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Performance evaluation of multirate time division multiplexed wavelength routed optical networks

C. Fenger*, A.J. Glenstrup

Research Center COM, Technical University of Denmark, Building 345v, DK-2800 Kongens Lyngby, Denmark

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Abstract

We consider a wavelength routed all-optical mesh network, where the wavelengths are divided into individually routed timeslots to improve utilization and to allow for a higher degree of optical transparency. The multirate scheduling problem is defined mathematically by integer linear programming formulations. The equivalence of this problem to traditional wavelength routed optical networks is shown. An approximative analytical expression for the gain of using timeslots is derived and verified by simulation. We find that this type of network improves scalability and utilization of all-optical networks significantly when the typical size of a traffic demand corresponds to a couple of wavelengths or less.

Keywords: Time slot; Wavelength routing; All-optical; Integer linear programming

1. Introduction

This article is concerned with dividing wavelengths into timeslots to alleviate the capacity granularity problem.

1.1. Motivation

Switching cost has become increasingly expensive [1] and optical–electric-optical conversion causes unnecessary delay for transit traffic. A solution would be to go all-optical such as static or dynamic wavelength routed optical networks (WRONs) or optical packet switched networks. The WRON—a connection-oriented technology—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. Traffic demands smaller than this will still occupy a full wavelength, but only make use of a fraction of the available capacity.

The optical packet switched network—a connectionless technology—could in principle solve the capacity granularity problem, but unfortunately packet switched optical networks will have to overcome major technological hurdles, such as lack of optical buffering and problems of optical label reading and processing, before they can be deployed.

1.2. Time division multiplexed wavelength routed optical networks

In the setup presented in this article, namely time division multiplexed wavelength routed optical networks (TDM-WRON), connections are connection-oriented, but since the wavelengths here consist of frames, which are divided into timeslots, the granularity of a connection is only a fraction 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 are preserved.

In the TDM-WRON wavelengths are divided into frames which are composed of timeslots, followed by gaps for synchronization purposes, as illustrated in Fig. 1. One timeslot per frame is the minimum capacity unit for traffic demands. Each timeslot in a frame is routed separately, so after each timeslot, the nodes are reconfigured to reflect the routing pattern for the next timeslot. Due to the switching of timeslots, they must arrive in alignment to the node inputs.

* Corresponding author. Tel.: +45-4525-3778; fax: +45-4593-6581.
E-mail address: cf@com.dtu.dk (C. Fenger).

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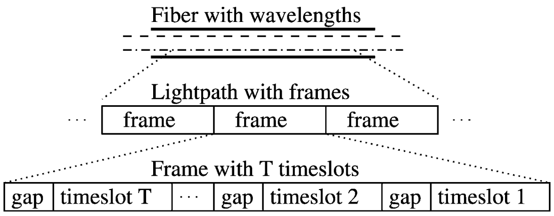

Fig. 1. Illustration of relation between lightpaths, frames, and timeslots.

Timeslot alignment can be done by the schemes of input synchronizers described in Ref. [2].

The timeslots in the TDM-WRON 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 connection-oriented eliminate 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 TDM-WRON.

When a connection in the TDM-WRON 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, the default timeslot for the next hop is determined by that of the preceding hop. 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 TDM-WRON is in principle similar to wavelength conversion in the WRON. To do timeslot conversion, the signal in a timeslot must be delayed by a predetermined amount of time. Fixed, predetermined delays can be achieved optically with fiber-optic delay lines.

1.3. Related work

In Huang et al. [3] the TDM-WRON concept is described, and a scheduling algorithm for mesh networks is proposed. The blocking probability in capacitated networks for different static traffic types are compared.

In Subramaniam et al. [4] the scheduling problem of timeslot and wavelength assignment is studied for rings, and a heuristic is proposed. The equivalence between the single rate scheduling problem of time slot and wavelength assignment and the scheduling problem of wavelength assignment is proved for rings.

The idea of using timeslots on the wavelengths to serve more connections have been realized in broadcast and select all-optical networks in an American ARPA project [5]. A similar setup has been demonstrated in the European ACTS project SONATA [6]. In Ref. [7] quality of service requirements are considered in these broadcast and select networks and a protocol is proposed.

1.4. This work

In this paper we mathematically formulate the multirate scheduling problem of assigning timeslots and wavelengths in the TDM-WRON network. We study the advantages of using TDM-WRON compared to WRON by minimizing the number of wavelengths on each link needed to accommodate the traffic. Each link is assumed to contain two directional fibers, one in each direction.

The problem of routing and assigning timeslots and wavelengths in the TDM-WRON is solved both by a heuristic and by integer linear programming (ILP). In both circumstances the problem is solved sequentially, i.e. routing is performed independent of the timeslot and wavelength assignment. This practice is close to optimal, because the multirate scheduling problem of TDM-WRON is equivalent to the scheduling problem of WRON, which we prove later in this paper, and because wavelength converters have a negligible effect on wavelength usage in the static WRON [8,9].

All our numerical experiments were performed on a Pan-European network with 19 nodes and 39 links. In the experiments we vary the number of timeslots per frame and the gap between each timeslot.

2. Mathematical formulations

In this section we give ILP formulations of the problem of assigning timeslots and wavelengths to traffic demands. The objective is to minimize the number of used wavelengths.

2.1. ILP indices and constants

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

In summary, the following indices are used:

$d \in \{1, \dots, D\}$ traffic demands
$w \in \mathbb{N}$ wavelengths
$t \in \{1, \dots, T\}$ timeslots
$l \in \{1, \dots, L\}$ links.

The following constants describe the volume of the traffic demands, and the predefined paths for these demands:

$h_d \in \mathbb{N}_0$ volume of demand d (measured in units of timeslots)
$a_{ld} \in \{0, 1\}$ 1 if link l supplies demand d, otherwise 0.

2.2. ILP formulation for TDM-WRON

Below we give the formulation when neither wavelength nor timeslot conversion is available.

Objective minimize W

Variables

x_{dwt} 1 if demand d uses wavelength w and timeslot t, otherwise 0

y_w 1 if wavelength w is used, otherwise 0.

Constraints

$\sum_w y_w = W$ number of used wavelengths
$\sum_{w,t} x_{dwt} = h_d$ $\forall d$ satisfy all demands
$\sum_d a_{ld} x_{dwt} \leq 1$ $\forall l, w, t$ use each wavelength/timeslot on a link only once
$x_{dwt} \leq y_w$ $\forall d, w, t$ compute which wavelengths are used
$x_{dwt}, y_w \in 0, 1$ $\forall d, w, t$ use binary decision variables

Let $W_{TDM\text{-}WRON}$ denote the result of the optimization, i.e. the minimum number of wavelengths needed for this problem.

2.3. Transformation of TDM-WRON to WRON

In this section we show how the TDM-WRON scheduling problem can be transformed into the plain WRON problem. This transformation shows that the two problems are equivalent, whereby solving one of them solves both. We sketch how the TDM-WRON problem can be transformed to the WRON problem.

To transform the problem, introduce extra variables $y_{wt} = y_w; \forall t$, whereby the objective becomes *minimize* $W' = W \cdot T$. Then replace all occurrences of wt with w', and w, t with w'. Finally, replace w' with w and W' with W, to obtain the ILP for the WRON problem.*Objective* minimize W*Variables*

x_{dw} 1 if demand d uses wavelength w, otherwise 0

y_w 1 if wavelength w is used, othewise 0.

Constraints

$\sum_w y_w = W$ the number of used wavelengths
$\sum_w x_{dw} = h_d$ $\forall d$ satisfy all demands
$\sum_d a_{ld} x_{dw} \leq 1$ $\forall l, w$ use each wavelength on each link at most once
$x_{dw} \leq y_w$ $\forall d, w$ compute which wavelengths are used
$x_{dw}, y_w \in \{0, 1\}$ $\forall d, w$ use binary decision variables

Let W_{WRON} denote the result of the optimization, i.e. the minimum number of wavelengths needed for this problem.

The fact that the results for the TDM-WRON and WRON problem formulations are equivalent except for a factor T can be stated formally as.

Corollary 1. *Given identical parameters, h_d and a_{ld}, for the two ILP formulations above, then*

$$W_{TDM\text{-}WRON} = \left\lceil \frac{W_{WRON}}{T} \right\rceil$$

The result also applies when full wavelength and timeslot conversion is present.

3. Converting from wavelength to timeslot units

As the traffic demand volume is originally given in granularity of wavelengths, we wish to determine the required number of timeslots to accommodate this demand volume.

Consider the structure of a frame, displayed in Fig. 2. We let f denote the frame length in time, g the gap length in time, t the timeslot length in time, and T the number of timeslots in a frame. As each frame consists of T timeslots and T gaps, we have that $f = (t + g)T$, i.e. $t = f/T - g$.

Setting the time unit such that the length of f is 1, the required number of timeslots, h_d, for satisfying a specific traffic demand of A_d wavelengths, varies only 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 $h_d = \lceil A_d/t \rceil = \lceil A_d/(1/T - g) \rceil$. Obviously, if $g = 1/T$, the entire frame is filled with gaps, and then no number of timeslots can accommodate the traffic demand, so we consider only $g < 1/T$.

4. Routing

We use shortest path routing with load balancing, similar to the one used in Ref. [8], for the overall traffic routing.

When routing an individual traffic demand, we employ shortest path routing, using the number of hops as distance measure. Since usually more than one shortest path exists between each node pair, a certain degree of freedom

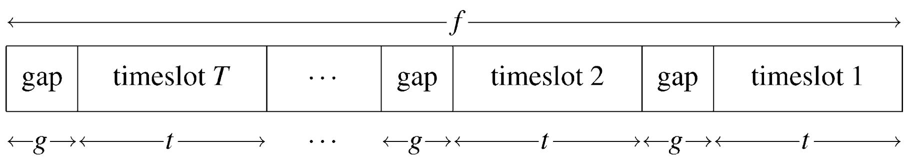

Fig. 2. A frame is composed of T timeslots and gaps.

is available, which is used to balance the traffic load on the links as evenly as possible. This contributes to the reduction of the maximum number of lightpaths to be rerouted in case of a link failure and to minimize the wavelength requirements.

Given an initial routing of all the traffic, load balancing is performed by considering every node pair in turn. If the most loaded link on the path currently assigned to the node pair uses more channels than the most loaded link on an alternative shortest path would do, the alternative shortest path is assigned to the node pair. The process is repeated until no further improvement can be made. Although using longer paths than the shortest path between a node pair could lower the number of channels used on the most loaded link, we do not allow this, since the overall capacity usage would be increased. For simplicity we do not split demands to be routed on different paths. Note that the routing depends on the traffic demands: when the demands change, rerouting must be performed.

5. Analytical derivation of expected timeslot usage

In this section we analytically derive an expression for the lower bound of the expected wavelength usage when using timeslots.

We define the modulus T operator, $\%T : \mathbb{N} \curvearrowright \{1, \ldots, T\}$, such that $x\%T = r$ if $x = dT + r$ for $d \in \mathbb{Z}$ and $r \in \{1, \ldots, T\}$.

Theorem 1. *Assume wavelength and timeslot conversion, and that the traffic demand volume between each node pair, given in granularity of wavelengths is chosen from the uniform distribution from 0 to K, where K is a positive real. Assume further that one link carries a significantly higher number of demands than all other links in the network. Then the expected number of wavelengths is*

$$\langle\lambda\rangle = \begin{cases} \left\lceil \dfrac{D}{T} \right\rceil & \text{for } \dfrac{KT}{1-Tg} \le 1 \\ \dfrac{D+T-1}{2T} + \dfrac{D}{2}\dfrac{K}{1-Tg} + \dfrac{D\left(\left\lceil \dfrac{KT}{1-Tg} \right\rceil - \dfrac{KT}{1-Tg}\right)\left(1 - \left(\left\lceil \dfrac{KT}{1-Tg} \right\rceil - \dfrac{KT}{1-Tg}\right)\right)}{\dfrac{2KT^2}{1-Tg}} + C & \text{for } \dfrac{KT}{1-Tg} > 1 \end{cases}$$

where T is the number of timeslots per frame, D is the number of demands on the link, which carries the maximum number of demands, g is the gap size in units of frame lengths, and $C \in [-T - 1/2T; T - 1/2T]$, and $C = 0$ when $K/1 - Tg \in \mathbb{N}$.

Proof. Let A_d be the volume of traffic demand d in granularity of wavelengths. Since one link is significantly more loaded than other links, then the average wavelength usage is determined by that link. The number of timeslots used by demand d is $\lceil A_d, T/1 - Tg \rceil$. To find the number of used wavelengths, we have to divide by the number of timeslots per wavelength and round up:

$$\partial\varepsilon\lambda = \left\lceil \frac{\sum_{d=1}^{D} \left\lceil \dfrac{A_d T}{1-Tg} \right\rceil}{T} \right\rceil$$

In the case that $KT/1 - Tg \le 1$ then one timeslot is needed for each demand and the expression reduces to $\lceil D/T \rceil$.

We now explore the case for which $KT/1 - Tg > 1$. We use the fact that $\lceil x/y \rceil = x/y + (y - x\%y)/y$ for $x, y \in \mathbb{N}$, and that the mean value operator is linear:

$$\langle\lambda\rangle = \left\langle \frac{\sum_{d=1}^{D} \left\lceil \dfrac{A_d T}{1-Tg} \right\rceil}{T} \right\rangle + \left\langle \frac{T - \left(\sum_{d=1}^{D} \left\lceil \dfrac{A_d T}{1-Tg} \right\rceil\right)\%T}{T} \right\rangle. \quad (1)$$

Since

$$P(\lceil A_d T \rceil = n) = \begin{cases} \dfrac{1-Tg}{KT} & \text{for } 1 \le n < \left\lceil \dfrac{KT}{1-Tg} \right\rceil \\ \dfrac{1 - \left\lceil \dfrac{KT}{1-Tg} \right\rceil + \dfrac{KT}{1-Tg}}{\dfrac{KT}{1-Tg}} & \text{for } n = \left\lceil \dfrac{KT}{1-Tg} \right\rceil \\ 0 & \text{otherwise} \end{cases}$$

then

$$\left\langle \frac{\sum_{d=1}^{D} \left\lceil \dfrac{A_d t}{1-Tg} \right\rceil}{T} \right\rangle = \frac{D}{2T} \frac{\left\lceil \dfrac{KT}{1-Tg} \right\rceil}{\dfrac{KT}{1-Tg}} \left(1 + 2\frac{KT}{1-Tg} - \left\lceil \frac{KT}{1-Tg} \right\rceil\right) \quad (2)$$

and

$$\left\langle \frac{T-\left(\sum_{d=1}^{D}\left\lceil \frac{A_dT}{1-Tg}\right\rceil\right)\%T}{T} \right\rangle = 1-\frac{1}{T}\left\langle\left(\sum_{d=1}^{D}\left\lceil\frac{A_dT}{1-Tg}\right\rceil\right)\%T\right\rangle \quad (3)$$

Inserting expressions (2) and (3) in expression (1) we find that:

$$\langle\lambda\rangle=\frac{D+T-1}{2T}+\frac{D}{2}\frac{K}{1-Tg}+\frac{D\left(\left\lceil\frac{KT}{1-Tg}\right\rceil-\frac{KT}{1-Tg}\right)\left(1-\left(\left\lceil\frac{KT}{1-Tg}\right\rceil-\frac{KT}{1-Tg}\right)\right)}{\frac{2KT^2}{1-Tg}} -\frac{1}{T}\left(\left\langle\left(\sum_{d=1}^{D}\left\lceil\frac{KT}{1-Tg}\right\rceil\right)\%T\right\rangle-\frac{T+1}{2}\right)$$

Defining the latter term as

$$C\equiv-\frac{1}{T}\left(\left\langle\left(\sum_{d=1}^{D}\left\lceil\frac{KT}{1-Tg}\right\rceil\right)\%T\right\rangle-\frac{T+1}{2}\right)\in\left[-\frac{T-1}{2T};\frac{T-1}{2T}\right]$$

If $K/1-Tg\in\mathbb{N}$ then $\lceil A_dT\rceil\%T$ is uniformly distributed in $\{1,\ldots,T\}$, and then $(\lceil A_dT\rceil+n)\%T$ is also uniformly distributed in $\{1,\ldots,T\}$ for every $n\in\mathbb{N}$. Therefore $(\sum_{d=1}^{D}\times\lceil A_dT\rceil)\%T$ is uniformly distributed in $\{1,\ldots,T\}$, and we find the expression:

$$\left(\sum_{d=1}^{D}\left\lceil\frac{KT}{1-Tg}\right\rceil\right)\%T=\frac{T+1}{2}$$

whereby $C=0$, which finalizes the proof. □

Corollary 2. *If* $K/1-Tg\in\mathbb{N}$ *then*

$$\langle\lambda\rangle=\frac{D+T-1}{2T}+\frac{D}{2}\frac{K}{1-Tg}$$

Theorem 1 is a lower bound for the expected wavelength usage in a network without conversion, partly because full conversion was assumed in the theorem, and partly because it was assumed that one link is significantly more loaded than other links. In practice the load will be levelled out such that more links will have approximately the same high load, which will raise the expected wavelength usage.

6. Results and discussion

In this section we first look at the idealized TDM-WRON where the gap is zero and verify this special case of Theorem 1 by the use of simulations.

Secondly, we describe a method to determine the optimal number of timeslots per frame for any gap size by use of Theorem 1.

The network used is the Pan-European network used in the OPEN project [10] consisting of 19 nodes and 39 links as displayed in Fig. 3.

6.1. Verification and consequence of analytical result

To compare the theoretical result of Theorem 1 with the result of assigning timeslots and wavelengths to the demands we follow the procedure illustrated by the flow diagram in Fig. 4.

In Fig. 5 we plot the expected wavelength usage given by Theorem 1 and the wavelength usage computed using heuristics for the timeslot and wavelength assignment for different traffic distributions and number of timeslots per frame. The traffic is given from different symmetric uniform distributions in the interval $[0;K[$ for $K=0.5$, 1, 2, 4 with up to 32 timeslots per frame. The gap is kept at zero. To achieve precise results for the wavelength usage, up to 10^3 different traffic matrices have been simulated for each K and number of timeslots per frame, and average is reported. When calculating the analytical result we have ignored the very small term C in Theorem 1.

It suffices to find the wavelength usage for WRONs. The wavelength usage for TDM-WRONs follows then from Corollary 1. The method used for finding the wavelength usage is the same as in Ref. [9], i.e. converting the wavelength assignment problem into a path collision graph, which is then colored using the graph coloring methods, *descending-order-of-degree* and *Dsatur*. We find that the difference in wavelength usage with and without wavelength converters is negligible. Therefore the results are in general valid both with and without wavelength converters. This is important since the use of timeslot converters would cause unnecessary delay of signal and increase in node complexity.

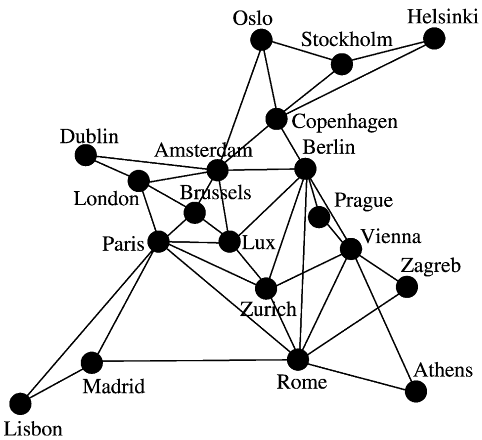

Fig. 3. The Pan-European network.

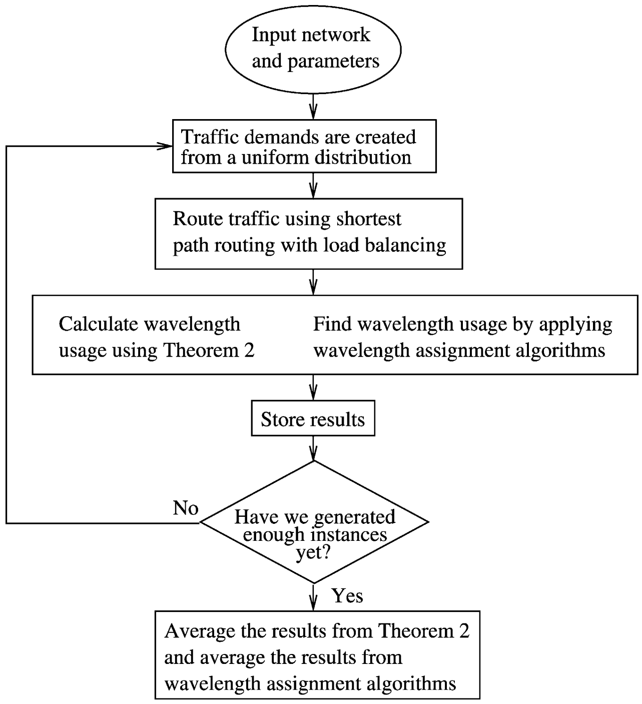

Fig. 4. Flow diagram for simulations yielding both theoretical and real result.

Error bars on the simulation result for the 95% confidence interval have been included in Fig. 5. The confidence intervals have the length of four times the estimated spread of the mean value of wavelength usage under the assumption that the error is Gaussian distributed. Although the number of paths on the maximum loaded link, D, used for calculating the analytical result, varied from traffic matrix to traffic matrix, we did not show the error bars for the analytical result, since the spread here was significantly smaller in comparison. Both the simulation results and the theoretical results for the wavelength usage vary with the traffic matrix. All the results for the wavelength usage from simulations are higher than or very close to the theoretically expected wavelength usage. The routing levels out congestion, whereby more links are candidates to be the most congested link in terms of largest traffic volume, which will raise the average wavelength usage compared to the theory. The result obtained theoretically will therefore be a lower bound for the average wavelength usage for the TDM-WRON. From Fig. 5 and from Theorem 1 we see that the absolute gain in wavelength usage from using TDM-WRON compared to WRON is independent of K, except for variations in D.

With small demand volumes and only one timeslot per frame, many demands will not efficiently fill up a timeslot, i.e. the utilization will be low, and dividing the frames into several timeslots would raise the utilization and lower the wavelength usage as we have seen. When the typical demand volume is several wavelengths then for one timeslot per frame the relative number of inefficiently filled timeslots is smaller. In conclusion, the smaller the demands are, the larger is the gain of using TDM-WRON.

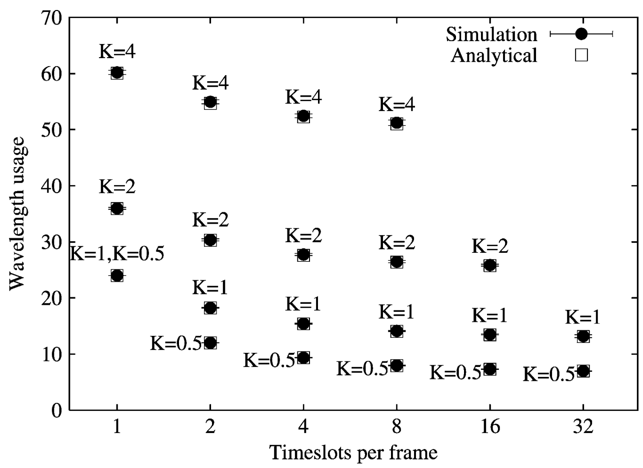

Fig. 5. Analytically predicted usage of wavelengths compared to simulation. The 95% confidence interval is shown for the simulation results. Traffic is symmetrically uniformly distributed in the interval $[0; K[$. Zero gap.

6.2. Optimal timeslot number

We now describe a graphical method for determining the optimal number of timeslots per frame as function of the gap size. Theorem 1 gives the behavior for the wavelength usage for given parameters K, T, and D. The term C in Theorem 1, has been ignored. In Fig. 6 we have plotted the behavior for different values of T. For each T the wavelength usage is a growing function and approaches infinite as g approaches $1/T$. In terms of wavelength usage the most efficient choice of T for $T \in \{1, 2, 4, 8\}$ and $K = 1$ for a given g can be seen from Fig. 6. For given g the T representing the lowest curve is the optimal choice. For instance, if $g \lesssim 0.02$ then $T = 8$ yields the lowest number of wavelengths, and if $0.02 \lesssim g \lesssim 0.08$ then $T = 4$ is the optimal choice.

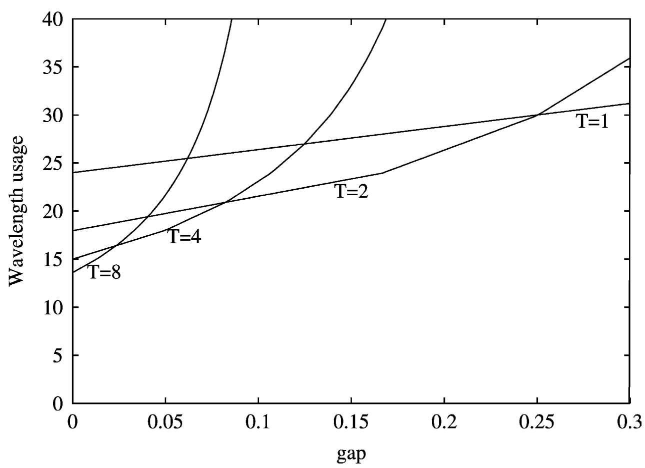

Fig. 6. Wavelength usage versus gap for different number of timeslots per frame according to Theorem 1. Traffic is symmetric uniformly distributed in the interval $[0; 1[$.

The size of the gap is given in units of frame lengths. Therefore the larger the frame the smaller gap (in units of frame lengths). However, the longer frame, the larger is the delay between identical timeslots in different frames, i.e. there is a trade off between delay and utilization.

7. Conclusion

We have described the time division multiplexed wavelength routed optical network as a solution to the wavelength granularity problem. The multirate scheduling problem has been described mathematically by an integer linear programming formulation. The equivalence to the multirate scheduling problem of wavelength routed optical networks has been shown, and an approximative analytical expression for the wavelength usage has been derived and verified by simulation. We find that the advantage of using timeslots is significant when the average traffic demand is less than one wavelength.

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