Payoff

Modeling the thought processes of a team of human experts, a prototype extended network expert operating system (ENEOS) at the Bank of America in San Francisco is helping manage multivendor, multinetwork communications facilities of arbitrary types and topologies. ENEOS's seven knowledge bases, 380 operating rules, 65 LISP procedures, and finite inference frame processor enable it to perform parallel rule processing for the real-time oversight of multinetwork events. This article describes ENEOS and its network control implications and details its communications protocols and standards, architecture, and knowledge bases.

Introduction

The tide of postdivestiture technology has swept through corporate communications networks, replacing the previously pervasive Bell System's centralized networks with multivendor distributed networks. Managing these networks involves real-time surveillance and control to ensure that all their components operate efficiently and reliably. A system for managing these large, diverse, multivendor networks is long overdue.

Network technology is entering its fifth generation. The characteristics of each generation are:

- First generation—Shared transmission facility.
- Second generation—Switched utility networks of data and voice.
- Third generation—Standardized architecture networks, including the Tymnet and Telenet X.25 networks, IBM System Network Architecture (SNA) networks, Northern Telecom SL-1 Private Automatic Branch eXchange, IBM and Rolm computerized private automatic branch exchange (PABX), and AT S/85 private automatic branch exchange (PABX).
- Fourth generation—Fully interoperable application networks, including the Manufacturing Automation Protocol and technical office protocol (MAP/TOP), IBM System Application Architecture (SAA), Open Systems Interconnection file-transfer access management service (FTAM), and International Telegraph and Telephone Consultative Committee recommendation X.400 message-handling service.
- Fifth generation—New and proposed standards and protocols, including the broadband integrated switched digital network (B-ISDN), Synchronous Optical Network (SONET).
Transport, Bellcore Switched Multimegabit Data Service, American National Standards Institute Fiber Distributed Data Interface, and the IEEE 802.6 Metropolitan Area Network.

During the next decade, all five generations of network technologies will coexist in network environments. Given the current and emerging network technology, the cost of network operations and management for a three-year period could far exceed the capital appropriation cost of the networks themselves, and the qualified MIS professionals to operate them could become increasingly scarce and expensive. The cost of a labor-saving expert system (e.g., ENEOS) for integrated and interoperable multinetwork administration and control could easily be justified.

Eneos Design

The ENEOS architecture was designed to manage networks of multiple and arbitrary types and topologies and consists of seven knowledge bases, more than 16 units, 200 frames, 380 operating rules, and 65 LISP procedures. It is an easily maintainable expert system capable of autonomously operating various corporate networks and can be easily upgraded to accommodate emerging fifth-generation technologies that contain embedded management channels and protocols.

The ENEOS elements use parallel processing to operate in real time and are partially distributed. A finite inference frame processor engine, the key component of ENEOS, organizes its collection of rules into frames. The finite inference frame processor performs parallel rule processing at high speeds by using frames as case or situation inferences. The use of a frame-based inference engine gives ENEOS the following capabilities and features:

- End-to-end connection management through several heterogeneous networks (e.g., public and private local area, wide area, and Metropolitan Area Network with multivendor facilities and semi-autonomous operations).
- Self-learning, self-reconfiguring, self-improving, and self-repairing algorithms for fault-tolerant and autonomous operations.
- Mechanisms for adapting to internal and external environmental changes or problems by deducing tasks and reorganizing, and for the parallel execution of expert programs for optimal, self-preserving network operations.
- Real-time expert systems control for trouble-free voice, video, and data communications.
- The use of standard, high-level human-machine and machine-network protocols with flexible interface adaptations to accommodate such current and emerging management channels as SONET’s embedded operating channel and T1/T3 data channels.
- A uniform intelligent user interface that prompts the user for input and suggests actions for optimal network operations.

These features enable ENEOS to:
· Provide online network servicing, including in-service tests and controls, ensuring maximum uptime and minimal service outages.

· Measure, with loopback capability, the bit-error rate, the error-free seconds, and the line-signal-to-noise characteristics of any desired line segment.

· Use International Telegraph and Telephone Consultative Committee B-ISDN specifications to control signals and catastrophic degradation.

· Identify the cause of gradual or catastrophic degradation.

· Perform self-repair operations by reconfiguring with alternate or backup facilities where available.

· Advise the network administrator regarding repair and recovery procedures when manual operations are required.

ENEOS can inject various stress and monitoring signals into a pseudochannel (e.g., the embedded operating channel of the Synchronous Optical NEtwork Transport, the extended super frame data channel of T1 links, and the management channel of proprietary networks). 138

ENEOS then uses an expert module to analyze the measured test data, identify the most likely cause of events, and decide to take appropriate actions on the relevant network elements.

An ENEOS network operating environment (see Exhibit 1) involves multiple ENEOSs to ensure reliability and survivability throughout the network; each ENEOS controls its own local network. At any given time, however, only one ENEOS can exercise global control, although all ENEOS elements are physically identical.

**ENEOS Multinetwork Distributed Management**

An important attribute of ENEOS is its ability to recognize multivendor, multigeneration networks and to adapt its operations to manage them. On a real-time basis, given a global network view, ENEOS can do the following for network management:

· Configuration—Reporting network status, including bandwidth management information and autorouting and rerouting.

· Problem-resolution—Performing comprehensive diagnostics and reporting all problems, noting status and resolution.

· Change—Executing changes in links, circuits, and nodes and reporting prior and pending moves and changes.

---

Notes:
LAN  Local area network
MAN  Metropolitan area network
PABX Private automatic branch exchange
SNA  System network architecture
WAN  Wide area network
· Performance oversight—Combining the reporting of alarms with the use of circuit-connection details.

· Security—Keeping out unauthorized users.

ENEOS can also perform the following offline network management functions:

· Asset management to track network assets inventory (e.g., workstations, file-servers, printers and servers, modems, multiplexers, Channel Service Unit, circuits, leased lines, and hosts) and generate inventory reports.

· Customized billing and accounting and generation of appropriate reports.

· Network administration, expansion and modification, and resource allocation.

Protocols and Standards

Large business networks consist of elements that range from host computers, workstations, and terminals, to front-end communications processors, multiplexers, statistical multiplexers, Channel Service Unit, and wideband and narrowband leased lines that use terrestrial fiber-optic cables, copper wires, and microwave satellite transmissions. No single vendor can supply all of these network elements.

There are many popular methods of network control and operation, including subdividing large and complex networks into smaller networks or installing them separately according to geographic region, vendor or equipment type, or application type. Current network management methods are based on six product categories: modems, LANs, Private Automatic Branch eXchange, and T1/T3 multiplexers, host-based, and public inter- and intra-LATA Wide Area Network-based management systems covering the spectrum of all the other management systems (see Exhibit 2).

Network Management Methods Organized by Product Categories

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Note:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>LATA (Local and transport area)</td>
</tr>
</tbody>
</table>

National and international committees are developing standards for network management protocols and messages. Some of the more important of these are the

---

American National Standards Institute X3T5 standard for Open Systems Interconnection management and the Exchange Carriers Standards Association's T1M1.5 standard for Synchronous Optical NEtwork Transport management and maintenance. Important de facto standards created by dominant vendors include the IBM NetView and AT&T Unified Network Management System and network management and operation standards. ENEOS incorporates these standards as well as significant enhancements.

Exhibit 3 lists the OSI network management layers and the protocols that have been adopted in ENEOS.

**OSI Layer Services and Protocols Adopted by ENEOS**

ENEOS integrates an installed base of subdivided networks into a cooperative network that uses expert system applications, broadening the scope of the emerging OSI network management standards. ENEOS extends its services to multinetworks with three basic modules: the presentation adaptation and learning module, the function adaptation and learning module, and the interface adaptation and learning module (see Exhibit 4).

**ENEOS Extended Services for Multinetwork Integrated Management**

**Architecture**

ENEOS models the thought processes of a team of human experts when it assesses the current network environment and determines the most reasonable solution to any problem, choosing from a pool of existing possibilities. For ENEOS to support online management with a global network perspective, its architecture had to include stringent real-time capabilities.

ENEOS is vulnerable to damage, however, like any network element. To ensure continued operation in the event of damage, the ENEOS architecture allows the cloning and replication of ENEOS functions at alternate ENEOS sites. One ENEOS is elected as a master according to certain election rules; it then controls the global network operations with continuous help from the other ENEOS elements that have local control of their respective domain networks (see Exhibit 1). If the master ENEOS is disabled, a second ENEOS is elected as a master to provide continuous control of global network operations, avoiding communication outages. If a local ENEOS fails, the nearest ENEOS assumes control of the domain. Exhibit 5 shows an architectural functional block diagram for ENEOS.

**ENEOS Architectural Functional Block Diagram**

---

# OSI Model Diagram

<table>
<thead>
<tr>
<th>Layer 7: Application</th>
<th>Transaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>File Transfer</td>
<td>Application Service Element</td>
</tr>
<tr>
<td>File Transfer Access</td>
<td>Common Management Information Service Element</td>
</tr>
<tr>
<td>Management Service-ISO 8571</td>
<td></td>
</tr>
<tr>
<td>Application Control Service Element</td>
<td></td>
</tr>
<tr>
<td>Remote Operation Service Element</td>
<td></td>
</tr>
<tr>
<td>Application Control Service Element</td>
<td></td>
</tr>
</tbody>
</table>

## Layer 6: Presentation
- ISO 8822, 8823; CCITT X.216, X.226; ASCII; EBCDIC; Alpha Graphics

## Layer 5: Session
- ISO 8326, 8327, CCITT X.215, X.225

## Layer 4: Transport
- ISO 8072, 8073; CCITT X.214, X.224

## Layer 3: Network
- ISO 8348, 8473
- X.25

<table>
<thead>
<tr>
<th>Layer 2: Data Link</th>
<th>Integrated Switched Digital Network</th>
<th>High Level Data Link Control Protocol</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEEE 802.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Message Authentication Code</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Layer 1: Physical
- IEEE 802.3 CSMACD
- IEEE 802.4 Token Bus
- IEEE 802.5 Token Ring
- IEEE 802.6 Metropolitan Area Network
- ANSI X3T9.5 FDDI
- EIA RS-232
- EIA RS-449
- CCITT 1431
- X.21

### Notes:
- CSMA/CD - Carrier-sense multiple access/collision detect
- FDDI - Fiber distributed data interface
### Presentation Adaptation and Learning Module
Virtual Terminal Service and Protocol OSI Layer 6
CCITT X.3, X.28, and X.29 Terminal Protocols

<table>
<thead>
<tr>
<th>Local Craft Interface</th>
<th>ASC II Dumb Terminal</th>
<th>Microcomputer</th>
<th>Intelligent Workstation</th>
<th>Superminicomputer Terminal</th>
<th>Future Brilliant Terminal</th>
</tr>
</thead>
</table>

### Function Adaptation and Learning Module
Real-Time Inter- and Intranetwork Functions:
- Network Inventory
- Reconfiguration
- Topology
- Performance
- Alarm Handling
- Problem Resolution
- Security and Auditing
- Accounting

Offline Functions:
- Archiving
- Traffic Statistics
- Network Designs
- Management Reports

OSI Layer 7

### Interface Adaptation and Learning Module
Wide Area Networks
- Analog Leased Lines
- Digital Services:
  - T1/T3
  - Satellite
  - SONET
- Switching Type:
  - Circuit (T1 Time-Dimension Multiplexing)
  - Packet (IBM's SNA, X.25)
- Metropolitan/Local Area Network Types:
  - IEEE 802.6
  - Fiber Distributed Data Interface
  - IEEE 802.3, 802.4, and 802.5
  - Gateways, Bridges, and Routers

OSI Layers 1-4
Multiple networks can be managed through either a centralized system or a distributed system with several linked expert systems.141

ENEOS uses a distributed approach because—through smaller mass-produced processors—it provides more computing power than a centralized approach. In a distributed approach, expert system modules can be applied wherever needed throughout the system by working in parallel with local processors, thereby reducing the chances of a failure at a single point.

The disadvantages of a distributed processing approach include overhead for cooperative communications among the ENEOS entities, complex election rules for choosing a master ENEOS to control global operations, complex timing and synchronization for coordinating subordinate and master ENEOS entities, and the amount of bandwidth for the management channels. These disadvantages are gradually being eliminated by development of fast processors, inexpensive bandwidth, and sophisticated expert systems technologies.

Event Analyzer

As shown in Exhibit 5, the ENEOS event analyzer collects data on events as they are generated by network elements and their components. This analyzer gathers and interprets raw data intelligently, simulating a team of human experts. Its output is either an operational command to a network element, accompanied by an alarm, or simply a status report for the operator. When ENEOS encounters a problem, the system activates audio and visual alarms.

In large networks, event analyzers perform several complex tasks. An abnormal condition triggers many events, each of which provides information that can help identify and resolve the overall problem. A single event is generally not significant, but a group of events taken together can be critical, depending on their patterns.

Correlating events for problem determination and analysis is not a straightforward task; it is affected by time correlation, event attenuation, redundant events, location correlation, partial data, and multiple problems. These factors are explained in the following sections.

Time Correlation

A particular problem may cause other events to occur during a finite time period at unpredictable intervals that range from microseconds to days. Isolating and characterizing a problem that involves a degrading component may take days, and the frequency of events can have a critical bearing on the problem. For example, one frame slip on a T1 line during a day may not be serious, but 10 frame slips an hour can be quite serious.

Event Attenuation

Events generated by some types of problems may not be communicated. Examples are jitter (i.e., short-term variations in signal interval phases commonly caused by nonlinear transmission circuit elements) and wander (i.e., long-term variations in signal phase intervals) in T1 lines due to intermediate repeaters and cross-connect systems that use large buffers. Error-correction codes processed at intermediate network elements can also go unreported.

---

Redundant Events
Some events occur as a consequence of other events and provide no new information; they may even be reported after the problem has been resolved. This type of event should be masked in the system to avoid distractions while the cause of the problem is being isolated.

Location Correlation
An abnormal problem can have consequences in other network components. In this situation, a problem must be determined from related events that are reported by other properly functioning components.

Partial Data
Problem resolution often proceeds despite incomplete data. Data is gathered incrementally as more events are reported over time. In some cases, event analysis does not always produce a definite conclusion; events can be lost, mutilated, or not reported because of damaged network elements, or false events can be reported as a result of noisy communications. The ENEOS event analyzer generates hypotheses about a given problem, analyzing additional events as they occur and using this information to revise and refine the hypothesis. The inference processor must allow the system to make plausible revisions. Occasionally, the absence of events may be very significant and should also be processed by the inference engine. For example, if events indicating a faulty component or degraded signal stop occurring, any hypothesis regarding a faulty component or degraded signal should be abandoned.

Multiple Problems
A large network usually has some independent problems that are pending resolution. Events generated by these problems are mixed with events caused by the problem. The inference processor should be able to separate such a mixture of events, assigning priorities to the problems according to their severity.

Knowledge Bases
An expert system's knowledge base contains items called objects. ENEOS's knowledge base contains such objects as corporate networks, gateways, specific network types, sites, nodes, ports, paths, links, intermediate multiplexers, repeaters, front-end controllers, and terminal types. Ad hoc collections of objects are created as needed for resolving particular problems. See Exhibit 6 for a condensed taxonomy of ENEOS objects and parameters. Objects and their associated measurements performed or acquired during a problem-resolution session are listed in Exhibit 7.

Condensed Taxonomy of ENEOS Objects and Parameters

Typical Network Element Operators

Network element operators manipulate network objects through a combination of heuristics, test commands, and algorithms, triggering the actions needed for problem resolution. When operations are applied to objects, they may produce children and grandchildren within the hierarchy of objects and sets. Operators' properties characterize
Managed Objects

Types
- Traffic Source
  - Hosts
  - Terminals
  - Video Cameras
  - Telephones
  - Workstations
  - TV Display
  - Facsimile
  - Printers
  - Humans
- Network Components
  - Links
  - Trunks
  - Ports
  - Bridges
  - Multiplexers
- Switching
  - Pairs and Tuples
- Network Components
  - Cabinets
  - Racks
  - Shelves
  - Modules
  - Software Programs
- Transmission
  - Single-Mode Fiber
  - Dispersion Flattened Satellite Microwave
  - Time-Circuit Switching
  - Packet Switching
  - Integrated Switching
  - Broadband Switching

Characteristics
- Discrete
  - Events
  - Traps
  - Outages
  - Time
  - Rate
  - Round-Trip Delay
  - One-Way Delay
  - Sectional Delay
  - Queue Delay
  - Process Delay
- Continuous
  - Bit-Error Rate
  - Frames per Second
  - Packets per Second
their domains and ranges in the network object taxonomy; they also have procedures that can generate presentation-layer descriptions of icons, tables, charts, and graphic displays. Operators can trigger further actions in network elements that assist in problem resolution (e.g., rerouting traffic through an alternate path to bypass a failed element).

**Object-Oriented**

Object-oriented knowledge bases, data bases, and programming are state-of-the-art artificial intelligence concepts, offering significant advantages over conventional programming techniques. In ENEOS, objects communicate with one another by sending and receiving messages. An object consists of a collection of information and the protocols needed to manipulate it.

The knowledge base consists of factual, algorithmic, and heuristic knowledge. Examples of factual knowledge in the ENEOS knowledge base are:

- Transmission media, including single-mode dark fiber in dispersion-flattened and polarization-preserving formats and transmitter lasers (e.g., thermoelectric cooled, distributed feedback, and Fabry-Perot lasers).
- Switching and connectivity frames and rules.
- Test commands and invocation rules.
- Electrical and optical test definitions, including noninvasive optical Time Domain Reflectometry and stress signal tests.
- Test thresholds and limits.

The declarative knowledge of network elements and communication paths consists of three entities: sets of network element classes, classes of network elements, and instances of network element classes in which each element is represented as a frame. Frame-based knowledge representation provides a system with deep knowledge because of the complex structures within the frames. Rule-based knowledge systems, however, provide only surface knowledge because of the limited way information can be presented. A typical frame describing an instance of a specific entity contains the following information:

- Element class and hierarchy.
- Functional description.
- Structural description.
- Behavioral description.
- Legal operations, including test, preventive, corrective, and adaptive procedures.
- Bandwidth resource management procedures.
- Routing algorithms and procedures.
One of ENEOS's most essential tasks is instantiating these types of frames. (See Exhibit 8 for a simple instantiated frame.)

**An Instantiated Frame**

A specific instance of a class of network elements could have two terminals—workstation A and host B—specified in the frames as communicating in connectionless packet mode. By establishing the communications mode between the terminals, ENEOS creates a direct correspondence between the relationships in a given situation, facilitating the natural presentation of global network knowledge.

All knowledge that is to be processed must be represented in frames. Because the operations and manipulations of these frames are expressed as specialized procedures, ENEOS uses factual knowledge of such network elements as the state of communicating terminals, communications protocols, connection mode, links, and time slots in a time multiplexer.

Naming a frame helps control the proper matches of the restricted variables, allowing ENEOS to derive all the test points and test operations for a given problem resolution. In a frame-based procedure, a frame stored in the knowledge base is selected and matched against the collected data to predict the structure of the data.

Using frame-based rather than rule-based processing provides real-time parallel processing capabilities in ENEOS (e.g., how ENEOS relates alarms). A frame is selected with many alarms pointing to other objects and their relationships. The alarms are classified according to their level in the hierarchy of network components that are sending the alarms; this level number is added to the alarm-signal knowledge base. The frame with the highest alarm level is the master frame, and the matching process is performed according to ENEOS's procedures. Alarm-data collection, processing, and matching must be done in real time for meaningful network-management operations to occur. Coding these procedures, therefore, requires real-time considerations.

**Finite Inference Frame Processor**

Inference generation in ENEOS is performed in the finite inference frame processor. As noted, this processor is the key component of ENEOS; its functional block diagram is shown in Exhibit 9. The design of all the knowledge bases in the finite inference frame processor is similar to that of the interpreter knowledge base, shown in the central box in Exhibit 9. The design of the knowledge base is an important aspect of the finite inference frame processor. 

---

A Functional Block Diagram of the ENEOS Finite Inference Frame Processor

Knowledge-Base Design

Researchers at Stanford University, pioneers in expert system technology, have designed several expert system capable of performing medical diagnostics: EMYCIN, MYCIN, and NEOMYCIN.\textsuperscript{143}

The most important design principle of relevance to ENEOS to come from the MYCIN project is that all control knowledge should be represented abstractly and separately from the domain knowledge on which it operates. Control knowledge, like rule-clause ordering, specifies when and how a program should perform such operations as pursuing a goal, acquiring data, focusing on an object, and making an inference.

Conclusion

In ENEOS, the knowledge bases and the associated inference engine of the finite inference frame processor have separate components for encoding control knowledge, factual knowledge, and judgmental rules. The inference engine applies the judgmental rules according to the embedded control procedures that define distinct control steps. The control knowledge, coded through an applicative and imperative programming language, defines the control actions that will be executed in a multitask environment. The separate encoding of the control knowledge allows ENEOS to generate inferences that are readily intelligible, explainable, modifiable, and upgradable.

To provide a transparent presentation of both control knowledge and factual knowledge, the knowledge bases in ENEOS are organized in distinct frames that contain an ordered rule structure of separately encoded control blocks. Factual knowledge is coded with network-defined objects, class types, legal-value hierarchies, class instances, and attributes. The imperative control knowledge cooperates with the structures of the declarative factual knowledge to provide built-in control.

Author Biographies

Yemmanur Jayachandra

Yemmanur Jayachandra is a senior consultant at the Bank of America, San Francisco, specializing in expert systems, fiber-optic communications, network management, and B-ISDN.

Hal Sanders

Hal Sanders is chief executive officer of Nusan Corp of Watsonville CA, a telecommunications research company.

Gita Jayachandra

Gita Jayachandra is a graduate student in AI and expert systems at San Jose State University and has consulted at major financial institutions in the areas of network management, LANs, and algorithm development.