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Reach-Dependent Capacity in Optical Networks Enabled by OFDM

Adriana Bocoi[1], Matthias Schuster[2], Franz Rambach[3], Moritz Kiese[4], Christian-Alexander Bunge[2], Bernhard Spinnler[3]

[1] *Student at Technische Universität München, Institut für Informatik ,CSE, Garching, Germany, bocoi@in.tum.de*
[2] *Technische Universität Berlin, Fachgebiet Hochfrequenztechnik, Berlin, Germany, matthias.schuster@tu-berlin.de*
[3] *Nokia Siemens Networks GmbH & Co. KG, Munich, Germany, {franz.rambach, bernhard.spinnler}@nsn.com*
[4] *Technische Universität München, Institute of Communication Networks, Munich, Germany, moritz.kiese@tum.de*

Abstract: In today's optical networks, the channel capacity is designed for the system's maximum reach. By using OFDM, reach dependent capacity can be realized which improves the network performance substantially.
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1 Reach-Dependent Capacity

Today, optical networks transmit at guaranteed fixed data rate. To be able to guarantee this data rate, the capacity is limited to the capacity at maximum reach of the system, although for higher signal-to-noise ratio (SNR), i.e. lower reach, the theoretically available capacity increases significantly. It is proposed that in future systems optical orthogonal frequency-division multiplexing (OFDM) utilizes the available capacity for data transmission.

In recent years, the OFDM modulation technique has been discussed [1-2] for the physical layer of optical communication systems, which distributes data on a high number of low data rate subcarriers. This technique is very flexible as each subcarrier can be modified individually. Furthermore, it requires digital signal processing in both the receiver and the transmitter and therefore easily allows changing the signal properties by software in contrast to traditional fixed hardware implementations. Thus, it is proposed to change the modulation format with respect to the current SNR, which corresponds mostly to the reach. Hence, for every 3 dB gain in SNR, an additional bit can be added per symbol, i.e. 8-QAM instead of QPSK, 16-QAM instead of 8-QAM and so on [3]. By changing the modulation for each subcarrier simultaneously, the capacity increases stepwise to multiples of the initial capacity used for BPSK. The network cost of such a case was compared to fixed data rate grooming in [4].

Additionally, to allow a finer granularity for possible data rate increments, here we propose to not only adjust the modulation format per subcarrier, but also the relative power of the subcarriers. Thereby, for a high number of subcarriers, a quasi-continuous dependency between reach and capacity can be obtained. In wireless communications this is known as adaptive OFDM. For this several algorithms have been proposed e.g. in [5]. For optical OFDM a similar concept was suggested in [6]. However, in contrast to most wireless scenarios, optical channels can be assumed to be flat channels. Hence, it is sufficient to replace the optimization algorithms from adaptive OFDM by a simple fixed rule to reduce complexity and overhead.

The "smoother" increase of the available capacity based on a given system performance for QPSK modulation with initial capacity C_0 and a reach l_0, is reflected in the link capacity C given by

$$C = \frac{C_0}{2}\left(1 + \log_2 \frac{2 \cdot l_0}{l}\right) \quad where \;\; l \leq 2 \cdot l_0 \qquad (1)$$

with link length l. For every halving of the transmission distance l, the SNR improves by 3 dB allowing for an increase of the modulation format by 1 bit: While for l_0 only QPSK with 2 bits per symbol is possible, 8-QAM with 3 bits per symbol can be used for distances of $l \leq l_0/2$ and so forth. It even would be possible to extend the reach up to $l \leq 2l_0$, by using BPSK with only 1 bit per symbol. However, this was not considered in the work presented here. As a result the capacity can be any value. Therefore, either a pure packet-based network or alternatively a scenario with mixed SDH and packet traffic is assumed. The OFDM-transponders were assumed to be directly implemented in the IP router or Ethernet switch.

In this work, a network deploying the quasi-continuous adaptive OFDM technique capable of utilizing the available capacity depending on the reach is compared to a network deploying current fixed data rate technique. Two networks with equal cost are compared in performance. For this a rate-based approach is used.

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2 Considered Optical Equipment

Traditional ultra long-haul transponders with fixed data rate were compared to adaptive OFDM transponders. For both cases coherent transmission with polarization multiplexing was assumed with a data rate of C_0=40 Gb/s over a reference distance of l_0=3000 km. The applied modulation format for this reach was QPSK in both systems. As coherent polarization multiplexed transmission was chosen for both transponders, the main difference in the cost of both transponders is the required signal processing. Complexity there seems to be less [7] for OFDM there. However, for simplicity the cost for both transponders was assumed to be the same, i.e. difference in performance can be directly compared. The reach at 40 Gb/s exceeds the longest link slightly. Therefore no regenerators were required.

3 Network Model and Methodology

The network was assumed to be an opaque network with IP-routers or Ethernet switches, thus an optical-to-electrical-to-optical conversion is performed at every node. The fiber was assumed to be deployed. The number of WDM-channels per fiber was limited to 40 channels and the network was built up completely either with OFDM transponders or with 40 Gb/s transponders. The demands were assumed to be directional. The simulation was carried out in two steps: First, the network was planned for the fixed data rate transponders. In a second step, the possible load for the network was determined in a flow based simulation. For the OFDM setup the same planning was used as for the traditional case. The fixed data rate transponders simply were replaced by OFDM-transponders. We considered the NOBEL-US network (14 nodes, 21 edges) from sndlib [8], as shown in Fig. 1.

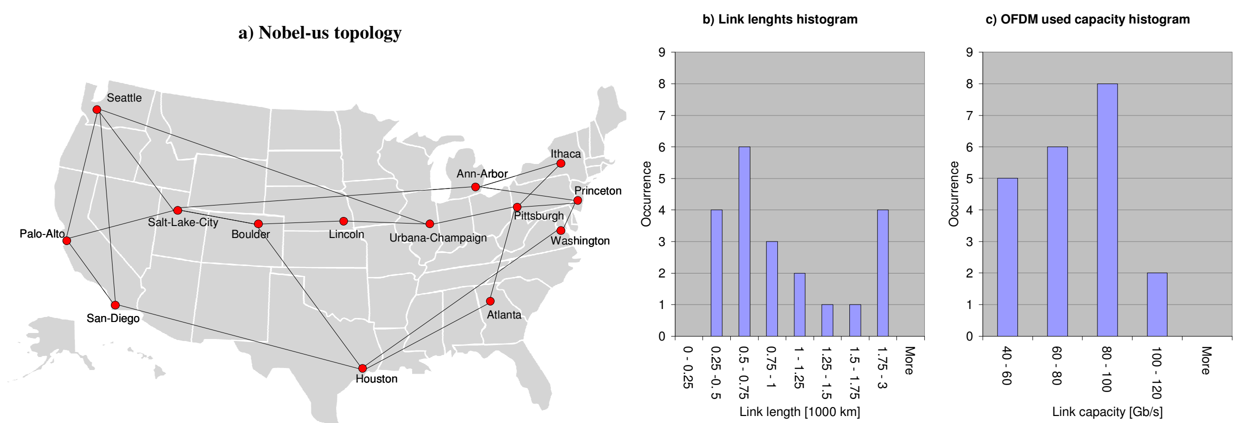

Fig. 1 The topology of the considered NOBEL-US network, the distribution of the edge lengths and the assigned capacities to the OFDM-transponders

The network was planned using an integer linear programming (ILP) path-based formulation, in which the number of transponders deployed in the network was optimized using SCIP [9]. The planning was based on two times the traffic matrix given in sndlib. The optimization step computes the optimal paths and equipment used for operation in the second step.

In order to compare the performance of both systems, a time step simulation was performed by considering each flow in the network as data rates instead of considering single packets as proposed in [10]. Thus, the demand and the link capacity were measured in Gb/s. For each individual demand a flow was created and routed along the optimal path determined in the planning step before. It was assumed that within one time step all flows travel from one node to the next node on their path, independent from the link length. A number of 254 independent time steps with random traffic, based on the initial traffic matrix, were simulated. These demands were generated using random values according to the probability density function (PDF) given by $PDF=|1/(\alpha \cdot d_0 \cdot sqrt(2 \cdot \pi)) \cdot exp(-(d-d_0)^2/(2 \cdot \alpha^2 \cdot d_0^2))|$, with d being the resulting and d_0 the initial demand. The statistical factor α is the standard deviation normalized to the demand which was varied between 0 and 2 with a step width of 0.2.

In today's networks data travels much faster compared to the demand change in the backbone, e.g. every few minutes. One demand matrix is used for several steps. It is used until the loss stabilizes, i.e. previous loss equals the current one, and ensuring that the longest path in the network has been traversed at least once.

The performance of the network was measured in terms of the amount of data that can be routed in the network. Thus the simulation is performed several times by varying the demand matrices with a traffic factor. The traffic factor was varied between 0.3 and 2.5 with a step width of 0.1. By increasing the traffic, the available resources based on the initial planning decrease and data is lost due to unavailable capacity. The overall loss ratio is computed

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as the ratio between the total data lost and the total routed demands in the network. For very low losses the accuracy is limited due to a finite number of simulations. Results were compared at a loss ratio of 10^{-3}.
On a standard personal computer one of the 254 simulation steps for fixed traffic factor and statistical factor takes about 2 minutes for the considered network.

4 Simulation Results

The results for a statistical factor α of 0.6 are shown in Fig. 2a. To adapt the results to different traffic behavior, the statistical factor α was varied and the gain in network load, i.e. the ratio of the traffic factors at a loss ratio of 10^{-3}, is given in Fig. 2b. A clear gain of about 45% can be observed in Fig. 2b for OFDM-transponders with a loss ratio of 10^{-3}. The reason is that the flexibility of the OFDM technology is used in this case. As can be observed in Fig. 1c, 38% of the links in the network are using a capacity between 80 Gb/s and 100 Gb/s and 28.5% of the links have a capacity between 60 Gb/s and 80 Gb/s in the OFDM case compared to the constant capacity of 40 Gb/s in the traditional case. Thus, when using this technology, the amount of data that can be sent in the network increases. On the other hand, no link carries more than 100 Gb/s. Initially the maximum capacity was limited to 160 Gb/s to avoid problems in system design especially with increasing capacities at IO-interfaces of the components. Obviously this limit can be lowered to 100 Gb/s for this network without any penalty in the performance.

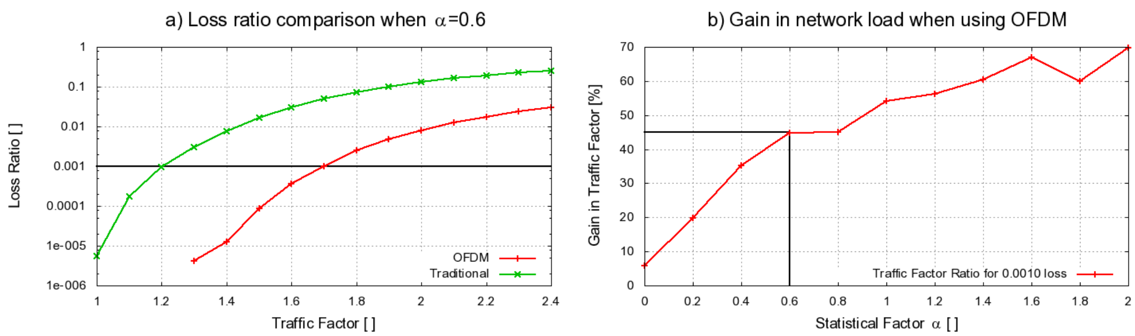

Fig. 2 Performance comparison between the traditional fixed data rate and the proposed adaptive data rate OFDM technology. In a.) the loss is compared for a statistical factor α=0.6 whereas b.) shows the gain in network load at a loss ratio of 10^{-3} for different α.

Fig 2b additionally shows that the higher the traffic varies the higher the benefit for OFDM is. This also implies a remarkably higher tolerance to deviations between real traffic and forecast.
The presented results are for specific transponder properties, network, and demand. Nevertheless, similar results were obtained by simulations of other networks where different capacities, i.e. remarkably different reaches are used. Besides these results, other factors speak for OFDM. For example, only one single type of transponder has to be developed, enhanced and maintained for a system dealing with different data rates and the increased flexibility leads to optimized reach, network performance and cost. Additionally, it is possible to increase the reach by decreasing the data rate, which was not considered in this work.

5 Conclusion and Outlook

We have shown that adaptive OFDM will perform remarkably better in optical networks, when compared to the traditional technology using fixed data rates if there are links in the network which are significantly shorter than the maximum reach of the transponder. In this way, the capacity of the shorter links and therefore the capacity of the total network can be increased remarkably. The results also indicate that the tolerance to differences between forecast and actual traffic increases notably. An even higher gain for OFDM than shown here can be expected at same network cost when the planning is optimized for OFDM.

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