Synchronous Optical Hierarchy

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Abstract

We introduce and describe the problems and challenges for the SOH (synchronous optical hierarchy), which is a form of WRON (wavelength routed optical network) where the signals occupy fractions of a wavelength through the use of timeslots in frames. Using timeslots for transparent optical networks will solve the capacity granularity problem which is present in the WRON.

We define the problem of assigning wavelengths and timeslots to traffic demands by mathematical formulations in integer linear programming. By solving the integer linear programs for networks with static traffic assumptions we compare efficiency of SOH networks with WRONs measured in wavelength usage. Further, the influence of the timeslot and frame parameters describing SOH networks is studied. The effect of timeslot and wavelength conversion in SOH networks are also studied, as well as the presence of delay of timeslots.

1 Introduction

As switching cost has become increasingly expensive [19], several ideas have been put forward to reduce the switching cost and OEO (optical-electric-optical) conversion delay by applying optical switching to transit traffic [20]. These suggestions include static or dynamic WRONs (wavelength routed optical networks) [1, 4, 7, 15, 16, 17, 18] and optical packet switching networks [8, 13, 16, 10]. This paper introduces and studies a practical and efficient alternative to these structures, called the SOH (synchronous optical hierarchy).

The WRON, a circuit switched all-optical network, has long been seen as the solution to drive down cost because electrical processing in large is avoided. The problem with the WRON is that the capacity granularity for connections is in wavelengths, presently up to 40 Gbit/s. Traffic demands smaller than this will still occupy a whole wavelength, only making use of a fraction of the available capacity: This is the capacity granularity problem.

Optical packet switched networks could in principle solve the capacity granularity problem, because only the number of packets necessary to accommodate the traffic demands are sent through the network, but unfortunately packet switched optical networks will have to overcome major technological hurdles before they can be deployed. The problems are, among others, a lack of optical buffering and problems of optical label reading and processing [8, 11]. Until these problems are solved, the SOH network can be seen as a practical solution for telecom operators.

The idea of the SOH network was proposed by Huang et.al. [9] as time shared wavelength channels. Connections in the SOH are circuit switched like in the WRON. However, since the wavelengths here consist of frames, which are divided into timeslots, the granularity of a connection is only a fraction of the capacity of a wavelength, whereby the capacity granularity problem is reduced. Consequently, the technological hurdles which arise in optical packet switched networks are avoided, while the speed and much of the flexibility of optical packet switched networks is preserved.

In the SOH network wavelengths are divided into frames which are composed of timeslots, followed by gaps for synchronisation purposes. One timeslot per frame is the minimum capacity unit for traffic demands. Bianco et.al. [2] and Kannan et.al. [14] have also considered timeslots, but in configurations where the wavelengths or timeslots were predetermined between specific groups of users, reducing the load flexibility for the individual end-to-end demand. The number of connections in the SOH network are only limited by the link capacities, and a connection can drop in and out of different wavelengths via timeslot add/drops and timeslot cross connects.

The timeslots in the SOH are synchronized, i.e. all switches send a specific number of frames per second, with well-defined positions of timeslots and gaps in the frame. This characteristic and the fact that the network is circuit switched avoids the need for buffering. Further, as a connection is uniquely determined by a timeslot on a wavelength, no label reading is necessary. Thus, the buffering, label reading and processing which are the major hurdles of packet switched optical networks are entirely avoided in the SOH.

A hierarchy is naturally implemented in the SOH, thereby eliminating any granularity problems and saving cost in networks with different traffic levels. There are more ways to introduce the hierarchy: Either a minimum timeslot length is defined, and multiples of this timeslot length would then be available; or a minimum bit rate is defined, and multiples of this bit rate is then available. In this article the hierarchy further discussed.

In this article we study the advantages of using SOH compared to WRON, measured in wavelength usage in the single fiber case, that is, the number of wavelengths needed in the maximum loaded network link to accommodate the offered amount of static traffic. Huang et.al. [9] also considered static traffic, but for the capacitated problem, measuring the percentage of allocated traffic, and only for a fixed number of timeslots per frame, either allocating or rejecting the entire amount of offered traffic between two nodes.

We define uncapacitated network design problems by ILP (integer linear programming) programs, using a link-path formulations, i.e. the paths are pre-calculated. Link-path formulations are well-known for WRONs [7, 15, 17, 18], but here we extend them to include timeslots, with wavelength conversion, timeslot conversion, and delay of timeslots. One advantage of using a link-path formulation instead of an arc-flow, i.e no paths are pre-calculated, formulation like that used by Cinkler et.al. [4] is that the problem size can be kept reasonable by restricting the number of pre-calculated paths for each demand.

The ILP programs are used for experiments with a Pan-European network, where we vary the number of timeslots per frame and the time gap between each timeslot.

2 Switching timeslots in SOH networks

When a connection in the SOH network is to be set up, a timeslot can be chosen freely at the source node, as long as the timeslot is empty. At the intermediate nodes, by default the timeslot for the next hop can be determined by that of the preceding hop. Naturally, this timeslot must not be occupied by any other connection—if this is the case, either timeslot conversion must be used, or the entire connection must use a different timeslot.

Timeslot conversion in the SOH is similar to wavelength conversion in the WRON, but technically simpler. To do timeslot conversion, the signal in a timeslot must be delayed by a predetermined amount of time, calculated as a positive integer times the length of the minimum slot time. This type of fixed, predetermined delay is different from indefinite buffering, which requires large and complex optical buffers [12]. Fixed, predetermined delays and are easily achieved optically with FDLs (fiber-optic delay lines).

Due to the switching of packets in timeslots, they must arrive in phase at the node inputs. The simplest way to synchronise the timeslot is to arrange all fiber spans connecting nodes in such a way that the time delay is equal to a whole multiple of the timeslot length. However, for example due to temperature induced path variations, this solution is not sufficiently reliable in practice, and optical synchronisers are necessary [6, 8, 9]. To enable exact determination of the timeslot position, time gaps between timeslots, and between frames, are needed.

It is also conceivable to align the entire frames, such that timeslot 1 from all incident links enter a switch simultaneously, then timeslot 2, etc. However, frames are a virtual concept without any significance for the optical signal; switching does not become any easier for this reason, and aligning frames would just cause unnecessary transmission delay.

In the case that the entire frames are not aligned, the packet on timeslot i on an input frame could be switched to a timeslot j on an output frame, where $i \neq j$. In Figure 2, the timeslot synchronisation and switching is illustrated by an example of two input ports and two output ports with four timeslots per frame. In the figure the frames in the two input links a and b arrive out of phase, with a phase shift after synchronisation of exactly two timeslots.

This frame phase shift is no problem for the switch, as long as it is constant over time. Thus we characterise each link by a delay, and in the following we assume that this delay, including the synchronisation, is constant and independent of the direction of the traffic on the link.

When routing the traffic demands, we simply employ shortest path routing, using the number of hops as the distance measure. While this routing method is not the most efficient in reducing the load of the maximum loaded link in the network, it is widely used in telecommunication practice. Furthermore, it is well-suited for illustrating the quantitative and qualitative differences between a WRON and a SOH network.

3 Mathematical formulations

In this section we give the integer linear programming (ILP) formulations of the problem of assigning timeslots and wavelengths to traffic demands.

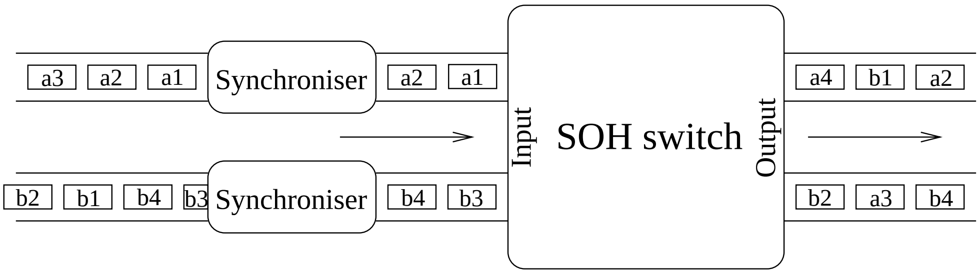

Figure 1: Illustration of synchronisation and timeslot switching. Here four timeslots per frame are assumed.

Given a network represented by a set of L links, and a set of D traffic demands, we assume the path for each demand is pre-calculated and expressed as a set of links. Each fiber holds W wavelengths, and each frame consists of T timeslots.

The main objective is always to minimise W.

In summary, we use the following indices:

$d = 1,\dots,D$	traffic demands
$w = 1,\dots,\infty$	wavelengths
$t = 1,\dots,T$	timeslots
$k,l = 1,\dots,L$	links

And we introduce constants that describe the volume of the traffic demands, the predefined paths for these demands, including an ordering relation for the paths, and the delay:

h_d	volume of demand d (measured in timeslots)
a_{ld}	set to 1 if link l supplies demand d, otherwise 0
p_{dkl}	set to 1 if link k is the predecessor of link l on the path satisfying demand d, otherwise 0
q_l	the delay in timeslots of a timeslot transported on link l

We present five flavours of the wavelength and timeslot assignment problem for the SOH network and one wavelength assignment problem for the WRON. The name in brackets represents the optimal result for that problem:

SOH: Both wavelengths and timeslots must be assigned, and delays are assumed to be zero (modulo the frame length), i.e. all frames at all switches are in phase. No conversion is present. Optimal result: W_{SOH}.

WRON: Only wavelengths must be assigned (there are no timeslots). No conversion is present. Optimal result: W_{WRON}.

SOH with delay: Both wavelengths and timeslots must be assigned, and delays are given for each link. No conversion is present. Optimal result: W_{delay}.

SOH with wavelength conversion: Both wavelengths and timeslots must be assigned, but wavelengths can change at each node along a path. Optimal result: $W_{\lambda\ conversion}$.

SOH with timeslot conversion: Both wavelengths and timeslots must be assigned, but timeslots can change at each node along a path. Optimal result: $W_{slot\ conversion}$.

SOH with full conversion: Both wavelengths and timeslots must be assigned, and both can change at each node along a path. Optimal result: $W_{full\ conversion}$.

In the following, we use for each flavour some decision variables to keep track of the assigned flow and wavelengths, and give a list of constraints for describing the particular problem.

3.1 ILP formulation for SOH

Variables

x_{dwt}	set to 1 if demand d uses wavelength w in timeslot t
y_w	set to 1 if wavelength w is used, otherwise 0

Constraints

$$\begin{array}{rcll}
\sum_w y_w & = & W & \text{main minimisation objective} \\
\sum_{t,w} x_{dwt} & = & h_d, \quad \forall d & \text{satisfy all demands} \\
\sum_d a_{ld} x_{dwt} & \leq & 1, \quad \forall l,w,t & \text{use each wavelength/timeslot on each link at most once} \\
x_{dwt} & \leq & y_w, \quad \forall d,w,t & \text{compute which wavelengths are used} \\
x_{dwt}, y_w & \in & \{0,1\} & \text{use only binary decision variables}
\end{array}$$

3.2 Transformation to ILP formulation for SOH to WRON

By transforming the ILP formulation for the SOH problem to an ILP formulation for the WRON problem it is shown that these two problem are equivalent, whereby solving one of them solves both.

To transform the problem introduce extra variables $y_{wt} = y_w \ \forall t$, whereby the objective becomes minimise $\frac{1}{T}\sum_{wt} y_{wt}$. Then remove all occurrences of t in the preceding section, and set $w' = w \cdot t$, and replace w' with w. Except for the factor $\frac{1}{T}$ in the objective function we get the ILP for the WRON problem.

Variables

x_{dw}	flow for demand d on wavelength w
y_w	set to 1 if wavelength w is used, otherwise 0

Constraints

$$\begin{array}{rcll}
\sum_w y_w & = & W & \text{main minimisation objective} \\
\sum_w x_{dw} & = & h_d, \quad \forall d & \text{satisfy all demands} \\
\sum_d a_{ld} x_{dw} & \leq & 1, \quad \forall l,w & \text{use each wavelength on each link at most once} \\
x_{dw} & \leq & y_w, \quad \forall d,w & \text{compute which wavelengths are used} \\
x_{dw}, y_w & \in & \{0,1\} & \text{use only binary decision variables}
\end{array}$$

That the results for the SOH and WRON problem formulations are equivalent except for a factor is here rigorously stated and proved:

Theorem 1 $W_{SOH} = \lceil W_{WRON}/T \rceil$

Proof: Let the solution to the WRON problem be given, i.e let W_{WRON} and the corresponding values of x_{dw} and y_w be given. It is assumed that a solution to this problem always exists.

Without loss of generality we assume that $y_w = 0$ for all $w > W_{WRON}$; this also implies that $x_{dw} = 0$ for all $w > W_{WRON}$ and $y_w = 1$ for all $w \leq W_{WRON}$. Let $W' = \lceil W_{WRON}/T \rceil$, and for $w' = 1,\ldots,W'$ and $t = 1,\ldots,T$ let $x_{dw't} = x_{dw}$, where $w = t + T(w'-1)$, and let $y_{w'} = \max_t\{y_{t+T(w'-1)}\}$. This implies that $y_{w'} = 1$ for all $w' \leq W'$. We find that constraints of the SOH formulation are indeed fulfilled with the variables W', $x_{dw't}$, and $y_{w'}$:

$$\begin{array}{rcll}
\sum_{w'} y_{w'} & = & W' & \\
\sum_{t,w'} x_{dw't} = \sum_{t=1}^{T}\sum_{w'=1}^{W'} x_{d,t+T(w'-1)} = \sum_{w=1}^{T\cdot W'} x_{dw} = \sum_w x_{dw} & = & h_d & \forall d \\
\sum_d a_{ld} x_{dw't} = \sum_d a_{ld} x_{dw} & \leq & 1 & \forall l,w',t \\
x_{dw't} = x_{dw} \leq y_w & \leq & y_{w'} & \forall d,w',t
\end{array}$$

To see that this solution is optimal, i.e. $W' = W_{SOH}$, suppose a better solution $W'' = \lceil W_{WRON}/T \rceil - a$ exists, where a is an integer greater than zero. Again, without loss of generality assume that $y_{w'} = 0$ for $w' > W''$ and thus $x_{dw't} = 0$. Setting $y_{w'} = y_w$ and $x_{dw't} = x_{dw}$ for $w = 1,\ldots,W''\cdot T$, where $w' = \lceil w/T \rceil$, we find that

$$\begin{array}{rcll}
\sum_{w'} x_{dw't} = \sum_w x_{dw} & = & h_d & \forall d \\
\sum_d a_{ld} x_{dw't} = \sum_d a_{ld} x_{dw} & \leq & 1 & \forall l,w' \\
x_{dw't} = x_{dw} & \leq & y_w = y_{w'} & \forall d,w'
\end{array}$$

but $\sum_w y_w = \sum_{w'} T \cdot y_{w'} = T\sum_{w'} y_{w'} = T \cdot W'' = T(\lceil W_{WRON}/T \rceil - a) < W_{WRON}$, which contradicts the optimality of W_{WRON}. Therefore $W_{SOH} = \lceil W_{WRON}/T \rceil$. ■

3.3 ILP formulation for SOH with delay

Variables

x_{dwtl}	set to 1 if demand d uses wavelength w in timeslot t on link l
y_w	set to 1 if wavelength w is used, otherwise 0

Constraints

$\sum_w y_w = W$	main minimisation objective
$\sum_{t,w} x_{dwtl} = a_{ld}\, h_d, \forall d,l$	satisfy all demands
$\sum_d a_{ld} x_{dwtl} \leq 1, \quad \forall l,w,t$	use each wavelength/timeslot on each link at most once
$x_{dwtl} \leq y_w, \quad \forall l,d,w,t$	compute which wavelengths are used
$x_{dwtk} = x_{dwt'l}, \forall d,w,l,t,$	change slot position of demand
$k\colon p_{dkl}{=}1,$	use the predecessor link to link l
$t'\colon t'{=}(t{+}q_k) \bmod T$	t' is the new timeslot after link k
$x_{dwtl}, y_w \in \{0,1\}$	use only binary decision variables

In this formulation we must keep track of the timeslot used on each link of a path, which requires an extra index l on the flow variable x. We then add a constraint ensuring that if link k is a predecessor of link l on the path of demand d, the timeslots are cyclically delayed q_k slots when going from k to l.

3.4 ILP formulation for SOH with wavelength conversion

Variables

x_{dt}	number of wavelengths used by demand d in timeslot t

Constraints

$\sum_t x_{dt} = h_d, \quad \forall d$	satisfy all demands
$\sum_d a_{ld} x_{dt} \leq W, \quad \forall l,t$	compute number of wavelengths used for each timeslot on each link
$x_{dt} \in \mathbb{N}_0$	decision variables are non-negative integers

With wavelength conversion the wavelength index w on the x-variable is not needed.

3.5 ILP formulation for SOH with timeslot conversion

Variables

x_{dw}	number of slots used by demand d on wavelength w
y_w	set to 1 if wavelength w is used, otherwise 0

Constraints

$\sum_w y_w = W$	main minimisation objective
$\sum_w x_{dw} = h_d, \quad \forall d$	satisfy all demands
$\sum_d a_{ld} x_{dw} \leq T, \quad \forall l,w$	use at most T timeslots on each wavelength of each link
$x_{dw} \geq 1 \Rightarrow y_w = 1, \quad \forall d,w$	compute which wavelengths are used
$x_{dw} \in \mathbb{N}_0$	number of slots is a non-negative integer
$y_w \in \{0,1\}$	wavelength usage is a binary decision variable

In this formulation we need not keep track of precisely which timeslots are used for each demand, only the total number for each wavelength. As $x_{dw} \leq T$, the implication constraint is simply implemented in the ILP program as $x_{dw} \leq T \cdot y_w$.

3.6 ILP formulation for SOH with full conversion

Constraints

$\sum_d a_{ld} h_d \leq T \cdot W, \quad \forall l$ each link can carry T slots on each wavelength

With full conversion the number of needed wavelengths is determined by the links loaded with the highest volume of traffic.

3.7 Relationships between optimal values of different formulations

We mention without rigorous proof that given the same traffic demands, the following relationships between the optimal values of W found by the various ILP formulations hold:

$$\begin{array}{lclcl} W_{SOH} & \geq & W_{\lambda\ conversion} & \geq & W_{full\ conversion} \\ W_{SOH} & \geq & W_{slot\ conversion} & \geq & W_{full\ conversion} \\ W_{delay} & \geq & W_{slot\ conversion} & \geq & W_{full\ conversion} \\ W_{SOH} & = & \lceil W_{WRON}/T \rceil & & \end{array}$$

In each case, the solution whose value is represented on the left side of one of the inequalities will also be a feasible solution to the problem represented on the right side.

4 Results and discussion

We perform some experiments with the ILP programs to determine whether there are any significant differences between the various formulations. The Pan-European network shown in Figure 2 is the basis for the experiments, where the traffic is generated from The point of using the this Pan-European network with the traffic demand matrix generated from the gravitational model is not to guarantee realistic traffic, which we can not. Rather, this is a known network with a traffic demand matrix created by a well known model. Any network with any traffic demand matrix could be used as long as they are not too computationally demanding.

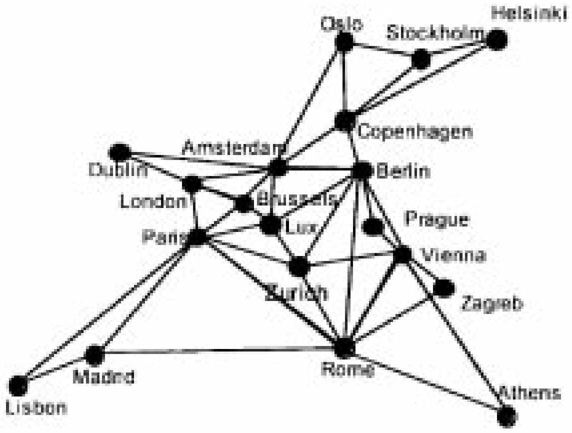

Figure 2: The Pan-European network used in the OPEN project [3] consisting of 19 nodes and 39 links.

4.1 Generation of traffic

The traffic to be routed is static and symmetric, with each demand A_d between two nodes measured as a fraction of f. To generate the traffic we have here used the gravitational model: the traffic demand between two cities is the product of their population sizes, scaled with an appropriate constant (here 10^{-15}). The traffic demand matrix for the network in Figure 2 is shown in Table 1. The unit of the elements in the traffic matrix is in wavelengths. For example the traffic demand between Helsinki and Berlin is 0.43 wavelength. This number is given by multiplying

Table 1: Traffic demand matrix in unit of wavelengths.

	Hel.	Sto.	Oslo	Cop.	Ber.	Ams.	Dub.	Pra.	Lux.	Bru.	Lon.	Vie.	Zur.	Paris	Zag.	Ath.	Rome	Mad.	Lis.
Helsinki	0	0.046	0.023	0.028	0.43	0.083	0.02	0.053	0.0023	0.053	0.31	0.042	0.038	0.31	0.022	0.055	0.3	0.21	0.052
Stockholm	0.046	0	0.04	0.048	0.74	0.14	0.034	0.091	0.0039	0.091	0.53	0.072	0.065	0.53	0.038	0.094	0.51	0.36	0.089
Oslo	0.023	0.04	0	0.024	0.37	0.072	0.017	0.046	0.002	0.046	0.27	0.037	0.033	0.27	0.02	0.048	0.26	0.18	0.045
Copenhagen	0.028	0.048	0.024	0	0.44	0.086	0.021	0.055	0.0024	0.055	0.32	0.044	0.039	0.32	0.023	0.057	0.31	0.21	0.054
Berlin	0.43	0.74	0.37	0.44	0	1.3	0.32	0.85	0.037	0.85	5	0.68	0.6	4.9	0.36	0.88	4.8	3.3	0.84
Amsterdam	0.083	0.14	0.072	0.086	1.3	0	0.061	0.16	0.0071	0.16	0.95	0.13	0.12	0.95	0.069	0.17	0.92	0.64	0.16
Dublin	0.02	0.034	0.017	0.021	0.32	0.061	0	0.039	0.0017	0.039	0.23	0.031	0.028	0.23	0.017	0.041	0.22	0.15	0.039
Prague	0.053	0.091	0.046	0.055	0.85	0.16	0.039	0	0.0045	0.11	0.61	0.084	0.075	0.61	0.044	0.11	0.59	0.41	0.1
Luxembourg	0.0023	0.0039	0.002	0.0024	0.037	0.0071	0.0017	0.0045	0	0.0045	0.026	0.0036	0.0032	0.026	0.0019	0.0047	0.026	0.018	0.0045
Brussels	0.053	0.091	0.046	0.055	0.85	0.16	0.039	0.11	0.0045	0	0.61	0.084	0.075	0.61	0.044	0.11	0.59	0.41	0.1
London	0.31	0.53	0.27	0.32	5	0.95	0.23	0.61	0.026	0.61	0	0.49	0.43	3.6	0.26	0.63	3.4	2.4	0.6
Vienna	0.042	0.072	0.037	0.044	0.68	0.13	0.031	0.084	0.0036	0.084	0.49	0	0.059	0.49	0.035	0.087	0.47	0.33	0.082
Zurich	0.038	0.065	0.033	0.039	0.6	0.12	0.028	0.075	0.0032	0.075	0.43	0.059	0	0.43	0.032	0.077	0.42	0.29	0.073
Paris	0.31	0.53	0.27	0.32	4.9	0.95	0.23	0.61	0.026	0.61	3.6	0.49	0.43	0	0.26	0.63	3.4	2.4	0.6
Zagreb	0.022	0.038	0.02	0.023	0.36	0.069	0.017	0.044	0.0019	0.044	0.26	0.035	0.032	0.26	0	0.046	0.25	0.17	0.044
Athens	0.055	0.094	0.048	0.057	0.88	0.17	0.041	0.11	0.0047	0.11	0.63	0.087	0.077	0.63	0.046	0	0.61	0.43	0.11
Rome	0.3	0.51	0.26	0.31	4.8	0.92	0.22	0.59	0.026	0.59	3.4	0.47	0.42	3.4	0.25	0.61	0	2.3	0.58
Madrid	0.21	0.36	0.18	0.21	3.3	0.64	0.15	0.41	0.018	0.41	2.4	0.33	0.29	2.4	0.17	0.43	2.3	0	0.4
Lisbon	0.052	0.089	0.045	0.054	0.84	0.16	0.039	0.1	0.0045	0.1	0.6	0.082	0.073	0.6	0.044	0.11	0.58	0.4	0

the number of citizens in Finland with the number of citizens in Germany and scaled: $5.2\,10^6 \cdot 8.3\,10^7 \cdot 10^{-15} = 0.43$. If one wavelength corresponds to 40 Gbit/s then the traffic between Finland and Germany corresponds to 21.2 Gbit/s in each direction. The traffic ranges from 0.0017 to 5 wavelengths.

Consider the structure of a frame, shown in Figure 3. We let f denote the frame length in seconds, g the time gap length in seconds, t the timeslot length in seconds and T the number of timeslots in a frame. As each frame consists of T timeslots followed by T gaps, we have that $f = (t+g)T$, i.e. $t = f/T - g$. There is no extra gap in between frames, but the last timeslot in a frame is followed by a time gap, of course.

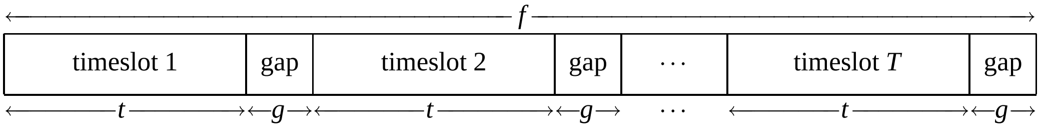

Figure 3: Frames are composed of timeslots and time gaps. Here 1 frame with T timeslots and gabs are shown.

As we fix f to one time unit, the required number of timeslots, h_d, for satisfying a specific traffic demand, A_d, varies with T and g. We disallow fractional timeslots—any such values are rounded up to the nearest integer, so the required number of timeslots is $h_d = \lceil A_d/t \rceil = \lceil A_d/(1/T - g) \rceil$. It is seen that if $g = 1/T$ then no number of timeslots can accommodate the traffic demand. In this case the gaps between the timeslots in the frame fill up the entire frame, such that the timeslot length has to be zero, which, of course, is unrealistic.

4.2 Optimisation results

The ILP programs have been solved optimally on a 1GB 440MHz HP J7000 using GAMS and CPLEX 7.1.

In Table 2 we give the wavelength usage as function of the number of timeslots on a frame with a gap of 0.01 frame length between each timeslot. The wavelength usage is given for the five different flavours of the SOH ILP problems presented in Section 3. We have 1 to 32 timeslots per frame, where 1 timeslot per frame corresponds to WRON except for a gap on each frame, since a timeslot is followed by a gap.

It can be seen that wavelength conversion, timeslot conversion or both does not reduce the wavelength usage, which confirms and extends previous results on the RWA (routing and wavelength assignment) problem for unprotected WDM networks [1, 5, 18]. Furthermore, the introduction of delays, such that connections must use different timeslots on different links of their routes, does not raise the wavelength usage. For 16 and 32 timeslots per frame it was not possible to solve the linear problem due to too high memory usage; this could possibly be avoided by using the independent set formulation [18] (also called the independent routing configuration formulation [15]). The minimum wavelength usage is reached with 4–8 timeslots per frame. Compared to 1 timeslot per frame, which corresponds to a WRON with frames, at least 62.5% fewer wavelengths are needed with SOH at the most favourable number of timeslots.

The traffic demand matrix used here has many elements of just a fraction of a wavelength. In case of only one timeslot per frame, many demands would not efficiently fill up a timeslot, i.e. the utilization would be low, and

Table 2: Number of necessary wavelengths for the Pan-European network as function of the number of timeslots. The time gap between timeslots is 0.01.

timeslots	W_{SOH}	W_{delay}	$W_{\lambda\ conversion}$	$W_{slot\ conversion}$	$W_{full\ conversion}$
1	40	40	40	40	40
2	22	22	22	22	22
4	15	15	15	15	15
8	15	15	15	15	15
16	16	*out of memory*	16	16	16
32	19	*out of memory*	19	19	19

dividing the frames into several would raise the utilization and lower the wavelength usage as we have seen. Had the typical demand been several wavelengths then for one timeslot per frame the relative number of inefficiently filled timeslots would have been smaller. In conclusion, the smaller the demands are, the larger the gain is of using SOH.

In Table 3 we find the wavelength usage as function of the gap when the number of timeslots is 8. It can be seen that the wavelength usage is approximately inversely proportional to $1/8-g$, where g is the length of the gap. Clearly, to minimize the wavelength usage the gap should be zero, but as long as the gap is small ($\lesssim 0.03$) the difference in wavelength usage is small.

Table 3: Varying the size of the time gap between timeslots. 8 timeslots per frame.

Time gap	W_{SOH}
0	14
0.01	15
0.03	18
0.06	25
0.09	46
0.12	312

5 Conclusions

We have described the concept of SOH networks, which we see as an optical solution to alleviate the capacity granularity problem.

Further, we have defined the problem mathematically by ILP formulations in the case of static traffic for various cases of conversion capabilities for wavelengths and timeslots and the presence of delay of timeslots on links.

From the ILP formulation it has been possible to reduce the problem of allocating demands in the SOH network to the simpler problem of allocating demands in the WRON, which we have shown by manipulating the ILP formulation.

By using integer linear programming we have compared wavelength usage for WRONs and SOH networks with different number of timeslots per frame and differently sized time gap between timeslots. We have studied 5 different setups of the SOH: no conversion, conversion for wavelengths, timeslots, and both, and delay of the signal. All setups required the same number of wavelengths for the studied number of timeslots per frame implying that delay and conversion capabilities of neither wavelengths nor timeslots have any significant effect.

Depending on the traffic volume, the required number of wavelengths can be significantly reduced. In this case more than 60% less wavelengths were needed. Generally, the smaller the individual demands are, the larger the gain is of SOH in used number of wavelengths compared to WRON.

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