Communication Protocols

• Layering
  – Lower levels provide services to higher level
  – Easier to design
  – Physical layer
    • Lowest level in hierarchy
    • Medium to carry data from one actor (device or node) to another

• Protocols: real-time or best effort
  – Parallel
  – Serial
  – Wireless
Parallel communication

• Multiple data, control, and power wires
  – One bit per wire

• High data throughput with short distances

• Typically used when connecting devices on same IC or same circuit board
  – Bus must be kept short
    • long parallel wires result in high capacitance values which requires more time to charge/discharge
    • Data misalignment between wires increases as length increases

• Higher cost, bulky
Parallel Protocols: PCI Bus

- PCI Bus (Peripheral Component Interconnect)
  - High performance bus designed by Intel in the 1990’s
  - Interconnects CPUs, expansion boards, memory
  - Data transfer rates up to 1GBs for 64 bit addresses
  - Synchronous bus architecture
  - Multiplexed data/address lines

- PCI express
  - Serial, point-to-point protocol

Source: http://computer.howstuffworks.com
Parallel Protocols: ARM Bus

• ARM Bus
  – Designed and used internally by ARM Corporation
  – Interfaces with ARM line of processors
  – Many IC design companies have own bus protocol
  – Data transfer rate is a function of clock speed
  – 32-bit addressing
Serial Communication

- Single data wire – transmit one bit at a time
- Higher data throughput with long distances
  - Less average capacitance, so more bits per unit of time
- Complex protocol and interfacing logic
  - Sender needs to decompose word into bits
  - Receiver needs to recompose bits into word
  - Control signals often on the same wire -> increasing protocol complexity
Serial Communication

- Parameters:
  - Baud (bit) rate.
  - Number of bits per character.
  - Parity/no parity.
  - Even/odd parity.
  - Length of stop bit (1, 1.5, 2 bits).
Serial Protocol: 8251 UART

- Universal asynchronous receiver transmitter
- Takes parallel data and transmits serially at up to max 450 Kbps
- 8251 chip functions are integrated into standard PC interface chip.
Serial Protocols: $I^2C$

- $I^2C$ (Inter-IC)
  - Two-wire serial bus protocol developed by Philips Semiconductors ~20 years ago
  - Enables peripheral ICs to communicate using simple communication hardware
    - appropriate for peripherals where simplicity and low manufacturing cost are more important than speed
  - Normal mode: 100 Kbps with 7-bit address
  - Fast mode: 3.4 Mbpbs with 10-bit address
  - Common devices capable of interfacing to $I^2C$ bus:
    - EPROMS, Flash, and some RAM memory, real-time clocks, watchdog timers, and microcontrollers
    - Raspberry PI 2
Serial Protocols: USB

- **USB (Universal Serial Bus)**
  - Easier connection between PC and peripherals
  - USB 1.1 has 2 data rates:
    - 12 Mbps for increased bandwidth devices
    - 1.5 Mbps for lower-speed devices (joysticks, game pads)
  - USB 2.0 runs at 480 Mbps; USB 3.0 up to 5 Gbps
  - Tiered star topology can be used
    - One USB device (hub) connected to PC
    - Up to 127 USB devices can be connected to hub
  - USB host controller
    - Manages and controls bandwidth and driver software required by each peripheral
    - Dynamically allocates power downstream according to devices connected/disconnected
PCI Express (PCIe)

- Serial, point-to-point protocol
- Bandwidth is very scalable: 1x-16x links
- Max 6.4GBps in either direction on x16
- Switches for connecting different devices

Source: http://computer.howstuffworks.com
Real-Time Communication & Protocol Examples
Real-time Comm. Requirements

- Real-time behavior
- Efficient, economical
  (e.g. centralized power supply)
- Appropriate bandwidth and communication delay
- Robustness
- Fault tolerance
- Maintainability
- Diagnosability
- Security
- Safety
Real-time behavior

• Field bus:
  – A family of industrial computer network protocols used for real-time distributed control

• Carrier-sense multiple-access/collision-detection (CSMA/CD)
  – E.g. Ethernet: no timing guarantees

• Alternatives:
  – Token rings, token busses
  – Carrier-sense multiple-access/collision-avoidance: CSMA/CA
    • Each partner gets an ID (priority). After each bus transfer, all partners try setting their ID on the bus; partners detecting higher ID disconnect themselves from the bus. Highest priority partner gets guaranteed response time; others only if they are given a chance.
Event vs. time triggered

• Event Triggered (ET):
  – Computation/communication triggered by an external event
  – Events are primarily generated by changes in the environment
  – Efficient — only do things when they need to be done; rest and save energy/cpu time/bandwidth
  – High peak-load if multiple events happen at once
  – Hard to analyze due to asynchronous nature of events

• Time Triggered (TT):
  – Computation/communication triggered by system clock
  – Events happen according to a fixed schedule:
    • Inefficient — does things periodically, whether needed or not
  – Enhanced analizability due to easily characterizable load, predictable interaction sequences, bus use, etc.
Time division multiple access

• Each assigned a fixed time slot:

  - Master sends sync
  - Some waiting time
  - Each slave transmits in its time slot
  - Variations (truncating unused slots, several slots per slave) exist

http://www.ece.cmu.edu/~koopman/jtdma/jtdma.html#classical
Advantages of TDMA-busses over priority-driven schemes

- Can provide QoS guarantees
- TDMA resources support temporal composability, by separating resource access of different subsystems
- TDMA resources have a very deterministic timing behavior
- Can be made fault tolerant
- Support for error detection
- Support for error contention
  - a faulty subsystem does not affect the correct behavior of the remaining system

Field busses: Profibus

- More powerful and expensive than sensor interfaces
- Mostly serial; apps transmit a few bytes at a time
- Example: Process Field Bus (Profibus)
  - Designed for factory and process automation.
  - Focus on **safety**; comprehensive protocol mechanisms.
  - 20% market share for field busses.
  - **Token** passing.
  - $\leq 93.75$ kbit/s (1200 m); 1500 kbits/s (200m); 12 Mbit/s (100m)
  - Integration with Ethernet via Profinet.
Controller area network (CAN)

– Designed by Bosch and Intel in 1981;
– Key concept:
  • every device can be connected by a single set of wires, and every device that is connected can freely exchange data with any other device
– Originally designed for cars; now used also for:
  • elevator controllers, copiers, telescopes, production-line control systems, and medical instruments
– Binary countdown arbitration (CSMA/CD)
  • Start from MSB, transmit each bit of priority
  • Highest priority wins
– Throughput: 10kbit/s - 1 Mbit/s
– Low and high-priority signals
  • maximum latency of 134 μs for high priority

www.can.bosch.com
Aircraft communication systems

– **Information exchange**
  - **information**: many bytes of data: e.g. digital map, flight plan, etc.
  - **exchange**: a response is expected, at min acknowledgment
  - higher speed data link needed

– **Control platform**: sampling and data transmission
  - **data**: digital value of an analog parameter: e.g. speed; height etc.
  - No response is expected, but:
    - **Time, integrity and availability** are the key drivers.
    - The stability of the flight relies on this transmission
  - **Aeronautical response**: ARINC 429 protocol
ARINC 429 overview

• Developed by Aeronautical Radio, Incorporated (ARINC)
• Commonly used standard for the aircraft
• Electrical and data format standard for a 2-wire serial bus with one sender and many listeners.
• Each data is individually identified (by a label) and sent
Information system requirements

- Ensure that the information is transmitted without any error.
  - Data needs to be acknowledged
  - Messages can be sent again in case of error
- Past aircraft uses A429 but added acknowledgement.
ARINC 629

- Multi-transmitter protocol where many units share the same bus; originally designed for Boeing 777.

- Based on "waiting room" protocol:
  - Each node is assigned a unique number of mini slots that must elapse with silence on the channel before the data transmission begins

- Three (groups of) time-out parameters:
  - SG — synchronization gap controlling access to the waiting room
  - TGi — terminal gap, the personal time-out of node i
  - TI — transmit interval preventing monopolization of channel
  - TI > SG > max{TGi}

![Diagram of ARINC 629 parameters]
TTP (Time-Triggered Protocol)

TTP – more than just a protocol
- Network protocol
- Operating system scheduling philosophy
- Fault tolerance approach

Time-Triggered approach
- Stable time base
- Simple to implement
- Cyclic schedules
TTP versions

• TTP/A (Automotive Class A = soft real time)
  – A scaled-down version of TTP
  – A cheaper master/slave variant
    • Distributed master slave is expensive

• TTP/C (Automotive Class C = hard real time)
  – A full version of TTP
  – A fault-tolerant distributed variant
Protocol Layer in TTP/A

1. Application
2. Mapping of TTP-messages to application relevant data elements
3. Communication Network Interface
4. Message Checking and Error Detection
5. Serial Communication Interface
6. Bus Driver
7. Transmission Medium
TTP/A: Polling

• **Operation**
  – Master polls the other nodes (slaves)
  – Non-master nodes transmit messages when they are polled
  – Inter-slave communication through the master
Polling Tradeoffs

• **Advantages**
  – Simple protocol to implement
  – Historically very popular
  – Bounded latency for real-time applications

• **Disadvantages**
  – Single point of failure from centralized master
  – Polling consumes bandwidth
  – Network size is fixed during installation (or master must discover nodes during reconfiguration)
TTP/C

• TTP/C
  – A time-triggered communication protocol for safety-critical (fault-tolerant) distributed real-time control systems
  – Based on a TDMA (Time Division Multiple Access) media access strategy
    • has clock synchronization
  – Fail Silence
    • A subsystem is fail-silent if it either produces correct results or no results at all, i.e., it is quiet in case it cannot deliver the correct service
# TTP/C Protocol Layer

<table>
<thead>
<tr>
<th>Layer</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Host Layer</td>
<td>Application software in host</td>
</tr>
<tr>
<td>FTU CNI</td>
<td>Fault tolerance unit Communication Network Interface (CNI)</td>
</tr>
<tr>
<td>FTU Layer</td>
<td>Group two or more nodes into FTUs</td>
</tr>
<tr>
<td>Basic CNI</td>
<td>Provide the mechanisms for the cold start of a TTP/C cluster</td>
</tr>
<tr>
<td>RM Layer</td>
<td>Store the data fields of the received frames</td>
</tr>
<tr>
<td>SRU Layer</td>
<td>Provide the means to exchange frames between the nodes</td>
</tr>
<tr>
<td>Data Link/Physical Layer</td>
<td></td>
</tr>
</tbody>
</table>

- **FTU CNI**
  - Fault tolerance unit Communication Network Interface (CNI)

- **FTU Layer**
  - Group two or more nodes into FTUs

- **RM Layer**
  - Provide the mechanisms for the cold start of a TTP/C cluster

- **SRU Layer**
  - Store the data fields of the received frames

- **Data Link/Physical Layer**
  - Provide the means to exchange frames between the nodes
Structure of TTP/C System

- **CNI**: Communication Network Interface
- **TTP**: TTP Communication Controller
- **FTU**: Fault Tolerant Unit
- Controller to run protocol
- DPRAM (dual ported RAM)
  - Used for memory-mapped network interface
- BG (Bus Guard)
  - Hardware watchdog to ensure “fail silent”
- HW must use highly accurate time sources
  - Even dual redundant crystal oscillators are used for Boeing 777
(a) Two active nodes, two shadow nodes
(b) Triple modular Redundancy: three active nodes with one shadow
(c) Two active nodes without a shadow node
Cycle in TTP/C

- **TDMA Cycle**
  - One FTU sends results twice
  - Then next FTU sends some results
  - And so on, until back to the next message from the first FTU

- **Cluster Cycle**
  - Cluster cycle involves scheduling all messages and tasks
TTP/C Frame

- I-Frames used for initialization
- N-Frames used for normal messages
Pros and Cons of TTP

• Advantages
  – Simple protocol to implement
  – Deterministic response time
  – No wasted time for master polling messages

• Disadvantages
  – Wasted bandwidth when some nodes are idle
  – Stable clocks
  – Fixed network size during installation
# TTP/A vs. TTP/C

<table>
<thead>
<tr>
<th>Service</th>
<th>TTP/A</th>
<th>TTP/C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clock Synchronization</td>
<td>Central Multimaster</td>
<td>Distributed, Fault-Tolerant</td>
</tr>
<tr>
<td>Mode Switches</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Communication Error Detection</td>
<td>Parity</td>
<td>16/24 bit CRC</td>
</tr>
<tr>
<td>Membership Service</td>
<td>simple</td>
<td>full</td>
</tr>
<tr>
<td>External Clock Synchronization</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Time-Redundant Transmission</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Duplex Nodes</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Duplex Channels</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Redundancy Management</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Shadow Node</td>
<td>no</td>
<td>yes</td>
</tr>
</tbody>
</table>
FlexRay

- Robust, scalable, deterministic, and fault-tolerant digital serial bus system designed for use in automotive applications
- Developed by consortium: BMW, Ford, Bosch, Daimler-Chrysler, etc.;
  - Specified in SDL; finalized in 2009
- Built as extension to TTP and Byteflight protocols.
  - Improved error tolerance and time-determinism
  - Meets requirements with transfer rates >> CAN
    - initially targeted for ~ 10Mbit/sec;
    - design allows much higher data rates
- TDMA (Time Division Multiple Access) protocol:
  Fixed time slot with exclusive access to the bus
- Cycle subdivided into a static and a dynamic segment.
TDMA in FlexRay

- Exclusive bus access enabled for short time in each case.
  Dynamic segment for transmission of variable length information.
  Fixed priorities in dynamic segment: Minislots for each potential sender.
  Bandwidth used only when it is actually needed.

http://www.tzm.de/FlexRay/FlexRay_Introduction.html
Structure of Flexray networks

Bus Guardian (BG) protects the system against failing processors by gating access to Bus Driver (BD)
Comparison of real-time protocols

FIP = Flexible time triggered protocol; statically scheduled with centralized arbitration
LON = for building automation, uses TDMA with CSMA/CA and dynamically varies the number of slots per device for each schedule
Wireless communication

• Infrared (IR)
  – Frequencies just below visible light spectrum
  – Diode emits infrared light to generate signal
  – Infrared transistor detects signal
  – Cheap to build but need line of sight, limited range
  – Data transfer rate of 9.6 kbps and 4 Mbps

• Radio frequency (RF)
  – Electromagnetic wave frequencies in radio spectrum
  – Analog circuitry and antenna needed on both sides
  – Line of sight not needed, transmitter power determines range
• Use of EM field to transfer data, for identifying and tracking tags attached to objects; no need for line of sight

• Active vs. passive tags
  – Active transmits ID, they are low power (~10-100uA) but higher cost ($10-$200/unit retail)
  – Passive can be read by RF - no intrinsic power consumption (powered by EM induction) and cheaper ($0.20-0.40)

• Readers
  – $100+ to $1000s, range from read and report to smart tracking, etc.

• Using RFID for real-time location systems (RTLS)
  – Only active tags work with range 100m+ in line of sight, or 1-20m obstructed
  – Battery - up to years on a single charge @ <1Hz transmission rate
  – Location accuracy as close as 30cm with reader presence
Bluetooth, BLE, Zigbee

- **Bluetooth**
  - IEEE 802.15.1
  - Developed and licensed by the Bluetooth Special Interest Group (SIG)

- **BLE**
  - Adopted into Bluetooth specification
  - *Bluetooth Low Energy Technology*

- **ZigBee**
  - IEEE 802.15.4
  - Maintained and published by the ZigBee Alliance
## Side By Side Comparison

<table>
<thead>
<tr>
<th></th>
<th>Bluetooth</th>
<th>BLE</th>
<th>ZigBee</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Band</strong></td>
<td>2.4GHz</td>
<td>2.4GHz</td>
<td>2.4GHz, 868MHz, 915MHz</td>
</tr>
<tr>
<td><strong>Antenna/HW</strong></td>
<td>Shared</td>
<td></td>
<td>Independent</td>
</tr>
<tr>
<td><strong>Power</strong></td>
<td>100 mW</td>
<td>~10 mW</td>
<td>30 mW</td>
</tr>
<tr>
<td><strong>Battery Life</strong></td>
<td>Days – months</td>
<td>1-2 years</td>
<td>6 months – 2 yrs</td>
</tr>
<tr>
<td><strong>Range</strong></td>
<td>10-30 m</td>
<td>10 m</td>
<td>10-75 m</td>
</tr>
<tr>
<td><strong>Data Rate</strong></td>
<td>1-3 Mbps</td>
<td>1 Mbps</td>
<td>25-250 Kbps</td>
</tr>
<tr>
<td><strong>Network Topologies</strong></td>
<td>Ad hoc, point to point, star</td>
<td>Ad hoc, point to point, star</td>
<td>Mesh, ad hoc, star</td>
</tr>
<tr>
<td><strong>Time to Wake and Transmit</strong></td>
<td>3s</td>
<td>3ms</td>
<td>15ms</td>
</tr>
<tr>
<td><strong>Security</strong></td>
<td>128-bit encryption</td>
<td>128-bit encryption</td>
<td>128-bit encryption</td>
</tr>
</tbody>
</table>
Wireless Protocols: 802.11

- **IEEE 802.11**
  - Standard for wireless LANs
  - Specifies parameters for PHY and MAC layers of network
    - **PHY layer**
      - handles transmission of data between nodes
      - data transfer rates up to 600 Mbit/s for 802.11n
      - operates in 2.4 / 5 GHz frequency band (RF)
    - **MAC layer**
      - medium access control layer
      - protocol responsible for maintaining order in shared medium
      - collision avoidance/detection
Summary

• Interfacing: on & off chip
• Real-time IO
  – Profibus
  – CAN
  – ARINC
  – TTP/A & TTP/C
  – FlexRey
• Wireless
  – IR, BLE, ZigBee, RFID, 802.11