Performance Analysis of Star Based WDM/TDM Network Topologies

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Abstract. Photonic telecommunication networks gain increasing importance in various fields extending from access to wide area networks. Due to limitations of fast all-optical switching technology, many promising concepts are based on circuit switching. In this paper, we propose a simple star topology using fixed wavelength assignment and a combination of wavelength and time division multiplexing (WDM, TDM). Owing to the fixed assignment, no tunable components or wavelength converters are needed in the central star element. For the receivers, we consider the two cases "single tunable receiver" and "fixed receiver array". A performance evaluation based on a probabilistic method is presented, which is validated by simulation. The results allow a system comparison and an evaluation of the trade-off between capacity increase either by additional wavelengths or additional time slots in the system.

1. Introduction

Photonic networks attract raising attention due to several advantages of optical technology like huge transmission capacity of optical fibres and increasing network reliability due to optical transmission. An important aspect is wavelength division multiplexing (WDM), which allows the transportation of multiple wavelengths on one fibre without interference. Additionally, this mode profits from EDFAs (Erbium Doped fibre Amplifiers) which allow the simultaneous amplification of multiple wavelengths.

The increasing interest in photonic networks is manifested by several special issues published lately [6, 7]. They show that the focus is moving from component oriented research towards network aspects and display the wide scope of applications ranging from on-chip communication to wide area networks (WANs). Numerous network concepts, which can be classified in single-hop and multi-hop systems [10, 11], have been proposed. A large part of the proposals considered star based networks which are supposed to be mainly applied as local or metropolitan area networks (LANs, MANs) with higher transmission rates than today [19]. But there were also suggestions to build wide area telecommunication networks using star networks (for example in [4]). Up to now, most concepts were based on packet transmission mode. Nevertheless, recently circuit switching again attracted more attention [5], since it is possible to show that for some application areas circuit switching offers serious advantages over packet switching [17].

In this work, we will therefore concentrate on the call level in circuit switched WDM star networks. However, instead of a broadcast star coupler as central element, we propose a simple exchange element using fixed wavelength assignment. The networks could be favourably applied as regional networks where single end users are connected with moderate bit rates (i.e. a fraction of a wavelength's bandwidth). Most likely, pure WDM systems will play a minor role to connect end users because the bandwidth available on a wavelength cannot be fully utilized by a single user. Moreover, the enhancement with TDM offers a simple way to allow multiple connections for each user. Thus, we will concentrate on combined WDM/TDM systems in this work. Moreover, we will describe a simple call control scheme which could be applied in the proposed network.

The following section describes the proposed architecture whereas in Section 3 a call control scheme is suggested. Section 4 contains the performance evaluation, i.e. our modelling and analysis approach as well as some results. Finally, we conclude with an outlook on further work.

2. Network Architecture

For the physical topology a star structure is supposed. However, instead of using a passive star coupler, we apply fixed wavelength routing in the star, which can be realized with simple grating elements [9, 16]. Thus, the wavelength that has to be chosen for a transmission is explicitly determined by the link to which the destination node is connected. Fig. 1 shows a simple example with 3 links connected to the star. *m* end stations (each comprising one transmitter and one sender) are connected to every link. They have common access to *a* time slots carried on each wavelength of a single link. There are at least two realisation possibilities for the station receivers: they can be equipped either with one tunable receiver or with an array of fixed receivers (one for each wavelength). A simple call control scheme is described in Section 3.

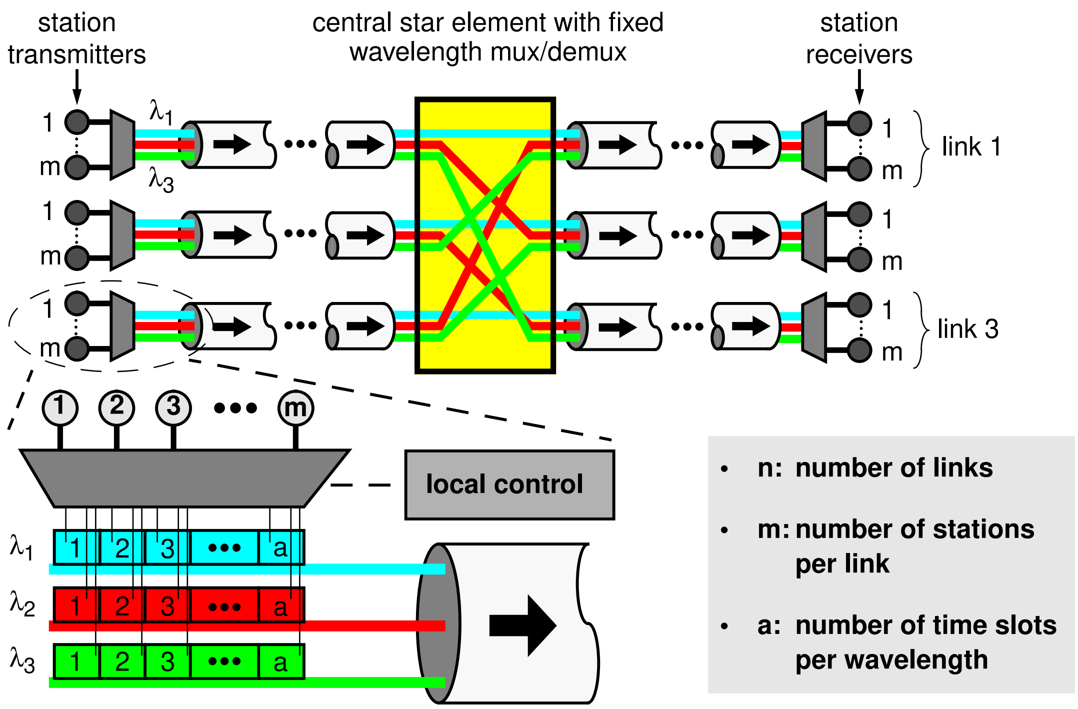

Figure 1: Network architecture, example for n = 3 links

This architecture provides several advantages concerning technological demands and implementation complexity.

- No tunable elements are required in the star element leading to reduced realization cost.
- Fixed wavelength routing offers various advantages. It can be realized using simple and fixed elements. In [4], the principle of a simple grating device is shown allowing wavelength multiplexing and demultiplexing. Progress for integrated wavelength demultiplexers based on waveguide arrays was announced recently for example in [12] and [15]. Moreover, there is no signal splitting amongst multiple links and therefore the power degradation is less than in the case of passive broadcast star couplers. Furthermore, the limited set of available wavelengths can be reused in the proposed fixed arrangement allowing a multiple, simultaneous use of the same wavelength on different links.
- No wavelength converters are required. These elements are still complex and difficult to realize (see for example [20]). In particular to achieve satisfying all-optical solutions, a lot of research is still necessary.
- In our system, we carry multiple time slots of constant length on each wavelength. When a connection is established, the wavelength access is periodically assigned to the stations for a certain period of time. During this time, a transparent channel that is independent of signal format or bit rate is available for the stations. The length of a slot depends on the achievable tuning speed of optical components on the one hand and the maximum allowed packetization delay on the other hand.

- From a technological point of view, several promising results were reported for OTDM (Optical Time Division Multiplexing). A practical use seems realistic in the near future and various groups are working on a quick introduction of OTDM networks [1]. An up to date overview and description of the state of the art is given in [13].

For the described architecture, one wavelength is required for each link connected to the star (i.e. as many wavelengths have to be transported in WDM mode as links are connected). The architecture could be extended by using multiple fibres for each link. Nevertheless, this requires more resources (i.e. transmitter and receiver) at the stations and increases system complexity. Larger networks could be realized by connecting several star networks via a higher layer network, in which wavelength routing and time slot exchange should be provided by electrical means. Moreover, bidirectional transmission on a wavelength by using directed couplers could be used instead of using one fibre for each direction as shown in Fig. 1.

3. Call Control

To provide call control and signalling possibilities, several realizations are possible. A separate overlay network serving as signalling network could be installed for example by providing an additional control wavelength operated in broadcast mode. Such a control channel is necessary if a station can only receive one wavelength at a time (called "single receiver case" in the following). Then, sender and receiver have to coordinate their actions so that the receiver is tuned to the right wavelength for each slot occupied. Numerous signalling protocols were already presented in literature for this case.

However, we propose another, extremely simple solution for the case that each station is provided with an array of receivers so that all wavelengths can be received simultaneously (called "receiver array case"). Each slot contains an address field depicting the receiver station for which the slot is determined. If a sender wants to establish a (bidirectional) connection, it has to apply to the *local control* for a slot position in the frame on the specific wavelength determined by the fixed routing scheme. The *local control* is responsible for only one link and manages the available slots. If a slot could be allocated, the sender starts sending immediately without checking whether the receiver is willing to accept the connection. This cannot cause any blocking at the receiver side: a free slot on the wavelength at the sender side is also free at the receiver side, because no station attached to another link can occupy a slot on this wavelength at the receiver.

The receiver listens to all wavelength channels and if he wants to accept the connection he tries to get a slot in the opposite direction in the same way as described before. The whole process is supervised by timers and if the allowed waiting time for a positive acknowledgement is exceeded, a sender stops his sending process and frees the allocated slot.

The proposed scheme provides several advantages due to its simplicity. No separate signalling channels are necessary and no active routing elements are required in the network. The local link control instance is a very simple one due to the fact that is has only to consider the stations attached to one link. However, this instance needs the possibility to resolve collision events and also some simple signalling possibilities with each sender station (realizable for example by a simple electrical overlay channel/network). Furthermore, slot assignment to each station can be done following numerous schemes as for example according to rate based or polling schemes.

On the other hand, this simple scheme also has some drawbacks. First, by introducing an address field in each slot, the transparency of the channels provided by a connection is reduced. Second, due to the fact that all receivers can listen to all information transmitted, additional effort is required to provide security and privacy for information exchange.

In combined WDM/TDM systems it is of high interest to work out the relations between the parameters like number of WDM channels, bit rate per wavelength channel, number of slots per frame, bit rate per connection, number of stations per link, and number of fibres per link. Recently, some work was reported to evaluate the trade-off between these parameters from an economical and technological point of view [3, 8]. Another interesting perspective is a comparison with regard to traffic theoretical aspects. In the following, we present a method which allows a comparison of call blocking probabilities.

4. Performance Evaluation

4.1 Modelling and Analysis

For performance investigations of systems like the one described in Section 2, there are several suitable methods. One consists in analysing the state space of a system which often leads to large systems of linear equations practically unsolvable for networks with realistic complexity. Moreover, transformations to well known link systems as spatial equivalents are possible. Probabilistic methods combined with permutation investigations can also be applied and finally, simulative investigations allow in principle an examination of any system. The latter are restricted only by the acceptable computational effort.

In the following, we present a probabilistic method to investigate our system. The analytical results are verified by simulation. Tab. 1 lists the parameters used for the following analysis.

Table 1: System parameters for Analysis

n	number of links (equals number of wavelengths)
m	number of stations per link
a	number of time slots per wavelength
λ	rate of connection requests from each station
ε	reciprocal mean holding time of a connection

Each connection between two end users occupies one time slot. A source selects a receiver randomly out of the $n \cdot m$ stations connected to the network. (The case of a source connecting to itself is not excluded from the following analysis because it would make the analysis much more complex without significantly changing the results). The optical wavelength which the new connection will be carried on is determined by the *fixed wavelength routing* scheme introduced before. Let S be the random variable denoting the number of time slots occupied at the source transmitter just before the new connection is to be set up. Let J be the random variable for the occupation of the sending channel, i.e. the number of time slots occupied on the wavelength which must be used to route the connection to the selected receiver. Finally, let D be the random variable for the number of time slots occupied at the destination station's receiver for the "single receiver case".

Assuming stationarity, we have the following Erlang probability distributions for loss systems for S and J. The probability distribution for D is the same as for S. The loss due to blocking at other places is neglected, i.e. for high blocking probabilities the result will over-estimate the blocking probability.

$$P\{S=s\} = \frac{\frac{A_S^s}{s!}}{\sum_{i=0}^{a} \frac{A_S^i}{i!}}, \quad (0 \le s \le a) \qquad\qquad P\{J=j\} = \frac{\frac{A_W^j}{j!}}{\sum_{i=0}^{a} \frac{A_W^i}{i!}}, \quad (0 \le j \le a) \tag{1}$$

In equation (1), the offered traffic per station A_S and per wavelength A_W are given by

$$A_S = \frac{\lambda}{\varepsilon} \qquad \text{and} \qquad A_W = \frac{m}{n} A_S \tag{2}$$

Single Receiver Case

Assuming independence of S and J and random selection of one out of the free time slots at connection set-up, we find the conditional distribution for the number of time slots Q which are free both at the source transmitter *and* on the wavelength:

$$P\{Q{=}q|S{=}s,J{=}j\} = \frac{\binom{a-s}{q}\binom{s}{a-j-q}}{\binom{a}{a-j}} = \frac{\binom{a-s}{q}\binom{s}{a-j-q}}{\binom{a}{j}} \tag{3}$$

$$(q \in [\max\{0, a-j-s\}, \min\{a-j, a-s\}])$$

Now, proceeding to the destination receiver, we are looking for the probability of loss under the condition that we can choose from Q time slots on the wavelength and there are D time slots busy at the receiver. Loss occurs if all Q time slots are busy at the receiver:

$$P\{\text{loss}|Q{=}q,D{=}d\} = \frac{\binom{d}{q}}{\binom{a}{q}} \quad , (q \le d) \tag{4}$$

Defining the binomial coefficient $\binom{a}{b}$ to be zero for $a < b$, $a < 0$ or $b < 0$ and taking S, J and D to be independent, we obtain the loss probability from (3) and (4):

$$B = \sum_{s=0}^{a}\sum_{j=0}^{a}\sum_{d=0}^{a}\sum_{q=0}^{a} P\{\text{loss}|Q{=}q,D{=}d\}P\{Q{=}q|S{=}s,J{=}j\}P\{S{=}s\}P\{J{=}j\}P\{D{=}d\} \tag{5}$$

$$= \sum_{s=0}^{a}\sum_{j=0}^{a}\sum_{d=0}^{a}\sum_{q=0}^{a} P\{S{=}s\}P\{J{=}j\}P\{D{=}d\}\frac{\binom{a-s}{q}\binom{s}{a-j-q}\binom{d}{q}}{\binom{a}{j}\binom{a}{q}}$$

Receiver Array Case

In contrast to the analysis of the tunable receiver setup [14], there is no extra blocking effect from occupied receivers if a receiver array is used as described above. A receiver is blocked on a specific wavelength and time slot if and only if this time slot on that wavelength is occupied on the link as well.

The simultaneous reception of all wavelengths has certain control advantages, as mentioned above. In this case, the number of time slots D occupied at the receiver is irrelevant: The time slots occupied on a certain receiver wavelength are the same J slots that are occupied on this wavelength from the sender to the receiver. Therefore, the blocking case can be described by the conditional probability B(s,j), which denotes the probability of blocking under the condition that $S = s$ time slots are occupied at the transmitter and $J = j$ time slots are occupied on the selected wavelength, given by simple combinatorial arguments:

$$B(s, j) = \frac{\binom{j}{a-s}}{\binom{a}{a-s}} = \frac{\binom{j}{a-s}}{\binom{a}{s}} = \frac{j!}{(j-a+s)!(a-s)!} \cdot \frac{s!(a-s)!}{a!} = \frac{j!s!}{a!(j+s-a)!} \tag{6}$$

for $j + s - a \ge 0$, using the definition $0! = 1$. For $j + s - a < 0$, $B(s, j) = 0$. The total blocking probability in this case is given by

$$B = \sum_{s=0}^{a}\sum_{j=a-s}^{a} B(s, j) \cdot P\{S{=}s\} \cdot P\{J{=}j\} \tag{7}$$

4.2 Results for the Single Receiver Case

Comparison for systems with a given number of stations

Using the parameters of our system according to Tab. 1, we get the total number of stations in the system $m_{total} = m \cdot n$. Moreover, the number of resources (i.e. slots) per link is given by $R_{link} = n \cdot a$ and the number of resources in the star element by $R_{star} = n^2 \cdot a$.

Fig. 2 shows the call blocking probability versus the offered load per station A_S for a system with $m_{total} = 1600$ stations. The solid line represents a system where $m = 100$ stations are connected to each of the $n = 16$ links (at present, a number of channels in a WDM system in the range of 8 to 32 is under discussion at standardization bodies) and $a = 4$ time slots are available on each of the 16 required wavelengths (we name this system *reference system* in the following).

The dashed lines also describe a network with $m_{total} = 1600$ stations, but now using $n = 32$ links with $m = 50$ stations per link. It can be seen that for the same value of $a = 4$ the blocking probability decreases significantly due to the reduced traffic per wavelength. Compared to the reference system, $a = 2$ leads to higher blocking probabilities although R_{link} is constant and R_{star} is even doubled. This is due to the smaller bundles resulting in a smaller economy of scale. For the case $a = 1$, leading to the same R_{star} as in the reference system, blocking probabilities are even higher.

Fig. 2 also contains simulation results which are depicted with a 0.95 confidence interval in all figures. They indicate that the analytical results are overestimating the exact values for high loads. This effect is due to the influence of the correlation between the link, transmitter and receiver states which we neglected in our analysis. This correlation slightly decreases the blocking probabilities at high traffic load per station.

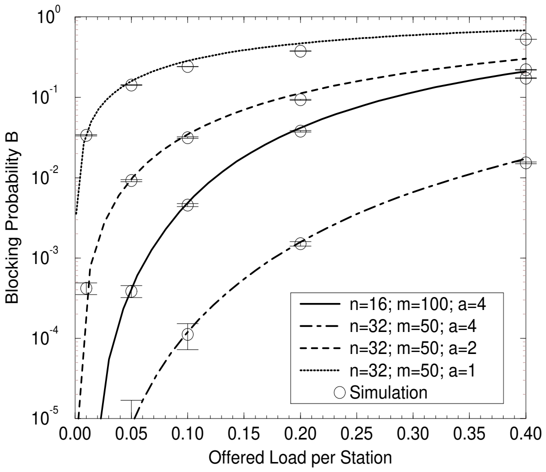

Figure 2: Call blocking probability for $m_{total} = m \cdot n = 1600$ stations

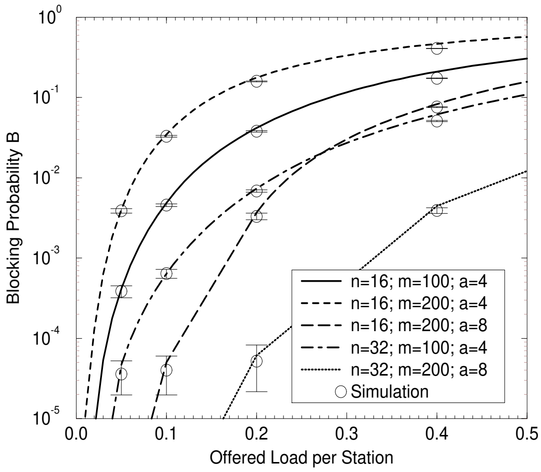

Figure 3: Blocking probability for scaled systems

System Scalability

Fig. 3 shows the influence of system scaling on blocking probabilities. Compared to our reference system, increasing m to $m = 200$ and therefore doubling m_{total} leads to higher blocking probabilities as expected. However, if we simultaneously double the number of time slots a to $a = 8$ thus holding R_{link} / m constant, we see lower blocking probabilities. This can be explained by the economy of scale.

Another way of doubling the system size is doubling the number of attached links ($n = 32$). If m and a are not changed, we see a reduction of blocking probabilities although m_{total} is doubled. This can be explained by the increase of resources (R_{link} and R_{star}). As R_{link} grows proportional to n, the number of resources available for a bundle of m stations is doubled. Moreover, R_{star} grows quadratically with n.

This is also the reason that the results for twice as many stations per link ($n = 32$, $m = 200$, $a = 4$) are *identical* to the reference system although now m_{total} equals 6400. Obviously, blocking probabilities decrease further if we additionally raise a to $a = 8$. For high traffic load per station, we see again slightly higher blocking in the analytical results compared to simulation, as discussed before.

It can be seen that system scaling based on additional links improves the performance while the number of time slots per wavelength (and thus the required tuning speed for each station) remains the same. However, the effect of decreasing blocking probabilities with increasing number of stations is limited by the number of wavelengths which have to be transported in WDM mode. Moreover, the stations are more complex if they have to support a higher number of wavelengths.

4.3 Comparison between Single Receiver and Receiver Array

Fig. 4 compares the blocking probabilities according to equations (5) and (7) for the cases "single tunable receiver" and "array of fixed receivers". The results for the system with n = 16, m = 100, a = 4 show that the receiver array case provides only a small improvement for the case m >> n. This is due to the fact that for m >> n blocking occurs mainly at the wavelength access on the sender side so that additional receivers only have little influence. The improvement by using a receiver array increases for smaller m / n as can be seen for the cases n = 32, m = 50, a = 2 and even more for the case n = 16, m = 16, a = 4.

Finally, we see a good correspondence between analytical and simulative results. As described in Section 4.2, the analysis slightly overestimates the real blocking values – especially for high traffic load – due to two effects: the correlation effects between the time slots occupied at a sender and the time slots occupied on a wavelength and the influence of blocking on the probability distributions for S and J are neglected.

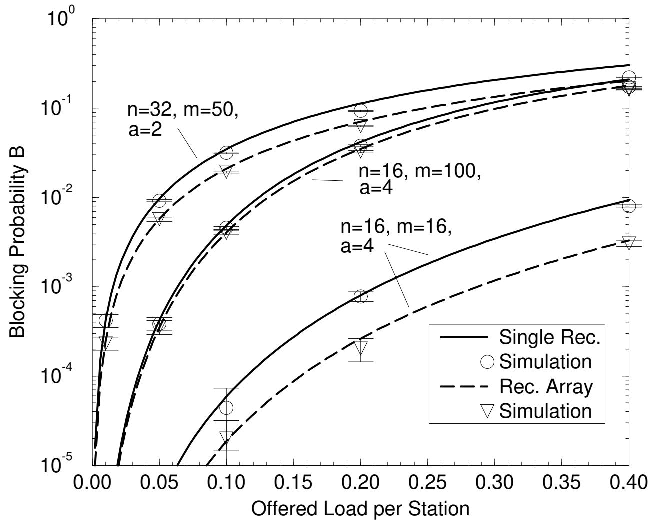

Figure 4: Comparison between "single receiver case" and "receiver array case"

5. Conclusions

In this paper, we proposed a WDM/TDM network architecture based on a simple star exchange using fixed wavelength assignment. We considered two receiver realizations, namely "single tunable receiver" and "fixed receiver array". For these architectures, we presented a performance evaluation based on a probabilistic method to calculate call blocking probabilities for circuit switching mode. The analytical results allow the evaluation of the trade-off between wavelength and time slot resources in the network and a comparison between different system architectures.

The results show that our approach using a receiver array is very promising due to a simple call control scheme, a better performance (especially for m in the order of n) compared to one tunable receiver, and the relative simple realisation possibility owing to the fact that no tunable receivers are required.

Further work should consider comparisons with other realizations as for example passive broadcast or wavelength routing star solutions and possible extensions towards larger networks.

The proposed model can be extended in several ways. An interesting field already well known in classical networks [2] is the influence of hunting modes for the available time slots. Instead of implementing a random selection of free time slots, the performance could be increased by other searching modes like for example *first free first*. Moreover, time slot interchanging or wavelength routing in the star element or even time slot rearrangement for existing connections [18] could be considered. However, these extensions will lead to increasing analytical complexity.

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