

# Fault localization in Communication Networks

Vijay Akkineni

Department of Computer Science and Engineering  
Georgia State University

`vakkineni1@student.gsu.edu`

## Abstract

This paper is about fault localization techniques in communication networks worked for Phd qualifiers examination. Fault Localization is an important aspect of network fault management and is a process of deducing the source of a failure from the set of observed indications. It has been an important research area in the field of networking both communication networks and wireless sensor networks. As communication networks grow in size and complexity it has been imposing new set of requirements on fault localization. Despite the amount of research done in this field we can still argue that it is an area of open for research. The paper essentially discusses the work that has been done in this field in the past few years with emphasis on the both the papers given for the examination.

## Categories and Subject Descriptors

H.4 [Communication Networks, Sensor Network Applications]: Miscellaneous

## Keywords

Fault Localization, Communication Networks, Root Cause Analysis, Causal Inference

## 1 Introduction

Fault diagnosis is an important part of networking. Faults are unavoidable in communication systems but their quick detection and isolation and repair is critical for the robustness, reliability and health of the system. When the networks get large and cumbersome automatic fault diagnosis and fault management is a crucial aspect.

A basic taxonomy in this field is mentioned below.

Event, defined as an exceptional condition occurring in the operation of hardware or software of a managed network, is a central concept pertaining to fault diagnosis.

Faults (also referred to as problems or root causes) constitute a class of network events that can cause other events

but are not themselves caused by other events. Faults may be classified as: (1) permanent, (2) intermittent, and (3) transient. A permanent fault exists in a network until a repair action is taken. Intermittent faults occur on a discontinuous and periodic basis causing a degradation of service for short periods of time. However, frequently re-occurring intermittent faults significantly jeopardize service performance. Transient faults cause a temporary and minor degradation of service.

Error(Failure) is defined as a discrepancy between a computed, observed, or measured value or condition and a true, specified, or theoretically correct value or condition. Error is a consequence of a fault. Faults may or may not cause one or more errors. Errors may cause deviation of a delivered service from the specified service, which is visible to the outside world. Errors do not need to be directly corrected, and in many cases they are not visible externally. However, an error in a network device or software may cause a malfunctioning of dependent network devices or software. Thus, errors may propagate within the network causing failures of faultless hardware or software.

Symptoms are external manifestations of failures. They are observed as alarm notifications of a potential failure. These notifications may originate from management agents via management protocol messages (SNMP trap and CMIP EVENT-REPORT), from management systems that monitor the network status, e.g., using command ping, system log-files or character streams sent by external equipments.

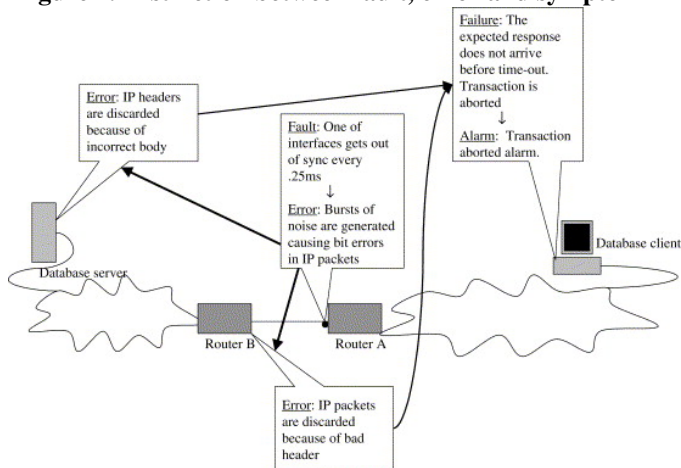
Figure 1 shows the concepts described above in an end to end perspective.

The process of fault diagnosis usually involves three steps as cited in [1]:

- Fault detection, a process of capturing on-line indications of network disorder provided by malfunctioning devices or fault detection agents in the form of alarms.
- Fault localization (also referred to as fault isolation, alarm/event correlation, and root cause analysis) is a set of observed fault indications is analyzed to find an explanation of the alarms.
- Testing is a process that, given a number of possible explanations, determines the actual faults.
- Fault Correction, by which we mean not only to diagnose, but also to repair all faulty components within a

network (This includes the testing component).

**Figure 1. Distinction between fault, error and symptom**



The difficulty in the fault localization process arise from the ambiguity of the observed set of alarms as same alarm can be generated from multiple different faults and multiple alarms can correlate back to the same fault. The incompleteness of the alarm stems from the fact that the alarm doesn't have all the information or there is a loss of alarm. Inconsistency among the observed alarms results from device perception of the fault is different from device to device.

A set of alarms generated by a fault may depend on many factors such as dependencies among network devices, current configurations, services in use since fault occurrence, presence of other faults, values of other network parameters, etc. Due to this non-determinism the system knowledge may be subject to inaccuracy and inconsistency. Fault evidence may also be inaccurate because of spurious alarms, which are generated by transient problems or as a result of overly sensitive fault detection mechanisms. When spurious symptoms may occur, the management system may not be sure which observed alarms should be taken into account in the fault localization process. Event management systems should identify and eliminate multiple simultaneous related or unrelated root causes.

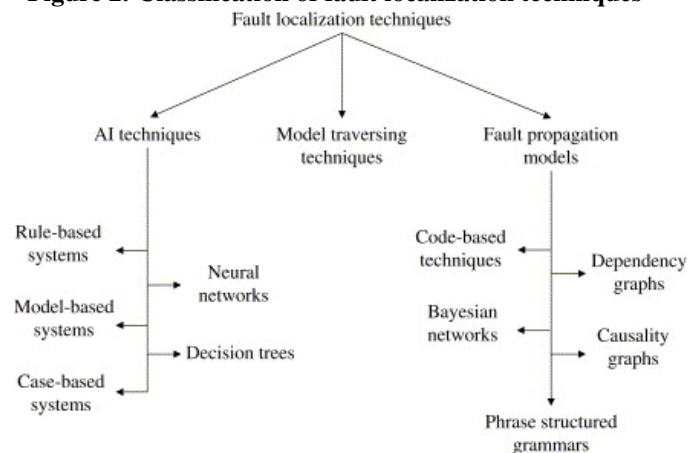
In large networks distributed fault localization process should be performed in distributed fashion. Many researches [2] and [3] have concluded that distributed fault localization using a set of event management nodes is a better approach than centralized process. The complexity arises from the nature of error propagation, they propagate either horizontally to the peers or vertically from bottom layer to upper layers or affecting higher level services. The errors also propagate from one management domain to a different management domain making the process even difficult. Therefore the distribution of complexity to distributed fault localization processes and inferring from the collective process makes the process computationally feasible and efficient.

An alarm can insinuate different type of faults that occurred in different communication devices where in fault localization process may not come up with a definitive answer. Few approaches that will be discussed in this paper combine

fault localization with testing and fault correction process to validate the hypothesis. Therefore there should be some kind of optimality measure or confidence measure that should be employed in measuring the hypothesis that the localization process came up with and it could include the lowest cost or min failure probability or some heuristic function which optimizes the process of validating the hypothesis.

Numerous works have been proposed on fault localization process. The techniques are derived from different areas of artificial intelligence, graph theory, neural networks, automata theory and many other approaches. Figure 2 broadly classifies the existing solutions. The two papers provided for the exam falls into the category of end to end testing scenarios and probabilistic reasoning and derive their roots from Bayesian network analysis.

**Figure 2. Classification of fault localization techniques**



This paper presents the background research that has been done before paper 1 in section 2 - 4 and in section 5 presents the paper 1 [30].

## 2 Expert Systems techniques

Most widely used technique in the field of fault localization and diagnosis are expert systems as they try to mimic the actions of human expert. Most expert systems use rule based system as their inference engine. [4],[5] and [6] are examples of expert systems.

The expert systems developed differ in the knowledge they use. Rule based fault localization solely depend on the structure of the knowledge base as rule definition language. In [7] the knowledge base is divided to reusable knowledge modeled as core knowledge and customized knowledge. in [5] the rules are organized as composite events and an intervention of human expert is required to update the event base. The rule based systems can act as a powerful tool to eliminate least likely hypothesis. Although the RBR paradigm is appropriate for problem-solving tasks that are confined and well-understood its limitations are.

- an in-ability to learn from experience.
- Fan inability to deal with novel problems.
- the difficulty of updating the systems to keep up with rapidly changing domains such as expanding heteroge-

neous network.

in Model bases expert systems like [6] conditions are usually associated with rules which includes predicates referring to system model. These predicates test the system for existence of relationship among system component. [6] uses correlation tree skeletons describing cause and effect relationships between event. regardless of what expert system is being used localization process is always driven by inference engine and correlation rules between events.

[8] and [9] are examples of Case-based reasoning systems. The goals of CBR systems are (i) to learn from experience, (ii) to offer solutions to novel problems based on past experience, and (iii) to avoid expensive maintenance. The basic idea of CBR is to recall, adapt, and execute episodes of former problem-solving in an attempt to deal with a current problem. Former episodes of problem-solving are represented as cases in a case library. When confronted with a new problem, a CBR system retrieves a similar case and tries to adapt the case in an attempt to solve the outstanding problem. The disadvantages of such a system is the time complexity in retrieving a case that is the closest match to the event and the close tailoring of the application to the domain.

In addition to the above mentioned techniques there are other notable techniques are neural networks based approaches [10] [11] and decision tree based approaches [12]. Neural networks have parallel computing architecture and are very fast avoiding bottlenecks which commonly arises from serial processing. But the main disadvantage is that the learning process requires intensive training and in communication networks where all the alarms signatures are not readily available for pattern recognition.

Decision tree approaches are simple and allows expressive representation of expert knowledge however they are limited by the dependencies specific applications had degraded accuracy in noisy scenarios [13] [14].

### 3 Model traversing techniques

[16], [17], [18] and [19] are all Model Traversing that use formal representation of communication system with clearly marked relationships across network entities. This technique identifies faults by traversing a model of entities starting from the entity which reported an alarm and also involves a fault identification process to identify and locate faulty network entities.

The model representation used by this technique is object-oriented representation of the given system. It is based on the OSI management framework and uses GDMO (Guidelines for Definition of Managed Objects) with extensions to the MO to model dependencies and services between the entities. This approach can make automated testing possible which can test for various testing entities availability and quality of service standards.

The event correlation in model traversing techniques is event driven as when an event occurs it is being mapped to the reported entity and the managed object representing that entity. For every event the search begins from the MO reporting the event and is searched recursively following all relationship links between MO's using fault localization algorithms. Fault localization algorithms used in this technique

can be of various flavours. models every event as singleton classes and merges them whenever they are traced to the same node. Typical properties of such techniques involve

- Level at which a particular fault has occurred in the model.
- Event Type.
- Event severity.
- Event Origin - to identify if the event occurred is primary or secondary.

**Figure 3. Architecture of a model traversing technique prototype**



The MO's provide functions which lets the process test the entity for its operational status. The root cause is found when the process stops at an entity and validates that it is a malfunctioning object and doesn't depend on any other object. In a multi layer model vertical search is performed first and then horizontal search in the next lower layer to check its peer at the end of search process votes are collected to identify the faulty elements and the device that receives the most votes is declared faulty and a testing process kicks in to test the validity of the hypothesis.

Model traversing techniques are pretty robust against network configuration changes and very useful in the scenario's where automated testing is a requirement and the dependency model is very natural as they are modeled as Trees or Graphs.

The biggest drawback is the Fault Propagation Patterns and when there fault is a logical combination of multiple devices and byzantine problems. It also incurs heavy testing costs.

### 4 Graph-theoretic techniques

Graph theoretic techniques depend on graphical model of a system called fault propagation model(FPM). FPM represents fault and symptoms that occur in a system. The symptoms that are observed are mapped into nodes in the FPM and localization algorithms analyze the graph to infer the best explanation of the observed symptoms.

These techniques require a knowledge of dependencies among the abstract and physical system components and how these failures in one component are related to other components. The success of the fault localization algorithm depends on the accuracy of this a priori specification.

FPM's are generally modeled as (i) Causality graph is a DAG whose nodes are events and edges represent the causality implications i.e cause effect relationships between events. They are carry probabilities to the nodes and edges implying the probability of a certain event to happen. Dependency

Graph is a directed graph  $G=(O,D)$  where  $O$  represent a finite set of nodes and  $D$  are the dependency edges between Objects. The directed edge  $(o_i, o_j) \in D$  represents that when  $o_i$  fails  $o_j$  fails or emits some kind of error. The edges are also labeled with conditional probabilities. Figure 4 represents such a dependency graph.

**Figure 4. A Network example along with the dependency graph [24]**



A lot of approaches using dependency graph, a critical assumption involves that an entity may fail in only one way. If that is the case the causal graph and dependency graph would be the same. In the case of multiple failures associated to a single entity they can be divided into sets such as *complete failure*, *abnormal transmission delay*, *high packet loss*, etc.. The dependency graph in this case would have multiple edges between failure modes and the Object(entity). Sethi et al in [23], [22], [21] have modeled using multiple failure modes principle.

A fault localization algorithm, based on the provided FPM generally returns a number of hypothesis that best explain the observed symptoms. The problem of finding best explanation of the received alarms is *NP-hard* problem and proved in [24] by reducing the given problem to a Min Set-Cover problem.

#### 4.1 Divide and conquer algorithm

The divide and conquer algorithm uses a FPM assuming that one type of failure is allowed per object. It is a window based technique i.e gathers all the faults in a time window and analyzes them.

System model is a directed graph  $G = (E, D)$  called the dependency graph, where  $E$  is a finite nonempty set of active terminal objects  $e_i$ , and a directed edge  $(e_i, e_j) \in D$  denotes the fact that a fault in  $e_i$  has a side effect on  $e_j$  i.e.,  $e_j$  is dependent on  $e_i$ . Each vertex  $e_i$  is assigned a weight  $p_i$  that is the probability that the object  $e_i$  fails independently of the state (failed or not failed) of any other active terminal object that is dependent on it. Each directed edge  $(e_j, e_i)$  is assigned a weight  $p_{ji}$  which represents the strength of dependency between the entities it connects. Specifically,  $p_{ji}$  is the conditional probability  $p_{ji} = P(e_j \text{ fails} | e_i \text{ fails})$  that entity  $e_j$ , fails

as a result of the failure of entity  $e_i$ . In addition, the weight of a directed path is defined as the product of all the weights of the edges that compose the path. Finally, the strength of dependency  $p_{kl}$  between two non-adjacent vertices  $e_k$  and  $e_l$ , is defined as the maximum of the weights of all directed paths from  $e_k$  to  $e_l$ .

Let  $D(a_i)$  for every  $a_i$  alarm be the domain of alarms that defines as the set of objects that might have caused the alarm. The domain of an alarm calculation is a variation of single source problem that finds the min cost paths from a source vertex to all other graphs and the nodes are chosen such that the cost of path  $e_i$  to  $e_j$  is subject to restriction that we include only the minimum cost paths with cost  $\leq \log(W)$  where  $W$  is a parameter.

The outline of the algorithm run has been given below.

- Start with the set  $S$  of objects associated with the alarm cluster.
- Find the partitioning of the set  $S$  resulting in two disjoint sets so in each set the objects exhibit the maximum mutual dependency, i.e., for every object  $e_i$  and  $e_j$ , that belongs to the same set and  $e_k$  that does not belong to the set, the dependency weight  $p_{ij}$  is greater than the dependency weights  $p_{ik}, p_{ki}, p_{jk}, p_{kj}$ .
- Of the two sets, select the one that explains all the received alarms and has the maximum probability that at least one of the entities in the set is a fault. If there is no such set then find the subset of alarms that each set explains and select both.
- Apply the previous two steps of the algorithm recursively to the selected sets until the resulting sets of the current partitioning are singletons.

By partitioning with the maximum mutual dependency criterion we group together objects that are highly dependent on each other and when the result of partitioning, both the sets are capable of explaining all the alarms then we select one set that has higher probability of having one of them at fault.

When determining atleast on member of the subset is faulty it is calculated using.

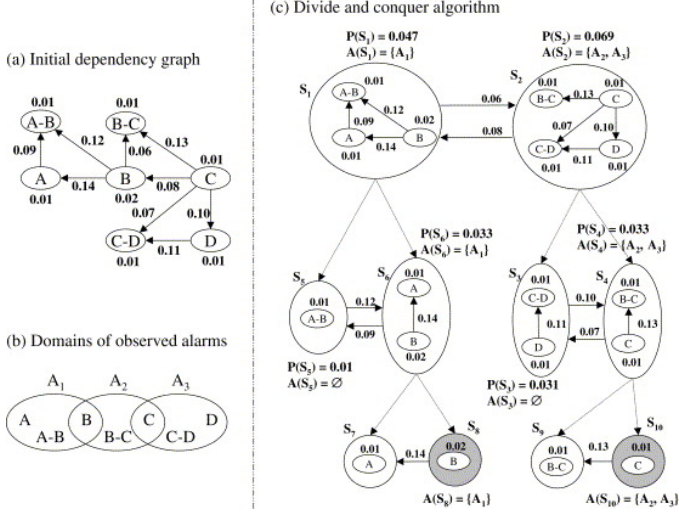
$$P(S) = \sum_{\forall i: e_i \in S} [p_i + \sum_{\forall j: e_j \in S, j \neq i} p_{ij} \cdot p_j]$$

In algorithm runs in two phases where in the first phase algorithm finds the maximum mutual partitionings of the entities in the set  $S$ . The result of Phase I is a hierarchical clustering of the entities in the set  $S$ . In the Phase II a fault localization algorithm is recursively invoked to find the subsets that are supposed to be used. The first subcluster contains all alarms that may be explained using the subset with the higher probability that one of its members was a primary source of a failure. The second subcluster contains the remaining alarms from the original alarm cluster. Its domain is the other of the two subsets. The recursive procedure is then invoked twice, taking the two subclusters and their respective domains as parameters. The recursion continues until the input alarm cluster domain is a singleton.

The algorithm mentioned above gives the explanation of the observed alarms but may not produce the best output as



**Figure 5. Divide and Conquer algorithm [24]**

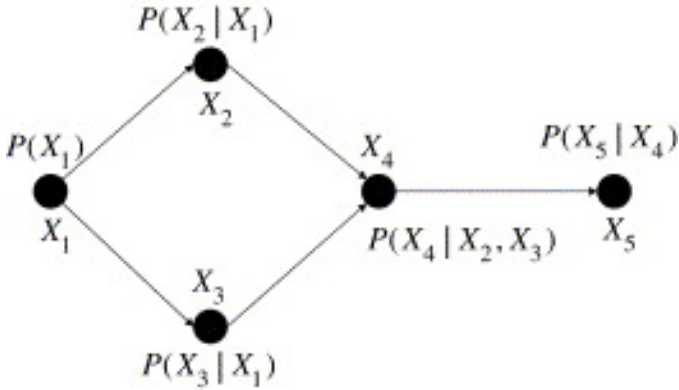


it is a approximation algorithm based on maximum mutual dependency heuristic. The runtime complexity of the algorithm is  $O(N^3)$  and the partitioning phase runtime is  $O(\log N)$ . The drawback of the algorithm is it cannot handle the lost or spurious alarms and is a time window based deterministic algorithm.

#### 4.2 Bayesian Reasoning approach

Bayesian network or probabilistic graphical model represents a set of random variables and their conditional dependencies using a directed acyclic graph. In the context of fault localization the random variables represent the state of network entities and the occurrence of network events.

**Figure 6. A example bayesian network**



Belief networks are used to make four basic queries given evidence set  $e$ : belief assesment, most probable explanation, maximum a posteriori hypothesis, and maximum expected utility [25]

[26], [23], [22] and [21] all the papers try to model the FPM as a bayesian network using a layered fault model approach and in general fault component models are divided into services, protocols and functions. The recursive dependencies between services, protocols and functions constitute a dependant graph. Uncertainty about dependencies between

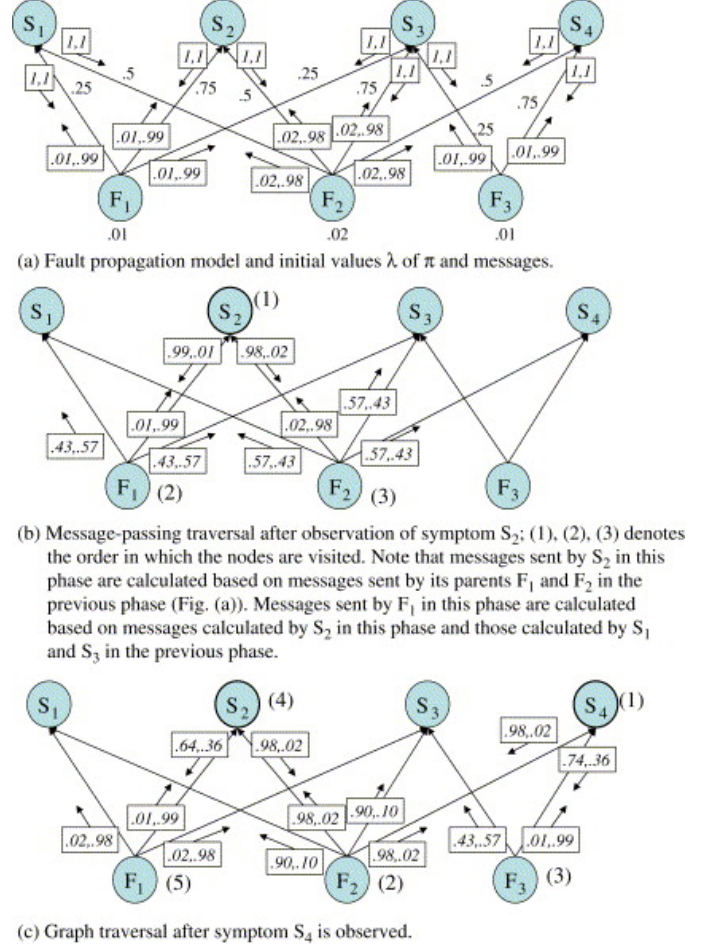
communication system entities is represented by assigning probabilities to the links and/or nodes in the dependency or causality graph.

The queries for belief assesment and most probable explanation are of particular interest in the approaches mentioned above. The belief assesment task is to compute  $bel(V_i = v_i) = P(V_i = v_i | e)$ . given an evidence  $e$ ,  $bel$  gives the certainty of an event happening under the evidence. The most probable explanation task is to find an assignment that best explains the observed evidence  $e$ , i.e.,

$$P(A_{max}) = \max_A \prod_{i=1}^n P(V_i = v_i^A | Par(V_i)^A) \quad [25].$$

It is known that the above tasks are NP-hard in the regular belief networks. A belief updating algorithm, polynomial with respect to  $|V|$ , is available for *polytrees*, i.e., directed graphs without undirected cycles. The exact calculation of the best explanatory hypothesis requires a number of steps that is exponential with respect to the number of graph nodes. One of the most popular exact algorithms bucket elimination is used as a reference algorithm against *iterative belief updating* algorithm and *iterative MPE query* algorithm.

**Figure 7. Bayesian Network message passing algorithm example**



The algorithms utilizes a message passing schema in which BN nodes exchange messages that encode certain con-

ditional probabilities. The message that node  $X$  sends to its parent  $V_j$  for every valid  $V_j$ 's value  $v_j$  is denoted by  $\lambda_X(v_j)$ . The message that node  $X$  sends to its child  $U_i$  for every valid value of  $X$ ,  $x$ , is denoted by  $\pi_{U_i}(x)$ . Messages  $\lambda_X(v_j)$  and  $\pi_{U_i}(x)$  are calculated by node  $X$  based on messages it receives from its neighbors using the following equations (where  $\beta$  is any constant and  $\alpha$  is a normalizing constant) based on messages the  $bel(x) = \alpha \lambda(x) \pi(x)$ .

The algorithm proceeds in an event driven manner when a symptom is observed and applying a message passing iteration traversing the graph based on an order. Figure 7 shows an example bayesian network with fault nodes  $F_1, F_2, F_3$ . Once the algorithm ends every node is assigned a belief probability, the probability of its existence given the symptoms. The final hypothesis is chosen using the following heuristic: (1) a most-likely fault is chosen and placed in the final hypothesis, (2) the chosen fault node is considered a part of evidence, and (4) one iteration of message passing starting from the chosen fault node is performed. Steps (1)(3) are repeated as long as (1) the posterior distribution contains fault nodes whose probability is greater than 0.5, and (2) unexplained negative symptoms remain. An inherent property of the adapted algorithm is the capability to isolate multiple simultaneous faults even if their symptoms overlap.

However one limitation to the modeling of the domain as bayesian network is the model has to adopt canonical models used in the literature mentioned above like noisy-OR gates, AND gates to limit the algorithm runtime to polynomial time. The comparison of different algorithms in bayesian networks is mentioned in the table 1 below.

[29] Shrink a tool for failrue diagnosis in IP Networks. Shrink outputs the most likely explanation for the network's faulty state i.e., the collection of SRLGs whose failure is most likely given the IP link status. Shrink works on three modules (1) building the bayesian model (2) augemnting the model with guess edges (3) inferring the most likely explanation.

Figure 8. Shrink system setup

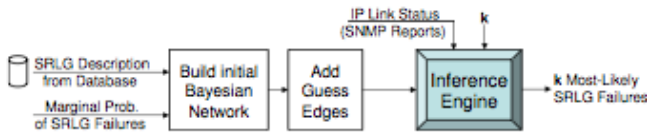
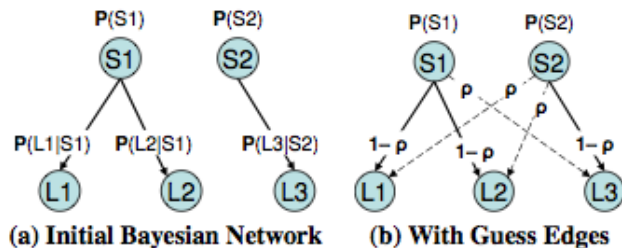


Figure 9. Shrink's network model



if  $E_k$  denotes the event that at most  $k$  SRLGs failed within any hour, there are exactly  $k$  combinations of  $n$  possible SRLG assignments that satisfy  $E_k$ . Given the observed link status, shrink algorithm greedily picks the most likely SRLG assignment in  $E_k$ ; i.e., it picks  $(S_1, \dots, S_n) \in \{0, 1\}^n$  such that:

$$\arg \max_{S_1, \dots, S_n} P(S_1, \dots, S_n | L_1, \dots, L_n) \text{ subject to number of } \{S_i=1\} \leq k$$

There are fewer than  $n^k$  value assignments in  $E_k$ , and for each assignment  $P(S_1, \dots, S_n | L_1, \dots, L_n)$  can be computed in  $O(m + n)$  time, where  $m$  is the number of IP links and  $n$  is the number of SRLGs. So, Shrink's running time is  $O(n^k(m+n))$ .  $k=3$  is a valid case for a wide range of ISP network sizes and SRLG failure probabilities and when  $k \geq 3$  the hypothesis performance is exponential.

### 4.3 Misc approaches

There are several other approaches to fault localization like codebook approach which uses hamming distances to find the fault and also context free grammar which allows expressions to be built from subexpressions, may be effectively used to represent a hierarchically organized communication system. However these are not discussed in this paper due to the poor applicability to the real world systems and poor performance of these approaches. [27], [28], [3] are papers that discuss about these techniques.

## 5 Paper 1: Toward Optimal Network Fault Correction in Externally Managed Overlay Networks

[30] Paper 1 is an end-to-end approach of inferring probabilistic data-forwarding failures in an externally managed overlay network, where overlay nodes are independently operated by various administrative domains. The optimization goal is to minimize the expected cost of correcting (i.e., diagnosing and repairing) all faulty overlay nodes that cannot properly deliver data. Instead of first checking the most likely faulty nodes as in conventional fault localization problems it chooses a *candidate node* proceed based on a potential heuristic function and is bound to infer correctly atleast 95% of the time.

[24], [21] and [29] state of the art techniques that diagnose (i.e detect and localize) the components that are root causes of the network faults, however they do not focus on the *network fault correction* that is not only diagnosis but also considering the repair and checking costs. [30] conveniently outperforms all of them and tries to derive a strategy for efficient network fault correction at minimum cost.

Another set of research papers focus purely on the failure detection of network faults [31], [32] and [34] uses distributed techniques and all networks nodes to collaboratively achieve the fault detection. [34] uses inspection on packets from previous hop and reports when founded corruption. The problem with this approach is that an inspection logic or monitoring points have to be setup across the network and incurs heavy costs and different administration domains prove to be obstacle in the above cases too.

Paper1 considers an end-end inference approach using end-end measurements, infers components that are faulty in

Algorithm	Bucket Elimination	Iterative Belief Updating	Iterative MPE
Theoretical Bound	$n^2 \exp(n)$	$n^5$	$n^6$
Detection Rate	96-100%	93-98%	95-100%
False Positive Rate	0-4%	2-5%	0-8%
Max Network Size	10	50	25
Algorithm iterative?	no	yes	yes

**Table 1. Comparison of algorithms**

forwarding data. This applies perfectly to the scenario like CAN[35] and CHORD[36] where each overlay node builds a routing tree with itself as a root and in this setting every root to leaf path is monitored to find faulty path and anomalous behaviours on the path. One anomalous behaviour could be number of correct packets not being delivered in a fixed time period, such a validation could prove to be very important in QOS factor. The authors are particularly interested in diagnosing and repairing faulty nodes in overlay networks like RON[37], SON[38] and SOS[39]. The proposed fault correction mechanism suits well to this type of networks.

### 5.1 Problem Formulation

[30] considers a logical tree as  $T=(N, \{p_i\}, \{c_i\})$ , where  $N$  is the set of overlay nodes,  $p_i$  is the failure probability of node  $i \in N$ , and  $c_i$  is the checking cost of deciding if node  $i \in N$  is faulty. Overlay set node  $N$  provides a topology information and sequence of nodes. The construction of failure probabilities and cost probabilities depend on Failure model and Cost model.

**Failure Model** focus on the nodes that cannot forward data or fails to comply with a QOS because of which packets get dropped or fails to get delivered. Focus mainly stands on fail-stop failures like power outages, full transmission queues, hardware errors and route misconfigurations. The failure probabilities are calculated using statistical measurements of reliability indexes of node elements (vulnerability modelling). Authors also performed analysis of the mechanism under inaccurate probabilities and is provided in the results section of this paper. Important consideration to be made is that failure probabilities of nodes are independent of each other.

**Cost Model** provides the checking costs using personnel hours, wages and time effort that goes into debugging the problem or even the cost of the equipment. Important criteria to be noted in the cost model the repair costs are not considered as eventually every fault has to be repaired.  $p_i$  and  $c_i$  can be any values between  $[0,1]$  and  $[0,\infty]$ .

Each node in a logical tree  $T$  is classified as fault or non-faulty, and definitions are being made on each root to leaf path that exhibits an anomalous behaviour. Since an end-to-end inference mechanism is being made we only know that something is wrong with the path rather than which node is at fault. Each node in  $T$  is referred to as *bad* if it is faulty and *good* if it is non-faulty and a path in  $T$  is bad if it has at least one *bad* node. An important consideration is that the node behaviour remains the same across all the paths as only fail-stop considerations are being made.

Given a logical tree  $T$  we can infer the good path and bad paths by end to end inference mechanism, for example root can send a probe and collect all measurement results. We now create a bad Tree by pruning of all the good paths

form the logical tree and also call it  $T$  with abuse of notation. Bad tree now becomes input to the inference algorithm which determines which set of nodes to be corrected (checked and repaired).

The optimization goal of this paper is to minimize the expected cost of correcting all faulty nodes in a given tree. repairing cost is not considered as eventually all the nodes have to be repaired and any strategy that is employed will eventually correct all the nodes. Here we focus only on the sequential case as checking the nodes in parallel doesn't improve the total expected checking cost so the inference algorithm only return one single node that is supposed to be the best node to check first. The best node is the first node that is from a diagnostic sequence  $S = \{l_1, l_2, \dots, l_N\}$  and gives us  $N!$  diagnostic sequences.

When a particular node  $l_i$  lies on a bad path we do not know whether it is a good node or a bad node but if it is on a good node we know for sure it is a good node.  $l_i$  gets *checked or skipped* based on the examination of the node. Thus we can summarize the total cost of checking a tree  $T$  is given by

$$\sum_{i=1}^{|N|} c_{l_i} \Pr(\text{node } l_i \text{ is checked} \mid \text{nodes } l_1, \dots, l_{i-1} \text{ known to be good})$$

So the best node would be the first node in the diagnosis sequence and the inference works on the current topology to identify this node and when the node is corrected the revised topology is fed into the inference algorithm to output the next node. The total complexity of calculating the expected cost of a diagnosis sequence is  $O(n^3)$  and since there are  $n!$  different sequences, the brute force approach has a complexity of  $O(n^3 n!)$ . The complexity and the way to calculate the total cost for the diagnostic sequence is mentioned in Appendix A of [30]. In the interest of space and length only the highlights are being mentioned here.

**Conditional Failure Probabilities:** the nodes in  $T$  by 1 to  $|N|$  in breadth-first-search order.  $T_i$  is the subtree rooted at node  $i$ .  $C_i$  is the set such that  $k \in C_i$  if node  $k$  is a child node of  $i$ . thus conditional failure probability is given by bayesian probability rule where  $\Pr(X_i)$  is the independent failure probability of a node, and  $\Pr(T_1)$  is the probability of the tree is bad at root,  $\Pr(T_1|X_i)$  is the probability that a tree is a bad tree upon the event that a node is bad.

$$\Pr(X_i|T_1) = \frac{\Pr(T_1|X_i)\Pr(X_i)}{\Pr(T_1)} \text{ by baye's rule.}$$

where

$$\Pr(T_i) = p_i + (1 - p_i) \prod_{k \in C_i} \Pr(T_k), \forall i \in [1, |N|]$$

$$Pr(T_i|X_j) = \begin{cases} Pr(T_i) & \text{if } i > j \\ 1 & \text{if } i = j \\ p_i + (1 - p_i) \prod_{k \in C_i} Pr(T_k|X_j) & \text{if } i < j \end{cases}$$

The idea here is that a subtree  $T_i$  is bad if either the node itself is bad or node  $i$  is good and the subtree rooted at  $i$  is bad. Using dynamic programming the above equation can be computed in  $O(N^2)$  which is the conditional failure probability of a node.

**Expected Cost of a Diagnosis Sequence:** Let  $T_i^D$  be the event that the subtree rooted at node  $l_i$  is a bad tree after nodes  $l_1, \dots, l_{i-1}$  have been examined (i.e., checked or skipped). Let  $A_i^D$  be the event that every ancestor  $j$  of node  $l_i$ , such that  $j \in \{l_{i+1}, \dots, l_N\}$  (i.e., node  $j$  is examined after node  $l_i$ ), is a good node. Since every node is examined in a sequential way in the diagnosis sequence, when  $l_i$  is examined, nodes  $l_1, \dots, l_{i-1}$  have been examined and they are good. Thus,

$$Pr(T_i^D) = Pr(T_i | p_{l_1} = \dots = p_{l_{i-1}} = 0), \text{ and}$$

$$Pr(A_i^D) = Pr(A_i | p_{l_1} = \dots = p_{l_{i-1}} = 0)$$

Where  $T_i$  is the event that the subtree rooted at node  $l_i$  is bad, and  $A_i$  is the event that all ancestors of node  $l_i$  are good. If the subtree rooted at node  $l_i$  remains a bad tree or at least one of the ancestors of node  $l_i$  is a bad node, then node  $l_i$  still lies on bad path and needs to be checked. Thus,

$$Pr(\text{node } l_i \text{ is checked} | T, \text{nodes } l_1, \dots, l_{i-1} \text{ known to be good}) = Pr(T_i^D \cup \neg A_i^D | T)$$

Thus the expected cost of  $S$  given that  $T$  is a bad tree is:

$$\sum_{i=1}^n c_{l_i} Pr(T_i^D \cup \neg A_i^D | T)$$

Brute force algorithm which inspects all the sequences is given in figure 10. This algorithm makes a good reference for comparing against the heuristic based ones.

**Figure 10. Bruce Force Algorithm**

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**Algorithm 1** Brute-force inference algorithm

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Input: Bad tree  $T = (N, \{p_i\}, \{c_i\})$

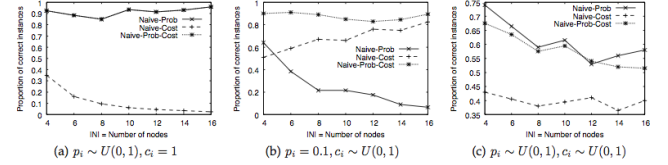
- 1:  $S^* = \phi, c^* = \infty$
  - 2: **for all** diagnosis sequence  $S$  **do**
  - 3:   compute  $c$  = the expected cost of  $S$
  - 4:   **if**  $c < c^*$  **then**
  - 5:      $S^* = S, c^* = c$
  - 6: **return** the first node in  $S^*$
- 

## 5.2 Naive Heuristics for Inference Algorithm

Intuitively the best node returned by the inference algorithm can be either based on the highest conditional failure probability or checking cost. The authors provided a simple counter example in which neither the selection of node based on conditional failure probability nor the one selected based on checking cost gave the optimal solution. The three heuristics authors chose naively are (1) *Naive\_Prob* (2) *Naive\_Cost* (3) *Naive\_Prob\_Cost*. Based on the experimental setup

where a 200 bad trees are tested with the three heuristic mentioned above with varying probability and cost distributions. Depending on the distributions of  $p_i$  and  $c_i$ , the proportion of instances where the best choice is made can be as low as 10% for *Naive\_Prob* and *Naive\_Cost* and less than 55% for *Naive\_Prob\_Cost*.

**Figure 11. Naive-Prob, Naive-Cost, and Naive-Prob-Cost performance**



## 5.3 Candidate Node

The authors show that instead of selecting a node to test based on naive choices we should select a *candidate node* based on the maximization of a *potential function*. Let  $A_i$  be the event that the ancestors of node  $i$  are all good. If node  $r$  is the root node, then we let  $A_r$  be always true and  $Pr(A_r) = 1$ . The potential of a candidate node is calculated using the formula.

$$\phi(i, T) = \frac{Pr(T|X_i, A_i)p_i}{c_i(1-p_i)}$$

Intuitively the candidate node should have low conditional failure probability and low checking cost and a higher likelihood of having a bad tree with respect to tree topology. The potential of node  $i$  can be obtained by first computing  $Pr(T|X_i, A_i) = Pr(T | p_i = 1, p_j = 0 \forall j \in A_i)$ , where  $A_i$  is the set of ancestors of node  $i$ . and the time complexity of computing is  $O(|N|^3)$ . For each path  $W$  in a tree  $T$  we select node  $i$  that has the highest potential  $\phi(i, T)$  among all the nodes. In case of a tie we choose the one closest to the root.

## 5.4 Optimality Results

The optimality results that were presented in the paper drive the potential function definition provided above.

**Theorem 1:** Given a bad tree  $T$ , there always exists an optimal diagnosis sequence that starts with a candidate node.

**Proof of Theorem 1:** Consider two diagnosis sequences  $S_j = (j, k, l_3, \dots, l_N)$  and  $S_k = (k, j, l_3, \dots, l_N)$ . Now two scenarios crop up (1) when  $j$  and  $k$  are ancestrally related i.e they are on the same path and (2) when  $j$  and  $k$  are on two different paths. In the second case when they are unrelated they have no impact on each other. thus  $S_j$  and  $S_k$  will have the same cost. When  $j$  and  $k$  are ancestrally related checking node  $j$  (resp  $k$ ) if it reveals a good path then  $k$  (resp  $j$ ) can be skipped checking and save  $c_k$  (resp  $c_j$ ). But to validate the given statement we need certain conditions to hold good.

- node  $j$  (resp.  $k$ ) is bad.
- node  $k$  (resp.  $j$ ) is good.
- there exists a path  $W_{jk}$  containing nodes  $j$  and  $k$  such that all nodes other than nodes  $j$  and  $k$  on  $W_{jk}$  are good.

$$\begin{aligned} & \text{Thus, } E[\text{cost of } S_j | T] - E[\text{cost of } S_k | T] \\ &= \frac{c_j c_k Pr(W_{jk}) Pr(X_j) Pr(X_k)}{Pr(T)} [-\phi(j, T) + \phi(k, T)] \dots (*) \end{aligned}$$

From (\*) we can deduce that for expected cost of sequence starting with  $j$  would be no greater than that of  $k$  when



$\phi(j, T) \geq \phi(k, T)$ , therefore the node with the highest potential should be checked first.

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