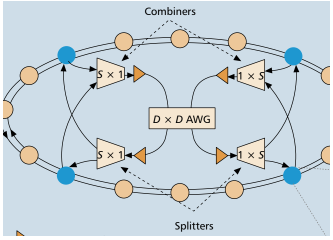

AWG-Based Metro WDM Networking

Martin Maier, Centre Tecnològic de Telecomunicacions de Catalunya (CTTC)
Martin Reisslein, Arizona State University

Abstract

A plethora of metropolitan area wavelength-division multiplexing networks have been proposed and examined in recent years with the aim to alleviate the bandwidth bottleneck between increasingly higher-speed local/access networks and high-speed backbone networks. Many of the considered metropolitan area networks use the arrayed waveguide grating as an optical building block. As we review in this article, in ring, interconnected ring, and meshed metro WDM networks, the AWG is typically used to realize wavelength multiplexers, demultiplexers, or optical add-drop multiplexers without capitalizing on spatial wavelength reuse. By using the AWG as a wavelength router, highly efficient star metro WDM networks can be realized due to extensive spatial wavelength reuse. We give an overview of star metro WDM networks that are able to meet modular upgradability, transparency, flexibility, efficiency, reliability, and protection requirements of future metro networks. AWG-based star networks also enable an evolution path of ring networks toward highly efficient and fault-tolerant hybrid star-ring metro network solutions.

Introduction

Optical networks can be found at all levels of the Internet network hierarchy, which may be viewed as consisting of backbone, metropolitan, access, and local networks, as depicted in Fig. 1. Today's optical backbone networks provide huge pipes of bandwidth by using wavelength-division multiplexing (WDM) on the abundantly available fiber infrastructure. At the network periphery a large variety of networking technologies, such as Gigabit Ethernet (GbE) local area networks (LANs) together with the IEEE 802.3ae 10 GbE standard as well as the IEEE 802.3ah Ethernet in the first mile (EFM) standard, are expected to provide sufficient bandwidth for at least the next few years. These broadband access technologies in conjunction with wireless services, such as Universal Mobile Telecommunications System (UMTS) and wireless LANs (WLANs), and high-speed protocols, such as asynchronous transfer mode (ATM), frame relay (FR), synchronous optical network/synchronous digital hierarchy (SONET/SDH), IP, enterprise system connection (ESCON), and Fibre Channel, will require a large amount of bandwidth and flexible support for different quality of service (QoS) from the networks higher up in the hierarchy in Fig. 1.

Between these high-speed clients with different service requirements and the huge pipes in the backbone lie the access and metro networks. Access networks were initially hybrid fiber coax (HFC) systems, where only the feeding part between the central office and the remote node of the network is optical, while the distribution network between the remote node and the subscribers is still electrical. In so-called fiber to the x (FTTx) access networks, the fiber-to-copper discontinuity point is steadily moved out toward the network periphery, leading to completely optical access networks. Typically, for cost reasons such all-optical access networks are unpowered and accordingly are called passive optical networks (PONs) [1]. The ATM-based broadband PON (BPON) and the recently evolving Ethernet PON (EPON) are promising candidates for providing QoS and enough bandwidth to increasingly higher-speed end users.

Metro Gap

With increasing bandwidth demands and improving access technologies, overloading metro networks becomes a major issue. Today's operational metro networks are mostly SONET/SDH-based infrastructures whose low provisioning flexibility, service flexibility, and scalability present a very significant bottleneck between increasingly higher-speed end users and the abundant long-haul WDM bandwidth. This bottleneck, often called the *metro gap*, tends to result in low utilization of the abundant core capacity [2]. Metro networks can be categorized into metro edge and metro core networks. Typically, metro edge networks are rings that collect traffic from several access networks. The collected traffic is mostly outbound and is thus forwarded by a hub node toward one or more metro core rings. The metro core rings are linked together and usually form interconnected rings or meshes.

Metro Network Requirements

To alleviate the metro gap and thus let increasingly higher-speed end users and clients tap into the vast amounts of bandwidth available in optical WDM backbone networks,

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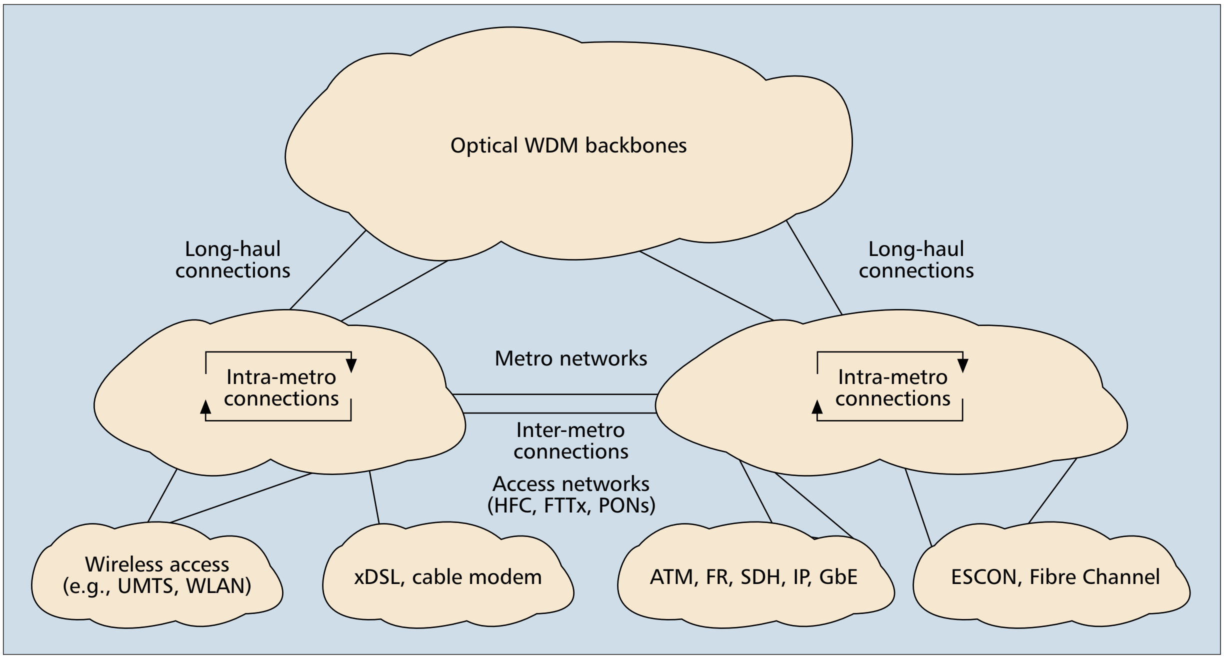

FIGURE 1. Network hierarchy: metro networks interconnect access and local networks, which employ a wide variety of networking technologies and provide a range of increasingly higher-speed services, with the high-speed optical WDM backbone networks.

next-generation metro networks have to meet the following requirements:

- *Modular upgradability*: Future metro networks have to provide more capacity in order to cope not only with current traffic loads but also with unexpected future demand growth. Due to the cost sensitivity of metro networks, capacity upgrades should be feasible in a pay-as-you-grow manner.
- *Transparency*: To support multiple legacy services/protocols, provide backward compatibility, guarantee future proofness of the network against new services/protocols, and also simplify operation and management of the network, future metro solutions need to be transparent with respect to protocol, line rate, and modulation format.
- *Flexibility*: Future metro networks must be able to support a wide range of heterogeneous protocols with different and time-varying bandwidth granularities and QoS requirements.
- *Efficiency*: To meet the cost constraints, network resources have to be used efficiently and be dynamically assigned on demand.
- *Reliability/protection*: New metro networks must be highly reliable, and protection timescales must be comparable to SONET/SDH systems.

A plethora of new metro WDM networks and access protocols have been proposed and examined that aim to meet the above mentioned requirements [3–7]. In many of these architectures, an arrayed waveguide grating (AWG)

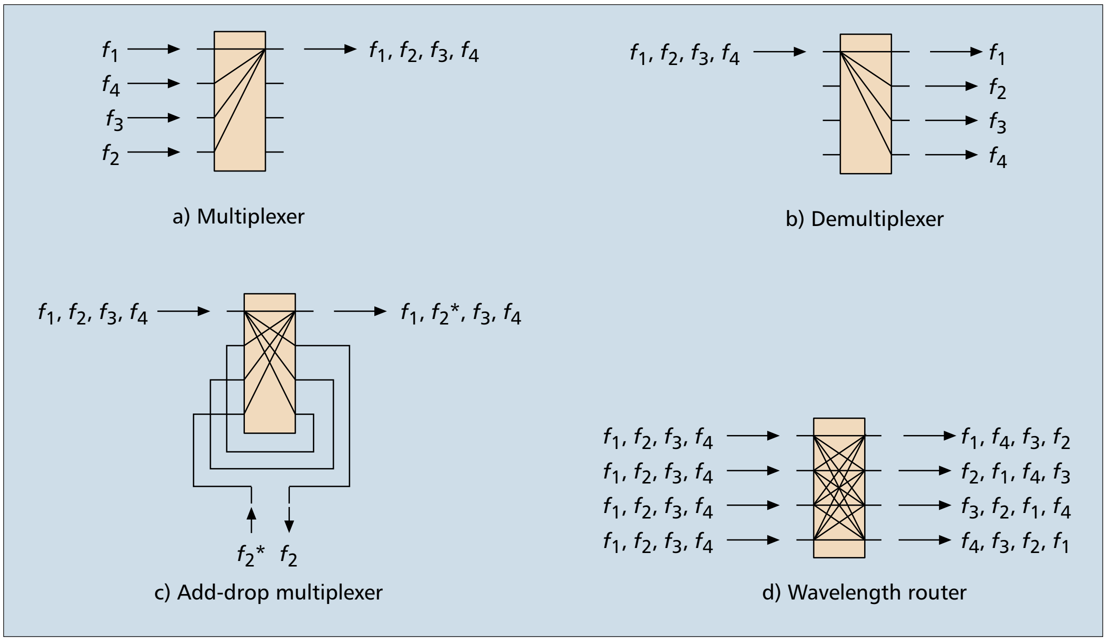

FIGURE 2. Basic WDM functions of a $D \times D$ arrayed waveguide grating (AWG), with $D = 4$.

is used as an optical building block to realize cost-effective, reliable, and efficient metro networks. In this article we review the various applications of an AWG in ring, interconnected ring, meshed, and star metro WDM networks. We pay particular attention to the spatial wavelength reuse capability of an AWG in star metro WDM networks. In addition, we present a novel AWG-based hybrid star-ring metro WDM network that particularly takes the pay-as-you-grow upgradability, efficiency, reliability, and protection requirements of future metro networks into account.

PROPERTIES OF ARRAYED WAVEGUIDE GRATING

The AWG is a passive wavelength-selective device. In the following, we describe the main features of an AWG and their implications from a networking perspective (for more details on the physical properties of an AWG, e.g., crosstalk or temperature sensitivity, the interested reader is referred to [5, references therein]. As shown in Fig. 2, a $D \times D$, $D \geq 1$, AWG provides four basic WDM functions. (Note that in the figure f_i denotes the optical frequency that is equivalent to the corresponding wavelength λ_i. Frequency and wavelength are used interchangeably below.) It can be used as a simple $D \times 1$ multiplexer or a $1 \times D$ demultiplexer. As an optical add-drop multiplexer (OADM) the AWG carries out both multiplexing and demultiplexing.

Most interestingly, the AWG can also be used as a strictly nonblocking full-interconnect wavelength permutation router, as shown in Fig. 2d. As a wavelength router, a $D \times D$ AWG accepts D wavelengths from each input port and routes each wavelength to a different output port. Each optical frequency gives routing instructions that are independent of the input port. More precisely, f_i's routing information is to exit the output port that is $i - 1$ ports below the corresponding input port (i.e., wavelength f_i entering at input port j is routed to output port $j + i - 1$). For instance, f_1 goes from input port 1 to output port 1 and from input port 4 to output port 4. Similarly, f_3 incident on input port 1 is directed to output port 3, whereas if f_3 were incident on input port 2 it would be routed to output port 4. If $j + i - 1 > D$, the frequencies are wrapped around (i.e., wavelength f_i entering at input port j with $j + i - 1 > D$ is routed to output port $j + i - 1 - D$). For instance, f_3 incident on input port 4 is routed to output port 2. In general, frequency f_i, $i = 1, \ldots, D$, incident on input port j, $j = 1, \ldots, D$, is routed to output port $(j + i - 1) \bmod D$. Note that each output port receives D different wavelengths, one from each input port, as illustrated in Fig. 2d. In the illustration of the frequencies exiting the AWG in Fig. 2d, the frequencies at a given output port are sorted from left to right according to the corresponding input port number (e.g., f_3 exiting at output port 3 originates at input port 1, while f_4 exiting at output port 3 originates at input port 4). Note that the $D \times D$ AWG allows for *spatial reuse* of all D wavelengths at all D input ports without resulting in channel collisions at the AWG output ports. Thus, highly efficient network architectures can be realized by using all D wavelengths at all ports of a $D \times D$ AWG simultaneously, as we will see shortly.

In so-called frequency-cyclic AWGs, multiple free spectral ranges (FSRs) can be used for data transmission. Each FSR of a frequency-cyclic $D \times D$ AWG provides D wavelength channels, which are routed similar to the routing pattern described above. With a frequency-cyclic $D \times D$ AWG, optical frequency f_i, $i \geq 1$, entering at input port j, $j = 1, \ldots, D$, is routed to output port $(j + i - 1) \bmod D$. Note that each FSR provides exactly one wavelength channel from each input port to each output port.

AWG-BASED APPLICATIONS IN RING AND MESHED WDM NETWORKS

RINGS AND INTERCONNECTED RINGS

In ring WDM networks, nodes typically use the AWG as a wavelength multiplexer/demultiplexer or OADM. In both cases, the incoming WDM comb signal is separated into individual wavelength channels. Some of the wavelength channels are converted into the electrical domain at the node for receiving or processing the data carried on the channels. The other wavelength channels remain in the optical domain, (i.e., the channels optically bypass the node). The optical bypassing reduces the processing burden at the node, as the node does not need to electronically process the transit traffic carried on the optically bypassed wavelength channels. Note that when upgrading a ring network operating with a single wavelength channel to a WDM ring network operating with multiple wavelength channels, typically *all* nodes need to be WDM upgraded, be it by wavelength (de)multiplexers or transceiver arrays. We will get back to this issue later when discussing an alternative WDM upgrade of ring networks.

In interconnected rings, the AWG can be used as a wavelength router [8]. Specifically, the AWG is deployed as a central hub to interconnect multiple ring WDM networks in a star topology. In doing so, any pair of rings are directly connected by the central AWG. As a consequence, traffic does not have to pass multiple intermediate ring networks, which leads to a reduced traffic load on each ring, increased bandwidth efficiency, and simpler management of the network. Alternatively, rings can be interconnected by means of optical crossconnects (OXCs), which can be constructed with AWGs acting as demultiplexers and multiplexers in conjunction with tunable transmitters and receivers [9].

MESHED NETWORKS

OXCs can also be used in meshed metro WDM networks to improve their flexibility and survivability. Furthermore, OXCs enable restoration and reconfiguration of the network to accommodate load changes (traffic engineering) and compensate for link and/or device failures. There are a large number of further AWG-based applications for meshed and other WDM networks. Among others, the AWG can be used to realize discretely tunable receivers, discretely tunable filters/equalizers, discretely tunable single- or multifrequency lasers, dispersion (slope) compensators, wavelength interleavers, or switches (for more details the interested reader is referred to [10, 11] and the corresponding references given in [5]). All these applications make use of the wavelength multiplexing/demultiplexing nature of the AWG without benefitting from the spatial reuse capability of the AWG.

We note that in today's operational networks, the reviewed ring and mesh network architectures operate typically as *circuit-switched* networks, and the AWG is used to route lightpaths (circuits) in these networks. We also note that the AWG has been employed as multiplexer/demultiplexer in studies of packet-switched WDM ring networks. In the subsequent sections we turn our attention to emerging *packet-switched* star and star-ring metro WDM networks that exploit the spatial wavelength reuse of the underlying AWG wavelength router.

TT-TR AWG STAR WDM NETWORK

In the following, we highlight the main characteristics of the TT-TR AWG star WDM network architecture and access protocol. We refer the interested reader to [5] for more details and to [12] for an AWG-based national-scale network.

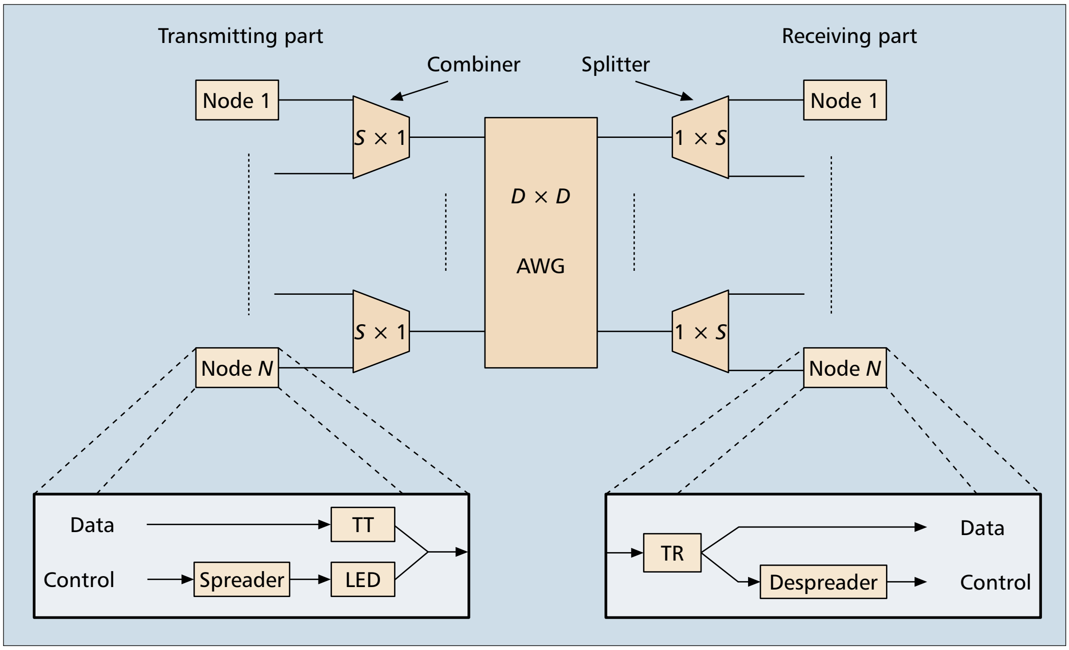

FIGURE 3. Network and node architecture of the TT-TR AWG-based single-hop star WDM network.

ARCHITECTURE

Figure 3 depicts the network and node architecture of the TT-TR AWG-based star WDM network, which is based on a $D \times D$ AWG. A wavelength-insensitive $S \times 1$ combiner is attached to each AWG input port, and a wavelength-insensitive $1 \times S$ splitter is attached to each AWG output port, where $S \geq 1$. Each combiner collects the signals from S different nodes. Similarly, each splitter equally distributes signals to S different nodes. Thus, the network connects $N = D \cdot S$ nodes. Each node contains a fast tunable transmitter (TT) and a fast tunable receiver (TR) with negligible tuning times for data packet transmission and reception, respectively. Fast tunable transmitters with tuning times on the order of a few nanoseconds, which is typically a negligible fraction of the transmission time of a packet, are currently available. Fast tunable optical receivers with negligible tuning times are currently not technologically feasible, but are the subject of intense research efforts. Note that packet switching with negligible tuning time penalty can be realized by using two alternating tunable receivers, whose non-negligible tuning times are masked by using one receiver while the other one is being tuned to the wavelength on which the next packet will be received. Each TT is tunable over one or more FSRs of the underlying AWG. Consequently, each node is able to send data to all AWG output ports and thus all nodes directly in a *single hop* (i.e., without forwarding at intermediate nodes). Similarly, each TR is tunable over one or more FSRs in order to pick up data originating from all nodes. In addition, each node deploys a broadband light source (e.g., an off-the-shelf LED) for broadcasting control packets. The broadband LED signal (10–100 nm) is spectrally sliced by the wavelength-sensitive AWG such that all nodes receive the control packets. The signaling is done in-band simultaneously with data transmission (i.e., TT data and LED control signals overlap spectrally). In order to distinguish data and control information, direct sequence spread spectrum techniques are used.

ACCESS PROTOCOL

The tunability of both transmitters and receivers allows for high flexibility in data transmission and reception, and has the potential to achieve load balancing across all wavelength channels. However, with a TT-TR node structure not only channel collisions but also receiver collisions may occur (a receiver collision, also known as destination conflict, happens if the receiver of the intended destination node is not tuned to the wavelength on which the corresponding source node sends data). Typically, a medium access control (MAC) protocol is employed to arbitrate access to the wavelength channels and thus prevent or mitigate collisions. Generally, MAC protocols for single-hop WDM networks fall into three main categories:

- Preallocation protocols
- Random access protocols
- Reservation protocols

Unlike preallocation and random access protocols, reservation protocols deploy pretransmission coordination (reservation signaling) to assign wavelengths and receivers on demand. With the so-called attempt-and-defer type of reservation protocol, data packets are only transmitted after a successful reservation (as opposed to tell-and-go reservation protocols where data packets are sent irrespective of reservation success), thus avoiding both channel and receiver collisions. Furthermore, for bursty data traffic this approach achieves higher channel utilization efficiency than static preallocation protocols, and we therefore adopt it in our TT-TR AWG star WDM network.

In our MAC protocol, time is divided into cycles that are repeated periodically. Each cycle consists of D frames. Each frame is partitioned into two parts. In the first part, control transmission takes place simultaneously with data transmission. In order to avoid receiver collision of control packets, the receivers at all nodes must be tuned (locked) to one of the LED slices carrying the control information, whereby it is important to note that the receiver schedule "lags behind" the transmitter schedule by the one-way end-to-end propagation delay across the network. Due to the wavelength routing characteristics of the AWG and the fact that each node is equipped with a single receiver, only nodes attached to the same combiner can send control packets in a given frame without receiver collision. Specifically, all nodes attached to AWG input port o (via a common combiner) send their control packets in frame o of the cycle, where $1 \leq o \leq D$. Thus, nodes can send control packets only in one frame per cycle.

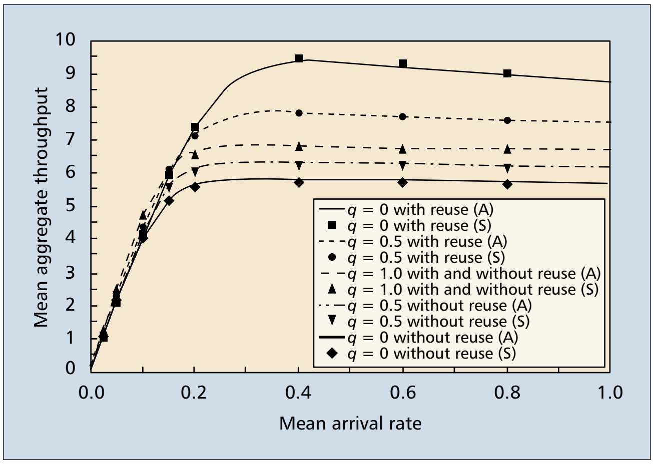

FIGURE 4. TT-TR AWG-based single-hop star WDM network: mean aggregate throughput (packets/frame) vs. mean arrival rate (packets/cycle) with and without spatial wavelength reuse for different fractions of long data packets $q \in \{0, 0.5, 1.0\}$.

Successfully transmitted control packets are processed in a distributed manner to determine a common transmission schedule of the corresponding data packets. In the first part of frame o, data packets can be sent simultaneously by the nodes attached to AWG input port o. During this time interval the transmitters at the other AWG ports cannot send data; therefore, spatial wavelength reuse is not possible. In the second part of each frame, no control packets are sent. The receivers are unlocked, allowing data transmission between any pair of nodes in each frame (i.e., spatial wavelength reuse is possible), provided that the corresponding data packet fits into the second part of each frame.

RESULTS

We now show that spatial wavelength reuse dramatically increases the throughput of the TT-TR AWG-based single-hop star WDM network. We consider $N = 200$ nodes interconnected by a 4×4 AWG (i.e., $D = 4$ and $S = 50$) and assume a transceiver tuning range of two FSRs of the underlying 4×4 AWG. We consider uniform unicast traffic. Packets are of variable size: With probability q, $0 \leq q \leq 1$, a generated packet is long (i.e., the packet transmission time equals one frame). With probability $(1-q)$ a generated packet is short (i.e., the packet transmission time equals the second part of each frame). Figure 4 depicts results from a probabilistic analysis (A) and verifying simulation (S) for the mean aggregate throughput vs. mean arrival rate for different $q \in \{0, 0.5, 1.0\}$ (for details on the performance evaluation and additional results the interested reader is referred to [5]). To illustrate the benefit of spatial wavelength reuse, we operate the star network with and without reuse for a given q. We observe from Fig. 4 that for $q = 1.0$ (i.e., all data packets are one frame long), the mean aggregate throughput is the same no matter whether wavelengths are spatially reused or not. This is because the data packets can be transmitted in only one frame per cycle (simultaneous with control), but are too long to be transmitted in the second part of the remaining $(D - 1)$ frames of the cycle where spatial wavelength reuse would be possible. The benefit of spatial wavelength reuse is most pronounced for $q = 0$, for which each data packet fits into the second part of a frame and can thus take advantage of spatial wavelength reuse. This increases the maximum aggregate throughput by more than 60 percent. Note that spatial wavelength reuse is not possible in broadcast-and-select star WDM networks that are based on a wavelength-insensitive passive star coupler (PSC), where each wavelength is broadcast to all output ports and can thus be used at only one input port at any time. Therefore, AWG-based star WDM networks are able to achieve significantly higher throughput than their PSC-based counterparts.

Note that the wavelength-insensitive splitters of the TT-TR AWG star WDM network enable optical multicasting. In single-hop star WDM networks with a small number of receivers at each node, multicast transmissions are typically limited by the number of available receivers. Partitioning multicast transmissions into multiple multicast copies mitigates the receiver bottleneck. However, in PSC-based star WDM networks, which do not allow for reuse, multicast copies can cause a channel bottleneck. The spatial wavelength reuse in the TT-TR AWG star WDM network alleviates this channel bottleneck, resulting in dramatically improved multicast throughput-delay performance compared to PSC-based star WDM networks.

The presented MAC protocol can also be used to set up a single-hop dedicated circuit in the form of periodic timeslots on a wavelength or a full wavelength (lightpath) between a source and destination node to support circuit-switched traffic (e.g., from SONET).

The TT-TR AWG star WDM network meets many requirements of future metro networks. Due to spatial wavelength reuse the capacity of the network is increased dramatically. By applying transceivers with a larger tuning range, either at all nodes or only at some source-destination node pairs with high traffic demands, additional FSRs of the AWG can be used for data transmission. Note that different pairs of source-destination nodes are able to operate at different line rates due to the lack of forwarding at intermediate nodes. Thus, the network allows for modular upgrades at the network periphery without requiring any modification of the central network architecture. As a single-hop network, the TT-TR AWG star network inherently provides transparency to legacy and future protocols. Due to its passive nature, the network is highly reliable, and the operation and management of the network are simplified. Multiple services with different and time-varying QoS requirements can be efficiently supported by means of on-demand bandwidth reservation and network reconfiguration [13]. However, there are some remaining shortcomings and system bottlenecks, such as partial spatial wavelength reuse in only the second part of the frame, slow LED signaling, and the single point of failure formed by the central AWG, which are addressed in the following sections.

FT^{Λ}–FR^{Λ} AWG STAR WDM NETWORK

In the FT^{Λ}–FR^{Λ} AWG star WDM network, nodes use readily available and technically mature arrays consisting of Λ fixed-tuned transceivers instead of a single fast tunable transceiver which is technologically less mature [14]. In doing so, the network not only becomes practical but also allows for high-speed signaling over the AWG while the receiver arrays relieve the receiver bottleneck arising from multicasting in conjunction with spatial wavelength reuse, as discussed in the following.

ARCHITECTURE

Except for the node architecture, the $FT^{\Lambda} - FR^{\Lambda}$ network architecture is identical to that of Fig. 3. Instead of a single fast tunable transceiver, each node is equipped with an array of Λ fixed tuned transmitters and an array of Λ fixed tuned receivers, each operating at a different wavelength, where Λ denotes the number of available wavelengths. A wavelength multiplexer is used to combine the transmitters of a given node onto a common fiber, which in turn is attached to the corresponding combiner. Similarly, a wavelength demultiplex-

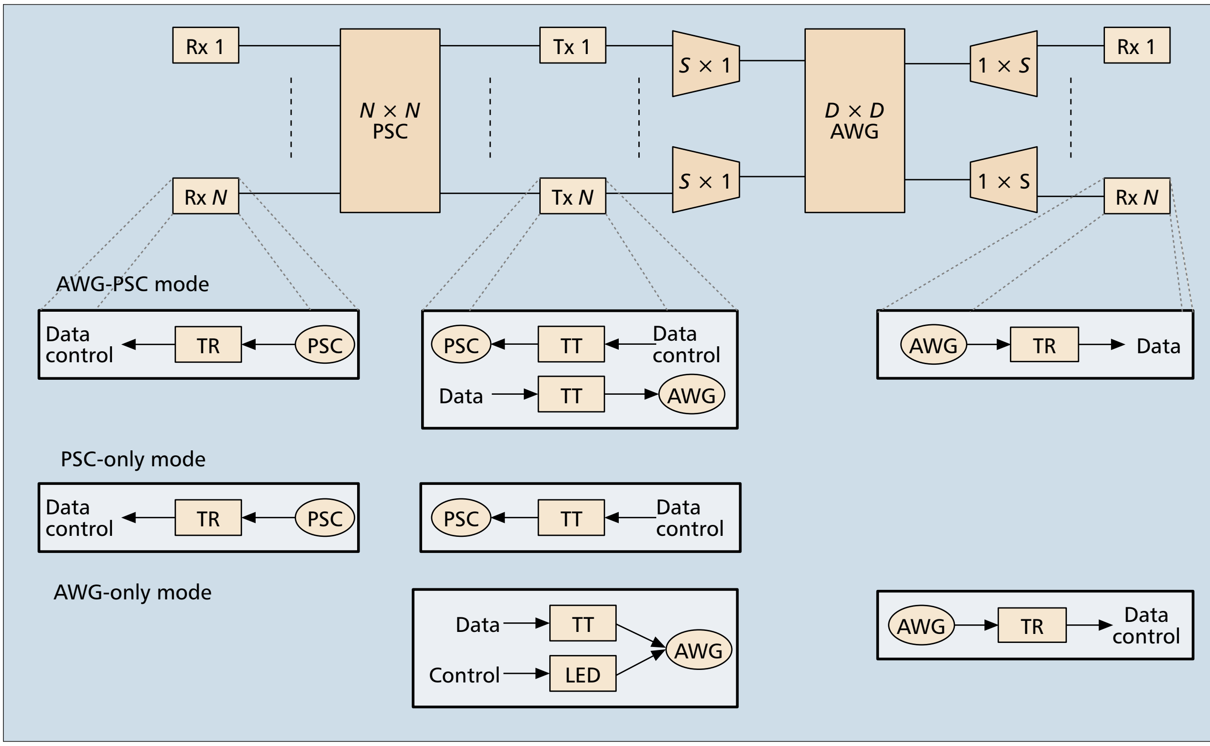

FIGURE 5. AWG||PSC single-hop star WDM network: detailed node architecture with transmitter and receiver connections to AWG and PSC for the three different modes of operation, where a given node's transmitter and receiver are collocated. (The AWG and PSC are arranged in parallel; for illustration the network is "unfolded" here.)

er is used to separate a WDM comb signal coming from the corresponding splitter to the receivers of a given node. Given the transceiver arrays, each node is able to transmit and receive on all Λ wavelength channels at any time.

ACCESS PROTOCOL

In the access protocol of the $FT^{\Lambda} - FR^{\Lambda}$ AWG network, time is divided into frames without requiring the cyclic structure of the TT-TR AWG network. Each frame consists of a control phase and a data phase. In the control phase of each frame, nodes ready to send data packets broadcast reservation control packets. Broadcasting is done by means of simultaneous transmission of the control packet on all wavelengths spanning a single FSR of the underlying AWG. In doing so, the control packet is sent to all AWG output ports and can thus be received by all nodes. By exploiting the spatial reuse capability of the AWG, control packets can be transmitted at all AWG input ports simultaneously, resulting in a further increase in signaling speed. The transmission schedule is computed similar to the TT-TR AWG star network.

RESULTS

As analytical and simulative results in [14] show, transmitter arrays significantly increase the throughput of the network for unicast data traffic by exploiting the large number of available wavelength channels obtained through spatial wavelength reuse and achieving faster signaling. For multicast traffic, the results clearly demonstrate that the receiver array at each node alleviates the receiver bottleneck of the TT-TR AWG star network and improves multicast performance significantly. The $FT^{\Lambda} - FR^{\Lambda}$ AWG star network achieves particularly good throughput-delay performance for multicast data traffic with small multicast group sizes or localized multicast destination nodes, as well as for a mix of unicast and multicast data traffic. However, for large multicast groups with destination nodes attached to several different AWG output ports, the partitioning of multicast transmissions into multiple multicast copies restricts the multicast performance of the FT^{Λ}–FR^{Λ} AWG star network. In this case, PSC-based broadcast-and-select networks provide a more bandwidth-efficient solution in that a multicast data packet must be sent only once. As discussed below, using a PSC in parallel with an AWG not only enables efficient transport of multicast traffic destined for a large number of receivers, but also allows broadcasting of the control information on the wavelength-insensitive PSC.

AWG||PSC STAR WDM NETWORK

Besides the aforementioned performance improvements we also address survivability issues in this section. Note that both TT-TR and FT^{Λ}–FR^{Λ} AWG-based single-hop star networks are immune from node failures since nodes do not have to forward traffic. Moreover, they are fairly reliable due to their passive nature. However, both suffer from a single point of failure. If the central hub fails, network connectivity is entirely lost due to missing alternate paths. In the following we describe the AWG||PSC single-hop star WDM network where the AWG and PSC protect each other in a highly efficient manner [15].

ARCHITECTURE

Figure 5 depicts the architecture of the AWG||PSC single-hop star WDM network with the AWG operating in parallel with the PSC. Each node is equipped with two fast TTs, two fast TRs, each with a tuning range of one or more FSRs of the underlying AWG, and one LED. (Alternatively, the tunable transceivers can be replaced with transceiver arrays.) Both pairs of TTs and TRs can be used to transmit and receive packets over the AWG and PSC simultaneously. The AWG||PSC star WDM network operates in three different modes:

- *AWG-PSC mode*, with both AWG and PSC functional
- *PSC-only mode*, with the AWG down
- *AWG-only mode*, with the PSC down, as explained in greater detail next

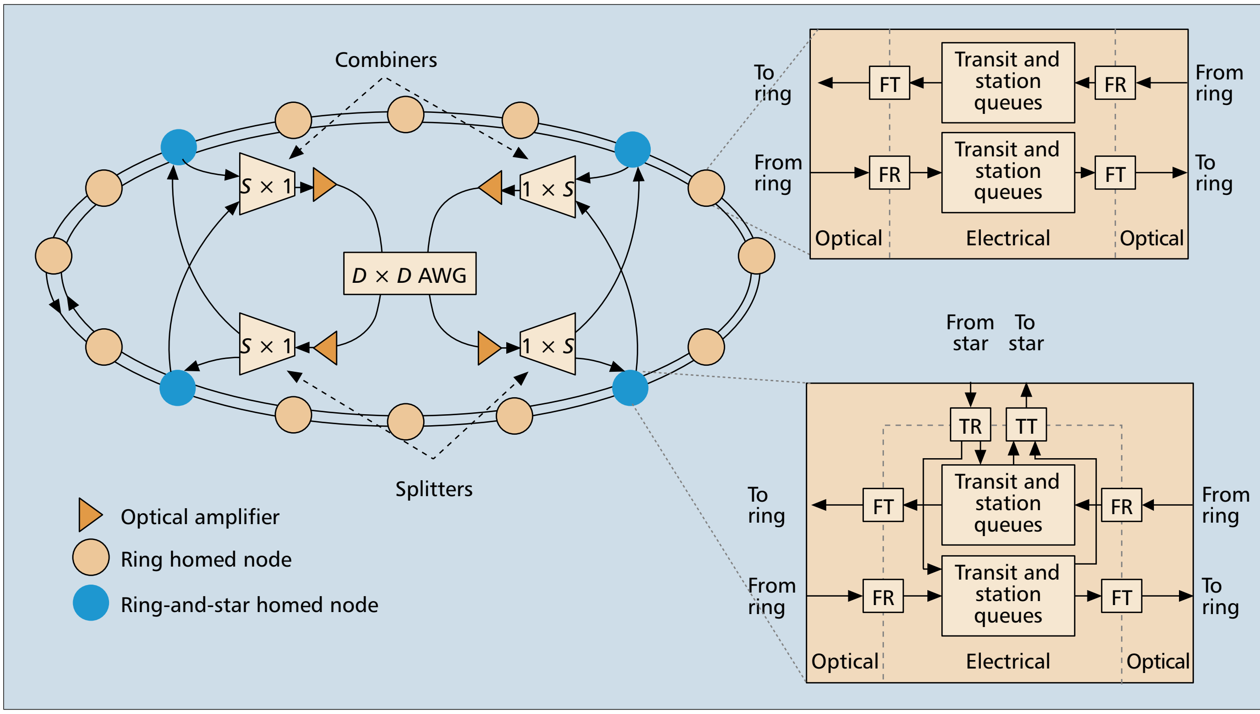

FIGURE 6. Hybrid star-ring multihop WDM network: A subset of the ring nodes are interconnected by an AWG based single-hop star WDM subnetwork.

ACCESS PROTOCOL

In all three operation modes, wavelength channel access is governed by a reservation-based MAC protocol with pretransmission coordination. Successfully transmitted control packets are processed in a distributed manner to schedule the transmission of the corresponding data packets.

- AWG-PSC mode: Similar to the $FT^{\wedge}$–$FR^{\wedge}$ AWG star network, time is divided into frames in AWG-PSC mode. Specifically, on the PSC each frame is divided into a control phase and a data phase. During the control phase of each frame all nodes tune their PSC TR to a preassigned wavelength. The frames on the AWG are fully used for data.
- PSC-only mode: In PSC-only mode, control and data communications take place only across the PSC.
- AWG-only mode: In the AWG-only mode, the AWG||PSC star network is identical to the TT-TR AWG star network, applying the same cyclic timing structure and signaling approach.

RESULTS

The AWG||PSC single-hop star WDM network provides enhanced throughput-delay performance by exploiting the respective strengths of the AWG (spatial wavelength reuse) and PSC (broadcast) during normal operation. The performance analysis in [15] shows that the throughput is significantly larger than the total throughput obtained by combining the throughput of a standalone AWG star network with the throughput of a standalone PSC star network. Furthermore, the AWG||PSC star network gives, over a wide operating range, better throughput-delay performance than a network consisting of either two load sharing PSCs in parallel or two load sharing AWGs in parallel. The proposed heterogeneous protection of an AWG in parallel with a PSC is more efficient than conventional 1 + 1 and 1:1 protection schemes that use two identical devices.

HYBRID STAR–RING WDM NETWORK

In this section we put the above mentioned AWG star WDM networks into perspective and discuss how they can be efficiently combined with optical ring networks. Recall from an earlier section that in WDM rings *all* nodes need to be WDM capable, be it by means of transceiver arrays, wavelength (de)multiplexers, or OADMs. In WDM rings, data packets generally have to traverse multiple intermediate nodes to reach their destination, which leads to inefficiencies. Moreover, bidirectional rings are fault-tolerant against any single node or fiber failure (by steering away traffic from the failed fiber or node by means of ring wrapping).

Figure 6 depicts a hybrid star-ring multihop WDM network that enhances the aforementioned performance characteristics of ring networks. The star-ring network makes use of the TT-TR AWG-based single-hop star WDM network described earlier (alternatively, the $FT^{\wedge}$ – $FR^{\wedge}$ AWG or AWG||PSC star WDM networks with their respective strengths could be used). A subset of the ring nodes are attached to the TT-TR AWG star network. The ring network is a bidirectional dual-fiber network with each fiber carrying a single wavelength and optical-electrical-optical (OEO) signal conversion at each node, similar to IEEE 802.17 resilient packet ring (RPR). By routing ring traffic across single-hop shortcuts of the star network instead of the peripheral ring, the traffic is restricted to smaller segments on the ring. As a result, fewer ring network resources are utilized and spatial wavelength reuse on the ring is increased. The AWG-based star network provides additional spatial reuse gain of all wavelengths used in the star network. Most important, only a subset of ring nodes need to be WDM upgraded (by a single tunable transceiver), as opposed to conventional WDM upgrades that affect all ring nodes. Thus, the hybrid star-ring network is able to increase spatial wavelength reuse and decrease the number of nodal WDM upgrades at the expense of interconnecting the corresponding nodes by a star subnetwork. The star subnetwork, however, can be built in a cost-effective way by using dark (unlit) fibers, which are typically abundantly available in metropolitan areas. The hybrid star-ring network is modularly upgradable in a pay-as-you-grow manner; that is, additional ring nodes can be WDM upgraded (with a single tunable transceiver) and connected to the star network as traffic demands grow. Finally, the star-ring network provides greater resilience against fiber and/or node failures than ring networks. Traffic can be steered away from the failure by using not only the ring but also the fibers of the star network.

CONCLUSIONS

The AWG plays a key role in current and future metro WDM network solutions. Besides several WDM applications in ring, interconnected ring, and meshed networks, the AWG can be used as wavelength router. Using the AWG as a central wavelength routing hub, highly efficient star network architectures can be realized by exploiting the spatial reuse capability of the AWG. The described AWG-based star metro WDM networks and access protocols are able to meet the key requirements of future metro solutions (i.e., modular upgradability, transparency, flexibility, efficiency, reliability, and protection). Hybrid AWG-based star-ring metro WDM networks provide an increased degree of spatial wavelength reuse and resilience. To cope with future increasing traffic demands current metro ring networks must evolve accordingly. The star-ring metro WDM network is a promising candidate that inspires the development of efficient hybrid WDM network architectures and access protocols.

ACKNOWLEDGMENT

The authors would like to thank Hyo-Sik Yang, Chun Fan, Michael Scheutzow, Martin Herzog, Stefan Adams, Adam Wolisz, and W. Matthew Carlyle for fruitful collaboration and their significant contributions over the last few years.

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BIOGRAPHIES

MARTIN MAIER (martin.maier@cttc.es) was educated at Technical University Berlin, Germany, and received Dipl.-Ing. and Dr.-Ing. degrees (both with distinctions) in 1998 and 2003, respectively. Currently, he is a research associate at CTTC, Barcelona, Spain, and focuses on evolutionary WDM upgrades of optical access and metro networks. He is author of the book *Metropolitan Area WDM Networks — An AWG Based Approach* (Kluwer, 2003).

MARTIN REISSLEIN (reisslein@asu.edu) is an assistant professor in the Department of Electrical Engineering at Arizona State University, Tempe. He received his Ph.D. in systems engineering from the University of Pennsylvania in 1998. From July 1998 through October 2000 he was a scientist with the German National Research Center for Information Technology (GMD FOKUS), Berlin, and lecturer at Technical University Berlin. He maintains an extensive library of video traces for network performance evaluation, including frame size traces of MPEG-4 and H.263 encoded video, at http://trace.eas.asu.edu