Energy efficiency of optical grooming of QAM optical transmission channels

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Abstract: Analysis of the energy use for optical grooming of quadrature amplitude modulated signals in optical transmission systems is used to determine the potential efficiency benefits. An energy model is developed for both optical and electronic grooming and used to study the relative efficiency for three different network scenarios. The energy efficiency is evaluated considering both coherent and direct detection transceivers including power management strategies. Results indicate efficiency improvements up to an order of magnitude may be possible for 100 GBaud rates and 25-30 GBaud is a critical point at which optical grooming becomes the more efficient approach. These results are further shown to apply for the case of projected efficiency improvements in the underlying device technologies.

OCIS codes: (060.2330) Fiber optics communications; (060.1155) All-optical networks; (060.1660) Coherent communications.

References and links

1. Introduction

There is a growing demand for bandwidth intensive data applications like enterprise cloud computing, interactive video, multimedia sharing, and scientific computing. It is estimated that by 2020 there will be 50 billion devices connected to the Internet which will be six times the human population [1]. This continued increase in the number of connections and bandwidth is bringing focus to network scalability and a new generation of intelligent and dynamic energy efficient networks. While equipment efficiency has continued to improve, recent studies have shown that it may be substantially lagging traffic growth, which will over time result in increased energy use [2]. In particular, electronic switching and network processing technologies such as Internet Protocol (IP) routers have reached thermal density limits and parallel system solutions are increasingly required for capacity growth. The electronic processing in optical systems are also showing dramatic increases in power requirements and a shift toward growth through parallelism as transceiver technologies reach 100 Gb/s and beyond using coherent methods with advanced digital signal processing. While processing intensive operations require an electronic solution, other operations might be more efficiently handled through optical switching or processing technologies. Several new and potentially energy efficient optical device technologies were recently investigated [3–5] to address this challenge. In addition to device improvements, considerable attention has focused on network architectures that enable more efficient overall operation and bandwidth utilization [7–9]. Simple or few operation optical processing, which recent studies have shown may be more efficient than electronic techniques at very high data rates [10], may have further advantages when considered in an overall optical networking context.

Interest in increasing the spectral efficiency in optical systems has increased emphasis on higher order modulation formats. In order to efficiently utilize and manage such signals and their unique transmission constraints, methods are needed to move data between wavelengths of different spectral densities, a process that is one of a set of different operations referred to as optical signal grooming. In networks today, such grooming that involves changes in wavelength and modulation is exclusively carried out using electronic processing and optoelectronic or O/E/O conversion. We refer to this approach here as electronic grooming. In contrast to electronic grooming, optical grooming (often referred to by the term ‘all-optical’ processing) employs nonlinear optical phenomena to coherently mix signals and perform these grooming functions without O/E/O conversion. Various optical grooming techniques were recently proposed that can be used to increase spectral efficiency [3–5]. These generally involve combining two or more low rate signals or data flows into a higher rate signal. A specific case of optical grooming is considered here in which one or more low information rate signals of different modulation formats are combined into a single higher information rate
optical signal with a different modulation format. Recent demonstrations of optical manipulation of higher order modulation format optical signals include multiplexing two 10 Gb/s quadrature phase-shift keying (QPSK) signals to a 10 Gb/s 16-QAM signal [4] and achieving six different higher order modulation formats by multiplexing 10 Gb/s on-off-keying (OOK) signals and 80 Gb/s 16 QAM signals [5]. In other work, orthogonal frequency-division multiplexed (OFDM) signals with orbital angular momentum modes were used to achieve high spectral efficiency [11]. These demonstrations open the possibility to optically groom signals at any arbitrary location within the network to increase the spectral efficiency of the network and reduce wavelength blocking. In fact, wavelength conversion has long been recognized as an important approach to reduce wavelength blocking and fragmentation. However, its effectiveness is severely limited when signals share common paths, as was recognized very early on [12] and in part has been an obstacle to commercial interest. Grooming or aggregating such signals into fewer higher rate signals is an important capability to mitigate these blocking scenarios and overcoming the limited benefit of simple wavelength conversion.

Nonlinear optical techniques operate on the native optical signals with very fast response times. Although cost and complexity can be high, as the information rates increase, the cost and energy generally scales down directly on a per bit basis, i.e. the total cost or energy varies little as the speed increases so the per bit efficiency improves for higher speeds. Furthermore, at high data rates the electronic processing may become costly or problematic. Therefore, the potential exists for all-optical techniques to become competitive. While this advantage has been recognized for some time, the situation is complicated by the emergence of coherent modulation and a slowing of the increase in signal baud rates. Nevertheless, the electrical power for long haul class 100 Gb/s and higher coherent transceivers is measured in the 100’s of Watts and custom high speed ASICs can be costly [2]. Considering nonlinear optical systems, temperature control requires a few Watts of power and the optical amplifiers needed to achieve high powers for nonlinear optical processes are often 20-30 Watts. Thus, bulk optical components and temperature control for nonlinear methods are competitive against the power required for today’s transceivers. Furthermore, emerging photonic integrated device techniques for nonlinear optics can greatly reduce the power requirements and potentially provide even greater benefit [13]. Our motivation for this paper is to evaluate the energy use of these optical grooming techniques for optical signals with different baud rates and modulation complexity (i.e. constellation size) in different aggregation scenarios and evaluate their energy savings compared to electronic grooming and existing technologies.

Optical grooming is being studied as an alternative to electronic switching in layers 2 and 3. S.R Nucico et al. experimentally illustrate the ability of wavelength conversion and optical grooming [4]. Different power consumption models for optical components have been introduced depending on device size [17], but not considering particular functionality. The analysis in this paper expands on this work to provide the first energy models for optical grooming methods along with models for electronic grooming and directly compares the two approaches. The proposed energy model is used to study the impact of optical grooming focusing on a network segment under different aggregation scenarios and with various power management strategies. Three grooming scenarios are examined depending on the placement of the optical grooming modules. The energy benefits of using optical grooming is evaluated relative to technologies used in current networks. Furthermore, the benefit of optical grooming compared to next generation network technologies is projected following trends for efficiency improvements in the underlying devices.

The rest of the paper is organized as follows. In section 2 the architecture and the elements used in optical grooming and electronic grooming is described. Section 3 outlines the network model used for analysis and network in-casting. In Section 4 the energy model for optical and electronic grooming is defined. Section 5 contains the results obtained by numerical analysis.
2. Grooming technologies and architecture

Methods for both optical and electronic grooming can be modelled using typical technology configurations. Figure 1 illustrates a block diagram of the elements considered for the energy evaluation of an electronic grooming module. This model was first introduced in [14] and is elaborated on here. In Fig. 1, the electronic grooming module consists of \( k \) receivers and one transmitter where \( k \) represents the number of signals that will be aggregated. Each receiver consists of a local oscillator, multiple photodetector modules (with associated electronics), analog to digital converters (ADC), digital signal processing (DSP), framing, and forward error correction (FEC) electronics that contribute to the energy consumption of the receiver. Similarly, a transmitter consists of a laser module, modulators and driver electronics and FEC encoding electronics which contribute to its energy consumption. The energy consumption model of the electronic grooming module is discussed in section 4. The electronic grooming may include coherent or direct detection (on-off keying) receivers. While here we use a dedicated grooming transceiver with different line rate inputs and outputs, often this functionality is achieved by using separate transceivers for each of the lower rate signals and connecting them through client optics to a single higher rate transceiver. This approach would result in slightly higher power due to the additional client optics. The energy of the receivers strongly depend on the symbol rate. A substantial part of the energy is due to the data processing by the digital signal processing blocks. The energy of such electronic devices is proportional to the cube of clock frequency [9]. Thus as the symbol rate increases the energy use of the module follows a power law.

![Fig. 1. A k×1 Electronic grooming module. The input signals may have traversed similar or different transmission paths.](image-url)
Figure 2 describes the structure of the optical grooming module. Although a number of different nonlinear optical platforms can be used such as highly nonlinear fiber, chalcogenide glasses, or semiconductors, here a periodically poled lithium niobate (PPLN) based method that includes erbium doped fiber amplifiers (EDFA), polarization beam splitter/combiners (PBS/PBC), tunable filters and tunable delays is used. PPLN techniques are well studied and serve as a good reference case. Since the power associated with the nonlinear element is primarily due to temperature control and the pump laser, similar results are expected for any such optically pumped bulk element. As discussed later, reducing the temperature requirements, pump power, and optical losses, for example by using photonic integration, may lead to improved efficiency. The inputs to the optical grooming module are two PDM QPSK signals. The tunable delay shown in Fig. 2(a), is used to align the bit periods of the incoming signals. Different methods for bit alignment have been reported in the literature and typically involve obtaining the error signal from the strength of a nonlinear mixing component, which will be maximized when the bits are aligned [10]. Ideally this can be extracted from the same mixing used in the grooming process by means of a tunable filter as indicated by the phase detector block [13]. The signals then propagate through PPLN-1 which is used to generate a copy of the signal amplitude and phase using second harmonic generation and difference frequency generation [4]. The PBS/PBC and circulator depicted in the Fig. 2(a), provides polarization diversity [3]. The output of the circulator passes through the liquid-crystal-on-silicon (LCoS) filter. The LCoS filter is used to apply complex weights (amplitude and phase) on the signals. These weighted signals are then passed through a spool of dispersion compensating fiber (DCF) to induce a one-symbol delay between the signal and their corresponding copies. The output of the DCF is sent to another PPLN waveguide where they interact with their corresponding copies and pump-2 and are multiplexed coherently at a desired wavelength. The LCoS filter and the final tunable filter are used to remove unwanted mixing terms and input wavelength signals. This process can be followed by another PPLN stage to perform wavelength conversion and place the final signal on any channel in the spectrum. However, in principle the mixing technique is tunable and this additional stage in the best case would not be needed so we exclude it here. In practice today, such tunability is limited in performance and would require further improvements.

The optical grooming module shown in Fig. 2(a), can aggregate two PDM-QPSK signals to a single 16-QAM signal. Pump-2 in Fig. 2(a), can be replaced with a PDM-QPSK signal which would enable grooming of three QPSK signals to a single 64-QAM signal. Figure 2(b),
shows the architecture of a 4 × 1 optical grooming module. It consists of a 3 × 1 grooming module followed by a 2 × 1 grooming module. We also note that many practical challenges would need to be resolved in order for these methods to become fully compatible with commercial optical systems and additional components and power may be required for a final field implementation. Some of these challenges include adjusting the phase of the incoming signal and its conjugate copy [4], maintaining polarization diversity and balance in the presence of polarization mode dispersion and loss [3] and bit alignment to achieve maximum signal strength for the nonlinear mixing component [10] in the presence of jitter and other transmission effects. Coordination between nodes to establish the groomed connection will also be required along with proper decoding on the receive side to sort the bits from different ingress locations that have been combined into the single modulation constellation. In this study we are evaluating the potential of the underlying technology which is independent of the specifics of the final implementation. Through such analysis one can determine the viability of pursuing practical implementations as well as identifying any key limitations that must be addressed from an energy standpoint.

3. Network in-casting scenarios

For our analysis we consider a network segment that can represent a combination of paths through a mesh network. Figure 3 illustrates a reference network segment with four parallel paths. Each segment consists of a transceiver, two add-drop nodes and amplifiers. We consider the network depicted in Fig. 3 as our base reference case to evaluate the benefits of optical grooming for network in-casting. In-casting occurs when multiple signals are brought together to form a single signal—the opposite of multi-casting. Thus an alternative to Fig. 3 is to perform in-casting at some point along this path grooming the signals into a smaller set of channels. The number of amplifiers used in the path depends on the span length \( D \), transmission distance \( L \) and the number of parallel paths between nodes \( C \). For our calculations we assume span length to be equal to 100 km. For transmission distance we only consider cases where it is less than the signal reach for a given modulation format. To ensure this condition the distance between the transmitter and the first node, \( L_1 \) is set to 600 km. The distance between the first and the second node, \( L_2 \) is 300 km and the distance between the second node and the receiver, \( L_3 \) is 100 km. The values used for the distance in our model are based on the maximum reach achieved by the various modulation formats. The maximum reach for PDM QPSK, 16 QAM, 64 QAM and 256 QAM are 1200 km, 600 km, 300 km and 100 km respectively [15]. For longer distances the energy benefits of grooming in general will be diminished depending on the specifics of the topology and traffic patterns. \( C_1 \) represents the number of parallel paths between source and the first node \( C_2 \) denotes the number of parallel paths between the first and the second node while \( C_3 \) is the number of parallel paths between the second node and the receiver. Table 1 lists the number of amplifiers used in the networks depicted in Fig. 3. Since we assume that this is a segment of a larger network, we only count the fraction of amplifier energy used by the channel compared to the total capacity. Thus, signals within the same fiber will have the same power as signals in different fibers and ‘number of amplifiers’ can be taken as number of times the amplifier power per channel is taken in the calculation.

The benefits of optical grooming relative to electronic grooming can be evaluated for network in-casting. Using the optical grooming module at any point between the source and the destination reduces wavelength blocking and associated spectral fragmentation. Energy efficiency of optical and electronic grooming modules depends on both the signal baud rate and its modulation format. When optical grooming is performed signals with lower order modulation formats are multiplexed to a signal with a higher order modulation format but the same symbol rate. To make our analysis tractable we consider three general in-casting scenarios for grooming four streams of data. These include changing the modulation format from DP-QPSK to 16 QAM, 16-QAM to 64-QAM and DP-QPSK to 64-QAM as represented...
in Fig. 4. Although optical grooming of OFDM signals is also possible, it would involve different configurations due to the multi-carrier aspect and whether it is electrical or optical OFDM. Therefore we do not consider OFDM methods in this work. Incoming signals can be groomed in either $2 \times 1$, $3 \times 1$ or $4 \times 1$ configurations. Figure 4, illustrates these three configurations. As shown in Fig. 4, there are two add-drop nodes between the transmitter and the receiver. Each add-drop node is equipped with a bank of optical grooming modules. Optical grooming can be used in a network at any location between the source and the destination. The only factor to be considered before grooming is that the signals to be groomed are travelling to the same destination. We also note that currently there is not a method for disaggregating the signals that are transmitted in the opposite direction for arbitrary modulation formats. For a typical system today equivalent rate signals are transmitted in opposite directions between every source and destination pair. Therefore today one would be forced to use transceivers to groom and disaggregate the signals in the reverse direction.

![Network segment with four parallel light paths.](image)

**Fig. 3.** Network segment with four parallel light paths.

**Table 1.** Number of amplifiers $M$ and ROADM ports $N$ used in the network where $C$ is the number of parallel signals between aggregating nodes, $L_1 = 600km$, $L_2 = 300km$, $L_3 = 100km$, $D = 100km$ is the span length.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Number of parallel links between two nodes $M$</th>
<th>$N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2 \times 1$</td>
<td>$C_1 4, C_2 2, C_3 1$</td>
<td>31</td>
</tr>
<tr>
<td>$3 \times 1$</td>
<td>$C_1 4, C_2 2, C_3 1$</td>
<td>31</td>
</tr>
<tr>
<td>$4 \times 1$</td>
<td>$C_1 4, C_2 4, C_3 1$</td>
<td>37</td>
</tr>
<tr>
<td>$4 \times 4$</td>
<td>$C_1 4, C_2 4, C_3 4$</td>
<td>40</td>
</tr>
</tbody>
</table>
4. Power model for network elements

4.1 Power model for ROADM, amplifiers and buffers

The energy use of ROADMs and amplifiers is data rate independent. Assuming that $\delta$ is the degree of a given node and $W$ is the number of wavelengths in a fiber, the number of line side wavelength ports in a ROADM is given by $W\delta$. Hence the power contribution of a ROADM per port is given as $p_{\text{trans}} = \frac{p_{\text{roadm}}}{W\delta}$. The typical values for the power consumption of a ROADM per connection is in the range from 400mW to 900mW [7]. Like ROADMs, an EDFA is shared by multiple lightpaths so the power consumption of an EDFA for a single wavelength is given by $p_{\text{amp}} = \frac{p_{\text{amp}}}{W}$, the power consumption of a typical amplifier varies from 20 to 100W [7]. For our analysis the power consumption of the amplifier is assumed to be 25 W. Buffers are required in the network to process the sudden surges in traffic. Buffers are mainly composed of DRAM cells. The power consumed by the buffers depends on the mode of operation and the buffer size $B$. Buffers typically have three modes of operation sleep, idle and active. The power consumed during these modes are 0.01 W/Gb, 0.1W/Gb and 1W/Gb respectively [16].

4.2 Power model for coherent transceiver and direct-detection transceiver

For our reference cases and the end points of our optically groomed scenarios, we consider both coherent and direct detection transceivers. The coherent receivers are assumed to be symbol rate adaptive. The structure of the coherent transceiver is similar to that of a single rate 100 Gb/s transceiver [9]. The power consumption of the symbol rate adaptive transceiver does not depend on the optical reach in our model, but it depends on the incoming symbol rate. In general coherent transceivers can have a coarse dependence on the reach [15]. A considerable amount of the power consumption in the coherent transceiver is due to the data processing performed by the forward error correction codec and digital signal processing blocks. Table 2 shows the power consumption of the elements of a coherent transmitter and receiver [9]. Our power model of the coherent transmitter and receiver is summarized in Table 2. Summing each of the terms for the rate-adaptive coherent transceiver results in the following rate dependent powers for the fully on state transmitter and receiver in Watts.
When the transceiver is in the idle state we assume that the laser, local oscillator and the photo diode are the only elements of the transceiver that consume power. From Table 2, we model the power consumption of the idle mode coherent transmitter as $P_{tx}^{idle} = 8$ W and the power consumption of the receiver as $P_{rx}^{idle} = 10$ W. The energy consumption of a network with coherent transceivers during the transmission state and idle state is modeled as follows.

$$P_{net}^{trans} = K P_{tx}^{trans} + P_{rx}^{trans} + M P_{amp}^{trans} + N P_{roadm}^{trans}$$

$$P_{net}^{idle} = K P_{tx}^{idle} + P_{rx}^{idle} + M P_{amp}^{idle} + N P_{roadm}^{idle}$$

In the above equations $K$ is the number of in-cast signals, $M$ is the number of times the energy consumption of the amplifiers is included in a network and varies depending on the connectivity scenario. The values of $M$ used in our analysis are reported in Table 1. Similarly, $N$ is the number of ROADM line side wavelength ports used in the network and for the three cases depicted in this paper the values used for $N$ is calculated and listed in Table 1.

For our analysis in addition to a network with coherent transceivers we consider a network which employs direct-detection (DD) transceivers. For comparison the network is designed to have $\alpha$ parallel links between the transmitter and receiver, $\alpha$ is data-rate ($R$) dependent and is given as follows $\alpha = \frac{R}{R_{trans}}$, where $R_{trans}$ is the maximum data rate a transceiver can process. $\alpha$ uses a roof function to round up to the nearest integer. We consider two cases for evaluation of the DD network: a network with 10 Gb/s DD transceivers ($R_{trans} = 10$ Gb/s) and a network with 40 Gb/s DD transceivers ($R_{trans} = 40$ Gb/s). In this paper, the energy consumption of a 10 Gb/s transceiver in the transmission state $P_{tx}^{trans}$ is assumed to be 35 W [7] and the energy consumption of a 40 Gb/s transceiver in the transmission state is assumed to be 98 W [18]. Similarly the energy consumption of the DD transceiver in the idle state $P_{rx}^{idle}$ is estimated at 18 W [7]. The energy consumption of a network with DD transceivers is modeled as follows.

$$P_{net}^{trans} = \alpha(K P_{tx}^{trans} + K P_{rx}^{trans} + M P_{amp}^{trans} + N P_{roadm}^{trans})$$

$$P_{net}^{idle} = \alpha(K P_{tx}^{idle} + K P_{rx}^{idle} + M P_{amp}^{idle} + N P_{roadm}^{idle})$$

### 4.3 Power model for electronic grooming module

The electronic grooming module consists of an OE interface, framer, de-framer, and forward error correction (FEC) electronics, lasers, drivers, DSP and ADC as depicted in Fig. 1. The power consumption for the electronic grooming module depends on the number of wavelengths aggregated $k$. Table 2 includes the power consumption of various components of an electronic grooming module. Two sets of parameters for analyzing the operation of the electronic grooming module are considered: current grooming model and improved grooming model. Current grooming model represents the power consumption for commercially available devices. The energy values used for the element of the grooming module in the current grooming model are taken from [6]. In the improved grooming model the values used for power consumption are reduced four times following the trend shown in [19] to model...
future efficiency improvements and technology maturation. Based on the values in Table 2, the power consumed by the electronic grooming module in transmission and idle states can be expressed as the sum of the energy consumption of the elements used in the electronic grooming module and is given as follows. \( K \) in Eq. (5) which represents the total number of transmitters (or incoming signals that need grooming). On the other hand, \( k \) in Eq. (7) represents the multiplexing (aggregation) ability of a grooming module. For example a \( 2 \times 1 \) electronic grooming module is capable of multiplexing two incoming signals and hence \( k = 2 \).

\[
P_{\text{ele, groom}}^{\text{trans}} = 42.6 + 16.2k + 32\left(\frac{R}{28}\right)^{1.6} + 132k\left(\frac{R}{28}\right)^{1.3} \text{ W.} \tag{7}
\]

\[
P_{\text{ele, groom}}^{\text{idle}} = 6.6 + 8.2k \text{ W.} \tag{8}
\]

In Eq. (7) \( R \) represents the symbol rate. The energy consumption by a network with electronic grooming during the transmission state and idle state can be modeled as follows.

\[
P_{\text{net}}^{\text{trans}} = KP_{\text{tx}}^{\text{trans}} + KP_{\text{rx}}^{\text{trans}} + MP_{\text{amp}}^{\text{trans}} + NP_{\text{readm}}^{\text{trans}} + P_{\text{ele, groom}}^{\text{trans}} \tag{9}
\]

\[
P_{\text{net}}^{\text{idle}} = KP_{\text{tx}}^{\text{idle}} + KP_{\text{rx}}^{\text{idle}} + MP_{\text{amp}}^{\text{trans}} + NP_{\text{readm}}^{\text{trans}} + P_{\text{ele, groom}}^{\text{idle}} \tag{10}
\]

Table 2. Power consumption breakdown of a \( k \times 1 \) electronic grooming module and symbol-rate adaptive coherent transceiver supporting symbol rate of \( R \) (GBaud) is given in Watts. The • symbol represents components that remain on during the idle state.

<table>
<thead>
<tr>
<th>Component</th>
<th>Unit</th>
<th>Power Dissipation (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Electronic grooming Module</td>
</tr>
<tr>
<td>Client Side</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Framer</td>
<td>1</td>
<td>( 25 \times \left(\frac{R}{28}\right)^{1.6} )</td>
</tr>
<tr>
<td>FEC</td>
<td>1</td>
<td>( 7 \times \left(\frac{R}{28}\right)^{1.6} )</td>
</tr>
<tr>
<td>Drivers</td>
<td>4</td>
<td>( 4 \times 9 )</td>
</tr>
<tr>
<td>Laser •</td>
<td>1</td>
<td>6.6</td>
</tr>
<tr>
<td>O/E Modulation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Local Oscillator •</td>
<td>( k )</td>
<td>( k \times 6.6 )</td>
</tr>
<tr>
<td>Photodiode + TIA •</td>
<td>( 4k )</td>
<td>( 4 \times k \times 0.4 )</td>
</tr>
<tr>
<td>ADC</td>
<td>( 4k )</td>
<td>( 4 \times k \times 2 )</td>
</tr>
<tr>
<td>DSP</td>
<td>( k )</td>
<td>( k \times 100 \times \left(\frac{R}{28}\right)^{1.6} )</td>
</tr>
<tr>
<td>FEC</td>
<td>( k )</td>
<td>( k \times 7 \times \left(\frac{R}{28}\right)^{1.6} )</td>
</tr>
<tr>
<td>Client Side</td>
<td></td>
<td></td>
</tr>
<tr>
<td>De-framer</td>
<td>( k )</td>
<td>( k \times 25 \times \left(\frac{R}{28}\right)^{1.6} )</td>
</tr>
<tr>
<td>Management •</td>
<td></td>
<td>+ 20% of total power</td>
</tr>
</tbody>
</table>

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The energy consumption of the grooming module depends on its type and the number of signals $k$ it can aggregate. The optical grooming module is composed of elements shown in Fig. 2 and discussed in section 2 of this paper. In this section, the energy consumption of the elements of the optical grooming modules is discussed. In this paper, nonlinear mixing based on PPLN is considered. The electrical power consumed by the PPLN is due to thermal management and assumed to be equal to 25W [17]. Like PPLN, the power consumption of the tunable filter, LCoS filter, and pump laser is data rate independent. Table 3 lists the typical energy values of optical components available today and those for improved grooming. For improved grooming, the dominant energy consumers of the optical grooming module including EDFA, tunable filter, LCoS, PPN and pump laser is reduced by an order of magnitude which would be expected for cases in which active thermal management is removed due to passive techniques and/or integration. Based on these values and considering the optical grooming module architecture of Fig. 2, the total power consumption of the grooming module (note that it is data rate independent) is calculated. This analysis assumes no transition delay while switching the mode from transmission state to idle state and hence the power consumption of the optical grooming module in the idle state is negligible or zero. For a network that employs an optical grooming module, the energy consumption of the network in the transmission state and the idle state can be modeled as follows.

$$P_{\text{net}}^{\text{trans}} = KP_{\text{tx}}^{\text{trans}} + P_{\text{rx}}^{\text{trans}} + MP_{\text{amp}}^{\text{trans}} + NP_{\text{road}}^{\text{trans}} + P_{\text{opt-groom}}^{\text{trans}}$$

$$P_{\text{net}}^{\text{idle}} = KP_{\text{tx}}^{\text{idle}} + P_{\text{rx}}^{\text{idle}} + MP_{\text{amp}}^{\text{idle}} + NP_{\text{road}}^{\text{idle}} + P_{\text{opt-groom}}^{\text{idle}}$$

$P_{\text{opt-groom}}^{\text{trans}}$ represents the power consumption of the optical grooming module and depends on the number of signals that are aggregated (but is independent of the baud rate of those signals). In a network that uses an optical grooming module, the groomed signals travel to the same destination and require a single receiver as compared to un-groomed coherent detection where $K$ receivers are required at the output. This reduction in the number of receivers at the output contributes significantly to the reduction in the energy consumption of the network.

Table 3. Power consumption breakdown of a kx1 optical grooming module that is data-rate independent is given in Watts.

<table>
<thead>
<tr>
<th>Component</th>
<th>2 x 1</th>
<th>3 x 1</th>
<th>4 x 1</th>
<th>4 x 1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Grooming</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EDFA</td>
<td>2 x 25</td>
<td>2 x 2.5</td>
<td>2 x 25</td>
<td>2 x 2.5</td>
</tr>
<tr>
<td>Tunable Filter</td>
<td>1 x 12</td>
<td>1 x 1.2</td>
<td>1 x 12</td>
<td>1 x 1.2</td>
</tr>
<tr>
<td>LCoS Filter</td>
<td>1 x 20</td>
<td>1 x 2</td>
<td>1 x 20</td>
<td>1 x 2</td>
</tr>
<tr>
<td>PPLN</td>
<td>2 x 25</td>
<td>2 x 2.5</td>
<td>2 x 25</td>
<td>2 x 2.5</td>
</tr>
<tr>
<td>Pump laser</td>
<td>2 x 20</td>
<td>2 x 0</td>
<td>2 x 20</td>
<td>2 x 0</td>
</tr>
<tr>
<td>Circulator</td>
<td>2 x 0</td>
<td>2 x 0</td>
<td>2 x 0</td>
<td>2 x 0</td>
</tr>
<tr>
<td>Time Delay</td>
<td>2 x 0.5</td>
<td>2 x 0.5</td>
<td>2 x 0.5</td>
<td>2 x 0.5</td>
</tr>
<tr>
<td>Mgmt. Overhead  (%)</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td><strong>Total Power</strong></td>
<td>219.6</td>
<td>23.04</td>
<td>189.6</td>
<td>20.04</td>
</tr>
</tbody>
</table>
5. Operating modes

Two operating schemes are used to evaluate the energy consumption of the optical grooming module in a network. In the first scheme of operation the network elements retain full power irrespective of the incoming traffic conditions. The energy efficiency of the network can be quantified by the energy per bit parameter denoted by $E^\text{on}_b$. This energy per bit can be estimated by calculating the average power consumed by the network elements for a constant time duration and is modelled as $E^\text{on}_b = \frac{P^\text{trans}}{\lambda \overline{x}}$, where $\lambda$ is the average traffic demand request rate and $x$ is the mean transaction or file size in bits [7]. The process of data arrivals is defined as a Poisson process where $\lambda$ denotes the average rate of requests per second [7] and is assumed to be equal to 0.25/s. In this analysis, the average file size follows a certain statistical distribution $f(x)$ in which the first-order statistics $\overline{x}$ are used [7]. The average file size is assumed to be equal to 10 Gbits.

The second scheme of operation considered, is a power management operation in which the transceiver is put into an idle mode while not transmitting. In this case we consider a model for the traffic statistics and take into account energy lost during transitions between operating states. The power management scheme includes 5-states of operation namely, transmit, wait, tear-down, idle and set-up. The power management scheme operates as follows: after transmission of the last bit of data the system goes into the wait state for a duration of $T^\circ$. $T^\circ$ is a design parameter and impacts the delay analysis of the system [7]. Since the focus in this paper is to evaluate the energy consumption of the optical grooming module we assume $T^\circ$ to be equal to zero. That is, the system goes into the tear-down state directly if there is no data to transmit. Data transmission is halted prior to entering the tear-down state and the transmission energy use of the system is gradually decreased as components are switched off or idle. We assume that the average energy use during this period is assumed to be approximately half the full transmission energy use. As long as there is no data to be transmitted the system stays in the idle state. Upon the arrival of new data the system goes to the set-up state. Similar to the tear down state, the energy use is assumed to average to one half the full operating power and data transmission commences upon exiting the set-up state. The energy efficiency of the system in the power management scheme can be quantified by the energy per bit parameter denoted as $E^\text{wait}_b$. The energy per bit of the system in the power management mode can be modeled as follows:

$$E^\text{wait}_b = \frac{P^\text{idle} + p_s P^\text{setup} + p_d P^\text{trans} + p_{td} P^\text{teardown}}{\lambda \overline{x}}$$

(13)

The energy consumption of the system in the idle, set-up, transmit and tear-down states are denoted by $P^\text{idle}$, $P^\text{setup}$, $P^\text{trans}$ and $P^\text{teardown}$ respectively. Similarly $p_s$, $p_d$, $p_{td}$ represent the fraction of the time the system is in the idle, set-up, transmit and tear down phases. In section 6 the equations used for calculating these parameters are discussed. For our evaluation two cases in the power management scheme are considered, in the first instance, the set-up and tear-down time is equal to zero. In the second instance, the set-up and tear-down time is equal to 1s.
6. Results and discussion

Figure 5 illustrates the energy consumption of the optical grooming module when it is employed in three different network scenarios and is measured after fiber transmission. These scenarios are represented in Fig. 4 where in the first case two, 2 × 1 optical grooming modules are used. In the second case we use two, 3 × 1 grooming modules and in the last case a single 4 × 1 grooming module is considered. Figure 5, has three sub-plots, each sub-plot demonstrates the energy consumption of the optical and electronic grooming module when it operates in the “Always on” scheme and the two cases of the power management scheme (with and without tear down/set-up delays). The numerical calculations are carried out in MATLAB and are based on the equations derived in section 4 and section 8. The energy per bit increases as the symbol-rate increases for both electrical and optical grooming. The optical grooming module on its own is data rate independent but the network model using optical grooming is data rate dependent because of the coherent transmitters and receivers used at either end of the connections in the network. Figure 5, elucidates that optical grooming is not beneficial for transmission of traffic with symbol-rates below 30 GBaud. For symbol-rates below 30 GBaud the optical grooming module reduces the energy efficiency of the network. After careful analysis we observe that the energy consumption of the optical grooming module in the three different network scenarios differs marginally. We also observe that when the grooming module is in the 4 × 1 network configuration it shows a small improvement in the energy per bit consumption compared to the other configurations. This improvement can be attributed to the architecture of 4 × 1 grooming module which uses one pump laser while the other configurations use two pump lasers. Unlike the optical grooming modules a considerable difference in the energy consumption of an electronic grooming module for different numbers of tributary signals is noticed. It is observed that when the electronic grooming module is applied in the 2 × 1 network configuration it shows maximum energy efficiency. The larger increase in the energy consumption can be associated to the cubic symbol-rate dependency of the electronic grooming module. For symbol-rates beyond 30 GBaud optical grooming shows considerable energy savings as compared to electronic grooming. This can be associated to the inherent symbol-rate independence of the optical grooming module. Figures 5(b) and 5(c) demonstrate the impact of the power management schemes. The energy per bit decreases significantly when the power management scheme is implemented.
While the results in Fig. 5 are illustrative of the potential for optical grooming in today’s technology, further development of the optical techniques is required before they will be used in commercial solutions. Therefore, one would like to understand how these techniques compare against other approaches considering improvements expected in the future. Furthermore, photonic integrated optical techniques are far more promising than bulk solutions. Ideally one would like to know the merits of an optimized photonic integrated approach relative to future conventional technologies. In Fig. 6, an estimate of the projected energy consumption of networks employing advancements in both the electronic and optical grooming techniques is provided. In [19] the projection for the energy consumption of optical and electrical devices is calculated using published data. Based on the projections in [19] we have assumed the energy consumption of an improved optical grooming module to be reduced by an order of magnitude. Similarly, for electronic grooming we have considered the energy consumption to be optimized by four times of the energy consumption in existing networks [19]. Figure 6, demonstrates that the energy consumption of the electronic grooming module again becomes comparable to that of the electronic grooming module below 30 Gbaud and therefore higher baud rates are the most promising opportunity for these methods.

Fig. 6. Projections for energy per bit as a function of symbol rate using electronic grooming module and optical grooming module in future transmission networks.

Fig. 7. Projection of power consumption versus symbol rate based on different grooming technologies.
To investigate the benefits of using optical grooming further, we evaluate the energy consumption of a $4 \times 1$ network configuration which employs an optical grooming module and compare it to the energy consumption of existing legacy networks. Our selection of the $4 \times 1$ network configuration for optical grooming is based on the observation that in Fig. 5 this corresponds to the most power-optimized energy configuration, similarly for electronic grooming we select the $2 \times 1$ configuration. Three networks are considered for our comparison: a network with coherent transceivers, a network with 10 Gb/s direct detection transceivers and a network with 40 Gb/s direct detection transceivers. In all three cases there is no grooming involved at the intermediate add-drop nodes. Figure 7, similar to Fig. 5, represents the modes of operation of the network. Figure 7(a), verifies that for symbol-rates above 30 GBaud networks with optical grooming modules again show energy benefits compared to other technologies. From Fig. 7(a), we deduce that the energy savings using optical grooming in a network compared to a network with coherent transceivers end to end in the “Always On” mode, is in the range of 35-60 percent. The energy consumption of a network with coherent transceivers increases exponentially and shows significant increase in energy consumption for symbol-rates above 80 GBaud. Similar to coherent transceivers the energy consumption of electronic grooming follows an exponential trend. With DD transceivers in a network the energy consumption increases linearly, although with the penalty of reduced spectral efficiency. The energy consumption of a coherent transceiver has a cubic dependency on the symbol rate of the incoming signal whereas the energy consumption of the DD transceiver is linearly proportional to symbol rate. As a result, for signals with symbol rate above 70 GBaud, networks with DD transceivers outperform networks with coherent transceivers in terms of signal grooming energy efficiency. Figures 7(b) and 7(c), describe the energy consumption of the network in the power management mode. Figure 7(b), represents the case for which the set-up and tear-down time for the power management mode is set to one second. The energy consumption of the networks with significant state transition times follow the same trend that is depicted in Fig. 7(a), the always on case. Although we observe that the energy consumption reduces five times compared to its energy consumption in the “Always On” mode.

Figure 7(c), illustrates the network operation in the power management mode when the set-up and tear-down time is set to zero. Since the set-up and tear-down time is set to zero the energy consumption of the network during tear-down and set-up states is zero. This causes the energy consumption of the networks to reduce by an order of magnitude when compared to their energy in the “Always On” scheme. In Fig. 7(c), we also observe that apart from the trend line that depicts the energy consumption of a network with 10 Gb/s and 40 Gb/s DD transceiver, the energy consumption of the network follows the same behavior as in the other modes of operation. This discrepancy sheds light on energy consumption of the network with DD transceiver in the idle mode. The energy consumption of the coherent transceiver when it is in the idle mode does not depend on the incoming data rate and is a constant value. Similarly, the power consumption of DD transceiver during idle mode is constant. For our evaluation we consider a DD transceiver which can process signals with data rate up to 10 Gb/s. For analysis of signals with data rate above 10 Gb/s we setup $\alpha$ parallel paths between the source and the destination. While evaluating the energy consumption of the DD transceiver in idle mode the power consumption of the transceiver is multiplied by $\alpha$. Hence unlike networks with coherent transceivers, networks with DD transceivers in the idle mode have energy consumption which depend on the incoming data rate. This effect causes the energy consumption trend-line for the DD network to increase significantly compared to energy consumption of other networks in the same mode of operation.

7. Conclusion

In this paper, the power consumption and efficiency of optical grooming in a network segment is investigated. An energy model for an optical grooming module is derived and
incorporated in three different network in-casting scenarios. In addition, two operating schemes are considered: a scheme in which the network elements maintain full power even when there is no traffic to send and a power management scheme which varies the operating mode depending on the network traffic variation.

Our studies show that 30 Gbaud is a critical threshold above which new optical grooming techniques hold promise for efficiency improvements. This same threshold applies to both current technology using bulk optical components and future technology incorporating photonic integration. However, using optical grooming in future networks at high baud rates has the potential to reduce the energy consumption by an order of magnitude. Future work in this research would involve the study of energy benefits of optical grooming in more complex topologies and implementing network experiments in a lab setting.

8. Appendix

In this section the variables used in Eq. (13) are defined. We denote, $p_t$, $p_s$, $p_i$ and $p=id$ as the fraction of time that the transmission system stays in *wait, tear-down, idle, setup* and *transmit* respectively. Also, $P_{trans}$, $P_{setup}$, $P_{trans}$ and $P_{teardown}$ are the power consumption of the system in the *wait, tear-down, idle, set-up* and *transmit* states respectively.

The equations used for calculating these time variables are given as follows.

$$p_t = \rho$$

$$p_s = (1 - \rho) e^{-\lambda T} \frac{T_s}{\tau}$$

$$p_i = (1 - \rho) e^{-\lambda T} \frac{1}{\lambda}$$

$$p=id = (1 - \rho) e^{-\lambda T} \frac{T_{id}}{\tau}$$

$$p_u = (1 - \rho) e^{-\lambda T} T_e + (1 - e^{-\lambda T}) \frac{1}{\lambda}$$

The equations used for determining the energy consumption in the transmission, wait, set-up, idle and tear-down states are given as follows.

$$P_{trans} = P_{wait} = P_{trans} + P_{act}$$

$$P_{setup} = P_{teardown} = \frac{1}{2} P_{trans} + P_{act}$$

$$P_{idle} = P_{idle} + P_{act}$$

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