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Review

Artificial intelligence approaches to network management: recent advances and a survey

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Abstract

With increased number of new services and users being added to the communication network, management of such networks becomes crucial to provide assured quality of service. Finding skilled managers is often a problem. To alleviate this problem and also to provide assistance to the available network managers, network management has to be automated. Many attempts have been made in this direction and it is a promising area of interest to researchers in both academia and industry. In this paper, a review of the management complexities in present day networks and artificial intelligence approaches to network management are presented. Published by Elsevier Science B.V.

Keywords: Network management; Artificial intelligence; AI in networks; Integrated network management; Blackboard architecture

1. Introduction

Recently network management (NM) has received prime attention, both in industry and in academic environments. The primary reason for this is the growth in network and network based applications. As the use of the network grows, increasing number of services are offered, resulting in difficulty in managing them. Attempts to manage the networks effectively started from the time the networks evolved, but management of such networks plays a vital role as the network size increases and the data transferred is crucial. It is difficult to define network management since new tasks are being added to its role. Nevertheless, NM includes operations, administration, maintenance (OAM) and provisioning functions to provide, monitor, interpret and control the network and the services it offers.

Network management is a crucial part, but it is very difficult to find a network manager for each management center who has entire knowledge of the network. It is also important that the network managers be available round the clock to handle the network, to make sure that it runs in a healthy condition. Having such manpower all the time and working in the event of network failure, when everybody expects the network to come back to normalcy in the stipulated time, is a very tough job. This demands the use of an automated program, which either imitates the manager in his/her absence or assists in the presence of the manager. The literature provided in special issues of the journals [1–4], the collection of papers provided in [5,6] and the textbooks [7,8] are of great help for those interested in knowing more about the current trends in NM.

Artificial intelligence (AI) [9] is a branch of computer science that includes such automated programs in the form of an expert system (ES) [10] which is expected to mimic an expert of one particular domain. The idea of deploying such expert systems to assist network managers has motivated the application of artificial intelligence methods to network management [11,12].

The rest of the paper is organized as follows. Section 2 gives an overview of network management, covering the standard network monitoring protocols, the management information base (MIB), functionalities of network management, the concept of telecommunication management network (TMN) and the existing industry implementations on NM. Section 3 describes various AI approaches to optimal network partitioning to achieve fault tolerant network management and the network management functionalities. Section 4 presents the concept of integrated network management (INM). Section 5 concludes with a few remarks and future directions.

2. Overview of network management

Open systems interconnection (OSI) of the International

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Standards Organisation (ISO) management model [13] separates network protocols into different layers, similar to the OSI reference model [14]. In the OSI reference model, there are seven layers namely, physical, data link, network, transportation, session, presentation and application layers from bottom to top. The first three layers provide the network capability while the last four carry out the processing required to present the data to the end user in an appropriate form.

2.1. OSI management model

The OSI management model divides the task into several management entities within the layered network model [15] as shown in Fig. 1. Each layer of the protocol has an embedded protocol entity, called a layer management entity (LME), which collects pertinent information about that layer, e.g. fault reports, sending management information to the management information base. The layer management interface (LMI) coordinates between the MIB and the seven-layer OSI protocol stack. The system management interface (SMI) coordinates the interface between the system management application process and the managed object using any of the monitoring protocols, discussed later. The management information collected in such a way will be used by the management center to control the managed nodes. OSI has defined the following to be the important entities of network management: (i) fault management; (ii) performance management; (iii) configuration management; (iv) security management; (v) accounting management.

Though the OSI layer management architecture has been defined, many parts have not yet been implemented. In the internet community, the Internet Activities Board (IAB) looks into the development of standards. The Internet Engineering Task Force (IETF) works on protocols, MIBs, and liaison to other committees. IETF has identified simple network management protocol (SNMP) [16] as a short term solution to the network management problem while common management information services/common management information protocol (CMISE/CMIP) [17] as a long term solution. SNMP is being developed at a faster pace and is produced by many vendors [18].

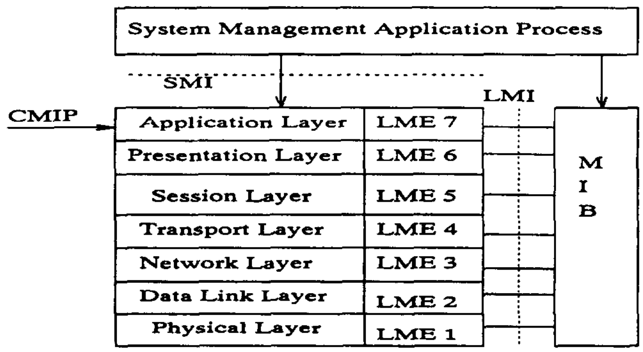

Fig. 1. OSI layer management architecture.

2.2. NM functionalities

In this section, a brief description of the network management functionalities is given.

2.2.1. Fault management

Fault management (FM) comprises the following aspects [19,20].

- Alarm surveillance—a monitoring aspect of the network management activity that looks into obtaining the information and processing to identify events of interest.
- Fault localization—a fault identification aspect of the fault management task.
- Fault correction—a remedial measure to counter faults that occur in the network.

2.2.2. Performance management

Performance management (PM) [21] refers to ensuring that the network performance does not fall from the expected level. This task can be split into the following.

- Quality of services (QoS)—ensures that the offered QoS is achieved or an alarm is raised.
- Performance monitoring—similar to alarm surveillance as mentioned in the FM.
- Performance analysis—similar to the fault localization of FM.
- Performance management control—a control measure taken to bring the network back to normal behavior, meeting the assured quality of service.
- Traffic management—looks into the traffic management in the network and its behavior.

2.2.3. Configuration management

Configuration management (CM) comprises two parts.

- Collection of the monitoring information and display to appropriate centers in the required format.
- Network restoration in the case of node/link failures.

2.2.4. Security management

Security management (SM) can be viewed as having two aspects.

- Preventive approach—strengthens the existing security protocols.
- Reactive approach—assumes, in spite of having a strong protocol, that intrusions are still likely, catching them is the task here.

2.2.5. Accounting management

Accounting management (AM) is essential and is considered most important for the obvious reason that the whole service provided is not devoid of economy. Proper accounting of the resource usage and then charging the users of the same to yield highest satisfaction are the goals of AM.

2.3. Management information base

The management information base is the heart of the network management system. It gathers the relevant information required by the network manager and makes it available for use by several functionalities of the manager. Standards have been fixed for representing and communicating management information [22–24]. The management information can be classified into four groups: (i) status, e.g. node UP/DOWN/TESTING; (ii) counters which measure some quantity of interest, e.g. input packets and output errors; (iii) descriptive objects, sequences and tables, e.g. change in routing table indicating a link up/down; (iv) time ticks which measures the time since an event has occurred, e.g. node uptime [25]. Database techniques have been widely used to maintain the MIB [26].

2.4. Standard monitoring protocols

In this section, a comparison of the two management protocols is listed (see Table 1.)

2.5. Telecommunication management network

CCITT (now International Telecommunications Union (ITU)) recommendation X.700/ISO 7498-4 of OSI systems management describes the architecture of the telecommunication management network. The purpose of TMN is to provide a set of standard interfaces that will facilitate easy management of operations, administration and maintenance functions and network elements. TMN physical architecture addressed the TMN concept, reference points, interfaces and functional and physical models [31]. TMN recommendations include a generic information model (M.3010), methodology for specifying TMN interfaces (M.3020), TMN management services (M.3200) and TMN management functions (M.3300).

2.6. Existing NM implementations

A few intelligent network management systems have been developed in the recent past. HP's Open View, IBM's System View AIX and SNA [32], Cabletrons's Spectrum, DEC's Polycenter, Sunsoft's SunNet Manager, OSEYENode are a few popular network management implementations. [33] provides a good survey of the network management platforms. These basically take up the task of network monitoring and presenting the information in a suitable form with general graphic user interfaces (GUI) that support relational databases, SNMP, CMIP and proxy agents and raise alarms on demand. Most of these platforms provide basic configuration and fault management functions but do not support a rich set of applications tools to manipulate third party or private MIBs or interface with tools to any specific network management functional areas. CORBA based applications to network management using Guidelines for the Definition of Managed Objects (GDMO) as

Table 1
A comparison of SNMP and CMIP

Number	Feature	SNMP	CMIP
1.	Agent intelligence	Simple agents	Complex and powerful agents
2.	Environment	TCP/IP [27]	OSI
3.	Manager intelligence	Polling-based	Agents can filter events, accept 'action' commands (event-based) [28]
4.	Bandwidth requirements	Excessive polling can result in high bandwidth requirements	Larger messages can result in high bandwidth consumption
5.	Code size	Small	Fairly large
6.	Cost per network element	Inexpensive to implement since SNMP, UDP and IP have no or low license fees	License fees are of order few 10000 US$
7.	Scalability	Polling methods require careful tuning of network. Polling times are an issue	Event driven creates a more scalable solution for large reliable networks
8.	Security	Secure SNMPv2 [29] offers authentication and access control, including alarm	CMIP offers security as well as audit trial service
9.	Naming	Local naming requires more information to make it globally unique	Uses X.500 [30] naming to facilitate manager to manager distribution
10.	Communications	Connectionless datagram using UPD/IP; places burden on manager for recovery	Connection oriented upper layers using OSI seven layer stack
11.	Data retrieval	Simple reads and writes	Structured queries
12.	Perspective on data	Flat file	Object oriented
13.	Modes of operation	Unconfirmed	Confirmed
14.	Redundancy of management	Agents may send traps to multiple managers	Management services can be distributed to multiple destinations
15.	Representation	ASN.1	Object oriented
16.	Data synchronization	One row at a time	Scoped GET provides agent synchronization of data

described in ISO/IEC 10165-4/X.722 are being implemented at several organizations.

3. AI methods used in network management

In this section, we present the AI approaches that have been used and that are promising for network management [34]. At the outset, we discuss the optimal partitioning of the network which enables efficient network management since the partitioning of the network simplifies the network management task. Then we describe the AI approaches to network management functionalities and review the models devised to integrate the network management functionalities.

3.1. Optimal network partitioning

The first aspect the network designers consider is optimal partitioning of the geographical area into various networks, which are then managed independently and cooperatively. The network management activities are addressed by chosen special nodes in the network called network management centers (MCs). It is typically very difficult to manage the entire network using a single management center. This necessitates partitioning the network into regions that are managed by respectively assigned management centers. Here a region comprises a cluster of nodes with assigned MCs. Management centers may in turn report to the central management center in the case of hierarchical network management. [35] presents a recent approach followed in hierarchical network management using SNMPv2. In the case of distributed network management, MC in one region communicates with MC in another region depending on the requirement. For reliability, it is essential to assign more than one network management center to each region. This provides inherent fault-tolerance in network management applications. Inside a cluster, management centers are assumed to form a logical chain. Even though all the management centers in a cluster receive status information from all of the nodes in that cluster, only one of them will be the acting management center. When the acting management center fails, the next live management center in the chain takes over the responsibility.

The problem reduces to partitioning the network into a given set of non-overlapping regions such that the number of nodes and the number of management centers in each region are constrained and a criterion function, representing the communication cost, is minimized. Finding an optimal network partition is a combinatorial optimization problem and it has been proved to be NP-complete [36,37].

In order to make the network management fault tolerant, more than one management center is assigned to each cluster of nodes in the partition. Gradient descent partition methods converge to locally optimal partitions. In contrast, a stochastic search method called evolutionary programming [38–40] is employed in [41] to search for a globally optimal partition that minimizes the communication cost.

3.2. AI approaches used in NM functionalities design

3.2.1. Fault management

The fault management module looks at the symptoms (abnormal behavior) of the network and diagnoses to yield the faults that caused such behavior.

The information related to this is often gathered by one of the monitoring protocols as discussed earlier. If the information is gathered by a polling protocol, the need arises of what is called information filtering [17] to filter the data not useful for fault management. This problem can be overcome if the information is gathered using an event based protocol, which collects only the specific events of importance. The information thus gathered is placed in an MIB at the manager which is an extensive database containing the description of the structure of the events of interest.

Many of the tasks in fault management involve analysis, correlation, pattern recognition. Methods in artificial intelligence can be used here to infer the root cause of the fault and generate the reports in appropriate fashion.

The knowledge engineer elicits the knowledge from the domain expert, anticipating all the possible scenarios. Then the knowledge can be represented in a suitable fashion in the knowledge base. The diagnostic mechanism should be able to infer the fault in an efficient way. Finally, an appropriate user interface is provided to the network manager to indicate the place of failure and suggest a suitable remedy [42].

There are specialized problems that have to be addressed by network fault diagnostic systems. The entire diagnostic information may not be available at once and there may be missing information. In both cases, the management center needs to confirm such information with the respective managed nodes before initiating the diagnostic process.

Various reasoning methods have been in use for the purpose of general fault diagnosis, especially in the medical domain. In general, the reasoning mechanisms in AI can be grouped into three: (i) inductive reasoning; (ii) deductive reasoning; (iii) abductive reasoning.

Induction involves proposing hypotheses and testing them. Using the inductive reasoning strategy, from a specific case and specific result, a general rule can be hypothesized. Significant work has not been carried out to apply inductive reasoning to network fault diagnosis.

In deductive reasoning, from a general rule and a specific result, a specific case can be hypothesized. The result produced is a logical consequence of a rule and a specific case. So, the result is 'true' as long as the rule and the case are 'true'. Most of the work in the area of fault diagnosis is based on deductive inference, which is also true for network fault management. Deductive reasoning is widely employed to solve the network fault diagnosis problem [43–45]. Rabie et al. [46] have used a real-time expert system for monitoring of data packet networks. Koga et al. [47] have used an expert system for fault location in paired cables. Vesonder et al. [48] have used an expert system for telephone cable maintenance. Also, intelligent knowledge based systems for network management have been studied by Malcolm et al. [28]. Time-synchronized agents are deployed to collect information about the network segments in [49]. ATM based network fault management in the area of local area networks is discussed by Blact et al. [50]. Gruber [51] described an approach to SONET/SDH and ATM network fault management.

In abductive reasoning, from a given rule and a specific case, a specific result is inferred with a plausibility [52–57].

The attempt to use abductive reasoning for fault diagnosis has been addressed by many researchers [58,59]. In [60,61], abductive reasoning is identified as a suitable scheme for the specialized case of network fault management. Since in its bare form of abductive reasoning, it generates too many explanations for a given set of symptoms, the reasoning mechanism is refined to suit a realistic scenario and a new model is proposed [62]. Since the number of explanations may still be more than one, a strategy is designed to order the explanations in decreasing order of plausibility till the real fault is isolated and corrected [63,64]. This network fault management model is applied to a hypothetical B-ISDN network, which uses ATM as the mode of transfer [65–72], and the results [73] are interesting.

3.2.2. Performance management

While fault management looks into the diagnosis of hard failures in the network like device failure, the job of performance management is to make sure that in a system where no physical part has failed or a service is purposefully terminated, performance degradation will not take place resulting in erroneous behavior or overload condition. The performance degradation problem has several consequences because one problem can manifest in another after a while [74–76]. The performance degradation caused by the last problem can be brought to normalcy only when the previous problems are corrected [77]. In [78], a model for network performance management and planning is discussed. [79] uses a protocol analyzer for network performance analysis. [80] describes the ISO model for PM. Real-time management of telephone operating company networks is addressed in [81]. A real-time packet network PM is discussed in [82]. An integrated methodology for packet network PM is described in [83]. [51] describes an approach to SONET/SDH and ATM network performance management.

A performance management model using a queueing model or any such analysis includes a lot of computation and also the model still may not be as exact as expected with a few approximation methods based on neural networks [84] and fuzzy logic [85] have been developed that are suitable for the application. Application of neural networks to performance management control has been tried in [86,87] by modeling a control measure based on back propagation neural network. The congestion control aspect of the PM is addressed in [88]. Traffic control for ATM networks using neural networks is studied in [89]. The special issue [90] provides neurocomputing aspects in high-speed networks in the areas of adaptive control in ATM networks, B-ISDN flow control and intelligent traffic control for ATM networks. Fuzzy logic technique for adaptive traffic routing to meet performance requirements is discussed in [91].

In [63,92], the performance management has been considered as a special case of fault management and is solved using the realistic abductive reasoning model, as discussed above to identify the soft-failures in Ethernet environment [93,94]. Then, a recurrent neural network based reinforcement learning mechanism [95,96] is used to tune the network performance to bring the network behavior back to normalcy [97].

3.2.3. Configuration management

The job of configuration management is to report the network status to the network manager and keep the required sources updated of the network behavior [98,99]. This can be carried out using any of the standard network management protocols available like simple network management protocol [18] or common management information protocol [24]. Reconfiguration of the network when there is a physical change in the network like addition or deletion of link or node failure is also an integral part of the network configuration management (generally known as restoration).

Presenting the network information in a suitable form to the network manager is handled these days by a graphical user interface [100]. Out of all the information collected by the monitoring protocol, only information of relative importance has to be provided in a form that indicates configuration changes to the manager to observe the state of the network.

Network restoration has been an equal area of importance as the network fault management since the first measure taken in the event of network failure is to restore the network rather than network fault identification and correction. The argument persists on the use of source based/local/local destination rerouting [101]. The location of the node/link failure also plays a role in deciding which method works well. The debate also persists on issues like should the restoration be centralized [102] or distributed [103], and choosing the alternate before/after failure [104]. In [101,102] methods for ATM network restoration using virtual paths are discussed. Network service restoration for self-healing ATM networks is presented in [105].

While choosing a combination of the above strategies is one factor in deciding the restoration, computation of the alternative path is another. Since rerouting is no different from routing, with possibly a different source and reduced number of links, finding an optimal path for a given source-destination is also a computationally hard problem. Several heuristics have been proposed as against Dijkstra's deterministic shortest path algorithm [106] to find a (near-) optimal route. Some of them are (i) simulated annealing that uses the Boltzman function [107], (ii) neural networks based on the Hopfield model [78,108–110], (iii) genetic algorithm based [111], (iv) evolutionary algorithm based [112], (v) nearest neighbor [113], (vi) branch and bound [114] and (vii) local search [115]. Methods (i)–(iv) attempt to solve the routing problem by formulating it as some form of traveling sales person (TSP) problem [113].

In designing the routing algorithm [116], an assumption is made that the fixed length, i.e. one with minimum hop count, is expected to give an optimal path length between the source and the destination. So, first the minimum number of hops required to reach the destination is calculated by computing the route matrix (generally, the channel bandwidth matrix) by multiplying as many times as required until the element corresponding to the channel bandwidth between the source and the destination in the resulting matrix is non-zero, using Walsh's algorithm [117]. Then attempts are made to find out, for so many hops between the source and destination, the route which yields the minimum cost or maximum channel bandwidth. This computation to find the minimum hop count between the source and the destination itself is a costly method. Also, exhaustively enumerating the cost of the route to determine a path is certainly an NP-hard problem, taking a shape similar to that of a traveling sales person problem. However, finding all the possible ones goes on exponentially and should only be restricted by the network connectivity. The other problem is that, in spite of doing all this exercise, the channel on the alternate path identified may not be available and the entire process has to be repeated. In [118] a different approach which uses the variation of the Hopfield neural network to identify the path of any length but finds an optimal route is sketched. However, this approach has the problem of entering local minima.

In [119], configuration management has been proposed to be collecting the network information using the SNMP [18] and then the required restoration is done by a centralized static restoration after failure using a hybrid approach. A new heuristic rerouting algorithm is developed which optimally routes the traffic in case of failure of a link of a node based on simulated annealing, using recurrent neural networks that alleviates the problem of local minima.

3.2.4. Security management

Security management in communication networks can be described in two parts [120]. The first part, called the preventive approach, explores the use of robust security protocols for access control to network resources.

Several secret and public key cryptographic protocols have been used for establishing the necessary secrecy of the information [121–127]. [128] discusses an approach to OSI security management. Capability based security systems are discussed in [129]. Security architectures for open distributed systems are discussed in [130]. In [131], a security architecture for access control to network resources is discussed comprising user access control to the network using a variation of the method described in [132]; the user, as a client, accessing the network services using what is called a client server model for both self usage and proxy [133,134]; and accessing the inter domain services. In this model, any intrusion by the local or remote users is appropriately logged into the security management information base (SMIB).

In the second part, called the reactive approach, it is assumed that the protocols are still not robust enough as no security protocol can be anticipated to be fool-proof, and somehow an intruder gains access to the network resources [135,136].

AI techniques have been widely used in intrusion detection systems [137]. Rule based systems are used for intrusion detection in [138,139]. State transition analysis is carried out to identify the intrusion in [140]. Petrinets are used for state transition analysis in [141] for intrusion detection. These state transition techniques suffer from the problem that it is difficult to visualize the intrusion till the final state is reached and if the intruder carries them out in a different order, it fails. Another drawback with few intrusion detection systems is that, when several users cooperate or when the same user attempts intrusion, it will be difficult to identify the intrusion, unless intrusion related information is collected globally.

Intrusion detection based on the time interval between successive keystrokes while typing a known sequence of characters using multilayer neural network system is suggested in [142] and that by using algorithms based on fuzzy logic in [143]. Neural network based intrusion detection schemes have been developed by a few researchers [144] that predict the next command of a user and if the intrusion is likely to take place, this is reported to the managers and measures are taken to stop the same. However, carrying out this task for each of the commands of each of the users is definitely a laborious job and kills a major portion of the system time and memory. In [131], using the information collected in the SMIB, a neural network based on the back-propagation principle [145] is modeled to learn the rules related to intrusion scenarios and detect them.

3.2.5. Accounting management

The sole idea of accounting is to make the services available on the network and charge them based on usage [146]. The next aspect is to identify the user classes who need urgent services and non-urgent services and charge them according to their demand, i.e. the user who needs immediate access to the network pays a little cost of the less urgent user, without affecting the operator revenue [147,148]. Recently, a few network accounting products have become commercially available [149]. [150] studies the policies in accounting cordless telecommunication systems. Accounting management has not drawn much attention to AI techniques. There is scope to work on heuristic models to solve such combinatorial optimization problems using AI approaches.

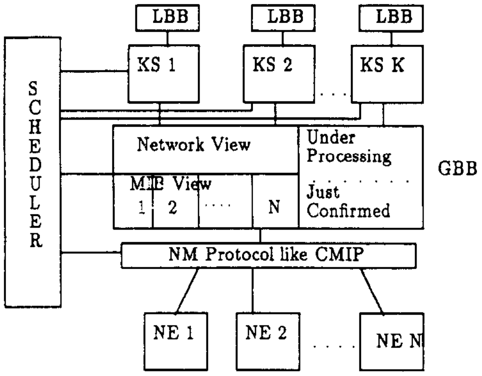

Fig. 2. Proposed INM-BBA for network management.

4. Integrated network management

There is a necessity for the network management functionalities to interact among themselves towards an integrated model of NM. Several special issues [151,152] have appeared in the areas related to integrated network management. Network management interoperability is discussed in [153]. A model for global network management is discussed in [154] and similar ideas are motivated in [155,156].

In [157], an attempt is made to integrate the five functionalities of network management by designing an INM-BBA system. This is based on a well known model in distributed artificial intelligence called blackboard architecture (BBA) [158–161]. It is a centralized network management architecture, where each of the network management functions turns out to be an individual expert system called a knowledge source (KS) and shares a global information base called global blackboard (GBB). Each KS may use a different inference mechanism depending on the domain. GBB represents the global network information collected by any of the monitoring protocols, using the object oriented approach, and makes it available for all the expert systems. Each of the expert systems in turn has a local blackboard (LBB) for local computations. The entire operation is coordinated by using a scheduler (see Fig. 2). These experts solve the network management problem incrementally and whenever possible, run parallelly.

5. Conclusion and scope

This paper discussed the network management standards, existing implementation and implications and then gave a picture of the AI approaches that have been adopted for network management. The scope of AI approaches to network management is unlimited. It is the need of the hour to think of using such applications of AI for this complex subject and derive the potential benefit of AI techniques to solve the possible problems.

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