WDM Star Subnetwork Upgrade of Optical Ring Networks for Maximum Spatial Reuse under Multicast Traffic

Michael Scheutzow, Patrick Seeling, Martin Maier, and Martin Reisslein

***Abstract*— We examine a recently proposed multichannel upgrade of optical single-channel ring networks where a subset of ring nodes is WDM upgraded and interconnected by a single-hop star WDM subnetwork in a pay-as-you-grow fashion. This evolutionary approach not only allows for fast and efficient multiple-failure recovery but also is well suited to efficiently sustain unpredictable changes and shifts in traffic loads. In this paper, we analytically investigate the maximum achievable capacity of the WDM star subnetwork upgrade of optical single-channel networks under a variety of unicast and multicast traffic scenarios and compare it to that of conventional WDM ring networks. In our analysis, we take priority of ring in-transit traffic, destination stripping, and maximum spatial reuse into account. Our findings show that under multicast traffic the configuration of the star subnetwork plays an important role in order to achieve high multicast capacity. Furthermore, under multicast traffic WDM upgrading and interconnecting a subset of ring nodes might be sufficient to achieve a larger multicast capacity than in WDM rings.**

***Index Terms*— Capacity, destination stripping, multicast, optical rings, shortest path routing, spatial reuse, wavelength division multiplexing (WDM).**

I. Introduction

OPTICAL ring networks are widely deployed in today's existing telecommunications networks infrastructure due to their simplicity in terms of operation, administration, and maintenance (OAM) as well as their capability of fast protection switching in the event of a single link or node failure. Optical ring networks have initially been single-channel systems, where each fiber link carries a single wavelength channel, e.g., IEEE 802.5 Token Ring and ANSI Fiber Distributed Data Interface (FDDI). The interest in single-channel optical rings is still high, as witnessed by the recently approved standard IEEE 802.17 Resilient Packet Ring (RPR) [1], [2].

Multichannel upgraded optical ring networks have been receiving a great deal of attention, where each fiber link carries multiple wavelength channels by means of wavelength division multiplexing (WDM) [3]. WDM ring networks leverage on the existing fiber ring infrastructure and thus do not require additional fiber. Furthermore, WDM rings allow the design of all-optical (OOO) node architectures in which a part of the optical WDM signal, namely all wavelengths except the locally dropped wavelength(s), remains in the optical domain and does not need to be converted into the electrical domain, electronically stored and processed, and converted back to an optical signal. The resultant OOO node structures provide transparency against protocol, data rate, and modulation format. This transparency facilitates the support of a wide variety of both legacy and future traffic types, services, and applications.

At the downside, both single-channel and multichannel (WDM) optical ring networks suffer from a number of shortcomings. Their limited recovery against only a single failure might be insufficient for optical metropolitan and regional area networks which have to be extremely survivable [4]. Survivability of optical ring networks becomes crucial in particular for storage networking protocols, which are one of the important applications without built-in adequate survivability that rely almost entirely on the failure recovery techniques of the optical layer [5]. More importantly, ring networks have been recently shown to be worst suited to support unpredictable traffic, which stems from events that are hard to predict by current traffic forecasting techniques, e.g., breaking news, flash crowd events, and denial-of-service attacks, and the presented results indicate the need for topological modifications of ring networks [6].

Apart from deploying WDM on the fiber ring infrastructure, there exists another recently proposed approach to multichannel upgrade optical single-channel ring networks where a subset of ring nodes is interconnected by a dark-fiber single-hop star WDM network [7]. In this approach, a subset of ring nodes are attached to the star WDM subnetwork in a pay-as-you-grow fashion according to given traffic demands, cost constraints, and/or network operator preferences. Clearly, unlike WDM rings this approach requires additional fiber links to build the star WDM subnetwork. However, this evolutionary approach allows nodes to be WDM upgraded and attached to the star WDM subnetwork one at a time, as opposed to deploying WDM on the ring which affects each network node. Furthermore, the additional star subnetwork enables the fast and efficient recovery from *multiple* link and node

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failures in optical ring networks without losing full network connectivity [8]. In addition, the resultant hybrid optical ring-star network is well suited to efficiently sustain unpredictable changes and shifts in traffic load [9]. It was shown in [10], that ring-star networks provide a larger lifetime, i.e., ability to sustain unexpected changes and shifts in traffic loads, than conventional rings, meshed rings, and chordal rings.

In this paper, we analytically investigate the maximum achievable capacity of the WDM star subnetwork upgrade of optical (single-channel) networks under a variety of unicast and multicast traffic scenarios and compare it to that of conventional WDM ring networks. The remainder of the paper is organized as follows. The following subsection reviews related work. Section II describes the WDM star subnetwork upgrade in greater detail. In Section III, we analytically evaluate the capacity of the WDM star subnetwork upgrade. Numerical results are presented in Section IV. Section V concludes the paper.

A. Related Work

Optical WDM ring networks were experimentally demonstrated in [11], [12]. The capacity of various empty-slot medium access control (MAC) protocols for unidirectional WDM rings with destination stripping was investigated for unicast traffic in [13]. The scheduling of connections and cost-effective design of bidirectional WDM rings was addressed in [14]. Cost-effective traffic grooming approaches in WDM rings have been studied in [15], [16]. The routing and wavelength assignment in reconfigurable bidirectional WDM rings with wavelength converters was examined in [17]. Meshed rings using a reduced number of wavelengths were investigated in [18]. For more details on the graph-theoretical aspects of augmented ring networks that deploy short-cut links in addition to the ring the interested reader is referred to [19]. The design of high-reliability topological architectures under independent and correlated failures was studied in [20].

We note that the capacity of bidirectional WDM ring networks with suboptimal spatial reuse has been analyzed for multicast traffic in [21], where a source node is allowed to send a given multicast packet in only one direction (either clockwise or counterclockwise) on each wavelength channel. In contrast, in this paper a source node is allowed to send copies of a given multicast packet in both directions on each wavelength channel in order to minimize the number of required hops and thus maximize spatial reuse. Also, we note that a preliminary analysis of a hybrid ring-star network was presented in [22] for unicast traffic. This work differs from [22] in that (i) we consider multicast traffic, and (ii) investigate a different star WDM subnetwork which is able to support multicast traffic more efficiently. In particular, an arrayed-waveguide grating (AWG) based star subnetwork is considered in [22], whereas a star subnetwork consisting of an AWG in parallel with a passive star coupler (PSC) is considered in this work.

II. WDM Star Subnetwork Upgrade

A. Motivation

The considered WDM star subnetwork upgrade targets metro core rings which have to meet several requirements. Aside from configurability, reliability, flexibility, scalability, and large capacity, metro core rings have to be extremely survivable [4]. If the metro core ring network fails, all customers are potentially left without service. Thus, survivability in metro core ring networks is crucial. Recently, we have shown in [8] that by interconnecting a subset of the ring nodes with a single-hop star WDM network, the ring network is divided into separate domains, each being fully recoverable from a single link or node failure without losing full network connectivity. The resultant hybrid ring-star network provides fast and efficient recovery against multiple failures, as opposed to conventional WDM rings which can survive only a single failure. Furthermore, for unicast traffic, the hybrid ring-star network clearly outperforms conventional WDM rings in terms of spatial wavelength reuse, capacity, and scalability [23].

B. Architecture

Each ring node has a pair of fixed-tuned transmitters and fixed-tuned receivers, one for each single-channel fiber ring (FT^2–FR^2). The subnetwork is a single-hop star WDM network whose hub consists of a wavelength-routing $D \times D$ arrayed-waveguide grating (AWG) in parallel with a wavelength-broadcasting $D \times D$ passive star coupler (PSC), where $D \geq 1$. A subset of $D \cdot S \leq N$ nodes with indices $[(d-1)SN + iN]/(DS)$ with $i = 1, \ldots, S$ are attached to the input port d and output port d, $d = 1, 2, \ldots, D$, of the AWG and PSC via a common combiner/splitter with S ports, $S \geq 1$, as shown in Fig. 1 for $N = 16$ and $D \cdot S = 2 \cdot 2 = 4$. We refer to the nodes attached to the star subnetwork as ring-and-star homed (RS) nodes and to the other nodes as ring-homed nodes. We refer to the part of the ring between two adjacent RS nodes as *RS segment*. Thus, with N network nodes and DS RS nodes there are DS RS segments in the network, each containing $N/(DS) - 1$ ring-homed nodes. Note that the rather complex star subnetwork in Fig. 1 can be simplified dramatically according to given traffic demands, cost constraints, and/or network operator preferences by setting the parameters D and S to sufficiently small values. For instance, for $D = 1$ and $S = 2$ two opposite ring nodes are interconnected by a pair of counterdirectional fiber links and both AWG and PSC reduce to a simple piece of fiber.

The set of Λ contiguous wavelength channels used on the star subnetwork is given by:

- *For control*: One control wavelength λ_c on the PSC.
- *For data*: A set of Λ_{PSC} wavelength channels on the PSC and a set of Λ_{AWG} wavelengths on the AWG. Λ_{PSC} can comprise any number of wavelength channels while on the AWG we have $\Lambda_{\text{AWG}} = D \cdot R$, where R denotes the number of used free spectral ranges (FSRs) of the underlying $D \times D$ AWG.

Thus, a total of $\Lambda = 1 + \Lambda_{\text{PSC}} + D \cdot R$ contiguous wavelength channels are used on the star WDM subnetwork.

As shown in Fig. 1, the signals from S ring-and-star homed nodes on the Λ wavelength channels are transmitted on S distinct fibers to a $S \times 1$ combiner, which combines the signals onto the Λ wavelength channels of one fiber leading to a waveband partitioner. The waveband partitioner partitions the set of

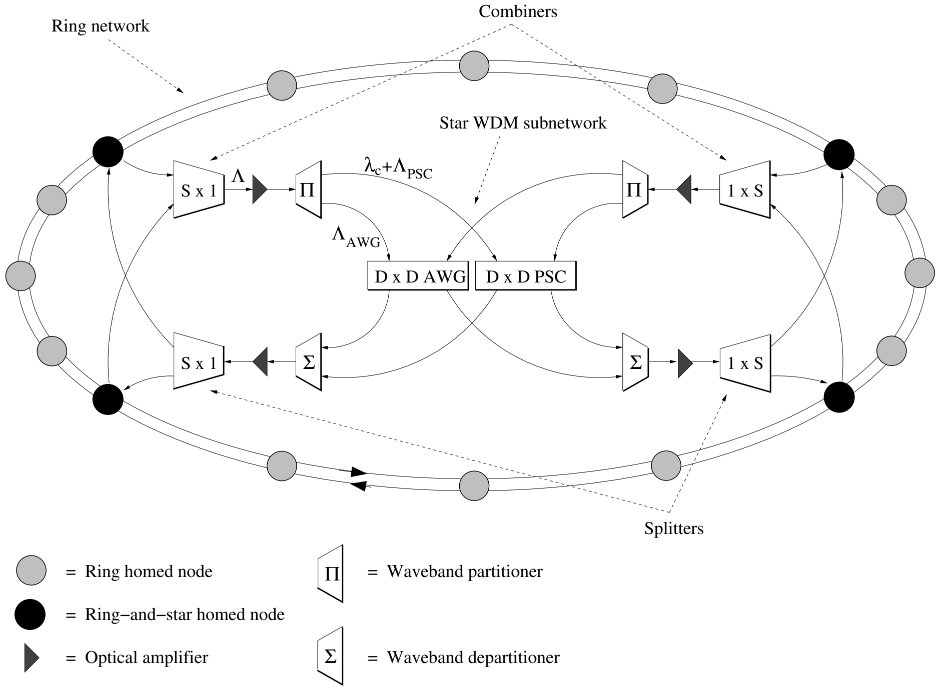

Fig. 1. Ring network with $N = 16$ nodes upgraded by a star WDM subnetwork, where $D \cdot S = 2 \cdot 2 = 4$ are ring-and-star homed (RS) nodes and $N - D \cdot S = 12$ are ring homed nodes. There are one control wavelength λ_c and Λ_{PSC} data wavelengths on the PSC, $\Lambda_{\mathrm{AWG}} = D \cdot R = 2 \cdot R$ data wavelengths on the AWG, for a total of $\Lambda = 1 + \Lambda_{\mathrm{PSC}} + 2 \cdot R$ wavelengths in the star WDM subnetwork.

Λ wavelengths into two wavebands: one waveband comprising the control wavelength λ_c and the Λ_{PSC} PSC data wavelengths which is fed into a PSC input port, and another waveband comprising the Λ_{AWG} AWG data wavelengths which is fed into an AWG input port. The signals from the opposite PSC and AWG output ports are collected by a waveband departitioner and then equally distributed to the S ring-and-star homed nodes by a $1 \times S$ splitter. If necessary, optical amplifiers are used between combiner and partitioner as well as splitter and departitioner to compensate for attenuation and insertion losses of the star subnetwork. A total of D of these arrangements, each consisting of combiner, amplifier, waveband partitioner, waveband departitioner, amplifier, and splitter, are used to connect all $D \cdot S$ ring-and-star homed nodes to the central hub.

For transmission and reception on the star WDM subnetwork each ring-and-star homed node is equipped with the following additional transmitters and receivers:

- For λ_c: One pair of fixed-tuned transmitter and fixed-tuned receiver (FT–FR).
- For the Λ_{PSC} PSC data wavelengths: One tunable transmitter (tuning range of Λ_{PSC}) and an array of Λ_{PSC} fixed-tuned receivers (TT–FR$^{\Lambda_{\mathrm{PSC}}}$).
- For the Λ_{AWG} AWG data wavelengths: An array of Λ_{AWG} fixed-tuned transmitters and Λ_{AWG} fixed-tuned receivers (FT$^{\Lambda_{\mathrm{AWG}}}$–FR$^{\Lambda_{\mathrm{AWG}}}$). (Note that each ring-and-star homed node could be alternatively equipped with a different transceiver set-up, e.g., a single transceiver tunable over Λ_{AWG}. However, we prefer the aforementioned fixed-tuned transceiver array in order to fully exploit the potential of the AWG by spatially reusing all Λ_{AWG} wavelength channels at each AWG port simultaneously, resulting in a dramatically increased network capacity [24]. We also note that using transceiver arrays is the preferred solution in real-world AWG based star WDM networks [25].)

C. Access Control

Since we are interested in evaluating the maximum achievable capacity of the WDM star subnetwork upgrade rather than the maximum achievable throughput of a given medium access control (MAC) protocol running on it, we do not consider any specific MAC protocol in our subsequent analysis. The obtained capacity results may be used to examine the throughput efficiency of any given MAC protocol by considering the ratio of throughput of the MAC protocol and the maximum achievable capacity of the WDM star subnetwork upgrade. However, we do make the following basic reasonable assumptions on the access control. First, on the ring in-transit traffic is given priority over locally generated station traffic. Second, in order to increase spatial reuse all ring nodes perform destination stripping, i.e., destination nodes pull packets destined for them from the ring. Third, access to the wavelength channels of the star subnetwork is arbitrated by using a distributed reservation protocol that enables all ring-and-star homed nodes to exchange their current backlog status by broadcasting control packets on λ_c, which are used to build a common distributed data transmission schedule on the $\Lambda_{\mathrm{PSC}} + \Lambda_{\mathrm{AWG}}$ data wavelengths according to the following routing strategies.

D. Routing

All N nodes deploy shortest path routing, using the single-hop short-cuts of the star subnetwork in order to minimize the number of required hops and thus maximize spatial reuse on the ring network. One exception is the transmission by a ring-homed node to the other ring-homed nodes on the same RS segment, which is always conducted over the ring to keep the loading of the segments attached to the RS nodes low, see Section III-B. Unicast packets as well as multicast packets that need to be sent to less than B AWG output ports, $B \leq D$, are sent on the corresponding wavelength channel(s) over the AWG. Whereas multicast packets that needed to be sent to at least B AWG output ports are sent on any wavelength channel over the PSC.

E. Discussion

We note that the star subnetwork shown in Fig. 1 provides excellent survivability at the expense of additional hardware, e.g., combiners/splitters, AWG, and PSC. Depending on given cost constraints and survivability requirements, the star subnetwork can be dramatically simplified by setting the parameters D, S, and R to sufficiently small values [9]. For instance, with $D = 1$ and $S = 2$ two opposite ring nodes are interconnected by a pair of counterdirectional fiber links and both AWG and PSC reduce to a simple piece of fiber. Also note that the star subnetwork is built using low-cost optical passive components off the shelf and dark fibers which are abundantly available in most of today's metropolitan areas. For transmission and reception on the star subnetwork, only a subset of the ring nodes need to be equipped with additional WDM transceivers. In contrast, conventional ring WDM upgrades affect all ring nodes. For practical implementation, an interesting approach might be to deploy a small number of wavelength channels on the ring network and attach ring nodes with high traffic loads to the star subnetwork in order to benefit from its single-hop short-cut links and thereby offload the ring network [7].

III. Evaluation of Capacity of WDM Star Subnetwork Upgrade

A. Traffic Model and Performance Metrics

Throughout the work, we consider the following traffic model: Each generated packet is destined to F nodes, $1 \leq F \leq N - 1$, where the probability mass function of F is given by

$$\mu_l = P(F = l), \quad l = 1, 2, \ldots, N - 1, \tag{1}$$

with $0 \leq \mu_l \leq 1$ and $\sum_{l=1}^{N-1} \mu_l = 1$. We consider uniform traffic, i.e., (i) each node generates the same amount of traffic, (ii) a source node must not send any packets to itself, and (iii) the fanout set (set of destination nodes) $\mathcal{F}$ for a given packet with given fanout F is drawn uniformly randomly from among the remaining $(N-1)$ nodes. Our assumption of uniform multicast traffic is motivated by the fact that traffic demands in metro core rings are typically uniform with any-to-any traffic between all attached nodes [26]. (For more detailed information on the throughput-delay performance analysis under nonuniform unicast traffic demands (both symmetric and asymmetric) the interested reader is referred to [27].)

We examine the maximum throughput (stability limit) achieved with the two complementary WDM upgrades. In particular, we consider the maximum number of multicast packets (with a given traffic pattern) that can in the long run average be sent simultaneously and refer to this metric as *effective multicast capacity* C_M. Importantly, the wavelength channels on the individual ring segments between nodes are generally unevenly loaded in WDM ring networks [13], [21] and also on the ring augmented with the WDM star subnetwork. The effective capacity is therefore limited by the utilization of the most heavily loaded ring segments, as analyzed in greater detail in the following two sections. Generally, in WDM rings, the shortest path routing, which maximizes spatial reuse, minimizes the utilization of the most heavily loaded segment and thus maximizes the capacity [28]. With the WDM star subnetwork, the ring segments connecting the RS segments to the RS nodes experience typically the highest utilization and we therefore limit the number of transmissions over these "critical" segments, see Section III-B. For brevity, we use in the following the term *capacity* to refer to the effective multicast capacity, unless otherwise noted.

Initially, we focus on the limitation on the capacity due to the RS segments of the single wavelength ring network between two adjacent ring-and-star homed (RS) nodes. Recall that with N network nodes and DS RS nodes there are DS RS segments in the network, each containing $N/(DS) - 1$ ring-homed nodes. The analysis of the capacity of the RS segment provides the limitation on the capacity imposed by the ring subnetwork. Subsequently, we examine the limitations imposed by the PSC and the AWG of the WDM star subnetwork on the capacity. The overall capacity of the network is then obtained as the minimum of the capacity limitations of the various network components, as detailed in Section III-D.

B. Capacity of RS Segment

Without loss of generality we focus on an arbitrary RS segment. We denote the set of ring-homed nodes on the considered RS segment by $\mathcal{A}$ and note that $|\mathcal{A}| = N/(DS) - 1$. We refer to the directed ring segments connecting the individual nodes on the RS segment as *segments*. Note that there are $\Gamma = N/(DS)$ segments in the clockwise direction and $\Gamma = N/(DS)$ segments in the counter clockwise direction in an RS segment. Without loss of generality we consider the segments in one direction, which we refer to henceforth as being from *left* to *right*, and index the successive segments in that direction by $i, \ i = 1, \ldots, \Gamma$. Note that segment $i = 1$ connects the ring-and-star homed node bordering from the left on the RS segment with the first (left-most) ring-homed node in the RS segment. Segment $i = \Gamma$ connects the right-most ring-homed node with the ring-and-star homed node bordering from the right on the considered RS segment.

We denote $u_i, \ i = 1, \ldots, \Gamma$, for the probability that a given arbitrary multicast utilizes the directed segment i. We define $u^r_{\max} = \max_{i=1,\ldots,\Gamma} u_i$ as the maximum utilization probability of a directed segment. The limitation on the capacity imposed by the RS segments is then given as the reciprocal of the maximum utilization probability, i.e.,

$$C^r_M = 1/u^r_{\max}. \tag{2}$$

We distinguish two types of traffic contributions to the utilization probability u_i, namely *source traffic* and *destination* *traffic*. Source traffic originates from one of the ring-homed nodes in the considered RS segment, and may have destinations inside and/or outside the considered RS segment. We denote s_i for the probability that a given arbitrary multicast utilizes the directed segment i in the form of source traffic. Destination traffic originates from a node outside the considered RS segment and has at least one destination among the $|\mathcal{A}|$ nodes in the RS segment. We denote d_i for the probability that a given arbitrary multicast utilizes the directed segment i in the form of destination traffic. Since the segment utilization due to source and destination traffic are complementary events, we have

$$u_i = s_i + d_i, \qquad i = 1, \dots, \Gamma = N/(DS). \tag{3}$$

Toward the evaluation of the segment utilization probability u_i we first evaluate the utilization probability due to destination traffic d_i and then due to source traffic s_i. Throughout this analysis we consider the general shortest path routing principle. Specifically, destination traffic enters the RS segment from the bordering RS node that reaches all ring-homed destination nodes in the RS segment with transmission in one ring direction with the smallest hop count. The ring-homed destinations are reached by a transmission from one bordering RS node to keep the load on the typically heavily loaded segment $i = 1$ connecting the RS segment to the RS node low (see Section III-B.5 for details), even though sending the packet from both bordering RS nodes may result in a lower hop count. Also, source traffic is sent to the left and to the right to reach all destinations in the RS segment, which is again advantageous to keep the load on the segment $i = 1$ low. If there is at least one destination outside the RS segment, then the packet is sent to the bordering RS node that can be reached with the smallest overall hop distance.

1) Segment Utilization Probability d_i due to Destination Traffic: First note that the source node of the considered multicast is outside the considered RS segment with probability $(1 - |\mathcal{A}|/N)$, and the probability for having ℓ multicast destinations in the considered RS segment under the condition that the source node is outside the considered RS segment is

$$\sum_{l=1}^{N-1} \mu_l \cdot \frac{\binom{|\mathcal{A}|}{\ell}\binom{N-1-|\mathcal{A}|}{l-\ell}}{\binom{N-1}{l}}. \tag{4}$$

The key idea toward the evaluation of d_i is to consider (i) the gap between the left ring-and-star homed node and the left-most destination node (which we refer to as the left *border gap*), and (ii) the gap between the right ring-and-star homed node and the right-most destination node (right border gap). Suppose the larger of these two gaps has k hops. Then, exactly $\Gamma - k$ segments are utilized in the RS segment to reach all the multicast destination nodes in it. For the considered uniform traffic it is by symmetry equally likely that the gap on the left or the right is the largest. So with probability 1/2 the largest gap is on the right, and the considered segments $i = 1, \dots, \Gamma - k$ (directed from left to right) are utilized. Formally we let $\gamma_\ell(k)$ denote the probability for the event that on an RS segment with ℓ destination nodes the larger of the two bordering gaps has k hops under the condition that the source node is outside the considered RS segment. With this definition we obtain

$$d_i = \frac{1}{2}\left(1 - \frac{|\mathcal{A}|}{N}\right)\sum_{l=1}^{N-1} \mu_l \sum_{\ell=1}^{\min(l,|\mathcal{A}|)} \frac{\binom{|\mathcal{A}|}{\ell}\binom{N-1-|\mathcal{A}|}{l-\ell}}{\binom{N-1}{l}} \sum_{k=1}^{\Gamma-i} \gamma_\ell(k). \tag{5}$$

For the evaluation of $\gamma_\ell(k)$ we view the RS segment as a ring, which is formed by merging the left and right ring-and-star homed nodes bordering on the considered RS segment. This ring model of the RS segment is equivalent to a single channel ring considered in [29]. In particular, note that $p_{\ell,\Gamma}(k) = \binom{\Gamma-k-1}{\ell-1}/\binom{\Gamma-1}{\ell}$ as given by Eqn. (13) in [29] represents the probability for the event that a particular considered gap in the ring model has k hops. We are interested in the two gaps bordering on the merged ring-and-star homed node. The larger one of these two gaps has k hops if one of two complementary events occurs: (A) the gap on the right side of the ring-and-star homed node has exactly k hops and the other gap has no more than k hops, or (B) the gap to the right has strictly less than k hops and the other gap has exactly k hops. Formally,

$$\begin{aligned}\gamma_\ell(k) &= p_{\ell,\Gamma}(k) \sum_{j=1}^{\min(k,\Gamma-k-\ell+1)} p_{\ell-1,\Gamma-k}(j) \\ &\quad + \sum_{j=1}^{\min(k-1,\Gamma-k-\ell+1)} p_{\ell,\Gamma}(j) \cdot p_{\ell-1,\Gamma-j}(k) \qquad (6)\\ &= \frac{1}{\binom{\Gamma-1}{\ell}} \left\{ 2\binom{\Gamma-k-1}{\ell-1} - 1_{\{\Gamma-2k \geq \ell-1\}}\binom{\Gamma-2k}{\ell-1} \right. \\ &\quad \left. -1_{\{\Gamma-2k \geq \ell\}}\binom{\Gamma-2k-1}{\ell-1} \right\}. \qquad (7)\end{aligned}$$

2) Segment Utilization Probability s_i due to Source Traffic: We distinguish two complementary scenarios: $\alpha)$ *pure source traffic* in which all multicast destinations are in the considered RS segment, and $\beta)$ *mixed source traffic* in which there is at least one destination node outside the considered RS segment. We denote s_i^α for the utilization probability due to pure source traffic, and s_i^β for the segment utilization probability due to mixed source traffic.

We note that the probability for the event that there are $l,\ l = 1, \dots, \Gamma - 2$, destinations in the multicast and all of them are located in the considered segment is given by $\sum_{l=1}^{\Gamma-2} \mu_l \binom{|\mathcal{A}|}{l+1}/\binom{N}{l+1}$. To see this note that there are $\binom{|\mathcal{A}|}{l+1}$ possible ways to choose the l destination nodes and the source node out of the $|\mathcal{A}| = \Gamma - 1$ nodes on the considered RS segment. We condition the utilization probability of the (directed) segment i on the hop lengths of the left and right border gaps. We denote

$$\begin{aligned}\epsilon_{k,m,l}(i) &= P(\text{ dir. segm. } i \text{ used } |l \text{ dest., all in RS seg.,} \\ &\quad \text{left border gap = } k \text{ hops, right border gap = } m \text{ hops}). \qquad (8)\end{aligned}$$

With this definition we have

$$\begin{aligned}s_i^\alpha &= \sum_{l=1}^{\Gamma-2} \mu_l \frac{\binom{|\mathcal{A}|}{l+1}}{\binom{N}{l+1}} \sum_{k,m=1}^{\Gamma-1} P(\text{left border gap = } k \text{ hops, right} \\ &\quad \text{border gap = } m \text{ hops} | l \text{ dest. and all in RS seg.}) \epsilon_{k,m,l}(i). \qquad (9)\end{aligned}$$

Modelling the RS segment as a ring as in the preceding section, and noting that now $l + 1$ nodes need to be placed on the ring (l destination nodes plus one source node, these $l+1$ nodes may be viewed as destination nodes and the merged ring-and-star homed node as the source node in the ring model) we obtain for the border gaps next to the merged ring-and-star homed node

$$P(\text{left border gap } = k \text{ hops, right border gap} = m \text{ hops} \mid l \text{ dest. and all in RS seg.}) = p_{l+1,\Gamma}(k) \cdot p_{l,\Gamma-k}(m) = \frac{\binom{\Gamma-k-1}{l}}{\binom{\Gamma-1}{l+1}} \cdot \frac{\binom{\Gamma-k-m-1}{l-1}}{\binom{\Gamma-k-1}{l}}. \quad (10)$$

Thus,

$$s_i^\alpha = \sum_{l=1}^{\Gamma-2} \frac{\mu_l}{\binom{N}{l+1}} \sum_{k=1}^{k_{\max}} \sum_{m=1}^{m_{\max}} \binom{\Gamma-k-m-1}{l-1} \epsilon_{k,m,l}(i) \quad (11)$$

with $k_{\max} = \min(i-1, \Gamma-l-1)$ and $m_{\max} = \min(\Gamma-i, \Gamma-k-l)$.

For the evaluation of $\epsilon_{k,m,l}(i)$ note that $\epsilon_{k,m,l}(i) = 0$ if the considered segment i falls into the left gap (i.e., if $i \le k$), or if the segment falls into the right gap (i.e., if $i \ge \Gamma - m + 1$). It remains to consider the range $k < i \le \Gamma - m$. In this case the directed segment i is used if the source node lies to the left of the segment. This is the case if (i) the source node lies all the way to the left in the considered range, which occurs with probability $1/(l+1)$, or (ii) the source node lies neither at the left nor the right end of the range, which has probability $1 - 2/(l+1)$, and the source node lies to left of segment i, which occurs with probability $(i-k-1)/(\Gamma-k-m-1)$ for $k + m < \Gamma - 1$. Thus, overall

$$\epsilon_{k,m,l}(i) = \begin{cases} 0 & \text{for } i \le k \text{ or } i \ge \Gamma - m + 1 \\ \frac{1}{l+1} & \text{for } k < i \le \Gamma - m \text{ and } k + m \ge \Gamma - 1 \\ \frac{1}{l+1} + \left(1 - \frac{2}{l+1}\right) \frac{i-k-1}{\Gamma-k-m-1} & \text{otherwise.} \end{cases} \quad (12)$$

For the case β) we obtain with reasoning that mirrors the evaluations leading to (11) that

$$s_i^\beta = \frac{|\mathcal{A}|}{N} \sum_{l=1}^{N-1} \mu_l \left\{ \frac{\binom{N-|\mathcal{A}|}{l}}{\binom{N-1}{l}} \frac{(2i-\Gamma-1)^+}{2(\Gamma-1)} \right. \quad (13)$$
$$\left. + \sum_{\ell=1}^{\min(l-1,|\mathcal{A}|-1)} \frac{\binom{|\mathcal{A}|-1}{\ell}\binom{N-|\mathcal{A}|}{l-\ell}}{\binom{N-1}{l}} \left(\sum_{k=1}^{i-1} \sum_{m=1}^{\Gamma-k-\ell} \frac{\binom{\Gamma-k-m-1}{\ell-1}}{\binom{\Gamma-1}{\ell+1}} \epsilon_{k,m,\ell}^\beta(i) \right) \right\},$$

whereby $|\mathcal{A}|/N$ is the probability that the source node is located in the considered RS segment and $\binom{|\mathcal{A}|-1}{\ell}\binom{N-|\mathcal{A}|}{l-\ell}$ is the number of possible ways for choosing ℓ multicast destinations in the RS segment and $l - \ell$ destinations outside the segment.

For the case β) we furthermore have

$$\epsilon_{k,m,\ell}^\beta(i) = \begin{cases} \epsilon_{k,m,\ell}(i) & \text{for } i \le \Gamma - m \\ 1 & \text{for } i > \Gamma - m \text{ and } m < k \\ \frac{1}{2} & \text{for } i > \Gamma - m \text{ and } m = k \\ 0 & \text{for } i > \Gamma - m \text{ and } m > k. \end{cases} \quad (14)$$

The last three cases in (14) account for the transmission to the border ring-and-star homed node such that all destination nodes inside the considered RS segment and the ring-and-star homed node are reached with the smallest overall hop count. In particular, if the right border gap is smaller than the left border gap (i.e., $m < k$), then the packet is sent on by the right-most destination node inside the RS segment over the considered directed segments i, $i > \Gamma - m$, to the right border ring-and-star homed node. If the border gaps have equal hop count (i.e., $m = k$), then the packet is sent on to either border ring-and-star homed node with equal probability, and if the left border gap is smaller (i.e., $m > k$), then the packet is sent to the left.

3) Unicast and Broadcast Traffic: In this section we briefly examine the RS segment capacity for the special cases of unicast traffic (for which $\mu_1 = 1$ and $\mu_l = 0$ for $l = 2, \ldots, N-1$) and for broadcast traffic (for which $\mu_{N-1} = 1$ and $\mu_l = 0$ for $l = 1, \ldots, N-2$). For unicast traffic, consider the directed (from left to right) segment i in a given (arbitrary) RS segment. According to the considered shortest path routing, this directed segment is utilized by an arbitrary unicast in the form of destination traffic if the source node is outside the RS segment, which occurs with probability $(N - |\mathcal{A}|)/N$, and the destination node is inside the considered RS segment and is reached with a smaller hop count by traversing the directed segment, which for even $|\mathcal{A}|$ and $i = 1, \ldots, (\Gamma-1)/2$ occurs with probability $[|\mathcal{A}|/2 - (i-1)]/(N-1)$. Hence,

$$d_i = \frac{N - |\mathcal{A}|}{N} \cdot \frac{\frac{|\mathcal{A}|}{2} - (i-1)}{N-1} \quad \text{for} \quad i = 1, \ldots, (\Gamma-1)/2 \quad (15)$$

and $d_i = 0$ for $i = (\Gamma+1)/2, \ldots, \Gamma$. The segment i is utilized in the form of pure source traffic if the source node is to the left (which occurs with probability $(i-1)/N$) and the destination node is to the right (which occurs with probability $(\Gamma - i)/N$) in the considered RS segment. Hence,

$$s_i^\alpha = \frac{i-1}{N} \frac{\Gamma - i}{N-1} \quad \text{for} \quad i = 1, \ldots, \Gamma. \quad (16)$$

Note that for the considered shortest path routing, the segment utilization due to mixed source traffic in the RS segment is a "mirror image" of the segment utilization due to destination traffic, i.e., for even $|\mathcal{A}|$ we have $s_i^\beta = d_{\Gamma-i+1}$. Overall we see from that the maximum utilization is attained by segment $i = 1$ (and segment $i = \Gamma$), i.e.,

$$u_{\max} = u_1 = \frac{N - |\mathcal{A}|}{N} \cdot \frac{|\mathcal{A}|}{2(N-1)}, \quad (17)$$

which for a large number of nodes N with the number of RS nodes DS held constant, approaches $(DS-1)/[2(DS)^2]$.

For broadcast traffic we obtain the following. A broadcast does not originate in a considered RS segment and hence enters the considered RS segment as destination traffic with probability $(1 - |\mathcal{A}|/N)$. The destination traffic traverses the considered RS segment in either direction up to the last ring-homed node with probability one half. Hence, $d_i = (1 - |\mathcal{A}|/N)/2$ for $i = 1, \ldots, \Gamma - 1$ and $d_\Gamma = 0$. For broadcast there are always destinations outside the considered RS segment, hence $s_i^\alpha = 0$ for $i = 1, \ldots, \Gamma$. For the segment utilization due to mixed source traffic note that a broadcast packet originates in a considered RS segment with probability $|\mathcal{A}|/N$ and utilizes the directed (from left to right) segment i, $i = 2, \ldots, \Gamma-1$, with probability $(i-1)/|\mathcal{A}|$ (which is the probability for having the source node to the left of segment i). Hence, $s_i^\beta = (i-1)/N$ for $i = 1, \ldots, \Gamma-1$. The broadcast packet generated in a given RS segment is transmitted to the left or right bordering RS node with equal probability, hence $s_\Gamma^\beta = |\mathcal{A}|/(2N)$. From these utilization probabilities we see that segment $\Gamma - 1$ attains the maximum utilization probability of

$$u_{\max} = u_{\Gamma-1} = \frac{1}{2} + \frac{|\mathcal{A}| - 2}{2N}. \quad (18)$$

Note that this $u_{\max}$ value is for $|\mathcal{A}| > 1$ larger than the utilization probability of $(N-1)/(2N)$ when sending broadcast traffic around the ring to the node preceding the source node. That is, the considered shortest path routing policy is suboptimal for broadcast traffic with $|\mathcal{A}| > 1$.

4) Bounds on Multicast Capacity C_M Due to RS Segments: In this section we provide upper and lower bounds on the utilization probability of RS segments and the corresponding bounds on the multicast capacity C_M of the hybrid ring-star network. For any routing policy and any traffic pattern (including uniform and non-uniform traffic patterns) we make the following observation. Let $\tilde{S}$ denote the number of RS segments containing at least one multicast destination (including the RS segment with the sender if it contains a destination). Then the multicast packet needs to enter at least $\tilde{S}$ RS segments, except for the RS segment containing the source node. Hence, the utilization $u_{\max}$ of the segment connecting an RS segment (in a given direction) with a given RS segment is at least

$$u_{\max} \geq \frac{1}{2}\frac{E[\text{\# of RS segm. with at least one dest.}] - 1}{\text{DS}}. \quad (19)$$

Therefore, the multicast capacity is upper bounded by $C_M \leq 2DS/(E[\tilde{S}] - 1)$. This bound can be further tightened by letting $\bar{S}$ denote the number of RS segments that contain at least one destination node, and not the source node. In each of these $\bar{S}$ RS segments, at least one of the segments $i = 1$ (in either ring direction) is utilized. Hence, we obtain the following upper bound on the multicast capacity $u_{\max} \geq E[\bar{S}]/(2DS) \;\Rightarrow\; C_M \leq 2DS/E[\bar{S}]$, which does *not* depend on the employed routing strategy and can be used to assess the performance of a specific routing strategy.

For uniform traffic, the probability that an RS segment contains at least one multicast destination is the same for every one of the DS RS segments in the network. Thus, for a routing policy that ensures that the individual segments in any given RS segment (including the RS segment with the source node) are traversed in the same direction, then $u_{\max} \leq E[\tilde{S}]/(2DS) \;\Rightarrow\; C_M \geq 2DS/E[\tilde{S}]$. On the other hand, for a routing policy that serves the destination nodes in the RS segment with the sender by sending one packet copy to the left and on to the right, then the bound loosens to $u_{\max} \leq E[\tilde{S}+1]/(2DS) \;\Rightarrow\; C_M \geq 2DS/(E[\tilde{S}]+1)$.

Overall we obtain

$$\frac{2DS}{E[\tilde{S}]} \leq C_M \leq \frac{2DS}{E[\tilde{S}] - 1} \quad (20)$$

for the routing policy that transmits a single packet copy in one direction into all the RS segments with a multicast destination. Correspondingly, $2DS/(E[\tilde{S}]+1) \leq C_M \leq 2DS/(E[\tilde{S}]-1)$ for the routing policy that sends the packet copy in one direction only in the RS segments that do not contain the source node. We also conclude that for $E[\tilde{S}] \ll DS$ the hybrid ring-star network archieves a significantly larger multicast capacity than the single-channel RS ring.

5) Considerations on Optimality of Shortest Path Routing Policy: In this section we present considerations on assessing the optimality of the shortest path routing policy, which minimizes the load on the (directed) segment $i = 1$ connecting an RS segment to the bordering RS node. As observed in Section III-B.3 for this routing policy, the maximum segment utilization is attained by segment $i = 1$ for unicast traffic. Thus, the considered routing policy is indeed optimal for unicast traffic in that it minimizes the utilization $u_{\max} = u_1$ of the most heavily loaded segment, and thus maximizes the multicast capacity $C_M = 1/u_{\max}$. On the other hand, we observed for broadcast traffic that segment $i = \Gamma - 1$ is the most heavily utilized segment with the considered routing policy, which is hence not optimal for broadcast traffic.

To assess the optimality of the considered routing policy for mixed traffic, we consider a traffic mix consisting of unicast traffic and broadcast traffic according to the distribution $\mu_1 = u,\ \mu_{N-1} = 1 - u$. Clearly, either u_1 and $u_{\Gamma-1}$, which are

$$u_1 = \frac{u}{2}\cdot\frac{N - |\mathcal{A}|}{N}\cdot\frac{|\mathcal{A}|}{N-1} + \frac{1-u}{2}\left(1 - \frac{|\mathcal{A}|}{N}\right) \quad (21)$$

$$u_{\Gamma-1} = \frac{u}{2}\cdot\frac{N - |\mathcal{A}|}{N}\cdot\frac{|\mathcal{A}| - 2}{N-1} + (1-u)\left(\frac{1}{2}\left(1 - \frac{|\mathcal{A}|}{N}\right) + \frac{|\mathcal{A} - 1|}{N}\right), \quad (22)$$

attains the maximum segment utilization probability. The considered shortest path routing policy is optimal when $u_1 \geq u_{\Gamma-1}$, i.e., when

$$u \geq \frac{(|\mathcal{A}| - 1)(N-1)}{N + 1 - 2|\mathcal{A}| + (|\mathcal{A}| - 1)(N-1)}, \quad (23)$$

which is the case for many practical traffic scenarios that are dominated by unicast traffic.

C. Stability Conditions for Star Subnetwork

In this section we analyze the stability conditions for the star subnetwork. We initially state general stability conditions for arbitrary traffic and routing strategies, and then consider the specific case of uniform traffic.

1) General Stability Conditions: We initially consider an arbitrary traffic pattern (which may be non-uniform) and an arbitrary (fixed) routing strategy. Let $\alpha_j,\ j = 1, \ldots, DS$, denote the rate in packets per time unit at which packets need to be transmitted from ring-and-star homed node j over the PSC. Then the stability condition for the PSC is

$$\sum_{j=1}^{DS} \alpha_j < \Lambda_{\text{PSC}}. \quad (24)$$

In addition, it is necessary that $\alpha_j < 1$ for all $j \in \{1, \ldots, DS\}$. Note that for uniform traffic the α_j are all identical and the conditions $\alpha_j < 1$ follow from $\Lambda_{\text{PSC}} \leq DS$ (with $\Lambda_{PSC} > DS$ there would be more wavelengths than transmitters).

Let $\beta_{ij},\ i,j = 1,\ldots,D$, denote the rate at which packets need to be transmitted from AWG input port i to AWG output port j. Then the stability conditions for the AWG are

$$\beta_{ij} < R \quad \text{for all } i,j \in \{1,\ldots,D\}. \tag{25}$$

We have assumed here that the packet size is fixed and normalized such that per time unit one packet can be transmitted onto the ring, the PSC, or the AWG. If the packet sizes are random, but independent from the fanout and the fanout set, then the α_j and β_{ij} would need to be multiplied with the expected value of the packet length.

In the following we consider uniform traffic and let σ denote the rate at which packets are generated in the network in packets per time unit. For an exact evaluation of the transmission rates over the star subnetwork we introduce the probability $d_l(k,j)$ for the event that

- a given arbitrary multicast packet with $l,\ l = 1,\ldots,N-1$, destination nodes requires transmission over the star subnetwork, and
  - if the packet would be transmitted over the AWG it would require $k,\ k = 1,\ldots,D$, copy transmissions, and
  - one of the copies would be destined to AWG output port $j,\ j = 1,\ldots,D$, counting in the clockwise direction (of the ring-and-star homed nodes on the ring perimeter as they are attached to the AWG output ports) from the AWG input port.

We define $d_l(0)$ as the probability for the event that a given arbitrary multicast packet does not require transmission over the star subnetwork, i.e., the packet is only transmitted over the ring subnetwork. From the probabilities $d_l(k,j),\ k = 1,\ldots,D$, we obtain

$$\sum_{j=1}^{D} d_l(k,j) = E_l\left[\sum_{j=1}^{D} 1_{\{k \text{ copies}\}} 1_{\{\text{port } j \text{ receives copy}\}}\right] \tag{26}$$

$$= E_l\left[1_{\{k \text{ copies}\}} \cdot k\right] = k \cdot P_l(k \text{ copies}), \tag{27}$$

whereby $E_l[\cdot]$ and $P_l(\cdot)$ denote the expected value and probability when there are l destination nodes. From (27) we obtain

$$P_l(k \text{ copies}) = \frac{1}{k}\sum_{j=1}^{D} d_l(k,j) \quad \text{and} \tag{28}$$

$$P_l(\text{pkt. transm. over star subnetw.}) = \sum_{k=1}^{D} \frac{1}{k} \sum_{j=1}^{D} d_l(k,j). \tag{29}$$

Suppose the routing strategy is such that fewer than B packet copies are transmitted over the AWG, and if B or more packet copies would be required over the AWG, then the multicast packet is transmitted over the PSC. Then the stability condition for the PSC is

$$\sigma \cdot \sum_{l=B}^{N-1} \mu_l \left(\sum_{k=B}^{D} P_l(k \text{ copies})\right) < \Lambda_{\text{PSC}}, \text{ i.e.,} \tag{30}$$

$$\sigma \cdot \sum_{l=B}^{N-1} \mu_l \left(1 - d_l(0) - \sum_{k=1}^{B-1} P_l(k \text{ copies})\right) < \Lambda_{\text{PSC}}, \tag{31}$$

whereby the expression (31) has the advantage that the probabilities $P_l(k \text{ copies})$ (and $d_l(k,j)$) are only required for $k = 0,\ldots,B-1$ to assess the stability condition. From (31) we see that the limitation on the multicast capacity imposed by the PSC of the star subnetwork C_M^{PSC} is given by

$$\sigma < \frac{\Lambda_{\text{PSC}}}{\sum_{l=B}^{N-1} \mu_l \left(1 - d_l(0) - \sum_{k=1}^{B-1} P_l(k \text{ copies})\right)} = C_M^{\text{PSC}}. \tag{32}$$

The stability conditions for the AWG are

$$\frac{\sigma}{D} \cdot \sum_{l=1}^{N-1} \mu_l \sum_{k=1}^{B-1} d_l(k,j) < R, \qquad j = 1,\ldots,D \tag{33}$$

and the corresponding limitations $C_M^{\text{AWG},j}$ imposed by the AWG of the star subnetwork on the multicast capacity are given by

$$\sigma < \frac{R \cdot D}{\sum_{l=1}^{N-1} \mu_l \sum_{k=1}^{B-1} d_l(k,j)} = C_M^{\text{AWG},j},\ j = 1,\ldots,D. \tag{34}$$

It remains to evaluate the $d_l(k,j)$, which depend on the specific routing policy employed in the network.

2) Evaluation of $d_l(k,j)$: In this section we evaluate the probabilities $d_l(k,j)$ for the event that a multicast packet with l destinations is transmitted over the star subnetwork and if it were transmitted over the AWG would require k copy transmissions, one of them destined to the jth AWG output port from the sender. In this evaluation we continue to consider shortest path routing, i.e., when an RS node receives a packet from a ring homed node on the attached RS segment, then the RS node sends the packet over the star subnetwork to the RS nodes that can reach the destinations in the other RS segments with the minimum hop count. Furthermore, if the packet requires the transmission of fewer than B packet copies over the AWG then the packet is transmitted over the AWG, and if B or more packet copies would be required over the AWG, then the multicast packet is transmitted over the PSC.

In the subsequent analysis we focus on the case $B = 2$, i.e., if one packet copy is required for transmission over the AWG then the packet is sent over the AWG, otherwise it is sent over the PSC. Correspondingly, in the evaluation of the probabilities $d_l(k,j)$ we focus on the cases $k = 0$ and $k = 1$ required packet copy transmissions over the AWG. For this analysis we first introduce some additional terminology. We refer to an RS segment as *occupied* if it contains the sender or at least one multicast destination, otherwise it is referred to as *unoccupied*. Similarly, we refer to an RS node as *occupied* if it is the sender or a destination of the multicast, otherwise it is referred to as *unoccupied*.

We proceed to evaluate $d_l(0)$ and $d_l(1,j)$ for $j = 1,\ldots,D$. We consider a particular $l \in \{1,\ldots,N-1\}$. Let χ be a random variable denoting the number of occupied RS nodes. Similarly, let ψ be a random variable denoting the number of occupied RS segments. We evaluate the joint distribution of χ and ψ as

$$\kappa_l(s,k) = P_l(\chi = s, \psi = k) \tag{35}$$

$$= \frac{\binom{DS}{s}\binom{N-DS}{l+1-s}}{\binom{N}{l+1}} \cdot \gamma_{DS,\Gamma-1,l+1-s}(k), \tag{36}$$

with $s = 0, 1, \ldots, DS,\ k = 0, 1, \ldots, DS,\ k \leq l + 1 - s \leq N - DS$, whereby we denote by $\gamma_{Q,m,r}(k)$ the probability for the event that when drawing r balls without replacement from an urn containing $Q \cdot m$ balls with Q different colors, the drawn balls have exactly k different colors. This probability can be evaluated for $k \geq 1$ and $r \geq 1$ with the recursion

$$\gamma_{Q,m,r}(k) = \frac{km - (r-1)}{Qm + 1 - r} \cdot \gamma_{Q,m,r-1}(k) + \frac{[Q - (k-1)]m}{Qm + 1 - r} \cdot \gamma_{Q,m,r-1}(k-1) \quad (37)$$

with the initial conditions

$$\gamma_{Q,m,r}(0) = \begin{cases} 1 & r = 0 \\ 0 & \text{otherw.} \end{cases};\ \gamma_{Q,m,0}(k) = \begin{cases} 1 & k = 0 \\ 0 & \text{otherw.} \end{cases}. \quad (38)$$

For the considered uniform traffic, for a given fanout $F = l$, the $\chi = s$ occupied RS nodes and the $\psi = k$ occupied RS segments are uniformly distributed over the ring perimeter. We assign to each occupied RS segment uniform randomly one of the adjacent RS nodes (independent of the other RS segments). This uniform random assignment of RS nodes to occupied segments models the facts that (i) with probability one half the destinations inside an RS segment can be reached with minimum hop count from one (given) of the adjacent RS nodes, and (ii) with probability one half one (given) of the adjacent RS nodes is reached with the minimum hop count by the source node. We mark all RS nodes that are either occupied (because they are sender or destination) or have been assigned to an adjacent segment. Let $\mathcal{M}$ denote the set of marked RS nodes, and let M denote the cardinality of this set. Note that M is a random variable which takes on the values $1, \ldots, DS$.

We note that according to the considered routing strategy the multicast packet is *not* transmitted over the star subnetwork if and only if $M = 1$. We obtain

$$\begin{aligned} P_l(M = 1) &= P_l(M = 1, \chi = 0, \psi = 1) \quad (39) \\ &+ P_l(M = 1,\ \chi = 0, \psi = 2) + P_l(M = 1, \chi = 1, \psi = 0) \\ &+ P_l(M = 1,\ \chi = 1, \psi = 1) + P_l(M = 1, \chi = 1, \psi = 2) \\ &= \kappa_l(0,1) + \frac{1}{4} \cdot \frac{2}{DS - 1} \cdot \kappa_l(0,2) + \kappa_l(1,0) \\ &+ \frac{1}{2} \cdot \frac{2}{DS} \cdot \kappa_l(1,1) + \frac{1}{4} \cdot \frac{1}{\binom{DS}{2}} \cdot \kappa_l(1,2) = d_l(0). \quad (40) \end{aligned}$$

In (40) note that in the second summand, $2/(DS - 1)$ is the probability that the two occupied segments are adjacent and 1/4 is the probability that both are assigned to the RS node inbetween the two segments. The event of having only one RS node marked and no occupied segment would correspond to one RS node being sender as well as the only destination of a multicast, which is impossible, hence $\kappa_l(1, 0) = 0$. For the fourth summand in (40) note that $2/(DS)$ is the probability that the occupied segment is adjacent to the occupied RS node and $1/2$ is the probability that the occupied RS node is assigned to the occupied segment. For the fifth summand in (40) note that $1/\binom{DS}{2}$ is the probability that the two occupied segments are adjacent to the occupied RS node and 1/4 is the probability that both occupied segments are assigned to the occupied RS node.

For the following analysis we introduce the following terminology. We refer to the $S-1$ RS segments that lie between the lowest indexed ring-and-star homed node $[(d-1)SN + N]/(DS)$ and the highest indexed ring-and-star homed node dN/D that is attached to AWG port d as *internal segments* of port d. We refer to the RS segment between the highest indexed ring-and-star homed node at port d and the lowest indexed ring-and-star homed node at port $d+1$ (with the wrap-around $D+1 \equiv 1$) as the *border segment between ports i and $i+1$*.

Then we have for the AWG port $j = D$, i.e., the port that the source node is associated with,

$$\begin{aligned} d_l(1, D) &= P_l(\mathcal{M} \text{ is at one port and } M \geq 2) \quad (41) \\ &= D \cdot \sum_{s=0}^{S} \frac{\binom{S}{s}}{\binom{DS}{s}} \left\{ \sum_{k=0}^{S-1} \frac{\binom{S-1}{k}}{\binom{DS}{k}} \kappa_l(s,k) \right. \quad (42) \\ &+ \sum_{k=1}^{S} \frac{\binom{S-1}{k-1}\binom{DS-S+1}{1}}{\binom{DS}{k}} \cdot \frac{2}{DS - S + 1} \cdot \frac{1}{2} \cdot \kappa_l(s,k) \\ &+ \left. \sum_{k=2}^{S+1} \frac{\binom{S-1}{k-2}\binom{DS-S+1}{2}}{4\binom{DS}{k}} \cdot \frac{\kappa_l(s,k)}{\binom{DS-S+1}{2}} \right\} - P_l(M = 1). \end{aligned}$$

To follow (42) note that the factor D accounts for the number of possible ports to which the considered set of nodes $\mathcal{M}$ is attached. The fraction $\binom{S}{s}/\binom{DS}{s}$ is the probability of having s out of the S RS nodes on the considered port occupied, and no occupied RS node at any other AWG port. The first summand in the expression in braces in (42) gives the probability for having k of the $S-1$ internal RS segments at the considered port occupied, and none of the other RS segments. The second summand gives the probability of having $k-1$ of the internal segments and one of the border segments occupied, whereby $2/(DS - S + 1)$ is the probability that the occupied border segment is adjacent to the internal segments of the considered port, and 1/2 is the probability that the destinations in the border segment are reached with the smallest hop count from the RS node attached to the considered port. Finally, the third summand gives the probability of having $k-2$ of the internal segments occupied as well as the two border segments that are adjacent to the internal segments of the considered port.

The probabilities $d_l(1, j),\ j = 1, \ldots, D-1$ are derived with analogous reasoning, as detailed in [30].

D. Overall Capacity of Ring Network with WDM Star Subnetwork Upgrade

Combining the limitations on the multicast capacity imposed by the RS segments of the ring subnetwork, as derived in (2), as well as the PSC and AWG of the WDM star subnetwork, as derived in (32) and (34), we obtain for the overall multicast capacity of the ring network upgraded with the WDM star subnetwork

$$C_M = \min\{C_M^r, C_M^{\text{PSC}}, C_M^{\text{AWG},1}, \ldots, C_M^{\text{AWG},D}\}. \quad (43)$$

IV. Numerical Results

We set the parameter B and the number of used FSRs R of the underlying $D \times D$ AWG to the following default values $B = 2$ and $R = 1$, where the latter one implies that $\Lambda_{\text{AWG}} = D \cdot R = D$. In the following, we examine the multicast capacity C_M vs. number of nodes N for the WDM star subnetwork

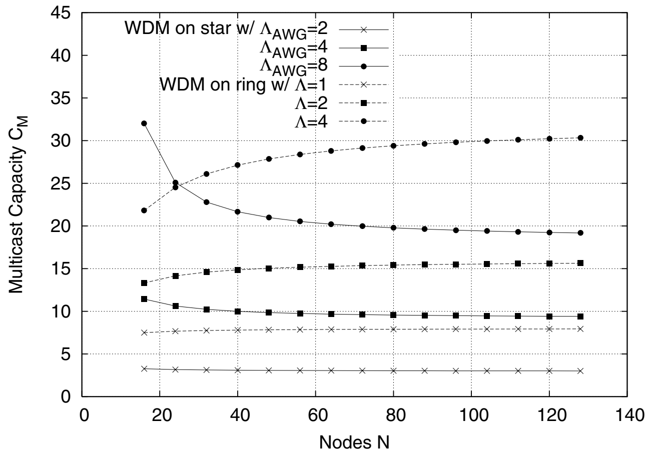

Fig. 2. Multicast capacity C_M of WDM star subnetwork upgrade for different $\Lambda_{\mathrm{AWG}} \in \{2, 4, 8\}$ and WDM ring for different $\Lambda \in \{1, 2, 4\}$ under unicast traffic, with $D \cdot S = 8$ and $\Lambda_{\mathrm{PSC}} = 1$.

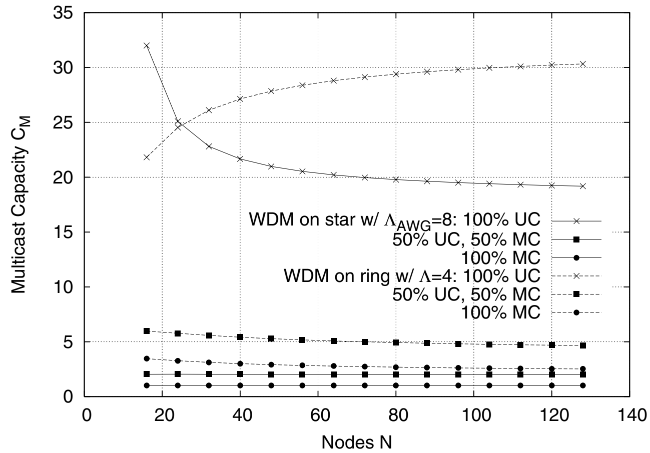

Fig. 3. Multicast capacity C_M of WDM star subnetwork upgrade with $\Lambda_{\mathrm{AWG}} = 8$ and WDM ring with $\Lambda = 4$ for unicast-only (100% UC), multicast-only (100% MC), and a mix of 50% unicast and 50% multicast traffic.

upgrade and compare it to that of conventional WDM rings under various unicast and multicast traffic scenarios. The WDM ring under consideration is a bidirectional dual-fiber ring network comprising N nodes, where each directional fiber ring carries Λ wavelength channels, amounting to a total of 2Λ wavelength channels. In the considered WDM ring, each ring node is assumed to be able to transmit on any of the Λ wavelength channels and receive on its home wavelength channel on both directional fiber rings. Each home channel is dedicated to a separate ring node if $N = \Lambda$. Otherwise, if $N > \Lambda$ each home channel is equally shared by two or more ring nodes.

Fig. 2 depicts the multicast capacity C_M of the WDM star subnetwork upgrade for different $\Lambda_{\mathrm{AWG}} \in \{2, 4, 8\}$ and of the WDM ring for different $\Lambda \in \{1, 2, 4\}$ under unicast traffic, i.e, $\mu_1 = 1$ and $\mu_l = 0$, $l = 2, 3, \ldots, N-1$. On the PSC of the star subnetwork, the number of wavelength channels is set to $\Lambda_{\mathrm{PSC}} = 1$. Thus, the number of used wavelength channels is roughly the same in the WDM star subnetwork and WDM ring. Furthermore, the number of ring nodes attached to the star subnetwork equals $D \cdot S = 8$, whereby $D = 2$ and $S = 4$ for $\Lambda_{\mathrm{AWG}} = 2$, $D = 4$ and $S = 2$ for $\Lambda_{\mathrm{AWG}} = 4$, and $D = 8$ and $S = 1$ for $\Lambda_{\mathrm{AWG}} = 8$. We let all curves start at $N = 2 \cdot DS = 16$ since we are interested in multichannel upgrades where only a subset DS of the N ring nodes are attached to the star WDM subnetwork. Let us first consider the WDM ring. For $\Lambda = 1$, we observe that the multicast capacity asymptotically approaches $C_M = 8$ for increasing N. This is due to the fact that with shortest path routing and destination stripping the mean hop distance a packet needs to travel from source to destination roughly equals $N/4$ for increasing N. Consequently, on each directional fiber ring up to four transmissions can take place simultaneously, resulting in a capacity upper bound of $C_M = 8$ for the dual-fiber ring. This upper bound linearly increases for increasing number of wavelength channels. Specifically, for $\Lambda = 2$ and $\Lambda = 4$ the multicast capacity asymptotically approaches $C_M = 2 \cdot 8 = 16$ and $C_M = 4 \cdot 8 = 32$ for increasing N, respectively. Similarly, by increasing the number of wavelengths Λ_{AWG} on the star WDM subnetwork the multicast capacity is increased significantly. Note, however, that for all three values of Λ_{AWG}, the multicast capacity decreases for increasing N, as opposed to the WDM ring. This is because keeping the number of ring-and-star homed nodes $D \cdot S = 8$ fixed, the links on the ring next to the ring-and-star homed nodes become increasingly congested for increasing N, resulting in a decreasing multicast capacity. Also note that for $\Lambda_{\mathrm{AWG}} \in \{2, 4\}$ the WDM star subnetwork is inferior to the WDM ring using $\Lambda \in \{1, 2\}$ wavelengths in terms of multicast capacity for any number of nodes N. Whereas for $\Lambda_{\mathrm{AWG}} = 8$ and $\Lambda = 4$ we observe from Fig. 2 that for small values of N the WDM star subnetwork upgrade outperforms the WDM ring in terms of multicast capacity, while for increasing N we observe the opposite due to the aforementioned link congestion on the ring network.

Next, let us consider unicast traffic together with multicast traffic. Fig. 3 depicts the multicast capacity C_M vs. number of nodes N for the WDM star subnetwork upgrade with $\Lambda_{\mathrm{AWG}} = 8$ ($D = 8$, $S = 1$) and $\Lambda_{\mathrm{PSC}} = 1$ and the WDM ring with $\Lambda = 4$ under unicast-only traffic, multicast-only traffic, and a mix of 50% unicast and 50% multicast traffic. For the multicast traffic we set $\mu_1 = 0$ and $\mu_l = 1/(N-2)$, $l = 2, 3, \ldots, N-1$. We observe from the figure that in the presence of multicast traffic the WDM ring is superior to the WDM star subnetwork upgrade for any number of nodes N. Furthermore, we observe that the multicast capacity of both WDM ring and WDM star subnetwork upgrade decreases for an increasing fraction of multicast traffic and increasing number of nodes N. This is because for increasing multicast traffic and number of nodes each multicast packet needs to traverse more intermediate nodes in order to reach the corresponding multicast destination nodes, resulting in a decreased spatial reuse and a decreased number of simultaneously ongoing multicast transmissions.

In Fig. 4, we examine multicast traffic in greater detail and set $\mu_l = 1/(N-1)$, $l = 1, 2, \ldots, N-1$. The number of wavelength channels in each direction of the WDM ring is set to $\Lambda = 4$. For the WDM star subnetwork upgrade, the total number of wavelength channels used on the star WDM subnetwork is kept at $\Lambda_{\mathrm{PSC}} + \Lambda_{\mathrm{AWG}} = 9$ fixed. Fig. 4 shows the impact of three different star WDM subnetwork

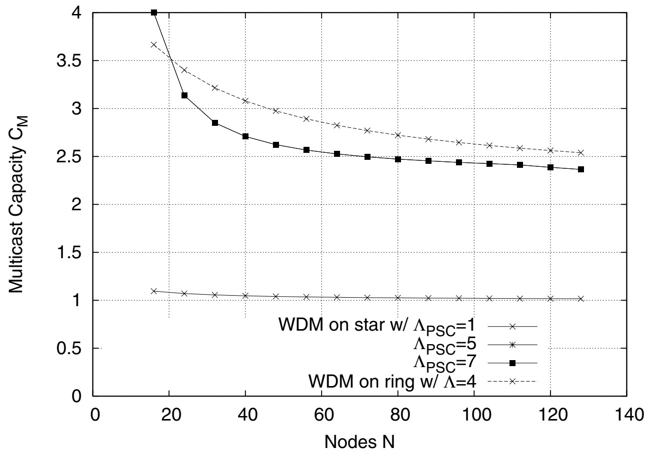

Fig. 4. Multicast capacity C_M of WDM star subnetwork upgrade for different $\Lambda_{\rm PSC} \in \{1,5,7\}$ and WDM ring with $\Lambda = 4$ under multicast traffic, with $\Lambda_{\rm PSC} + \Lambda_{\rm AWG} = 9$ fixed.

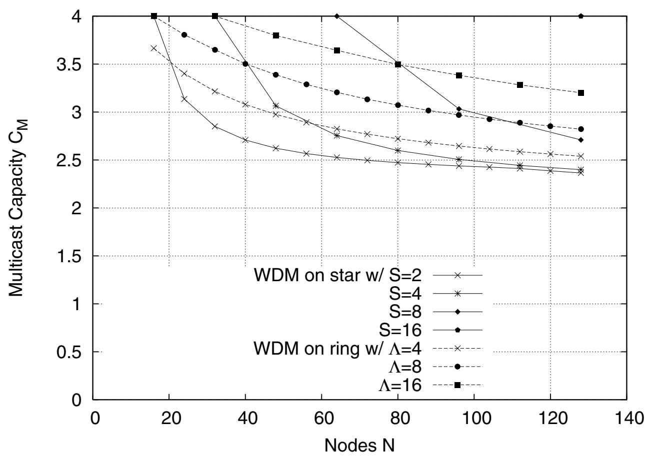

Fig. 5. Multicast capacity C_M of WDM star subnetwork upgrade with $\Lambda_{\rm AWG} = 4$ and $\Lambda_{\rm PSC} = 5$ for different $S \in \{2,4,8,16\}$ and WDM ring for different $\Lambda \in \{4,8,16\}$ under multicast traffic.

configurations. More specifically, we consider (i) $\Lambda_{\rm PSC} = 1$ with $\Lambda_{\rm AWG} = 8$ $(D = 8, S = 1)$, (ii) $\Lambda_{\rm PSC} = 5$ with $\Lambda_{\rm AWG} = 4$ $(D = 4, S = 2)$, and (iii) $\Lambda_{\rm PSC} = 7$ with $\Lambda_{\rm AWG} = 2$ $(D = 2, S = 4)$. Apparently, using only one wavelength channel on the PSC of the star subnetwork (and eight wavelength channels on the AWG) leads to the smallest multicast capacity. In contrast, shifting some of the AWG wavelength channels to the PSC improves the multicast capacity of the WDM star subnetwork upgrade significantly by exploiting the wavelength-broadcasting nature of the PSC which is well suited to efficiently support multicast traffic, as opposed to the wavelength-routing AWG which is better suited for unicast traffic. Note that for both $\Lambda_{\rm PSC} \in \{5,7\}$ we obtain the same multicast capacity. Also note that again for small values of N the WDM star subnetwork upgrade outperforms the WDM ring in terms of multicast capacity, and vice versa for increasing N. Again, this is due to the above mentioned increasing link congestions on the ring for increasing N.

To mitigate the decreasing multicast capacity of the WDM star subnetwork upgrade for increasing N the link congestion on the ring network must be alleviated. This can be achieved by attaching more ring nodes to the star subnetwork, as shown in Fig. 5. In this figure, we again consider multicast traffic and set $\mu_l = 1/(N-1)$, $l = 1, 2, \ldots, N-1$. For the star WDM subnetwork we set $D = 4$, $\Lambda_{\rm AWG} = 4$, and $\Lambda_{\rm PSC} = 5$. Fig. 5 depicts the multicast capacity C_M of the WDM star subnetwork upgrade for different combiner/splitter degree $S \in \{2,4,8,16\}$ and the WDM ring for different number of wavelength channels $\Lambda \in \{4,8,16\}$. By increasing S more ring nodes are attached to each port of the AWG and PSC, leaving fewer ring-homed nodes between two adjacent ring-and-star homed nodes. As a result, each ring-and-star homed node needs to collect traffic from fewer ring-homed nodes in order to send it across the single-hop short-cuts of the star subnetwork. In doing so, the link congestions next to each ring-and-star homed node are alleviated and the multicast capacity is increased, as shown in Fig. 5. For comparison, we also show the multicast capacity of WDM rings using different number of wavelength channels $\Lambda \in \{4,8,16\}$. For instance, under multicast traffic the WDM star subnetwork upgrade with $S = 8$ outperforms the WDM ring with $\Lambda = 8$ for a wide range of N. In other words, WDM upgrading and interconnecting a subset of $D \cdot S = 4 \cdot 8 = 32$ nodes by a star WDM subnetwork with $\Lambda_{\rm AWG} + \Lambda_{\rm PSC} = 9$ wavelength channels achieves a larger multicast capacity than a WDM ring with a total of $2 \cdot \Lambda = 16$ wavelength channels, where each ring node needs to be WDM upgraded.

V. Conclusions

We have examined two complementary upgrades of optical single wavelength bidirectional ring networks to wavelength division multiplexing (WDM) networks. With the WDM on the ring upgrade no new fiber is required, but all network nodes need to be upgraded to support WDM. With the WDM on the star subnetwork upgrade additional fiber is required to connect a subset of the nodes to the central star hub. This additional fiber could be provided by lighting up already installed dark fiber, which is available in many metropolitan areas. In contrast to the WDM ring upgrade where all nodes need to be upgraded to support WDM, with the WDM star subnetwork upgrade only a subset of the network nodes need to be upgraded to support WDM and connected to the star hub.

We have formally analyzed the multicast capacity (maximum mean number of simultaneously ongoing multicasts). Our analysis provides easy to evaluate expressions for these capacities for uniform traffic with arbitrary fanout distribution. Our analysis thus provides a useful tool for assessing the capacity tradeoffs when upgrading single-channel optical ring networks to WDM. The capacity analysis of the WDM on star subnetwork upgrade provides the capacity limitations due to the individual components of the upgraded network, namely the single-wavelength ring (RS segment) between two upgraded nodes (RS nodes), the PSC of the star hub, and the AWG of the star hub. This analysis thus provides a basis for designing network upgrades where the components are dimensioned to give roughly matching capacity limitations.

The presented numerical results illustrate the trade-offs between the two upgrade approaches. We found for a range of example unicast, multicast, and mixed traffic patterns the following rough tradeoff: Upgrading and connecting every fourth network node to a WDM star subnetwork gives similar capacities as upgrading every node to support WDM on the ring.

There are many exciting avenues for future work on upgrading optical ring networks. One interesting direction is to combine both upgrades examined in this paper to create a hybrid high-performance network which operates only a few wavelengths on the ring and a larger number of wavelengths on a star subnetwork. Furthermore, the hybrid ring-star network provides multiple paths between each pair of source and destination nodes, enabling alternate routing and load balancing. In our future research efforts, we will examine the impact of advanced routing schemes on the performance of the hybrid ring-star network.

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