SWITCH-TO-COMPUTER NETWORKING IN THE NINETIES: THE EVOLUTION OF AT&T'S SWITCH-COMPUTER INTERFACES

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This paper highlights AT&T's role in the evolution of ISDN switch-to-computer interfaces. Initially, the digital multiplexed interface (DMI) provided a multiplexed channel for data communications between a computer and a private branch exchange (PBX). DMI evolved to the Integrated Services Digital Network (ISDN) primary rate interface (PRI) that forms the backbone of many customers' networks. While PRI and DMI provided data transport applications based on higher performance, speed, and economy, these applications addressed only part of the potential power of an ISDN-computer link. In telecommunications, the term "switch-computer applications interface" (SCAI) is applied to linking computers and switches on an application (as opposed to a connectivity) basis. SCAI combines switches and computers in a client/server arrangement that provides new applications to integrate communications and computing functions. This paper describes the architecture, capabilities, and applications of AT&T's SCAI, the adjunct/switch application interface (ASAI). It addresses the requirements for marketing ASAI, specifically the need to conformance-test ASAI interface implementations and test the interoperability of switch and computer applications. Finally, it identifies future trends for SCAI standards activities.

Introduction

In the last 30 years, basic office communications functions have been provided by a combination of network services from telephone company switching offices and premises PBXs. For both areas, digital systems and separate or out-of-band signaling been important

Panel 1. Terms and Acronyms in This Paper

ACD — automatic call distribution
ANSI — American National Standards Institute
API — application programming interface
ASAI — adjunct/switch application interface
ASE — application service element
BRI — basic rate interface
CCITT — Consultative Committee for International Telephony and Telegraphy
CCS — common channel signaling
CIT — Computer Integrated Telephony
CSTA — Computer-Supported Telecommunications Applications
DCS — distributed communication system
DMI — digital multiplexed interface
ECMA — European Computer Manufacturer's Association
ISDN — Integrated Services Digital Network
ISO — International Standards Organization
ISV — independent software vendor
NIST — National Institute of Science and Technology
OSI — Open Systems Interconnection
PBX — private branch exchange
PC — personal computer
PRI — primary rate interface
SCAI — switch-computer applications interface

technological trends. Digitizing the network began 30 years ago with the introduction of the T1 carrier. Today, all switches in the AT&T switched network are digital. The network has also made increasing use of a separate signaling technique called common channel signaling (CCS). As communications protocols have led to distributed processing environments for computers, so separate signaling lets network switches and processors communicate with each other, helping pass important information about calls. This signaling also allows distributed access to advanced network services.

These same trends toward digital systems and intelligent control have occurred even more rapidly with customer premises equipment. Digital PBXs such as AT&T's Definity® system offer advanced services and digital private networks between locations through a separate signaling network.

For example, one early use of a separate signaling network is AT&T's Distributed Communication System (DCS), introduced in 1982. DCS allows transparent operation of 20 PBX features such as transfer, forward, and distributed attendant control, across a private PBX network. The DCS out-of-band signaling network carries all the information needed to provide the feature transparency beyond basic addressing and call supervision.

These parallel trends in network and premises capabilities are now bridged with ISDN.[1] ISDN access defines a digital interface divided into two types of channels: B channels for customer information, and D channels for signaling and control information to manage the B channels. The digital connectivity of the ISDN B channels allows high-quality transmission of digitized information in a format transparent to the specific content of the information: voice, data, image, or graphics. Even more importantly, ISDN's extensive out-of-band signaling implemented via the D channel offers the means to integrate premises equipment and network intelligence.

For example, the out-of-band D channel signaling lets an ISDN PBX dynamically allocate the B channels being used to access network services. This allows the PBX to control the number of trunks used for any particular service on a call-by-call basis. In addition, by supporting the interworking of the D channel with the CCS network, ISDN makes call information available to the user as the call moves through the network. This information was previously available only for calls switched within a PBX. An ISDN network's ability to pass calling party information through the network to the customer premises has received the most attention in this area.

Besides bridging network and premises-based communications, ISDN also has stimulated interest in integrating communications and data processing environments in new methods of data communications and application development. For example, the DMI,[2] introduced by AT&T in 1984, uses out-of-band signaling (with either ISDN or non-ISDN bit-oriented procedures) to multiplex up to 23 channels onto two pairs of twisted wire, or indeed on any standard T1 transmission facility. Each channel can transmit up to 64 kilobits per second (kbps), depending on the particular data transport protocols used, offering effective high-speed connectivity between a computer and terminals.

ISDN Switch-Computer Application Interface Evolution

The ability of applications to take advantage of ISDN capabilities has grown considerably. At first, applications could use DMI to gain access to digital bandwidth for data connectivity. As DMI evolved to PRI, and basic rate interface (BRI) was introduced, new types of application control became possible that took advantage of ISDN's call-related capabilities, such as call-by-call service selection and delivery of calling party identifier. With "basic telephone control," for example, an application can monitor and control calls to or from itself.

An example of this type of application endpoint is AT&T's personal computer PC/ISDN Platform. This product consists of a BRI board that can be installed in a personal computer, and software that allows development of applications based on BRI messaging. An application running on a PC/ISDN endpoint (typically a personal computer and attached BRI voice terminal) can control basic telephone features and take advantage of more advanced features such as delivery of calling party identifier. But it is limited to monitoring and controlling calls that have been directed to itself. Similarly, PRI applications can use "basic network control" capabilities to take advantage of ISDN features such as call-by-call service selection and delivery of calling party information, but only for calls to which it is a party.

ISDN supports a broader type of application control, called "advanced switch control," that lets an application monitor and control any call or endpoint on the switch. Thus, if an application has advanced switch control, it does not have to participate in a call to receive information about that call, as with an application that supports only basic telephone functions. Some advanced switch control functions, such as monitoring when a call arrives at an endpoint, may be call-related; others, such as lighting the message-waiting lamp for an endpoint, may be invoked even if the endpoint is not currently involved in a call.

There are several types of switch control and monitoring functions. Some implementations may have the switch send call-related information to the computer application. Thus, the application would receive information that a particular extension had received a call and it was answered. The scope of application control is switch-wide, but the flow of information is only one way, from the switch to the computer. This may be adequate for many applications. But others, particularly those involving outbound call generation from the switch, require the computer to be able to request actions from the switch.

Thus, the next step in the evolution of switch-computer interactions is to view the switch and computer as equal partners in providing end-to-end telecommunications applications. The information flow must be two-way. The switch and computer each must perform two roles. Each must be able to act as a client and request services from the other. Each must also be able to act as a server that performs the requested services and notifies the client of the outcome.

A generic term for this type of two-way interface for advanced switch control is SCAI. Currently, there is considerable activity in standards bodies and vendor forums toward defining a standard SCAI. AT&T's involvement in this activity began as part of an AT&T-sponsored vendor forum, the ISDN/DMI Users' Group, consisting of

170 switch and processor vendors who formed a Special Interest Group in 1987 to study the technical considerations required for the implementation of a switch-computer applications interface.

The outcome of this work was the definition of the ASAI, representing AT&T's and the ISDN/DMI group's initial specification of a functional interface between a computer (or adjunct processor) and either a PBX or central office switch.

SCAI Customer Requirements

The goals of SCAI in general and ASAI specifically are based on these premises:

- Customers will use these interfaces to support a broad range of telecommunications applications that need real-time coordination and integration of telephony information with an application running on another computer processor. These applications include inbound and outbound call management, desktop automation, systems management, and enhanced call coverage.
- Customers want SCAI to support many equipment configurations and environments. They want to use the same application in different computing equipment environments (e.g., PC local area networks, minicomputers, mainframes) and different switches. They want to be able to modify their equipment environment easily to increase capacity, centralize or decentralize, or add new applications to protect their investment.
- Customers do not want to be bound to a single vendor, but want multivendor application environments. But they also want the flexibility of having a vendor work as a systems integrator to provide a single point of contact for a multivendor application.

This set of customer expectations can be translated into customer requirements for SCAI. ASAI has been designed specifically to meet these requirements, as follows:

- The interface must support a peer relationship between the switch and computer to provide the required breadth of applications. The computer application must be able to invoke switch features and receive event information from the switch; and the switch must be able to request actions by an application on the computer, including passing information needed for further call processing and call distribution. For example, the computer must be able to have the switch place a call between two endpoints and have the switch start sending call-related notification events for a specific endpoint. However, the switch must be able to request specific routing information so it can route a call based on information that is part of the computer application database. ASAI has been designed using a client-server model where the switch and computer both may play either the client or server role.
- The interface must support the functions that make telephony application development straightforward. Given the breadth of proposed applications, this might include advanced control of the major switch functions. ASAI, in the current specification, has identified over 40 functional capabilities needed for application support. These range from basic call set-up under application control, to complex features such as routing and other interactions with groups of agents controlled by automatic call distribution (ACD) software in the switch as well as other call distribution software.
- The interface must be based on and related to existing standards. Standards are needed to meet the goals of using the same application across different hardware environments, both single and multivendor. To meet the requirements of computer vendors, ASAI's application-level protocols are formally described in a reference model based on OSI (Open Systems Interconnect) concepts. The transport protocol definition is based on Consultative Committee for International Telephony and Telegraphy (CCITT) ISDN protocols. Using these standards as a base has helped insure the alignment of ASAI with emerging SCAI standards.
- The interface standards must be open and published so multiple vendors may build to it. The ASAI specification[3] was published in November 1989.

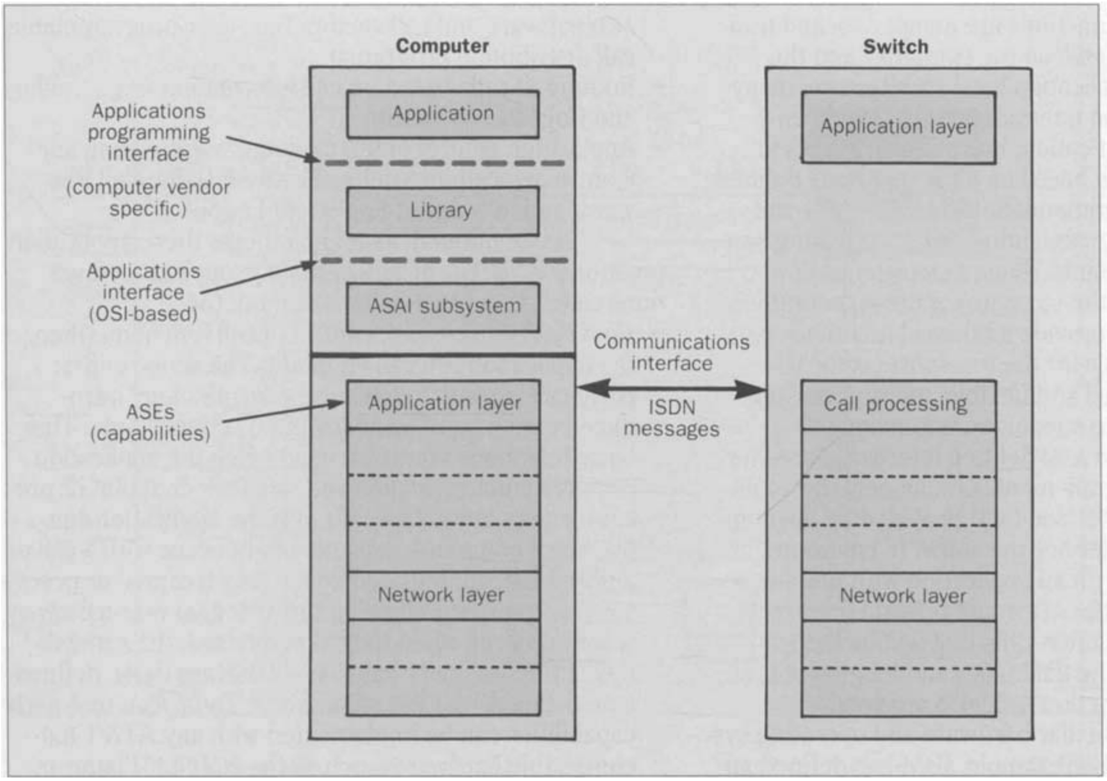


Figure 1. ASAI switch/computer environment showing the communications interface and operative protocols between the computer and switch.

Adjunct/Switch Application Interface

This section presents a detailed view of the architecture, capabilities, and applications of ASAI.

Architecture. Figure 1 gives a high-level overview of ASAI's switch-computer environment. ASAI defines two distinct interfaces: an applications interface and a communications interface. The applications interface, based on the OSI Application Layer Structure described in ISO (International Standards Organization) 9545,[4] defines a standard set of telephony functions that are common across different communications protocols. The OSI Application Layer was used because it provides a well-documented and well-understood formalism for describing how applications request functions, and how those function requests can be mapped into protocol elements. The applications interface defines a set of functions called application service elements (ASEs) that can be combined to meet the application requirements. These ASEs and the methods for ASE access are specified so the semantics of the functions are independent of the particular switch providing the functions, and of the lower level transport mechanisms used to communicate between the switch and computer.

The second ASAI interface, the communication interface, defines these lower-level transport mechanisms. Where the application interface defines the ASEs that provide telephony functions, the communications interface specifies how the ASEs' requests for and acknowledgements of functions are mapped to, and transported as, messages between the computer and the switch. Given ASAI's application level architecture, many different communication interfaces could have been defined. The ASAI specification, however, describes in detail only the interface, based on ISDN standards defined in the 1988 CCITT Recommendations Q.930, Q.931 and Q.932 for establishing, maintaining, and terminating connections between endpoints. Some extensions, allowed by and consistent with the structure of these recommendations, were added to provide additional functions. ISDN was selected as the basis for the transport protocol because it is well-defined and flexible, offering messaging structures needed to support SCAI functions.

Besides the two ASAI-defined interfaces, another interface is needed to implement SCAI, namely the application programming interface (API) provided by the computer vendor. The API defines the software environment a programmer uses to run an application with functions defined by SCAI. Thus, the API would provide the syntax and operation of the function calls that invoke the SCAI capabilities, as well as the data types and lengths of the parameters for each function call. APIs are vendor-specific, tied to the particular hardware and operating system the vendor offers. For example, IBM has defined an API known as CallPath Services Architecture. Digital Equipment Corporation supports an API known as Computer Integrated Telephony (CIT). Both APIs are designed to offer common programming interfaces across different switch environments, and to be consistent with the development environment and tools supported by each vendor.

Capabilities. To support the needs of current and potential applications and services, ASAI gives applications the following abilities:
- Simultaneous delivery of application database information when a call is delivered to a call center agent
- Application control of calls (e.g., call setup, transfers, and conferences)
- Application monitoring of calls, both those directed to individual extensions and those controlled by switch ACD software and call vectors (i.e., user-programmable call distribution programs)
- Routing of calls based on call information (e.g., Calling and Called Party number)
- Application control of the message-waiting lamp and feature invocations such as Send All Calls, Call Forward, and ACD Agent Login and Logout.

As mentioned, ASAI implements these application functions by means of well-defined groupings of functions called ASEs. ASAI defines eight of these:
- *First-party call control*: control of call functions when the application is a call endpoint. The scope of first party call control, following the terminology introduced earlier, is of basic telephone control only. This basic telephone control is used when the application requires communication with another endpoint or processor (e.g., for a data call) or if the application can use voice communication, as might occur with a call to a BRI-attached integrated voice/data terminal or personal computer. Following the ASAI goal of consistency with standards when they already exist, the capabilities in the first-party call control ASE are those defined by existing AT&T BRI standards.[6] Thus, ASAI first-party capabilities can be implemented with any AT&T-BRI-compatible hardware, such as the PC/ISDN Platform.
- *Third-party call control*: control of call functions for other endpoints on the switch when the application is not a call endpoint. Again, following the earlier terminology, ASAI uses the third-party call control ASE to support advanced switch control functions. With these capabilities, an application can specify two endpoints for a call, then tell the switch to connect those endpoints. Once the call is established, the application can control the specific communication function required by the call, e.g., placing one party on hold and transferring the call to a third party. Within third-party call control there are two subsets of functions, single-call control and domain control. With single-call control, the application is able to monitor and control calls from a call-oriented perspective, i.e, a call is monitored

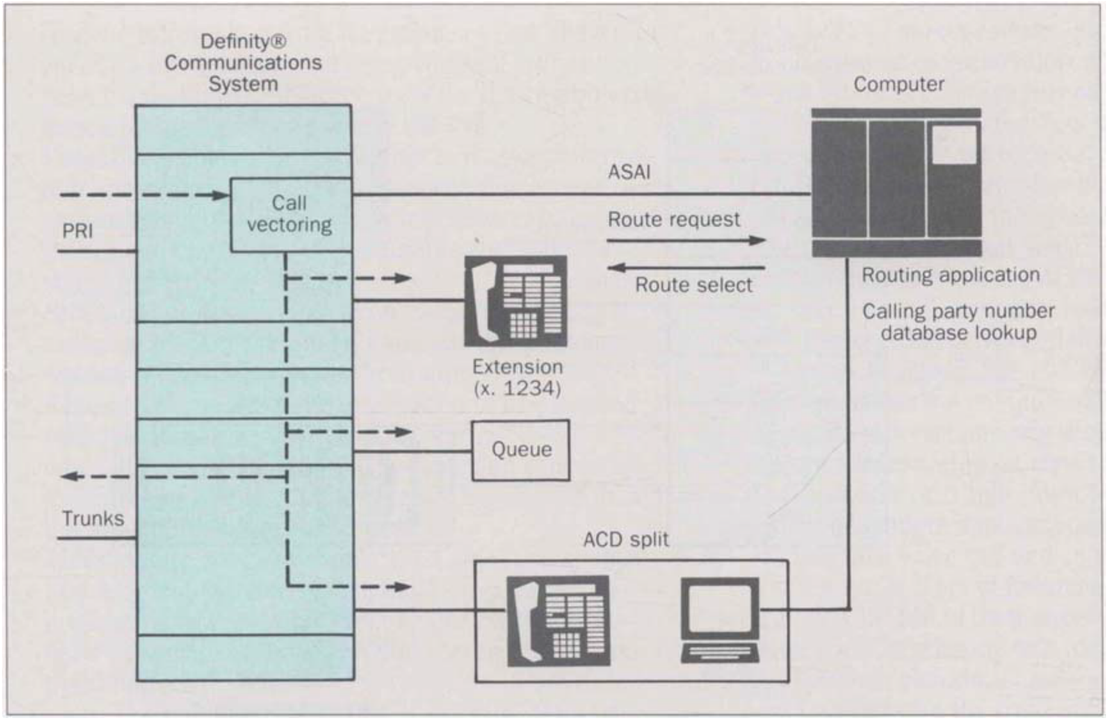


Figure 2.
ASAI/adjunct routing.

or controlled throughout its existence. This type of control is particularly valuable for telemarketing applications, because it eliminates the need to monitor all specific endpoints where a call might be transferred. However, with domain control the application can monitor and control calls only within a specific domain or endpoint type. With domain control for stations, an application may receive event reports and control calls that begin and end at a specific station. Unlike the case for single-call control, once the call leaves the station, the application no longer can monitor and control it. This type of control is particularly valuable for desktop applications where control of specific stations is the primary goal.

- *Notification*: allows the application to receive information about events occurring on the switch, and to cancel these event reports. The notification ASE may be used by applications trying only to monitor the events associated with calls, and not actually control them.
- *Routing*: allows the switch to request routing information for a call from an application on the processor (See Figure 2). The application provides a route or destination for the call. The destination may be any valid endpoint (e.g., extension, ACD split, call queue) on the switch, or may be an endpoint not on the switch. For example, when a call arrives at a call vector (call distribution software in the switch), an ASAI "Route Request" message containing information such as calling party number and called party number is sent from the switch to the computer. The routing application on the computer uses this information to

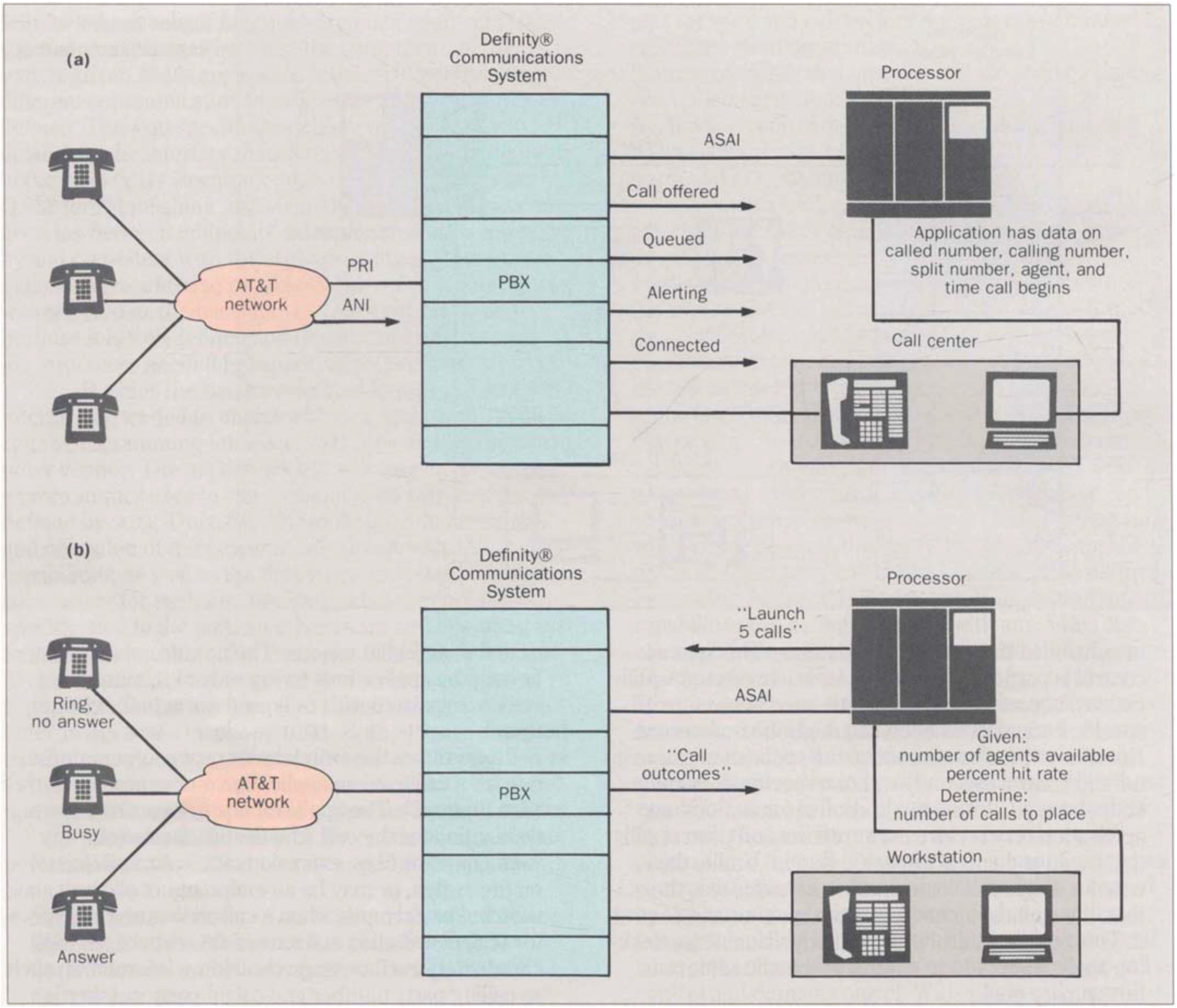


Figure 3(a) ASAI call center applications: inbound call management. (b) ASAI call center applications: outbound call management, showing predictive dialing.

retrieve information from its databases that allow it to specify a route for the call using the ASAI "Route Select" message. The switch uses the information contained in this message to route the call.

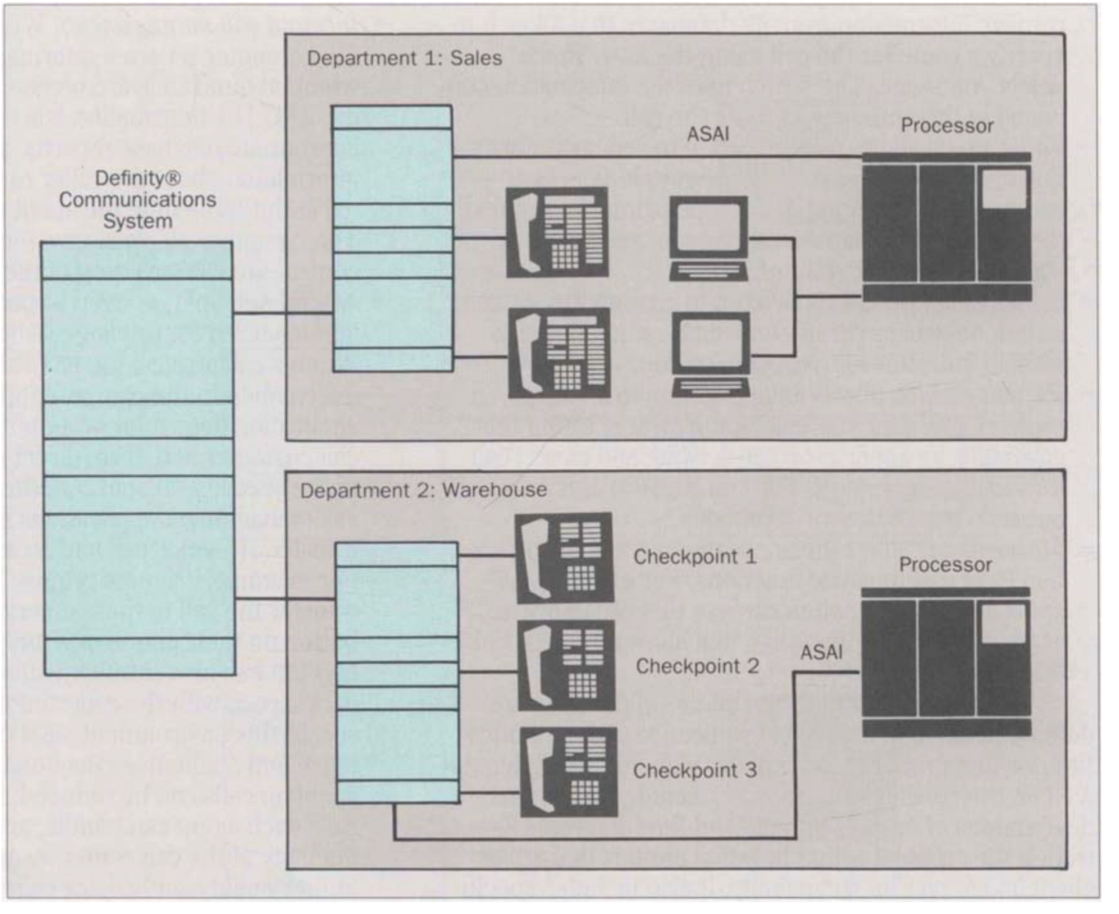
- *Value query*: allows an application to request information about the status or value of switch objects or parameters. For example, an application can request the time of day, status of ACD agents and splits, or status of particular stations.
- *Set value*: allows an application to change the status of switch objects or parameters such as the message-waiting indicator for a specific station.
- *Request feature*: allows an application to invoke a switch feature for stations on the switch. Using this capability, an application can activate and cancel call forwarding or Send All Calls, or log ACD agents in and out and change their work modes.
- *Maintenance*: gives the application access to application level maintenance functions. For example, an application or the switch can use this capability to send a "heartbeat" message that shows the ASAI link is operating.

The behavior and capabilities of the ASEs are defined in detail in the ASAI specification. The specification, written primarily for vendors planning to implement ASAI on their switch or computer, includes functional descriptions of each capability, and flow diagrams illustrating the protocol action between entities that act as client and server for a capability. It also includes specification description language diagrams describing the allowable sequence of actions within an ASE, complete parameter mappings, message structure, and cause-code definitions for each capability.

Applications. To show the power of a SCAI such as ASAI, Figure 3 illustrates some common applications that could be provided in an ASAI call center environment. Included in the configurations are a Definity PBX, a computer with ASAI, and the telephones and data terminals required for the agent's applications. In call center environments, two basic types of applications are implemented:

- *Inbound call management*: With this configuration, the computer receives information from the switch when inbound calls are received by the PBX (see Figure 3A). The information lets the computer query the appropriate database records, and send additional information about the caller to the agent's data terminal at the same time the agent receives the voice call. The computer also can give the PBX information to control the PBX's routing of the call. For example, a special ACD split, or even a specified agent, could be administered for privileged, high-volume customers. When a call arrives, the PBX can pass the calling party information to the computer application, have the application determine whether this call is from a special customer and, if so, direct the PBX to route the call to the special ACD split. Another feature of inbound call management applications is the simultaneous transfer of a voice call and an associated data session. For example, if agents require help, not only can they transfer the call to their supervisor (via the transfer button on their phone or a function key on data terminal) but can also simultaneously transfer the current data screen with the caller information to the supervisor. In this environment, ASAI can have both a quantitative and qualitative effect on the call center. The time spent on calls can be reduced, increasing how many calls each agent can handle, and increasing the productivity of the call center. ASAI also can produce higher quality service, for calls are routed more accurately and consistently through the call center.
- *Outbound call management*: ASAI in an outbound call management environment increases productivity by allowing agents to use both preview and predictive dialing capabilities. With preview dialing, the calling party information from calls dropped from the queue for an ACD split can be captured and placed in a list displayed on the agent's screen. When an agent becomes available, he or she can scan the list on the terminal, select a name, and have the application make the call. This allows the agent to recover business that otherwise would have been lost. With predictive

Figure 4. ASAI department PBX configuration.



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dialing (see Figure 3B) the application automatically places outbound calls consistent with the existing traffic and agent availability. The application receives information on whether the call has been answered, and an agent is connected only at that time. Predictive dialing significantly increases agent productivity since agents receive only answered calls.

Besides call center applications, ASAI can be used to support office automation applications. One possible configuration is illustrated in Figure 4. Here, a small switch is used to provide customized services for specialized communities of interest. With this departmental PBX configuration, different organizations in a building could be provided with customized call delivery applications. In Department 1, for example, ASAI might be used in an integrated voice and electronic mail system for sales personnel. Thus, sales personnel could have their message-waiting light turned on whenever they received an electronic mail message, or receive an electronic mail message whenever a voice mail message was received.

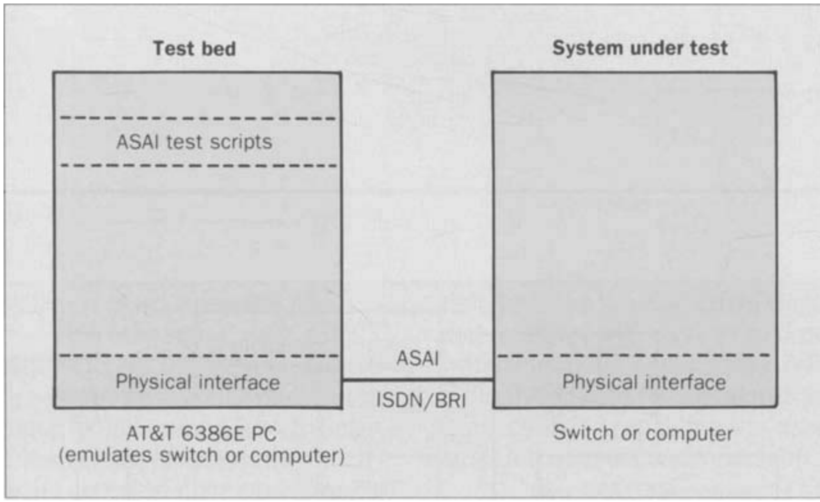


Figure 5. ASAI conformance testbed.

Department 2, on the other hand might use ASAI in a warehouse security application. Security personnel could make calls at scheduled times from existing checkpoint telephones in the warehouse. The ASAI application could monitor that calls are made at the proper time, and make outbound calls to the appropriate personnel if a security violation is detected.

Bringing ASAI to the Marketplace

Developing ASAI functional capabilities is only part of the effort to ensure successful implementation of an end-to-end customer premises application. As noted, ASAI increases the interaction between the switch and computer serving as an adjunct processor. The rich function set provided by ASAI depends on the underlying protocol that has a level of complexity commensurate with its functionality. Implementing complex protocols is more prone to development error and therefore needs more formal verification. Correct operation of the ASAI protocol and its supported applications requires intensive testing of the protocol implementation in both the switch and computer, as well as testing the application the implementation supports in an end-to-end environment. It also requires a multivendor field support plan.

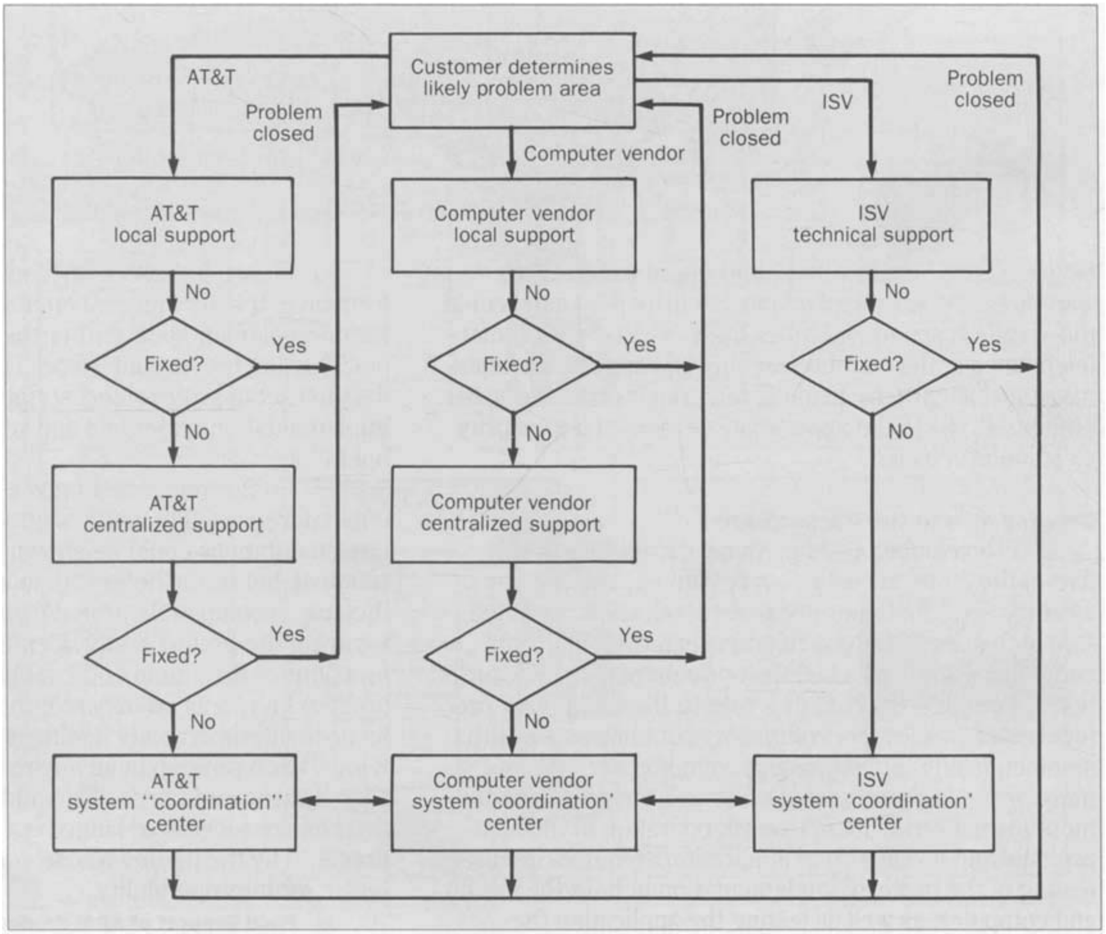
Conformance and Interoperability Testing. The testing procedures for ASAI fall into two main categories.[7] *Conformance testing* is detailed, systematic testing of an implementation to ensure that it correctly implements every applicable requirement of the interface specification. Both sides of the interface—for ASAI, the switch and computer—need to be verified for correct implementation of the protocol.

Figure 5 shows a testbed for verifying ASAI conformance. It shows an ASAI emulator connected to the tested implementation (either the switch or the computer) using the ASAI interface. The emulator contains a detailed set of protocol test scripts that exercise the implementation under test and verify the correct protocol operation.

Conformance testing is a necessary step for product interoperability, but it is not enough by itself. Two implementations could be shown to conform to the ASAI protocol, but nevertheless fail to interoperate because they use incompatible protocol options. Therefore, after verifying the protocol implementation, the user level functions of the end-to-end configuration are verified in a process known as *interoperability testing*. The primary focus in interoperability testing is on setting up and verifying a configuration in an environment as much as possible like the end-user's. The guiding document that determines success or failure is a test plan specifically prepared by the parties whose equipment is being jointly tested for interoperability.

Field Support of ASAI Products. Though conformance and interoperability testing require close cooperation between vendors, the need for true vendor partnerships is most apparent in field support of SCAI implementations. SCAI implementations often require equipment from several vendors to run a single customer application. Potentially, an application may involve a switch vendor, computer vendor, application software vendor, systems coordinator, and the customer, all working in conjunction to implement, install, and maintain it. To obtain quality service from the equipment and services provided by multiple

Figure 6. ASAI support model.



vendors, the vendors' field support processes must be integrated so they appear seamless to the customer.

Figure 6 shows a simplified overview of how a cooperative support plan should work. The figure illustrates the chain of potential events that might occur as they affect AT&T, a computer vendor, and an independent software vendor (ISV). A single customer request should be able to generate this chain of events to handle the problem.

To avoid finger-pointing, the cooperating vendors must give the customer tools to determine the likely cause of the failure or malfunction. This will allow the customer to contact the correct party when a problem is identified. The vendors should have negotiated a mutually satisfactory agreement so the vendor who received the first call is able to route the problem to the other vendors' organizations at an appropriate level.

Obviously, the goal of cooperating vendors is to give to the customer a total system maintenance program if there are problems. This may sound easy, but because different corporations follow different methods and procedures, in practice it may be complicated. At the least, it requires each vendor to understand how to link to another vendor's trouble tracking process. Also, each vendor should have mutually accepted documentation for trouble-resolution procedures until the fault has been localized in a particular vendor's equipment. This done, the independent procedures of the particular vendor can be followed until the problem is fixed. Finally, there should be a common approach to testing any solution requiring hardware or software fixes, before the fix is installed by the responsible vendor.

Future Directions

In many ways, SCAI is still in its infancy. It is not too early, however, to see some future directions for these interfaces.

Standardization Efforts. There will be increased efforts to standardize the interface. Technical Group 11 of TC32 of the European Computer Manufacturer's Association (ECMA) has produced an initial Technical Reference[8] describing the services making up an interface they call Computer-Supported Telecommunications Applications (CSTA). In the U. S., the T1 Committee of the American National Standards Institute (ANSI) is defining the official SCAI standard. Both standards organization plan to have issue standards by late 1991 or early 1992. The North American ISDN Users Forum, sponsored by the National Institute of Science and Technology (NIST), has user groups identifying ISDN applications they value. They have defined an initial call-management application profile that also has been sent to the ANSI Committee T1 to help supply user requirements for the standards work.

AT&T has submitted many ASAI concepts to the standards bodies, and currently there is strong alignment between ASAI and the developing standards in ECMA and T1. The standards, when issued, are likely to include fewer functions than those currently defined by ASAI, but they will serve as a common denominator for switch-computer applications. AT&T's plan is to continue to align ASAI with the standards as they evolve, but to offer advanced capabilities to users via the ASAI architecture until the standards catch up.

New SCAI Interactions. The initial versions of these interfaces had a strong PBX orientation. A second trend in SCAI is to allow greater interactions with network services and with Centrex. Currently, the ANSI Committee T1 is the primary forum for detailed discussions of how the applications-oriented SCAI interfaces relate to the network service creation requirements of the Intelligent Network (IN).

SCAI and IN approach the relationship between the computer and the switch in different ways. SCAI has been defined from a computer applications perspective that specifies the services an application might want to use without extensive concern for the stages of call processing required to implement a particular service. IN, on the other hand, is focused more on using the computer to aid the switch in call processing details. Clearly, the services available to the computer are influenced by the stages of call processing of the switch, so one active area of standards work will be how more formally to relate the SCAI and IN approaches.

New Interface Functionalities. A third trend will be adding new types of functionality to the interface. Areas such as security, switch administration, switch maintenance, link redundancy, performance, interworking with network management protocols, and interfaces with voice response units and other intelligent switch adjuncts, are only some of the functions that will be added to these interfaces as they mature.

Conclusion

Although it is not yet possible to predict the magnitude of the value-added applications made possible by SCAI, it is clear that these applications will be an important—if not dominant—networking trend of the

1990s and the next century. SCAI interfaces offer network providers, telecommunications equipment vendors, computer vendors, and software vendors an opportunity to cooperatively deliver new products and services in an open systems environment, providing economical benefits and growth opportunities to their customers.

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Biographies (continued)

AT&T in 1967 with a B.S. in electrical engineering from Lehigh University, Bethlehem, Pennsylvania; an M.S. in electrical engineering from Rutgers University, New Brunswick, New Jersey, and an M.S. in management from Pace University, New York. Mr. Verma is supervisor of the Systems Interoperability Group in the System Interworking Department of the Middletown, New Jersey facility. His responsibilities include AT&T cross-product and multivendor interoperability testing, and ASAI conformance testing. He joined AT&T in 1978 with a B.Eng. from the Indian Institute of Science, Bangalore, India, a doctorate in electrical engineering from Concordia University in Montreal, Quebec, Canada, and an M.B.A. from the Wharton School of the University of Pennsylvania, Philadelphia.

(Manuscript received April 9, 1991)