Communication Protocols for Embedded Systems

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Overview

• Definition of a protocol
• Protocol properties
• Basic Principles
• Embedded system communication protocols
• Summary
What is a communication protocol?

“A set of formal rules describing how to exchange data.”

“Low-level protocols define the electrical and physical standards to be observed, bit- and byte-ordering and the transmission and error detection and correction of the bit stream.”

“High-level protocols deal with the data formatting, including the syntax of messages, the terminal to computer dialogue, character sets, sequencing of messages etc.”

Requirements for Communication

• Agreed code space:
  How is the data encoded?

• Agreed time space:
  When is the data valid?

• Agreed name space:
  What does the transmitted data mean?”
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Properties of Data Exchange

- Message-based data exchange
  - Data flow
  - Control flow (controlling the information exchange between sender and receiver)

- Shared memory-based data exchange
  - No control flow over shared memory
State / Event Messages

• State messages: periodic exchange of state information

  \[ \text{State Information} := \langle \text{Name}, \text{Value}, t_{\text{obs}} \rangle \]
  – Time - triggered communication

• Event messages: sporadic exchange of event information

  \[ \text{Event Information} := \langle \text{Name}, \Delta \text{Value}, t_{\text{event}} \rangle \]
  – Event - triggered communication

State Information

• At sender:
  – At-least-once transmission
  – Non-consuming sending, one can send the same status data many times.

• At receiver:
  – Update in place
  – Non-consuming read (one can read the last valid message)

• No state synchronization required
• Idempotent

Event Information

• At sender:
  – Exactly-once transmission
  – Consuming sending

• At receiver:
  – Queuing
  – Consumed upon read

• History state required=>queuing
Communication Parameters

• Message delay
  – Latency - time interval between the start of message transmission at the sender node and the time of reception of the message at the receiver node
  – \(d_{\text{max}}\) maximum delay;
  – \(d_{\text{min}}\) minimum delay
  – Jitter \(\varepsilon = d_{\text{max}} - d_{\text{min}}\)

• Bandwidth
  – Net bandwidth vs. total bandwidth

• Fault handling
  – Message retransmission
  – Forward error correction
  – Message redundancy

Control Flow: Push and Pull Style

• Push style communication:

• Pull style communication:
The PAR Principle
(Positive Acknowledge or Retry)

- Sender initiates communication (Push principle)
- Sender waits for receiver's answer or timeout
- Communication errors are detected by the sender
- Time redundancy is used to correct an error (increased latency and traffic in the presence of errors)
- Problems:
  - Jitter
  - Thrashing (throughput decreases above particular load)
- PAR principle used in TCP

Message-based Clock Synchronization

- Simple Method – message transmission times are known:
  - A sends message containing its local time
  - Receiver B can correct with term \((d_{\text{min}} + d_{\text{max}})/2\)
  - Jitter affects precision
- Round-Trip Method – message transmission times are not known:
  - B requests timestamp message from A
  - B measures duration \(\Delta t\) until reception of answer
  - B corrects with term \(\Delta t/2\)
  - \(d_{\text{min}}\) and \(d_{\text{max}}\) must not be known
  - Jitter affects precision
Clock Synchronization with Shared Memory

- Shared Memory contains a real-time image of a clock
- Sender must guarantee that timestamp is not older than duration $d$
- $d$ affects precision

Time-Triggered vs. Event-Triggered

- Time-triggered communication protocols
  - sending and receiving actions are driven by the time
  - exchange of state messages
  - All communicating partner need to have a priori knowledge of the message send/receive time instants
- Event-triggered communication protocols
  - sending and receiving actions are driven by an event
  - exchange of event messages
  - No a priori knowledge of the message send/receive time instants is needed
Time-Triggered Communication

- Sender: Push style
- Receiver: Pull style
- Control flow is interrupted by memory element
  *Temporal Firewall*
- Communication between memory element occur at predefined instants

Time-Triggered Communication Schedule

<table>
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<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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<tbody>
<tr>
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<td>Receive</td>
<td>Receive</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Receive</td>
<td>Send</td>
<td>Receive</td>
<td>Send</td>
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<tr>
<td>C</td>
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<tr>
<td>D</td>
<td>Receive</td>
<td>Receive</td>
<td></td>
<td>Receive</td>
</tr>
</tbody>
</table>

![Diagram of Time-Triggered Communication Schedule]
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Token Principle

• token is passed from one station to another according to a set of rules
• Only the station in possession of the token is allowed to transmit data
• Token ring is a logical ring topology, but can physically implemented as bus, star, or ring
• Recovery from lost/duplicate tokens?
  – Token hold time
  – Token rotation time
• IEEE 802.5 (IBM token ring), FDDI (Fiber Distributed Data Interface)
Master/Slave Principle
Polling
- Master sends request message
- Slave answers on request
- Usually cyclic polling (e.g., ASi, LIN bus)
- Multiple masters as token ring (e.g., Profibus)

TDMA Principle
(Time Division Multiple Access)
- The time is the token
- Requires common time base and predefined schedule in all nodes
- Common time base via distributed reference clocks (TTP/C)
- Common time base via master reference clock (TTP/A)
**CSMA/CD Principle (Push)**

*(Carrier Sense Multiple Access/Collision Detection)*

- Listen before transmit. If channel is sensed busy, defer transmission
- Collisions may still exist, since two stations may sense the channel idle at the same time
- Verify transmission by read back
- If collision, back off and retransmit later
- CSMA/CD principle used in 10Mbps Ethernet (IEEE 802.3), Fast Ethernet (100Mbps), Gigabit Ethernet (1,000 Mbps)

**CSMA/CA Principle (Push)**

- There are two states on the communication channel
  - dominant and recessive
- Listen before transmit. If channel is sensed busy, defer transmission
- Node first sends an ID and verifies *bit by bit* by read back
- Node stops transmission if a *bit* of the ID is overwritten by other node
- ID with dominant Bits at beginning have higher priority
- Requires *Bit time > 2 · LineDelay*
- E.g. Bus length 40 m, propagation delay 200 nsec
Minislotting

- Minislotting requires that each node waits for a certain period after sending a message before it sends another message.
- Media access is controlled by three intervals:
  - TG: Terminal Gap controlling the access to the bus,
    - different for every node,
    - longer than the propagation delay of the channel
  - TI: Transmit Interval
    - Disabling the host from monopolizing the bus
      - same for all nodes
  - SG: Synchronization Gap
    - same for all nodes
    - Control the sequence of entrance in the waiting room
      - $SG > \max (TG)$
      - $TI > SG$
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TTP/C

• Synchronous system
• Common communication schedule - TDMA
• Known upper bound on the transmission time of a message
• Aerospace industry
• Bus and/or star topology
• Fault tolerant
  – two communication channels
  – fault tolerant midpoint (clock synchronization)
  – Using a priori knowledge (guardian)
TTP/A

- Time-Triggered
- TDMA
- Master/Slave
- Bus topology
- A priori knowledge

CAN protocol

- Event-Triggered
- Automotive industry
- Bandwidth up to 1 Mbit/sec
- Bus topology
- Different variants
  - Full CAN
  - CAN kingdom
  - ...
Arinc 629

- Aerospace industry (Boeing 777)
  - Synchronization Gap (SG) 4-128 μsec
  - Terminal Gap (TG) 0.5 – 64 msec
- Bandwidth: 2 Mbit/sec

FlexRay

- Combination of TDMA and mini-slotting
  - Communication bandwidth is divided into two segments:
    - Static segment (TDMA)
      - State messages
    - Dynamic segment (mini-slotting)
      - Event messages
- Automotive Industry
- Bandwidth up to 10 Mbit/s
- Bus or star topology
**Time-Triggered Ethernet**

- Integration of time-triggered and event triggered traffic into a same communication infrastructure
- TT traffic (periodic with 16 different periods)
- ET traffic – standard Ethernet, TCP/IP, UDP, …
- Star topology
- Bandwidth: 100 Mbit/s, 1 Gbit/s

**Principle of Operation**

- TT Ethernet switch - transmits TT msg. with a constant delay
- Transmission of ET msg. is preempted,
  - if during the transmission a TT msg. arrives at a switch port, ET msg. is stored in the buffer of the switch, and retransmitted as soon as the transmission of the TT msg. is finished
- If during the transmission of TT msg. an ET msg. arrives in a port of the switch, the ET msg. is stored in the buffer of the switch and transmitted after the transmission of TT msg. is finished

![Diagram of Time-Triggered Ethernet](image.png)
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Conclusion

• Communication needs a set of rules describing how to transmit data
• Push style communication in combination with retransmission mechanism leads to high jitter
• Polling, Token ring and TDMA are deterministic
• Usually tradeoff: Average performance <-> Determinism/Worst case performance
Questions?