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# Green optical orthogonal frequency-division multiplexing networks

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**Abstract:** Orthogonal frequency-division multiplexing (OFDM) has been proposed as an enabling technique for elastic optical networks to support heterogeneous traffic demands by enabling rate and modulation adaptive bandwidth allocation. The authors investigate the energy efficiency of optical OFDM-based networks. A mixed integer linear programming model is developed to minimise the total power consumption of rate and modulation adaptive optical OFDM networks. Considering a symmetric traffic, the results show that optical OFDM-based networks can save up to 31% of the total network power consumption compared to conventional Internet protocol over wavelength division multiplexing (WDM) networks. Considering the power consumption of the optical layer, the optical OFDM-based network saves up to 55% of the optical layer power consumption. The results also show that under an asymmetric traffic scenario, where more traffic is destined to or originates from popular nodes, for example data centres, the power savings achieved by the optical OFDM-based networks are limited as the higher traffic demands to and from data centres reduce the bandwidth wastage associated with conventional WDM networks. Furthermore, the achievable power savings through data compression have been investigated, considering an optical OFDM-based network.

## 1 Introduction

Following the increase in the networks size, the power consumption of network equipment, such as servers, amplifiers, routers, storage devices and communication links, has rapidly increased [1]. Given the ecological and economic impact, significant research efforts are focused on reducing the energy consumption of information and communication technology networks. Energy-efficient and cost-effective solutions are needed to meet the increasing demand for high capacity networking infrastructures. In the last decade, wavelength division multiplexing (WDM) has emerged as the technology of choice to increase the bandwidth of networks. Recent technological advances in optical networks have enabled data rates per wavelength of 40 and 100 Gb/s with extended transmission distance. In our previous work, we studied different energy-efficient approaches for Internet protocol (IP) over WDM [2–4]. The authors in [5] have shown that dynamic optical path switching is capable of reducing energy consumption by four orders of magnitude. However, the rigid nature and coarse granularity of WDM networks result in inefficient capacity utilisation because of the bandwidth mismatch between the application layer with bandwidth requirements varying from several to hundreds of Gb/s, and the wavelength channels with data rates of 10 Gb/s and beyond. Current WDM networks address this mismatch by allowing sub-wavelength granularity connections to be groomed onto a single lightpath which results in extra cost and power consumption [6], or by allocating multiple wavelengths to a connection if the requested bandwidth is higher than that of a single wavelength, however, such an approach suffers from low spectral efficiency as adjacent wavelengths must be separated by guard bands.

A promising solution to address this bandwidth mismatch is to support fine granularity through elastic spectrum allocation [7, 8], where connection requests are allocated the minimum spectral resources required. Recently, orthogonal frequency-division multiplexing (OFDM) has been proposed as an enabling technique for elastic optical networks [9, 10]. OFDM is widely used in different communication systems, such as wireless local area networks (WLAN) [11] and digital video broadcasting (DVB) [12]. OFDM is a multicarrier modulation technique where data is distributed over multiple orthogonal low-rate subcarriers [10]. Optical OFDM helps alleviate many of the drawbacks associated with single carrier systems. Fig. 1 compares the spectrum utilisation of WDM networks and OFDM-based optical networks. Optical OFDM-based networks support a higher spectral efficiency as they can exactly provide the bandwidth needed to cater for the requirement of building a link of a certain traffic rate and consequently, the relevant network components can work at the required rate. In contrast to conventional WDM where frequency guard bands are required between adjacent channels, OFDM improves the spectrum utilisation by

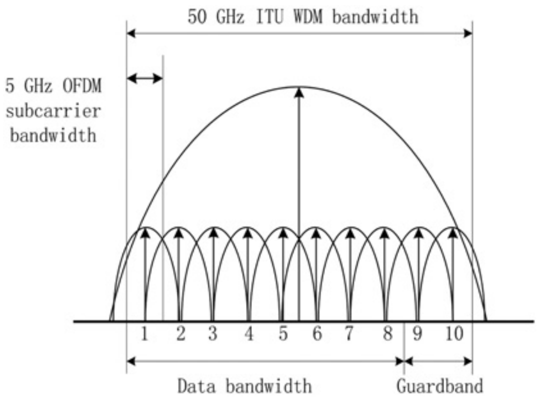


**Fig. 1** *Spectrum utilisation of WDM networks and optical OFDM-based networks*

allowing the spectrum of adjacent subcarriers to overlap as orthogonality ensures the separation of subcarriers at the receiver side [10].

In conventional optical networks, the available capacity is limited to the worst-case optical path design to ensure quality of transmission (QoT). However, optical paths of higher optical signal-to-noise ratios (OSNRs) (usually associated with lower reach) can support significantly higher capacities. Optical OFDM supports distance-adaptive spectrum allocation by adapting the modulation format according to the end-to-end physical conditions of the optical path [13, 14]. This advantage is further discussed in Section 3.

Moreover, OFDM is an effective solution to the inter-symbol interference (ISI) caused by a dispersive channel [10]. The parallel transmission of data results in a longer symbol period compared to single carrier systems with similar total data rates, limiting the ISI effect to a small fraction of a symbol period.

Fig. 2 illustrates the block diagram of a typical optical OFDM system. At the transmitter side, the serial-to-parallel (S/P) module converts the incoming high-bit-rate data stream to low-bit-rate parallel blocks of symbols. The bits are mapped by some type of quadrature amplitude modulation (QAM) or phase-shift keying (PSK) onto complex symbols. These complex symbols are mapped onto orthogonal carriers and the time-domain OFDM symbols are obtained by inverse fast Fourier transformation (IFFT). To mitigate ISI between OFDM symbols, a guard time, known as cyclic prefix (CP), is added to each OFDM symbol by copying the end of the block generated by the IFFT to the beginning of the block. A CP longer than the channel impulse response or multipath delay can eliminate the ISI, maintaining the orthogonality between subcarriers [10]. After the addition of the CP, the discrete parallel symbols go through parallel-to-serial (P/S) conversion and digital-to-analogue conversion (DAC) to generate a continuous time domain signal. In the optical transmitter module (OTM), electrical OFDM signals are modulated over an optical carrier using a directly modulated laser or an externally modulated laser [15]. At the optical receiver module (ORM), the optical OFDM signal detection systems can be classified as direct detection (DD) and coherent detection (CO-D) [9, 10, 15].

To recover data from the orthogonal subcarriers, the serial signal is converted to parallel data blocks, the CP is removed and the OFDM signal is converted back to the frequency domain using forward FFT. At the receiver side, the information symbols are affected by signal phase and amplitude level shifting caused by chromatic dispersion of the optical channel. Therefore, equalisation and forward error correction (FEC) are needed after the forward FFT, and FEC may have to be used [9, 15]. Note that equalisation is simpler in OFDM systems compared to single carrier systems. This is because OFDM symbols result in a flat channel as they are longer than the maximum delay spread and therefore can be easily equalised. After equalisation, each subcarrier is demodulated and data is converted to serial format.

In [16], the authors proposed a novel spectrum-efficient and scalable optical transport network architecture known as the spectrum-sliced elastic optical path network (SLICE). In [17], the authors consider supporting elastic bandwidth allocation as well as the virtualisation of optical access networks and optical backbone mesh networks. In [18, 19], the problem of routing and spectrum allocation (RSA) in an elastic OFDM optical network is investigated. In [20], the RSA problem in an elastic OFDM optical network is extended to select the modulation format of the connections.

In [21], the authors studied the energy efficiency of optical interconnects in data-centres considering the use of adaptive OFDM. The optical layer power consumption of optical OFDM systems in data centre scenarios has also been systematically analysed and compared with other advanced modulation formats in [22]. Moreover, the power consumption of optical OFDM systems for application in 100 Gb/s Ethernet, and for gigabit LED-based plastic optical fibre links has been investigated in [23, 24]. In this work, we investigate the energy efficiency of optical OFDM-based networks. In a recently published paper [25], the authors studied the energy efficiency of backbone networks with optical OFDM. They developed a mathematical model considering flexible bandwidth allocation. In [26], we conducted a more detailed study where we proposed a mixed integer linear programming (MILP) model for energy efficient optical OFDM-based networks that considers, in addition to flexible bandwidth allocation, distance-adaptive spectrum allocation where the modulation format of subcarriers is adapted according to OSNR, which is mostly associated with the transmission distance. In the model developed in [25], traffic flows are allowed to be groomed together. Implementing grooming, however, in the IP layer

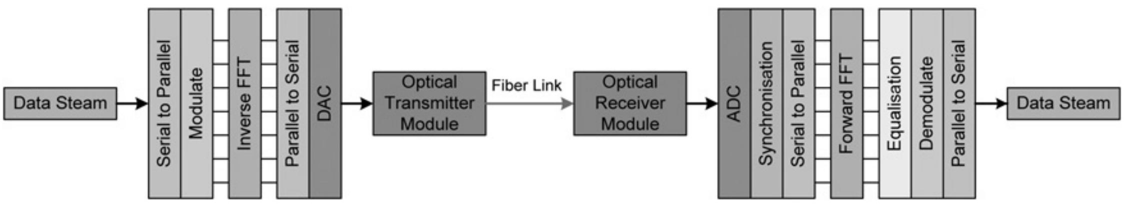


**Fig. 2** *Block diagram of a typical optical OFDM communication system*



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for optical OFDM-based networks is not the best approach as optical OFDM can flexibly allocate the bandwidth needed to cater for the requirements of a traffic demand. In [26], we compared optical OFDM-based networks to conventional IP over WDM networks with different wavelength rates (10/40/100 Gb/s) considering a symmetric traffic profile. We also compared optical OFDM-based networks to mixed line rate (MLR) networks where wavelengths of different rates are deployed over the same fibre. Compared to our initial results in [26], this paper extends the work (i) by analysing different scenarios in terms of IP over WDM approaches (non-bypass and bypass) and traffic symmetry; (ii) by providing guidance to manufacturers on the maximum levels of power consumption for OFDM transponders after which the optical OFDM-based network loses its advantage over conventional WDM networks and (iii) by investigating the power savings gained by employing data compression in an optical OFDM-based network.

The reminder of this paper is organised as follows: Section 2 discusses distance-adaptive spectrum allocation in optical OFDM-based networks. Section 3 analyses the power consumption of the optical OFDM-based network components. In Section 4, we introduce the proposed MILP model considering rate and modulation adaptive OFDM systems. The results are given in Section 5. Finally, the paper is concluded in Section 6.

## 2 Modulation format and QoT of optical OFDM-based networks

As mentioned in Section 1, OFDM supports distance-adaptive spectrum allocation. This advantage stems from the fact that each OFDM subcarrier can be processed individually. Unlike conventional fixed hardware implementations, in OFDM the signal properties can be easily changed by software as digital signal processing is implemented at both the receiver and the transmitter ends. Therefore, the modulation format can be adapted according to the end-to-end physical condition of the optical path [14]. In terms of OSNR, which is mostly associated with distance, we can add an extra bit per symbol for every 3 dB gain in OSNR. Therefore we can make use of the flexibility offered by OFDM to adapt the modulation format of subcarriers to increase the available capacity. The link capacity ($C$) is given as a function of the link length [14]

$$C = \frac{C_0}{2}\left(1 + \log_2 \frac{2l_0}{l}\right), \quad l \le 2l_0$$

where $l_0$ is the maximum distance, $C_0$ is the capacity associated with the worst-case optical path (path with the maximum distance) and $l$ is the link length. Note that the OSNR improves by 3 dB as the transmission distance decreases to half, allowing the modulation format to increase by 1 bit/symbol, for example 8-QAM (3 bits/symbol) can be used instead of QPSK (2 bits/symbol) or 16-QAM (4 bits/symbol) can be used instead of 8-QAM.

## 3 Power consumption of OFDM-based optical network

As discussed above, optical OFDM-based networks provide flexible bandwidth by supporting the allocation of a variable number of subcarriers and adapting the modulation format of subcarriers to increase the available capacity, resulting in significant reduction in the power consumption of the network. In this work, we investigate the power consumption savings introduced by OFDM-based optical networks compared to WDM networks. To enable bandwidth flexible transmissions, the fixed-bandwidth components used in WDM networks need to be replaced with network components that can work at flexible rates. In this section, we study the power consumption of the different network components in an optical OFDM-based network and compare it with the power consumption of similar components in IP over WDM networks. We consider the three most power consuming components: IP routers (ports), transponder and erbium-doped fibre amplifier (EDFA).

As the electronic processing of OFDM signals is implemented in the transponder, the IP over optical OFDM network can use IP router ports similar to those used in IP over WDM networks. We assume an adaptive line rate (ALR) power profile for the IP ports (although not available in routers today, it is targeted by router vendors [27]), where the power consumption depends on the load, to calculate the power consumption of router ports supporting flexible wavelength rates.

The large gain bandwidth of EDFAs makes them useful for WDM networks as a single EFDA can simultaneously amplify many data channels at different wavelengths within its gain region [28]. Similarly EDFAs can be used in OFDM-based optical networks.

In addition to the ability to allocate a variable number of subcarriers and modulate each subcarrier individually, OFDM transponders need to perform IFFT and FFT processes. The power consumption of the OFDM transponder depends on the modulation format used and the number of subcarriers. The highest power consumption of the OFDM transponder occurs when the optical OFDM signal uses the maximum number of subcarriers with the highest modulation format. We assume OFDM transponders have an ALR power profile [29]. In the following section, we develop the optical OFDM network MILP model.

## 4 MILP model for optical OFDM-based networks

In this section we develop a MILP model to minimise the power consumption of the IP over optical OFDM networks. The MILP model is based on the following scenarios:

- Traffic demands utilise a continuous spectrum, that is, a contiguous set of subcarriers (spectrum continuity constraint) [14]. To maintain the spectrum continuity constraint, the traffic between a node pair is not allowed to split.
- The maximum number of subcarriers that the OFDM transponder can process is limited.
- As discussed in Section 3, the maximum modulation format of the traffic demand between different node pairs depends on the OSNR, which is mostly associated with transmission distance. In this model, we assume that optical OFDM-based networks support three modulation formats: binary phase shift keying (BPSK), quadrature phase shift keying (QPSK) and 8QAM. To achieve the maximum spectrum efficiency, OFDM transponders modulate the subcarriers of a traffic demand using the highest modulation format allowed.

- There is no need to do the grooming in the IP layer as the flexibility of OFDM can provide each traffic demand with the data rate needed.

Before introducing the model, the following parameters are defined:

$\lambda^{sdt}$: The traffic demand between node pair $(s, d)$ at time $t$
$E_{mn}$: The number of EDFAs on physical link $(m, n)$. Typically, $E_{mn} = \lfloor L_{mn}/S - 1 \rfloor + 2$, where $S$ is the distance between two neighbouring EDFAs [30]
$C_r$: The capacity of a single subcarrier using modulation level $r$
$Np_i$: The neighbouring nodes set of node $i$
PR: Power consumption of an IP router port per 1 Gb/s
PE: Power consumption of an EDFA
$B$: The maximum number of wavelengths on an optical fibre
NSC: The maximum number of subcarriers supported by an OFDM-transponder
$\mathrm{PT}_{\max}$: The maximum power consumption of transponders working at the maximum line rate $\mathrm{LR}_{\max}$
$R$: The set of modulation levels for the subcarrier

The following variables are also defined:

$\mathrm{ns}_r^{sdt}$: The number of OFDM subcarriers using modulation level $r$ to serve the traffic demand $(s, d)$ at time $t$
$\mathrm{NS}_{mnr}^{sdt}$: The number of OFDM transponders using modulation level $r$ to serve demand $(s, d)$ that traverses physical link $(m, n)$ at time $t$
$\omega_{mnt}^{sd}$: $\omega_{mnt}^{sd} = 1$ if the OFDM subcarriers of traffic demand $(s, d)$ traverse physical link $(m, n)$ at time $t$, otherwise $\omega_{mnt}^{sd} = 0$.
$\mathrm{NF}^{mnt}$: The number of fibres on physical link $(m, n)$ at time $t$

The total network power consumption is composed of:

1. The power consumption of router ports

$$\sum_{s\in N}\sum_{d\in N:s\neq d}\lambda^{sdt}\cdot \mathrm{PR}$$

2. The power consumption of EDFAs

$$\sum_{m\in N}\sum_{n\in Np_m}\mathrm{NF}^{mnt}\cdot \mathrm{EA}_{mn}\cdot \mathrm{PE}$$

3. The power consumption of OFDM transponders (see equation at the bottom of the page)

$$\sum_{s\in N}\sum_{d\in N:s\neq d}\left(\sum_{m\in N}\sum_{n\in Np_m}\omega_{mnt}^{sd}\cdot\left(\mathrm{ALR}\left(\frac{\sum_{r\in R}\mathrm{NS}_{mnr}^{sdt}\cdot C_r}{\mathrm{LR}_{\max}}\right)\cdot \mathrm{PT}_{\max}\right)\right)$$

where ALR() is the ALR energy profile function.

For example, a traffic demand of 100 Gb/s with BPSK modulation will require two OFDM transponders working at the maximum line rate (40 Gb/s) and one transponder working at 20 Gb/s. As discussed in Section 3, the maximum line rate the OFDM transponder can support depends on the distance between the source and destination node pair.

The model is defined as follows:

Objective: Minimise

$$\sum_{t\in T}\left(\sum_{s\in N}\sum_{d\in N:s\neq d}\lambda^{sdt}\cdot \mathrm{PR}+\left(\sum_{s\in N}\sum_{d\in N:s\neq d}\sum_{m\in N}\sum_{n\in Np_m}\omega_{mnt}^{sd}\cdot\left(\mathrm{ALR}\left(\frac{\sum_{r\in R}\mathrm{NS}_{mnr}^{sdt}\cdot C_r}{LR_{\max}}\right)\cdot \mathrm{PT}_{\max}\right)\right)+\sum_{m\in N}\sum_{n\in Np_m}\mathrm{NF}^{mnt}\cdot \mathrm{EA}_{mn}\cdot \mathrm{PE}\right) \quad (2)$$

subject to

1. Flow conservation constraint in the optical layer

$$\sum_{n\in Np_m}\omega_{mnt}^{sd}-\sum_{n\in Np_m}\omega_{nmt}^{sd}=\begin{cases}1, & m=s\\ -1, & m=d\\ 0, & \text{otherwise}\end{cases} \quad (3)$$
$$\forall s,\ d,\ m\in N: s\neq d,\quad t\in T$$

Constraint (3) gives the flow conversion in optical layer and ensures that traffic demands are not allowed to split.

2. Capacity constraints

$$\lambda^{sdt}\le\sum_{r\in R}\mathrm{ns}_r^{sdt}\cdot C_r$$
$$\forall s,\ d\in N: s\neq d,\quad t\in T\quad (\text{Power}-\text{minimised})$$
$$\lambda^{sdt}\le\sum_{r\in R_{\max}}\mathrm{ns}_r^{sdt}\cdot C_r$$
$$\forall s,\ d\in N: s\neq d,\quad t\in T\quad (\text{Spectrum}-\text{minimised}) \quad (4)$$

Constraint (4) ensures that the capacity of the subcarriers allocated to a traffic demand is large enough to support the traffic demand. In this constraint, we differentiate between two optimisation problems: power-minimised and spectrum-minimised optical OFDM-based networks. In power-minimised optical OFDM-based networks, the MILP model selects the modulation format that minimises the power consumption of the network. However, this leads the model to choose the lowest possible modulation format to fit the traffic demand with the best granularity. In spectrum-minimised optical OFDM-based networks, the highest modulation format possible will always be used, and then the total bandwidth of the subcarriers is minimised.

3. Number of transponders constraint

$$\sum_{n\in Np_m}\mathrm{NS}_{mnr}^{sdt}-\sum_{n\in Np_m}\mathrm{NS}_{nmr}^{sdt}=\begin{cases}ns_r^{sdt}, & m=s\\ -ns_r^{sdt}, & m=d\\ 0, & \text{otherwise}\end{cases} \quad (5)$$
$$\forall s,\ d,\ m\in N: s\neq d,\quad r\in R,\quad t\in T$$

Constraint (5) ensures that for each traffic demand, the



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number of OFDM subcarriers using modulation level $r$ entering node $m$ is equal to the number of subcarriers using modulation level $r$ leaving node $m$. This is to conserve the number of OFDM subcarriers using modulation level $r$.

4. Physical link capacity constraints

$$\mathrm{NS}_{nmr}^{sdt} \geq 0 \quad \forall s,\ d,\ m \in N,\ n \in Np_m{:}s \neq d,\quad r \in R,\ t \in T \tag{6}$$

$$\mathrm{NS}_{nmr}^{sdt} \leq \omega_{nmt}^{sd} \cdot N\mathrm{MAX} \quad \forall s,\ d,\ m \in N,\ n \in Np_m{:}s \neq d,\quad r \in R,\ t \in T \tag{7}$$

$$\mathrm{NF}^{mnt} \cdot B \geq \sum_{s \in N} \sum_{d \in N:s \neq d} \left( \sum_{r \in R} \mathrm{NS}_{nmr}^{sdt} / \mathrm{NSC} \right) \quad \forall t \in T, m \in N, n \in Np_m \tag{8}$$

Constraints (6) and (7) guarantee that the value of the variable $\mathrm{NS}_{nmr}^{sdt}$ is related to the value of the binary variable, where $N$MAX is a large enough number. Constraint (8) ensures that the number of OFDM wavelengths allocated to a traffic demand does not exceed the number of wavelengths in an optical fibre.

## 5 Results and analysis

We considered the NSFNET network, depicted in Fig. 3*a*, to evaluate the power consumption of the optical OFDM-based network. The NSFNET network consists of 14 nodes and 21 bidirectional links. As NSFNET covers the US, different parts of the network fall in different time zones, that is, nodes experience different traffic demands at any given point in time: Eastern Standard Time (EST), Central Standard Time (CST), Mountain Standard Time (MST) and Pacific Standard Time (PST). There is an hour time difference between each time zone and the next; we use EST as the reference time. Note that time zones dictate habits and therefore network utilisation and traffic demands in our case.

Fig. 3*b* shows the average traffic demands in different time zones [31]. The average traffic demand between each node pair ranges from 20 to 120 Gb/s (the average is 80 Gb/s) and the peak occurs at 22:00. We assume that the traffic demand between each node pair in the same time zone is random with a uniform distribution and no lower than 10 Gb/s. In the following results, the network power consumption is given against the hourly variations of network traffic.

We compare the power consumption of optical OFDM-based networks to conventional WDM networks.

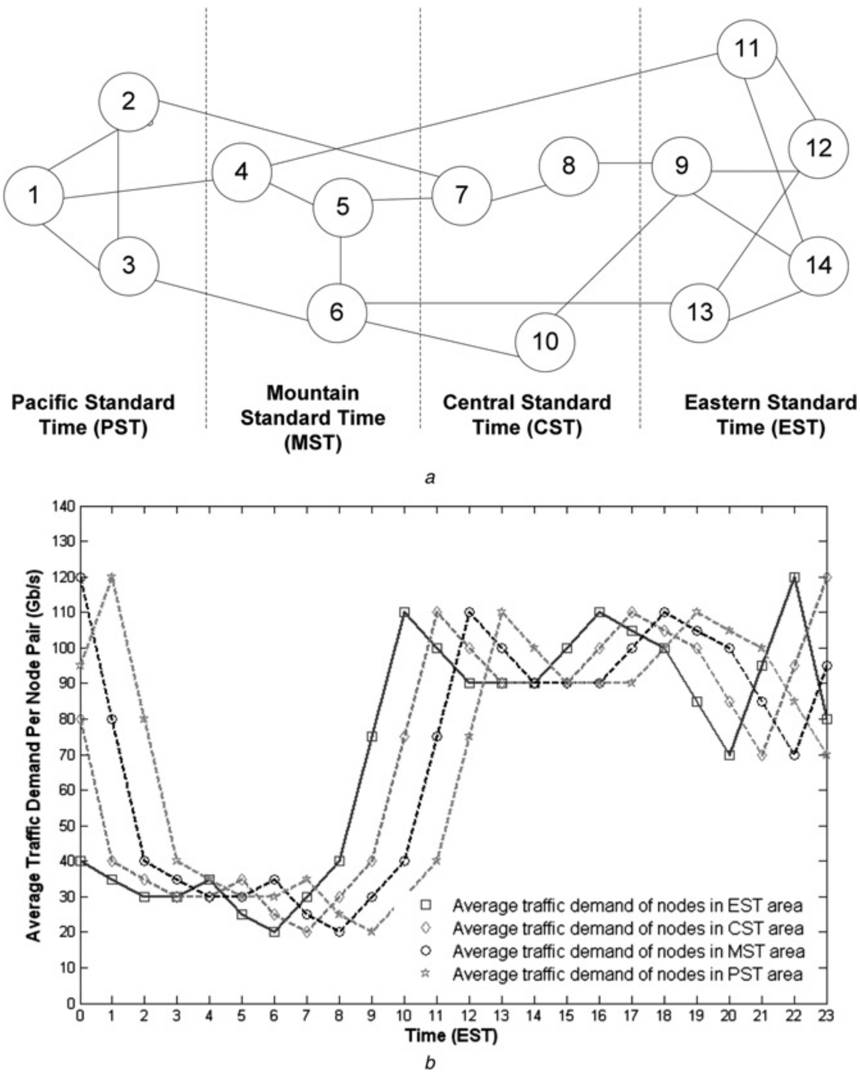


**Fig. 3** *The NSFNET network*

*a* The NSFNET network with time zones
*b* The NSFNET average traffic demand in different time zones


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**Table 1** Input data for the simulation

| | |
|---|---|
| distance between two neighbouring EDFAs | 80 km |
| capacity of each wavelength | 40 Gb/s |
| power consumption of a WDM router port | 25 W/Gb/s |
| power consumption of a WDM transponder (10 Gb/s) | 45 W |
| power consumption of a WDM transponder (40 Gb/s) | 73 W |
| power consumption of a WDM transponder (100 Gb/s) | 135 W |
| power consumption of an EDFA | 8 W |

We consider both systems with a channel bandwidth of 50 GHz (as in Fig. 1).

For the WDM network, we consider three different wavelength capacities: 10, 40 and 100 Gb/s and assume BPSK (1 bit/symbol) as the modulation format associated with the maximum transmission distance/in the NSFNET network (2000 km) between node 1 and node 14. As discussed in Section 2, in conventional optical networks, the available capacity is limited by the worst-case optical path. Therefore BPSK is the modulation format used for IP over WDM networks.

For the optical OFDM-based network, we consider a maximum number of subcarriers for each OFDM channel of 128, each of 0.39 GHz with a CP of 20%. With 8QAM, the highest modulation level for optical OFDM, the maximum line rate for an OFDM transponder $LR_{max}$ is: $0.312(\text{GHz}) \times 3(\text{Bit/Hz}) \times 128 = 120$ Gb/s.

As mentioned above, BPSK (1 bit/symbol) is used to modulate subcarriers over the largest transmission distance in NSFNET (2000 km). As discussed in Section 2, the modulation format increases by 1 bit/symbol as the transmission distance decreases to half. So, for the optical OFDM-based network at 1000 km, QPSK (2 bits/symbol) can be used and at 500 km 8QAM (3 bits/symbol) can be used. A number of papers in the literature have experimentally demonstrated optical OFDM systems over long distances. In [32], the authors have successfully demonstrated 100 Gb/s optical OFDM transmission using DQPSK modulation over 1300 km of ITU-T G.652 single-mode fibres including 10 ROADM nodes. Using an orthogonal-band-multiplexed OFDM scheme, the authors in [33] successfully transmitted 107 Gb/s using QPSK-PDM modulation over 1000-km standard single-mode fibre (SSMF) without optical dispersion compensation or Raman amplification. In [34], a data rate of 121.9 Gb/s was achieved using 8QAM modulation over 1000 km standard SSMFs without any inline dispersion compensation.

We compare optical OFDM-based networks to conventional WDM networks considering both the lightpath non-bypass and bypass approaches. With the lightpath non-bypass, all the lightpaths passing through an intermediate node must be terminated, processed and forwarded by IP routers. On the other hand, the lightpath bypass approach allows all the lightpaths, whose destination is not the intermediate node, to be directly bypassed via a cut-through. Lightpath bypass can significantly reduce the total number of IP router ports required. IP routers are the major power-consuming components in an IP over WDM network. Therefore, minimising the number of IP router ports reduces the power consumption of IP over WDM networks.

Table 1 shows the network parameters in terms of number of wavelengths, wavelength rate, distance between two neighbouring EDFAs and power consumption of different components in the WDM network. Given that the power consumption of a 40 Gb/s port in the Cisco's 8-slot CRS-1 router [35] is 1 kW and considering a linear power consumption profile [30] based on dynamic voltage and frequency scaling [36], the router port power consumption per Gb/s is calculated as 25 W/Gb/s. This value is used to calculate the power consumption of the 10 and 40 Gb/s WDM router ports and the OFDM router ports working at flexible rates.

The power consumption of 10 and 40 Gb/s WDM transponders are derived from Cisco ONS 15454 10 Gb/s multirate transponder card [37] and Cisco ONS 15454 40 Gb/s multirate transponder card [38], respectively. The power consumption of 100 Gb/s WDM transponder is calculated based on the ratio between the power consumption of the 40 Gb/s WDM transponder and the 100 Gb/s WDM transponder given in [39]. The power consumption of the EDFAs is derived from Cisco ONS 15501 EDFA [40].

We calculate the power consumption of an OFDM transponder working at the maximum rate of 120 Gb/s based on the structure shown in Fig. 4. A digital signal processor (DSP) module performs serial to parallel (S/P) conversion and modulation at the transmitter side and another DSP module performs equalisation, demodulation and parallel to serial (P/S) conversion at the receiver side. As shown in Fig. 4, the power consumption of the DSP

**Table 2** Power consumption of OFDM transponder

| Reach | Modulation format | Data rate, Gb/s | Power consumption | | | |
|---|---|---|---|---|---|---|
| | | | DSP, W | IFFT/FFT, mW | DAC/ADC, W | Total, W |
| 500 km [45] | 8QAM | 120 | 160 | 2448 | 42 | 204.4 |
| 1000 km [45] | QPSK | 80 | 106 | 1632 | 28 | 136.3 |
| 2000 km [45] | BPSK | 40 | 53 | 816 | 14 | 68.1 |

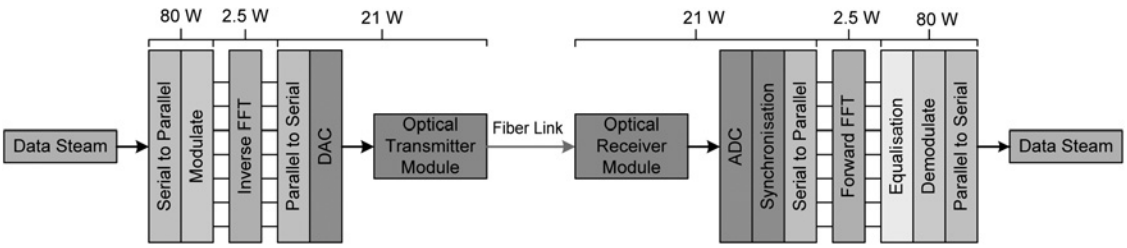


**Fig. 4** *Power consumption of different parts of an OFDM transponder*

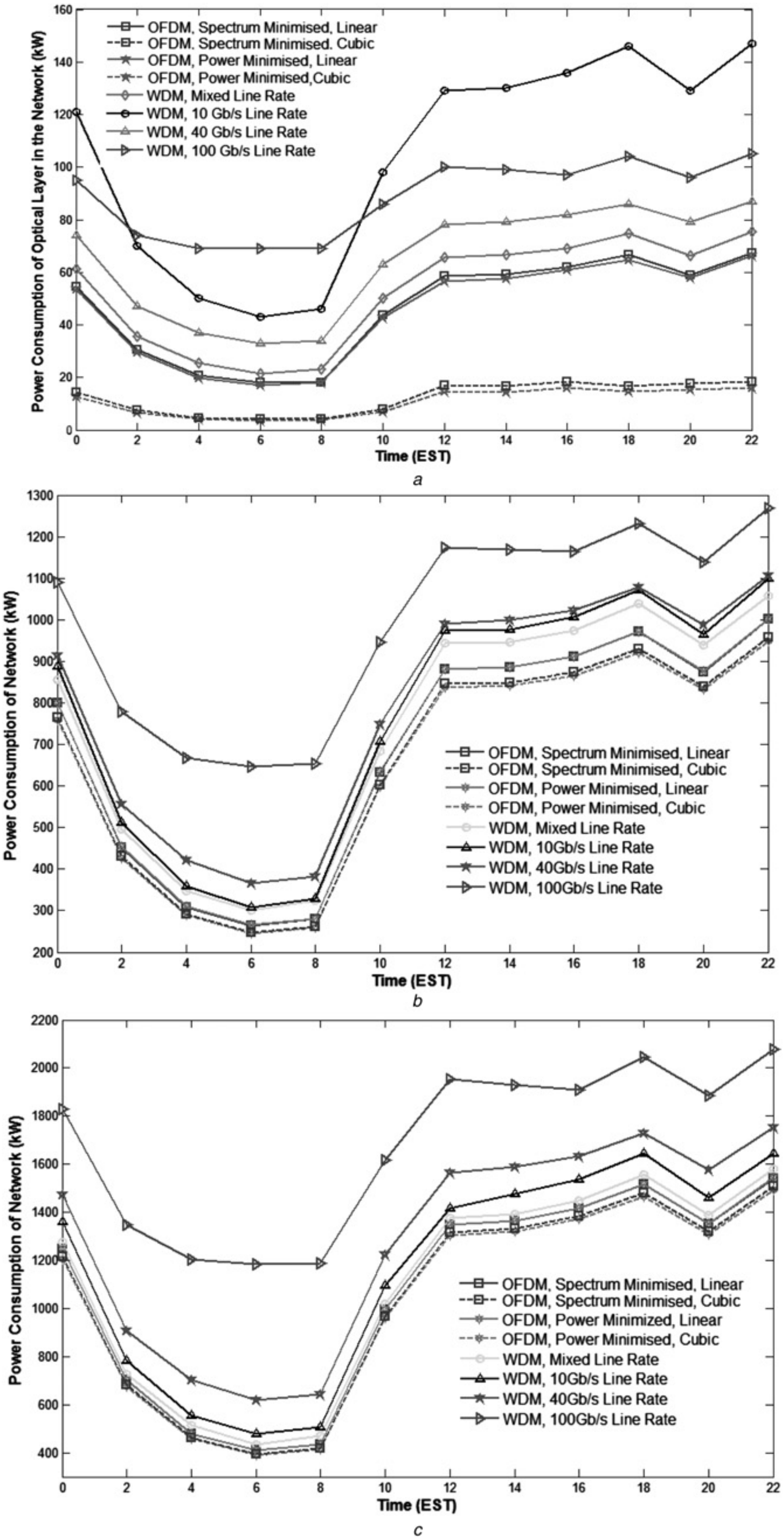


**Fig. 5** *The power consumption under a symmetric traffic profile*

*a* The optical layer power consumption considering optical OFDM and conventional WDM under a symmetric traffic demand and the bypass approach
*b* The total network power consumption considering optical OFDM and conventional WDM under a symmetric traffic demand and the bypass approach
*c* The total network power consumption considering optical OFDM and conventional WDM under a symmetric traffic demand and the non-bypass approach


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module is estimated as 80 W [41]. In addition, state-of-the-art parallel optical interconnects were shown to operate with less than 5 mW/Gb/s total power consumption [42]. The power consumption of the IFFT and FFT modules is estimated as 0.4 mW/Gb/s [43]. The power consumption of the P/S, DAC and the OTM is estimated as 21 W [44]. Also, the power consumption of the ORM and the analogue-to-digital (ADC) and S/P is estimated as 21 W.

We estimate the power consumption of OFDM transponders working at lower rates by assuming ALR power consumption profiles: linear and cubic [29]. The linear profile represents a conservative upper bound of the OFDM transponder power consumption. This is because the power consumption of IFFT/FFT and the DAC/ADC modules does not increase as the data rate increases. As the modulation format increases such as from BPSK to 8QAM, a lower number of subcarriers can be used and therefore the power consumption of IFFT/FFT decreases. Also, as higher modulation formats are used, the spectral efficiency improves and the DAC/ADC sampling speed can be reduced, which leads to reducing the DAC/ADC power consumption. Table 2 gives the details of the OFDM transponder power consumption considering different modulation formats under the linear power profile.

### 5.1 Symmetric traffic profile

To consider the power savings achieved by optical OFDM-based networks, Fig. 5*a* shows the power consumption of the optical layer under the bypass approach considering the symmetric traffic profile in Fig. 3*b*. The optical OFDM-based network with linear power profile saves 55, 29 and 48% of the optical layer power consumption compared to WDM networks deploying wavelength capacities of 10, 40 and 100 Gb/s, respectively. Under the cubic power profile, the savings increased to 89, 83 and 88%, respectively. In the optical layer, the maximum saving is achieved compared to the WDM network with the 10 Gb/s wavelength rate as the power consumption of transponders does not increase linearly with the wavelength rate (see Table 1). Therefore deploying 10 Gb/s wavelengths to support a traffic demand with an average of 80 Gb/s is less energy-efficient than deploying wavelengths of 40 and 100 Gb/s.

As a result of the higher efficiency of MLR networks compared to WDM networks deploying a single wavelength rate, the optical OFDM-based network saves 15 and 79% of the optical layer power consumption under the linear and cubic power profiles, respectively, compared to MLR networks.

Fig. 5*a* also shows that the difference in power consumption between the power-minimised and spectrum-minimised OFDM schemes is limited to 2%.

Fig. 5*b* shows the total network power consumption under the bypass approach. Considering the linear power profile, the power-minimised optical OFDM-based network saves 10, 14 and 31% of the total network power consumption compared to WDM networks deploying wavelength capacities of 10, 40 and 100 Gb/s, respectively. Similar power savings are achieved by the OFDM spectrum-minimised scheme with linear power profile. The maximum saving is achieved compared to the IP over WDM network with the 100 Gb/s wavelength rate as the lower wavelength granularity results in lower utilisation of the IP router ports and transponders and, consequently, lower power consumption as the power consumption of IP router ports (the most energy-consuming devices in the network) increases linearly as the capacity increases. This is not the case, however, for transponder as discussed above. Under the cubic power profile, the savings increased to 15, 18 and 34% compared to WDM networks deploying wavelength capacities of 10, 40 and 100 Gb/s, respectively.

The power savings achieved by the optical OFDM-based network compared to MLR networks is limited to 7 and 12% under the linear and cubic power profiles, respectively.

Similar power savings are obtained under the non-bypass approach as seen in Fig. 5*c*. The total network power consumption is higher under the non-bypass approach as IP routers (the most energy consuming devices in the network) are required at intermediate nodes.

### 5.2 Asymmetric traffic profile

The presence of data centres in the network creates a hot node scenario, where more traffic is destined to or originates from

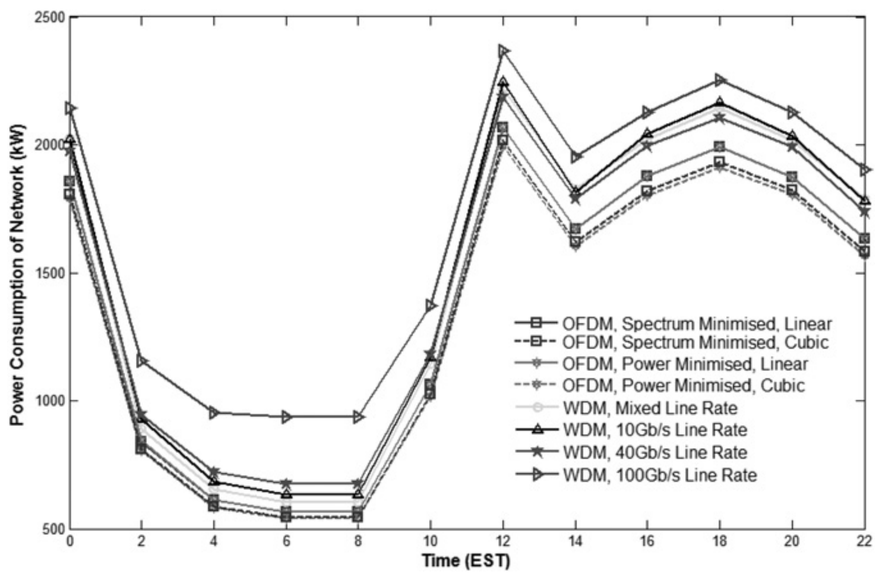


**Fig. 6** *Total network power consumption considering optical OFDM and conventional WDM networks under an asymmetric traffic demand and the bypass approach*



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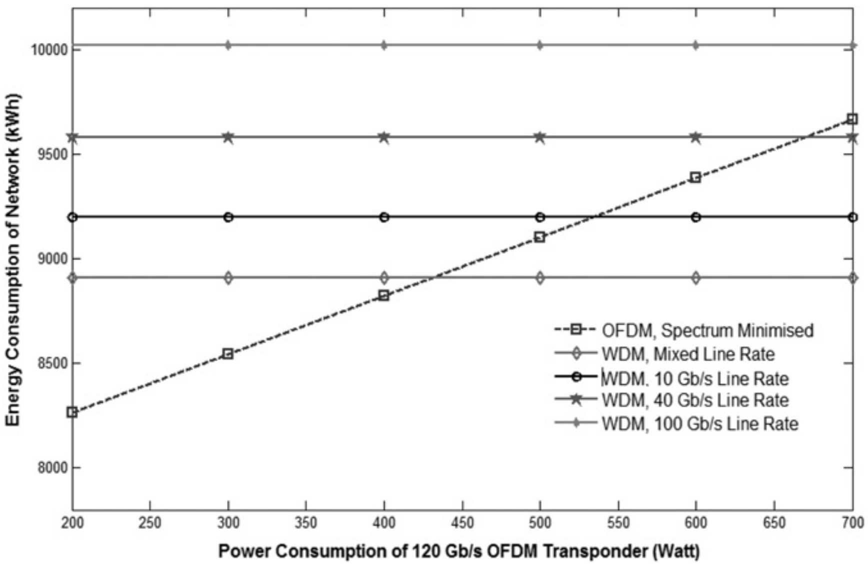


**Fig. 7** *Total network energy consumption against a range of OFDM transponder power consumptions*

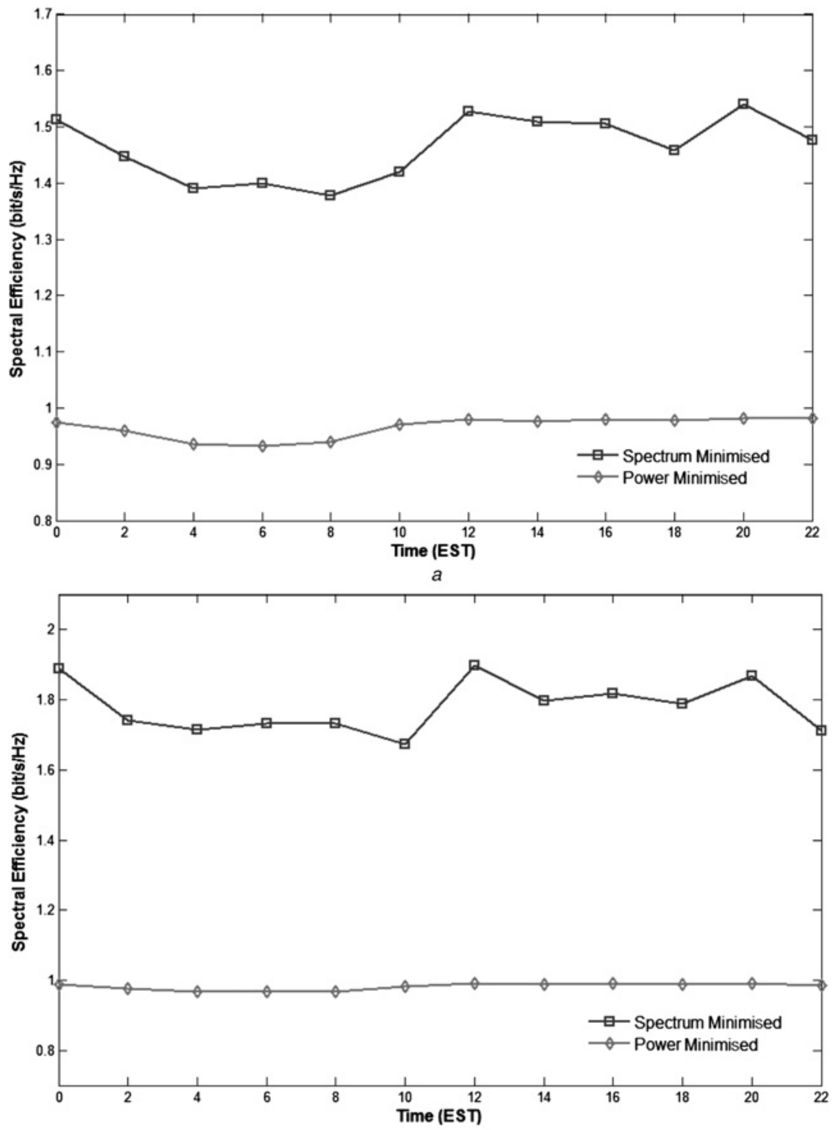


**Fig. 8** *Spectral efficiency of optical OFDM-based networks*

*a* Under symmetric traffic demand

*b* Under asymmetric traffic demand

data centres. In Fig. 6, we investigate the impact of the presence of such data centres on the power saving achieved by optical OFDM-based networks. We consider the following scenario:

1. Each node writes and retrieves data from all data centres equally and different data centres have different content.
2. The traffic demand between data centres and nodes at time $t$ is assumed to be a certain ratio of the regular traffic demand $\lambda^{sdt}$.
3. The uplink traffic demand (from nodes to data centres) ratio, $Ru$, is smaller than the downlink traffic demand (from data centres to nodes) ratio, $Rd$. The traffic demand between nodes and data centres is generated based on the regular traffic demand in Fig. 3a where we assume that $Ru = 0.3$ and $Rd = 2.5$. These values reflect the expected growth in data centre traffic [46].

In Fig. 6, the optical OFDM-based network with the linear energy profile has saved 8, 8, 18 and 7% of the power

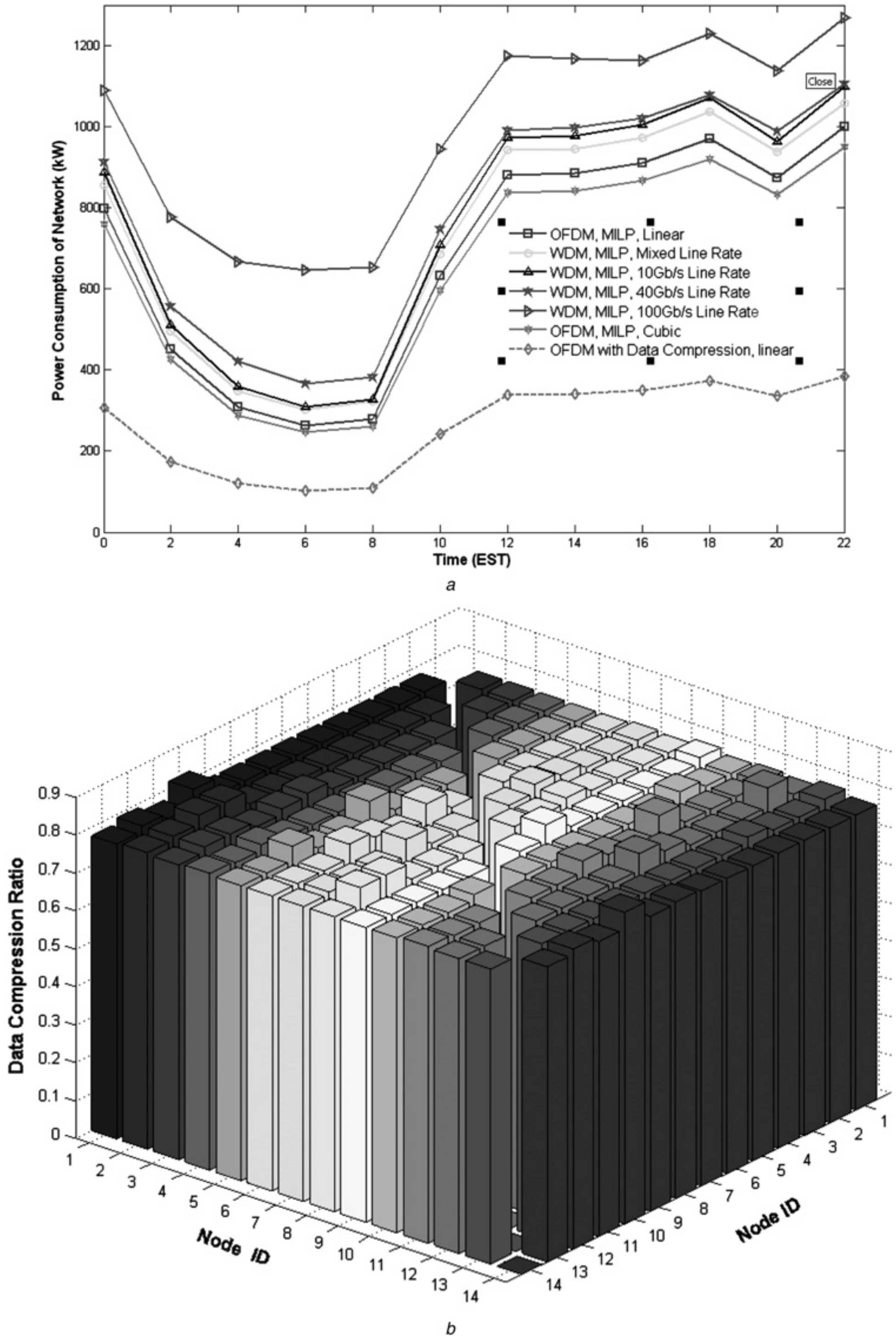


**Fig. 9** *Energy-efficient data compression for optical OFDM-based networks*

*a* The network power consumption with and without compression under the bypass approach for optical OFDM-based networks and conventional WDM networks
*b* The optimal data compression ratio of each node pair traffic demand under the bypass approach at 10 pm (maximum traffic)



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consumption compared to WDM networks deploying wavelength capacities of 10, 40, 100 and MLR, respectively, under the bypass approach. The higher traffic demands between data centres and other nodes reduce the bandwidth wastage associated with the rigid bandwidth allocation of conventional WDM networks, and therefore the benefit the network gets from implementing flexible bandwidth allocation is reduced. The savings considering a cubic energy profile for the OFDM transponders increased to 12, 11 21 and 11% compared to WDM networks deploying wavelength capacities of 10, 40, 100 Gb/s and MLR, respectively.

The total power savings achieved by optical OFDM depends on the assumptions made to calculate the power consumption of the OFDM transponders. As discussed above, we estimated the power consumption of a 120 Gb/s OFDM transponder based on of the power consumption of different modules. Fig. 7 shows the total network energy consumption against a range of power consumption values for the 120 Gb/s OFDM transponder. Fig. 7 can guide manufactures to the acceptable levels of power consumption for OFDM transponders after which the optical OFDM-based network loses its advantage over conventional WDM networks. Assuming a linear profile to estimate the power consumption of elastic bandwidth OFDM transponders, the power consumption of the 120 Gb/s OFDM transponder should not exceed 425 W.

In Fig. 8, we investigate the spectral efficiency of optical OFDM-based networks. Under symmetric traffic (Fig. 8*a*), the spectrum-minimised optical OFDM is 51% more efficient in utilising the spectrum compared to the power-minimised optical OFDM while similar power consumption savings are achieved by the two schemes. Under asymmetric traffic (Fig. 8*b*), the difference in spectral efficiency between the two approaches increased to 81%.

### *5.3 Energy-efficient data compression for optical OFDM-based networks*

In [47], we investigated the energy efficiency of data compression for conventional WDM networks. Data compression is becoming a desirable technique to save bandwidth which can consequently result in network energy savings as compressing traffic demands will result in reducing the traffic volume to be handled and the power used by network devices. The processing associated with compression and decompression, however, uses additional power as the compression ratio increases. Energy-efficient data compression should achieve a trade-off between the power consumption of computational resources and memory required to compress and decompress data and the network energy savings as a result of compression. We built a MILP model in [47] to optimise the data compression ratio for the traffic demands in IP over WDM networks to minimise the network power consumption. The decision on whether to compress a traffic demand or not and the compression ratio used depends on the available capacity on existing virtual links. The model results show that data compression under the bypass approach achieved an average power saving of 39% with an average optimal compression ratio of 71%.

In this section, we investigate the power savings gained by data compression considering an optical OFDM-based network. In WDM networks, traffic demands are compressed to fit the available capacity on existing virtual links to allow better grooming. The flexibility of OFDM in allocating bandwidth is expected to benefit from further compression as all traffic demands will be compressed to fit within the minimum number of subcarriers given that the network savings gained from compression exceed the power consumption of compression and decompression.

Fig. 9*a* shows that data compression in optical OFDM-based networks under the bypass approach can achieve an average power savings of 62 and 69% compared to an optical OFDM-based network and a 40 Gb/s conventional WDM network without compression.

Fig. 9*b* shows the optimal data compression ratio of each node pair traffic demand obtained from the MILP at 10 pm (maximum traffic) under the non-bypass approach. The optimal data compression ratio for most of the node pairs varies between 0.75 and 0.84. The average compression ratio is 0.8.

## 6 Conclusions

In this paper, we have studied the energy efficiency of optical OFDM-based networks. We have developed a MILP model to minimise the total power consumption of optical OFDM-based networks. In addition to the flexible spectrum allocation, we have also considered distance-adaptive spectrum allocation. Considering a linear profile to estimate the OFDM transponder power consumption, the results show that optical OFDM-based networks under a symmetric traffic demand with linear power profile save 10, 14 and 31% of the network power consumption compared to conventional IP over WDM networks with 10, 40 and 100 Gb/s wavelength rates, respectively. With cubic power profile, the savings are 15, 18 and 34%, respectively. Similar power savings are achieved by both the spectrum-minimised and power-minimised optical OFDM-based network. Considering the power consumption of the optical layer, optical OFDM-based networks save up to 89% of the optical layer power consumption. Under an asymmetric traffic demand, the advantage of OFDM is limited as the higher traffic demands to and from data centres reduce the bandwidth wastage associated with conventional WDM networks. Investigating the spectrum efficiency of the optical OFDM schemes, the results show that the spectrum-minimised optical OFDM-based network is 51 and 81% more efficient than the power-minimised network under symmetric traffic and asymmetric traffic, respectively. The results also show that to maintain the power efficiency of optical OFDM-based networks compared to conventional WDM networks, the power consumption of the 120 Gb/s OFDM transponder should not exceed 425 W. Furthermore, we have investigated the power savings gained by implementing data compression over an optical OFDM-based network. The results show that data compression can introduce 62% power savings to OFDM-based optical networks which is significantly higher than the savings gained by data compression over conventional WDM networks.

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