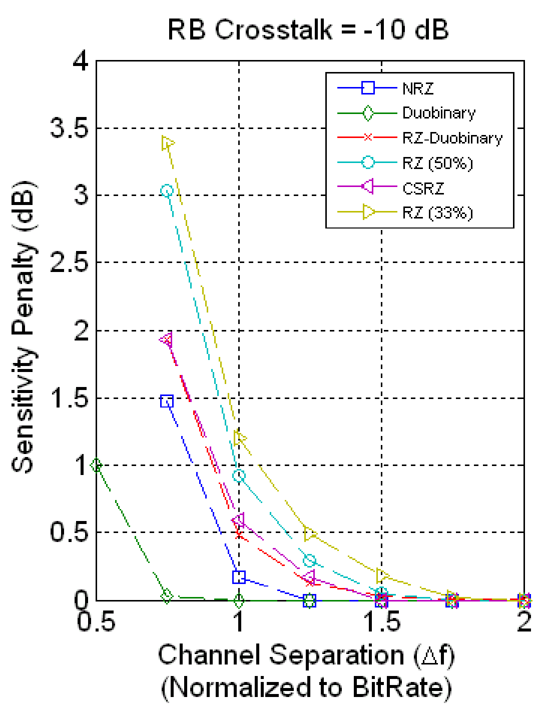

Fig. 3.13. Excess penalty for using ASE-limited optical receiver as a function of incoherent RB level. The penalty for using an ASE-optimized receiver is large for tight channel packing density.

incoherent RB in IB links. The trend shows that the vulnerability of the IB link to RB crosstalk increases with the bandwidth of the modulation format PSD. Based on the calculations, DB is highly resistant to incoherent RB up to channel separations of R/2 (i.e. SE = 2 bits/s/Hz.)

The final confirmation of the importance of receiver optimization in the presence of incoherent RB is shown in Fig. 3.13. This plot is analogous to Fig. 3.9 and compares the excess sensitivity which would be suffered if ASE-optimized filtering is used instead of RB-optimized filtering. While coherent RB penalties are roughly independent of B_o, incoherent RB penalties are highly sensitive to B_o fluctuations (see Fig. 3.11). Therefore, the penalty for erroneously implementing ASE optimized receiver filters is substantially greater in IB links. Beyond spectral efficiencies of 0.8 bits/s/Hz, the penalty is less than 0.5 dB. However, when ultra dense systems are considered, the penalty for *not* using optimal optical filtering grows rapidly. For adjacent channel spacing less than R, non-optimal filtering penalties exceed several dB for the widest modulation formats.

3.5 Conclusion

This chapter represents the first ever rigorous study on the impact of RB noise on receiver design. A summary of the results can be found in Table 3.1. Here, optimal B_o and QL values are listed for the four main systems under investigation. A clear delineation between coherent and incoherent RB has been exposed. Results indicate that it is not possible to improve coherent RB-limited performance using standard

Table 3.1.
Summary of Optimal Filtering and QL Penalty for ASE and RB Noise

	ASE Limited (ASE + Electrical Noise)		Coherent RB Limited (RB ONLY)		ASE + Coherent RB $OSNR_{RB}$ = 20 dB		ASE + Incoherent RB S.E. = 0.8 bits/s/Hz $OSNR_{RB}$ = 10 dB	
	Optimal Filter Bandwidth	*Penalty (dB)*	*Optimal Filter Bandwidth*	*OSNR Q=6 (dB)*	*Optimal Filter Bandwidth*	*Penalty (dB)*	*Optimal Filter Bandwidth*	*Penalty (dB)*
NRZ	1.4	2.76	>3	14.65	1.6	4.09	1.3	2.82
DB	0.7	4.24	0.7	15.1	0.7	5.39	0.7	4.24
RZDB	1.55	3.42	1.55	11.69	1.55	3.9	1.3	3.80
RZ50	2.4	1.65	>3	11.2	2.6	2.16	1.55	2.12
CSRZ	2.9	1.89	1	10.4	2.3	2.46	1.5	2.34
RZ33	3	1.48	>3	10.4	3.1	1.79	1.75	2.31

optical or electrical filtering techniques because the signal and RB field a perfectly overlapped in the frequency domain. When compared with ASE-optimized receivers, there is no appreciable difference in the overall receiver design for coherent RB. In some sense, this is fortunate as it means that coherent RB-limited links like Raman amplified networks and PONs do not require additional design considerations. However, this also implies that little can be done if RB levels become overwhelmingly large. In this case, the only choice is to limit coherent RB as much as possible. Incoherent RB has a distinct design paradigm compared to coherent RB. As was shown for IB links, incoherent RB can be well mitigated through optimal link design. In general, optimal filter bandwidths tend towards unconventionally narrow RB optical filtering while the electrical filter bandwidths remain roughly unchanged. When designing IB links, it has been illustrated that the best choice of modulation format depends the availability of optical demultiplexer bandwidths. As would be expected, wider modulation formats are best for low and moderate link capacities while spectrally narrow formats are best for very dense systems when performance is quantified in terms of excess RB penalty.

Interestingly, it was determined that DB is mostly unaffected by RB noise. For both coherent and incoherent RB noise, optimal DB filtering was almost always 0.7*R. This optimal value has been identified for ASE-limited DB performance in [13-15] and points to the complex ISI effects which accompany the intrinsic phase coding of the DB optical field. This study has shown that the optimization of DB is RB noise invariant. For this reason, DB is the modulation format of choice for ultra dense IB links since the impact of incoherent RB can be largely ignored.

3.6 References

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