Estimating divergently routed nonlinearly interfering channel powers using cross phase modulation

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Abstract: The deployment of coherent transceivers in legacy networks requires significant investment in installation. We propose a method enabling autonomous (re-)configuration of an optical channel, which would be advantageous in legacy networks and necessary in proposed future networks utilizing a flexible frequency grid and software defined components such as reconfigurable optical add drop multiplexers (ROADM). We consider potential interfering optical channels propagating with the prospective channel along part of the fiber link which are dropped before arrival at the receiver. The method uses a commercially available line card transmitting a 40Gbit/s polarization multiplexed quadrature phase shift keying (PM-QPSK) probe channel to characterize an optical channel. The power of the nearest neighboring channels is then inferred by examining its bit error rate (BER) which is impacted by cross phase modulation (XPM) from the aggressor channels. In a 4 node network with 2 ROADMs using up to 6 aggressor OOK channels, we successfully deduce the neighboring channel power down to -2 dBm, and an extra improvement down to -3.5 dBm is gained, by measuring at an offset to the international telecommunication union (ITU) grid which also reveals inequality in neighbor channel powers.

OCIS codes: (060.1660) Coherent Communications; (060.4510) Optical Communications; (060.4250) Networks.

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1. Introduction

Coherent detection technology is now an industry wide standard for 40+ Gbit/s optical transport. The polarization and phase diversity, of the coherent receiver allows for compensation of linear impairments, such as chromatic dispersion and polarization mode dispersion, as well as some nonlinear impairments through digital signal processing. This capability alongside its receiver sensitivity make it an attractive upgrade over legacy direct detection transmission. Most deployment strategies for the evolution from 10 Gbit/s on off keying (OOK) systems to 40+ Gbit/s coherent transmission mix coherent transmission with legacy OOK or replace OOK with coherent channels on the legacy 50 GHz grid, or implement coherent transmission on a flexgrid [1] as defined by the updated ITU G.694.1 standard. There is the realistic likelihood that as network operators migrate their systems, these technologies will operate in parallel. We believe that this situation requires a significant change in the management of these networks incorporating cognition and flexibility in the coherent transceiver [2, 3]. The cognitive network was defined by [4] as being, "a network with a process that can perceive current network conditions, and then plan, decide, and act on those conditions. The network can learn from these adaptations and use them to make future decisions, all while taking into account end-to-end goals." The components of a cognitive network can be separated [5] into *monitoring elements, software adaptable elements and cognitive processes*. The cognitive processes allow the network to take into account present and predicted network conditions and to then reconfigure itself without input from a human administrator.

2. Motivation

This work investigates the use of a coherent transceiver as a monitoring element, to probe a portion of bandwidth to provision a new channel across a multi node link with in line wavelength add/drop capability. If the optical link was a simple point-to-point link with no intermediate stage add-drop, the coherent receiver would be able to quickly sample the optical fields of other signals being transmitted through the fibre and using spectral estimation [6], it would be able to generate a view of the exact spectrum being transmitted as well as further characterize observed

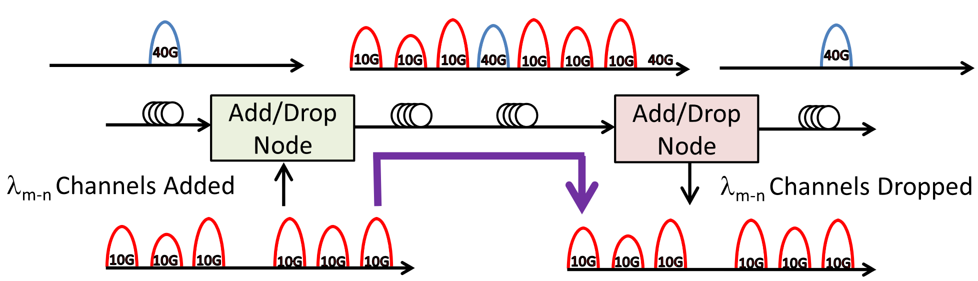


Fig. 1. Example network topology with non transparent aggressor channels

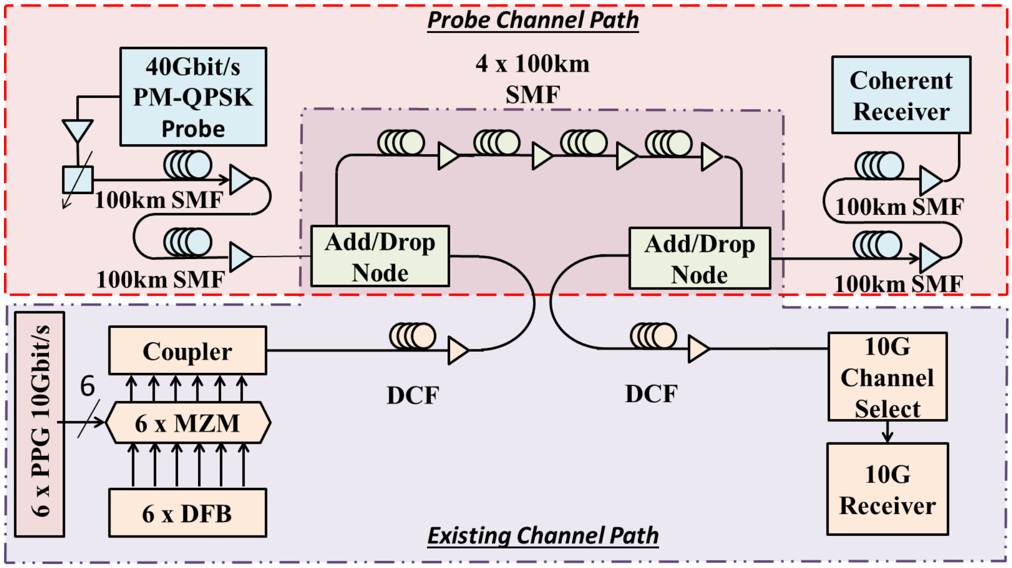
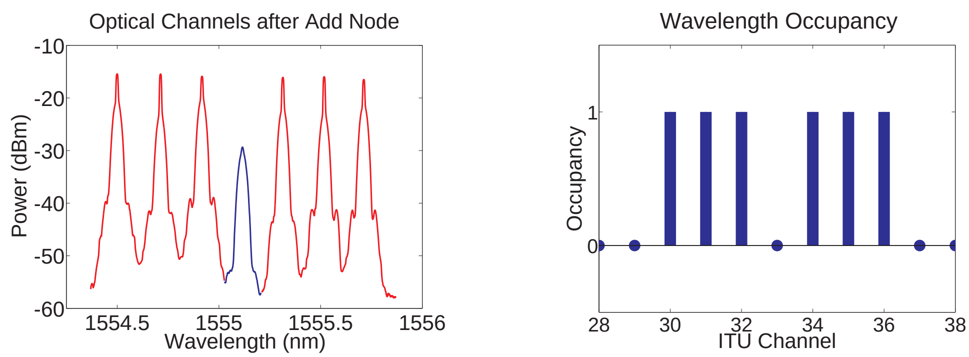


Fig. 2. Experimental Setup of a 4 node network with 6 10 Gbit/s OOK channels being added and dropped after 400 km co-propagation with 40 Gbit/s PM-QPSK probe channel.

channels [7]. However when moving away from a point to point link, this becomes unreliable since there are unknown actors on the selected network path, as shown by the example network topology in Fig. 1.

One of the decisions crucial for channel allocation is optimal transmission wavelength selection, in a situation where multiple spectral vacancies are available. In this work, the BER performance was investigated as a metric to infer the channel power of the nearest neighbor, for available spectral slots. By characterizing the BER performance of our probe signal transmitting in one of these slots, we can then deduce sufficient information to initialize the cognitive transceiver. In the case of the example network topology, Fig. 1, the required signal was transmitted over a length of fiber which passed through two reconfigurable optical add drop multiplexer (ROADM) nodes. Initially we must determine if a wavelength is already occupied. To do this, a low power probe was transmitted over the channels under investigation; if it was not received the wavelength was in use and had been dropped. Due to the low power level, the impact on the existing channels is non existent. The deduced vacant wavelength slots were then probed with increasing power to determine its BER performance in the possible presence of unknown interferers. We estimated the power of the nearest neighbors using the BER of the probe channel with respect to its transmission power, and from this characterization determined if operating at this wavelength will give the desired performance. The BER performance will change with respect to the power of the cross phase modulation generated by the interferer channels, impacting the probe channel. We also investigated the impact of the probe on the existing channel BER. A characterization of one spectral slot can therefore allow the cognitive transceiver to deduce the performance of other vacant spectral slots by looking at the power of the deduced neighboring channels, given no reconfiguration of the network.



(a) Transmitted Spectrum after ROADM node 1 with 6 aggressor channels

(b) Detected Spectral Occupancy

Fig. 3. Spectrum and corresponding detection of wavelength occupancy

3. Experimental Setup

A commercially available [10] line card was used to transmit a 40 Gbit/s PM-QPSK test signal over 800 km of standard single mode fiber(SMF), Fig. 2. Six 10 Gbit/s OOK aggressor channels were added after 200 km SMF at a ROADM. These were generated using 6 separate modulators each independently driven by a 10 Gbaud decorrelated PRBS of length 2^{15}-1, modulating six distributed feedback lasers (DFB) spaced at 50 GHz around the 40 Gbit/s PM-QPSK signal. The combined optical signal is then transmitted over 400 km of SMF to another ROADM. Figure 3(a) shows the combined spectrum after the first ROADM node. All of the 10 Gbit/s OOK channels were dropped before a single 10 Gbit/s channel was selected to be received. The 40 Gbit/s channel was transmitted over another 200 km SMF and then received by the line card. Dispersion compensating fiber (DCF) was utilized to pre-compensate for 50% of the chromatic dispersion for the 10 Gbit/s channels prior to being combined with the 40 Gbit/s probe, to avoid the nonlinearities on the probe channel being increased by in-line dispersion compensation, with the remaining 50% of chromatic dispersion being compensated by the DCF after the 10 Gbit/s channels had been dropped (see Fig. 2). The total amount of chromatic dispersion compensated by the DCF is 3,200 ps/nm-km. The line card digitally compensates for the linear impairments (6,400 ps/nm-km of chromatic dispersion), polarization mode dispersion and carrier phase recovery) on the 40 Gbit/s probe channel. We realize the ROADMs of this network setup using Finisar Waveshaper 4000S, couplers and Polatis 16x16 optical switch.

4. Algorithm

Check for existing data - The algorithm first checks for available information on the network setup before proceeding, e.g. previous characterizations and estimation, knowledge of channels already in service along the proposed transmission path. *Generate spectral slices and Digital stitching* - In previous work [6], spectral estimation was employed to rapidly scan a portion of bandwidth in multiple spectral slices, which were then digitally stitched together to form the entire estimated bandwidth. A 50 GSample/s oscilloscope was used in addition to a high bandwidth coherent receiver to estimate 50 GHz windows of bandwidth at 25 GHz intervals, which allowed for 25 GHz of overlap between two adjacent slices to perform digital stitching. In this work, a commercially available 40 Gbit/s PM-QPSK line card is used. The hardware allows access to sweep the laser frequency up to 12 GHz from the ITU grid in either direction with a sampling speed of 23 GSample/s. Spectral estimation is performed with three slices

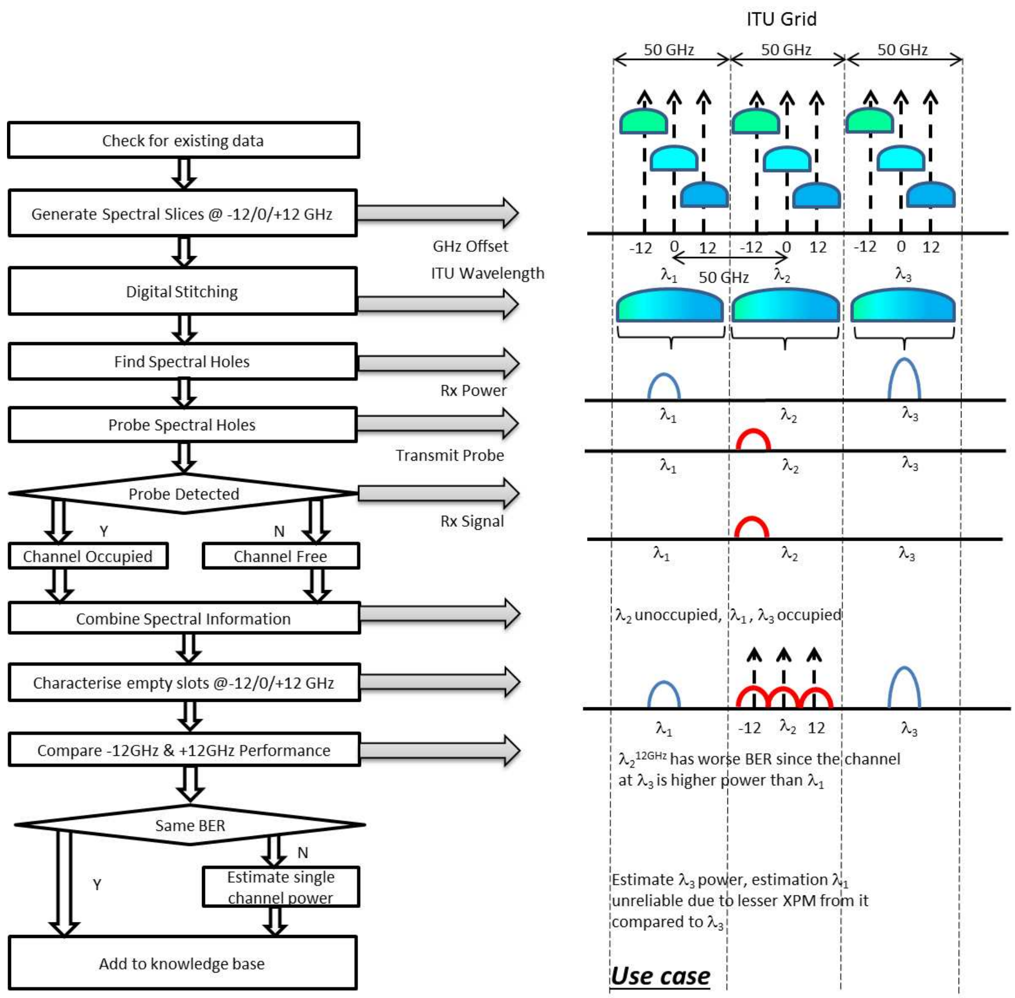


Fig. 4. Flowchart of the algorithm used to the left, use case to the right.

per wavelength instead of 2 per wavelength, centered around the -12, 0 and 12 GHz offset on the ITU 50 GHz grid. These slices are then digitally stitched for a wider spectral estimation. This digital stitching is performed by cross correlating the overlapping components, aligning the spectral slices and then stitching them together. Overlapping frequency components are averaged. A 3 GHz gap remains between each estimated portion which cannot be estimated, this gap is insignificant given the assumption that 10 Gbaud is the minimum granularity of a transmission channel. The frequency resolution of the estimation is not significant in this work so a relatively coarse estimation of 256 samples is performed at 23 GSample/s compared to the previous [6] 65536 at 50 GSample/s, the technique is employed as a frequency diverse power meter.

Find spectral holes - The spectral estimation is then used to find spectral holes on the 50 GHz grid. It should be noted that since the legacy optical network is not colorless, this is not a complete picture of wavelengths being used. It is quite possible that transmission occurs along part of the fiber link that is being examined. *Probe spectral holes* - Therefore, a very low power probe (-20 dBm) is sent along the detected spectral holes, offset 12 GHz from the grid frequency to avoid impacting the performance of existing channels (assuming that the baud rate is 10 Gbaud). The exact power should be determined by characterizing a known empty channel, such as one set aside for administration purposes i.e. one beyond channel 1 or 80. A reasonable BER is not required, but it must be detectable. If the probe is received, then the spectral slot is free. If the probe is not detected, then the spectral slot has been dropped part way through the link and the is therefore in use.

Combine spectral information - the occupancy of the spectrum can be determined from the combination of spectral estimation and probe information. *Characterize empty slots* - The spectral holes which have insufficient information to estimate their performance, can then be fully characterized. Characterizing a single spectral hole gives not only the information on its performance but also information on its neighboring channels. This comes in the form of cross phase modulation (XPM), which can be represented as a constant noise term if there is no change in the interferer power level. The power of the neighboring channels can therefore be estimated from the performance of the probe signal. This information is then added to stored knowledge.

The assumption being taken in this set of measurements is that both neighboring channels are being transmitted at the same power level. The characterization measurements are repeated at -12 and +12 GHz offsets to detect if the adjacent channels are being transmitted at the same powers. *Compare -12 GHz and +12 GHz performance* - if the two neighboring channels are being transmitted at the same power, the BER at the two offsets should be very close. These specific offsets are the maximum settings accessible with the transmitter used in this experimental setup. Ideally the half way point of 25 GHz would be used since the closer the probe approaches the neighbor, the greater the XPM experienced. This would allow this algorithm to estimate down to lower OOK channel powers. The region of interest is when the BER is at or just below the FEC threshold, and above the point where the nonlinear interference from the neighboring channels is negligible compared to ASE noise. The lower bound of the estimation is the point where the noise floor occurs for the performance of the probe channel. In order to provision the channel, in addition to using the information for future provisioning, it is not necessary to know the exact power in this situation. Similarly, estimation of the power of the aggressor channels when the BER performance is above a FEC threshold is unnecessary since transmission is not possible. This set of characterization measurements is then repeated for all empty wavelength slots that do not already have information about its neighboring channels. The appropriate slot is chosen and the channel is provisioned. *Add to knowledge base* - Information about the provisioned channel is added to the stored knowledge. Figure 4 shows the entire algorithm tree.

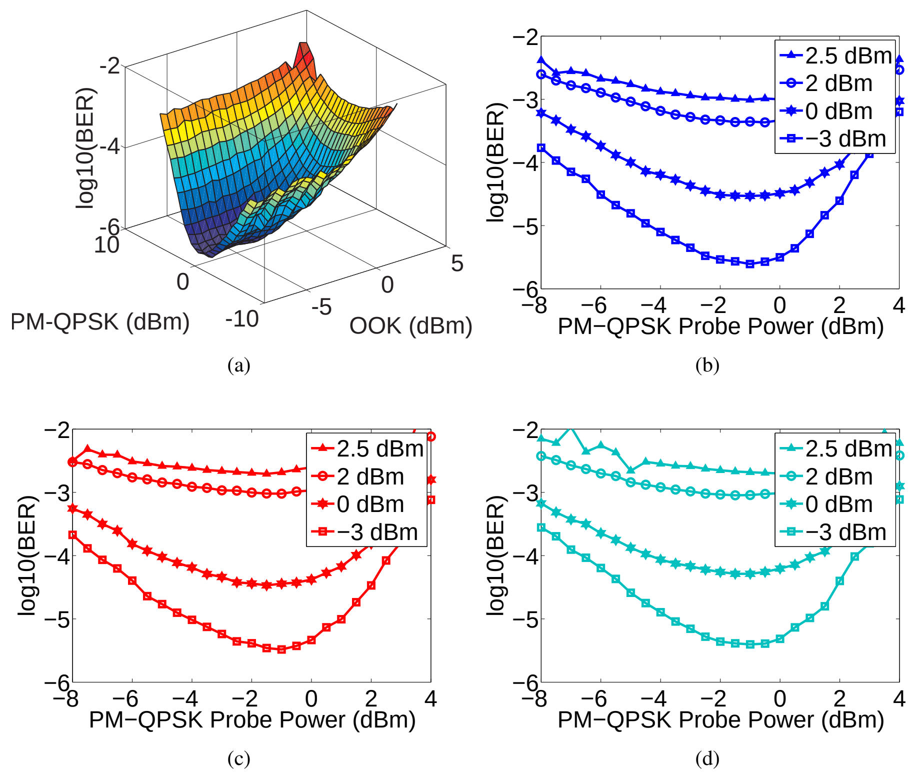
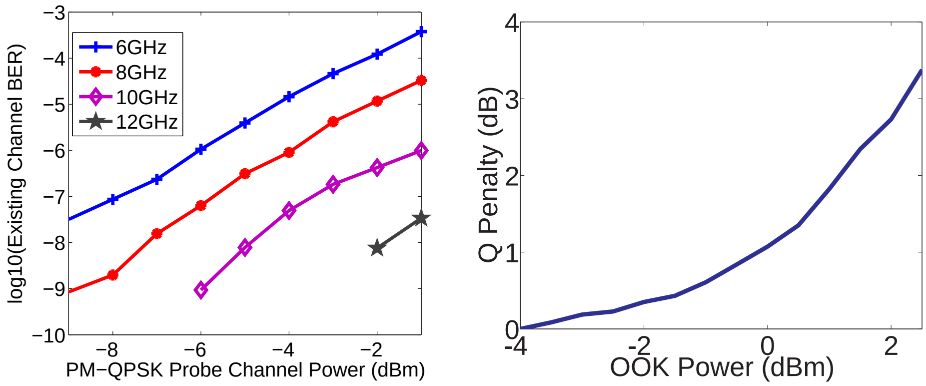


Fig. 5. BER Performance of probe PM-QPSK channel with 2, 4 and 6 OOK aggressors, (a) surface of power estimation 2 channel look up table, characterizations of prospective transmission channel with (b) 2 , (c) 4 and (d) 6 neighbors at different transmission powers.

5. Results

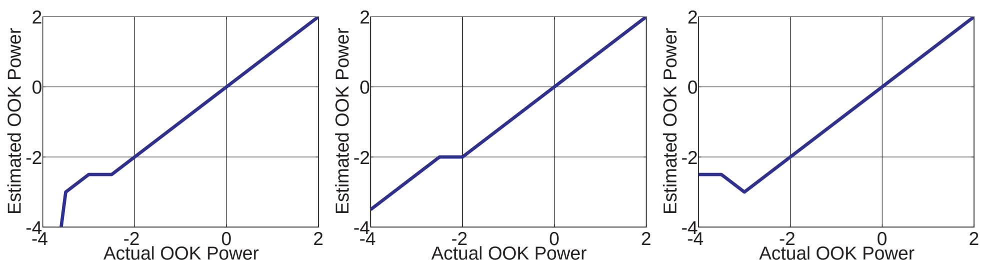
The performance of the estimation algorithm is first investigated using a single empty spectral slot with two neighboring OOK channels on a 50 GHz grid, the number of aggressor channels is then increased from 2 to 4, and then 6 to examine the impact on the accuracy of the algorithm. Fig. 3(b) shows the spectral occupancy as detected by the initial part of the algorithm.

The power reference look up table is first generated by incrementing the launch power of the two 10 Gbit/s aggressor channels from -8 dBm to 2 dBm in steps of 0.5 dBm. Higher powers were not investigated since measurement of the BER became unstable. For each power step the launch power of the 40 Gbit/s probe channel is swept from -8 dBm to 4 dBm in steps of 0.5 dBm. This creates the surface plot of BERs as in Fig. 5(a). In order to account for a sudden variation in transmission conditions due to factors such as gain transients from amplifiers, the 40 Gbit/s probe is transmitted multiple times to generate measurements which are taken at intervals of 3 seconds. Anomalous spikes in the BER performance are discarded and the rest averaged to generate an accurate measurement, this is particularly important since the algorithm is autonomous. The averaged BER performance is shown in the BER_{40G} curves for a given OOK launch power. This averaged BER measurement is then compared to the reference look up table, and the power of the OOK channels are estimated by taking the lowest BER of the PM-QPSK channel for the test measurement and minimizing the Euclidean distance between the lowest BER of the test measurements and the reference BER. Figures 5(b)– 5(d) show the



(a) (b)

Fig. 6. (a) Performance of the OOK channel when the probe PM-QPSK signal is moved closer at increasing transmission power. (b) Q penalty incurred by the probe channel at 0 GHz offset, when aggressor OOK power increases.



(a) (b) (c)

Fig. 7. Estimation of neighboring power with (a) 2 channels, (b) 4 channels and (c) 6 channels.

measured BER performance of the 40 Gbit/s channel for different OOK channel launch powers, it must be noted that the oscillation in the measured BER in the case of a 6 aggressor channels is caused by a combination of high aggressor power channel in addition to low probe channel optical signal to noise ratio. The effect of moving the probe channel closer to the existing channel is shown in Fig. 6(a). It can be seen that the impact of the probe at 12 GHz offset from the existing channel is negligible. Figure 6(b) shows the Q factor penalty when increasing the power of the OOK aggressor channels. The estimated OOK power is then plotted against the actual launch power Fig. 7(a)– 7(c). The estimation algorithm becomes less accurate when the effect of XPM on the probe channel decreases at -2 dBm. Prior to that the estimated power level corresponds to the transmitted power level.

The impact of different numbers of neighboring channels is measured. It is shown that the BER performance of the 40 Gbit/s channel becomes slightly worse when increasing from 2 channels to 4, however the increase from 4 to 6 neighbors is minimal. The power estimation algorithm remains accurate at high OOK channel powers down to -2 dBm (the optimum launch power in this network configuration is 3 dBm), when using the previously generated two channel look up table Fig. 5(a). If only 1 neighboring channel is present, it would be detected by the spectral occupancy test earlier in the algorithm and a more appropriate look up table can then

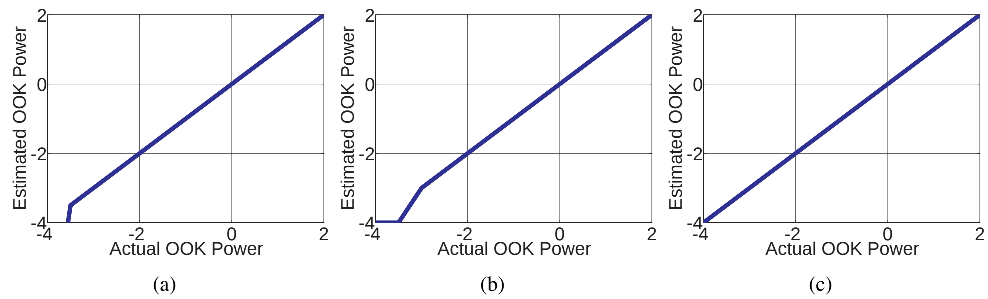


Fig. 8. Estimation of the higher power neighbor channel using a 6 channel look up table of -/+12 GHz BER performance with one attenuated neighbor, (a) 1, (b) 2 and (c) 3 dBm difference between the two nearest neighbors.

be selected.

The scenario in which the two nearest neighbors are at different powers is investigated. The BER of the probe channel is measured at -12 and +12 GHz from the grid, if they are equivalent then the two neighbors are at the same power. In the previous set of estimation, the performance of the algorithm was limited by the amount of XPM experienced by the probe channel. The probe channel is moved 12 GHz towards the higher channel, which is determined by comparing the BER measured at -12 GHz and +12 GHz. The worse performing offset is then the offset towards which contains the higher channel power. This measurement is then used in with the algorithm, using a different look up table to take into account the 12 GHz offset. It can be seen from Fig. 8 that the estimation performs accurately down to -3.5 dBm OOK power, an improvement from the previous limit of -2 dBm. The side that the higher power channel exists on is determined by the inequality in BER performance at the two offsets, however estimating the lower power aggressor is unreliable using this approach. We note that it is possible that the neighboring channels are changing in power, leading to a fluctuation in the measured BER. The measurements used in this work are averaged over a subset of 10 measurements taken over a period of 30 seconds. By averaging multiple measurements or taking the BER over a longer timescale, the effects of this fluctuation in BER can be minimized and the composite BER is then used for estimation. However, it is possible that the peak BER is higher than the FEC limit, which would render the channel unsuitable for provisioning.

6. Conclusions

The penalty in terms of BER performance of probing a 10 Gbit/s OOK channel with a 40 Gbit/s PM-QPSK signal was investigated, and found the impact of the probe to be negligible given sufficiently low power even at a spacing of 6 GHz. A method to infer the power of the neighboring OOK channels was demonstrated. By measuring the BER performance of the probe channel with respect to its transmitted power, and then comparing that to a look up table that was generated when the system was first calibrated, it was shown in this work that it is possible to estimate the neighboring channel power down to -2 dBm. The performance of this algorithm when using a base look up table constructed with two identical power neighboring OOK channels is investigated when the network has 2, 4 and 6 aggressor channels. The BER performance of the probe was measured at -12 GHz and +12 GHz offset from the ITU grid to infer if the channels were of equal power. The measurement with the higher BER closest to the higher power channel is then used with an appropriate look up table to estimate the channel's power. By exposing the probe to more XPM the channel power estimation improved to being able to estimate down to -3.5 dBm neighbor power. This is sufficient information for a cognitive transceiver to make a decision on the quality of an empty spectral slot since the neighboring channel powers are only relevant to the channel of interest when the non-linearities are impairing performance. This probe measurement would only need to be performed once for the network link, and can then be used to provision multiple 40 Gbit/s PM-QPSK channels in the absence of network reconfiguration.

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