Application of Distributed AI and Cooperative Problem Solving to Telecommunications

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Abstract

A cursory survey of applications in the DAI literature suggests that a primary area of using DAI technology for real-world systems can be found in telecommunications. This paper explores the current state-of-the-art of DAI and cooperative problem solving in this domain. Telecommunication networks have proven in the last five years to be a fertile ground for problems involving the coordination of distributed intelligence. A wide range of problems from distributed traffic management to resolution of service interactions in intelligent networks have led to conceptual studies and prototype developments involving systems of cooperative agents. Although there are currently no fielded systems that can be said to be DAI-based, we believe these will begin to appear within the next five years. We give an overview of the full range of potential applications found in the literature and additionally consider four applications in more detail, including the authors contributions to the field.

1 Introduction

Several trends in the telecommunications industry support and even require the advent of DAI technology: the traditional boundary between telephony and data network worlds is disappearing; public and private networks become increasingly interconnected; there is a complementary evolution of wireline, wireless and cable network infrastructures; and integrated broadband multimedia networks are emerging. In this environment, AI-based systems have found their niche. DAI will provide valuable input on how to integrate and coordinate collections of pre-existing AI-based systems and how to build distributed control systems with intelligent local components designed both to cooperate and to coordinate their activities.

DAI attaches specific conditions to cooperative exchanges between intelligent systems — often qualified as agents — that go far beyond simple functional interoperability. Ideally, systems that pursue local or global goals, coordinate their actions, share knowledge and resolve conflicts during their interactions within groups of similar or dissimilar systems can be viewed as cooperative in a DAI perspective on coarse grained systems. For example, lets take two expert systems, one managing T1 facilities and associated cross-connect units and another

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managing a logical packet network built with channels from the first one. Furthermore, we assume that the two systems share only a basic ontology of network problems but not of their respective specialized problem solving. Then these systems need to cooperate in a DAI sense to recognize the common elements of their problem — say a hardware fault (physical layer) that triggered transmission errors on the packet network it supports (logical layer) — and to achieve a compromise solution that could not have been envisaged in isolation by either system.

Even the current generation of telecommunication networks have been seen as natural domains for the investigation and application of Distributed AI. Telecommunication network administrations are vast organizations dedicated to operating and managing networks with broad functional segmentations: telephone network outside plant, switching and transmission plants; public network or alternate carrier's high bandwidth metallic or optical infrastructures supporting different layers of specialized customer or service networks; etc.. These networks are organized into multiple physical and logical layers built with large quantities of repeated network elements and subnetwork structures. All these elements need to be configured, monitored, and controlled, in the future, preferably by automated operation support systems and without substantial human intervention.

Network management and operations support systems are the nexus of both small and large telecommunications administrations. These systems need to be both distributed and cooperative. Distribution is warranted by the fact that the administrations are owned by different companies, located in different countries, and possibly even based on different technologies. Furthermore, the amount of data and processing involved makes centralization of management and operation practically impossible. Centralization is also not necessary because many of the management and operations tasks can be performed locally. However, cooperation is in certain cases unavoidable because the underlying networks are interconnected and management and operations tasks may involve systems in multiple administrations. The lack of a hierarchical organization of administrations and the unavailability of suitable information in one locus obstructs localization of the execution of such tasks, hence the need for cooperation of those systems involved.

We present a survey of recent efforts in applying DAI to telecommunications including some of our specific experiences with such applications. Our preference would be to review fielded systems based on distributed cooperating agents, but the DAI community cannot, as yet, claim such success in any domain. Instead we will review some experimental testbeds and many concept development efforts. One important restriction of this review is its focus on automated agent systems. This means that other efforts in DAI and connected fields such as attempts to support workgroups of humans and machines such as, e.g., topics in computer-supported cooperative work, human-machine interaction, cognitive science foundations, and control systems for robots, cannot be considered here. Telecommunication companies are very interested in agent systems that will function as information brokers for customers in the brave new world of information services. We will not cover them here even though there are similarities, conceptually and in terms of the communication infrastructure requirements, with the systems described here, since cooperative interactions between such agents appear embryonic at this stage. Also DAI is a multi-disciplinary endeavor, involving many other fields of AI for which we will only provide brief pointers.

This paper is organized as follows. Section 2 presents a general overview of currently known cooperative systems in various stages of development as well as some speculation about

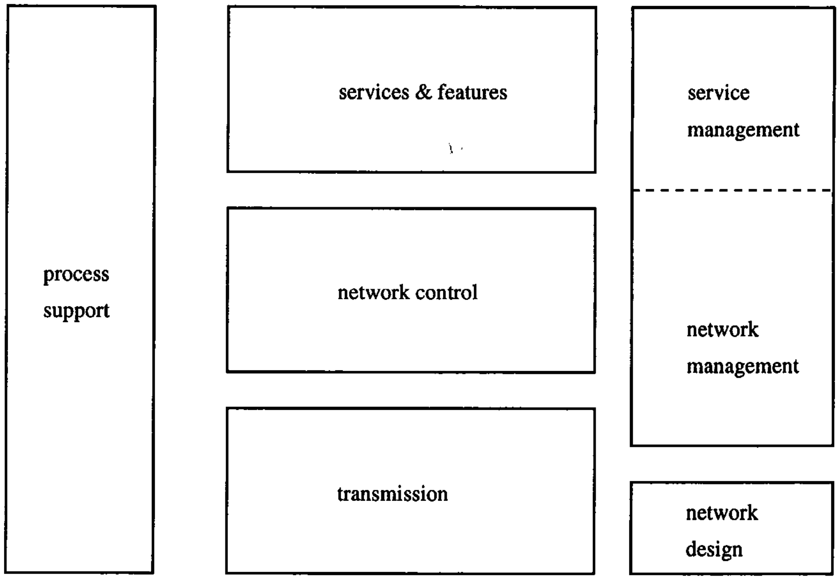

Figure 1: Subdividing the telecommunications domain.

prospective domains. Four systems are described in more detail in Section 3. They were chosen because they are the result of sustained domain analysis and justification efforts and of advanced implementation and testbed construction. In Section 4, we assess the relative success of DAI in telecommunications and speculate on perspectives for DAI applications in telecommunications for the future.

2 DAI in Telecommunications: applications and domains

This section offers a wide coverage of current references on DAI applications to telecommunications. Due to space limitations, however, we had to leave several applications out of account. The next section will consider some key applications in more depth. In order to organize our discussion, we subdivide the overall telecommunications domain into a number of subdomains (see also Figure 1). First, we recognize the following layering of telecommunications systems: the transmission layer, network control layer, and service layer. Second, there is network design, network management, and service management. And third, we distinguish process support, i.e., systems that support and automate business processes.

2.1 Characterization of distributed and cooperative features

Obvious criteria for determining whether a certain application lends itself to a DAI approach are the need for distribution (spatial, functional, temporal, etc.) and (intelligent) cooperation and coordination. Potential for distribution exists in telecommunications systems in many ways:

- along geographical or functional boundaries of administrative domains (e.g., **TEAM-CPS**— see Section 3);
- along the functional boundaries of management and operations support tasks (e.g., between fault management and performance management);
- between the physical layers or the logical layers of network organizations (e.g., between the network control and transmission layers);
- between physical network elements and logical network management layers (e.g., between respectively facility agents and customer agents in **TEAM-CPS**— see Section 3).
- between the information, knowledge, and capabilities of different entities and roles in a telecommunications system and its environment (e.g., between the service logics of different users in the Negotiating Agents approach — see Section 3).

A generalization of these opportunities for distribution will be provided by the objects and object classes in future object-oriented telecommunications architectures that can be expected given the current developments in TMN, TINA, and CASSIOPEIA.

Distribution is not the sole criterion for the appropriateness of application of DAI techniques; the need for (intelligent) cooperation or coordination is another. This restricts the full range of possible applications suggested by the above list somewhat. Obviously, systems of different administrative domains only need to cooperate when they actually share responsibilities for overlapping or at least adjacent network sections.

Coordination between systems for management or operations support is appropriate in some cases (e.g., between a fault management system and a traffic management system to reroute connections in case of failure), but not in others (e.g., between an accounting system and a planning system). Coordination between service logic of two subscribers involved in the same call is relevant to detect and resolve service interactions.

Efforts in the area of DAI and telecommunications have mainly addressed applications that support cooperation between management and operations support systems for the same task, but in different administrative domains (except for the Negotiating Agents approach to service-interaction resolution). Therefore, we will zoom in on these kind of applications in the next two sections and explain the rationale for choosing DAI techniques.

2.2 Current applications

The applications presented here have been reported in the literature and have reached various stages of development: from initial domain studies to operational trials, in one instance. We use the categories mentioned at the beginning of this section, with the exception that we lump together network control, services, and service management, because they are usually studied together.

2.2.1 Network design

AI techniques provide a way to augment the capabilities of systems for design and optimization of networks, when these networks become large and complex and the design algorithms intractable. Lirov and Melamed describe a network design system consisting of several loosely-coupled expert systems [16]. These expert systems perform different subtasks, such as designing an initial network configuration, optimizing the initial configuration, and simulating a configuration to evaluate performance. The distribution of the system facilitates the use of different and appropriate programming languages and paradigms for each of the subtasks.

Another distributed AI system for network configuration is presented in [15]. This system has a distributed blackboard architecture in which the components design separate sections of required connections and communicate with each other to arrive at an overall consistent solution. The system is distributed to coincide with the boundaries of districts of the Dutch network operator. Districts are responsible for operating their part of the network.

2.2.2 Network management

In network management we can distinguish between the traditional network management functions: configuration management, fault management, accounting management, performance management, and security management. Not all of these functions have been addressed by DAI approaches: accounting and security management are as yet unchartered grounds. In some other cases, one system combines more than one functionality, e.g., fault and performance management.

Local Area Networks (LANs) based on TCP/IP networks have been used as the subject of experiments applying DAI techniques to network fault management on a number of occasions. This is not so surprising if we consider that such networks are readily available in most research labs. Furthermore, these networks often exhibit a structure of interconnected, but somewhat independent constituent networks that make them interesting candidates for a network management organization of cooperating, but otherwise independent management systems.

We describe two systems for diagnosis and monitoring TCP/IP-based LANs in detail in Section 3: LODES and DBB. We mention here two of the most obvious distinctions between the two systems. The first distinction is that in LODES the agents are essentially copies of each other cooperating according to a peer-to-peer relationship with no central control, while in DBB the agents are hierarchically organized with a root agent in which centralized control of the whole system is placed. The second distinction is that LODES uses a communication scheme that was designed for this domain specifically, while DBB adopts a previously developed, general-purpose communication mechanism (i.e., the Contract Net Protocol). In fact, DBB contains a broad synthesis of existing DAI techniques.

In [32] a hybrid fault and configuration management application was prototyped using TEAM-CPS (ref. Section 3). It addresses application level (missile launch control, sensor fusion and asset tracking, etc.) fault tolerance for a wide area strategic defense network. The underlying network architecture is layered with application specific subnetworks, built from logical T1/T3 networks which are in turn derived from mixed leased-line common carrier and military-owned facilities. The problem here is to supplement centralized network management systems with a local capability that would be able to respond quickly and autonomously to faults in the final minutes of engagements. A distributed agent system was designed to perform dynamic network reconfiguration to maintain the integrity of logical application subnetworks in the face of physical network failures. In the concept prototype developed for this application, homogeneous TEAM-CPS agents control logical and physical network resources on a regional basis. Each agent is responsible to maintain the capacity assignment levels for application specific subnets that may have logical circuits terminating on locations outside their regional boundaries that are also built from facilities provided by other agents. Therein lies the interdependencies that require coordination. Problem solving and coordination approaches are satisficing heuristics similar to those reported in the TEAM-CPS application covered in Section 3. This application illustrates many features and requirements of telecommunication applications in general: functional layering, locality of information and control requirements, limited requirement for autonomous action constrained by a centralized network management environment, regional partitioning and resource dependencies across those partitions as well as the usual distributed and parallel processing requirements.

Circuit-switched network traffic control with cooperative agents was explored with two experimental testbeds: the Integrated Learning System (ILS) [19] and an early blackboard system approach [1]. Both efforts involve the same problem domain but address different aspects of it using very different approaches. The underlying problems fall in both fault and performance management categories: traffic monitoring and control acts to overcome trunk and circuit switch faults as well as congestion due to "abnormal" voice traffic patterns.

The latter effort was one of the earliest attempts to apply DAI to a "real world" telecommunication problem and was shaped in many of its aspects from knowledge engineering with domain experts in telephone traffic management. A regional partitioning scheme was assumed giving traffic management information and control over facilities status, traffic patterns, manual traffic controls at the switches for specific geographical areas. In turn each of these areas is managed by an agent assuming monitoring, computing and coordination tasks with other identical agents. The focus of the concept prototype was to explore blackboard problem solving architectures, plan-based coordination mechanisms and conflict resolution approaches.

Subsequently ILS was built for the same problem with a focus on learning of traffic control policies. Distribution in ILS does not follow geographical or regional lines but arises out of problem solving requirements. The complexity of learning in the traffic management domain is handled with a system of cooperative learning agents where each agent embodies a different learning algorithm and where learning performance is to some extent a function of collaborative efforts among the agents. In this domain, traffic overloads due to certain holidays, for example, or traffic congestion due to switch or trunk group failures, is handled by distributing throughout the network switch commands to alter trunk status, to reroute traffic, and to discard or change parameters. While regionally distributed agents in [1] compute such strategies by combining computed local plans that are coherent at their boundaries, ILS learns and improves its ability to develop such plans or traffic control strategies globally. ILS uses a central coordinator that gets advice from five learning agents [19]. It selects the best expected strategy and feeds this back to the agents who also critique each other's strategies. The learning algorithms in ILS are constructed to use each others inputs to learn better control strategies.

The Multistage Negotiation protocol developed by Conry et al. has been illustrated by application to the task of restoring transmission paths in telecommunications networks [4]. In the application, a telecommunications network is subdivided into segments. Each of these segments has assigned to it an agent that monitors and controls that subregion. If circuits (point-to-point connections) between nodes in the telecommunications network are broken, it becomes the task of these agents to restore circuits using alternative routes through the network. A route consists of links between nodes in the telecommunications network. Links are non-reusable resources. Circuits may span several segments controlled by different agents. An agent usually does not have information about which links in other segments are currently used. Also, an agent can only assign links in its own segment to be included in a circuit.

When a broken circuit is observed by an agent, that agent will construct a number of alternative plans that might be used to restore the connection. These alternative plans form a hierarchy with global plans for achieving the overall goal of restoring the circuit and partial plans for achieving subgoals in those global plans. Initially, an agent knows neither whether the resources in other segments necessary for restoration are available, nor whether there might be additional circuits that need to be restored. Thus, the plans generated by one agent are *local* plans. Cooperation is needed to find a global plan (a coherent collection of local plans) that restores as many circuits as possible.

2.2.3 Transmission layer

There exist several studies in DAI into dynamic resource allocation (starting with the Contract Net Protocol [5]). One particular such application has been studied also in the telecommunications domain. Ishida et al. applied multi-agent techniques to channel allocation in ATM networks [14, 18]. Asynchronous Transfer Mode (ATM) switching equipment will play a crucial role in integrated broadband communication networks. In this approach an agent is assigned to each traffic source. The task of an agent is to select a channel for transportation of data from the source to its destination for each new call from that source. The agents use channel utilization values that are locally known or estimated. Although the local processing in this distributed channel allocation scheme is quite simple, the approach has proven to achieve globally efficient channel allocation, even when network utilization is highly bursty.

2.2.4 Network control, services and service management

Operational routing and congestion control is usually associated with the lower working levels of current networks and consequently embedded into the protocols. [7, 6] outline early multi-agent concepts in those areas. The underlying assumption is that overhead and complexity of an agent-based approach may be offset by the increased dynamic bandwidth management capabilities. They consider routing models in packet data networks. In this context agents manage local or regional routing tables, ideas of organization structuring are invoked, and insure overall coherence of network routing given incomplete or incorrect routing information. As a general observation, there are many levels of routing problems, all posing different requirements for cooperative problem solving approaches. [32], for example, also involves routing, but, in contrast to this work its physical routing or combination of different facilities for end-to-end physical connectivity.

Moving up to service layers of the network but not quite yet to the IN (see below), we consider the problem of mediating between public network provisioning systems and integrated private network management systems [29, 30, 26, 31]. In contrast to the treatment of routing described above the focus here is on reconciling the perspectives of different problem solvers involved, on the one hand, in designing logical circuits, i.e. "routing" facilities, and, on the other hand, assembling these logical circuits to build switched connections. This is the subject of a detailed case study in Section 3.

The Intelligent Network (IN) is an architectural concept that aims to facilitate the rapid development and deployment of new telecommunications services. The IN architecture provides a network control layer on top of a telecommunications network. It defines how the basic call process supported by the network can be changed or augmented and provides functional building blocks to create and assemble new services and service features. We mention DAI applications in the area of network control, services, and service management, each of which are based on the IN concept.

Griffeth and Velthuijsen have applied negotiation between agents to resolve conflicts between the preferences of users involved in a telecommunications session. A user can subscribe to service features to change the way his or her calls are handled and thus to implement the user's preferences. This contribution arose as an attempt to address feature interactions. The approach is described in more detail in Section 3.

2.2.5 Process support

Many large businesses have complex workflows, i.e., processes that consist of many activities involving the use of possibly heterogeneous information systems. Telecommunications companies are no exception. Workflow management is aimed at supporting or automating workflows. We will not review here application of DAI to workflow management in general. However, we do mention one effort in this area that is applied to a workflow that is particular to telecommunications companies.

Huhns and Singh study the application of a multi-agent architecture to automating and supporting workflows in business environments. In particular, they describe application of their approach to provisioning digital services [13]. In this domain, the object is to establish a communication link between two specified points. The workflow is initiated when a set of forms is received describing the service that is requested. The process requires coordination among many operation-support systems and network elements (48 interactions with 16 different database systems in the described example).

2.3 Other potential application domains

In all the systems and ideas described above, engineers and researchers used DAI to solve or at least think about a telecommunication problem. Here we use some of our experience to hint at some additional telecommunication domains with applications which may benefit from DAI.

Operation support systems (OSS). The major tools telephone companies use to run their business are transaction management, distributed database systems and operation support systems for network and customer management. All these systems can be viewed and potentially reengineered as workflow systems, as described in [13]. Provisioning, planning, trouble ticket management, maintenance/repair dispatching, customer network management, are all functions where distribution and cooperation could, in some cases, benefit from either autonomous, in futuristic models, or organizational assistant-like agent subsystems.

LEC/IXC interactions. OSSs may cross company boundaries. As an example, in the US deregulated telecommunication market, LECs (Local Exchange Carriers), e.g., GTE, and IXCs (Inter-Exchange carriers), e.g., AT&T, have a strong customer/supplier relationship with each other which is reflected in tightly coupled business processes, manual systems and OSSs. As an application for DAI this would bear some resemblance to the TEAM-CPS customer network management application described in Section 3, where GTE, for example, would be a supplier of local access and special service circuits to the customer, here AT&T. The complexity of such IXC/LEC arrangements spans across multiple companies and is nationwide since AT&T may order point-to-point circuits for, say a corporate data network customer, that involves multiple LECs at the circuit end points. The corresponding interaction between OSSs in circuit provisioning and billing is like in customer network management characterized by requirements for local expertise, by local information that is private and solutions to problems that must be reached incrementally through negotiation-like processes.

Manager-Of-Manager applications. Manager-Of-Manager (MOM) systems have been a recurrent topic in the world of data network management. The typical internal corporate network in most telecommunication administration is an overlay data network on top of a customer-owned T1 network. Both logical data layers and physical T1 layers are supplied by vendor-specific network management platforms. Among the packet switches, the bridges and routers, the T1 cross-connect systems may be legacy systems from different vendors. A market for system integrators, e.g., NYNEX Allink, to coordinate the functionality of vendor specific element managers has emerged. These are referred to as MOM. For their functionality to grow beyond centralized reporting and towards real distributed systems management, forms of hierarchical agent-based cooperation need to evolve. As in human hierarchies, there needs to be evolution of authority and bidirectional control and data flow up and down the hierarchy. In this context hierarchical systems can be viewed as essentially cooperative organizations of intelligent agents.

3 Specific case-studies of four systems

Having looked at a broad set of telecommunication domains and some of the DAI approaches to those domains, we turn to a more in depth view of four DAI applications and their domains. Their significance lies in the range of DAI techniques used, the underlying domain analysis, and the extent of experimentation work.

3.1 Feature interaction and the Negotiating Agent approach

The Negotiating Agents approach was developed to detect and resolve certain kinds of feature interactions that occur in telecommunications systems [12, 9, 27]. Features in a telecommunications system provide packages of added functionality to basic communications services. Examples of features are Call-Forwarding and Caller-ID (display of the number of the caller at the phone of the callee). Interactions may occur between features when the operation of one feature influences the operations of another feature or another instance of the same feature. Sometimes such influences are intended (e.g., Caller-Number-Delivery-Blocking inhibits intentionally the operation of Caller-ID), but at other times these influences can be unexpected

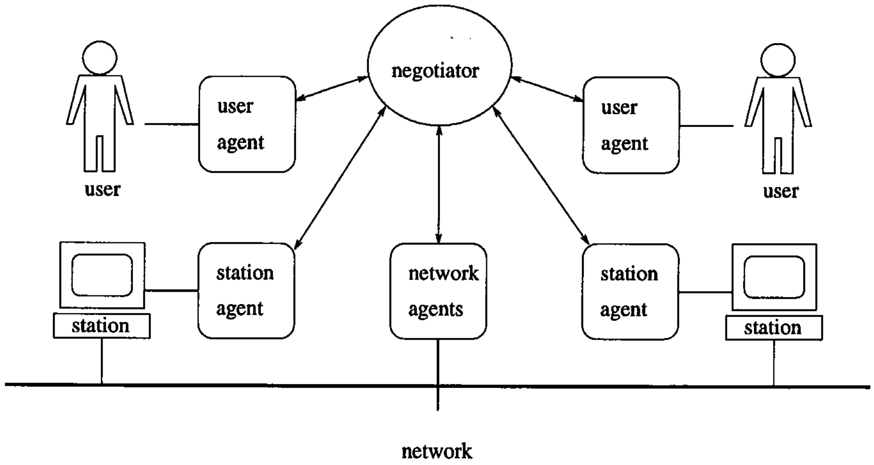

Figure 2: The logical structure of a negotiating system for telecommunications.

and undesired. Then feature interactions become a feature-interaction problem.

Features are a way for subscribers to tailor their use of telecommunications services to their specific needs and intentions. However, different parties to a call may have different needs and intentions which leads to conflicts between the intentions and, analogously, to interactions between the corresponding features.

The Negotiating Agents approach recognizes that a significant subset of feature interactions are the result of conflicting intentions of different subscribers, who are not necessarily party to the same call. These conflicts may arise over which medium and protocol to use for a call, over the use of shared resources such as terminals and bridges, over what information can be transmitted as part of a call, etc..

Negotiation provides a means to resolve conflicts. In order to resolve conflicts in telecommunications systems automatically, and thus resolve certain feature interactions at runtime, the Negotiating Agents approach uses an agent for every entity that may have an interest in how calls are set up and conducted in a telecommunications system, such as users, network providers, information providers, etc.. An agent is given information about the intentions of its owning entity and communicates with other agents via a negotiator to detect conflicts and to negotiate for resolutions of detected conflicts. The organizational structure is shown in Figure 2.

The Negotiating Agents approach builds on the experience with negotiation mechanisms found in the DAI literature, but extends mechanisms to meet the requirements of the particular domain [10, 11].

These requirements are basically two-fold: reticence of agents and a varying proposal space. Reticence stems from the observation that the available room for negotiation is usually private information and that subscribers may often be reluctant to make their feature profile public (e.g., the numbers on a screening list are often restricted information). Variance of the proposal space indicates that negotiation to resolve feature interactions will not necessarily involve an a priori known limited set of attributes, but may extend to include other attributes as they become relevant during the negotiation process (e.g., a counter proposal to set up a call may include in the original proposal an additional attribute describing the delivery of a number).

The following benefits were derived from a DAI approach to the problem:

distribution: The Negotiating Agents approach allows the distributed, local specification of user's intentions so that it becomes easier for users to tailor their use of communication facilities.

negotiation: The negotiation mechanism were derived from DAI insights in how to automate negotiation processes.

privacy: Encapsulating users' intentions in agents and the use of a reticent negotiation mechanism allow users to keep some of their preferences private.

The Negotiating Agents approach has been implemented and tested on top of the Touring Machine multimedia desktop conferencing research prototype^{TM}[2].

3.2 Customer Network Control and TEAM-CPS

TEAM-CPS (Testbed Environment for Autonomous Multiagent Cooperative Problem Solving) [29, 30, 26, 31] evolved from a number of communication domains requiring distributed problem solving among geographically and functionally distributed problem solvers performing interdependent planning tasks. As previously described, a number of domains were explored but TEAM-CPS proved most successful as a testbed for customer network management.

Customer networks are integrated voice/data networks where switching and transmission facilities are a mix of public-network provided leased and customer-owned facilities. Lets simplify and assume that the customer network is comprised of a voice/data PBX network with leased T1 links from the public network. From a transmission standpoint the customer network is a logical network, i.e., end-to-end pipes of bandwidth are provided so that CPS equipment can generate traffic or usage of those pipes. These are really complex assemblies of physical facilities (metallic T1, SONET-derived T1, cross-connect systems, etc.) constructed by the public network or alternate provider. An integrated customer network management system would manage CPE equipment, traffic and configuration of the leased line network through the PBXs and ancillary NM platforms. The latter is an activity that is in the early stages of automation, i.e., mostly a terminal-login-to-remote-host environment and requires people cooperation skills. Such skills become relevant when fault problems escalate to the levels of people who need to negotiate contingency plans in a resource constrained environment. In all the other cases we already have intelligent systems, i.e., expert systems that sometimes perform autonomous control functions, without humans in the loop.

In order to deliver the next generation customer network control services it therefore becomes imperative to anticipate the requisite delivery architecture in the public network. A distributed cooperative agent based architecture for customer network control was developed. Initially, facility provisioning in the public network is assigned to a computer system with the ability to satisfy real-time demand for circuit addition and deletion requests from multiple

^{TM}Touring Machine is a registered trademark of Bellcore.

customer network systems. This is the physical network layer to the logical customer network layer. The operational capabilities of such a system are based on the functions performed by the people and computer systems delivering services such as GTE's ControLink Digital Channel Service and the operation support systems managing customer trouble reporting and fault management. In addition the agentness of the system specifies a number of areas where negotiated solutions to specific problems, e.g., facility failures, can be arrived at without human intervention, by interfacing with specific local customer network management systems as well as potentially with other agent based systems in the public network, such as traffic managers. Customer network management systems, on the other hand, are required to accept requests for tradeoffs, to handle alternate network configurations and to compute specific local alternatives.

The key requirements satisfied by a DAI approach to this problem and domain are:

distribution & heterogeneity: The problem solvers are by necessity distinct and heterogeneous; each manages its own perceived infrastructure, which are functionally separated and involve private data and proprietary operations on services, traffic and usage.

intelligence: Local problem solving required is in both cases complex, knowledge intensive, and integrates lots of information.

performance: Folding public network provisioning into customer network management failure recovery and demand-based dynamic reconfiguration provides a faster, more broadly-scoped integrated solution with fundamental reduction of people communication bottlenecks.

TEAM-CPS evolved as a framework for building cooperative agents that are heterogeneous at the domain problem solving level but for which common agent control abstractions can be applied to coordinate their problem solving behavior. Figure 3 outlines the domain and the structure of TEAM-CPS agents. Customer and public network agents share agent control and problem solving mechanisms but can be endowed with different domain models, represented as PRODIGY domain theories, for planning and problem solving as well as different control policies, represented as rules in agent programs as described below. The TEAM-CPS framework integrates Agent-Oriented Programming (AOP) [20, 21] and classical AI planning (PRODIGY, [17]) as the "head" and "body" respectively of problem solving agents (to use the terminology from [7]).

TEAM-CPS enabled rapid-prototyping of robust software agents with the requisite flexibility to interface to most operation support systems involved and the potential of real-time compute speeds. In spite of this there lacked a technical and organizational infrastructure to support autonomous agent-based customer network management. A more advanced implementation of a simpler homogeneous TEAM-CPS agent system is described in [32] and was referred to in Section 2.

3.3 "Distributed Big Brother": Campus Network Management

"Big Brother" is a centralized LAN manager operational at the University of Michigan's Computer Aided Engineering Network (CAEN). "Distributed Big Brother" (DBB), on the

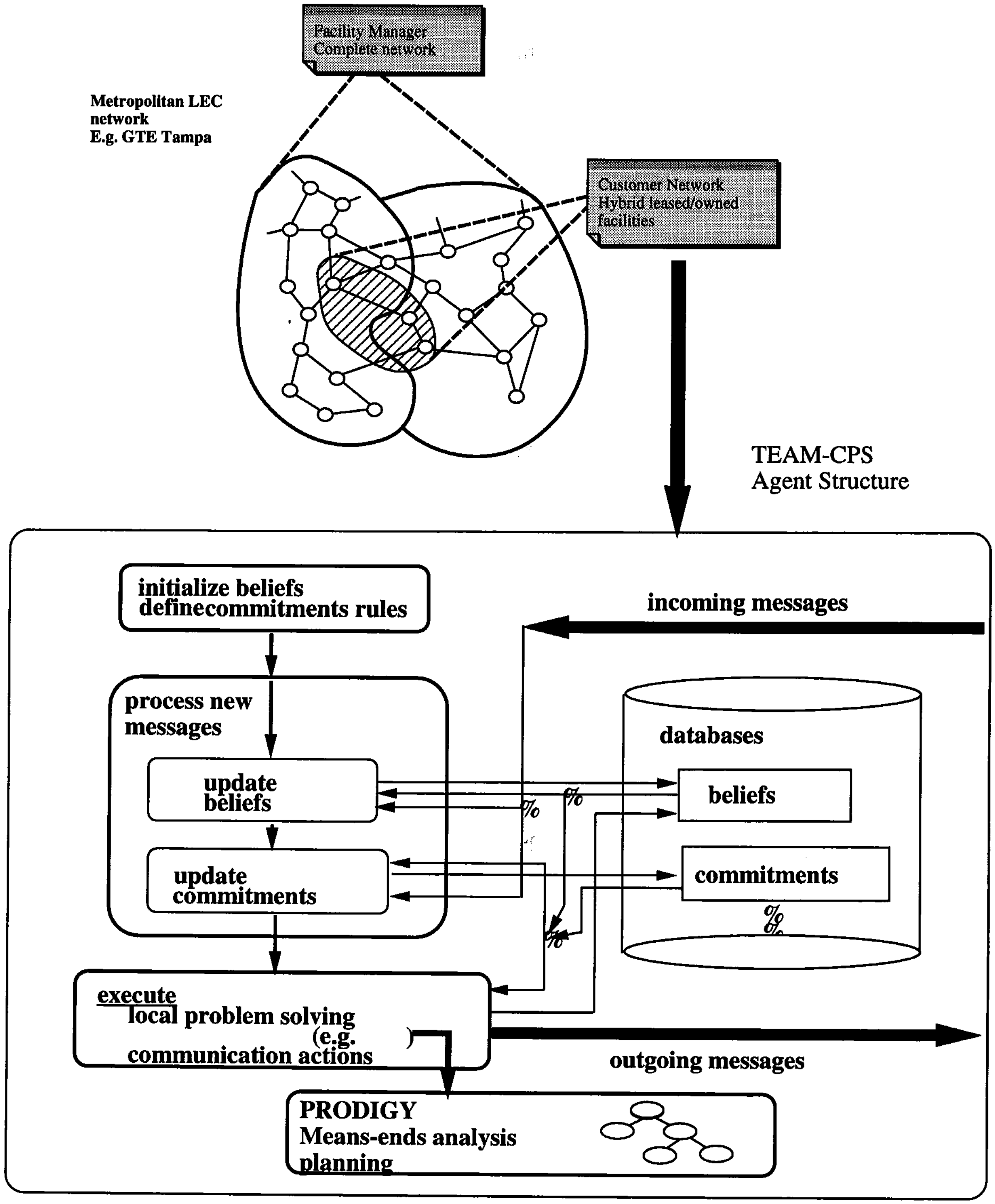

Figure 3: TEAM-CPS agent structure.

other hand, is a research testbed built at CAEN to investigate higher performance and more robust LAN management techniques using a combination of a number of DAI techniques seen appropriate to the task.

The specific domain under consideration is management of campus level LAN interconnect systems, i.e., multiple LANs connected with bridges, routers, gateways, etc., (less than 10 mile span) without intervening WAN. The target functionality is system support, specifically for fault management [22, 23].

The operational requirements for DBB include: maintaining a centralized view of network fault management, improving the robustness and increasing the performance and parallelism of network management processing. Individual LAN segments and local subnets are loosely-coupled in this domain but interdependent inasmuch as they share components, e.g., multiport bridges, and that decisions regarding these components have impact across subnet boundaries. In DBB, those are the entities across which distribution takes place.

The rationale for a DAI approach is to manage a distributed set of homogeneous LAN managers as a dynamically self-reconfigurable organization driven by fault conditions in the campus LAN network. This organization is hierarchical because centralized control remains embodied in a root management agent in the network but operates under a delegation of authority scheme to manage distributed manager agents. The intelligence of cooperative agents is thus geared towards maintaining this organization, organization structuring and hierarchical control, and performing load management of which agents manages what entities in the network, contracting and voting to distribute roles. From a domain viewpoint, this approach shares many features with the concept of a MOM system as discussed in Section 2. However, while in DBB we have a collection of essentially homogeneous problem solvers with specialization along organizational roles, functional heterogeneity of the element management subsystems is a defining characteristic of MOM systems, again as described in Section 2.

As in TEAM-CPS, DBB agents are fairly large and complex entities loosely-coupled in their activities. No single DBB agent, regardless of organizational role or position in the hierarchy, can be a single point of failure. The DAI techniques used in DBB represent a broad and original synthesis of work done with similar types of agent systems. The problem solving domain of these agents is essentially how to coordinate actions tied to the construction and life-cycle dynamics of the organization itself when confronted with domain conditions that triggers changes in responsibilities. DBB uses the classic Contract Net Protocol [5] to announce, bid and award roles and tasks. Hierarchical control is applied within the context of election procedures with simple rules to designate agents that officiate election to network management roles.

The organizational structure of DBB is defined by a set of roles which entail specific organization problem solving. Every agent is implemented with the capability to assume any of these roles and to assume many roles, in turn, as dictated by network and "social" conditions. The proper member roles are:

Chairman: A temporary role assumed, through a default rule, by an agent that will manage elections for a LAN manager.

Group manager: Contracted by the LAN managers to perform information gathering tasks in a subnet.

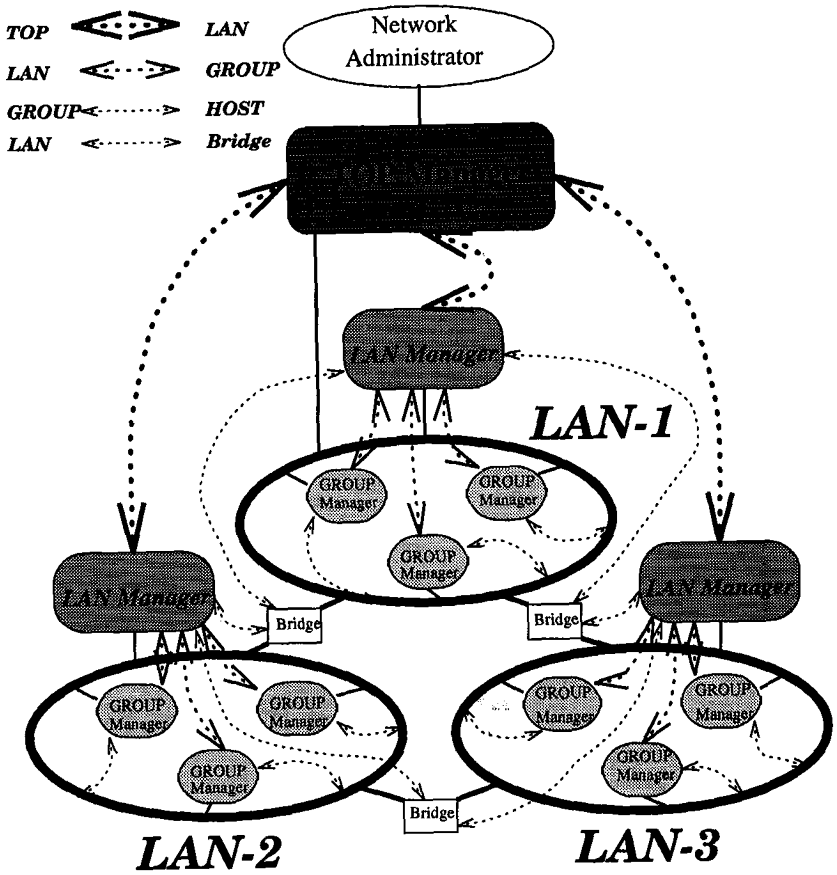

Figure 4: Overall DBB environment. (Reprinted with permission by So and Durfee.)

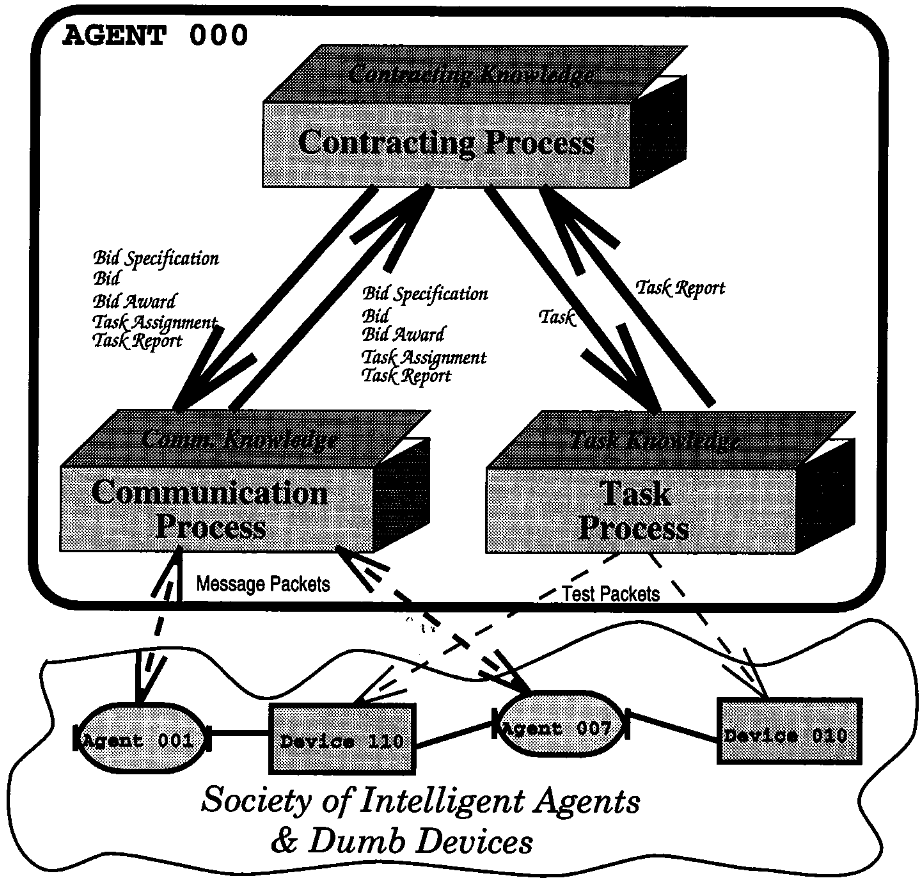

Figure 5: DBB agent architecture. (Reprinted with permission by So and Durfee.)

LAN manager: Overall responsibility for subnet and interface device, e.g., routers, management; subnet task requirement expert.

Top manager: Contracts the LAN managers to maintain a global view of the network.

Maintaining an organization entails initiating one, handling new arrivals, forming and reforming the hierarchy, etc.. The overall DBB environment and agent roles is described in Figure 4.

Agents are structured as interacting communication, contracting, and task processes. They use control problem solving and domain problem solving message types. The DBB agent architecture is shown in Figure 5.

DBB agents are homogeneous and are implemented as UNIX processes in their host workstation. An internal rule base specializes agent behavior based on dynamically assigned roles. Inter-agent communication occurs "in-band" using UDP over the TCP/IP LANs managed by DBB.

DBB is one of the very few DAI-based systems to be built and tested in an operational environment. [22] describes some early experiments in comparing DBB behavior with its centralized

"Big Brother" counterpart on a subset of the CAEN network: two LANs, 117 and 64 hosts respectively; DBB configured with 2 LAN managers and 1 to 4 Group managers. Current capabilities allow DBB to get up/down status, local loads and configuration parameters to build a global view of the network. The distributed approach did yield the expected benefits of parallelism through increased recency of gathered global information and greater scaling potential. hierarchical communication created overhead but bandwidth usage was more local than in the centralized case.

Although not currently addressed in DBB, issues of flexible organizational design and issues relating to mechanisms for cooperative distributed diagnosis and fault resolution are raised by its structure. Those are crucial for the success of future applied DAI systems.

3.4 LODES: Distributed TCP/IP Fault Management

The LODES system (Large-Internetwork Observation and Diagnostic Expert System) is an expert system for detecting and diagnosing problems in a segment of a local area network [25, 24]. Different LODES system copies can monitor and manage different network segments. LODES is designed in such a way that copies of the system can cooperate with each other. Thus, copies of LODES systems are made into the agents of a multi-agent system. Cooperation is necessary when it is not clear in which segment the cause of a problem is located, when a problem occurs in a part of the network monitored by more than one LODES agent, or when one agent needs additional information from another agent to perform its own tasks.

LODES is developed for TCP/IP local area networks (LANs) that consist of several constituent networks connected through routers. Each constituent network has its own LODES diagnostic system. Figure 6 shows an example of the organization of such LANs. Since TCP/IP has been implemented in various kinds of computers, a network organization based on this protocol leads to the development of heterogeneous networks. A common protocol also enables interconnection of pre-existing networks.

The problems in such networks that LODES systems typically address are problems with making a connection between computers on the network. Such problems could arise due to unintentional disconnections, slow transmission, and network congestion.

Finding the cause of these problems can be hard because of a number of reasons. Different causes may have the same symptoms and sometimes problems arise that don't have observable symptoms. An expert system approach was taken to overcome these difficulties in the diagnostic task.

A distributed approach was chosen over a centralized approach because of the following reasons:

distribution & heterogeneity: A distributed approach can exploit the natural physical and functional distribution of networks. Distribution can help to break down the complexity of managing a whole network. It can also provide a means to integrate pre-existing constituent networks.

privacy: A distributed approach enables local problem solving, facilitating the communication of only the *results* of analysis rather than *all* the information necessary for diagnosis, thus keeping sensitive data (such as passwords) local.

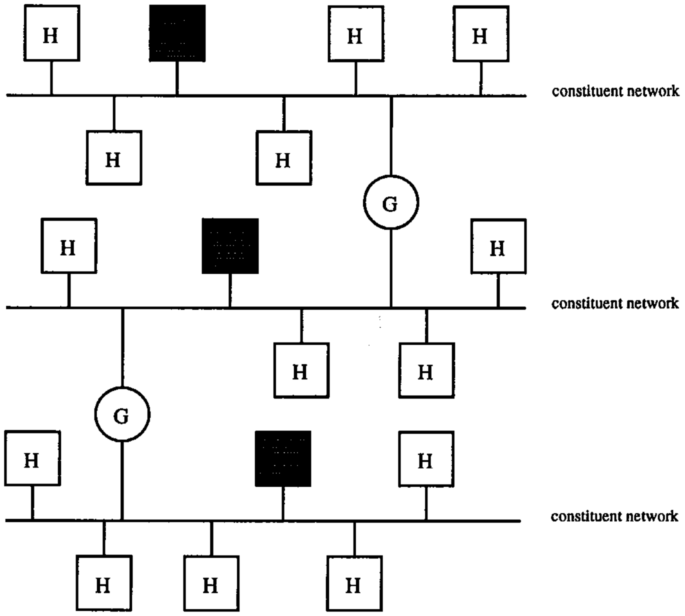

Figure 6: LAN with LODES diagnostic expert systems. **G** is an IP router; **H** is a host; and **E** is a LODES system.

performance: Distribution can be used to diminish the amount of problem-solving data that is exchanged between segments because most of the data can be processed locally.

The DAI aspects of LODES systems concern mainly the mechanisms for cooperation and communication. An error occurring in one place in the network can typically cause errors in other places and segments as well. It is sometimes hard to pinpoint the root of observed errors in a single segment, which explains why multiple LODES agents may be involved in a single diagnosis task.

Among LODES agents, three different categories of communications are recognized. The first is for setting up and initializing communication for diagnostic cooperation. This involves exchanging information to make known to each agent the configuration of the network and the LODES agents. Moreover, this category of communications is used for verifying that a communication path exists between agents that need to cooperate. The second category is for sending and requesting information and results between different agents. The third category is for controlling diagnostic activities in remote LODES agents. Once a communication path between LODES agents that need to cooperate is secured, the cooperative diagnostic process may begin.

The LODES system was primarily developed as a research testbed. However, the system has been tried on real networks with some success.

4 DAI and telecommunications, where do we stand?

Although most industrial activity in applying DAI technology to real-world domains has been seen in the area of telecommunications, there are no currently fielded DAI systems in public or private telecommunications. All known DAI-based applications in this area have been deployed in research testbeds.

The modernization of public networks is a slow, evolutionary process, because backward compatibility must be maintained in an environment of increasing reliability and availability requirements. Thus, the internalization of new technology often takes much longer than in other application domains. Because of this, it will probably take several years before the introduction of DAI techniques into the public network will be even considered: other, more conventional technologies will be applied first. In this section we will reflect on how the penetration of mainstream expert systems in such conventional arenas may be a precursor to distributed cooperative systems.

There is another point to note about mainstream applications. When we consider the role of DAI in key areas of telecommunication, we must also recognize that centralization may, depending on the application, be the best direction. Modernization of network management in public and private networks, for example, today means geographic centralization as far as monitoring and configuration goes. The potential for costs benefits through personnel reduction is very large when regional surveillance centers are consolidated into national centers. We see this trend at work in our own GTE experience, for example, where switch alarm, traffic, SS7 and SONET management are being consolidated into a national Network Operations Center. Pacific Bell [3] with its new Network Services Surveillance Center is also a documented example of this trend.

Problems with DAI approaches. Earlier we have noted several reasons why DAI systems are only slowly penetrating mainstream telecommunications earlier in this chapter. Having set the context above, we note that:

- One reason is the absence of adequate infrastructure autonomous agent-based control in present day communication systems.
- Public networks are systems with high reliability and availability requirements. Thus, public network operators are understandably cautious with the introduction of new technology into their day-to-day operations. While AI may be considered to have come of age to sufficient extent to break this barrier of caution, DAI adds distribution to the complexity of AI and may thus seen as even higher risk.
- The technology is still emerging and is only beginning to provide a solid foundation, principled practices and engineering methodologies required to produce maintream applications.

Our four examples of Section 4 illustrate some of these forces at work. As mentioned before, these are among the best current examples of telecommunication application driven DAI testbeds.

Feature Interaction: Although very sound in concept and experimental practice, the negotiating agents approach faces a number of hurdles as a fieldable system. How should it evolve? There are two possible views. i) As an abstract model of feature interaction mechanisms in the IN with a testbed that can emulate the functionality of IN systems. In this perspective it is an analysis tool rather than an implementation vehicle. ii) As an implementation vehicle for IN or future service platforms as a whole which must now create an infrastructure or "homes" for agents to get bound to communicating customers and resolve their feature conflicts. As such it becomes a major structuring element of the service platform. The question is then: are feature interactions a dominant element of such platforms and do they warrant a negotiating agent architecture instead of lower level algorithmic and procedural handlers? So far mainstream IN developments have not considered distributed problem solving as an essential component in their organization focusing instead on the service access, delivery mechanisms and information handling platforms. We thus see elements of infrastructure and risk that militate against an obvious DAI-based approach. Moreover we must not discount the technology related risks: the potential magnitude of a multi-agent approach does indeed stretch the practical boundaries of agent models for large, high performance systems.

TEAM-CPS: The customer network control domain appears to be a natural fit for heterogeneous interagent cooperation. The impetus for hybrid customer networks and coordinated public/private network management is reaffirmed constantly in the trade literature (e.g. ref. same issue as [3]). However the primary requirements of a fielded and productized multi-agent approach to customer network control are intelligent and autonomous operation support systems. Integrated network management systems for private networks and facilities management systems are still in early stages of automation. Geographically centralized monitoring, fault, performance and configuration management by reduced staffs of network operators and uniform handling of heterogeneous multi-vendor equipment is still the primary objective in this domain. In the public network, customer network control is still offered as a first generation product with terminal access to procedural workflow systems and operations support capabilities. Neither at the macro level, e.g., leasing/shedding of circuits, nor at the micro level, e.g., automatic synchronization of CSU/DSU parameters, are autonomous cooperative agent solutions considered in product offerings. Intelligence and autonomous local control is thus only slowly penetrating practical customer and public network operation support systems. As before, infrastructure is only one factor. Interactions have been shown to be very complex and difficult to automate. Heterogeneous multiagent coordination theory and practice needs to progress much further to allow practical systems to be built.

LODES: The LODES system has been applied in the setting of a laboratory LAN infrastructure. As such, the basic principles of cooperative fault detection, localization, and diagnosis between systems responsible for their own local segments of the network. The solutions to communication and coordination appear specific to the network and problems at hand and will thus be hard to generalize in light of new network elements and new network management tasks. Although fault management is a large and essential part of the duties of network management, integrated support for the operation, administration, and management of networks are in order. It signifies quite another step towards maturity of the technology if the lessons learned in an experiment such as LODES are used in more comprehensive support environments. Especially when such an environment is applied in an environment less tolerant to functional and operational shortcomings than a typical laboratory infrastructure.

DBB: Among the four systems, DBB is, in spite of its small scale experimental nature, the most advanced in many respects: pragmatic structure, operational environment and comparative performance with centralized counterpart. DBB competes in an established infrastructure for centralized TCP/IP network management. Its goal is to maintain the centralized perspective from a monitoring viewpoint introducing superior performance and reliability from the control and information gathering viewpoints. Even if preliminary results support some the benefits of DBB over BB, how can DBB evolve and become, say a standard for TCP/IP network management? DBB was created to answer questions in DAI pragmatics in general and organization structuring in particular. Here we see that the technological hurdle appears to be the most important factor. Answers to those questions and to all the engineering issues raised by the full complexity of TCP/IP network management in practice are not yet at hand.

The basic approach in all four examples was to consider a problem for which a cooperative agent solution appears to be the best approach and where there is no "legacy" system to integrate. Such an approach is suitable for proof-of-concept experimentation and allows a cooperative solution to be built from the ground up. However it is not conducive to fielded systems for all the reasons described above. We believe that DAI-based systems will appear along a different path.

Actually, the penetration of expert systems may offer a good predictor for the emergence of DAI-based applications. Good opportunities for the success of DAI in telecommunications will be in network management and operations support for public and private networks and in areas that are experiencing less flux or less constraints. Expert systems are slowly penetrating those areas. Our thesis is that they will provide the intelligent systems infrastructure and potentially the agents of future cooperative systems. Of course, many different AI and reasoning paradigms, not just rule-based reasoning, will provide the intelligence substrate for those mainstream expert systems. In this perspective, we consider the emergence of communication and knowledge sharing between these systems as requiring a DAI technology base that goes beyond basic coordination among rule-based inference engines and their knowledge bases.

Using DAI: an example [8] provides recent information on expert system deployment in various telecommunication domains. These domains cover a broad range, from network service support to remote testing. It is not yet possible to see applications that are closely related in function such as, for example, in the customer network control domain a facility manager and a customer network advisor, that would be intelligent and naturally benefit from cooperative automation. There is one application however that is showing some promise, not along the lines of functional but along those of geographic distribution. We will use this example as a model for the rest of this discussion on the potentials for emergence of DAI-based applications.

SSCFI (Special Service Circuit Fault Isolation) [8] is an expert system that is currently being deployed in all the GTE Telephone companies in the US. It function as an expert test technician that reads and interpret trouble reports on special service circuits, decides to conduct tests and interpret the results of those tests using in the process a number of remote test and database systems, and finally routes the report to the appropriate repair group with the results of its analysis. The first important feature of SSCFI for this discussion is its autonomy.

SSCFI processes operate in the background and has full control over the trouble report queues to which they are initially assigned. Only a minimal administrative interface is provided for administrators to start/stop and monitor SSCFIs. SSCFIs are in a sense our model of practical, narrow, but intelligent autonomous systems performing their tasks without direct human operational control. These tasks are not to present information to people but to act within the context of a workflow system where field repair crews are at the receiving end.

The current evolution of SSCFI is pointing towards some form of homogeneous multi-agent task allocation system involving SSCFIs throughout the GTE regions. SSCFIs need fast local access to all the OSS, database resources, test systems and test points involved in testing circuits. To maximize throughput these resources are locally available on their LANs. SSCFIs can do simple load balancing by spawning children processes subjected to computing resources and locally sharing test load. DAI begins to come into the picture as load sharing at a national level between all SSCFIs is being considered to exploit time zone differences and sharing of computing resources across regions. Some ideas under discussion are to use contracting schemes to request other SSCFIs to accept responsibility of testing circuits along with remote control of the resources required to perform those tests and to negotiate the conditions under which this is done. As with DBB, administration would be handled centrally by a "team supervisor" that would create the SSCFI teams, launch them, monitor them and only operate on them at a strategic level. Even current SSCFIs respond to administrator commands in delayed fashion and only when current testing load is completed. This example illustrates a possible if not likely future evolution of an existing intelligent operations system involving a "retrofit" of cooperative problem solving capabilities.

The above discussion on SSCFI evolution was meant to illustrate our thesis. We believe that naturally distributed systems with strong locality requirements, i.e., need to be close to resources used or operated upon, operating under autonomous control regimes (i.e., with the intelligence to do so) will be the first to require DAI-based approaches. Clearly, our four examples also share, albeit in less immediate fashion, these characteristics and are important candidates for the future.

5 Conclusion

In this paper, we discussed many different kinds of applications of DAI technology to telecommunications. These applications are in various stages of conceptualization and development but clearly the scope of domain specific knowledge engineering taking place shows rapidly growing maturity of this relationship. This makes telecommunications presently one of the most promising application areas for DAI. Even though there are no currently fielded systems, we believe that the potential is there for this to happen within the next five years. This is based on both the particular suitability of telecommunications systems for supporting DAI techniques and the benefits that DAI techniques can bring to issues that are open problems in the telecommunications domain. We review these two observations below.

Telecommunications systems have been seen as natural domains for studying application of DAI techniques because they are large, complex, and distributed. Segmentation occurs in telecommunications systems along several different lines: between network elements, operations support functionalities, organizational roles and responsibilities, administrative domains, physical and conceptual layers of network organizations, and user-specific interests, to name a few. The size and complexity of telecommunications systems solicit exploitation of these distribution opportunities to promote manageability. But although segmentation opportunities are plentiful, hardly any of them can be exploited to the full and coordination and cooperation remain necessary because of interconnectivity. Facilities for communication are a given in telecommunications systems, but using these for coordination an cooperation forms a challenge that is the very object of study in DAI.

Several reasons have been mentioned in the discussions of existing applications for choosing a DAI approach. These reasons have to do with such issues as distribution, heterogeneity, privacy, performance, dedication, intelligence, and conflicts.

Distribution is intrinsic to telecommunications systems. Centralization of tasks and functionalities is in most cases not only difficult, but also unnecessary and even undesirable. Centralization becomes hard especially in cases of heterogeneity, e.g., when legacy systems are connected or integrated. It is unnecessary because many tasks, such as the management of a private network, can be done mostly locally, with only exceptional interaction with other components. DAI techniques provide the technology to implement such exceptional interactions where globally correct behavior is obtained as the sum of local behaviors. It is undesirable if centralization would lead to violation of privacy: certain information, such as local-system passwords and user profiles, should not be transmitted freely. Centralization could also severely harm the high performance that is required in most telecommunications systems. Distributed AI provides modularization in which components are dedicated to addressing only a relatively small task in the operation and management of telecommunications systems. Only then can sufficiently intelligent mechanisms be brought into telecommunications systems to perform some of the more challenging tasks in operation and management.

DAI exploits the opportunities presented by distribution in telecommunications systems and provides solutions to many of the challenges presented by distribution.

References

[1] M.R. Adler, A.B. Davis, R. Weihmayer, and R.W. Worrest, Conflict-resolution strategies for nonhierarchical distributed agents, in: L. Gasser and M.N. Huhns, eds., *Distributed Artificial Intelligence, volume II*, Research Notes in Artificial Intelligence, chapter 7, pp. 139–161. Pitman, London, 1989.

[2] M. Arango et al., Touring Machine: a software infrastructure to support multimedia communications. In *MULTIMEDIA '92, 4th IEEE COMSOC International Workshop on Multimedia Communications*, Monterey, CA, 1-4 April 1992.

[3] C. Axelson, Managing intelligent networks with a better human interface, *Telephony*, January 3, 1994.

[4] S.E. Conry, K. Kuwabara, V.R. Lesser, and R.A. Meyer, Multistage negotiation for distributed constraint satisfaction, *IEEE Transactions on Systems, Man, and Cybernetics*, 21(6):1462–1477, 1991.

[5] R. Davis and R.G. Smith, Negotiation as a metaphor for distributed problem solving, *Artificial Intelligence*, 20:63–109, 1983.

[6] M. Fletcher, Some Further Design Considerations for the Congestion Management Mechanism MENTHOL, in: *Technical Report*, University of Keele, Keele, Staffordshire, Department of Computer Science, February 20, 1994.

[7] M. Fletcher and S.M. Deen, Design Considerations for Optimal Intelligent Network Routing, in: *CKBS-SIG Proceedings 1992*, S.M. Deen (ed.), University of Keele, September 1992.

[8] S.K. Goyal, Artificial Intelligence in support of distributed network management, in: M.Sloman, ed., *Network & Distributed Systems Management*, Addison Wesley, 1994 (to be published 3Q94).

[9] N.D. Griffeth and H. Velthuijsen, The negotiating agent model for rapid feature development, in: *Proceedings of the Eighth International Conference on Software Engineering for Telecommunications Systems and Services*, Florence, Italy, 1992.

[10] N.D. Griffeth and H. Velthuijsen, Reasoning about goals to resolve conflicts, in: M. Huhns, M.P. Papazoglou, and G. Schlageter, eds., *Proceedings International Conference on Intelligent Cooperating Information Systems (ICICIS-93)*, pp. 197–204, Rotterdam, 1993. IEEE Computer Society Press.

[11] N.D. Griffeth and H. Velthuijsen, Win/win negotiation among autonomous agents, in: *Proceedings 12th International Workshop on Distributed Artificial Intelligence*, pp. 187–202, Hidden Valley, PA, 1993,

[12] N. Griffeth, The negotiating agent model for establishing and modifying communications, in: *Proceedings Second Telecommunications Information Networking Architecture Workshop*, pp. 129–140, Chantilly, France, 1991.

[13] M. Huhns and M. Singh, Automating Workflows for Service Provisioning: Integrating AI and Database Technologies, in: *Proceedings 10th IEEE Conference on Artificial Intelligence Applications*, San Antonio, Texas, March 1-4, 1994.

[14] K. Kuwabara and T. Ishida, Symbiotic approach to distributed resource allocation: toward coordinated reasoning, in: A. Cesta, R. Conte, and M. Miceli, eds., *Proceedings MAAMAW '92*, San Martino al Cimino, Italy, 1992.

[15] E.P.M. van Liempd, H. Velthuijsen, and A. Florescu, BLONDIE-III: a distributed implementation of a network configuration problem, *IEEE Expert*, 5(4):48–55, 1990.

[16] Y. Lirov and B. Melamed, Expert design systems for telecommunications, *Expert Systems with Applications*, 2:219–228, 1991.

[17] S. Minton et al. PRODIGY 2.0: The Manual and Tutorial. Technical Report *CMU-CS-89-146*, Carnegie Mellon University, 1989.

[18] Y. Nishibe, K. Kuwabara, T. Suda, and T. Ishida, Distributed channel allocation in ATM networks, in: *Proceedings IEEE Globecom '93*, pp. 12.2.1–12.2.7, Houston, TX, 1993.

[19] B. Silver, W. Frawley, G. Iba, and J. Vittal, ILS: A System of Learning Distributed Heterogeneous Agents for Network Traffic Management, in: *Proceedings ICC'93*, Geneva, Switzerland, 1993.

[20] Y. Shoham, AGENT0: A Simple Agent Language and its Interpreter. in: *Proceedings of the Ninth National Conference on Artificial Intelligence*, July 14-19,1991.

[21] Y. Shoham, Agent-Oriented Programming *Artificial Intelligence*, 60 (1993), pp. 51–92, Elsevier Science Publishers.

[22] Y.-P. So and E.H. Durfee, A distributed problem solving system for computer network management, *International Journal of Intelligent and Cooperating Information Systems*, 1(2):??–??, 1992.

[23] Y.-P. So and E.H. Durfee, An organizational self-design model for organizational change, in: *Notes AAAI Workshop on AI and Theories of Groups and Organizations*, pp. ??–??, Washington, DC, 1993.

[24] T. Sugawara and K. Murakami, A multiagent diagnostic system for internetwork problems, in: *Proceedings of INET '92*, Kobe, Japan, 1992.

[25] T. Sugawara, A cooperative LAN diagnostic and observation expert system, in:*Proceedings of the International Conference on Computers and Communications*, pp. 667–674, Scottsdale, AZ, 1990.

[26] M. Tan and R. Weihmayer, Integrating agent-oriented programming and planning for cooperative problem solving, in: *Proceedings AAAI Workshop on Cooperation among Heterogeneous Intelligent Systems*, pp. 129–137, San Jose, CA, 1992.

[27] H. Velthuijsen and N.D. Griffeth, Negotiation in telecommunications Systems, in: *Working Notes AAAI Workshop on Cooperation among Heterogeneous Intelligent Agents*, pp. 138–147, San Jose, CA, 1992.

[28] H. Velthuijsen, Distributed Artificial Intelligence for runtime feature-interaction resolution, *Computer*, 26(8):48–55, 1993.

[29] R. Weihmayer and R. Brandau. Cooperative distributed problem solving for communication network management, *Computer Communications*, 13(9):547–557, 1990.

[30] R. Weihmayer and R. Brandau. A distributed AI architecture for customer network control, in: *Proceedings IEEE Globecom '90*, pp. 656–662, San Diego, CA, 1990.

[31] R. Weihmayer and M. Tan. Modeling Cooperative Agents for Customer Network Control using Planning and Agent-Oriented Programming. in: *Proceedings IEEE Globecom '92*, Orlando, FL, December 6-9, 1992.

[32] R. Weihmayer I. Ghaznavi and P. Sheridan. A Distributed Architecture for Cooperative Management of Strategic Communication Networks. in: *Proceedings IEEE MILCOM '93*, Boston, MA, October 11-14, 1993.