Real-Time Control Systems
- Controlled by one Computer Processor
  - Centralized control systems
  - Real-time operating systems
- Controlled by one Communication Medium
  - Distributed control systems
  - Real-time communications
**Definition:**
- Control systems with physically distributed processing power and network communication of control signals

### Networked Control Systems (NCS)

- **Continuous-Variable/Device Network**
- **Discrete-Event/Cell Network**
- **Information/System Network**

#### In-Vehicle Network Systems
- CAN
- J1850
- J1939
- IDB 1394

#### Network at Tractor and Implement
- Protocols:
  - J1850
  - J1939

#### Distributed Manipulation Systems
- Protocols:
  - RS232
  - RS485

Source: ITS Data Bus Forum

Source: BioSystems Engineering, Oklahoma State Univ.

Source: USA Today

Source: Professor Luntz, ME, Univ. of Michigan, Carnegie Mellon Univ.
Introduction: Networks in Use (4)

Advanced Manufacturing Systems

Protocols:
- DeviceNet
- Ethernet
- Remote I/O

Source: NSF-ERC/EMS, Univ. of Michigan.

Introduction: Networks in Use (5)

Beverage Packaging & Food Processing

Rhode Island Beverage Packaging Plant

Protocols:
- ControlNet
- DeviceNet
- Ethernet
- Profibus

Source: Open DeviceNet Vendor Association

Introduction: Networks in Use (6)

Automobile Production at OPEL, Germany

Computer Integrated Manufacturing

Final Assembly: Marriage of chassis and body

Protocols:
- ControlNet
- DeviceNet
- Ethernet
- Profibus

Source: Profibus

Introduction: Networks in Use (7)

Beer Brewing at Germany

Protocols: ControlNet, DeviceNet, Ethernet, Profibus

Source: Profibus
Introduction: Networks in Use (8)

Orange Picking Robot

Introduction: Networks in Use (8)

Network Protocol: Data Networks & Control Networks

Network Protocol: Command- & Status-Based Systems

Network Protocol: Network Topology

(c) tree

(a) bus
(b) star
(d) ring
(e) mesh
Network Protocol: Network Topology

- Control Room 1
  - Ethernet Switch
  - Database Server
  - Controller
- Control Room 2
  - Ethernet Switch
  - Controller

Network Topologies:
- Star
- Bus
- Ring

Hirschmann Network Systems: Distributed Communication Architecture 03/25/04

Network Protocol: ISO-OSI 7-Layer Model

Node A
- Application
- Presentation
- Session
- Transport
- Network
- Data Link
- Physical

Node B
- Application
- Presentation
- Session
- Transport
- Network
- Data Link
- Physical

Communication Medium

Network Protocol: Message Framing

Layer  | Framing
--- | ---
Data  | data 1 of 3 data 2 of 3 data 2 of 3
Application  | data 1 of 3 data 2 of 3 data 3 of 3
Presentation  | data 1 of 3 data 2 of 3 data 3 of 3
Session  | data 1 of 3 data 2 of 3 data 3 of 3
Transport  | data 1 of 3 data 2 of 3 data 3 of 3
Network  | data 1 of 3 data 2 of 3 data 3 of 3
Data Link  | 10010011011011010101010101100100110110101010101010101
Physical  | 110010011011111001010101010101

Network Protocol: ISO-OSI 7-Layer Model

Layer  | Functions
--- | ---
Application  | Real data to send to another network device (IE, FTP, telnet, email)
Presentation  | Encoding data (different computers have different coding systems)
Session  | Token management (task exchange), synchronization (checkpoint)
Transport  | Split data into packets, and manage to the connect (TCP)
Network  | Add addressing for switching and routing (IP, ROUTER/GATEWAY)
Data Link  | Add error detection, flow control, and physical addressing
Physical  | (Medium Access Control, BRIDGE/SWITCH)
          | Transmits data over the medium (i.e., cable: fiber, twisted pair, etc. HUB/REPEATER)
### Network Protocol: ISO-OSI 7-Layer Model

#### Layer Control Networking Requirements

- **Application**: Data objects, standardized networking structures, authentication, network management, addressing, unicast, multicast, broadcast, routers.
- **Presentation**: Networking structures, data interpretation.
- **Session**: End-to-end ACK, duplicate detection, automatic retries.
- **Transport**: MAC collision avoidance/detection, framing, data encoding, priority, media transceivers.
- **Network**: End-to-end ACK, duplicate detection, automatic retries, routers, MAC collision avoidance/detection, framing, data encoding, priority, media transceivers.
- **Data Link**: End-to-end ACK, duplicate detection, automatic retries, routers, MAC collision avoidance/detection, framing, data encoding, priority, media transceivers.
- **Physical**: Node cost, installation cost, data rate, range, characteristics.

### Typical Industrial Networks

#### Application layers
- **Application**: Network transport layers
- **Presentation**: Application layers
- **Session**: Application layers
- **Transport**: Application layers
- **Network**: Application layers
- **Data Link**: Application layers
- **Physical**: Application layers

#### Characteristic table

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Twisted Pair</th>
<th>Radio</th>
<th>Power Line</th>
<th>Coaxial</th>
<th>Infrared</th>
<th>Fiber Optics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Range (m)</strong></td>
<td>1-1000</td>
<td>50-10,000</td>
<td>10-10,000</td>
<td>0.5-30</td>
<td>10-10,000</td>
<td></td>
</tr>
<tr>
<td><strong>Data rate (kb/s)</strong></td>
<td>0.3-2000</td>
<td>1.2-9.6</td>
<td>0.06-10,000</td>
<td>0.05-20</td>
<td>1-100,000</td>
<td></td>
</tr>
<tr>
<td><strong>Node cost</strong></td>
<td>$10-$30</td>
<td>$50-$100</td>
<td>$50-$150</td>
<td>$30-$75</td>
<td>$75-$200</td>
<td></td>
</tr>
<tr>
<td><strong>Installation cost</strong></td>
<td>Low</td>
<td>None-Low</td>
<td>Medium</td>
<td>Low</td>
<td>Medium-high</td>
<td></td>
</tr>
</tbody>
</table>
### Capability Hierarchy

**Level of functionality**
- Enterprise bus (Ethernet)
- Control bus (HSE, ControlNet)
- Fieldbus (Foundation Fieldbus, Profinet PA)
- Device bus (DeviceNet, Profinet DP, Interbus-S)
- Sensor bus (CAN, ASI, Seriplex, LonWorks)

### Worldwide most popular field busses

<table>
<thead>
<tr>
<th>Bus</th>
<th>User*</th>
<th>Application</th>
<th>Sponsor</th>
</tr>
</thead>
<tbody>
<tr>
<td>CANs</td>
<td>25%</td>
<td>Automotive, Process control</td>
<td>CiA, OVDA, Honeywell</td>
</tr>
<tr>
<td>Profinet (3 kinds)</td>
<td>26%</td>
<td>Process control</td>
<td>Siemens, ABB</td>
</tr>
<tr>
<td>LON</td>
<td>6%</td>
<td>Building systems</td>
<td>Echelon, ABB</td>
</tr>
<tr>
<td>Ethernet</td>
<td>50%</td>
<td>Plant bus</td>
<td>allele</td>
</tr>
<tr>
<td>Interbus-S</td>
<td>7%</td>
<td>Manufacturing</td>
<td>Phoenix Contact</td>
</tr>
<tr>
<td>Fieldbus Foundation, HART7%</td>
<td>7%</td>
<td>Chemical Industry</td>
<td>Fisher-Rosemount, ABB</td>
</tr>
<tr>
<td>ASI</td>
<td>9%</td>
<td>Building Systems</td>
<td>Siemens</td>
</tr>
<tr>
<td>Modbus</td>
<td>22%</td>
<td>obsolete point-to-point</td>
<td>many</td>
</tr>
<tr>
<td>ControlNet</td>
<td>14%</td>
<td>plant bus</td>
<td>Rockwell</td>
</tr>
</tbody>
</table>

*Source: ISA, Jim Pinto (1999)
**European market in 2002: 199 Mio USD, 16.6 % increase (Profinet: 1/3 market share)
**Source: Elektronik, Heft 7 2002
Worldwide most popular field busses

<table>
<thead>
<tr>
<th>Criterion</th>
<th>WorldFIP</th>
<th>CAN+</th>
<th>LONTalk</th>
<th>Seriplex</th>
<th>ISP</th>
<th>BITBUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perf./Speed/Determinism</td>
<td>Good</td>
<td>Good</td>
<td>Poor</td>
<td>Medium</td>
<td>Good</td>
<td>Medium</td>
</tr>
<tr>
<td>Interoperability</td>
<td>Good</td>
<td>Good</td>
<td>Poor</td>
<td>Medium</td>
<td>Good</td>
<td>Medium</td>
</tr>
<tr>
<td>Cost and Tech. Leverage</td>
<td>Medium</td>
<td>Good</td>
<td>Medium</td>
<td>Poor</td>
<td>Medium</td>
<td>Poor</td>
</tr>
<tr>
<td>Product Availability</td>
<td>Medium</td>
<td>Good</td>
<td>Medium</td>
<td>Poor</td>
<td>Medium</td>
<td>Poor</td>
</tr>
<tr>
<td>Development and Upkeep Cost</td>
<td>Poor</td>
<td>Good</td>
<td>Medium</td>
<td>Good</td>
<td>Poor</td>
<td>Good</td>
</tr>
<tr>
<td>Outlook</td>
<td>Medium</td>
<td>Good</td>
<td>Good</td>
<td>Medium</td>
<td>Good</td>
<td>Medium</td>
</tr>
<tr>
<td>Reliability</td>
<td>Good</td>
<td>Good</td>
<td>Medium</td>
<td>Good</td>
<td>Poor</td>
<td>Good</td>
</tr>
<tr>
<td>Peer-to-Peer Capability</td>
<td>Medium</td>
<td>Good</td>
<td>Poor</td>
<td>Medium</td>
<td>Poor</td>
<td>Poor</td>
</tr>
<tr>
<td>Memory Requirements</td>
<td>Poor</td>
<td>Good</td>
<td>Medium</td>
<td>Good</td>
<td>Poor</td>
<td>Poor</td>
</tr>
<tr>
<td>User Friend./Tools</td>
<td>Medium</td>
<td>Medium</td>
<td>Good</td>
<td>Medium</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Ownership</td>
<td>Good</td>
<td>Good</td>
<td>Poor</td>
<td>Medium</td>
<td>Poor</td>
<td>Good</td>
</tr>
<tr>
<td>Scalable Data Ser./Protocols</td>
<td>Poor</td>
<td>Medium</td>
<td>Good</td>
<td>Poor</td>
<td>Poor</td>
<td>Poor</td>
</tr>
<tr>
<td>Board size</td>
<td>Poor</td>
<td>Good</td>
<td>Medium</td>
<td>Good</td>
<td>Poor</td>
<td>Poor</td>
</tr>
<tr>
<td>Msg. Passing Capability</td>
<td>Good</td>
<td>Medium</td>
<td>Good</td>
<td>Poor</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Remaining Work</td>
<td>Good</td>
<td>Poor</td>
<td>Good</td>
<td>Poor</td>
<td>Medium</td>
<td>Medium</td>
</tr>
</tbody>
</table>

Table: Qualitative Candidate Analysis W.R.T. Selection Criteria

Source: ANALYSIS OF SENSOR / ACTUATOR BUS INTEROPERABILITY STANDARD ALTERNATIVES FOR SEMICONDUCTOR MANUFACTURING James R. Moyne, Nader Najafi, Daniel Judd, and Allen Stock
University of Michigan, Center for Display Technology Manufacturing, Ann Arbor, MI 48109-2108, 1 IBM, 2 Arlington Laboratories, 3 SEMATECH / Advanced Micro Devices

Research Issues in Network Systems

- **Architecture:**
  - Information/System Network (Information)
    - Throughput Analysis, Flow Control, Database Management
  - Discrete-Event/Cell Network (Control)
    - Correct & Safe Operation, Logic Control
  - Continuous-Variable/Device Network (Instrumentation)
    - Real-Time Control & Processing

- **Static Parameters:**
  - Medium Length
  - Node Number
  - Data Rate

- **Dynamic Parameters:**

- **Performance:**

One bus type cannot serve all applications and all device types efficiently...

**Data Networks**
- Workstations, robots, PCs
  - Higher cost
  - Not bus powered
  - Long messages (e-mail, files)
  - Not intrinsically safe
  - Coax cable, fiber
  - Max distance miles

**Sensor Bus**
- Simple devices
  - Low cost
  - Bus powered (7)
  - Short messages (bits)
  - Fixed configuration
  - Not intrinsically safe
  - Twisted pair
  - Max distance 500m

**High Speed Fieldbus**
- PLC, DCS, remote I/O, motors
  - Medium cost
  - Non bus powered
  - Messages: values, status
  - Not intrinsically safe
  - Shielded twisted pair
  - Max distance 800m

**Low Speed Fieldbus**
- Process instruments, valves
  - Medium cost
  - Bus-powered (2 wire)
  - Messages: values, status
  - Intrinsically safe
  - Twisted pair (reuse 4-20 mA)
  - Max distance 1200m

Research Issues in Network Systems

- **Architecture:**

- **Static Parameters:**

- **Dynamic Parameters:**
  - Message Connection
  - Medium Access Control

- **Performance:**
  - Network QoS
    - Throughput
  - Network Utilization
  - Network Efficiency
  - Network Stability
  - Network Delay
    - Message Period
    - Delay Statistics
Components of Time Delay

- Total end-to-end delay is the sum of
  - Pre-processing time: microprocessor
  - Waiting time: network protocol - MAC
  - Transmission time: data rate & length
  - Post-processing time: microprocessor

Industrial Networks

- 3 main types of Medium Access Control (MAC)
  - Ethernet:
    - EIB, EtherNet/IP, LonWorks, Modbus/TCP
  - Token Passing:
    - BACnet, ControlNet, FDDI, MAP, P-Net, Profibus, SP50, WorldFIP
  - Priority Based:
    - CAN, DeviceNet, SDS, CANOpen, CAN-Kingdom

Ethernet

- Carrier Sense Multiple Access / Collision Detection (CSMA/CD)
  - listen $\Rightarrow$ busy $\Rightarrow$ wait
  - listen $\Rightarrow$ idle $\Rightarrow$ send
  - collision $\Rightarrow$ backoff
- Backoff algorithm
  - standard binary exponential backoff
  - max collision = 16
  - $\Rightarrow$ potential for lost data
- Random time delays
Concurrent Time Domain Multiple Access (CTDMA) / Implicit Token Passing Bus
- A token rotating around the logical ring
- Every device can listen to the network
- Without token → wait
- With token → send messages

Bounded time delays

Carrier Sense Multiple Access / Arbitration on Message Priority (CSMA/AMP)
- A bit-synchronized bus
- Devices and messages have different priorities
- Listen → busy → wait
- Listen → idle → send
- Collision → low-priority node backoff, high-priority node keep on sending

Constant time delays