Multicasting in a WDM-upgraded Resilient Packet Ring

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The recently approved IEEE 802.17 Resilient Packet Ring (RPR) network deteriorates under multicast traffic to legacy ring technologies that do not support spatial reuse. We extend our multicast approach with spatial reuse from a currently single-channel RPR to WDM-upgraded multichannel RPR networks, where each node can transmit packets on all wavelengths and receive on one wavelength, and analyze their multicast capacity. Our analysis provides a convenient method for evaluating the multicast and reception capacities of WDM-upgraded RPR networks for a wide range of uniform unicast, multicast, and broadcast traffic scenarios.

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1. Introduction

The new standard IEEE 802.17 Resilient Packet Ring (RPR) is an optical dual-fiber bidirectional ring network, where each fiber carries a single wavelength channel [1,2]. By using destination stripping and shortest path routing, the RPR allows for *spatial reuse* under unicast traffic, resulting in a significantly increased capacity compared with source-stripping legacy ring networks, e.g., Fiber Distributed Data Interface (FDDI) [3]. For multicast traffic, however, the performance of the RPR reduces to that of legacy ring networks, which do not support spatial reuse.

In [4], we have described and investigated a bandwidth-efficient and cost-effective multicast approach, in detail for (single-channel) RPR networks, which exploits the RPR's built-in topology discovery and supplementary time to live (*ttl*) field to enable spatial reuse for multicast traffic, leading to a significantly increased transmission capacity, multicast capacity, and reception capacity. In this paper, we extend our multicast approach and analysis to wavelength division multiplexing (WDM)-upgraded RPR networks, where each fiber carries multiple wavelength channels.

We note that in [5], the multicast capacity is analyzed for a WDM ring with a one-copy routing strategy, which does not minimize the hop distance. In contrast, in this paper, we build on [6] where the hop distance is analyzed for a WDM-upgraded RPR network with shortest path routing, which minimizes the hop distance and maximizes spatial reuse. Due to the nonuniform loading of the ring segments in a WDM ring (even for uniform traffic), the hop distance does not directly translate into the effective capacity (maximum achievable long-run average packet throughput). This paper analyzes the nonuniform segment loading and provides a methodology for evaluating the effective capacity.

2. Related Work

Complementary aspects of the RPR have been examined in several recent studies. The fairness of the RPR bandwidth allocation has, for instance, been studied in [7–12], while the access delay, congestion control, and quality of service of the RPR have been studied in [13–15]. The RPR protection performance has been studied in [16,17].

In general, capacity analyses of WDM ring networks have primarily focused on unicast traffic [18,19]. In contrast, we consider multicast (multidestination) traffic, which poses a number of unique challenges in WDM ring networks [20–23] and has begun to receive significant interest in optical metropolitan area networks [24,25].

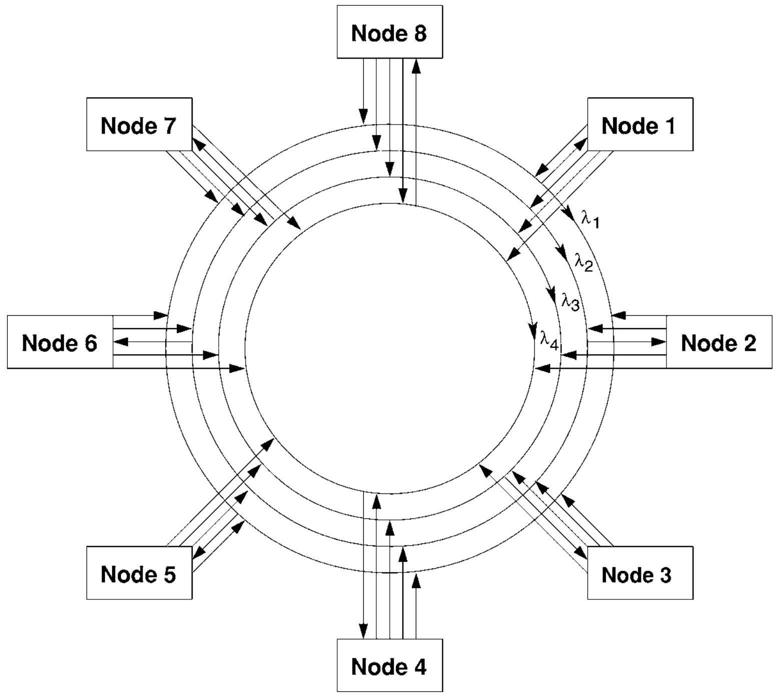

Fig. 1. WDM-upgraded RPR network with $N=8$ nodes and each fiber ring carrying $\Lambda=4$ wavelength channels.

3. WDM-Upgraded RPR

In the WDM-upgraded RPR network, the set of wavelength channels $\lambda \in \{1,2,\ldots,\Lambda\}$ is deployed on the clockwise as well as the counterclockwise fiber ring. The network interconnects N nodes, which we index without loss of generality sequentially in the clockwise direction as $n=1,2,\ldots,N$. Each node (i) can transmit on any wavelength using a single tunable transmitter or an array of fixed-tuned transmitters, and (ii) receive on one (home) wavelength using a single fixed-tuned receiver, whereby the nodes $n=\lambda+k\Lambda$ with $k=0,1,\ldots,(\eta-1)$ and $\eta:=N/\Lambda$ share the same home wavelength λ, $\lambda=1,2,\ldots,\Lambda$, as shown in Fig. 1 for $N=8$ and $\Lambda=4$ for the clockwise fiber ring (the node structure is replicated for the counterdirectional fiber ring).

The RPR topology discovery protocol runs on the RPR's original single-wavelength channel, which enables all N nodes to discover the number and ordering of the nodes. Each source node sets the *ttl* fields of the corresponding counterpropagating multicast packets such that they expire after the two final multicast destination nodes (which are formally defined in Subsection 4.A) are reached on the shortest path, and both multicast packets are taken off the ring.

4. Analysis

4.A. Traffic Model and Preliminaries

Analogous to [4], we consider uniformly randomly placed source and destination nodes with the number F of destination nodes distributed according to

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

and evaluate the multicast capacity C_M defined as the maximum number of packets that can simultaneously be sent in the long-run average. We extend the notion of the largest gap analyzed in [4] for a single-wavelength channel to multiple-wavelength channels as follows. For each wavelength λ, $\lambda=1,\ldots,\Lambda$, consider the set of nodes containing the source node, which we assume without loss of generality to be node N and the ℓ destination nodes homed on the considered wavelength λ.

Let $G_{\max}$ be a random variable denoting the largest gap in the number of hops between the considered set of nodes for a given λ, where one hop denotes the distance between two adjacent network nodes. There are two scenarios: (A) the largest gap borders on the source node, or (B) the largest gap is between two destination nodes, which we exploit to serve the multicast with the smallest hop distance. Specifically, in scenario (A), we send one multicast copy on the considered wavelength λ in the direction opposite the largest gap. In scenario (B), we send two multicast packet copies on λ, namely, one copy in the clockwise direction to the destination node bordering on the largest gap (let α denote the index of this node), and one copy in the counterclockwise direction to the destination node bordering on the largest gap (let ω denote the index of that node).

4.B. Evaluation of Multicast Capacity

The multicast capacity is governed by the mean utilization of the ring segments that attain the maximum mean utilization $u_{\max}$. In particular, we define the multicast capacity C_M and the reception capacity C_R as

$$C_M = \frac{1}{u_{\max}}, \quad C_R = C_M E[F]. \tag{2}$$

The maximum mean utilization $u_{\max}$ is attained by the ring segments that lead to the nodes homed on a wavelength; we refer to these ring segments attaining $u_{\max}$ as *critical segments* (e.g., on λ_1 in Fig. 1, the segment from node 8 to node 1 and the segment from node 4 to node 5 are critical segments). Note that there are $2N$ critical segments in the network. We evaluate the maximum mean utilization $u_{\max}$ in terms of the expected number of critical segments $\kappa_{\max}^{(\lambda)}$ traversed by the multicast copy transmission(s) on a wavelength λ to serve a given arbitrary multicast as

$$u_{\max} = \frac{1}{2N}\sum_{\lambda=1}^{\Lambda} \kappa_{\max}^{(\lambda)}. \tag{3}$$

We evaluate the expected number of traversed critical segments $\kappa_{\max}^{(\lambda)}$ on wavelength λ, by conditioning on the number of multicast destinations ℓ (out of a total of l multicast destinations) that are homed on wavelength λ. More formally, we define $h(\ell,\lambda)$ as the conditional expectation of the number of critical segments traversed by the multicast copy(ies) on wavelength λ on their way to reaching the ℓ multicast destinations on the wavelength. We also note that given a total of l multicast destinations, the conditional probability for ℓ of these destinations being homed on wavelength $\lambda \neq \Lambda$ (with Λ homing the source node), is given by

$$P(F_{\Lambda,\lambda} = \ell \,|F = l) = \frac{\binom{\eta}{\ell}\binom{N-1-\eta}{l-\ell}}{\binom{N-1}{l}}, \tag{4}$$

and the conditional probability for ℓ destinations being homed on Λ is given by

$$P(F_{\Lambda,\Lambda} = \ell \,|F = l) = \frac{\binom{\eta-1}{\ell}\binom{N-\eta}{l-\ell}}{\binom{N-1}{l}}. \tag{5}$$

See [5] for details. With these conditional expectations, we obtain

$$\kappa_{\max}^{(\lambda)} = \begin{cases} \sum_{l=1}^{N-1} \mu_l[\sum_{l=1}^{\eta} P(F_{\Lambda,\lambda} = \ell \,|F = l) h(\ell,\lambda)] & \text{for } \lambda \neq \Lambda \\ \sum_{l=1}^{N-1} \mu_l[\sum_{\ell=1}^{\eta-1} P(F_{\Lambda,\Lambda} = \ell \,|F = l) h(\ell,\Lambda)] & \text{for } \lambda = \Lambda \end{cases}. \tag{6}$$

4.C. Evaluation of Conditional Expectation $h(\ell,\lambda)$

If $\lambda=\Lambda$, we need to evaluate $h(\ell,\lambda)$ for $\ell=1,\ldots,\eta-1$, whereas if $\lambda\neq\Lambda$, we need to evaluate $h(\ell,\lambda)$ for $\ell=1,\ldots,\eta$.

Case $\boldsymbol{\lambda}=\Lambda$. First consider scenario (B) where two packet copies are sent on the wavelength. To reach node α, whose index is an integer multiple of Λ, i.e., $\alpha=k\Lambda$ for $k=1,2,\ldots$, the copy sent in the clockwise direction traverses α/Λ critical segments. Similarly, the copy sent in the counterclockwise direction traverses $(N-\omega)/\Lambda$ critical segments to reach node ω. Hence, a total of $[N-(\omega-\alpha)]/\Lambda=\eta-G_{\max}/\Lambda$ critical segments (and a total of $N-G_{\max}$ hops) are traversed. Analogously, we find that $\eta-G_{\max}/\Lambda$ critical segments are traversed in scenario (A).

Now we observe that the single-wavelength ring analyzed in [4] is equivalent to the wavelength channel $\lambda=\Lambda$ in the WDM ring. The only difference between the two is that successive nodes on wavelength $\lambda=\Lambda$ in the WDM ring are spaced Λ hops apart (with one critical segment between them), whereas successive nodes in the single-wavelength ring are one hop apart. Hence, the number of critical segments traversed when packet copies from a multicast travel $N-G_{\max}$ hops on wavelength $\lambda=\Lambda$ in the WDM ring is equivalent to $\eta-G_{\max}/\Lambda$ hops traveled in a single-wavelength ring connecting η nodes. Thus, the conditional expectation $h(\ell,\Lambda)$ of the number of traversed critical segments is obtained in terms of the expected length of the largest gap $g(\ell,\eta)$ when there are ℓ destinations on a single-wavelength ring with η nodes as

$$h(\ell,\Lambda)=\eta-g(\ell,\eta), \tag{7}$$

whereby $g(\ell,\eta)$ is given by Eq. 16 in [4] as $g(\ell,\eta)=\sum_{k=1}^{\eta-1}kq_{\ell,\eta}(k)$ with $q_{\ell,\eta}$ denoting the distribution of the largest gap and being calculated from the recursion $q_{\ell,\eta}(k)=p_{\ell,\eta}(k)\sum_{m=1}^{k}q_{\ell-1,\eta-k}(m)+\sum_{m=1}^{k-1}p_{\ell,\eta}(m)q_{\ell-1,\eta-m}(k)$ with the initialization $q_{0,\eta}(k)=1$ for $k=\eta$ and $q_{0,\eta}(k)=0$ for $k<\eta$ and with $p_{\ell,\eta}(k)=\binom{\eta-k-1}{\ell-1}/\binom{\eta-1}{\ell}$ denoting the probability that an arbitrary gap has k hops.

Case $\boldsymbol{\lambda\neq\Lambda}$. First consider scenario (B), where the largest gap is between neighboring destination nodes on λ (and is not bordering on the source node). Noting that neighboring nodes homed on wavelength λ are Λ hops apart, we observe that $G_{\max}$ is an integer multiple of Λ in scenario (B). The node α, whose index is $\alpha=\lambda+j\Lambda$ for some integer $j=0,1,\ldots$, is reached in the clockwise direction by traversing $\lceil\alpha/\Lambda\rceil$ critical segments. Similarly, node $\omega=N-(\Lambda-\lambda)-k\Lambda$ for some integer $k=0,1,\ldots$, is reached via $\lceil[N-\omega]/\Lambda\rceil$ critical segments in the counterclockwise direction. Thus, a total of $\lceil\alpha/\Lambda\rceil+\lceil[N-(G_{\max}+\alpha)]/\Lambda\rceil=\eta-G_{\max}/\Lambda+1$ critical segments are traversed.

In scenario (A), the largest gap is $G_{\max}=\lambda+j\Lambda$ for some integer j if the largest gap is clockwise from the source node, and $G_{\max}=\Lambda-\lambda+k\Lambda$ for some integer k if the largest gap is counterclockwise from the source node. We find analogous to the above reasoning that $\eta-\lfloor G_{\max}/\Lambda\rfloor$ critical segments are traversed. Combining scenarios (A) and (B), we find that $\eta-\lceil G_{\max}/\Lambda\rceil+1$ critical segments are traversed: on wavelength $\lambda\neq\Lambda$ to serve a multicast with ℓ destinations on this wavelength.

From the distribution of $G_{\max}$, which is derived in [6], we obtain for a given $\ell\geq 2$,

$$\begin{aligned}P(\lceil G_{\max}/\Lambda\rceil=j)&=r_{\ell-1,\eta}(j,j)+\frac{\eta-j}{\eta}\sum_{k=1}^{j-1}r_{\ell-1,\eta}(j,k)+\frac{1}{\eta}\sum_{k=j+1}^{\min(\eta,2j-1)}\{r_{\ell-1,\eta}(k,j)(2j-k)\}\\&\quad+\frac{2}{\eta}\sum_{k=j}^{\min(\eta,2j-2)}\sum_{m=1}^{j-1}r_{\ell-1,\eta}(k,m)+\frac{1}{\eta}\sum_{m=1}^{j-1}r_{\ell-1,\eta}(2j-1,m),\end{aligned} \tag{8}$$

whereby $r_{\ell-1,\eta}(k,m)$ is the joint distribution of the largest and second largest spacing, which was derived when evaluating the distribution of $G_{\max}$ in [6] for $m<k$ as $r_{\ell-1,\eta}(k,m)=\{\eta q_{\ell-2,\eta-k}(m)\binom{\eta-k-1}{\ell-2}\}/\{\binom{\eta}{\ell}\}$ and for $m=k$ as $r_{\ell-1,\eta}(k,k)=q_{\ell-1,\eta}(k)-\sum_{m=1}^{k-1}r_{\ell-1,\eta}(k,m)$. Thus,

$$h(\ell,\lambda)=\eta+1-\sum_{j=1}^{\eta}jP(\lceil G_{\max}/\Lambda\rceil=j). \tag{9}$$

Note that this expression for $h(\ell,\lambda)$ does not depend on λ, as long as $\lambda\neq\Lambda$. For $\ell=1$, we obtain

$$h(1,\Lambda)=\begin{cases}\dfrac{\eta^2}{4(\eta-1)}, & \eta\text{ even}\\[2ex]\dfrac{\eta+1}{4}, & \eta\text{ odd}\end{cases};\quad h(1,\lambda)=\begin{cases}\dfrac{\eta+2}{4}, & \eta\text{ even}\\[2ex]\dfrac{(\eta+1)^2}{4\eta}, & \eta\text{ odd}\end{cases}. \tag{10}$$

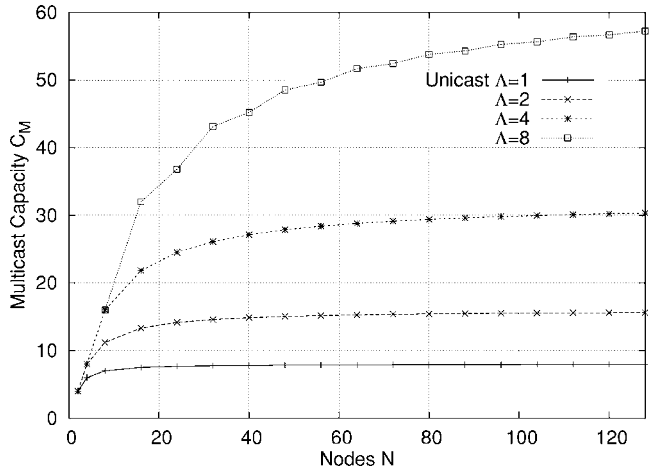

Fig. 2. Multicast capacity C_M versus the number of nodes N under unicast traffic ($\mu_1=1$ and $\mu_l=0$, $l=2,3,\ldots,N-1$) for a different number of wavelengths $\Lambda \in \{1,2,4,8\}$.

5. Numerical Results

Figure 2 depicts the multicast capacity C_M of the WDM-upgraded RPR network versus the number of nodes N for a different number of wavelengths $\Lambda \in \{1,2,4,8\}$ under unicast traffic. Note that for unicast traffic, the multicast capacity equals the reception capacity C_R. For the single-channel RPR network ($\Lambda=1$), we observe that the multicast capacity approaches $C_M=8$ for increasing N. This is because under uniform unicast traffic, a packet traverses approximately $N/4$ nodes on average, thus allowing for four simultaneous transmissions on each fiber ring and eight transmissions on the dual-fiber ring. Using more wavelengths increases C_M.

As depicted in Fig. 3, for broadcast traffic, C_M converges to two as the number of nodes N grows large, irrespective of Λ. With large N, broadcast traffic consumes the bandwidth of all Λ wavelengths of one fiber ring in order to reach all nodes, resulting in a total of two simultaneous broadcast transmissions on the dual-fiber ring. For multicast traffic, however, we observe that the multicast capacity C_M increases for increasing Λ. This is because our multicast approach with spatial reuse requires on each wavelength channel of the WDM-upgraded RPR ring only a decreasing fraction of either fiber ring to reach the corresponding multicast destination node(s). When the standard IEEE 802.17 RPR, which does not support spatial wavelength reuse for multicast traffic, is WDM upgraded, the multicast capacity C_M for multicast traffic is identical to the C_M for broadcast traffic, which does not permit spatial wavelength reuse. Thus, we observe, for instance, that in a network with $N=40$ nodes and $\Lambda=8$ wavelengths, the spatial wavelength reuse on each wavelength channel increases C_M

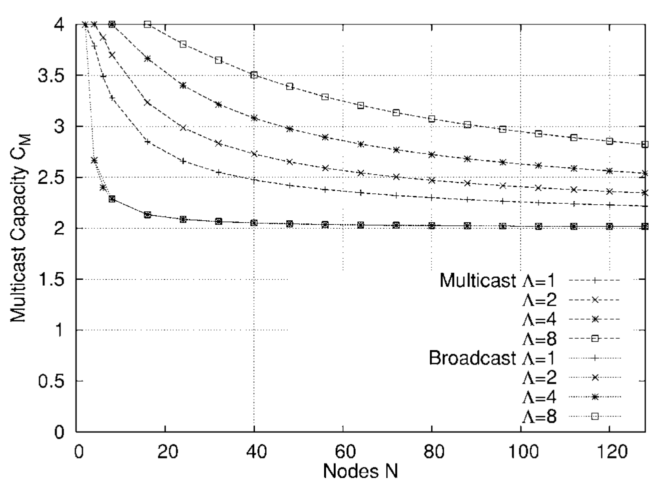

Fig. 3. Multicast capacity C_M versus the number of nodes N under multicast traffic ($\mu_l=l/(N-1)$, $l=1,2,\ldots,N-1$) and broadcast traffic ($\mu_{N-1}=1$ and $\mu_l=0$, $l=1,2,\ldots,N-2$) for a different number of wavelengths $\Lambda \in \{1,2,4,8\}$.

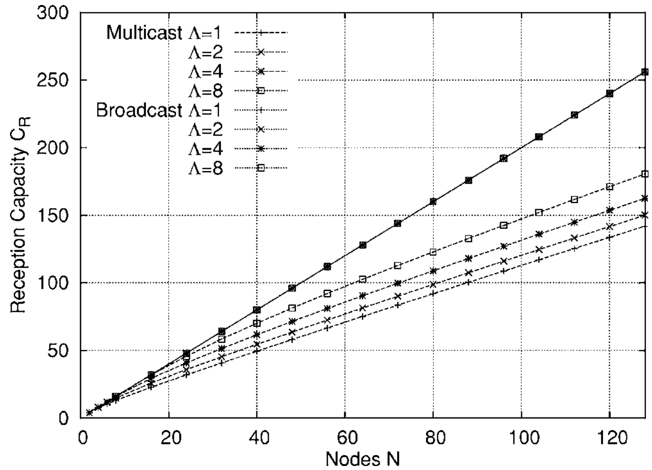

Fig. 4. Reception capacity C_R versus the number of nodes N under multicast traffic ($\mu_l = 1/(N-1)$, $l = 1, 2, \ldots, N-1$) and broadcast traffic ($\mu_{N-1} = 1$ and $\mu_l = 0$, $l = 1, 2, \ldots, N-2$) for a different number of wavelengths $\Lambda \in \{1, 2, 4, 8\}$.

for multicast traffic from approximately two without spatial wavelength reuse to approximately 3.5 with spatial wavelength reuse.

Figure 4 shows the reception capacity C_R of the WDM-upgraded RPR network versus the number of nodes N. For broadcast traffic, C_R increases linearly for increasing N, irrespective of Λ. For multicast traffic, C_R increases for increasing Λ. Again, this is because for increasing Λ, a decreasing fraction of each wavelength on either fiber ring is consumed, resulting in an increased C_M and thus an increased C_R for increasing Λ.

6. Conclusions

We have extended our bandwidth-efficient single-channel multicast approach that allows for spatial reuse for WDM-upgraded RPR networks and examined their multicast capacity and reception capacity by means of analysis. Our analysis allows for the evaluation of the multicast and reception capacities for a wide range of traffic mixes and is thus important for assessing WDM upgrades of currently single-channel RPR networks. Our numerical results show that for unicast and multicast traffic, the multicast capacity of WDM RPR networks is significantly increased by capitalizing on spatial reuse on each wavelength channel.

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