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Physical Layer Transmitter and Routing Optimization to Maximize the Traffic Throughput of a Nonlinear Optical Mesh Network

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***Abstract*—This paper investigates the physical layer optimization as a means of improving the utilization of limited network resources. A transparent optical network operating in the nonlinear transmission regime using coherent optical technology is considered. A physical layer model is described that allows the transmission signal quality to be included in the optimization process. Initially a fixed power, route-adapted modulation format approach is taken using integer linear programming to solve the static route allocation problem. It is shown that for the 14-node, 21-link NSF mesh network adaptation of the modulation formats leads to increases in data throughput of 17%. Optimization of the individual transmitter launch powers and spectral channel allocation results in a SNR margin of 2.3 dB, which is used to further increase the overall network traffic throughput exceeding the fixed PM-QPSK modulation format by as much as 50%. Compared to other work this paper highlights that increased gains in network throughput can be achieved if nonlinear interference is included in the routing and spectral assignment algorithm and individual transmitter spectral assignment and launch power is optimized to minimize nonlinear interference.**

I. Introduction

Optical fibre mesh networks connecting re-configurable optical add drop multiplexers, ROADMs, form the backbone of modern communications and the internet. These networks utilize wavelength routing to transparently connect source and destination nodes. Traditionally the transmitter-receiver pairs are designed to operate error-free in the worst case, for transmission between the furthest spaced nodes so that any route reconfiguration can be accommodated. This leads to over provisioning of resource with large margins for the majority of signals. With the development of software-defined transceivers [1]–[3] the transmitter can be re-configured allowing the transmission parameters to be adapted to the selected physical route. Given the continuing increases in network traffic and this ability to configure the transmitter parameters the physical network resources of bandwidth and power can be used more efficiently. In this work static offline network optimization was used in a DWDM fixed grid transparent optical network to maximize the network data throughput.

In the area of optical network optimization authors have used mixed line rates utilizing OOK, DQPSK and PM-QPSK signals with impairment-aware routing to reduce capital expenditure [4], although it is difficult to link cost savings with potential increases in traffic throughput. The recent development of elastic optical networks [5], [6] has greatly improved spectral efficiency, however in this paper we only consider a fixed DWDM grid, leaving the option of utilizing the potential gain of "elasticity" in future work. The extension of elastic optical networks to include modulation format adaptation based on the quality of transmission or reach has further improved overall spectral efficiency [7]–[9]. In this work we use modulation format adaptation, based on the physical link properties, specifically, the nonlinear quality of transmission.

Nonlinear impairments have been included in the routing and spectral assignment algorithms by including a nonlinearity constraint [10] and through a power optimized reach constraint [11]. Here, we wish to take advantage of the results presented in [12] which indicate that the correct routing and spectral assignment can lead to improved SNR and throughput. We include a nonlinear weight in the optimization objective function to initially group highly interfering channels so that highly interfering channels can be subsequently given well separated spectral assignments. Finally individual transmitter launch powers were optimized, to maximize the reach [11] while in [13] an altruistic minimization of transmitter power was found to benefit the wider network. Here we take a global view of the network and adjust individual transmitter powers to equally distribute the available SNR margin above error free transmission.

The aim of this paper is to explore if enhanced network throughput gains are possible, compared to the basic modulation format adaptation, by optimizing the routing, spectral assignment and launch power to reduce the overall effect of nonlinear interference within the network.

II. Physical Layer nonlinear Propagation Model

For the optimization considered in this paper a simple physical layer impairment model is required to allow rapid computation of the quality of signal transmission. The assumed signals formats are restricted to polarization-multiplexed coherent modulation schemes such that the linear impairments can be ideally and adaptively compensated in the coherent receiver. Signal degradation is caused by the combination of the accumulated ASE noise from the erbium doped fibre amplifiers, EDFAs, in the optical path and the accumulated nonlinear interference between co-propagating signals. For optical fibre infrastructure, that is dispersion uncompensated the Gaussian noise, GN, model has been assumed to predict the nonlinear interference as a source of additive Gaussian noise [14]–[17]. In this case the symbol SNR, SNR_i, of the i^{th} channel is given by

$$SNR_i = \frac{p_i}{n_{ASE,i} + n_{NLI,i}} \tag{1}$$

where p_i is the received signal power, $n_{ASE,i}$ is the ASE noise power and $n_{NLI,i}$ is the nonlinear interference noise power within the receiver filter bandwidth, all on the i^{th} channel.

As the transmission loss of each span is fully compensated by the EDFA gain, the received signal power is equal to the transmitter launch power and the ASE noise power is given by

$$n_{ASE,i} = 10^{\frac{F}{10}} h\nu R N_s \left(10^{\frac{A_{span}}{10}} - 1\right) \tag{2}$$

where F is the amplifier noise figure (dB), h is Planck's constant (6.626×10^{-34} J.s), ν is the channel carrier optical frequency (193.5×10^{12} Hz), R is the symbol rate (baud), A_{span} is the loss of a single fibre span (dB) and N_s is the number of spans in the route.

The Kerr effect leads to nonlinear interference noise that can be considered as self phase modulation, SPM, for nonlinear interference caused solely within the i^{th} channel, cross phase modulation, XPM, for interference on the i^{th} channel caused by signals in the j^{th} channel and four wave mixing, FWM, for interference caused by signals in multiple channels. For well spaced channels, such that there is negligible cross-talk of the nonlinear interference noise between channels, and under the assumption that the nonlinear interference noise due to FWM can be ignored as insignificant [15] then the nonlinear interference noise, $n_{NLI,i}$ on the i^{th} channel due to SPM and XPM can be written as [12], [18]

$$n_{NLI,i} = N_s p_i \sum_j X_{i,j} p_j^2 \tag{3}$$

where N_s is the number of spans over which the nonlinear interference accumulates, p are the channel launch powers and the summation j is over all channels, $\mathbf{X}$ is a single-span efficiency factor such that $X_{i,j}, i \neq j$ is a XPM factor and $X_{i,i}$ is a SPM factor. The nonlinear efficiency factor was calculated by numerical integration of the GN reference equation (1) in [19] such that $X_{i,j} = X\left(|\nu_i - \nu_j|\right)$ where ν_i and ν_j are the carrier frequencies of the i^{th} and j^{th} channels. It is assumed in this work that nonlinear interference from multiple spans adds incoherently [20] and also that the SPM has been ideally compensated using digital back propagation such that $X_{i,i} = 0$.

III. Network Topology

In order to test the routing, modulation format, spectral and power assignment optimization the reference NSF topology with 14-nodes and 21-links was used [21]. This is a well known reference core network topology, suitable for exact solution using linear programming techniques. Figure 1 shows the NSF topology and link lengths used.

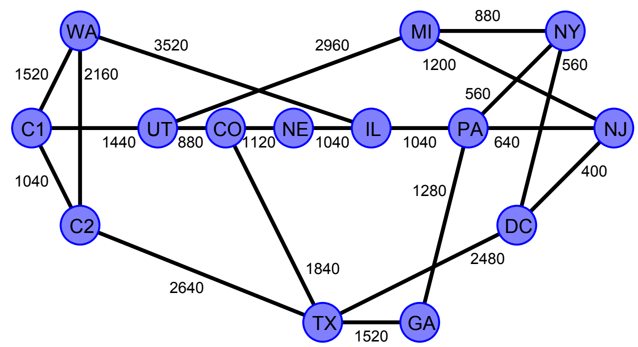

Fig. 1. The 14 node, 21 link NSF mesh topology showing the link lengths in (km).

Each link is assumed to be a fibre pair consisting of uncompensated, single mode fibre in 80 km spans with attenuation 0.22 dB.km^{-1}, chromatic dispersion 16.7 ps.nm^{-1}.km^{-1} and nonlinear coefficient 1.3 W^{-1}.km^{-1}. The loss of each span is assumed to be ideally compensated by an EDFA with a noise figure of 5 dB. Each fibre was assumed to support 80 DWDM channels on a 50 GHz fixed grid, each transmitting 28 GBaud signals with a root raised cosine spectral shape (roll off 0.5). The ROADM nodes were assumed to be ideal, and thus not contributing to the overall noise.

The required symbol SNR for error free data transmission is shown in table I for the various PM-mQAM modulation formats considered. The required symbol SNR was calculated as the theoretical symbol SNR required to give a pre-FEC BER of 4×10^{-3} in the presence of AWGN. Table I also shows the error free data transmission rate based on the 28 GBaud symbol rate.

Format Acronym	Bit Loading (b.Sym^{-1})	Data Rate (Gb.s^{-1})	Required Symbol SNR (dB)
PM-BPSK	2	50	5.5
PM-QPSK	4	100	8.5
PM-8xQAM	6	150	12.5
PM-16QAM	8	200	15.1
PM-32xQAM	10	250	18.1
PM-64QAM	12	300	21.1

TABLE I
Required symbol SNR to achieve a pre-FEC BER of 4×10^{-3} and data rate at 28 GBaud for various PM-mQAM formats.

In order to optimize the traffic throughput of a network the starting point is the assumed traffic demand. In this work it was assumed that the traffic demand is uniform and equal between all node pairs such that a normalized traffic matrix, $\mathbf{T}$, was defined with the traffic between source node, s, and destination node, d, given by $T_{s,d}$ as

$$T_{s,d} = \begin{cases} \frac{1}{182} & \text{for} \quad s \neq d \\ 0 & \text{for} \quad s = d. \end{cases} \tag{4}$$

IV. Static Routing and Modulation Assignment

This sections describes the approach used to optimize the routing and modulation format assignment when the launch power and nonlinear interference are pre-calculated and fixed. The primary aim of this optimization was to maximize the network traffic throughput, with a secondary aim of minimizing the number of transmitter-receiver pairs where possible. In order to remove the launch power consideration from this stage of the optimization the launch power was pre-optimized by setting a constant and equal optimized power and similar to the LOGON [22] strategy all the DWDM channels were considered fully occupied with a constant power. This assumption removes the exact routing and DWDM channel allocation from the SNR estimation, decoupling the choice of modulation format from the routing and spectral allocation. The symbol SNR of all the channels over a route was taken as equal to that of the worst, central, channel such that

$$SNR_m = \frac{p}{N_s n_{ASE} + N_s X_m p^3} \tag{5}$$

where N_s is the number of fibre spans the signal traverses, n_{ASE} is the ASE noise accumulated in a single fibre span and $X_m = \max_j \sum_i X_{i,j}$, is the maximum nonlinear interference from a single span. The launch power is optimized to maximize the SNR of equation (5). The optimum launch power is independent of the route length since both noise terms depend linearly on the number of spans here. For the fibre, EDFA and signal parameters used, the ASE noise accumulated from each fibre span, n_{ASE}, was 0.00064 mW, and the maximum nonlinear interference factor, X_m, was 0.00067 mW^{-2} such that the optimum launch power was 0.78 mW (-1.1 dBm). The worst case SNR, SNR_m, of each route can be simply calculated given the number of fibre spans traversed.

To solve the routing and spectral allocation problem there are two widespread integer linear programming, ILP, formulations; those based on flow and those based on routes [23], [24]. Since the transmission SNR for a given connection depends on the overall route, and not on individual links, the modulation format will be route-dependent and the route-based ILP formulation is more appropriate here.

As a preliminary stage to solving the ILP problem, first the k-shortest routes, k=25, between each source-destination node pair were calculated and the SNR_m of each route was calculated based on the number of fibre spans in the route as equation (5) assuming all DWDM channels are occupied with a signal at the optimized power. The highest modulation format where the route SNR exceeds the modulation formats required SNR was chosen for each route from the modulation formats listed in table I and the capacity of each route was calculated.

Next, the allocation of DWDM channels to routes was optimized as a mixed integer linear program, MILP, in order to maximize the traffic throughput. It should be noted that the traffic matrix is symmetric, $T_{s,d} = T_{d,s}$, and the network is symmetric with fibre pairs, so as is customary we reduced the problem by solving for $d > s$ only. In order to describe the MILP problem the following notation was used

Parameters:

- s,d: the source and destination nodes $\in 1, 14$,
- l: a link $\in 1, 21$,
- w: a DWDM channel $\in 1, 80$,
- $T_{s,d}$: the normalized traffic flow between source, s, and destination ,d,
- $r_{s,d,k}$: the k^{th} shortest route between source, s, and destination ,d,
- $\delta^L_{s,d,k,l}$: is set to 1 if route $r_{s,d,k}$ traverses link l, 0 otherwise,
- $SNR_{s,d,k}$: the symbol SNR for transmission over route $r_{s,d,k}$,
- $C_{s,d,k}$: the capacity of transmission over route $r_{s,d,k}$.
- $SNR^R_{s,d,k}$: the required symbol SNR for error free transmission over route $r_{s,d,k}$ at the capacity $C_{s,d,k}$,

Variables:

- c: the total throughput of the network, a multiplying factor to the normalised traffic matrix $\mathbf{T}$ to define the actual traffic flows,
- $\delta^F_{s,d,k,w}$: is 1 if a transceiver for route $r_{s,d,k}$ uses DWDM channel w, 0 otherwise.

The aim is to optimize c as a continuous variable and $\delta^F_{s,d,k,w}$ as binary variables, so that

$$c_{max} = \max_{c, \delta^F_{s,d,k,w}} c \tag{6}$$

subject to the total capacity between the source and destination nodes exceeding the demand

$$cT_{s,d} - \sum_w \sum_k \delta^F_{s,d,k,w} C_{s,d,k} <= 0 \qquad \forall \quad s, d > s. \tag{7}$$

and the number of signals occupying DWDM channel, w, in any link, l, does not exceed 1,

$$\sum_k \sum_s \sum_{d>s} \delta^F_{s,d,k,w} \delta^L_{s,d,k,l} <= 1 \qquad \forall \quad l, w. \tag{8}$$

Given the maximum network throughput c_{max} has been calculated the MILP is re-solved to minimize the total number of transmitter-receiver pairs. Optimize $\delta^F_{s,d,k,w}$ as binary variables to

$$\min_{\delta^F_{s,d,k,w}} \sum_w \sum_k \sum_s \sum_{d>s} \delta^F_{s,d,k,w} \tag{9}$$

subject to the constraints of equations (7) and (8) where c has been replaced by c_{max}. The ILP optimization was solved using IBM CPLEX® and for the results presented in this paper the computation took typically an hour on a dual quad core computer with 16 threads running at 2.3 GHz.

V. Modulation Adaption Results

For the network topology of figure 1 considered, the traditional fixed modulation format approach would use PM-QPSK since this format is suitable for all of the shortest routes between all the source-destination node pairs. The maximum network throughput obtained while utilizing just the PM-QPSK modulation format was calculated using the ILP formulation of section IV to be 109.2 Tb.s^{-1}, required 1092 transmitters and maintained a worst case SNR margin, for the assumption of full channel loading with fixed power, of 1.6 dB on the longest route. Allowing the adaptation of the modulation format based on the SNR of each route the maximum network throughput was increased to 127.4 Tb.s^{-1}, required 988 transmitters and maintained a worst case SNR margin, for the assumption of full channel loading with fixed power, just sufficient for error free operation.

The adaptation of the modulation format has increased the network throughput by just under 17%. Korotky et al [25] suggest that much larger gains should be possible and show a gain of 70% for a similar mesh network with lumped amplifiers and distance dependent SNR. This suggests that modulation format adaptation in this case has not fully accessed the possible gains in network traffic throughput.

VI. Transmitter Launch Power Optimization

The nonlinear interference noise equation (3) was developed with point-to-point links in mind however it applies equally well to mesh networks. The i^{th} and j^{th} transmitter-receiver pair each corresponds to one active $\{s, d, k, w\}$ connection between source, s, destination, d, by the k^{th} shortest route and utilizing wavelength channel w where $\delta^F_{s,d,k,w} = 1$. For the i^{th} transmitter in a mesh network the ASE noise, $n_{ASE,i}$ is given by

$$n_{ASE,i} = 10^{\frac{F}{10}}\, h\nu\, R \sum_l \delta^L_i N_{s,l} \left(10^{\frac{A_{span}}{10}} - 1\right) \qquad (10)$$

where $N_{s,l}$ is the number of spans in link l and δ^L_i is 1 if the signal from the i^{th} transmitter-receiver pair traverses link l, zero otherwise. Similarly the nonlinear interference is given by a summation of the nonlinear interference accumulated on the i^{th} transmitted signal as it traverses each link on its route, thus the accumulated nonlinear efficiency, $X^A_{i,j}$, is given by

$$X^A_{i,j} = \sum_l \left[\delta^L_i\, \delta^L_j\, N_{s,l}\, X\left(|\nu_i - \nu_j|\right)\right] \qquad (11)$$

Given that the i^{th} transmitter-receiver pair requires a symbol SNR, SNR^R_i, with an overall margin SNR_{margin} then the launch powers should be minimized to achieve this. The launch powers were initialized at the flat optimum used in section IV and adjusted to achieve the required SNR with margin. The variation of the SNR with launch power around the current network state, $\frac{\mathbf{dSNR}}{\mathbf{dp}}$ is given by

$$\frac{\mathrm{d}SNR_i}{\mathrm{d}p_j} = SNR_i^2 \left[\frac{n_{ASE,i=j}}{p_i^2} - 2X^A_{i,j}\, p_j\right] \qquad (12)$$

where $n_{ASE,i=j} = n_{ASE,i}$ for $i = j$, zero otherwise. The iteration update is given by

$$\Delta p = \left(SNR_{margin} SNR^R - SNR\right) \left(\frac{\mathbf{dSNR}}{\mathbf{dp}}\right)^{-1} \qquad (13)$$

In order to improve the speed of convergence and dampen oscillations in the computation the iteration update was restricted at each step by multiplying by $\mu < 1$ such that the maximum of $\mu\Delta p < 0.1$, and then $p = p + \mu\Delta p$ the algorithm was found to converge within 20 iterations for ≈ 600 transmitters provided the required SNR with margin can be achieved.

The SNR margin was increased until no launch power solution could be found. The maximum achievable margin was taken as the largest margin for which a solution to the power optimization was possible.

For the routing solutions in section V there is no preference in the wavelength channel selection. Two wavelengths can be swapped and the routing solution is still valid, that is if all the transmitters at wavelength 1 are switched to wavelength 2 and those at wavelength 2 switched to wavelength 1 then the routing solution will still hold. In [12] it was shown that the channel wavelength allocation affects the nonlinear interference and that there is an advantage to separate wavelengths channels with higher power signals. So, firstly the objective function of the final integer linear program was changed to direct the solution to allocate all the higher power signals together in the same DWDM channel where possible.

Optimise $\delta^F_{s,d,k,w}$ as binary variables to minimize

$$\min_{\delta^F_{s,d,k,w}} \sum_w \sum_k \sum_s \sum_{d>s} \delta^F_{s,d,k,w} \cdot \left[1000 + \frac{Z_{s,d,k}}{10000} \left(\frac{SNR^R_{s,d,k}}{SNR_{s,d,k}}\right)^2 \left(\frac{w}{10} + 100\right)\right]. \qquad (14)$$

subject to the total capacity between the source and destination nodes exceeding the maximized demand c_{max} as in equation (7), with c replaced by c_{max} and the number of signals occupying DWDM channel, w, in any link, l, does not exceed 1, as in equation (8). The large constant in the objective function ensures that the minimum number of transmitters are used. The term $\frac{SNR^R_{s,d,k}}{SNR_{s,d,k}}$ is the ratio of the modulation formats' required SNR to the basic SNR of the route used in the routing stage, the worst case where all channels are occupied. This ratio is related to the expected transmitter power thus the square multiplied by the route length $Z_{s,d,k}$ denotes the channels likelihood to cause nonlinear interference. By weighting the objective function with the channel number, more highly interfering signals will be placed in the lowest available channel number, thus grouping them together. The constant added to the channel weight ensures that nonlinear interference is always more weighted than channel number. So this objective function tries to, in order of priority, minimize the number of transmitters, then minimize the nonlinear interference and finally group highly interfering signals.

Solving the ILP with this new objective function retains the same maximum traffic throughput of 127.4 Tb.s^{-1} and utilizes the same number, 988, of transmitters but groups the signals with higher capacity for nonlinear interference into the lowest channels. Solving the launch power optimization to maximize the margin leads to an achievable SNR margin of 1.4 dB. Figure 2 shows the total launch power in each channel across the whole network and clearly shows the fact that higher power channels are grouped towards the lower channel numbers. The channels where then re-ordered to separate higher power channels as this has been shown [12] to reduce the overall interference. The re-ordering was initial done manually to

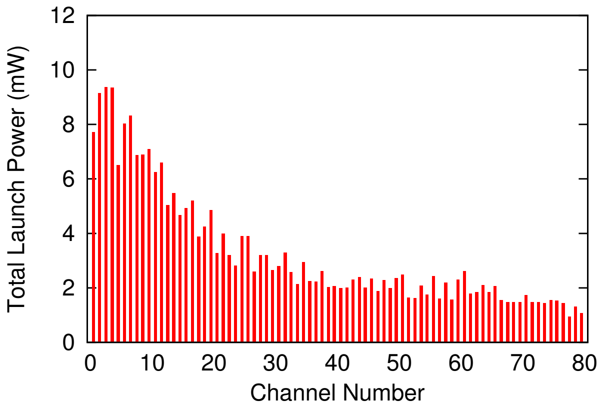

Fig. 2. Total power in each channel resulting from the ILP objective function of equation (9) for the adapted modulation solution with 127.4 Tb.s^{-1}.

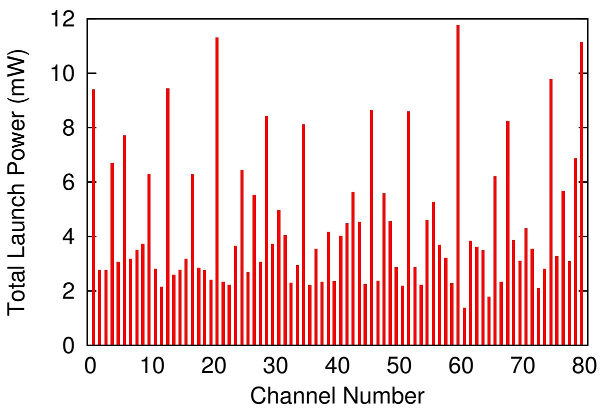

Fig. 3. Total power in each channel after an optimal re-ordering of the result from the ILP objective function of equation (9) for the adapted modulation solution with 127.4 Tb.s^{-1}.

separate the lower channel numbers and then improved by swapping random pairs of channels and either retaining the result if this improved the achievable margin or returning to the original positions if it did not. Random pairs were swapped until no further improvement in achievable margin could be made. For the ILP solution with traffic throughput 127.4 Tb.s^{-1} utilizing 988 transmitters a margin of 2.3 dB could be achieved by re-ordering the channels. Figure 3 shows the total launch power in each channel across the whole network for the final re-ordered channel allocation.

Given that the ILP solution for the NSF mesh network with a traffic throughput of 127.4 Tb.s^{-1} had an achievable margin of 2.3 dB can this margin be converted into further traffic throughput? The ILP problem was re-solved with two important differences. Firstly the number of modulation formats for each route was doubled to include the highest order modulation format that could be achieved for the route SNR and the next lower modulation format. This was included to prevent over provisioning of capacity in the ILP solution thus reducing the required SNR on a few transmitter-receiver pairs and reducing the nonlinear interference on the network. The maximum number of k-shortest routes was reduced to 12 and the number of routes doubled to include the two modulation format options, approximately maintaining the ILP complexity compared to the ILP of section IV. Secondly the required SNR was reduced by a factor of 1.5 dB based on the assumption that after the ILP is solved the power optimization will regain the necessary margin for error free transmission.

VII. Optimized Network Throughput Results

Table II shows the solutions found for the NSF mesh network for a uniform traffic pattern. The table shows the traffic throughput, number of transmitters required and achievable SNR margin. It can be seen that by moving from the fixed modulation format with a fixed launch power to an adapted modulation format and an individually optimized launch power the network traffic throughput can be increased by 50%, while keeping sufficient signal quality to maintain error free transmission. Figure 4 illustrates this result.

Routing Solution	Network Throughput Tb.s^{-1}	Number of Transmitters	Achievable SNR Margin dB
Fixed PM-QPSK, flat launch power, full occupancy	109.2	1092	1.6
Fixed PM-QPSK, optimized channels, optimized power	109.2	1092	3.3
Adapted PM-mQAM, grouped channels optimized power	127.4	988	1.4
Adapted PM-mQAM, optimized channels, optimized power	127.4	988	2.3
Adapted PM-mQAM, optimized channels, optimized power	163.8	1060	0.2
PM-QPSK to PM-16QAM, optimized channels, optimized power	163.8	1188	0.4

TABLE II
Results of optimization of the 14-node, 21-link NSF mesh network for uniform traffic.

It is shown, in table II, for the fixed PM-QPSK modulation that by optimizing the spectral allocation and individual launch power the achievable margin can be increased by more than 3 dB. This suggests, following the Shannon capacity theorem, that the traffic throughput of the network could be increased by 50%, although it is not possible to simply replace all channels with the higher PM-8xQAM format as this requires a 4 dB improvement in the SNR over PM-QPSK modulation. By using the full spectrum of PM-mQAM formats it is possible to increase the network throughput while maintaining a small achievable margin and reducing the number of transmitters.

It is also shown that while restricting the modulation formats to the more easily achievable set of PM-QPSK, PM-8xQAM and PM-16QAM that if the ILP objective function is changed to remove the objective of minimizing the number of transmitters, by removing the 1000 in equation (14), then a solution

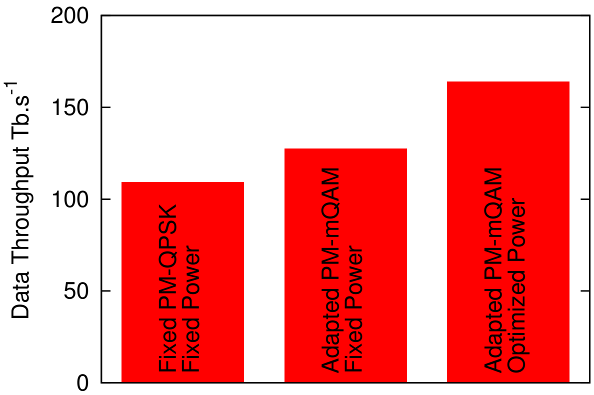

Fig. 4. Network traffic throughput for three network optimizations.

can be obtained that gives a 50% increase in traffic throughput while maintaining a small achievable margin at the expense of an increase in the number of transmitters.

VIII. Conclusion

It has been shown that the traffic throughput of an optical mesh network operating in the nonlinear regime can be increased by optimizing the assignment of the transmitter parameters and routing. Starting from a base where all transmitters utilize a fixed PM-QPSK modulation and a fixed launch power the network throughput was increased by 17% by moving to an adapted modulation format while maintaining the fixed launch power. A multi-stage optimization of routing, modulation format, spectral assignment and launch power showed that it was possible to increase the network traffic throughput by 50% with respect to the base fixed modulation, fixed launch power case. It was further shown that by optimizing the routing, modulation format, channel assignment and launch power, larger gains in network traffic throughput over merely optimizing the routing and modulation format can be achieved. It is intended to include the benefits of improved spectral efficiency through the use of a flexible grid in future work.

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