Dynamic Circulating-Loop Methods for Transmission Experiments in Optically Transparent Networks

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ABSTRACT
Recent experiments incorporating multiple fast switching elements and automated system configuration in a circulating loop apparatus have enabled the study of aspects of long-haul WDM transmission unique to optically transparent networks. Techniques include per-span switching to measure the performance limits due to dispersion compensation granularity and mesh network walk-off, and applied constant-gain amplification to evaluate wavelength reconfiguration penalties.
Keywords: transparent networks, circulating loop experiments, dispersion compensation granularity, wavelength reconfiguration.

1. INTRODUCTION

Optically transparent mesh networks take advantage of photonic cross-connects and reconfigurable optical add-drop multiplexers (ROADMs) to enable flexible wavelength routing in the physical layer. Neighbouring channels in the optical spectrum can traverse diverse routes through the network. The transmission performance of these channels will depend on the route physical parameters and on the different channel configurations encountered along the route. Physical parameters that influence transmission include factors such as the fiber span length, fiber type, and the dispersion management characteristics. Much is known about the propagation of signals over regular spans of similar types and lengths with well controlled dispersion maps [1]. In transparent networks, the number of different combinations of route parameters can quickly become too large to address explicitly in the system design. Understanding how the transmission varies as the route characteristics deviate from the design targets is important for accurately predicting performance and thereby reducing regeneration. In general, this requires thorough testing and validation for a specific system design [2]. Extensive simulation studies have been used to account for mesh transmission variations [2-4]. Circulating loop experiments, which are commonly used for long haul transmission, traditionally have not had the flexibility to examine a wide range of transmission characteristics [1]. Multi-loop experiments have been used to vary the fiber type over different transmission segments [5]. We introduced a dynamically reconfigurable circulating loop that enables long haul transmission experiments that examine the impact of dispersion map variations [6]. This new apparatus uses fast switches synchronized with the loop circulation in order to vary the length of fiber in each span. Further accounting for variations in the channel loading is complicated due to the strong dependence of the channel power on the amplifier dynamics and control. Typically channel reconfiguration is enabled in transparent networks by using optical amplifiers that are controlled to maintain a constant gain condition as the channel configuration is varied. Due to gain ripple and tilt, complex power dynamics can arise even for well controlled amplifiers [7]. In circulating loop experiments constant gain amplifier control is not desirable because the amplifiers are connected in a ring and unstable or highly complex power behaviour can arise due to the ring feedback. While this effect is problematic for the study of high speed power dynamics in loops, one still has the possibility to study the steady-state behaviour. Steady-state gain errors due to channel power transients have been measured in a circulating loop by explicitly adjusting the power settings of constant power controlled amplifiers such that their net gain remained constant after channels were cut due to a transient failure event [8]. We recently applied this method to study the impact of channel reconfiguration on transmission performance [9]. In the case of channel reconfiguration, the transmission performance depends on the both the static power evolution with distance and the power variation resulting from different system tuning operations, such as channel power levelling. The transmission performance for both the existing traffic and the reconfigured traffic will dictate limits to the allowed reconfiguration operations and the amount of tuning required and hence the reconfiguration time.

2. MESH NETWORK DISPERSION MAP WALK-OFF

Several different sources of error in the dispersion compensation can impact transmission performance. These can be separated into systematic and random errors. Statistical variations in the fiber plant characteristics such as the dispersion slope are an example of a random error. The magnitude of this error can be significantly reduced through detailed measurements at the time the fiber is commissioned, although environmental factors will still be a factor. In-service monitoring can further reduce the uncertainty. The extent of monitoring and even the choice

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of accuracy among different measurement techniques come at a cost. Statistical variations are important for both point to point and mesh transmission systems and will not be addressed here.

Systematic error in the dispersion compensation is a known deviation from the target compensation. A span that is measured to have a different dispersion slope than the design value is an example of systematic error. The use of dispersion compensating modules with a granularity of 10 km introduces a systematic error of +/- 5 km. Moving to finer granularity or using tuneable dispersion compensation can reduce this error, but again it comes at a cost. In the case of tuneable dispersion compensation the cost may include a performance loss due to the transmission characteristics of the tuneable devices or design limitations, for example due to the restricted channel bandwidth. In general, in-line dispersion compensation can be adapted to maintain a target mean residual dispersion per span such that the error due to systematic sources does not grow with distance.

Fig. 1(a) shows examples of the accumulated dispersion at the span launch point for a typical singly periodic map using pre-compensation of -500 ps/nm and an RDPS of 40 ps/nm. Such dispersion maps have been shown to be highly effective at managing the growth of non-linear transmission impairments over long distances [1, 2]. Without error, the accumulated dispersion will grow linearly with distance (circles). As described above, dispersion compensating modules with finite granularity can be chosen such that the mean RDPS is maintained, although the statistical variations may add noise about this mean resulting in a map similar to Fig. 1a (squares). If two such line systems intersect in a mesh network, however, one has the problem of deciding which systematic error to correct for at the output of the cross-connect node. For example, at the input to a T intersection, one span may have an error of +4 km, whereas the other input span may have an error of -5 km, due to a 10 km DCM granularity. If the span at the output of T cross-connect node is 78 km, then compensating for the first input, one would choose a DCM to compensate a 70 km span such that the final error will be: -8 km + 4 km = -4 km, which is within the expected +/- 5 km granularity error. However, this results in a large walk-off error for the other input: -8 km – 5km = -13 km. The maximum such walk-off error is 15 km per mesh cross-connect intersection. Note that choosing not to correct for the error on either of the two inputs results in at most a +/- 5km walk-off error per cross-connect intersection, which is the minimum error. Thus, a new form of systematic dispersion compensation error is introduced in mesh networks, which is a walk-off error at each cross-connect node (Fig. 1a, triangles), at worst case equal to the DCM granularity error. Since this is a known systematic error, it can be tracked and incorporated into the wavelength routing. Thus, it does not impact the performance of a given channel, but instead places limitations on the flexibility of the network because certain routes will require additional regeneration due to this effect. Designing a transmission system that can accommodate larger dispersion walk-off will result in less regeneration.

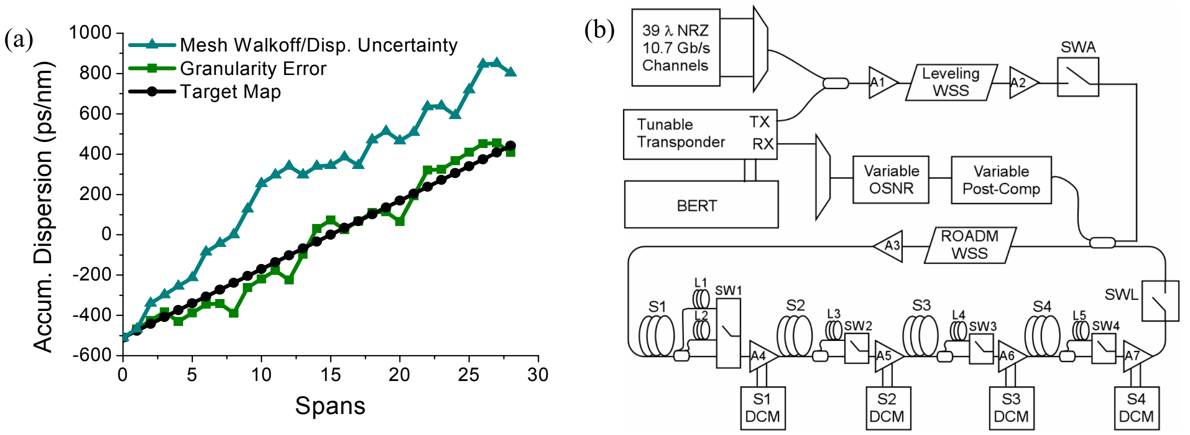

Figure 1. (a) Dispersion variations in point to point and mesh transmission systems. (b) Dynamically reconfigurable loop apparatus.

A new circulating loop apparatus was recently introduced to enable the experimental study of dispersion error in long distance transmission [6]. Traditional loops circulate optical signals repetitively through a series of transmission spans in order to achieve transmission over dozens of spans using the equipment of only a few spans, thus enabling flexible laboratory experimentation. The amount of dispersion variation in such loops however is limited by the number of distinct spans within the loop and this variation is repeated with each circulation. This problem is overcome by adding multiple spools of fiber at the output of each span which can be selected using a high speed switch. Each switch can be triggered synchronously with the loop such that a different spool may be selected with each circulation. This action provides different span lengths with a fixed DCM value, resulting in variations in the accumulated dispersion with distance. Fig. 1b shows the loop apparatus used to realize this dynamically reconfigurable circulation. Each span consists of a fiber spool with the nominal span length followed by a multi-port optical coupler that splits the signal onto multiple paths. Each output from the coupler is connected to a high speed switch port through either no fiber or a small spool of fiber. Span 1 is 77.5 km with 0, 5, and 10 km of fiber on each of three selectable output ports. Span 2 uses 82.5 km with 0, and 5.0 km on the output; span 3 is 90.2 km with 0 and 2.3 km on the output; and span 4 is 67.2 km with 0, and 5.3 km on the output. With this setup, a total of 3x2x2x2 span combinations are possible for each circulation. Thus, for 7 circulations, $24^7 = 4.6$ billion different dispersion maps can be realized. Of course, these maps are all within the maximum and minimum RDPS of +5.6 km and –2.5 km or 157 km and –70 km total SSMF walk-off.

In order to study the impact of dispersion map walk-off on transmission performance, the performance for different classes of map variation can be examined. For example, the performance near the maximum, minimum, and target values are obvious cases. Another interesting case is to consider maps with a range of standard deviation values about the mean RDPS. In Fig. 2a, the inset shows 34 different dispersion maps realized using the setup in Fig. 1b. The plot in Fig. 2a is the required OSNR for BER = 10^{-3} versus number of spans for each of the 34 dispersion maps realized using the setup in Fig. 1b. The dispersion and performance are shown for the 10.7 Gb/s NRZ-OOK channel at 1551 nm. A launch power of 4.3 dBm/chn and a post-compensation of -500 ps/nm were used. Fig. 2b shows the corresponding performance as a function of the standard deviation of each map about its mean RDPS, calculated after 24 spans (the dependence on mean RDPS is given in [6]). The performance after 28 spans is also shown for reference using the same 24 span deviation. No clear trend with RDPS variance is observed.

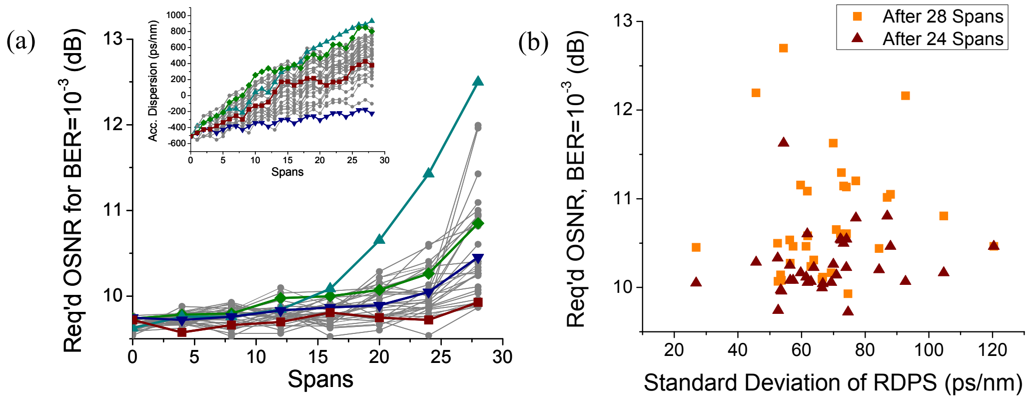

Figure 2. (a)Transmission performance for 34 different dispersion maps shown inset. (b) performance sensitivity to the RDPS statistical variations.

3. TRANSMISSION PERFORMANCE DURING RECONFIGURATION OPERATIONS

In addition to variations in the fiber plant encountered in transparent systems, transmission performance will also be impacted by the channel configuration. The strongest impact will typically come from variations in the channel power divergence due to wavelength dependent gain and loss. Static divergence can be compensated using gain levelling controls such as per-channel variable optical attenuators found in ROADM wavelength selective switches. In order to realize wavelength rerouting, these slow network tuning elements will need to be adjusted depending on the details of the new configurations and the pre-existing or initial settings of the tuning elements. Re-configuration events that do not require WSS tuning can potentially be accomplished much faster. Furthermore, certain re-configuration events may require special adjustment steps in order to avoid impacting the existing traffic. As a first step toward understanding the network tuning requirements for reconfiguration, we use the technique of applied constant gain control in a circulating loop [8, 9]. In this method, the constant gain control of the amplifiers is turned off and constant gain is maintained instead by adjusting the amplifier output powers as the loop conditions are modified. In order to understand the range and nature of the transmission penalties associated with wavelength reconfiguration, the channel configuration is varied through extreme cases of full loading (40 channels), 5 channels spread uniformly across the band, and 5 channels forming a narrow band of neighbours. Five different banded cases are considered, each with the central channel being one of the five channels from the uniformly spread configuration. The transmission performance is tracked as the network is reconfigured from the optimized 5 spread configuration to each of the banded configurations with the optimized full loading as the initial condition for the network tuning from which all other adjustments occur sequentially. These experiments were carried out using the setup in Fig. 1b with the RDPS fixed to 32 ps/nm and a mean per channel launch power of +6 dBm.

The network tuning required for re-configuration is divided into three steps in these experiments: (1) CG: the action of constant gain control in the amplifiers; (2) PT: adjustment of the amplifier gain and tilt in order to realize the target channel launch powers; and (3) FO: full system optimization including per-channel power adjustments at the ROADM nodes. The dynamics associated with each adjustment step are ignored and only the final post-adjustment transmission performance is evaluated. Fig. 3a shows the spectra for each of the 5 banded cases at the loop output after 7 round trips following the constant gain adjustment step (CG). The strong channel power divergences are expected to be a complex function of the configuration dependent stimulated Raman scattering and amplifier gain ripple and tilt. The corresponding transmission margins for the central channel in each band as a function of adjustment steps are shown in Fig. 3b-d after 3 round trips, 5 round trips, and 7 round trips. The margins are measured as the difference between delivered OSNR and required OSNR for a 10^{-3} BER. The channels at 1538 and 1546 nm suffer a large loss of margin due to a strong negative power divergence. The channel at 1532 nm shows a positive power divergence, resulting in improved margins for 3 and 5 round trips, but a strong penalty at 7 round trips from nonlinear impairments that accumulate more rapidly with distance.

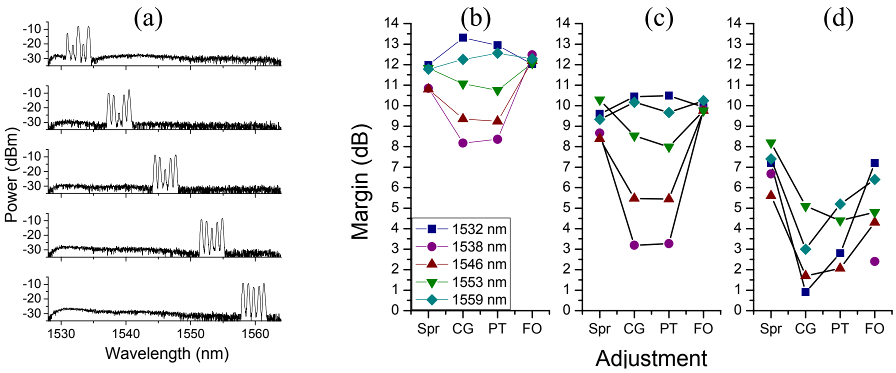

Figure 3. (a) Five channel banded spectra after 7 round trips; and transmission margins for central channel in each band (b) after 3 round trips, (c) after 5 round trips, and (d) after 7 round trips; spr = fully optimized 5 spread channel configuration, CG = constant gain adj., PT = power and tilt adj., FO = fully optimized.

4. CONCLUSIONS

Two new laboratory techniques were used to study long haul transmission in optically transparent mesh networks. Synchronous reconfiguration of the span lengths was used to examine the impact of dispersion walk-off on transmission performance. The use of a pre-compensated singly periodic dispersion map was shown to accommodate a wide dispersion variation with no systematic dependence on the statistics of the residual dispersion per span. Applied constant gain control was also demonstrated in a circulating loop in order to measure the transmission penalties due to wavelength rerouting after different network tuning adjustments.

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