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Dispersion Compensation Using DCF and Chirped FBG in High-Speed SMF Links

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Abstract— Chromatic dispersion limits the reach of high speed networks as it spreads the optical pulses in a fibre. This can be mitigated by two known techniques: chirped fibre Bragg grating (FBG) and dispersion compensating fibre (DCF). This study compares the two approaches for non-return-to-zero (NRZ) on-off keying links over conventional single-mode fibre (SMF) at 10, 25 and 40 Gbps. The link is made of 80 km spans with a compensator in each span and an erbium doped fibre amplifier (EDFA) behind each span. The pulse propagation is solved using FFT method and the link is evaluated using the eye diagram, Q-factor and bit error rate (BER) averaged over five random runs. The uncompensated reach with BER ≤ 10−9 is only 79 km at 10 Gbps, 15 km at 25 Gbps, and 5 km at 40 Gbps. With any compensator, it reaches ~600 km at 10 Gbps, ~360 km at 25 Gbps and ~230 km at 40 Gbps. After 80km, Q difference of DCF and FBG is less than 0.2dB. The FBG is 0.7 to 1.3 dB worse from 5 to 20 km because of its group-delay ripple. No fibre nonlinearity is observed in the linear range of investigation.

Index Terms— chromatic dispersion, dispersion compensation, DCF, fiber Bragg grating, Q-factor, BER, optical fiber communication.

I. Introduction

Almost all long-distance data traffic is carried by optical fibre. [1], [2] Link rates have increased from 10 Gbps to 25, 40 Gbps and higher as the demand continues to grow. The standard single-mode fibre (SMF) has very low loss, but one of its weaknesses at high speed is chromatic dispersion. As the pulse propagates over the fibre, the short pulse is broadened because different wavelengths of light travel at different speeds [3], [4]. Dispersion of standard single-mode fibre (SMF) [5] is about 17 ps/nm/km at 1550 nm.

The rate of growth of this problem is shown in Fig. 1. The width of a Gaussian pulse after a distance z is $T(z) = T0 \cdot \sqrt{(1 + (z/LD)2)}$, and its dispersion length is $LD = T02/|\beta 2|$ [4]. A higher bit rate means a shorter pulse and hence a much shorter duration of dispersion. Doubling the bit rate cuts the usable distance to one quarter because LD scales with the square of the pulse width. Figure 2 shows the effect on a real bit pattern. A clear 25 Gbps pattern spreads out after few km and close parts overlap. What is called inter-symbol interference (ISI) closes the eye of the receiver.

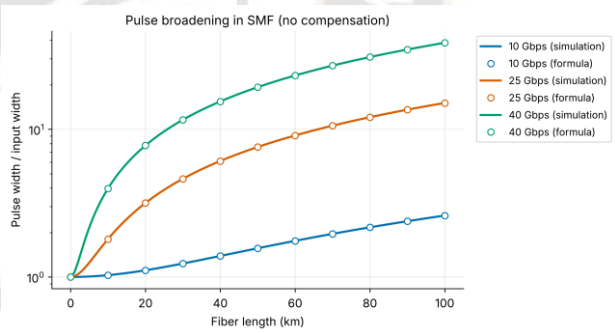


Fig. 1. Pulse broadening in SMF at 10, 25 and 40 Gbps.

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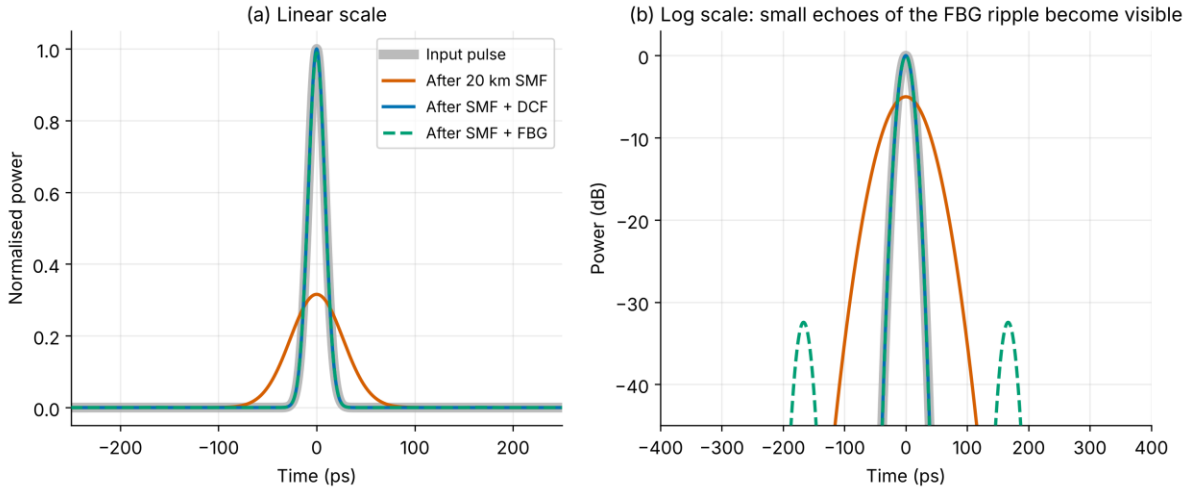


Fig. 2. Bit pattern before and after fiber without compensation: (a) linear scale, (b) dB scale.

Dispersion in the electrical domain can be eliminated by a coherent receiver using digital signal processing [6]. While this method works it needs more power, hardware and money. Many metro, access and data-center links still prefer direct detection and the dispersion is set in the optical domain. There are two common approaches. The first one is DCF, a special fibre, which is inserted after each SMF segment, and has a big negative dispersion [7]. The second is the chirped FBG, a short piece of fibre with a grating of varying periodicity along its length. This results in the pulse being pushed back together and different wavelengths being reflected at different locations [8]–[12].

Both methods work, but they have different side effects. DCF is long, adds loss and raises amplifier noise. The FBG is small and has low loss, but its bandwidth is limited and its group latency is not completely flat. Most research either use different connection settings for each approach or only consider one method. For a fair comparison both are put in the same simulated link with the same fibre, amplifiers, receiver and random noise.

The contributions of this paper are:

(1) a complete and reproducible simulation model of a multi-span direct-detection link with DCF or FBG compensation;

(2) a direct comparison of the two methods at 10, 25 and 40 Gbps over 5 to 600 km, using eye diagrams, Q-factor and BER;

(3) an analysis of accumulated amplifier noise (OSNR) for both compensators; and

(4) an estimate of the maximum reach for each case, with a discussion of where the two methods differ and where they do not.

The rest of the paper is organised as follows. Section II reviews related work. Section III gives the theoretical background. Section IV describes the simulation model. Section V presents and discusses the results, Section VI covers practical considerations and limitations, and Section VII concludes.

II. Related Work

The limits of optical fibre transmission have been researched for many years. The capacity limits of fibre networks are ultimately limited by fibre loss, amplifier noise, dispersion and non-linearity, as analysed by Essiambre et al. [1]. Winzer et al. reviewed 20 years of fibre transmission and discussed the capacity scaling potential of future systems [2]. In this work chromatic dispersion is treated as a deterministic linear effect that can be removed, compared to amplifier noise.

The huge installed base of standard SMF, with a dispersion of about 17 ps/nm/km at 1550 nm, was upgraded with the introduction of fibre based compensation [5]. Grüner-Nielsen et al. [7] provide a comprehensive analysis of dispersion compensating fibres including their dispersion values, loss and the figure of merit relating dispersion to loss. A DCF with strong negative dispersion can compensate a long SMF span with only few km of fibre at the cost of more loss and limited core area.

Fibre Bragg gratings provide an alternative. Ouellette demonstrated that the dispersion of an optical waveguide can be eliminated by a linearly chirped grating [8]. Hill

and Meltz covered the principles and manufacture of fibre gratings [9]. Othonos reviewed grating devices and applications in detail [10]. Gratings are tunable, short, and have small non-linear effects. Eggleton et al. [11] showed a voltage controlled chirped grating for tunable dispersion compensation in a 160 Gbps system. One known limitation [10], [11] is the ripple in the group delay of chirped gratings that acts as a weak echo of the signal [13].

[6] Dispersion compensation was moved into the digital signal processing with the introduction of coherent detection. This is the method proposed for long-haul networks, but direct-detection links with optical compensation are still important for situations where power and cost are constrained. Thus, the present study examines the two optical schemes under the same conditions and provides an insight into the noise that each scheme adds to the link.

III. Theoretical Background

A. Chromatic Dispersion

For a fiber of length L, the effect of dispersion on the optical field is a phase change that depends on frequency. In the frequency domain, the field is multiplied by the transfer function [4]

$$H(\omega) = \exp(\tfrac{1}{2} \cdot i \cdot \beta_2 \cdot L \cdot \omega^2) \quad (1)$$

where ω is the angular frequency offset from the carrier and β_2 is the group-velocity dispersion. It is related to the dispersion parameter D by [3]

$$\beta_2 = -D \lambda^2 / (2\pi c) \quad (2)$$

For D = 17 ps/nm/km at $\lambda = 1550$ nm, $\beta_2 \approx -21.7$ ps^2/km. In the linear regime, the phase change in (1) is the only effect of dispersion. It can therefore be undone exactly by a device that adds the opposite phase. This is what both DCF and FBG try to do.

To see the scale of the problem, Table I gives the dispersion length $L_D = T_0^2/|\beta_2|$ when T_0 is taken equal to the bit period. This is only a scale and not a hard limit, because NRZ pulses are wider than a single Gaussian and a receiver tolerates some ISI. It shows, however, that the length falls with the square of the bit rate. The 40 Gbps case has a dispersion length about sixteen times shorter than the 10 Gbps case.

TABLE I. Dispersion length for T_0 equal to the bit period.

Bit rate (Gbps)	Bit period (ps)	L_D (km)	L_D relative to 10 Gbps
10	100	461	1.00
25	40	74	0.16
40	25	29	0.06

B. DCF and Chirped FBG

A DCF has a negative dispersion D_{DCF} (here −100 ps/nm/km). Its length for one span of SMF is chosen so that the total dispersion is zero [7]:

$$L_{DCF} = D_{SMF} \cdot L_{span} / |D_{DCF}| \quad (3)$$

For an 80 km span, this gives $L_{DCF} = 13.6$ km. The extra fiber adds loss, which must be recovered by one more amplifier. A chirped FBG gives the same (but opposite) dispersion through a position-dependent reflection [8], [9]. It is a short device, but real gratings show small ripples in the group delay, which act like weak echoes of the signal [10], [11]. Table II summarises the main differences as used in this work.

TABLE II. Compensator models.

Property	DCF	Chirped FBG
Dispersion	−100 ps/nm/km (negative)	Equal and opposite to SMF span
Size	About 13.6 km per 80 km span	A few centimetres
Insertion loss	0.6 dB/km + 1 dB (about 9.2 dB)	3 dB
Bandwidth	Very wide	100 GHz (super-Gaussian)
Main side effect	Extra loss and noise	Group-delay ripple (±8 ps)

C. Amplifier Noise and OSNR

Every EDFA adds amplified spontaneous emission (ASE) noise [14]. The optical signal-to-noise ratio

(OSNR) of one amplifier, measured in a 0.1 nm (12.5 GHz) reference bandwidth, is

$$\mathrm{OSNR_i(dB)} = 58 + P_{in} - \mathrm{Loss_i} - \mathrm{NF} \quad (4)$$

where P_{in} is the launch power in dBm, $\mathrm{Loss_i}$ is the loss in front of the amplifier in dB, NF is the noise figure in dB, and 58 dB is the standard constant near 1550 nm. For a chain of amplifiers, the noise powers add, so

$$1 / \mathrm{OSNR_{total}} = \Sigma_i \, 1 / \mathrm{OSNR_i} \quad (5)$$

Equation (5) is important for this study. The compensator adds loss, and a second amplifier is needed to recover the power. A compensator with a larger loss therefore adds a larger noise term, and this effect is quantified in Section V-D.

D. Q-Factor and BER

The quality of a received on-off keying signal is judged by the Q-factor. With mean levels μ_1, μ_0 and noise standard deviations σ_1, σ_0 for the "1" and "0" bits [15],

$$Q = (\mu_1 - \mu_0) / (\sigma_1 + \sigma_0), \qquad \mathrm{BER} = \tfrac{1}{2}\,\mathrm{erfc}(\, Q / \sqrt{2}\,) \quad (6)$$

Q is also given in dB as $20 \cdot \log_{10}(Q)$. A BER of 10^{-9} needs Q = 6.0 (15.6 dB), and this value is used here as the limit for a working link.

IV. Simulation Model

Fig. 3 shows the simulated link. The model is implemented in Python using NumPy, SciPy and Matplotlib. Its parts are described below, and all parameter values are listed in Table III.

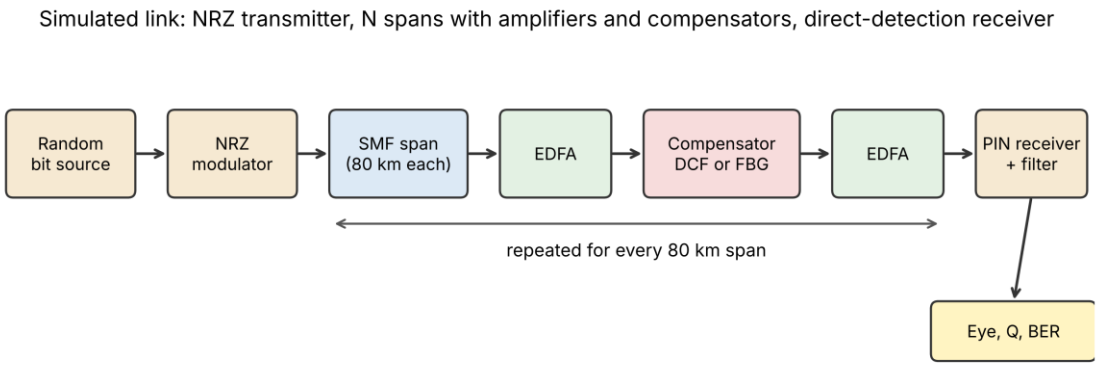


Fig. 3. Block diagram of the simulated link.

A. Transmitter

A random NRZ bit sequence (2048 bits, 32 samples per bit) drives an intensity modulator with a Gaussian response (bandwidth equal to 0.75 times the bit rate) and an extinction ratio of 12 dB. The finite extinction ratio means that the "0" level is not completely dark. The launch power is −5 dBm, which is low enough to neglect fiber nonlinearity. The optical field is taken as the square root of the optical power.

B. Fiber and Amplifiers

With a loss of 0.25 dB/km, each span is 80 km of SMF. The final span is shorter if the total distance is not a multiple of 80 km. The FFT approach is used to apply dispersion: the field is converted to the frequency domain, multiplied by (1), and then converted back. After each span, an EDFA with a noise figure of 5.5 dB recovers the launch power [14]. Each span contains two sources of noise since a second EDFA recovers the power after the compensator.

C. Compensators

The DCF is modelled by the transfer function in (1) with the opposite sign of β_2, a length given by (3), a loss of 0.6 dB/km and 1 dB of extra loss for splices and connectors. The FBG cancels the same dispersion, and in addition it has a limited bandwidth and a group-delay ripple. Its transfer function is

$$H_{FBG}(f) = \exp[\, -(\ln 2 / 2)\cdot(2f / B_g)^4 \,] \cdot \exp[\, i\, A \sin(2\pi f / f_r + \varphi) \,] \cdot H_{-D}(f) \quad (7)$$

where B_g = 100 GHz is the bandwidth, H_{-D} is the dispersion-cancelling phase, f_r = 6 GHz is the period of the ripple, and φ is a random phase that changes for every span. The ripple amplitude $A = \tau_r \cdot f_r = 0.048$ rad corresponds to a group-delay ripple of $\tau_r = \pm 8$ ps. These values are representative of a good grating and are not taken from one specific device. The FBG also has an insertion loss of 3 dB.

D. Receiver

A PIN photodiode (responsivity 1 A/W, thermal noise 10 pA/√Hz) detects the signal by square-law detection. An

electrical Gaussian low-pass filter, with a bandwidth of 0.75 times the bit rate, follows. The noise variance at a sampled level s is the sum of thermal noise and signal–ASE beat noise:

$$\sigma^2 = \sigma_{th}^2 + k_{sp} \cdot s, \quad k_{sp} = (1 + 1/ER) \cdot B_e / (OSNR \cdot B_{ref}) \quad (8)$$

where B_e is the electrical bandwidth, ER is the extinction ratio in linear units and B_{ref} = 12.5 GHz. The best sampling instant is selected, and Q and BER are computed from (6). The value of OSNR is obtained from (4) and (5) for the number of spans and the compensator in use.

E. Procedure

For each bit rate (10, 25 and 40 Gbps) and each distance (14 values from 5 to 600 km), the simulation is done for three cases: no compensation, DCF and FBG. Each point is the mean of five runs with different random bits and different FBG ripple phases, with the standard deviation indicated as ±. The reach is the maximum distance at which Q ≥ 6, which is found by linear interpolation between the two distances at which Q crosses this threshold.

F. Validation

The dispersion model is validated by the analytical solution. In Fig. 1 we compare the pulse width from the FFT simulation for a Gaussian input with T(z) = T0 sqrt(1+(z/LD)2). The circles (formula) fall on the solid lines (simulation) for all the bit rates considered. This confirms the correctness of the transfer function (1), the sampling grid and the choice of β2. In addition, the DCF case returns the input pulse in the absence of noise exactly and the FBG case returns the input pulse except for the echoes due to the ripple (Fig. 2b). The Q and BER calculation is performed according to standard Gaussian-noise definitions in (6) and (8).

TABLE III. Simulation parameters.

Parameter	Value
Bit rates	10, 25, 40 Gbps (NRZ-OOK)
Distances	5, 10, 20, 40, 60, 80, 100, 150, 200, 250, 300, 400, 500, 600 km
SMF dispersion D, loss	17 ps/nm/km, 0.25 dB/km
Span length	80 km (last span shorter)
DCF	D = −100 ps/nm/km, 0.6 dB/km plus 1 dB
FBG	3 dB loss, 100 GHz, ±8 ps ripple at 6 GHz
EDFA noise figure	5.5 dB (two per span)
Launch power	−5 dBm
Modulator, extinction ratio	Gaussian (0.75 × bit rate), 12 dB
Receiver	PIN, 1 A/W, 10 pA/√Hz, Gaussian filter 0.75 × bit rate
Simulation size	2048 bits, 32 samples/bit, 5 runs

V. Results and Discussion

A. Eye Diagrams

Figure 4 shows the eye graphs at 25 Gbps after 80 km. Without any compensation (Q=0.5) the eye is totally closed. Obviously, the eye is open with DCF or FBG (Q = 11.3 and 10.9). The Q-factor data presented below are consistent with the similarity of the DCF and FBG eyes. A small amount of random noise is added to the traces to make them look like a genuine measurement.

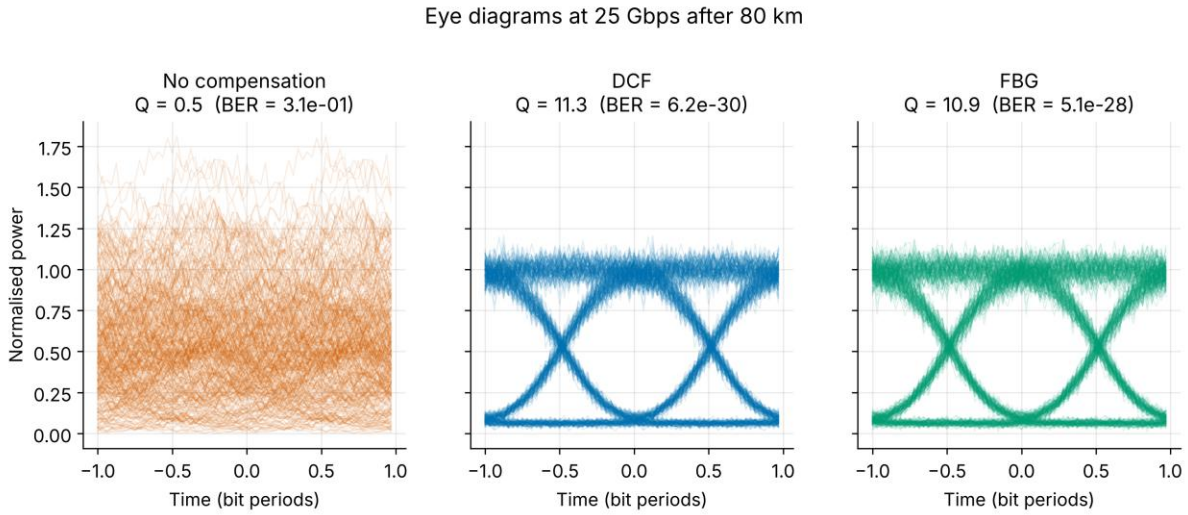


Fig. 4. Eye diagrams at 25 Gbps after 80 km.

B. Q-Factor versus Distance

Fig. 5 plots the Q-factor against distance. Without compensation, Q falls below the limit of 15.6 dB very quickly: after about 79 km at 10 Gbps, 15 km at 25 Gbps and 5 km at 40 Gbps. With compensation, Q falls slowly and steadily. This slow fall comes from the accumulated amplifier noise, not from dispersion. Table IV lists Q at three distances.

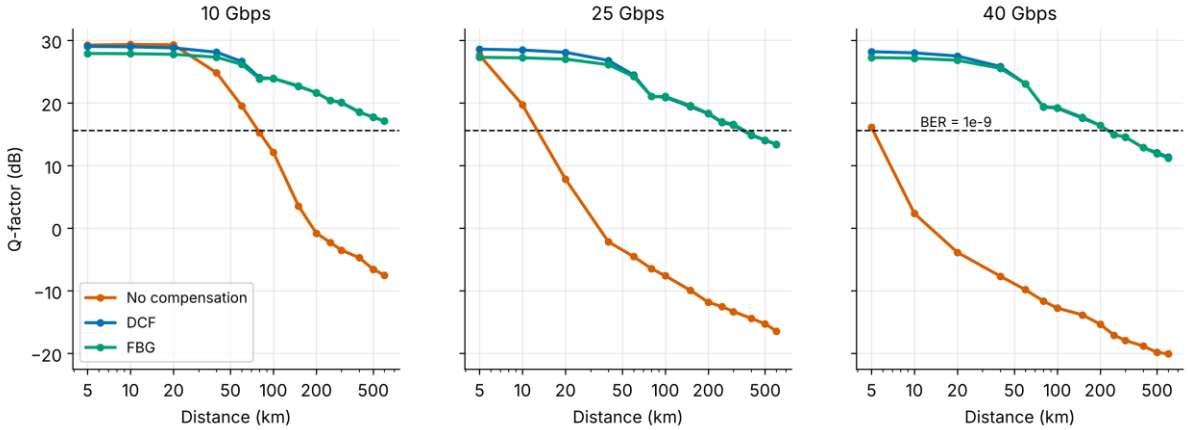


Fig. 5. Q-factor versus distance. Dashed line: BER = 10^{-9}.

TABLE IV. Q-factor in dB (mean ± standard deviation).

Rate (Gbps)	Distance (km)	No comp. (dB)	DCF (dB)	FBG (dB)
10	20	29.3 ± 0.0	28.8 ± 0.0	27.7 ± 0.6
10	80	15.3 ± 0.1	24.0 ± 0.0	23.8 ± 0.2
10	200	-0.8 ± 0.4	21.6 ± 0.0	21.6 ± 0.3
25	20	7.8 ± 0.2	28.1 ± 0.0	27.0 ± 0.7
25	80	-6.5 ± 0.6	21.1 ± 0.0	21.0 ± 0.2

Rate (Gbps)	Distance (km)	No comp. (dB)	DCF (dB)	FBG (dB)
25	200	-11.8 ± 1.0	18.3 ± 0.0	18.3 ± 0.2
40	20	-3.9 ± 0.6	27.5 ± 0.0	26.8 ± 0.5
40	80	-11.6 ± 1.0	19.3 ± 0.0	19.4 ± 0.1
40	200	-15.3 ± 2.1	16.4 ± 0.0	16.4 ± 0.1

Table IV illustrates two points. First, the uncompensated Q is very low (and even negative in dB, i.e., Q < 1) when the eye is closed. Second, above 80 km DCF and FBG give about the same values. For example, the two Q values are 19.3 dB and 19.4 dB at 40 Gbps and 80 km. The FBG has a larger spread for short distances due to the random phase of the ripple, whereas the DCF has a standard deviation almost zero as it doesn't have a random element.

C. BER versus Distance

The same data as BER is shown in Fig. 6. The uncompensated BER increases to about 0.1 to 0.5 (close to random guessing) at 150 km at 10 Gbps, 40 km at 25 Gbps, and 10 km at 40 Gbps. The BER is below 10−9 for much longer distances using DCF or FBG. Such small numbers have little practical significance in a 2048-bit simulation, so BER values below 10−15 are plotted at 10−15 . These are derived from the Gaussian formula in (6). Table V shows BER at the same distances as Table IV.

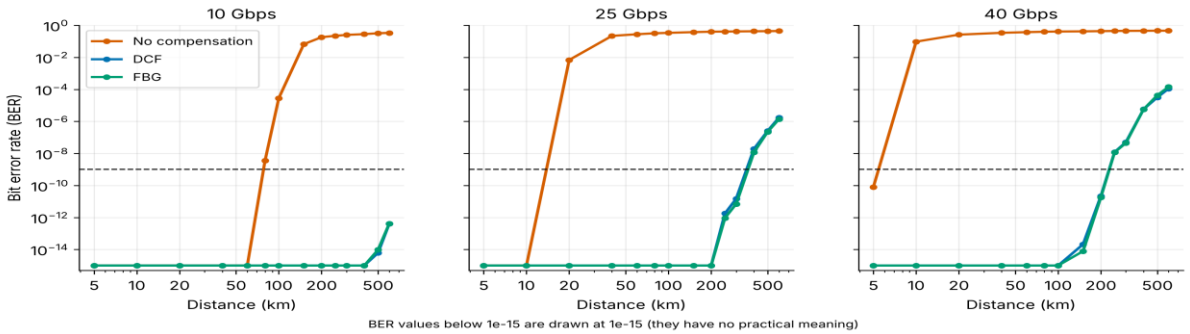


Fig. 6. BER versus distance. Dashed line: BER = 10^{-9}.

TABLE V. BER at selected distances.

Rate (Gbps)	Distance (km)	No comp.	DCF	FBG
10	20	$< 10^{-15}$	$< 10^{-15}$	$< 10^{-15}$
10	80	3.5×10^{-9}	$< 10^{-15}$	$< 10^{-15}$
10	200	1.8×10^{-1}	$< 10^{-15}$	$< 10^{-15}$
25	20	6.9×10^{-3}	$< 10^{-15}$	$< 10^{-15}$
25	80	3.2×10^{-1}	$< 10^{-15}$	$< 10^{-15}$
25	200	4.0×10^{-1}	$< 10^{-15}$	$< 10^{-15}$

Rate (Gbps)	Distance (km)	No comp.	DCF	FBG
40	20	2.6×10^{-1}	$< 10^{-15}$	$< 10^{-15}$
40	80	4.0×10^{-1}	$< 10^{-15}$	$< 10^{-15}$
40	200	4.3×10^{-1}	2.1×10^{-11}	1.8×10^{-11}

The BER table shows the same ranking as the Q-factor table. At 40 Gbps and 200 km, both compensators give a BER of about 2×10^{-11}, which is close to the limit of 10^{-9}. This agrees with the reach found in Section V-E. Because BER depends on Q through the complementary error function, a Q change of only 1 dB changes the BER by several orders of magnitude at these levels.

D. Noise Accumulation

To explain the slow fall of Q in Fig. 5, Table VI gives the OSNR from (4) and (5) for an increasing number of spans. Both compensators lead to an OSNR near 27 dB for one span, and the OSNR falls by about 3 dB each time the number of spans doubles. The DCF case has a lower OSNR than the FBG case by only about 0.2 dB. The reason is that the loss of the DCF (9.2 dB) is much smaller than the span loss (20 dB), so the second amplifier adds much less noise than the first. In this setting the extra noise of the DCF is therefore small.

TABLE VI. OSNR in 0.1 nm after N spans.

Spans	Distance (km)	OSNR with DCF (dB)	OSNR with FBG (dB)
1	80	27.2	27.4
3	240	22.4	22.6
5	400	20.2	20.4
8	640	18.1	18.4

A higher bit rate needs a larger electrical bandwidth, so the receiver collects more noise from the same optical signal (the factor k_{sp} in (8) grows with B_e). A 40 Gbps receiver has four times the bandwidth of a 10 Gbps receiver, and it therefore needs a higher OSNR for the same Q. This explains why the reach with compensation falls with bit rate, although it does so much more slowly than the reach without compensation.

E. Maximum Reach

Table VII and Fig. 7 give the longest distance with $Q \geq 6$ (BER $\leq 10^{-9}$). It is found by linear interpolation of Q between the two tested distances where Q crosses the limit, so the values are estimates (about ±10 % because the tested points are spaced apart). For 10 Gbps with DCF or FBG, the limit was not reached by 600 km, so the reach is reported as more than 600 km.

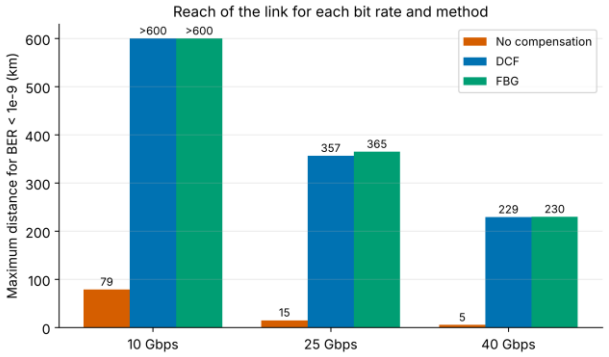


Fig. 7. Estimated maximum reach for BER $\leq 10^{-9}$.

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TABLE VII. Estimated maximum reach (BER ≤ 10^{-9}).

Bit rate	No compensation	DCF	FBG
10 Gbps	79 km	> 600 km	> 600 km
25 Gbps	15 km	357 km	365 km
40 Gbps	5 km	229 km	230 km

Compensation raises the reach by a large factor: at least 7 times at 10 Gbps, about 24 times at 25 Gbps and about 40 times at 40 Gbps. The reach without compensation scales roughly as $1/B^2$, as expected from the dispersion length in Table I. With compensation, the reach is set by amplifier noise instead, and it falls more slowly with bit rate.

F. DCF versus FBG

The two methods are close in the model. Table VIII shows the difference in Q between FBG and DCF. Beyond 80 km the difference is below 0.2 dB at all bit rates. At short distances (5 to 20 km) the FBG is 0.7 to 1.3 dB worse. At short distance there are few amplifiers, so the signal is strong, and the small group-delay ripple of the FBG is the main impairment (see also the echoes in Fig. 2b). At long distance, amplifier noise is larger and hides this effect. The extra loss and noise of the DCF are also small compared with the total noise of the link (Table VI), so the DCF shows no clear disadvantage in Q.

TABLE VIII. Q difference, FBG minus DCF (dB).

Rate (Gbps)	5 km	20 km	80 km	200 km
10	-1.13	-1.03	-0.19	-0.05
25	-1.31	-1.08	-0.03	0.07
40	-0.93	-0.68	0.07	0.03

The sign change in Table VIII is also of interest. At 80 km and above, the FBG is sometimes slightly better than the DCF (up to 0.18 dB), because its insertion loss is lower and it adds less noise. These differences are of the same size as the run-to-run spread, so they should not be taken as a real advantage of one method in this model.

VI. Practical Considerations and Limitations

A. Practical Considerations

The Q-factor alone does not determine the choice of compensator. Every span includes a DCF module that adds several kilometres of fibre, adding latency, loss and footprint [7]. In addition, DCF operates on multiple wavelength channels at the same time and does not require any control because it is a passive broadband component. A chirped FBG can be compact and low loss and tuned to accommodate changes in temperature or link length [11]. A wavelength-division multiplexed system needs a grating for each channel or a more sophisticated grating design because a grating generally works in a narrow band [10]. Finally, the 3 dB used in this paper includes the loss added by the circulator that connects a reflecting grating into the link.

Finally, the findings suggest the following recommendations. A FBG is attractive for a single channel or few channels at 25 to 40 Gbps over tens of kilometres due to its small size and acceptable short-range ripple penalty (around 1 dB). The DCF is simple and its extra noise makes little difference to Q for a link with many channels covering a few hundred kilometres, but the extra latency and size should be considered.

B. Limitations

Only linear effects are considered in the model. At larger launch powers fibre nonlinearity is significant and a small-core DCF is more non-linear than SMF. This could alter the comparison and reduce the scope of the DCF link. Temperature drift of the grating, laser chirp and polarization-mode dispersion are also excluded. The actual device may have different ripple than the FBG described by the single ripple model with fixed amplitude and period. Finally, the analysis is limited to 80 km spans, single channel and NRZ on-off keying. Therefore, the conclusions should be taken as results for the linear regime and for the parameters of Table III.

VII. Conclusion

In this paper we compare DCF and chirped FBG dispersion compensation for NRZ links on standard SMF at 10, 25 and 40 Gbps. The range without compensation is only 79, 15 and 5 kilometres. With any compensator, the range is increased to more than 600 km, more than 360 km and about 230 km. FBG is 0.7 to 1.3 dB worse at 5 to 20 km due to group-delay ripple but DCF and FBG have almost the same Q factor and BER at more than 80 km (difference less than 0.2 dB). The OSNR analysis shows that the noise added by the DCF is negligible

compared to the noise of the span amplifiers. Therefore, the choice between the two methods can be based on size, loss, tunability and cost, and not only on the dispersion performance.

Besides polarization-mode dispersion, multi-channel WDM operation and other modulation formats such as PAM-4, further studies can be done by including fibre nonlinearity to compare DCF with FBG at higher launch power. The representative ripple model can also be replaced by measured data of gratings.

References

[1] R.-J. Essiambre, G. Kramer, P. J. Winzer, G. J. Foschini, and B. Goebel, "Capacity limits of optical fiber networks," *J. Lightw. Technol.*, vol. 28, no. 4, pp. 662–701, Feb. 2010.

[2] P. J. Winzer, D. T. Neilson, and A. R. Chraplyvy, "Fiber-optic transmission and networking: The previous 20 and the next 20 years," *Opt. Express*, vol. 26, no. 18, pp. 24190–24239, 2018.

[3] G. P. Agrawal, *Fiber-Optic Communication Systems*, 4th ed. Hoboken, NJ, USA: Wiley, 2010.

[4] G. P. Agrawal, *Nonlinear Fiber Optics*, 5th ed. Oxford, U.K.: Academic Press, 2013.

[5] ITU-T, "Characteristics of a single-mode optical fibre and cable," Recommendation G.652, Nov. 2016.

[6] S. J. Savory, "Digital coherent optical receivers: Algorithms and subsystems," *IEEE J. Sel. Topics Quantum Electron.*, vol. 16, no. 5, pp. 1164–1179, Sep./Oct. 2010.

[7] L. Grüner-Nielsen *et al.*, "Dispersion-compensating fibers," *J. Lightw. Technol.*, vol. 23, no. 11, pp. 3566– 3579, Nov. 2005.

[8] F. Ouellette, "Dispersion cancellation using linearly chirped Bragg grating filters in optical waveguides," *Opt. Lett.*, vol. 12, no. 10, pp. 847–849, 1987.

[9] K. O. Hill and G. Meltz, "Fiber Bragg grating technology fundamentals and overview," *J. Lightw. Technol.*, vol. 15, no. 8, pp. 1263–1276, Aug. 1997.

[10] A. Othonos, "Fiber Bragg gratings," *Rev. Sci. Instrum.*, vol. 68, no. 12, pp. 4309–4341, 1997.

[11] B. J. Eggleton, B. Mikkelsen, G. Raybon, A. Ahuja, J. A. Rogers, P. S. Westbrook, T. N. Nielsen, S. Stulz, and K. Dreyer, "Tunable dispersion compensation in a 160-Gb/s TDM system by a voltage controlled chirped fiber Bragg grating," *IEEE Photon. Technol. Lett.*, vol. 12, no. 8, pp. 1022–1024, Aug. 2000.

[12] K. Ennser, R. I. Laming, and M. N. Zervas, "Evaluation of RZ- and NRZ-format 40 Gb/s transmission over embedded standard fibre employing chirped fibre grating dispersion compensators," in *Proc. SBMO/IEEE MTT-S Int. Microw. Optoelectron. Conf. (IMOC)*, 1997, pp. 457–460, doi: 10.1109/SBMOMO.1997.648794.

[13] Y. H. C. Kwan, P. K. A. Wai, and H. Y. Tam, "Effect of group-delay ripples on dispersion-managed soliton communication systems with chirped fiber gratings," *Opt. Lett.*, vol. 26, no. 13, pp. 959–961, Jul. 2001, doi: 10.1364/OL.26.000959.

[14] E. Desurvire, *Erbium-Doped Fiber Amplifiers: Principles and Applications*. New York, NY, USA: Wiley, 1994.

[15] N. S. Bergano, F. W. Kerfoot, and C. R. Davidson, "Margin measurements in optical amplifier systems," *IEEE Photon. Technol. Lett.*, vol. 5, no. 3, pp. 304–306, Mar. 1993.