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Mining the Rings: Strategies for Ring-to-Mesh Evolution

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Abstract – We assess the scope for serving ongoing growth in transport demand while deferring or eliminating expenditure for additional capacity by reclaiming the protection capacity and inefficiently used working capacity in existing rings. Reclamation is through re-design of the routing and restoration in the network using mesh principles within the pre-existing ring capacities. The installed working and protection capacity of existing rings is viewed as a sunk investment, an existing resource, to be "mined" and incorporated into a mesh-operated network that serves both existing and ongoing growth. Three ways of approaching the idea are given. The last is a detailed planning model for minimum cost evolution out to a given total growth multiplier that considers the costs of new mesh capacity additions, nodal costs for mesh access to existing ring capacity and selective ADM conversions and re-use decisions. Depending on the type of initial ring network design results show that in some cases a complete doubling or even tripling of demand could be supported with little or no additional capacity investment through the period of ring-to-mesh conversion by ring-mining. The strategy may mean that an operator that could handle the administrative process of conversion could access the opportunity to grow their business for a year or more without capital additions for transport capacity. This re-capture of existing installed protection capacity for conversion to service-bearing use would be a one time business strategy opportunity made possible by a ring mining conversion from ring to mesh.

Keywords – Spare Capacity Allocation, Network Protection and Restoration, Network Planning and Optimization, Network Design Theory.

I. Introduction

Today many network operators have a deployed ring-based network but state that they see "mesh" as the way to go in future with DWDM-based optical networking [1]. It is generally recognized that while rings have been a practical and economic alternative, especially in metro networks, ring networks consume a lot of transmission capacity, making them less suitable for long-haul applications. We have previously analyzed that even efficiently designed ring networks may embody total capacity that is up to three times the shortest-path capacity for the amount of demand they serve [2]. Ring protection capacity is a source of 100% minimum redundancy, but the efficient utilization of working capacity tends to also be limited by ring loading and "stranded capacity" issues. Additionally demand routing can rarely follow the true shortest path over the facilities graph. At the same time as rings are locking up so much physical transport capacity, some operators can barely deploy new capacity fast enough to keep up with demand. In circumstances of such rapid growth, transport efficiency is important: Even if the cost of the capacity was zero, more efficient transport architectures can serve more revenue-bearing demand for the same installed base of transmission systems.

Thus anticipating an era of ring to mesh evolution, we have posed some research questions. The first of these questions captures the basic idea and motivation that we call "ring mining". The question is: *To what extent could an existing ring-based network "soak up" ongoing demand growth, simply by providing access to its raw span capacities and converting the mode of operation to a restorable mesh architecture?* As stated this is pure "ring mining" where there would be *no* new capacity added at all while nonetheless sustaining ongoing growth solely by conversion to a mesh-restorable mode of operation under the span capacities represented by the rings. The obvious benefit would be to support revenue growth without adding new transmission equipment for a possibly significant period of time. The strategy could be financially attractive if it meant an operator could serve growth, for possibly a year or more, while capping or deferring major capital additions for transport capacity.

While this first question about ring mining serves to give the basic interest and philosophy, it is somewhat idealized because in practice we expect there would be some kind of costs associated with converting ring ADMs for access by mesh-based cross-connects, changes in network element software, and network management changes. In addition, the basic question as posed may not be the most advantageous one to ask for a practical evolution strategy. There could be ring-mining potential to be unlocked if relatively small new capacity additions were allowed in conjunction with pure ring mining during the ring-to-mesh evolution. Accordingly, we present theory and test case results to assess the potential extent and benefits of ring mining by studying the following three approaches to the idea:

- **Q1.** Without adding any new capacity, what is the largest common multiplier (λ) on the whole demand matrix that can be served and made restorable under mesh span restoration?
- **Q2.** If a total growth of λ is forecast to some date in the future, what is the minimum total capacity investment needed to meet this forecast using a combination of ring mining and mesh capacity additions?
- **Q3**. What is the minimum total cost strategy for growth to a meet future demand multiplier of λ involving ring-mining, selective new capacity additions and allowing for selective conversions or re-use of ADMs with a cost for each node so adapted?

II. PRELIMINARIES

There are some immediate clarifications that can be anticipated about this proposal. Let us here try to deal with those before developing each of the ring mining questions / strategies in technical depth.

A. Operational Complexity Cost versus Equipment Savings Benefit

An understandable first concern is that network management may be made more complex by this proposal and that existing OSS systems would have to be changed, and so on. We recognize that but do not here judge the cost or complexity of the management changes that would be required to pursue a ring-mining strategy for ring to mesh evolution. From a network management standpoint it would presumably be simpler to "cap the rings" and serve all new demand growth with a mesh overlay. Eventually with continued growth the network will be almost all mesh-based and demands served in the residual rings could be rolled into the mesh at a suitable date in the future. We take this as the conventional reference strategy for a ring to mesh evolution. It would be the most cost-effective strategy if operational costs and ring-mining nodal conversion were high enough to outweigh the ring-mining advantages. The important point for the present is not to pre-judge the associated operational complexities and cost / benefit without at least finding out what the potential benefits could be from ring mining. The present work thus addresses the benefit side of the cost/benefit question. Individual network operators are in a better position to assess the cost side of accessing this opportunity. Given the magnitude of the cost-savings and expense deferral we see in some cases, however, it seems possible that an operator who could manage the strategy would access a financial advantage over competitors during their period of ring mining. Keep in mind that the annual budget for incremental transport equipment purchases for a long-haul network can be typically \$ 300 to 400 million dollars. It is this entire budget that in some cases the ring mining strategy could reclaim for one or more years depending on the growth rate of demand.

B. What about ring types?

Another a priori concern is that ring mining must depend intricately on the ring types involved in the initial network By type, we mean the logical protocol on which the ring is working, e.g., BLSR, UPSR, MS-SPRing, SNCP ring, etc. However, it is really only the transmission line capacity of the ring, the fraction of the line capacity that is accessible for add/ drop at the ADMs, and the "extra traffic" accessibility of the protection channel (or redundant working tributary copies) that matters to ring mining. All rings are structurally 100% redundant regardless of their type in that every unit of useful working capacity is matched by an equal unit of protection or redundant working path capacity on the same span of the ring. In the case of BLSR or MS-SPRings their line-loop-back restoration mechanism does, however, mean that they may be especially amenable to ring-mining because at degree-2 locations they can remain in place functioning as part of a new mesh–restorable network. This is because the loop-back reaction of shared protection ring ADMs retained within chain sub-networks of a mesh is identical to the reaction within the same chain of either a span or path-restorable network with respect to intra-chain flows. Additionally we understand that at least in N. America, where rings are used in metro high-capacity core or long-haul applications, they are invariably of the BLSR type. Accordingly in our third strategy where ADMs can be either converted or re-used, the re-use decision is based on the assumption that they are BLSRs for use of their line loop-back function in the mesh role.

C. How is Ring Capacity Accessed for Ring Mining?

Mesh-oriented access to the capacity of a ring is proposed to be through ADM nodes of the ring that have been "converted" for ring mining. There may be many different technical means of arranging such access but from a ring-mining planning standpoint, the important characteristics are the total amount of ring capacity that can be made accessible to a co-located cross-connect, and the corresponding cost of making this capacity accessible. Figure 1 is one example of how the entire working and protection capacity of a BLSR-type ring might be accessed. If the protection channel is accessible through the extra traffic feature (which most ADMs have) and the ADM has 100% add/ drop access, then the ADM can be converted for ring-mining by programming it into the configuration shown in Figure 1 and "freezing" it that way.

This is just an example, however. The basic idea is to get line-rate or tributary-level access to both spans of the ring at converted nodes including its protection (or redundant working) channels. Other models are obviously possible depending on the ADM vendor, features, and so on. The "costs" for conversion may even be negative if there is a salvage value for removing the ADM entirely and terminating the fiber line systems directly on optically interfaced cross-connects. Perhaps the ideal ADM architecture for conversion to ring mining would be one where the optical line interface functions can be left in place and the ADM function salvaged (i.e., an ADM with separate OLTE). Since there is obviously a range of circumstances that each operator may find in this regard, we treat the cost of the technical means required to access the ring capacity as a parameter in our study. Costs for a cross-connect core at each site are assumed common to all strategies given the premise of the study that a mesh future is the common goal. Cross-connect cores are therefore present whether arrived at by ring mining or through a conventional cap and grow approach. Costs for incremental cross-connect terminations are meant to be part of the cost model for additional mesh capacity. Costs for cross-connect termination of ring-mined capacity are an assumed part of the ADM conversion cost.

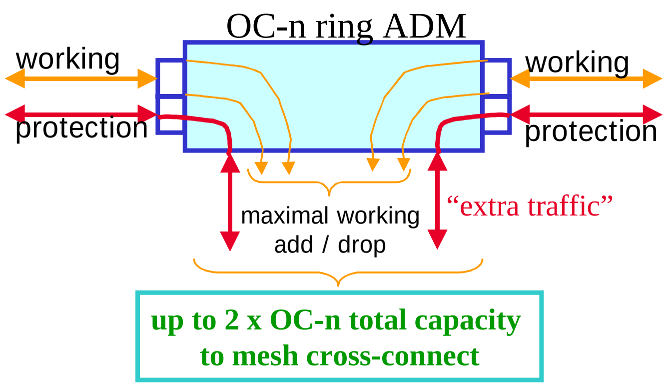

Figure 1. One example of arrangements to convert an ADM for ring-mining access by mesh cross-connects. The cross-connects access 2 times the line-rate of the ring on each of two logical spans from the mesh node assuming 100% add/ drop capacity and access to protection through an "extra traffic" feature.

D. The Initial Ring Network Designs

For quantitative studies of the ring mining idea we needed some representative designs of multiple-ring networks to start with. Complete specifications of existing ring networks and their demand patterns were not available to us so we made use of a supply of nearly optimal ring network designs produced by various methods in recent PhD studies of ring network design methods [3]. These research-based designs are probably more efficient and well-loaded than most real networks, which tends to work against the ring mining case. All designs fully serve the demand matrix for which they were designed and the same demand matrices are used as the starting point for ring-mining studies. Six of the ring-networks were produced by a "fixed charge and routing IP" (*fcrip)* formulation in which modular rings are selected jointly with the demand routing and ring loading decisions. These designs are capable of extremely high ring loading efficiencies and span elimination [4]. Another six designs are from a "span coverage IP" (*scip*) formulation in which demands are first shortest-path routed over the graph and then a minimum cost modular capacitated ring cover is found. *scip* designs are generally less efficient than *fcrip* and do not exhibit span eliminations. A final five designs were produced by a RingBuilder-based *Tabu Search* (TS) heuristic. The TS procedure calls RingBuilder for a starting design, and for subsequent search diversifying re-starts. Between re-starts it generates ring drop and ring add moves, with revised demand routing at each move, seeking a lower cost design that still serves all demands. The TS procedure can lead to very efficient ring designs, packing the demands to be served into very few rings. Each method is described further in [3]. There are three different test network graphs for each design method and all designs for the same topology serve the same demand matrix. Table 1 summarizes these and other attributes of the ring mining test cases. The designs on the (32,45) topologies were synthesized with OC-48 and OC-192 module options. The (15,28) and (20,31) test cases were synthesized with OC-12 and OC-48 module options. Module costs followed an economy of scale model based on industry data. As evidenced in Table 1 the resultant designs adopted a single most economic module size so that for our tests, these turn out to all be single-modularity ring network designs. This is an effect arising from design for minimum cost, not necessarily minimum capacity. This is an effect that tends to favour ring mining. It is nonetheless consistent with the nature of real ring-based network designs that would be candidates for ring-mining.

TABLE I RING-MINING TEST NETWORKS

Design	(nodes, spans)	# rings	Design method	Module Sizes	Total Capacity	# span eliminations
1	15, 28	6	fcrip	OC-12	960	3
2	15, 28	5	fcrip	OC-48	2976	3
3	20, 31	14	fcrip	OC-12	1728	0
4	20, 31	6	fcrip	OC-48	2880	6
5	32, 45	12	fcrip	OC-48	8448	0
6	32, 45	8	fcrip	OC-192	21504	0
7	15, 28	9	scip	OC-12	1200	0
8	15, 28	5	scip	OC-48	3264	0
9	20, 31	18	scip	OC-12	2136	0
10	20, 31	7	scip	OC-48	3840	0
11	32, 45	12	scip	OC-48	8544	1
12	32, 45	7	scip	OC-192	18048	3
13	15, 28	6	TS	OC-12	1944	3
14	15, 28	5	TS	OC-48	4032	2
15	20, 31	10	TS	OC-12	2232	0
16	32, 45	7	TS	OC-48	7296	3
17	32, 45	6	TS	OC-192	21504	5

III. IMMEDIATE DEMAND GROWTH POTENTIAL

The first question (Q1.) is relatively easily addressed with the Mixed Integer Programming formulation detailed below. This formulation determines the highest uniform multiplier λ that can be applied to every element of the demand matrix while keeping the demand both routable and 100% mesh-restorable under span restoration. The formulation is a type of joint working and spare capacity optimization [5] but under span capacity limits set by the "broken up" rings. The main use of this formulation is to give a broad indication of the basic potential for ring mining.

$\boldsymbol{D}$ Set of O-D pairs with non-zero demands

$\boldsymbol{S}$ Set of spans

$\boldsymbol{P_i}$ Set of eligible restoration routes for span i

$\boldsymbol{Q^r}$ Set of eligible working routes for r^{th} O-D pair

t_j^m Number of modules of size m on span j in the ring-design (including ring protection)

d^r Initial demand for the r^{th} O-D pair

$\delta_{i,j}^p$ 1 if the p^{th} restoration route for span i uses span j, 0 otherwise

$\zeta_j^{r,q}$ 1 if the q^{th} working route for the r^{th} O-D pair uses span j, 0 otherwise

M Set of different capacity module sizes

Z^m Number of capacity units for the m^{th} module size

λ Uniform demand multiplier (variable)

$g^{r,q}$ Working capacity required on the q^{th} working route to satisfy the demand between the r^{th} O-D pair (variable)

f_i^p Restoration flow through the p^{th} route for failure of span i (variable)

w_i Mesh logical working capacity needed on span j (integer variable)

s_j Mesh logical spare capacity needed on span j (integer variable)

IP 1: Maximize λ (3.1)

Subject to:

$$\sum_{q\in \boldsymbol{Q^r}} g^{r,q} = \lambda \cdot d^r \qquad \forall r \in \boldsymbol{D} \tag{3.2}$$

$$\sum_{r\in \boldsymbol{D}} \sum_{q\in \boldsymbol{Q^r}} \zeta_j^{r,q} \cdot g^{r,q} \le w_j \qquad \forall j \in \boldsymbol{S} \tag{3.3}$$

$$\sum_{p \in \boldsymbol{P}_i} f_i^p = w_i \qquad \forall i \in \boldsymbol{S} \tag{3.4}$$

$$\sum_{p \in \boldsymbol{P}_i} \delta_{i,j}^p \cdot f_i^p \le s_j \qquad \forall (i,j) \in \boldsymbol{S}^2 \tag{3.5}$$

$$w_j + s_j \le \sum_{m \in \boldsymbol{M}} t_j^m \cdot Z^m \qquad \forall j \in \boldsymbol{S} \tag{3.6}$$

Constraints (3.2) scale the demand served to be λ times the original demand. In practice the same growth multiplier will not necessarily arise for every individual demand pair, but for research characterization the maximal flat demand multiplier gives a relative characterization of the potential for ring mining. Constraints (3.3) ensure that there is enough working capacity in the network to support the routing of all the demands. Constraints (3.4) ensure that the sum of restoration flows for each single span cut is equal to the working capacity to be restored. Constraints (3.5) ensure that there is enough spare capacity on each span to support all the restoration flows that cross it in every span failure case. Constraints (3.6) ensure that the sum of working and spare capacity on each span in the logical mesh does not exceed the amount of capacity on that span as provided by the initial ring set.

Figure 2 summarizes the results of this experiment on the 17 test case ring networks in Table 1. The results show a uniform growth potential λ on the entire demand pattern that ranges from 10% *to as much as a tripling in demand served*. Over a third of the test cases could sustain a doubling in demand just by ring-to-mesh conversion. Not surprisingly the greater growth multipliers tend to arise in ring networks using the largest ring modular capacities but this is not always the case. One of the OC-48 designs shows only 1.07 sustainable growth factor while two other OC-48 designs are up at $\lambda \approx 2.9$. No simple generalization seems warranted as to which designs will yield the greatest λ in this pure ring mining sense. Rather, the potential of the ring mining strategy seems to depend on the details of each network. Inspection of such details lead us next to hypothesize that some relatively small additions of new capacity might act like a catalyst to "unlock" significantly more of the ring capacity present. This is the key idea of the next strategy.

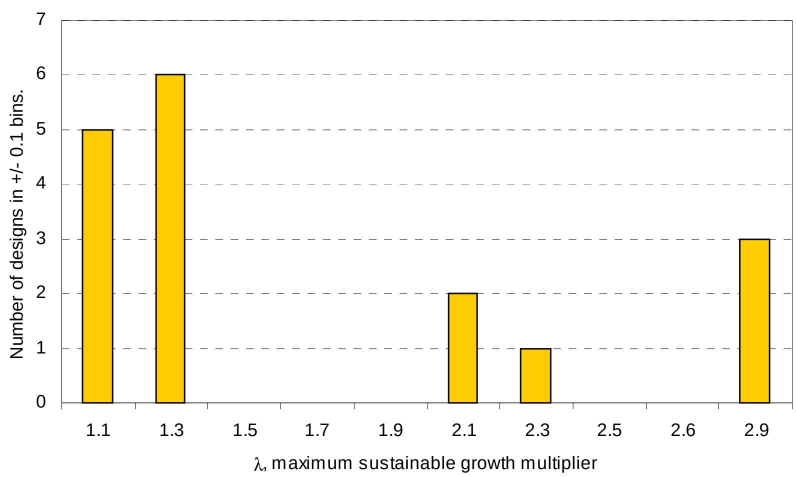

Figure 2. Distribution of the pure ring-mining potential to sustain flat uniform demand growth.

design	λ	design	λ
1	1.24	10	2.24
2	2.91	11	1.07
3	1.05	12	2.05
4	1.16	13	1.36
5	1.02	14	2.91
6	2.05	15	1.31
7	1.32	16	1.24
8	2.91	17	1.38
9	1.13		

IV. RING-MINING WITH SELECTIVE MESH ADDITIONS

In this section we consider scenarios in which the demand growth exceeds the maximum sustainable growth multiplier obtained in the previous section. Additions of new capacity are now allowed in conjunction with ring mining. This strategy will be compared to the strategy that consists of putting a cap on the ring network and building a new mesh network overlay on top of it to serve all future demands. The overlay is designed using the joint modular working and spare capacity optimization method in [5].

As explained in the previous section, the immediate growth potential is only an indication of how much demand can be served with only the capacity from the ring design. It is possible that in some cases more capacity will be unlocked if small capacity additions are allowed. If this is the case then we expect that the capacity investments required by the ring mining strategy will be smaller than with the cap & grow strategy.

A second IP formulation was developed to determine the amount of added capacity that is needed on top the ring-mined capacity to sustain a growth of the demand matrix that is higher than the immediate growth potential calculated with IP1. With this second formulation, the uniform demand multiplier λ becomes *an input* to the problem and the number of mesh capacity modules to add to the network are new variables.

New Parameters and Variables:

λ Total growth multiplier to be satisfied

C_j^m Cost of a module of the m^{th} size on span *j*.

n_j^m Number of modules of the m^{th} size added on span *j*. (integer variable)

IP 2: Minimize $\sum_{j \in \mathbf{S}} \sum_{m \in \mathbf{M}} n_j^m \cdot C_j^m$ (4.1)

Subject to constraints (3.2) to (3.5) plus:

$$w_j + s_j \le \sum_{m \in \mathbf{M}} (t_j^m + n_j^m) \cdot Z^m \qquad \forall j \in \mathbf{S} \quad (4.2)$$

In constraints (4.2) the available capacity on each span is now the sum of the capacity reclaimed from the ring design and the added mesh capacity. The formulation minimizes the total capacity investment needed to meet a demand that is λ times the original demand served by the ring design.

Figure 3 shows results for two ring mining capacity profiles and the cap + grow strategy for one of them. The one for ring design 16 shows that compared to pure mesh growth for new demands, the overall investment profile to meet the next 220% growth is 50% lower with ring mining and most expenditure is deferred until after the first 40% of added growth. Design 16 is one of the designs showing a smaller potential for ring mining on Figure 2 and is therefore a challenging case. This ring design serves 354 demand units on 72 O-D pairs. The mesh growth model uses OC-48 and OC-192 module sizes with costs of 1 and 2 respectively. Design 10, in the middle group on Figure 2, shows here a complete deferral of capacity growth costs until over 200% growth from current demand. The obviously desirable characteristics of deferral and reduction of new capacity investment are apparent relative the baseline of capping the rings and putting all growth on mesh.

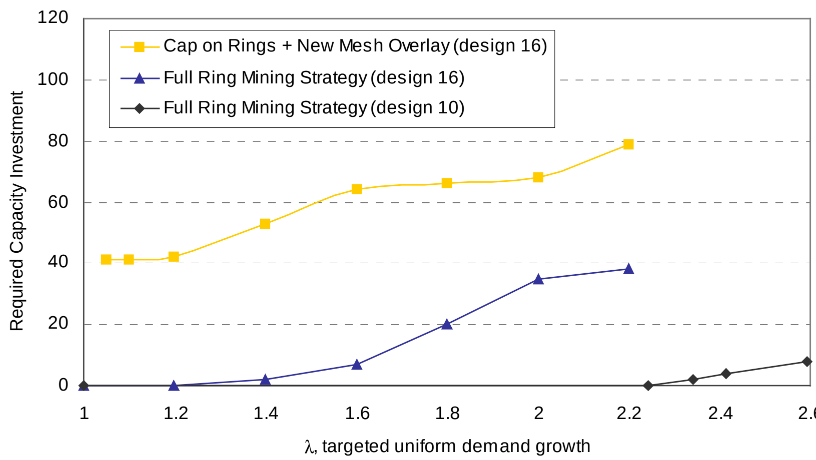

Figure 3. Serving growth with and without ring mining. Top curve is the cap ring and grow mesh capacity expenditure profile for ring design 16. The lower design 16 curve shows reduced and delayed expenditure with ring mining. Ring design 10 shows complete deferral of capacity growth costs until over 200% growth from current demand.

V. Minimum Cost Transition Strategy With selective ADM Conversion /Re-use

We now extend the ring mining framework to provide a complete optimization model for transitional growth to get from an existing ring set and demand matrix to a future demand growth multiplier of λ at minimum total cost. Here we take into account that there is a cost for ADM node *conversion* and we assume a small but non-zero cost (for example for network management software changes) to permit *re-use* of an ADM as a chain element in the resulting logical mesh design. For comparative results we also consider a reference strategy of capping the ring network and serving all new demands in a separate mesh network overlay. This ring mining model is more realistic of the economic factors involved and can exactly specify at which nodes to break into the rings, where to add new capacity, which ADMs to re-use, and which segments of ring capacity to actually abandon to avoid conversion costs if the overlying mesh can more efficiently carry the relevant demands (The latter may be candidates for salvage but we have not assumed any such benefit to the ring mining strategy). The general model allows each ADM to have a different conversion cost but we will assume a generic conversion cost of *c* per ADM converted. *c* = 1 is defined as conversion costs equal to the cost of adding one OC-48 unit of transmission capacity on the average length ring span. Only ADMs located in a geographic site of degree 3 or higher in the basic facilities topology graph are considered for conversion. All other ADMs are considered for simple re-use as degree-2 network elements for the mesh. ADMs have a *re-use* cost of *c*/10. The new parameters and variables are:

$\boldsymbol{R}$	Set of rings from the ring design
x_l^m	Number of modules of the m^{th} size on ring *l*
$\boldsymbol{A}$	Set of ADMs from the ring design
E_k	Conversion/re-use cost for ADM *k*
$\gamma_{j,l}$	1 if span *j* is covered by ring *l*, 0 otherwise
$\eta_{k,l}$	1 if ADM *k* is on ring *l*, 0 otherwise
$\beta_{j,k}$	1 if span *j* is adjacent to ADM *k*, 0 otherwise
$\mu_{j,l}$	1 if capacity from ring *l* is used on span *j*, 0 otherwise (variable)
ρ_k	1 if ADM *k* is converted, 0 otherwise (variable)

IP 3:

$$\text{Minimize } \{\sum_{j\in \boldsymbol{S}}\sum_{m\in \boldsymbol{M}} n_j^m \cdot C_j^m + \sum_{k\in \boldsymbol{A}} \rho_k \cdot E_k\} \tag{5.1}$$

Subject to constraints (3.2) to (3.5) plus:

$$w_j + s_j \le \sum_{l\in \boldsymbol{R}}\sum_{m\in \boldsymbol{M}} \mu_{j,l}\cdot x_l^m \cdot Z^m + \sum_{m\in \boldsymbol{M}} n_j^m \cdot Z^m \qquad \forall j\in \boldsymbol{S} \tag{5.2}$$

$$\mu_{j,l} \le \gamma_{j,l} \qquad \forall j\in \boldsymbol{S} \quad \forall l\in \boldsymbol{R} \tag{5.3}$$

$$\rho_k \ge \mu_{j,l}\cdot \beta_{j,k}\cdot \eta_{k,l} \qquad \forall k\in \boldsymbol{A} \quad \forall j\in \boldsymbol{S} \quad \forall l\in \boldsymbol{R} \tag{5.4}$$

The first term in the objective function represents the cost for adding new capacity modules. The second term represents the cost of converting or re-using ADMs. Constraints (5.2) ensure that the sum of mesh working and spare capacity on each span does not exceed the amount of available capacity on that span. The available capacity in this case is the sum of the capacity reclaimed from some rings covering that span plus the sum of newly added modules. Constraints (5.3) ensure that the capacity from a ring is not reclaimed on a span that is not covered by that ring. Finally, constraints (5.4) force any ADM to be converted (if at a degree 3+ site) or re-used (if at a degree 2 site) if the capacity of the ring it belongs to is reclaimed on one of its two adjacent spans.

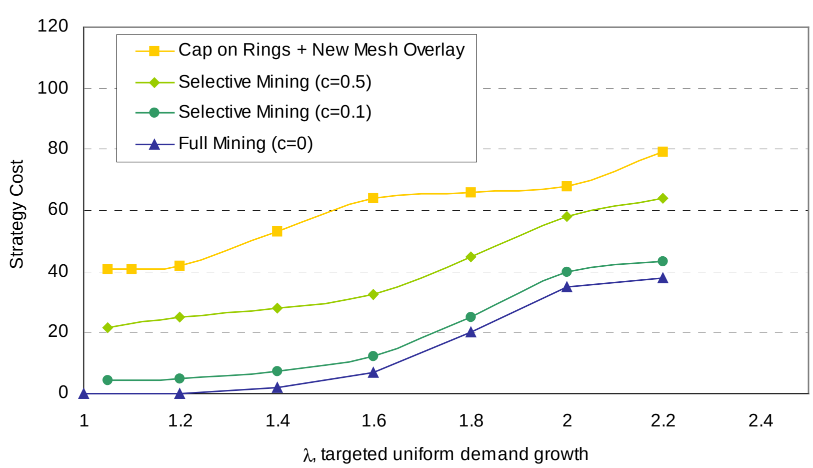

Figure 4. Comparison of reference strategy cost and ring-mining strategy costs with ADM conversion (and re-use) costs as a parameter.

Figure 4 shows the time profile of expenditures to meet growth out to λ = 2.2 with ring design 16. Even with significant costs for ADM conversion the ring mining strategy is significantly less costly than the reference model of "cap and grow new mesh". Note that as expected when *c* = 0 the total strategy cost is equal to the pure capacity investment profile in Figure 3.

Figure 5 and Figure 6 show the effect of the conversion cost on the total evolution cost to a growth factor λ = 2. In Figure 5 one can see that above *c* = 0.8 the cost of the ring mining strategy exceeds the baseline cap and grow strategy due to ADM conversion costs. Referring back to Figure 4, *c* = 0.8 would be the value for which the curve for the selective mining and the one for "Cap on Rings + New Mesh" coincide at λ = 2. Since the curves on Figure 4 are roughly parallel, the conversion cost for which the min cost strategy changes will not depend greatly on the λ considered in the decision. Figure 6 shows the percentage of eligible ADMs converted for each strategy depending on *c*. It is interesting to notice that even when *c* is low, the selective ring mining strategy only selects 90 % of the ADMs for conversion. This shows an advantage of the third formulation in that it is able to identify the ADMs that are not worth converting or re-using. Figure 6 also shows that the pure min cost strategy jumps directly from 90% conversion to 0% conversion at a critical conversion cost between *c*= 0.6 and *c*=0.8 in this network. At this critical point, even before the selective ring mining strategy starts reducing the number of converted ADMs, the reference strategy is more economical.

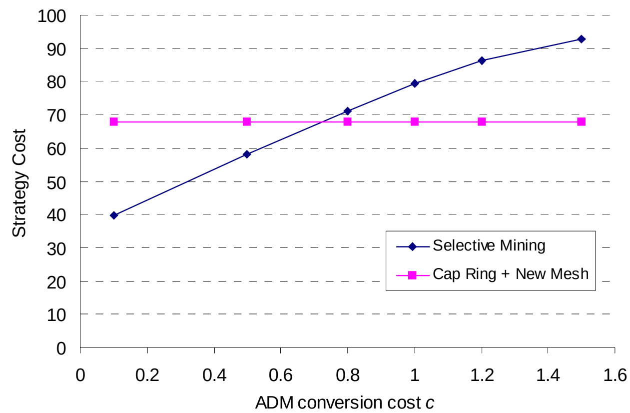

Figure 5. Effect of ADM conversion cost on total transition cost to λ=2.

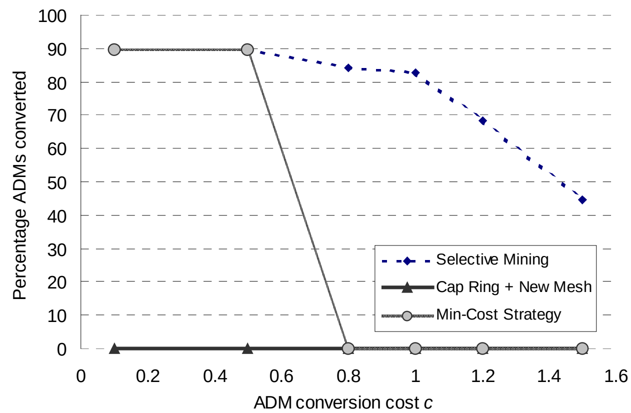

Figure 6. Effect of ADM conversion/re-use cost on the extent of ADM conversions for λ=2.

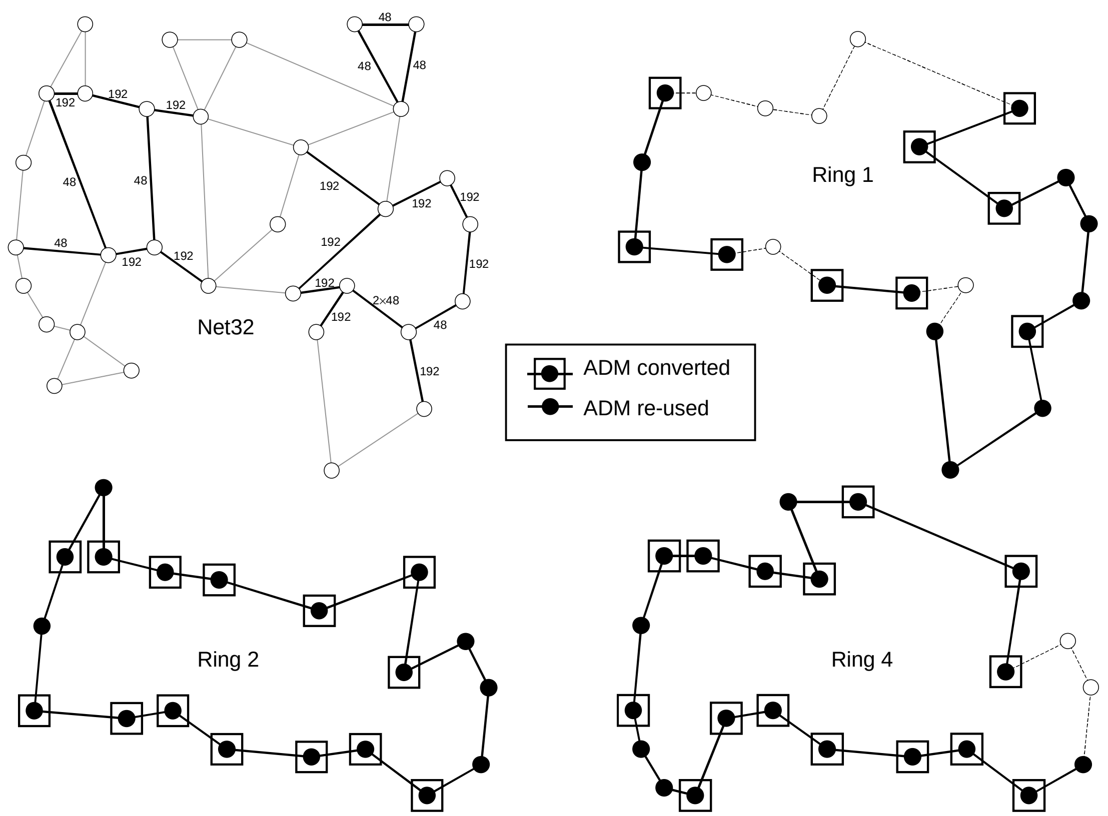

Figure 7. Selective mining strategy result for the three largest rings in test design 16 with $c = 0.5$.

Figure 7 shows part of the detailed ring mining solution in the 32 node test network of ring design 16 assuming an ADM conversion cost c = 0.5 and re-use cost of 0.05 growing out to a uniform doubling of demand. The facilities graph topology is shown in the upper left where added mesh capacity onlays are indicated in bold, annotated with the added module size. Other panels give isolated views of the three largest rings indicating which ADMs were converted for mesh access to their ring capacity and which ADMs are re-used in the ring mining solution. Note that as may be expected all the conversions are at geographic sites with degree of 3 or more. It is at these sites that accessed ring capacity is being cross-connected for mesh routing and restoration efficiencies. Re-used ADMs are those that play a cost-effective role in a chain of the resulting logical mesh. In this example 89% of all the eligible ADMs are converted and 92% of ADMs at degree 2 sites are re-used.

VI. Concluding Discussion

This study suggests that in possibly most of ring-based networks there may be significant advantage from the ring mining strategy. The transition from ring to mesh networking can thus represent a financial opportunity for the deferment and reduction of ongoing investment in transport capacity for significant periods of time as represented by sustainable growth factors of 40 to as much as 290 %. At the higher end, the sustainable growth potential could represent years of ongoing service growth without the usual transport expenditures. The results presented here were based on quite efficient fully loaded and optimized ring designs. This implies that the ring mining potential in real networks, which may be only partway to their planning horizon or less optimally loaded, may be greater still. Another factor that could either increase or decrease the ring mining potential in practice would be non-uniform growth in the demand matrix, assuming the equivalent overall growth in total demand as with the multipliers used here. This could be evaluated for each case in detail using the methods given here, however. The strategies and models presented here are suggested for use in network planning systems. Further work on the topic could look at the possibility of using ring mining in the context of a transition from ring to ring-mesh hybrid [6] where demands' restoration speed requirements could be the factor of decision whether to leave a demand within the remaining ring layer or to move it to mesh.

VII. References

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