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DISTRIBUTED INPUT/OUTPUT SUBSYSTEM FOR TRAFFIC SIGNAL CONTROL

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EXECUTIVE SUMMARY

In an effort to add more and more features (preemption, malfunction management, weather monitoring, and dynamic lane assignment, among others) to traffic signal systems, the traffic signal cabinet has become very complicated (Figure 1). Furthermore, none of the standard family of traflic signal controllers (NEMA, 170, 179, aud ATMS 2070) have interfaces more sophisticated than 24-volt input/output logic. In fall 1993, a proposal was submitted to the Transportation Research Board (TRB) Intelligent Transportation Systems (ITS) Ideas Deserving Exploratory Analysis (IDEA) program to develop a distributed input/output subsystem for this new controller. That proposal described a “drive by wire” distributed control technology for electrically interfacing the ATMS 2070 to sensors (loop detectors) and actuators (signal lamps). The unique and novel characteristic of this proposed model was that only two alternating current (110VAC) conductors were required to be connected instead of the 100 conductors usually connected to a NEMA or 170 controller (Figure 2). This novel interface would greatly reduce the quantity of wiring installed at traffic signals. Agencies would save money by reducing labor and material costs. Furthermore, this distributed control model could be easily expanded to accommodate additional sensors and actuators.

The general name of the distributed control architecture presented in this report is LonWorks. A LonWorks network is composed of one or more Neurons linked over a data communication media running a protocol called LonTalk Figure 3 shows three Neurons linked together using a LonTalk network. The unique and noteworthy characteristic of these Neurons is the central processing unit (CPU) architecture. Instead of having one CPU per Neuron, each Neuron contains three identical CPUs (Figure 3). Two of these CPUs are dedicated to implementing the seven-layer ISO/OSI

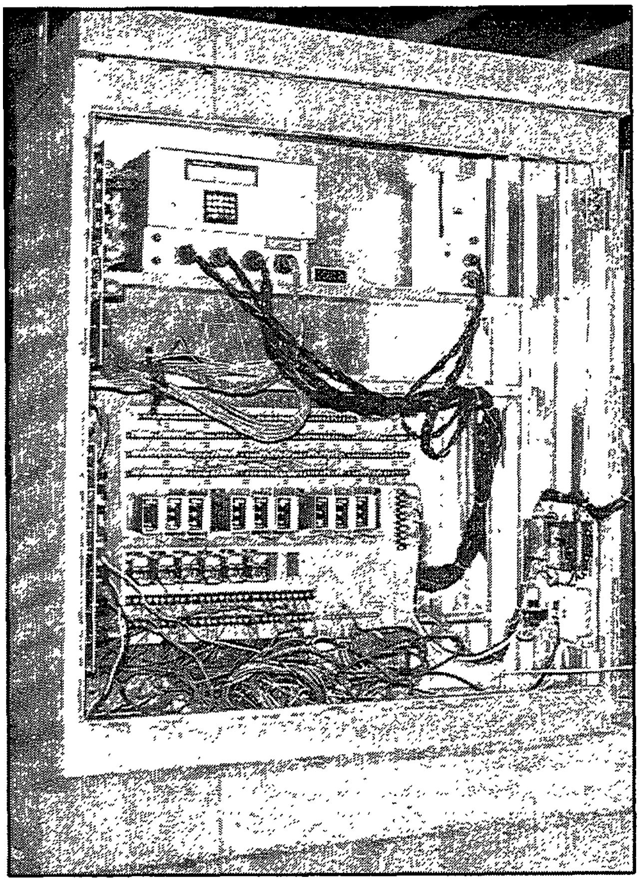

FIGURE 1 Typical traffic signal controller cabinet.

reference model and the third is available for executing application specific software (Figure 3, CPU 3). These Neuron packages are connected to media-specific transceivers that contain the appropriate electrical interlaces for the network selected. The software implementing the networking protocol on the first two CPUs is provided on every Neuron chip. Since this communication software is embedded in the chip, communication protocol compatibility is ensured.

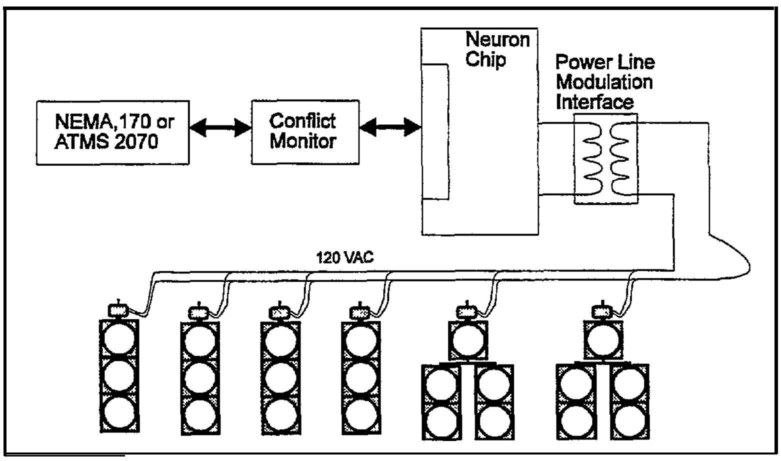

FIGURE 2 Proposed wiring model.

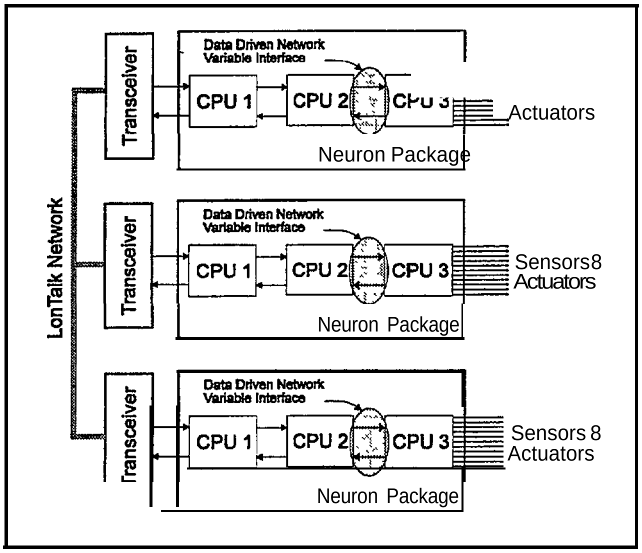

FIGURE 3 LONWORKS networking architecture.

Consequently, auy sensing, actuation, or control device that incorporates a Neuron chip is guaranteed to be compatible with the LONTALK network protocol. This new concept of providing a programmable microprocessor and embedded communication protocol provides a tremendous amount of flexibility while ensuring a truly open architecture.

Conventional techniques for controlling signal heads require a conductor to be run to each lamp as well as a common return. The novel idea described in the IDEA proposal was to construct a distributed input/output subsystem similar to that shown in Figure 2. In this model only two conductors would be run to each head. Messages transmitted over the power line signal smart switches in each head to change state. Figure 4 shows a five-section assembly with a "smart control" module mounted in the disconnect hanger. A simplified schematic for this control module is shown in Figure 5. This control module has five solid state relays controlled by five separate pins on the Echelon PLC-10 (IO 0, 1,2, 3, and 4). Five separate current sensors monitor the current to each lamp. The state of each of the current sensors is monitored by the PLC-10 (IO 5,6, 7, 8, and 9). Since the PLC-10 knows which lamps have been switched on, it knows what to expect on the current sensor input pins. If the predicted inputs do not agree with the actual inputs, a malfunction has been detected. Figure 6 shows a photo of the circuit board before the circuit board layout was reduced to fit in the disconnect hanger (Figure 4). The small circuit board on the left is the Echelon PLC-10. The larger board on the right is connected to the PLC-10 with a ribbon cable. On the left side of the larger circuit board, the five rectangular modules are solid state relays. To the right of the solid state relays are five current sensors arranged in a 3-2 pattern. The connector near the top of the larger board is

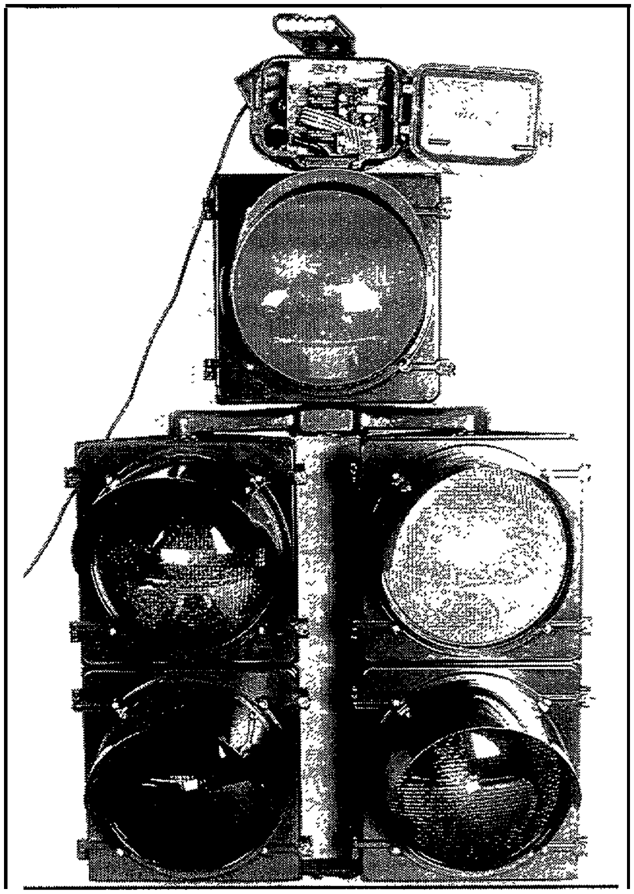

FIGURE 4 Signal head with control module mounted in disconnect hanger.

the power connector. Power is carried from the larger board to the PLC-10 by the wire **leaving** the upper left comer of the larger board. The connector on the right side of the larger board is a Jones Cinch connector for plugging in a standard signal head. The control module shown in the disconnect hanger (Figure 4) uses these same circuits as shown in Figure 6, but in a compressed form factor. Approximately ten of these control modules (in the form factor of the one shown in Figure 6) were fabricated, tested, and found to work as expected.

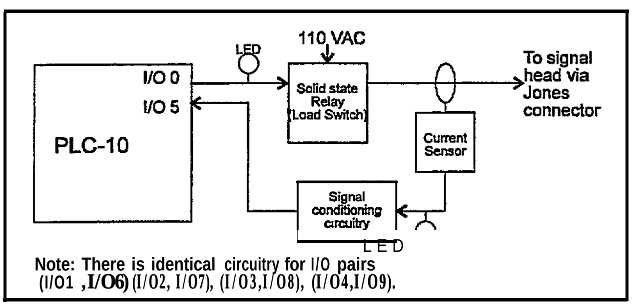

FIGURE 5 Schematic of circuit board controlling lamps.

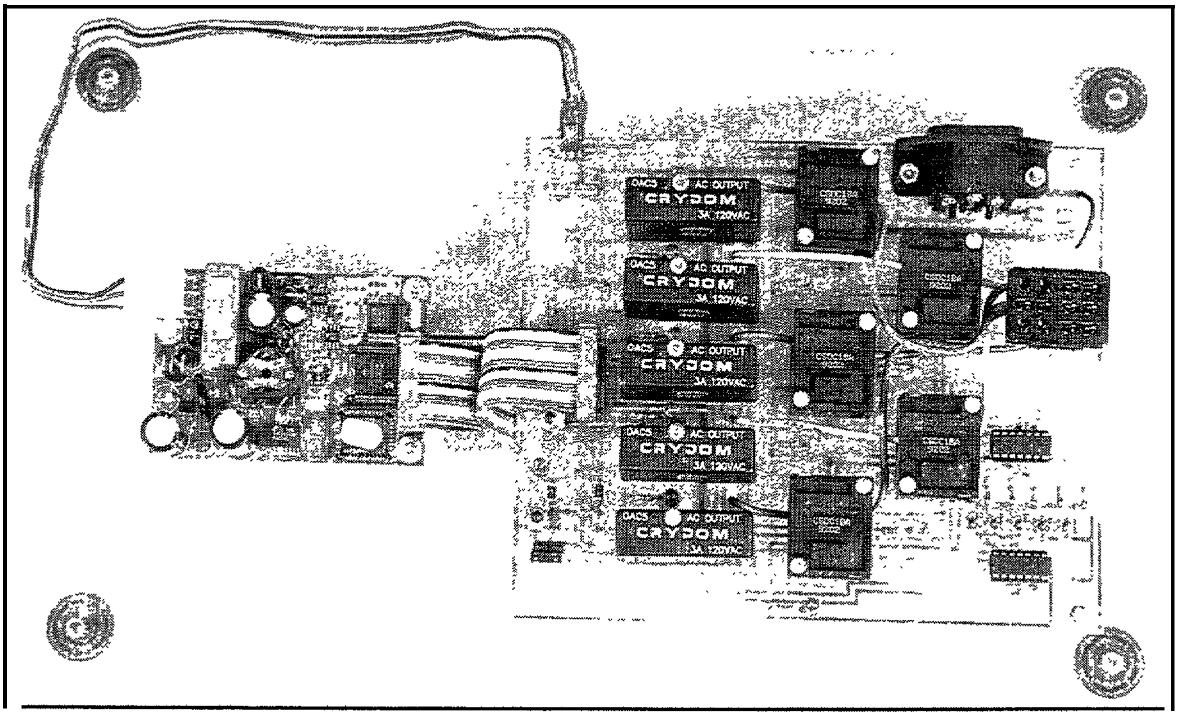

FIGURE 6 Signal head control module before circuit board layout **size was reduced.**

We achieved our proposed objective of demonstrating distributed signal head operation (Figure 2) and found that the LonWorks spread spectrum power line communication technology is extremely attractive for ITS applications with low data requirements such as message signs, remote ramp meter controllers, and fiber optic signs. However, when manufacturing costs, field maintenance practices, fault tolerance, and legal liability are all considered, it is not clear that installation of load switches in the signal head (Figure 4) could be justified at this time. Instead, we believe au in-cabinet LonWorks distributed input/output system would be the next appropriate development. Instead of using the spread-spectrum power line communication interface (10 kbps), a higher speed LonWorks twisted-pair interface (1.25 Mbps) would be used for in-cabinet distributed computing and communication. The intelligent input/output modules would be distributed inside the traffic signal cabinet (Figure 7) instead of around the intersection. This in-cabinet Echelon data bus would operate approximately 125 times faster than the power line carrier. Although it would not simplify the wiring out at the signal heads, it would still dramatically simplify the cabinet wiring (Figure 1 versus Figure 7). Furthermore, it would provide au open architecture communication protocol for adding in devices such as preemption receivers, sign control, air-quality sensors, and other emerging peripheral input/output devices. As traffic engineers gain confidence in this approach, distributed control modules residing outside of the cabinet could be added. Devices requiring

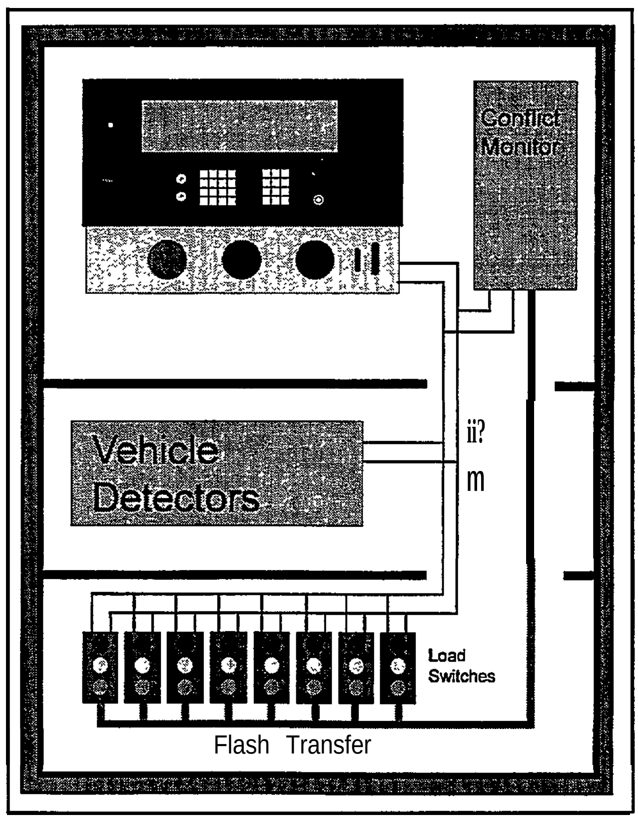

FIGURE 7 In-cabinet bus.

quick communication responses could use the dedicated twisted-pair communication interface while devices such as fiber optic signs or air quality sensors could use the slower power line interface.

Other projects are under way that closely tie in with this ITS-IDEA project.

- Matrix Corporation introduced a controller built to the preliminary ATMS 2070 specification with NEMA connectors at the ITS America show in April 1994. In addition to following the preliminary ATMS 2070 specification, the CPU module included an Echelon LonTalk bus for reading and writing the I/O pins on the A, B and C connectors (Figure 7). Since the controller already supports the LonTalk bus, it would be simple to extend the bus outside the controller to the load switch and loop detector racks.
- The Texas Transportation Institute (TTI) Intelligent Vehicle Highway System (IVHS) Research Center of Excellence (RCE) has initiated a research project for developing a smart diamond intersection controller. In its eventual deployment this controller is expected to employ advanced video tracking, real-time optimization, fiber optic dynamic lane assignment signs, priority transit service, and coordination with adjacent ramp meters. As part of that project, the TTI IVHS RCE has funded the Louisiana State University (LSU) team to develop a LonTalk interface for fiber optic signs.
- One of the loop detector vendors is very interested in adopting the LonWorks technology to provide enhanced detection capabilities.

Given the very promising results obtained from this IDEA project and other ITS projects under way, we are currently forming a consortium to further develop the ITS application of the Echelon LonWorks system.

In conclusion, this research project achieved its stated objectives and has stimulated a broad interest in distributed input/output systems for traflic signal control. We have made presentations to the 1995 TRB Annual Meeting (Session 91B), Louisiana Department of Transportation, Texas Department of Transportation, TTI, Traffic signal equipment vendors, Federal Highway Administration officials, several traffic engineering consultants, and the local Institute of Transportation Engineers chapter. In general, we have received the most enthusiastic interest from people involved in maintenance activities because they see a big benefit in reducing the wiring and in standardizing the communication interface.

PROBLEM STATEMENT

Advanced Traffic Management Systems (ATMS) rely heavily on traffic signal controllers for collecting data and implementing signal timing plans. It is through these devices that traflic management systems are able to observe field conditions and control the flow of traflic. Over the past four years, traflic signal controllers have been rapidly evolving in au effort to meet the demands of these new ATMS. In August 1993, the California Department of Transportation (Caltrans) released a draft specification for a new generation traffic signal controller called the ATMS 2070. This controller is intended to be used for ITS-related projects. The ATMS 2070 contains a powerful microprocessor and is considered to have an "open architecture" because it is based on widely accepted hardware and software standards.

In au effort to add more and more features (preemption malfunction management, weather monitoring, and dynamic lane assignment, among others) to traffic signal systems, the traffic signal cabinet has become very complicated (Figure 1). Furthermore, none of the standard family of traffic signal controllers (NEMA, 170, 179, and ATMS 2070) have interfaces more sophisticated than 24-volt input/output logic. In fall 1993, a proposal was submitted to the TRB ITS-IDEA program to develop a distributed input/output subsystem for this new controller. That proposal described a "drive by wire" technology for electrically interfacing the ATMS 2070 to sensors (loop detectors) and actuators (signal lamps). The unique and novel characteristic of this proposed model was that only two alternating current (110VAC) conductors were required to be connected instead of the 100 conductors usually connected to a NEMA or 170 controller (Figure 2). This novel interface would greatly reduce the quantity of wiring installed at traffic signals. Agencies would save money by reducing labor and material costs. Furthermore, this model could be easily expanded to accommodate additional sensors and actuators.

RESEARCH APPROACH

Although cabinet wiring has been growing increasingly complex, it is only recently that commercial open architecture control equipment has been looked at for traflic signal control. The innovation of this IDEA project is the use of the distributed control technology manufactured by Echelon called LonWorks for ITS applications.

Compared with other real-time control domains (factory automation, building automation, and automotive automation), the real-time traflic control industry is very small. This makes it difficult to justify making a large investment in a computing and control architecture that would only be used in the traffic control industry. Consequently, one of the objectives of this research was to identity an existing distributed control technology that can be adapted to the traffic control industry.

Several general-purpose, distributed, real-time control technologies have been developed and potentially can be used for traffic signals. For example, CAN, SP 50, CEbus, ISP, WorldFIP, and DeviceNet are protocol-oriented specifications. However, they tend to be targeted to specific industries and provide little support for user training, development tools, and physical hardware devices. Alternatively, Allen-Bradley Data Highway, Rosemount HART, Modicon MODbus, and Siemen Profibus provide a rich supporting infrastructure. However, these solutions are only supported by their manufacturers and are not available as an open, interoperable technology. The LonWorks technology was selected for this project because the inexpensive Neuron processors ensured compatibility, and there is extensive support, including user training, development tools, transceivers, routers, gateways, connectivity devices, network management tools, and diagnostics.

There are three fundamental components of the Echelon LonWorks technology:

- Distributed processors called Neurons. These application processors are programmed using the C language, have 11 input/output pins, 512 bytes of EEPROM, 2048 bytes of RAM, and about 50,000 bytes of external ROM. These Neurons are manufactured by multiple vendors and cost about $3 per package when purchased in significant quantities. Given this relatively small cost, these processors can provide cost-effective interfaces to a variety of I/O devices such as signal load switches, loop detectors, preemption systems, and even airquality sensors.
- Standard communication protocol is embedded in the Neurons. Since the communication protocol is embedded in the Neuron, developers do not have to write communication drivers. This is an enormous benefit to potential vendors because of the large software development costs associated with writing and maintaining communication software. Furthermore, since the protocol is embedded in the Neuron, vendors do not have to worry about other vendors adding proprietary tweaks to the communication protocol, which defeat interoperability.
- Several different media choices. Using the proper transceivers, these Neurons can be attached to several different media. In this project we are using 110 VAC. However, these devices can also be used over DC power lines, twisted pair, radio frequency, infrared, coaxial cable and fiber optics.

TECHNOLOGY BACKGROUND

The general name of the distributed control architecture presented in this report is LonWorks. A LonWorks network is composed of one or more Neurons linked over a data communication media running a protocol called LonTalk. Figure 3 shows three Neurons linked together using a LonTalk network. The unique **and** noteworthy characteristic of these Neurons is the CPU architecture. Instead of having one CPU per Neuron, each Neuron contains three identical CPU's (Figure 3). Two of these CPUs are dedicated to implementing the seven-layer ISO/OSI reference model and the third is available for executing application specific software (Figure 3, CPU 3). These Neuron packages are connected to media specific transceivers that contain the appropriate electrical interfaces for the network selected. The software implementing the networking protocol on the first two CPUs is provided on every Neuron chip. Since this communication software is embedded in the chip, communication protocol compatibility is ensured. Consequently, any sensing, actuation or control device that incorporates a Neuron chip is guaranteed to be compatible with the LonTalk network protocol. This embedded communication protocol is a new concept that provides a tremendous amount of flexibility while ensuring a truly open architecture.

The third processor is used for running application specific software and has 11 external interface lines that can be programmed for a variety of input and output functions. The C language used to program the Neurons is an extension of ANSI C. Application software running on this third processor (Figure 3) interfaces to application software running on other Neurons using network variables. Network variables, a special type of C variable, are powerful tools that greatly simplify software development for distributed computing applications. When updated, their new values are automatically propagated to all other Neuron nodes that have 'finked to them. An illustration of how these network variables are used is shown in Figure 8. As an example, assume application software is developed to control five digital outputs. Current sensors are used to monitor the output lines to determine if the circuit is behaving properly. A master control device would need to specify the desired output bit pattern and monitor the sensed output bit pattern. The sensor interface algorithm would run on

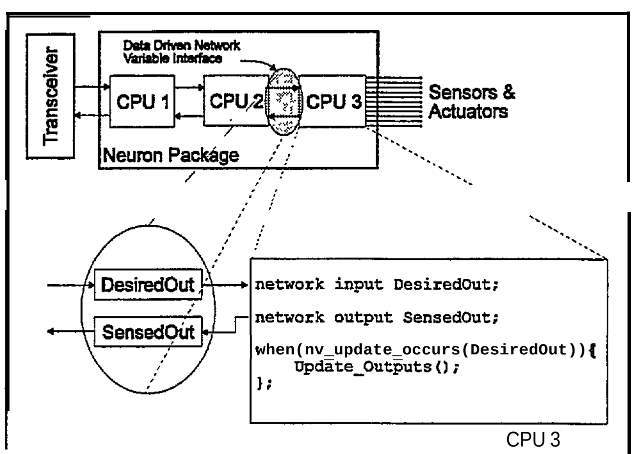

FIGURE 8 LonTalk network variable concept.

CPU 3 and obtain the desired output (Figure 8, DesiredOut) from the network input variable "DesiredOut." This variable would be updated or set by another Neuron on the network (probably the traffic signal controller). Similarly, the output status obtained from the current sensors would be stored in the output variable "SensedOut." Any other Neuron on the LONTALK network could obtain the position by declaring the "SensedOut" a network input variable. Whenever the Neuron to which the sensor was connected senses a change, it would broadcast the new value to all other Neurons, declaring that variable as a network input This type of networking is known as a data-driven network and makes it easy to develop distributed computing applications.

Since many applications routinely sense, control, or calculate the same data types such as angular velocity, current, flow rates, pressures, speeds, temperature, and so on, Echelon has defined approximately 60 common data types called Standard Network Variable Types (SNVTs). For each SNVT, a C typedef structure is defined with a specific resolution, range, and Systeme Intemationale (Sl) unit. An example of just a few of these data types are shown in Table 1. By defining these standard data types, different devices can be easily integrated on a LONTALK network. For example, say a manufacturer developed a device that could be embedded in the pavement to monitor the temperature and determine when icing might occur. If the data type SNVT temp was used for defining the network variable containing the probe temperature, this device could be readily integrated into a LONTALK network by simply connecting the network variables to a respective output and input variable somewhere else on the LONTALK network.

For the routine sensing applications such as counting loop detector pulses or controlling a dimming circuit, the Neurons have several built-in functions for decoding input signals, encoding output signals, and providing hardware handshaking operations. A summary of these functions is given in Table 2. These functions are called I/O objects and frequently eliminate the need to develop precise real-time code with very fast response times. However, typically real-time applications always require rapid and deterministic responses to certain I/O events or conditions. To handle these demands, the application CPU on the Neuron has a real-time event-driven scheduler that can activate C functions when certain prescribed events occur. The nv_update_occurs() function is an example of a real-time function that will activate the code inside the when statement when a network variable is updated.

The following sections detail the specific research conducted and prototype products fabricated during this research project.

POWER LINE COMMUNICATION TESTING

One of the first tasks carried out in this project was to define the performance envelope of the power-line communication method under real field conditions. This was done using a pair of Power Line Communication Analyzers (PLCAs) manufactured by Echelon. These boxes are used in pairs, with one PLCA set to transmit variable-size data packets and the other PLCA to receive the data packets. Packets are sent with serial numbers so that the receiving PLCA can detect when messages are lost. We selected an intersection in Gonzales, Louisiana, for this test. We connected one PLCA to the output load switch in the cabinet at the intersection. A man in a Louisiana Department of Transportation and Development (Louisiana DOTD) bucket truck connected

TABLE 1 STANI **ARD NETWORK VARIABLE TYPES (SNVT)**

Measurement	SNVT Data Type	SNVT Resolution	SNVT Range	Units
Angular Velocity	SNVT_angle_vel	0.1 radians/sec	-3276.8 .. 3276.7	radians/sec
Angular Velocity	SNVT_angle_vel_f	-	-1E38 .. 1E38	radians/sec
Current	SNVT_amp	0.1ampere	-3276.8 .. 3276.7	milliamps
Current	SNVT_amp_f	-	-1E38 .. 1E38	amps
Current	SNVT_amp_mil	0.1 milliamp	-3276.8 ..3276.7	milliamps
Flow	SNVT_flow	1 liter/sec	0 .. 65535	liters/sec
Flow	SNVT_flow_f	-	-1E38 .. 1E38	liters/sec
Flow	SNVT_flow_mil	1 milliliter/sec	0.. 65,535	milliliter/sec
Speed	SNVT_speed	0.1 m/s	0..65535.5	m/s
Speed	SNVT_speed_f	-	-1E38 .. 1E38	m/s
Speed	SNVT_speed_mil	0.001 m/s	0.. 65535	m/s
Temperature	SNVT_temp	0.1 °C	-274 .. 7269.5	°C

TABLE 2 NEURON INPUT AND OUTPUT MODELS

I/O Object Name	Description
Bit Input/Output	Read individual inputs and manipulating individual outputs.
Bitshift Input/Output	Shift data words in or shift data words out.
Byte Input/Output	Read or write eight connections simultaneously.
Frequency Output	Produce a repeating square wave output signal with a specified period.
Level Detect Input	Detect a transition from the logical I level to the logical 0 level on a single input.
Neurowire Input/Output	Transfer data to or from an external device using a fully asynchronous serial data format.
Nibble Input/Output	Read or write four connections simultaneously.
Oneshot Output	Produce a single output pulse with a specified duration.
On Time Input	Measures the high or low period of an input signal.
Parallel Input/Output	Implements an eight bit parallel interface with handshaking.
Period Input	Measures the total period of an input from edge to edge.
Pulse Count Input	Counts either rising or falling edges on an input over a fixed time interval.
Pulse Count Output	Produces a specified number of output pulses.
Pulse Width Output	Produces a repeating square wave with a specified duty cycle.
Quadrature Input	Uses two adjacent inputs to read a shaft or positonal encoder.
Serial Input/Output	Transfer data using an RS-232 asynchronous serial data format.
Total Count Input	Counts either rising or falling edges on an input since counter was last read and cleared.
Triac Output	Controls the delay of an output pulse signal with respect to an input trigger (typically zero-crossing).
Triggered Count Output	Control an output pin to the active state and keep it active until a specified number of negative edges are counted on a input sync pin.

the other PLCA to the terminal block of a traffic signal head hanging from the spanwire. With short runs of wire (<100 feet) we experienced very few communication errors. However, over longer runs (about 700 feet), we experienced unacceptably high error rates (about 30%).

To reproduce the problems we encountered during our tests on the long wire runs (700 ft.), we constructed a test facility at the Louisiana DOTD tragic signal shop. This test environment simulated an extremely long electrical run (2,200 ft) under the worst-case data-communication loading (1s flash with 50% duty cycle). We used actual load switches, lamps, and wire. A schematic of the test bed is shown in Figure 8. Table 3 identifies the location of the transmitter and receiver (Figure 9) for six different test cases. Using the laboratory test bed, we were able to reproduce the same problems we encountered in the field when the lamps turned on and off. We found that there were virtually no communication problems when the transmitter was near the load switch and the receiver was at the lamp (Tests la and 2a in Tables 4 and 5). However, when the transmitter was at the lamp and the receiver was at the load switch we encountered unacceptable communication errors (Tests lb, 2b, and 3b in Tables 4 and 5). After consulting with Echelon, their engineers pointed out the Triac-type load switch we were using was causing a lot of "ringing." We verified this on an oscilloscope. When we changed the type of load switch from a Triac to a Crydom OAC5 solid state relay (Table 6) or mechanical relay (Table 7), our communication errors dropped to an acceptable rate. When we repeated all these tests (even with noisy Triac load switches) using common mode transmission tests (three wires instead of two) we had absolutely no communication errors (Tables 8, 9, and 10).

To understand how robust this communication

TABLE 3 TEST CONFIGURATIONS

Test	Transmitter Location	Receiver Location	Packet Size
1a	Switch	Lamp	12 bytes
1b	Lamp	Switch	12 bytes
2a	Switch	Lamp	76 bytes
2b	Lamp	Switch	76 bytes
3b	Lamp	Switch	44 bytes
4	Switch	Switch	76 bytes

method would be under adverse electrical conditions, we selected a section of Florida Boulevard. in Baton Rouge, Louisiana, that has some particularly bad induced-voltage problems. This section of highway has a very old 7-wire interconnect system that runs approximately 1.6 miles (Figure 10). We put a PLCA transmitting in the cabinet at Monterey Boulevard and a PLCA receiving in the cabinet at Sherwood Forest Boulevard. The units were configured for differential mode transmission and auto threshold. The line used for communication was the 110 VAC "reset" line that carries a synchronization pulse every cycle (approximately every 150 seconds). The first series of tests we conducted used 12-byte data packets. We varied the output attenuation from 0 dB to 24 dB. Under normal circumstances, the transmit attenuation would be 0 dB. (Attenuation is measured using a logarithmic scale measured in dB.) For example, attenuating the output by 10 dB reduces the output by a factor of 10, attenuating the output 20 dB reduces the output by a factor of 100. By attenuating the output, we can determine how robust the communication is. From Table 11 we can see even under the worst conditions (24 dB attenuation), the error rate never exceeded 0.6 %. Since larger packet sizes have a bigger chance of getting "clobbered" by power line transients, we tried 76-byte packets. Table 12 shows that even with large packets sizes and 24 dB attenuation, we only lost 1.3% of the packets. Since these results were obtained using the two-wire differential mode transmission method as opposed to the common mode (Tables 8, 9, and 10), we felt the field performance was excellent.

SIGNAL HEAD CONTROL MODULE

Conventional techniques for controlling signal heads require a conductor to be run to each lamp as well as a common return. The novel idea described in the IDEA proposal was to construct a distributed input/output subsystem similar to that shown in Figure 2. In this model only two conductors would be run to each head. Messages transmitted over the power line signal smart switches in each head to change state. Figure 4 shows a photograph of a five-section assembly with a "smart control" module mounted in the disconnect hanger. A simplified schematic for this control module is shown in Figure 5. This control module has five solid state relays controlled by five separate pins on the Echelon PLC-10 (IO 0, 1, 2, 3, and 4). Five separate current sensors monitor the current to each lamp. The state of each of the current sensors is monitored by the PLC-10 (IO 5, 6, 7, 8, and 9). Since the PLC-10 knows which lamps have been switched on, it knows what to expect on the current sensor input pins. If the predicted inputs do not agree with the actual inputs, a malfunction has been detected. Figure 6 shows a photo of the circuit board before the circuit board layout was reduced to fit in the disconnect

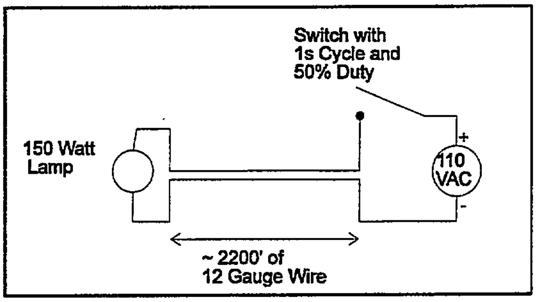

FIGURE 9 Laboratory communication test environment.

hanger (Figure 4). The small circuit board on the left is the Echelon PLC-10. The larger board on the right is connected to the PLC-10 with a ribbon cable. On the left side of the larger circuit board, the five rectangular modules are solid-state relays. To the right of the solid-state relays five current sensors are arranged in a 3-2 pattern. The power connector is near the top of the larger board. Power is carried from the larger board to the PLC-10 by the wire leaving the upper left corner of the larger board. The connector on the right side of the larger board is a Jones Cinch connector for plugging in a standard signal head. The control module shown in the disconnect hanger (Figure 4) uses these same circuits as those shown in Figure 6, but in a compressed form factor. Approximately ten of these control modules (in the form factor of the one shown in Figure 6) were fabricated, tested, and found to work as expected.

These control modules all have Neuron C code written for performing two functions: (1) The code checks for updates of the network variables associated with its particular signal head. When these updates occur the corresponding bulbs are turned on or off. (2) The code monitors inputs connected to the current sensors. When the state of any input changes, an event is triggered and the network variable representing the current sensor state is updated and propagated out over the LONTALK network (Figure 8).

DEMONSTRATION OF DISTRIBUTED SIGNAL HEAD CONTROL SYSTEM

For development purposes, several small aluminum boxes with five LEDs and five switches were fabricated. Each of these aluminum boxes was fitted with a PLC-10 that could be plugged into an ordinary 110 VAC outlet. Four of the boxes could be used to simulate four different signal heads on a lab bench. These boxes had the same pin connections as those shown in Figure 5, except that no load switches were connected and the current sensors had to be simulated using the switches. To demonstrate the distributed input/output concept we used a setup similar to that shown in Figure 11. In this setup, we used a standard Naztec 8-phase NEMA controller to provide

TABLE 4 TRIAC SWITCH TEST WITH DIFFERENTIAL MODE AND AUTO THRESHOLD

Test	Attenuation at Tx (dB)	Attenuation at Rx (dB)	Lost Packets	Total Packets
Ia	0 to -3	-3 to (-18 to -24)	0	1000
Ib	0 to -3	-3 to (-24 to -30)	101	1000
2a	0 to -3	-3 to (-18 to -24)	0	1000
2b	0 to -3	-3 to (-24 to -30)	310	1000
3b	0 to -3	-3 to (-24 to -30)	222	1000
4	0 to (-3 -9)	0 to -12	0	1000

TABLE 5 TRIAC SWITCH TEST WITH DIFFERENTIAL MODE AND FIXED THRESHOLD

Test	Attenuation at Tx (dB)	Attenuation at Rx (dB)	Lost Packets	Total Packets
1a	0 to -3	-3 to (-18 to -24)	0	1000
1b	0 to -3	-3 to (-24 to -30)	185	1006
2a	0 to -3	-3 to (-18 to -24)	0	1000
2b	0 to -3	-3 to (-24 to -30)	406	1000
3b	0 to -3	-3 to (-24 to -30)	305	1000
4	-	-	-	-

TABLE 6 SOLID STATE RELAY (CRYDOM OAC5) SWITCH TEST WITH DIFFERENTIAL MODE AND AUTO THRESHOLD

Test	Attenuation at Tx (dB)	Attenuation at Rx (dB)	Lost Packets	Total Packets
Ia				
Ib	0 to -3	-3 to -9	7	1000
2a			0	1000
2b	0 to -3	-3 to -9	1	1000
3b	0 to -3	-3 to -9	2	1000
A				

TABLE 7 MECHANICAL RELAY SWITCH TEST WITH DIFFERENTIAL MODE AND AUTO THRESHOLD

Test	Attenuation at Tx (dB)	Attenuation at Rx (dB)	Lost Packets	Total Packets
1a	0	-3 to -9	8	1000
1b	0	-3 to -6	5	1000
2a	0	-3 to -9	3	1000
2b	0	-3 to -6	10	1000
3b	0	-3 to -6	8	1000
4				

TABLE 8 TRIAC SWITCH TEST WITH COMMON MODE AND FIXED THRESHOLD

Test	Attenuation at Tx (dB)	Attenuation at Rx (dB)	Lost Packets	Total Packets
1a	0	0	0	1000
1b	0	0	0	1000
2a	0	0	0	1000
2b	0	0	0	1000
3b	0	0	0	1000
4				

TABLE 9 SOLID STATE RELAY (CRYDOM OAC5) SWITCH TEST WITH COMMON MODE AND AUTO THRESHOLD

Test	Attenuation at Tx (dB)	Attenuation at Rx (dB)	Lost Packets	Total Packets
1a	0	0	0	1000
1b	0	0	0	1000
2a	0	0	0	1000
2b	0	0	0	1000
3b	0	0	0	1000
4				

TABLE 10 MECHANICAL RELAY SWITCH TEST WITH COMMON MODE AND AUTO THRESHOLD

Test	Attenuation at Tx (dB)	Attenuation at Rx (dB)	Lost Packets	Total Packets
1a	0	0	0	1000
1b	0	0	0	1000
2a	0	0	0	1000
2b	0	0	0	1000
3b	0	0	0	1000
4				

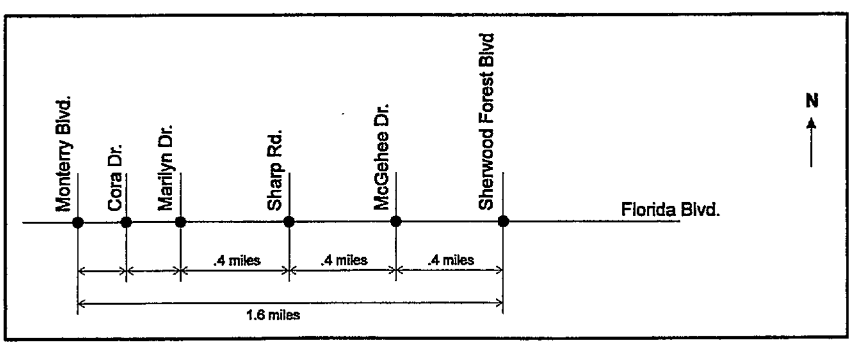

FIGURE 10 Arterial communication test environment.

TABLE 11 ERROR RATES FOR 12-BYTE PACKETS ON FLORIDA BOULEVARD

Attenuation (dB)	Packets Sent	Packets Lost	% Lost
0	176018	68	0.0
6	145258	47	0.0
12	200000	88	0.0
18	152381	175	0.1
24	141769	784	0.6

TABLE 12 ERROR RATES FOR 76-BYTE PACKETS ON FLORIDA BOULEVARD

Attenuation (dB)	Packets Sent	Packets Lost	% Lost
0	30020	47	0.2
6	31718	47	0.1
12	33727	231	0.7
18	200000	1196	0.6
24	31889	417	1.3

the sequence logic (shown in the upper left comer of Figure 11). All the outputs of this controller are connected to a multiplexing box with a Neuron chip and power line modulation interface (Figure 2). This small multiplexing box has all the outputs of the Naztec controller connected to it and is shown on the right of the Naztec controller (Figure 11). The multiplexing box is plugged into a 110 VAC power strip (to the right of the multiplexing box in Figure 11). The power strip has 4 aluminum test boxes plugged into it. Each of these boxes has an Echelon PLC-10 inside for manipulating the LEDs and monitoring the switch boxes. Every time the Naztec controller changes a phase indication the multiplexing box prepares the associated message and transmits that message over the power line. The appropriate aluminum box acknowledges the correct reception and displays the appropriate change in phase indication on the LEDs. We found these boxes so convenient during development that we have also used them as a portable demonstration.

In addition an enhanced system similar to that shown in Figure 2 was constructed. The “conflict monitor” was implemented on a Matrix VME system running OS-9. In addition to providing the capability of multiplexing the controller outputs, as was done by the aluminum box shown in Figure 11, this system also monitored the status of all the current sensors and logged bulb failures.

CHANGEABLE MESSAGE SIGN CONTROL MODULE

Another ITS-related application that could benefit from this technology is changeable message signs (CMS) such as those shown in Figure 12. These signs typically require a conductor for each pixel. Assuming that a sign has 20 characters per row, 4 rows, and each character is a 5 by 7 matrix, this would require 2,800 wires (plus neutral and ground). Such an application is a perfect candidate for the distributed input/output concept. Although not part of

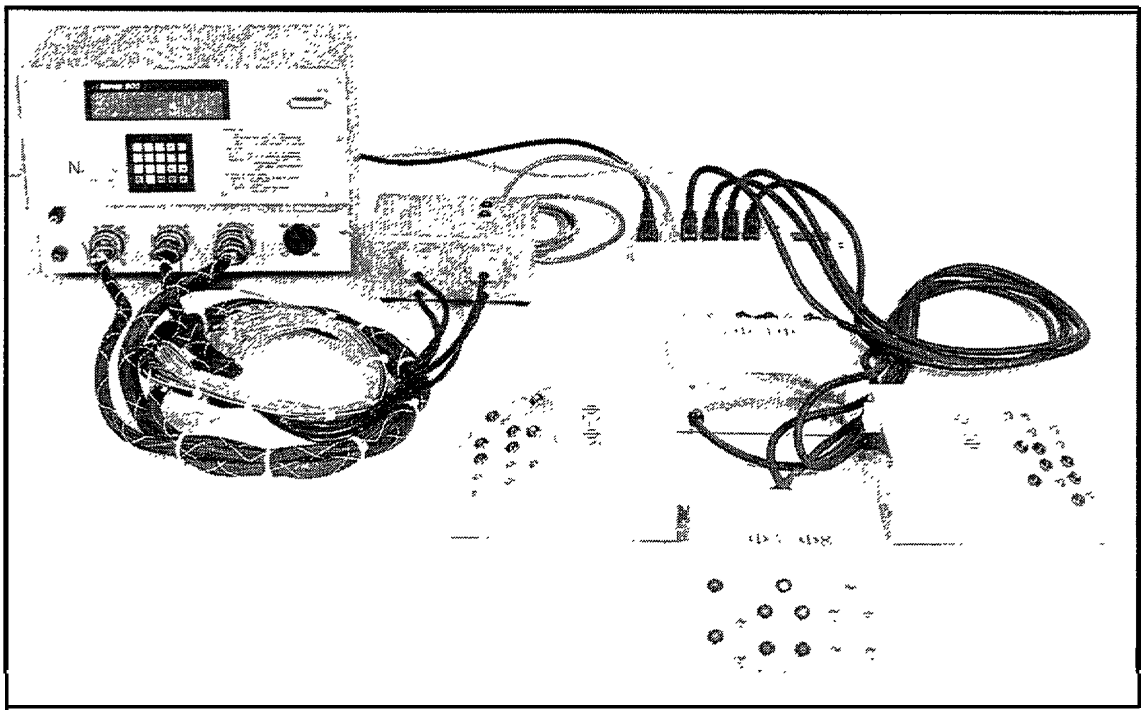

FIGURE 11 Equipment used to demonstrate distributed signal control.

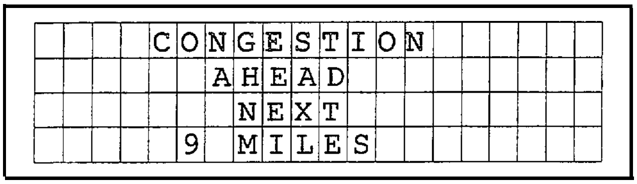

FIGURE 12 Typical changeable message sign layout.

the original proposal, we felt it was important to reduce this concept to a working prototype. Figure 13 shows a photograph of a prototype 5 by 7 cell displaying the number 1. A schematic diagram of the box is shown in Figure 14. We envision that adoption of this technology could dramatically change how these signs are constructed because these cells could be mass produced in a factory and then plugged into a power rail during final assembly. Maintenance would be easier because entire modules could be replaced instead of having to locate faulty wires in the field.

REMOTE RAMP METER CONTROL MODULE

Increasingly, ramp metering is being used in urban areas to improve the operating efficiencies of freeways. For example, if ramp meters were used for the diamond interchange shown in Figure 15 the two entrance ramps would have signal heads just before the merge area. To support the ramp meter operation, inputs from a queue detector (L1 and L10), a check-in detector (L2 and L11), a check-out detector (L3 and L12), and adjacent volume and occupancy detectors (L4, L5, L6, L7, L8, and L9) might also be required. If a cloverleaf interchange was used, the number of signal heads and loop detectors on the ramps would double. With all these input (loop detectors) and output (signal heads) devices geographically distributed about an interchange ramp metering appears to be an excellent candidate for the use

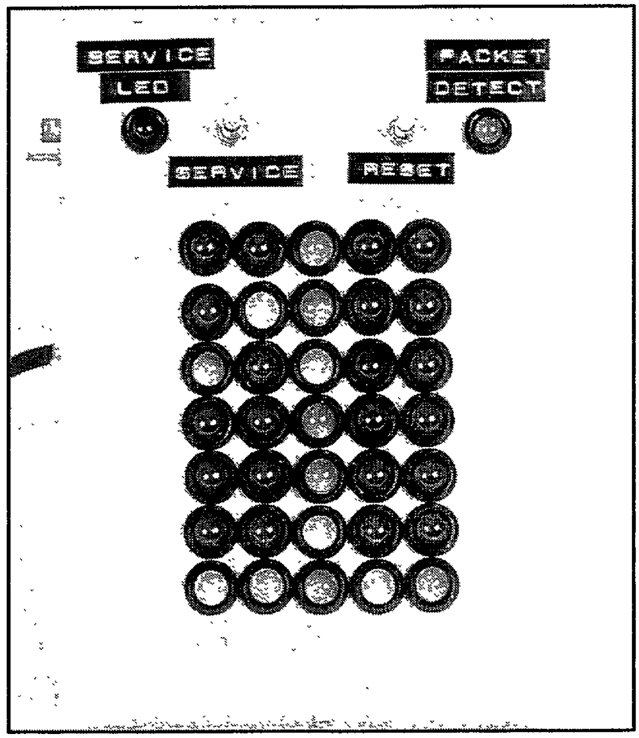

FIGURE 13 Prototype changeable message sign.

of a distributed input/output control model. Although not part of the original proposal, we felt it was important to reduce this distributed ramp metering concept to practice and fabricate the demonstration shown in Figure 16.

The demonstration equipment shown in Figure 16 consists of three. components: a remote interface box (left side of photograph), a scale model interchange on Plexiglas with working loop detectors (middle of photograph), and a two-section ramp meter head (right side of photograph). The scale model interchange replicates the right half of the diamond interchange

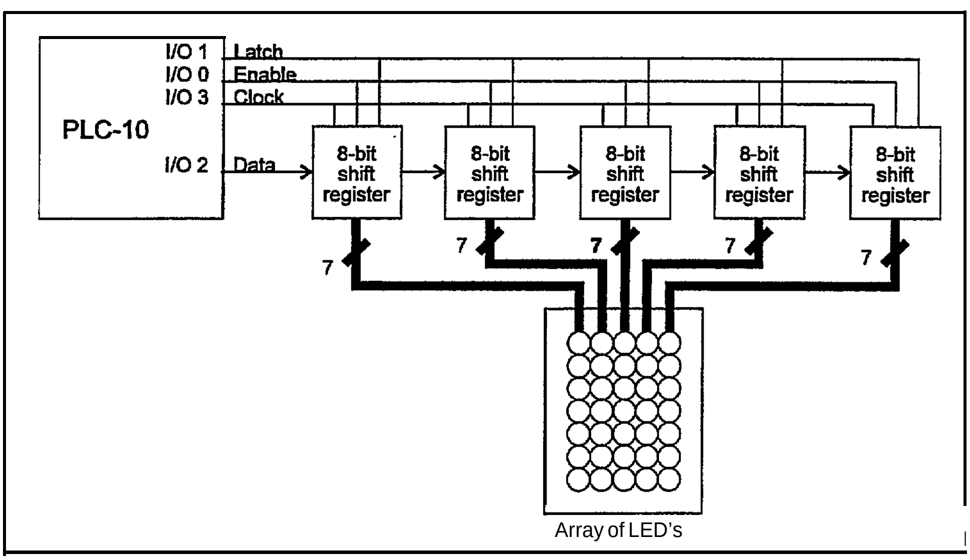

FIGURE 14 Changeable message sign cell schematic.

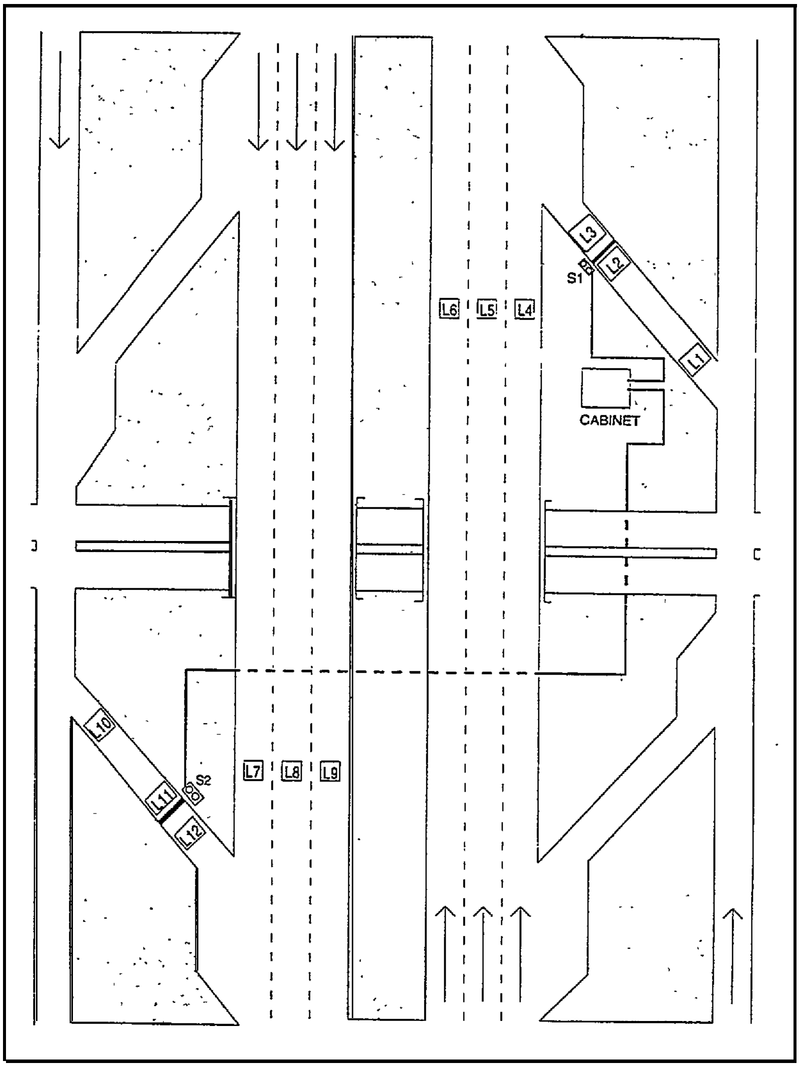

FIGURE 15 Distributed input/output requirements for ramp metering.

shown in Figure 15. Mounted underneath the Plexiglas are an Echelon PLC-10, a loop detector, and the necessary interface electronics (Figure 17). The remote interface box provides a power line carrier interface to the prototype remote ramp meter node (just as the cabinet would in a real installation similar to Figure 15). The interface box has a keypad, 4digit LED display, and four status LEDs. Inside the interlace box the keypad and status lights are connected to the PLC-10 through an interface shown schematically in Figure 18. From this remote interface box, we can upload parameters such as the occupancy of the mainline detectors (L4), the accumulated counts for Ll, L2, L3, and L4, the status of the solid state relays and the current sensors, the status of all the loops, the ramp meter cycle time, and the time duration of green displayed for each cycle. We can also download the metering rate, maximum green time displayed each cycle, and a flag that turns the meter on or Off.

The most important feature demonstrated in this prototype is the use of distributed computing devices to preprocess data. Normally, loop detectors provide a contact open/contact closed output. It is the traffic signal controller's responsibility to monitor this pulse train and calculate the appropriate traffic engineering summary statistics. When many loop detectors are combined to form more complicated systems (speed detection) this can place a significant demand on the controller. However, using this new approach, the controller only has to upload key parameters (presence, occupancy, and accumulated count) occasionally. This dramatically reduces the communication load on the traffic controller. Furthermore, using the network variable data-driven protocol concept, it is now feasible for loop detector vendors to incorporate new features in their loops such as malfunction management and vehicle classification. Several loop detector vendors have expressed a strong interest in introducing this concept into practice.

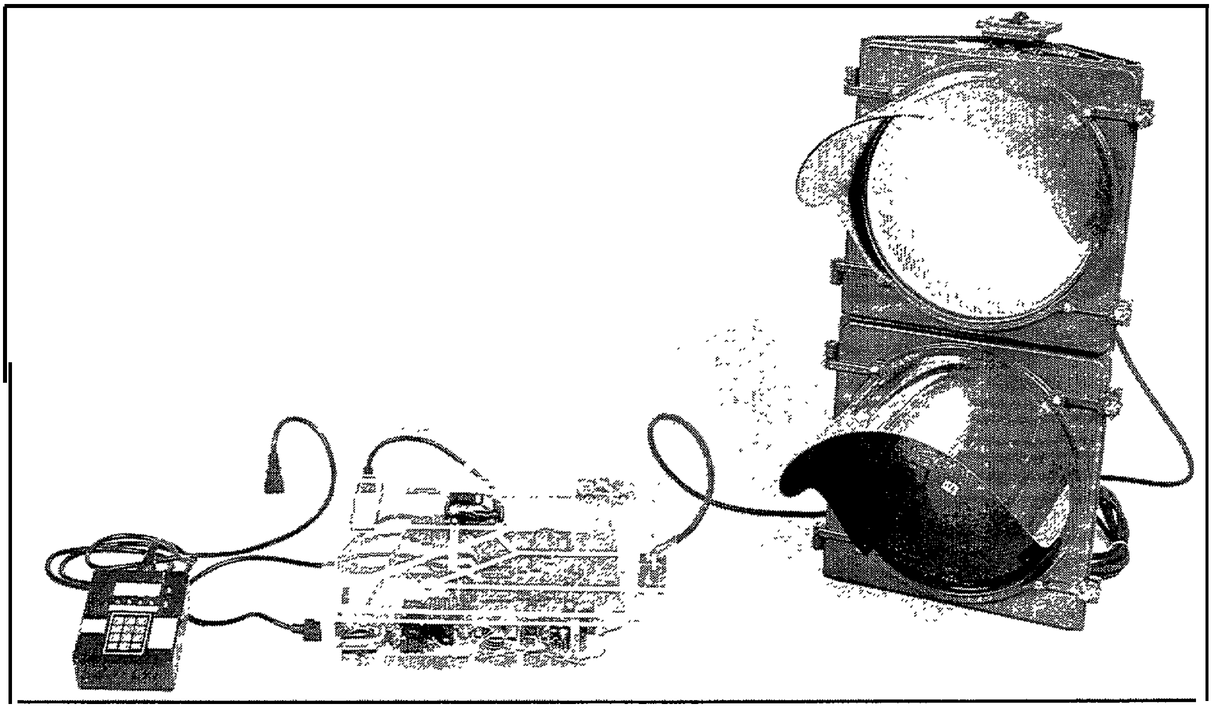

FIGURE 16 Prototype ramp meter controller and **remote interface.**

FIBER OPTIC SIGN CONTROL MODULE

Recently, the Federal Highway Administration designated Texas A&M University as a national Research Center of Excellence. As part of this research, TTI is developing a Smart Diamond traffic control system. Louisiana State University has a contract with the TTI IVHS RCE to work with the center on the development and implementation of a smart diamond intersection controller. One component of this system is a LONWORKS distributed dynamic lane control system. Although funding for the development of the dynamic lane control system was provided by the TTI IVHS RCE, all of the infrastructure used for fabricating the control modules was purchased through the ITS-IDEA contract.

Much of the freeway system throughout Texas has parallel frontage roads (Figure 15). The intersection of these frontage roads with cross streets are typically controlled using diamond intersection control logic. During certain periods of the day, it is desirable to favor left-turning movements on the frontage road. Figure 19 shows a photograph of a fiber optic sign designed by TTI and manufactured by National Sign. The sign is illuminating an R3-8 indication that would favor the left-turning movement. However, during other periods of the day, it is desirable to change the lane use indications so that the through movement is favored. Figure 20 shows a photograph of a fiber optic sign favoring the through movement.

Fiber optic sign displays like those shown in Figures 19 and 20 are used so that different lane use indications can be displayed on the same sign. Each fiber optic sign is made up of several different fiber bundles. For example, the pixels for the word "ONLY" in Figure 19 come from two different fiber bundles. Every other pixel in the word "ONLY' comes from alternating fiber bundles. During daytime operation, both bundles are illuminated so that the display is as bright as possible. During night operation, only one of the fiber bundles is illuminated to improve legibility. The sign has a total of 14 different fiber bundles that are illuminated by individual lamps. The lamps used to illuminate the fiber bundles are shown in Figure 2 1. Each of these lamps is powered by a transformer that steps the 110 volt line power down to 12 volts. Figure 22 shows the 14 transformers around the left, bottom, and right side. Current control practices for these signs rely on a few 110 VAC logic lines run from the controller to the sign. These lines determine which display is visible (Figure 19, Figure 20, or a transition display), and if the indications are bright or dim. Inside the sign relay logic is used to turn on and off the appropriate segments,

In these types of signs, it is extremely important to detect lamp failures since a missing segment changes the meaning of the sign. For example, during night operation, each segment is illuminated by only one lamp. If a lamp fails for a particular segment, it is important to detect that failure and then switch on the lamp powering the alternate fiber bundle. Once a malfunction is detected the traffic signal cabinet should log an appropriate alarm. However, if traditional cabinet control was used, individual conductors would have to be run for each

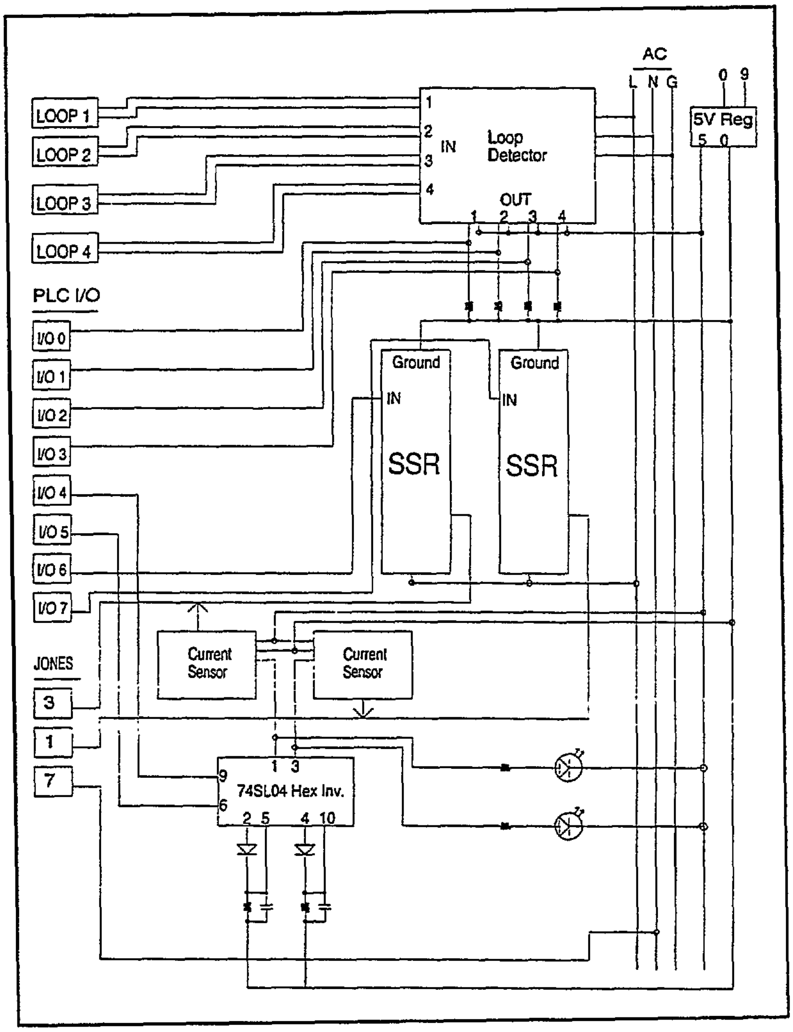

FIGURE 17 Ramp meter schematic.

transformer and each current sensor. For the sign shown in Figures 19 and 20, this would require that approximately 30 conductors be run between the cabinet and the sign. A typical diamond intersection would have two signs like those shown in Figures 19 and 20, as well as four smaller signs. To implement cabinet control and lamp monitoring for each sign would require a cabinet with approximately 56 load switches and 56 inputs monitoring the lamps. This would require a large cabinet and a tremendous amount of wiring.

As part of the TTI IVHS RCE, the LSU team developed a LONWORKS distributed control module that permits the traffic signal control cabinet to monitor and control the fiber optic sign over 110 VAC power lines. This control interface permits the controller in the cabinet to change lane indications and monitor the state of each lamp in the sign using only three conductors (Hot, Neutral, and Ground). The fiber optic sign control module communicates with the control cabinet by using the previously described spread-spectrum power line protocol. The control module in the sign has 14 solid state relays, 14 current sensors, and an Echelon PLC-10 module. In the traffic signal cabinet there is an interface box that controls each sign (Figure 19, Figure 20, and Dim or Bright) based on the state of two 24-volt logic lines. Outputs on the box indicate the status of each sign.

In summary, a distributed control module was developed that simplifies the cabinet wiring, reduces the number of conductors run to the signs, provides improved lamp monitoring, and implements intelligent malfunction management.

RESULTS

All the contracted tasks were completed as evidenced by the fabrication and demonstration of various prototype devices. On the basis of the work conducted during this research project, the following observations have been made:

- The LONWORKS technology was developed to enhance system integration in the industrial control sector, but is directly applicable to ITS. The heart of this

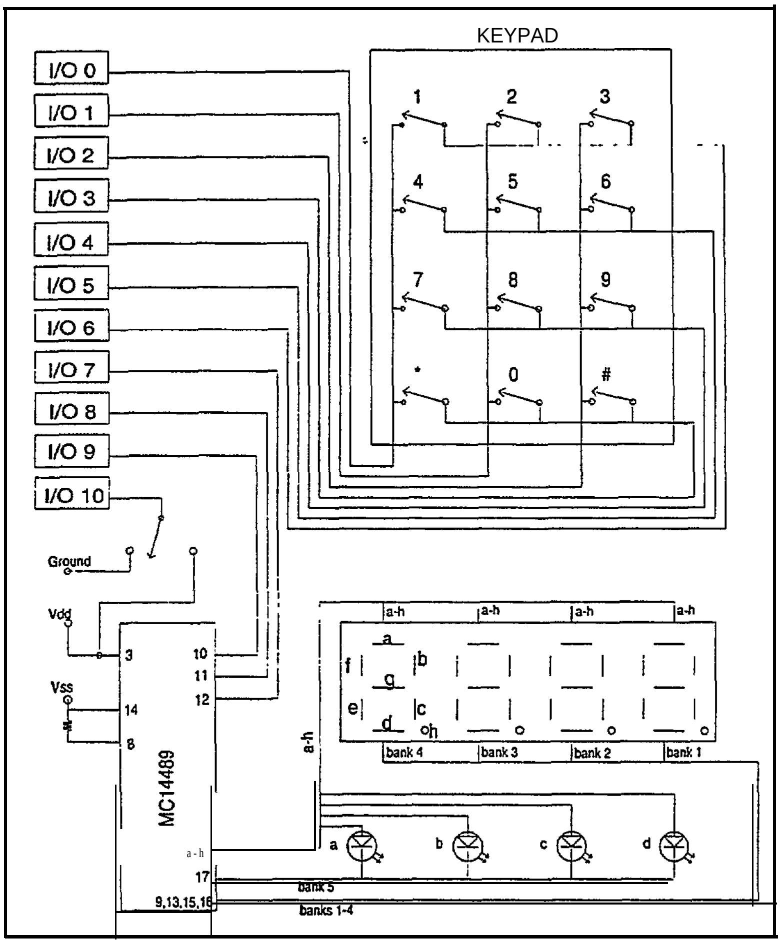

FIGURE 18 Schematic of interface box for remote ramp meter.

technology is a small computer called a Neuron. These devices cost about $3 apiece when purchased in significant quantities, are manufactured by multiple vendors, and provide sufficient computing power for controlling a variety of ITS-related sensors and actuators. Given this very low cost, we believe the savings accrued due to the reduced wiring will more than offset the cost of the Neurons and associated peripheral devices. Additional benefits will accrue over the life of a system because of reduced maintenance costs.

- Because the communication is embedded in the chip, vendors of new ITS devices do not have to incur the large

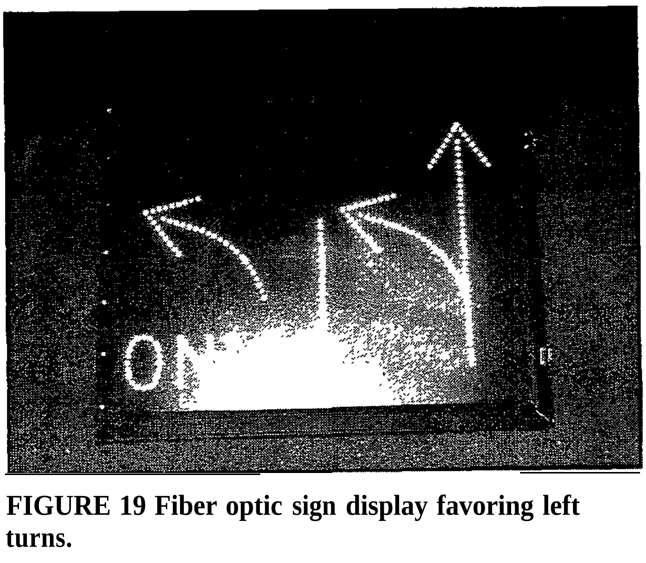

FIGURE 19 Fiber optic sign display favoring left turns.

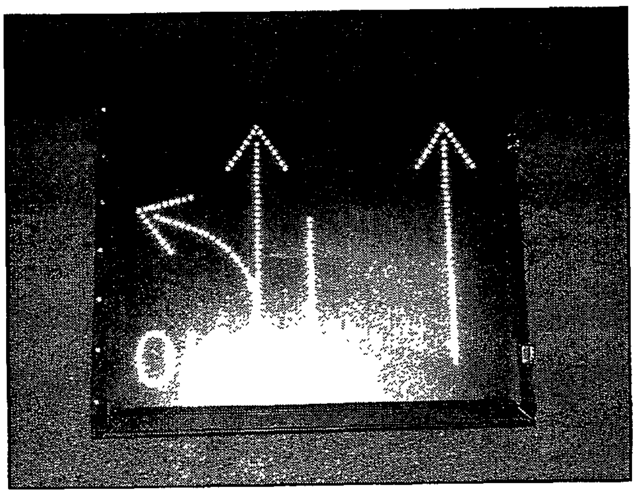

FIGURE 20 Fiber optic sign display favoring through movement,

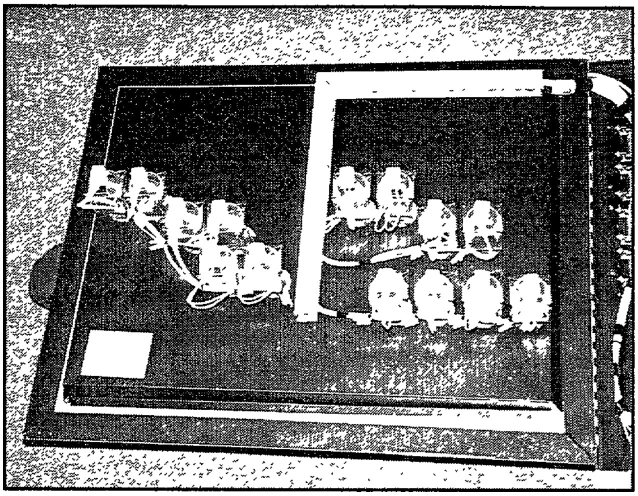

FIGURE 21 Lamps used to illuminate light fiber bundles.

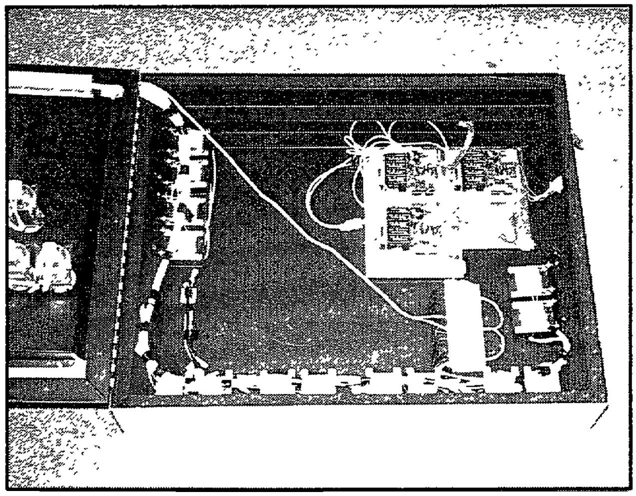

FIGURE 22 Transformers and distributed input/output control module.

software development costs associated with writing and maintaining communication software. Instead they can focus on their cure technologies.

- The spread-spectrum power line communication is extremely robust and typically packet loss rates are much lower than 1% (Tables 11 and 12). This robust communication technology is very promising for inexpensively retrofitting old 7-wire interconnect systems with moderate speed data communication requirements.
- Several prototype products (signal head control module, changeable message sign cell, ramp meter control module, and the TTI fiber optic sign control module) were fabricated and tested. The most promising prototype with near-term commercial implementation potential emerging from this research was the intelligent loop detector constructed for the ramp meter control module.
- We achieved our proposed objective of demonstrating distributed signal head operation similar to that shown in Figure 2. However, due to protocol overhead, we found the actual data throughput over the power line carrier is much less then 10 kbps. Consequently, under the worst case scenarios, the network shown in Figure 2 runs dangerously close to saturation.

CONCLUSION

The LonWorks spread-spectrum power line communication technology is extremely attractive for ITS applications with low data requirements such as message signs, remote ramp meter controllers, and fiber optic signs. However, when manufacturing costs, field maintenance practices, fault tolerance, and legal liability are all considered, it is not clear that installation of load switches in the signal head (Figure 4) could be justified at this time. We believe an in-cabinet LonWorks distributed input/output system, would be the next appropriate development. Instead of using the spread spectrum power line communication interface (10 kbps), a higher-speed LonWorks twisted-pair interface (1.25 Mbps) could be used for in-cabinet distributed computing and communication. The intelligent input/output modules could be distributed inside the traffic signal cabinet (Figure 7) instead of around the intersection. This in-cabinet Echelon data bus would operate approximately 125 times faster than the power line carrier. Although it would not simplify the wiring out at the signal heads, it would still dramatically simplify the cabinet wiring (Figure 1 versus Figure 7). Furthermore, it would provide an open architecture communication protocol to simplify adding in devices such as preemption receivers, sign controls, air quality sensors, and other emerging peripheral input/output devices. As traffic engineers gain confidence in this approach, distributed control modules residing outside the cabinet can be added. Devices requiring quick communication responses could use the dedicated twisted-pair communication interface whereas devices such as fiber optic signs or air quality sensors could use the slower power line interface.

Other projects are under way that closely tie in with this ITS-IDEA project.

- Matrix Corporation introduced a controller built to the preliminary ATMS 2070 specification with NEMA connectors at the ITS America show in April 1994. The CPU module included an Echelon LonTalk bus for reading and writing the I/O pins on the A, B, and C connectors (Figure 7). Because the controller already supports the LonTalk bus, it would be simple to extend the bus outside the controller to the load switch and loop detector racks.
- The TTI IVHS RCE has initiated a research project for developing a Smart Diamond Intersection controller. In its eventual deployment, this controller is expected to

employ advanced video tracking, real-time optimization, fiber optic dynamic lane assignment signs, priority transit service, and coordination with adjacent ramp meters. As part of that project, TTI has funded the LSU team to develop a LONTALK interface for fiber optic signs.

- One of the loop detector vendors is interested in adopting the LONWORKS technology to provide enhanced detection capabilities.

Given the promising results obtained from this IDEA project and other ITS projects under way, we are currently forming a consortium to further develop ITS applications of the Echelon LONWORKS technology.

In conclusion, this research project achieved its stated objectives and has stimulated a broad interest in distributed input/output systems for traffic signal control. We have made presentations to the 1995 TRB Annual Meeting (Session 91B), the Louisiana Department of Transportation, the Texas Department of Transportation, traffic signal equipment vendors, Federal Highway Administration officials, several traffic engineering consultants, and the local Institute of Transportation Engineers chapter. In general, we have received the most enthusiastic interest from people involved in maintenance activities because they see a big benefit in reducing the wiring and standardizing the communications interface.