Inter-Domain Routing Scalability in Optical DWDM Networks

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Abstract: Recent studies on inter-domain DWDM networks have focused on topology abstraction for state summarization, i.e., transforming a physical topology to a virtual mesh, tree, or star network. Although these schemes give very good inter-domain blocking reduction, associated inter-domain routing overheads are significant, particularly as the number of domains and border OXC nodes increase. To address these scalability limitations, novel routing update triggering policies for multi-domain DWDM networks are developed. The performance of inter-domain lightpath RWA and signaling schemes in conjunction with these strategies is then studied in order to gauge the overall effectiveness of these approaches.

Keywords: Multi-domain networks, optical networks, GMPLS, inter-domain DWDM routing, topology abstraction, routing scalability

I. INTRODUCTION

In recent years dense wavelength division multiplexing (DWDM) has seen fast growth in long-haul and metro sectors [1]. DWDM exploits the huge unused spectrum in single mode fibers (SMF) to transmit multiple data channels, thus yielding unprecedented terabit link rates. As this technology matures, the IETF has defined a generalized multi-protocol label switching (GMPLS) framework for optical network provisioning. Specifically, GMPLS provides extensions for routing, signaling and link discovery [2] by adapting packet-based multi-protocol label switching (MPLS) protocols for provisioning circuit-switched connections. In addition, the ITU-T has also finalized a comprehensive automatic switched transport network (ASTN) framework based upon a multi-level routing hierarchy approach [2].

On the research side, routing and wavelength assignment (RWA) algorithms [1] for DWDM circuit routing have been studied extensively. Specifically, the goal of RWA is to find an optimized route and wavelength so as to minimize the overall blocking rate. A broad survey in [3] presents a comprehensive performance analysis of various RWA schemes. Many DWDM network survivability techniques have also been developed, with proposals including dedicated path protection, shared path protection, and shared segment protection [1],[4]. However most of these DWDM studies have strictly focused on single-domain settings and assume the availability of full domain-level state, i.e., either via a-priori means or centralized and/or distributed routing. In general this is only germane in small-scale and/or single networks. Clearly, as the number of (DWDM) network nodes increase, such “flat” topology approaches pose many restrictions, such as high storage and low scalability. It is evident, therefore, that some effective form of domain-level partitioning is needed [5]-[9]. Furthermore, commensurate inter-domain RWA algorithms are also required to provision lightpaths.

The overall topic of inter-domain DWDM networking is only now starting to receive attention [10]-[17]. Specifically, researchers have studied a variety of schemes for lightpath provisioning in all-optical and mixed optical/opto-electronic conversion (regeneration) networks. The latter is an important consideration given the increased distance reach and coverage of optical networks. However the detailed inter-domain routing scalability implications of multi-domain DWDM networks have not yet been fully studied. This is a very crucial concern as optical networking resource state (wavelength, converters, etc) is very different and generally more voluminous than that in more traditional data/packet routing networks.

Along these lines this paper addresses inter-domain routing scalability in distributed multi-domain DWDM networks with wavelength conversion. Specifically, the work extends the recent effort in [16] by developing new and improved routing update/triggering schemes for full mesh topology abstraction. The paper is organized as follows. First Section II surveys some of the recent work in inter-domain DWDM network provisioning. Subsequently Section III outlines the framework of distributed inter-domain routing. Section IV then extends this scheme by presenting novel inter-domain routing update strategies to boost scalability for high-levels of virtual link state. Detailed performance evaluation studies are then conducted in Section V for a wide range of multi-domain network topologies. Finally conclusions and future research directions are presented in Section VI.

II. BACKGROUND

Many multi-domain studies have been conducted for packet-switching quality of service (QoS) routing networks, e.g., see [7]-[9]. From this work a key concept that emerged was topology abstraction to condense domain-internal state for inter-domain dissemination, originally evolved in [7]. As this area has matured, the focus has shifted to multi-domain DWDM networking evaluation and along these lines various related studies have been conducted. For example [10] presents a theoretical analysis of state aggregation in multi-domain DWDM networks with border node conversion. Here various information models are studied and lightpath assessment is modeled as a Bayesian decision problem. However this treatment only considers restricted bus topologies and does not discuss inter-domain state propagation schemes. Furthermore no routing protocols or distributed lightpath setup signaling procedures are detailed. Meanwhile [11] presents an earlier architecture that uses route advertise/withdraw messaging between domains running modified border gateway protocol (BGP). Namely specialized proxy lightpath route arbiters (LRA) are proposed to compute routes between border optical cross-connect
(OXC) nodes, which must maintain complete (alternate) route state. Nevertheless the detailed algorithmic study of this scheme is not done. Alternatively the authors in [12] present a domain-by-domain routing and signaling scheme for inter-domain lightpath setup in which domain gateways maintain complete (alternate) route state. However related resource propagation issues are not considered and hence this setup is more favorable to BGP-type implementation.

Meanwhile [13] tables a hierarchical inter-domain solution for ASON based upon a simple node (coarse) abstraction policy. However no signaling extensions are presented here and hence the scheme is best-suited for centralized implementation. Additionally no provisions are made for opto-electronic conversion, a critical necessity in inter-domain settings. Furthermore [14] extends the above work by presenting a new RWA strategy based upon the stochastic estimation of effective number of available wavelengths (ENAW) along inter-domain paths. Namely a Kalman filtering approach is used to refine the estimation. However detailed topology aggregation schemes and/or signaling setup extensions are still not considered—key requirements in distributed operational settings. Finally it is also noted that some have studied sub-path protection strategies for optical lightpaths [15]. Although these schemes present many saliencies, they are premised upon the availability of global state, i.e., “flat/single-domain” network, complicating their extension to distributed multi-domain DWDM networks.

III. DISTRIBUTED MULTI-DOMAIN PROVISIONING

In light of the above, a more comprehensive approach for inter-domain lightpath RWA is considered in [16]. Herein the authors develop a GMPLS-based hierarchical routing model to condense and propagate domain state using full-mesh topology abstraction. Furthermore, commensurate lightpath computation and setup algorithms are also tabled. Overall results show much-improved blocking performance with the incorporation of full-mesh abstracted state. However associated inter-domain routing loads are notably higher, and alternate, simpler star-based topologies are shown to give mixed results [17]. This forms the overall motivation of the work herein, namely, to extend the framework in [16] to improve inter-domain scalability. Specifically, this is done via the design of novel, highly-scalable inter-domain triggering update policies. Before presenting these new routing strategies, however, it is necessary to introduce the overall notation and inter-domain provisioning solution in [16].

A. Topology Abstraction

Consider a multi-domain DWDM network of $D$ domains, where the $i$-th domain has $n_i$ nodes and $b_i$ border nodes, $1 \leq i \leq D$. Each domain is represented as a sub-graph, $G(V^i, L^i)$, where $V^i = \{v_i^1, \ldots, v_i^{n_i}\}$ is the set of physical domain OXC nodes and $L^i = \{l_{ij}^i\}$ is the set of physical intra-domain links ($1 \leq i \leq D, 1 \leq j, k \leq n_i$), i.e., $l_{ij}^i$ is the link between OXC nodes $v_i^j$ and $v_i^k$. All links are bi-directional with $W$ wavelengths each. The set of border nodes with a domain $i$ is given by $B^i$ and it is assumed (without loss of generality) that these nodes are the first set of domain nodes, i.e., $B^i = \{v_1^i, \ldots, v_{b_i}^i\}$. Furthermore, inter-domain routing also defines a higher-level topology comprising border OXC nodes and inter-domain links, i.e., $\mathcal{H}(U,E)$, where $U = \sum_i(|B^i|)$ is the set of global border nodes and $E = \{e_{km}^j\}$ is the set of physical inter-domain links, i.e., $e_{km}^j$ inter-connects $v_i^k$ in domain $i$ with $v_j^m$ in domain $j$, $i \neq j$, $1 \leq j, k \leq D$, $1 \leq m \neq k$.

This graph contains all physical border nodes and inter-domain links but may not have full connectivity—which is achieved via subsequent topology abstraction. Note that all DWDM links (physical, virtual) have associated binary wavelength availability vectors, $\lambda_{\text{bw}}^j$, i.e., $\lambda_{\text{bw}}^j(n) = 1$ if the $n$-th wavelength is available, $1 \leq n \leq W$. Finally all OXC nodes have $C$ converters that can be utilized by any outbound link, e.g., shared-per-node architecture.

Before detailing full-mesh topology abstraction, it is instructive to review the more basic simple node abstraction [7],[16]. This scheme performs no domain compression and simply condenses a domain into a single virtual node, Figure 1. Clearly, inter-domain routing overheads are much lower here since link-state updates are only sent for physical links, i.e., $O(|E|)$ storage/update complexity. This transformation is represented as $\mathcal{H}(U,E) \rightarrow \mathcal{H}_\text{in}(U, E)$ where $U, E \rightarrow \{v_i\}$ is the condensed set of virtual nodes representing each domain $i$ and $E$ is the set of physical inter-domain links, Figure 1.

Conversely the full-mesh abstraction scheme of [16] computes a set of virtual links to summarize domain-level state. This is done by a designated routing area leader (RAL) border node [2]. Specifically the available wavelengths on multiple traversing intra-domain routes between borders pairs are summarized to generate virtual link availability vectors.

![Figure 1: Simple node and full-mesh topology abstraction](image-url)
Now domain-internal wavelength conversion adds notable complexity as converter state must be captured and used to check the wavelength continuity constraint on each “sub-path”, i.e., at least one common wavelength has to be available between two adjacent conversion-enabled OXC nodes. To resolve this issue, [16] develops a novel approach that precludes having to decouple and separately advertise (domain-internal) converter state. Specifically only the available wavelengths on the bottleneck sub-paths are summarized, indirectly capturing any conversion limitations. For example in Figure 2 the most congested sub-path is used to represent the traversing cost between border nodes $v'_i$ and $v'_j$, e.g., path $v'_i \rightarrow v'_j \rightarrow ^*v'_j \rightarrow v'_2$ becomes a feasible candidate if conversion is enabled at node $v'_3$. Here the sub-path $v'_j \rightarrow ^*v'_j \rightarrow v'_2$ with wavelength availability vector $[101000]$ is the bottleneck segment and is therefore chosen to represent the cost of the whole path, i.e., the virtual link between border nodes $v'_i$ and $v'_j$. The exact details of the full mesh algorithm are as follows.

![Figure 2: Virtual link abstraction with sparse/full conversion](Image)

The algorithm loops through each domain border node pair and computes a wavelength availability vector for the associated virtual link. Namely, the $K$-shortest paths between each border node pair are listed, denoted as $\{p_{i\rightarrow m}\}$ where $p_{i\rightarrow m}$ is the $m$-th path vector (node sequence) between border nodes $v'_i$ and $v'_j$ in domain $i$, $1 \leq m \leq K$. Here only paths which satisfy wavelength continuity constraint [3] are considered in this step. If no such a path can be found, then candidate opto-electronic paths are generated by trying all converter combinations along these paths searching for the minimum number of used converters. Finally, either the minimum hop count path or least loaded path is selected and the resultant wavelength availability vector ($\lambda_{jk}^{l}$) is computed for the virtual link between the border nodes, see for details [16].

Overall full-mesh is represented as $H(U,E)\rightarrow H_{mesh}(U, E \cup \{E_{mesh}\})$, where $E_{mesh}$ is the above-computed set of virtual links ($1 \leq D \leq D$), Figure 1. This approach provides good domain visibility, albeit at the cost of significant RAL compute complexity and inter-domain routing loads. Namely border nodes must maintain link state for $O(\sum_{j}(b'-1)) = O(\sum_{i} b_i^3)$ virtual links in addition to physical inter-domain links, i.e., quadratic storage/update complexity. To address these scalability concerns, novel routing update strategies are presented (Section IV).

8. Inter-Domain Lightpath RWA & Setup

Distributed inter-domain RWA computation uses the above-generated state along with RSVP-TE loose route (LR) signaling to expand all route links and identify wavelengths. Specifically, a hierarchical computation approach is evolved in [16] where a sourcing node first queries its closest border node (or RAL) to compute a loose route (LR) domain sequence to the destination, i.e., “skeleton path”. This queried border node essentially acts like a path computation element (PCE) entity [6]. Now the LR algorithm runs on the inter-domain graph, i.e., $H_{\text{intra}}(U, E) \cup \{H_{\text{mesh}}(U, E \cup \{E_{\text{mesh}}\})\}$, and considers all possible source/destination domain border node pairs to derive the “best” path. Specifically, for each such pair, the associated $K$-shortest paths are first searched to find the minimum hop-count path. Next, all converter combinations along this candidate LR are checked to minimize the number of used converters. This step identifies the exact border node locations for wavelength conversion. Overall, this scheme exploits wavelength converters to setup shorter inter-domain paths, loosely akin to a widest-shortest approach [7]. Given that inter-domain links will generally have much higher resource costs than intra-domain links, minimizing inter-domain link resources can be more beneficial for blocking reduction. Alternatively, future studies can also consider shortest-widest path strategies [7].

The sourcing node uses the above-computed LR sequences to generate a RSVP-TE PATH signaling message to resolve explicit end-to-end paths. This message contains an initialized “all-ones” path availability vector $a$ and also explicitly identifies all wavelength conversion locations in the LR sequence [16]. Foremost, downstream border nodes receiving these PATH messages perform explicit route (ER) expansion on the incoming LR sequence to resolve the explicit intra-domain OXC node sequence across their domains. This route computation is again done using a widest-shortest approach on the intra-domain topology database. Additionally all receiving nodes must process the PATH message in one of two ways. Namely, if the receiving node is not designated as a wavelength conversion site, it simply performs a logical AND of the incoming path availability vector with the wavelength availability vector on its outbound downstream link, i.e., $\lambda_{km}^{l}$. This operation effectively tracks available end-to-end wavelengths and the PATH message is only propagated if the resultant vector is not null. Conversely, if the node is designated as a wavelength conversion point it must first select a wavelength for all previous links in the expanded PATH LR sequence up to the last conversion OXC node (or source OXC) using most-used (MU) [3] selection. Additionally this conversion node must also re-set the path availability vector to “all-ones” and check for a non-zero nodal wavelength converter count, i.e., $C>0$. Only if a
converter is available is the \textit{PATH} message propagated downstream. This effectively “re-generates” a lightpath. The receiving destination OXC is responsible for wavelength selection up to the last conversion node in the expanded \textit{PATH} sequence, see \cite{16} (also \cite{17}) for complete details.

IV. INTER-DOMAIN ROUTING SCALABILITY

As described in Section III, the proposed routing scheme uses a two-level hierarchical \textit{link-state} routing approach to disseminate intra and inter-domain state. The first level runs the modified GMPLS OSPF-TE protocol between all domain-interval OXC nodes to help exchange full wavelength-level state for all links, i.e., extensions for DWDM links \cite{2}. Here \textit{link-state advertisement} (LSA) updates are generated via a \textit{significance change factor} (SCF) triggering policy \cite{18}. Namely DWDM LSA updates are flooded to all neighboring nodes if the \textit{relative} change in free wavelengths on a node’s link exceeds the SCF value and the duration since the last update exceeds a \textit{hold-down timer} (HT). These LSA updates contain wavelength vectors indicating the free/reserved wavelengths on the link. Meanwhile the second level of \textit{link-state} routing also uses OSPF-TE between border OXC nodes and exchanges both inter-domain physical link state as well as virtual/abstract intra-domain resource state.

Now full mesh abstraction generates $O(b^2)$ virtual links per domain, i.e., to aggregate the traversing cost between all potential border node pairs. Clearly, as the number of border nodes or the number of domains increases, this abstraction scheme will incur significant inter-domain routing overheads, thus resulting in poor scalability. By and large this issue is more a result of the abstraction scheme and not the nature of underlying DWDM link types. To resolve this challenge, some studies have proposed alternate topology abstraction schemes with fewer virtual links, e.g., \cite{7}-\cite{10} for data networks, \cite{17} for optical networks. In particular, \cite{17} adapts star abstraction to \textit{all-optical} DWDM networks by generating a virtual node for each domain. Although this reduces inter-domain routing overheads, resultant blocking performance is not as good as full mesh abstraction, e.g., approaching that of basic simple node abstraction at lighter loads. In addition, the compute complexity (at RAL nodes) is also much higher as the star abstraction algorithm sources off of the full mesh abstraction schemes, see \cite{17}. Further considerations for opto-electronic multi-domain settings are bound to increase overall computational complexities.

In light of the above, this contribution takes an altogether different approach to address inter-domain routing scalability with full mesh abstraction. Namely, rather than computing more advanced abstracted topologies, the inherent triggering mechanisms for propagating (inter-domain) virtual link state for existing mesh abstraction are altered. Before detailing these new strategies, however, it is instructive to quickly review the more basic routing update policy used in \cite{16} and \cite{17}. Specifically, upon expiry of an \textit{inter-domain hold-off timer} (IHT), a RAL node runs full mesh abstraction for its domain and propagates link state updates for any virtual link whose available (free) wavelengths change by over SCF. Physical inter-domain links are also handled in a similar manner. Hence this scheme is termed as “SCF-only” and is used as a baseline for comparison purposes, i.e., similar to relative change metrics studied in the intra-domain routing case \cite{18}. Now clearly under heavy connection loads the “SCF-only” approach can generate very high virtual LSA overheads. To resolve this concern and improve inter-domain scalability two new schemes are tabled.

**Maximum Relative Change (MRC):** This scheme only advertises updates for those virtual links that see the maximum relative change in available wavelengths, i.e., up to $h$ in total, where $h<<(b^2)$. In other words, upon expiry of the IHT a full mesh abstraction is still computed by the RAL and updated virtual links generated. However, subsequently only those virtual links whose change in available wavelengths exceeds the SCF value are short-listed and the top $h$ values are advertised at the inter-domain level. The detailed MRC pseudo-code is as follows:

1) Compute mesh abstraction, generate wavelength availability vectors $\lambda_{ii}$

2) For each virtual link, $e^i_{jk}$, compute wavelength changes since last update:

$$\Delta_{jk} = |\lambda^i_{jk} - \lambda^i_{jk}|,$$

where $\lambda^i_{jk}$ is the wavelength availability vector from the last update and $\cdot \cdot$ denotes the sum of vector components

3) Sort $\Delta_{jk}$ in decreasing order, select virtual links for first $h$ entries

4) Send above-sorted $h$ virtual link entries and send update if $\Delta_{jk} >= W\cdot SCF$

Note that step 4 above ensures routing update policy adherence to the basic SCF rule as well. In essence the $h$ parameter hard limits virtual state growth in a linear fashion with the number of domains, $O(hD)$, a notable decrease from full mesh abstraction overheads.

**Most Used-Maximum Relative Change (MU-MRC):** This scheme modifies the above proposal by further incorporating \textit{most-used} (MU) \cite{3} wavelength state. Specifically, link state updates are triggered based upon the actual wavelengths that have changed status since the last update (and not just the number of wavelengths that have changed status, as in MRC). In other words only those virtual links experiencing the most number of changes in the most MU wavelengths are updated.

The overall rationale of this approach is premised upon RWA research findings which indicate that MU state generally gives lower blocking as compared to other wavelength selection strategies \cite{3}. Specifically, the updates are generated as follows. First, as before, a full mesh abstraction is computed by the RAL upon expiry of the IHT. At this time all domain-level wavelengths are also listed in decreasing order of usage, e.g., by consulting the local intra-
domain OSPF-TE database. Next, the top \( m \) MU wavelengths are chosen and all virtual links scanned for changes therein, i.e., \( m << W \). Finally, updates are transmitted for the subset of virtual links which experience the maximum change in the above-selected \( m \) (i.e., MU) wavelengths. The detailed pseudo-code for the MU-MRC update triggering policy is:

1) Compute mesh abstraction, generate wavelength availability vectors \( \Lambda_{jk}^w \)
2) List domain wavelengths in decreasing order of usage, select top \( m \) wavelengths and generate binary MU mask vector:
\[
\Lambda(i) = \begin{cases} 
1 & \text{if wavelength } i \text{ is in MU list} \\
0 & \text{otherwise}
\end{cases}
\]
3) For each virtual link, \( e_{jk} \), compute MU wavelength changes since last update:
\[
\Delta_{jk} = | (\Lambda_{jk}^w - \Lambda_{jk}^i) \cdot \Lambda |,
\]
where \( \Lambda_{jk}^w \) is the wavelength availability vector from the last update, \( \cdot \) denotes the sum of vector components, and \( \cdot \) denotes vector AND-ing.
4) Sort \( \Delta_{jk} \) in decreasing order, select virtual links for first \( h \) entries
5) Scan above-sorted \( h \) virtual link entries and send update if \( \Delta_{jk} \geq W \cdot SCF \)

As per the MRC scheme, the above scheme also adheres to the SCF-based update policy. Moreover, the maximum number of updates is again limited to \( h \), where \( h << (b)^2 \).

Carefully note that the above-detailed routing updated policies are only applied to virtual link updates (mesh abstraction) and physical inter-domain links still rely upon SCF-only triggering to maintain signaling accuracy, i.e., deciding upon the wavelength channel to be reserved. Overall, these schemes are much more simplistic in terms of RAL computational complexity, e.g., as opposed to alternate star, tree, or bus topology transformation algorithms.

V. PERFORMANCE EVALUATION

Initial results for the proposed inter-domain architecture have been presented in [17] for “SCF-only” triggering and a single nine-domain topology. Although this represents a good reference, the work herein further studies the performance of the new routing update strategies presented in Section IV. Now all performance evaluation is done using discrete event simulation via the OPNET Modeler" tool. Specifically, new node and process models are coded for full inter-domain GMPLS operation. Table 1 summarizes some of the key simulation parameters used. In particular, all lightpath requests are generated between randomly-selected domains using a 70%-30% intra/inter-domain ratio. This is chosen to reflect practical networks which will likely field more intra-domain requests. Furthermore, the mean lightpath connection holding times are set to 600 sec (exponential) and commensurate request inter-arrival times are varied with loading (exponential). Within a given domain the source-destination OXC nodes are chosen randomly using a uniform distribution. Furthermore intra/inter-domain routing timers (HT, IHT) are set to 500 sec and all SCF update values set to 10\%, i.e., for both levels of OSPF-TE routing. Finally, all simulation runs are averaged over 200,000 connections.

Tests are conducted on a sample nine-domain topology, as shown in Figure 3. First, inter-domain lightpath blocking performance results are presented, comparing the baseline SCF-only and improved MRC and MU-MRC routing update policies. Namely, Figures 4 and 5 presents findings for \( W=8 \) and \( W=16 \) wavelengths, respectively. As expected, full mesh abstraction with SCF-only updates yields notably lower blocking than simple node abstraction (i.e., physical inter-domain link updates only), averaging about 30-50\% lower (logarithmic plots). This is due to the very accurate virtual link state being flooded, which allows intelligent inter-domain RWA schemes (Section III.B) to effectively bypass congested domain/border nodes.

![Image](image_url)

**Figure 3: Nine-domain topology**

More importantly the results in Figures 4 and 5 also show that coupling full mesh abstraction with improved MRC updates \((h=3)\) yields very comparable blocking performance to full mesh with SCF-only updates. Furthermore, the more selective MU-MRC update policy \((e.g., h=3,m=3\) and \(h=5,m=5\)) gives very good blocking gains, i.e., almost on par with full-mesh abstraction and notably better than single node abstraction. In fact these improved routing strategies closely track the blocking performance of the SCF-only scheme across the full range of tested load. To illustrate this more closely, the difference in failed inter-domain lightpaths (versus the baseline full-mesh scheme with SCF-only updates) is

| Intra/inter-domain traffic ratio | 70\%:30\% |
| Connection holding time | Exp (mean 600s) |
| Hold-off time | 500 sec |
| Inter-domain hold-off time | 500 sec |
| Significance change factor (SCF) | 10\% (0.1) |
| Wavelength assignment | Most-used |
| Connections per run | 200,000 |

Table 1: Multi-domain simulation setup
plotted in Figure 6. At lower loads it is seen that this discrepancy is almost negligible, albeit it does rise slightly at extremely high connection loads, i.e., 10-20% blocking range. These findings validate the general hypothesis that propagating a subset of virtual link state updates can be very beneficial in summarizing domain state change, particularly at low-to-medium blocking regimes (i.e., corresponding to most operational settings). In addition the results also confirm the effectiveness of using MU wavelength state for inter-domain routing, particularly for achieving domain state compression. Moreover these findings extend upon earlier studies on the efficacy of MU state for RWA in general, see survey in [3].

In addition to blocking performance, inter-domain routing loads are also tested, i.e., measured as the number of OSPF-TE update messages exchanged per second (LSA/sec). These results are shown in Figures 7 (W=8) and 8 (W=16), respectively. As expected, full mesh abstraction with SCF-only updates yields the highest routing loads, almost 4-5 times higher than simple node abstraction (which yields the lowest). Conversely, the improved MRC scheme reduces OSPF-TE update messaging loads anywhere from 20-40% (h=5) while still achieving comparable inter-domain blocking. More importantly the more-selective MU-MRC strategy yields even higher routing load reductions, particularly at low-medium load levels (typical of most normal operating settings). For example, for W=16 and 83 Erlang loading, Figure 7, MUMRC with h=m=3 gives an inter-domain routing load of 41 LSA/sec, about 46% lower than SCF-only (76 LSA/sec) and 12% lower than MRC with h=3 (50 LSA/sec). An even more pronounced reduction is shown in Figure 7 for MU-MRC with W=8 wavelengths and 30 Erlang loading, i.e., over 50% lower than full mesh with SCF-only. Note that MU-MRC approaches MRC at higher loads as IHT timers quickly limit overall LSA update rates, i.e., “clamp-down” effect [18].
VI. CONCLUSIONS

This paper focuses on inter-domain routing scalability in multi-domain DWDM networks. Namely two novel triggering policies are tabled for improved domain-level state summarization, i.e., maximum relative change (MRC) and most-used maximum relative change (MU-MRC). Detailed performance evaluation studies show notable reductions in inter-domain routing overheads versus more basic “SCF-only” update policies. Most importantly these gains come without any significant increase in inter-domain lightpath blocking, confirming the effectiveness of these state reduction strategies. Specifically, these improvements range anywhere from 20-45% lower inter-domain LSA rates, with the more selective MU-MRC scheme giving the most reduction. Future efforts will study the use of these inter-domain routing update policies in extended multi-layer, multi-granularity settings, such as IP-DWDM and SONET-DWDM networks.

REFERENCES