Rethinking Multi-Layer Multi-Domain Network Monitoring

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Abstract: Accurate and efficient network fault localisation based on monitoring is obviously one of the vital but also formidable tasks for successful network operations. With proliferations of large-scale network services, e.g. Géant E2E links, monitoring and fault localisation across multiple domains with data obtained from different network layers are becoming unprecedentedly important. Many efforts have been invested to tackle the challenges posed by fault localisation, nevertheless, most approaches only suggest partial solutions to the problematics of multi-domain multi-layer aspects. Most importantly, a comprehensive view and deep understanding of the problem is still missing. In this paper, we intend to systematically discuss challenges and their implications posed by fault localisation with consideration on multi-domain and multi-layer monitoring data. The contributions of this paper are manifold: *first* we identify key research challenges regarding multiple layer monitoring for fault localisation across domains; *then* based on the identified multiple layer network patterns, we establish comprehensive problem dimensions in a systematic and structured way which holds key to the solution development; *finally* we propose a formal definitions on information model which captures essential characteristics of multiple network layers across domains.

Keywords: Multi-domain/Multi-layer Network Management, Network Monitoring, Network Fault Localization, Network Modeling, Formal Methods.

1 Introduction

Maintaining of well-functioning networks is one of the prerequisites for offering high quality networking services. This implies that network outages of any kind should be detected and localized the soonest possible so that impact to network can be reduced to its minimum. To facilitate high efficient network fault detection and localization processes, we need support from accurate and effective network monitoring approaches which allow network events to be registered and reported in a timely and precise manner. With proliferation of large scale network services across multiple domains, such as Géant end-to-end link services [YHL$^+$10], monitoring mechanisms that are confined within a single administrative as well as technological domain are no longer suitable for performing monitoring tasks across several domains. Moreover, to increase the accuracy of the fault detection and localization processes, monitoring data from multiple network layers need to be aggregated and correlated so that network faults could be precisely pin-pointed [Gop00, SS02]. We argue that to cope with today's network management problems, especially for fault detection and localization, monitoring approaches have to consider and combine the multi-domain and multi-layer aspects. Unfortunately, despite its importance, only little has been done in this research area. Research challenges and problematics regarding multi-domain multi-layer monitoring are neither well-understood nor thoroughly investigated.

To bridge this gap, in this seminal paper, we focus on several important issues as foundations for building a viable monitoring approach for the multi-domain and multi-layer networks. The goals of this paper are manifold: first we identify and articulate research problems and challenges. Then based on the problem statement, we establish a rather comprehensive problem dimensions based on network patterns that we identified. The given problem dimensions could be used as a reference for solution development and further research. Finally and most importantly, we propose a formally defined information model using set-theoretic notations, which we argue is a concise and flexible way to model network links and paths with consideration on multi-domain and multi-layer aspects.

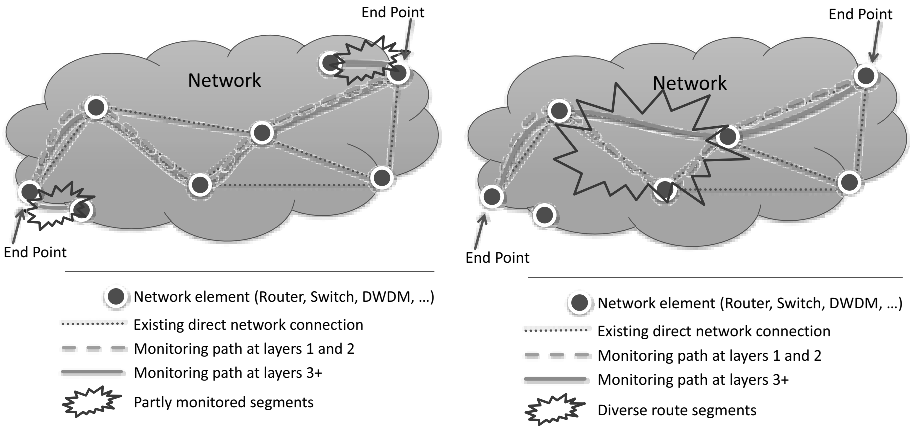
2 Problem Statement

In this section, we articulate research problems and challenges that are inherent to multi-domain multi-layer network monitoring approach. It is not our intention to provide an exhaustive list of problems, rather we try to identify and discuss some of the most important and fundamental ones.

Ideally all monitoring information that have to be correlated should be collected over the same infrastructure and at the same time. However, in the reality it is not always the case, we approach our problem statement with special focus on two main perspectives: *topology* and *time*.

For the matter of simplicity, for all examples in this section we assume that the monitoring information of ISO/OSI layers 1 and 2 should be correlated with the monitoring information obtained at ISO/OSI layer 3 and higher (noted as layer 3+ hereafter).

Topology: Measurement Points Regardless whether active or passive measurements are employed, monitoring should be performed between an actual pair of end-points (also known as measurement points) from which monitoring data are desired. Nevertheless, more than often, extra link segments lay between the measuring equipment and the actual measuring points, which is not only confusing but also may distort the monitoring results as well. The quality of network segment between actual measurement point and device to be measured can influence quality of results. Fig. 1(a) illustrates the discussed measurement points placement, in which equipment for ISO/OSI layer 3+ measurement is attached to two further components. To perform a multi-domain multi-layer monitoring operation, such scenarios must be considered.



(a) Monitoring between different end-points

(b) Monitoring different routes

Figure 1: Monitoring modes

Topology: Communication Path Even if the measurements are performed between an actual pair of end points, they are not always performed on the same monitoring subject. In Fig. 1(b) a typical situation of path diversity between ISO/OSI layer 1&2 and 3+ monitoring is depicted. In operations, the layer 1 and 2 monitoring is performed via access to the error counters at the installed network infrastructure. Usage of extra devices like Optical Time Domain Reflectometer (OTDR) is regarded as an expensive option. Consequently, monitoring at layers 1 and 2 can be seen as measurements over fixed path.

From ISO/OSI layer 3 upwards, a fixed path is not always guaranteed[1]. An network problem at layer 3 can force a router to switch to an alternative path. Such capability is overseen by almost every routing algorithms. This implies network problem at layer 2 cannot be detected if only layer 3 fault detection and localization is applied, since the self-repairing mechanism of routing algorithms mask such failure automatically. The alternative path may introduce extra network delay and it is a time-consuming process to find out the reason of network deterioration. A more advanced situation of route diversity is the route flipping, which means that there is no guarantee that the IP packets at layer 3 always routed through the same path. A direct consequence is that not only monitoring paths at different layers can differ but also the path difference can change over time. Further, this could also mean that the active probes for layer 3 monitoring can in worst case take a route which is completely different from the end user traffic. This in turn would lead to disagreements between monitoring data and end-user experience with the connection.

Time: Measurement Scheduling Even at ISO/OSI layer 3 along, different measurements can be performed. Due to its invasive nature, high-frequent usages of active measurements are not advisable. Less invasive approaches can be nevertheless applied fre-

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[1] Even if such a fixed path can be enforced, e.g. via traffic engineering with MPLS.

quently, as it does not influence use traffic too much, for instance, the period of back-to-back packets sent for jitter measurements can be held quite short. The throughput measurements vice versa can be scheduled only occasionally as they directly influence the end-user service quality. Furthermore, some of the measurements can be barely performed at the same time. For instance, the mentioned throughput measurement would negatively influence measurements of delay variation.

Consequently, at different layers different permanent, periodical, and scheduled measurements are available for correlation. Further, also the measurements which have to be performed during some period of time can be scheduled for different time. This means that the monitoring information at different layers might be based on the measurements performed under different network conditions.

Time: Clock Synchronization Similar to the discussion about measurement scheduling, not synchronized clocks might cause the drift between the measurements at different layers. However, the application areas are different from those of scheduling. For instance, especially in the case of multi-domain network connections the monitoring measurements can be performed by different organizations. Further, the past monitoring data might have to be evaluated. This all requires that the measurements provided by different monitoring infrastructure and organizations have to be correlated for the exact time period. This in turn requires that either the clocks between all monitoring infrastructures are synchronized during measurements or the clock deviation is known so that it can be taken in account during post-processing.

In addition to the aforementioned technical problems, a non-technical barrier worth mentioning is that various management policies reign among the participating domains. For example, a domain may be reluctant to share its information regarding network connectivities for security reasons, thus it may pose a very restrictive information-sharing policy towards external entities. Consequently lacking essential monitoring information, even the most sophisticated fault localization algorithm cannot produce expected results. To this end, fault localization approaches have been investigated based on partial network information. Inference techniques based on Bayesian theory, neural networks and decision trees, etc. have been applied to cope with incomplete network information.

3 Scenario Dimensions

For a better delimitation of the main problems concerning multi-layer multi-domain monitoring three scenario dimensions have been identified:

- Multi-layer: concerned with the influence the network layering has on monitoring. As on each network layer other metrics or parameters are needed, an overview of these layers and their interconnections is taken into account. Multi-layer is a vertical dimension.
- Multiple technical domains: this is only one part of the multi-domain dimension.

	QoS-Param	Topology	Time	Functionalities
Multi-layer	ML-Q	ML-To	ML-T	ML-F
Multiple technical domains	MT-Q	MT-To	MT-T	MT-F
Multiple organizational domains	MO-Q	MO-To	MO-T	MO-F

Table 1: The dimension matix

Monitoring a multi-domain network it is a challenge to bring together information from different technical domains, so domains that uses different techniques (Ethernet, MPLS, SDH etc.). This is a horizontal dimension.

- Multiple organizational domains: the second part of the multi-domain dimension. There is a difference between this and the former one, as there could be the same technique used in two different organizational domains as well as two different techniques within one organizational domain.

For the given dimensions following network properties are relevant in the different specificity:

- QoS-Parameter: as the most important quantifiable parameter for the network monitoring
- Topology: representing the real and logical components and their connection on all layers of the network.
- Time: challenges as measurement scheduling and clock synchronization are directly connected with the parameter of time.
- Functionalities (management and usage): generally represents what the network offers in terms of usage (connectivity, IP services etc.) and how this is managed.

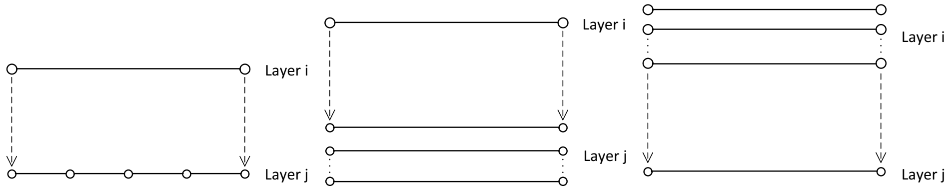
The dimension matrix (see Table 1) results from the combination between the different dimensions on the vertical(left) and the properties horizontal (on top).

In the following the fields of the dimension matrix will be explained. Not each of these fields have the same importance. We will begin with the multi-layer/topology (ML-To) field as the most complex of them. This is also the basic problem space on which all other are based on. Therefore we propose for ML-To item three different patterns (see Figure 2). In all of these we compare two general layers (i and j) of the network.

- Simplified Segmented Layering: For this pattern (see Figure 2(a)) we assume that for a link on layer i a segmented link on a lower layer (layer j) exists. The „margins" of the link on the upper layer correspond to some other nodes in the layer below. In the layer j as the name suggests more link segments are given which realize on this layer the pre-requisite for the functionality of the link on the upper layer.

- Bundling: In this case on layer i (upper) exists a link which is realized by bundling some links on a lower layer j. So here we have a projection of a layer i „margin” on more „margins” of all of the links in the bundle on layer j (see Figure 2(b))
- Link Sharing: In the last pattern proposed (see Figure 2(c)) on layer i there are a bunch of links realized all though one link on the lower layer j. As all these links on the upper layer use that one link on the lower layer, this has been named link sharing.

Although we present these three patterns, it could be possible that other patterns exist. These chosen patterns are that ones which bring for our multi-layer, multi-domain monitoring approach the most essential and needed information content.



(a) Simplified Segmented Layering (b) Bundling (c) Link Sharing

Figure 2: Multi-Layer/Topology Patterns

As stated before the ML-To field of the dimension matrix is the basis for all other. We will not detail here all of them, we only highlight some connections between them. Multi-layer/QoS-Parameter (ML-Q) is based on ML-To as all the QoS-Parameter are specific for each network layer respectively network topology. ML-T (multi-layer/time) is also strongly related on ML-To as synchronization and scheduling of measurements for a proper monitoring result have to be related to the multiple-layer/topology issue. Same problematic for ML-F (multi-layer/functionalities) as different functionalities can be delivered on different layers and naturally for different topologies. Also for each network layer/topology different management functionalities are assigned.

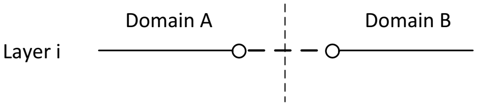


Figure 3: Multi-domain: intra-/inter-domain links per layer

The second row in the dimension matrix is dealing with the multiple technical domains in relation with the different parameters. All four fields are directly related to the upper one as each technical domain is organized as a multi-layer network. So MT-To (multiple technical domains/topology) is directly based on ML-To so the patterns described above meet at their margins other technical domains (see Figure 3). For the third row of the dimension matrix multiple organizational domains apply the same consideration as for the second row.

4 Solution Building Blocks

As presented in the precious sections, designing a comprehensive fault localization approach across multiple layers and multiple domains is a challenging task. The fact that, not only technical issues but also organizational, even political reasons contribute to the complexity, further deteriorates the problematic. Therefore, instead of offering a complete solution, as core contribution of this paper we rather intend to discuss the essential generic building blocks that must be considered and observed in a development of such an approach. The presented models could be used as templates or guidelines by designing specific network monitoring approaches across domains and layers. We argue that a set of clearly presented solution models are more crucial and provide piece-meal solutions.

We believe that a comprehensive solution must be designed with four different model-based views, including: *Information Model, Communication Model, Organisational Model* and *Functional Model*, as it is methodologically suggested in [HAN99]. However, concentration will be given to the information model at this stage, detailed discussion regarding other models will be provided in our series of paper in future.

4.1 Information Model

We use a formal model to clearly define and describe the essential elements and corresponding structural patterns introduced in Section 2. In addition to simplicity and conciseness, using mathematical model allows utilizing well-defined mathematical operations to manipulate the model. For later applications, the model can be simply mapped to data structure, in a selected programming language. We approach the modeling operation in two phases: first we provide a definition of a basic link model which can be regarded as the very elementary building block; then, based on the basic model, we describe formally the network patterns as we identified in the previous section.

4.1.1 Basic Definitions

In order to formally define the ML-To patterns it is necessary to introduce some general definitions borrowed from graph theory. This can be divided into two categories: the general/layer-independent and the layer-dependent definitions for link and path.

Definition 1. *Link*

A ***link*** *is defined as an edge* $e \in E$ *from* ***start node*** v_{start} *to* ***end node*** v_{end}*, with* $v_{start}, v_{end} \in V$*, with* E *the set of all potential links (edges) and* V *the set of all potential nodes.*

Following functions for edge/node relationships are defined:

`start` : $E \rightarrow V$ *with start node* $\texttt{start}(e) = v_{start}$ *and*
`end` : $E \rightarrow V$*, with end node* $\texttt{end}(e) = v_{end}$.

Definition 2. *Path*

*A **path** p from **start node** v_{start} to **end node** v_{end} is a (ordered) sequence of links $[e_1, e_2, \dots, e_n]$, with $e_1, e_2, \dots, e_n \in E$, $v_{start} = \mathtt{start}(e_1)$, $\mathtt{end}(e_{i-1}) = \mathtt{start}(e_i)$, for $i = 2, \dots, n$, and $v_{end} = \mathtt{end}(e_n)$*

Following functions for path/node relationships (using same names as for edge/node relationships, i.e. overloading the function names) are defined:

$\mathtt{start} : P \to V$ *with start node* $\mathtt{start}(p) = v_{start}$ *and*
$\mathtt{end} : P \to V$ *with end node* $\mathtt{end}(p) = v_{end}$.

The set of all such paths is denoted by P. In order to define the ML-To patters we need an additional description in the above given definitions to differentiate between the links and path on the different network layers. Therefore a refinement per layer – nodes, links, (and consequently paths) pertain to one particular layer $i \in I$ only and are connected only within the same layer – is needed. These is the layer-dependent definition for layer $i \in I$:

Definition 3. *Node, link, path layer-dependent definition*

In the layer-independent definition for link, node and path above replace E with E^i (links on layer i), V with V^i (links on layer i), and P with P^i (paths on layer i), with $i \in I$.

4.1.2 Formalising the ML-To Patterns

Having the basic link model defined, we further provide formal descriptions of network patterns as discussed in Section 2. The description uses the basic model as an elementary building block.

Definition 4. *Basic Path Mapping*

*Given 2 paths $p^i \in P^i$ and $p^j \in P^j$ on layer i and j, respectively, with $i > j$, the **basic path mapping** between p^i and p^j is the element (p^i, p^j) of the full relation $P^i \times P^j$.*

In detail, it describes the relationship $p^i \mapsto p^j$ between the two paths
$p^i = [e^i_1, e^i_2, \dots, e^i_n]$ from $\mathtt{start}(p^i) = \mathtt{start}(e^i_1)$ to $\mathtt{end}(p^i) = \mathtt{end}(e^i_n)$ and
$p^j = [e^j_1, e^j_2, \dots, e^j_m]$ from $\mathtt{start}(p^j) = \mathtt{start}(e^j_1)$ to $\mathtt{end}(p^j) = \mathtt{end}(e^j_m)$,
i.e. especially the start/end nodes are mapped correspondingly: $\mathtt{start}(p^i) \mapsto \mathtt{start}(p^j)$ and $\mathtt{end}(p^i) \mapsto \mathtt{end}(p^j)$.

Definition 5. *Set-theoretic notation for link segmentation pattern*

A single basic path mapping can be directly used to represent a link segmentation pattern: a link segmentation $p^i = [e^i_1, e^i_2] \mapsto p^j = [e^j_1, e^j_2, \dots, e^j_n]$ (compare Figure 2(a)) with $i > j$, is represented by (p^i, p^j) or more general by the singleton $\{(p^i, p^j)\} \subset P^i \times P^j$ (to make it compatible with the following notations for the other two patterns).

Definition 6. *Set-theoretic notation for link bundling pattern*

A link bundling is denoted by a set of related basic path mappings:
given a path $p^i \in P^i$ on layer i and n bundled paths $p^j_1, p^j_2, \dots, p^j_n \in P^j$ on layer j with $i > j$, $\mathtt{start}(p^j_k) = v^j_{start} = \mathtt{const}$, and $\mathtt{end}(p^j_k) = v^j_{end} = \mathtt{const}$ ($k = 1, \dots, n$),

the subset $\{(p^i, p^j_1), (p^i, p^j_2), \ldots, (p^i, p^j_n)\}$ *of* $P^i \times P^j$ *represents the corresponding link bundling* $p^i \mapsto p^j_1, p^j_2, \ldots, p^j_n$ *(compare Figure 2(b)).*

Definition 7. *Set-theoretic notation for link sharing pattern*

A link sharing is also denoted by a set of related basic path mappings:
given n *(multiplexed) paths* $p^i_1, p^i_2, \ldots, p^i_n \in P^i$ *on layer* i *and the shared path* $p^j \in P^j$ *on layer* j *with* $i > j$, $\texttt{start}(p^i_k) = v^i_{start} = \texttt{const}$, *and* $\texttt{end}(p^i_k) = v^i_{end} = \texttt{const}$ *(*$k = 1, \ldots, n$*), the subset* $\{(p^i_1, p^j), (p^i_2, p^j), \ldots, (p^i_n, p^j)\}$ *of* $P^i \times P^j$ *represents the corresponding link sharing* $p^i_1, p^i_2, \ldots, p^i_n \mapsto p^j$ *(compare Figure 2(c)).*

We described here the way the ML-To patterns proposed in Section 3 can be formalized: so each of the three link topology patterns (for layers $i > j \in I$) is represented as a relation between P^i and P^j (i.e. a subset of $P^i \times P^j$)

Nevertheless as we cannot find in real systems a pure form of these patterns the capacity to combine them essential. This has also to be formalized as well:

The combination of segmentation pattern with either bundling or sharing is already subsumed in the respective notations for bundling/sharing, as both are based on the definition of a basic link mapping (which subsumes segmentation as a particularization, compare above definition 5)

So it is left to show that the combination of bundling + sharing can be represented using these definitions.

A combination of n multiplexed links sharing on layer i a bundling of m links on layer j (with $i > j$) $p^i_1, p^i_2, \ldots, p^i_n \mapsto p^j_1, p^j_2, \ldots, p^j_m$ with
$\texttt{start}(p^i_k) = v^i_{start} = \texttt{const}$, $\texttt{end}(p^i_k) = v^i_{end} = \texttt{const}$ ($k = 1, \ldots, n$),
$\texttt{start}(p^j_k) = v^j_{start} = \texttt{const}$, and $\texttt{end}(p^j_k) = v^j_{end} = \texttt{const}$ ($k = 1, \ldots, m$),
can be represented by the relation

$\{(p^i_1, p^j_1), (p^i_1, p^j_2), \ldots, (p^i_1, p^j_m), (p^i_2, p^j_1), (p^i_2, p^j_2), \ldots, (p^i_2, p^j_m),$
$\ldots$
$(p^i_n, p^j_1), (p^i_n, p^j_2), \ldots, (p^i_n, p^j_m)\} \subset P^i \times P^j$

4.1.3 Extension for multi-domain

To support the distinction of different domains (technical and/or organizational ones, see the scenario dimension in Table 1), the set-theoretic notation for the ML-To patterns are extended:

For any layer $i \in I$ the pertaining to a particular technical/organizational is an characteristic of the nodes V^i. Therefore two functions $dom^i_{tech} : V^i \to D_{tech}$ and $dom^i_{org} : V^i \to D_{org}$ with D_{tech} and D_{org} being the sets of all potential technical and organizational domains, respectively, are introduced to model this characteristic.

Links on any layer whose start and end node pertain to the same technical resp. organizational domain, are technical resp. organizational intra-domain links, all others being technical resp. organizational inter-domain links.

This extension can be used with any combination of the notations defined for the ML-To patterns.

In Figure 4.1.3 an illustration for an example of combination with link bundling is given. For a short notation a node $v^i \in V^i$ for $i \in I$ which pertains to (technical or organizational) domain d is denoted by $v^{i,d}$. Similarly an intra-domain link $e^i \in E^i$ within domain d is denoted by $e^{i,d}$, while an inter-domain links e^i is denoted generally by $e^{i,inter}$. In the example the inter-domain path $[e^{i,inter}]$ (= $[e^i]$ with e^i being inter-domain) on layer i is based on the bundling of the two inter-domain paths $[e_1^{j,d_1}, e_2^{j,d_1}, \ldots, e_{n-1}^{j,d_1}, e_n^{j,inter}, e_{n+1}^{j,d_2}, \ldots, e_{n+m}^{j,d_2}]$ and $[f_1^{j,d_1}, f_2^{j,d_1}, \ldots, f_{k-1}^{j,d_1}, f_k^{j,inter}, f_{k+1}^{j,d_2}, \ldots, f_{k+l}^{j,d_2}]$ on layer j (the nodes of e^i being denoted by v^i_{start} and v^i_{end}, the nodes of e^j_x being denoted by $v^j_{x,start}$ and $v^j_{x,end}$ for $x = 1, \ldots, n+m$, and the nodes of f^j_x being denoted by $w^j_{x,start}$ and $w^j_{x,end}$ for $x = 1, \ldots, k+l$).

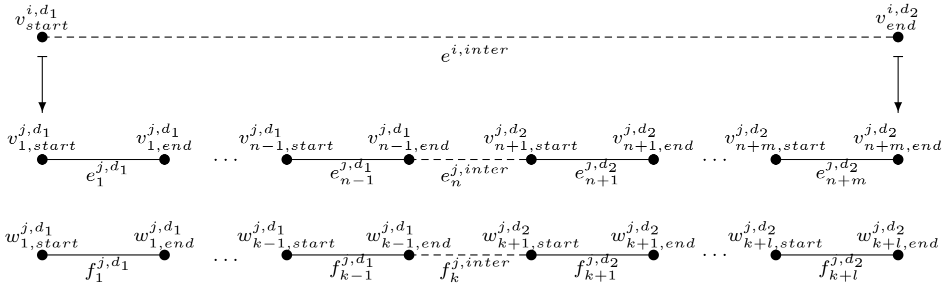


Figure 4: Example illustration of multi-domain mapping, combined with link bundling

4.2 Other Model-based Perspectives

In the former section the information model as base for multi-domain/multi-layer monitoring has been described. In order to fulfill the management architecture some more components should be described. These are not a main part of this paper but for the sake of completeness this will be here mentioned only. The *functional model* has to underline the most important functionalities concerning multi-domain/multi-layer monitoring based on the information model. The *organizational model* should reveal the roles and responsibilities in intra-/inter-organizational environments that are required in order to conduct efficient the multi-domain/multi-layer monitoring. Last but not least the *communication model* should deliver the required information communication exchange measures and procedures.

5 Existing Approaches

Given the importance of ensuring network stability and robustness, a plethora of researches have been done in the area of network monitoring. One of the ultimate goals of the invested efforts, above all, is to perform better network fault management based on the monitoring information in terms of time and accuracy. Nevertheless, the importance of the aforementioned cross-layer and cross-domain aspects in real-world network operation scenarios has been unfortunately understated. As revealed by our survey of related works, much effort has resulted in *partial solutions*, which means those solutions are specially tailored for some aspects of network monitoring and fault localization challenges as posed previously.

A survey from Sethi et al. [S^+04] documents fault localization techniques which covers AI techniques, model traversing and fault propagation models. Most of the surveyed approaches are limited to academic discussions based on relatively simple network models. A special attention has been given to approaches based on inference techniques such as neural networks, decision trees and Bayesian networks, etc. Among others, issues concerning multi-layer fault localization and temporal correlations are regarded as open problems, thus no solution is presented. Challenges regarding network monitoring and fault localization across multiple domains are not discussed at all. IETF RFC 3386 [LMB^+02] provides a solid groundwork and a useful reference for the further discussion of network monitoring across layers and domains. Even if the discussion focuses on the hierarchy and multi-layer *survivability*, however, terminology and concepts posed in the work can be directly applied in our discussion. Mas et al. [MT00] propose an algorithm for locating soft and hard network failures in WDM networks. Their approach mainly concentrate on the fault localization of WDM networks (ISO/OSI layer 1). Kompella et al. [KYGS05, Kom07] present a risk-modeling based method to facilitate fault localization in IP backbone network, in the meanwhile, it is also possible to detect and locate silent failures (so-called *network blackhole*). The suggested approach is mainly focused on locating faults at IP level. Also the inter-domain aspect is not considered as well. Pal et al. [PPM^+08] show in their work a scheme for detecting and locating multiple failures in WDM optical networks. Their approach is confined to layer 1. The work from Dhamdhere et al. [DTDD07] proposes an algorithm called NetDiagnoser to identify fault locations with the ability to perform multi-AS network troubleshooting. The approach is based on an extend Boolean tomography approach. However, the proposed algorithm works sheerly based on layer 3 network links. Xie et al. [XFY09] approach the challenge of cross-domain fault localization by applying the graph-digest based methods, including isolated inference, full disclosure and privacy preserving collaboration. Their proposed approaches considers different degree of information sharing between domains, ranging from totally uninformed inference to full collaborative data-sharing. The issues regarding collaborations throughout vertical network layers remains unanswered in their suggested approaches. Marcu [Mar11] proposes an architecture concept for inter-organizational fault management. It is designed to facilitate collaborations between organizations with regard to life cycle of faults of networked services. Such an architecture can be extended and applied as a information interchange platform for the cross-layer, cross-domain fault localization. In the context of management of future Internet, Liu [Liu11, Liu09] proposes to apply AI-based planning technique as a viable method to compose management action plans automatically. With a slight modification of the planning knowledge, such an approach can be used to encode fault localization procedural knowledge which is otherwise impossible. Based on the formalized planning knowledge, the planning engine then can make context-based decisions and compose one or several fault localization action plans. Event correlation for fault diagnosis is treated in the work of Hanemann [Han07], in which he proposes a framework to perform fault diagnosis using a hybrid approach involving event correlation and case-based reasoning techniques. Valta [Val90] proposes a formal description method for heterogeneous networks, which relies on graph-theoretical based approach called *layered attributed graph* to model networks. This work lays a solid foundation, on which we build our approach by integrating the inter-domain perspective and more detailed link patterns (as illustrated in Figure 2).

6 Conclusion and Future Work

With proliferation of large scale network services with high requirement on link qualities, network monitoring for fault localization across different domains becomes unprecedentedly important for the network management operations. To perform accurate fault localization, aggregation of monitoring data from different network layers also plays a decisive role, by which fault data could be correlated to precisely pinpoint the fault locations. Thus a precise and effective monitoring approach for fault localization of large scale network service should consider not only the multi-domain aspect, but also multiple data obtained from different participating domains. Despite of its importance and many invested efforts, multi-layer monitoring across domains boundaries has not been fully understood and the corresponding problematics are not throughly defined.

To fill-in this gap, in this paper we systematically analyzed and discussed network monitoring with consideration on the multi-layer and multi-domain aspects. We approach the problematic with a rather detailed deliberation and observation on the research challenges. We then establish a comprehensive problem dimension room which captures the essential factors as references for providing a solution. The problem dimension room is built based on the multi-layer/topology patterns we identified. Finally we provided a formally defined information model based on the set-theoretical principle. Additionally to its conciseness and clarity, a mathematically well-formulated model has the advantage of flexibility, by which mathematical operations could be performed to manipulate and operate on data. Having the information model formalized, one of our future work will discuss a set of mathematical operations that can be performed to extract relevant informations. Those operations could be then mapped to the programming languages by implementations of the information model. Since our work in this seminal paper currently concentrates on the information modeling, in our further work, we will give a detailed treatments on the other crucial aspects which include organizational model, communication model and functional model. Furthermore, our effort will be also dedicated to the adaptation of the presented information model to real-world scenarios, such as management of E2E links provided in Géant.

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