13
Embedded Communication Protocols

Distributed Embedded Systems

Philip Koopman

October 12, 2015

Carnegie Mellon

Where Are We Now?

- **Where we've been:**
  - Design
  - Distributed system intro
  - Reviews & process
  - Testing
- **Where we're going today:**
  - Intro to embedded networking
    - If you want to be distributed, you need to have a network!
- **Where we're going next:**
  - CAN (a representative current network protocol)
  - Scheduling
  - …

2

Preview

- **"Serial Bus"**
  = "Embedded Network"
  = "Multiplexed Wire" ~= "Muxing"
  = "Bus"

- **Getting Bits onto the wire**
  - Physical interface
  - Bit encoding

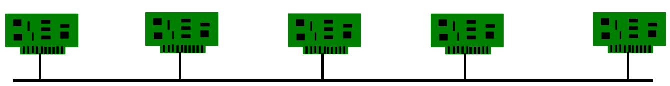
- **Classes of protocols**
  - General operation
  - Tradeoffs
    (there is no one "best" protocol)
  - Wired vs. wireless

"High Speed Bus"

3

Linear Network Topology

- **BUS**



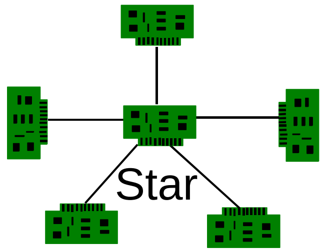
  - Good fit to long skinny systems
    - elevators, assembly lines, etc...
  - Flexible - many protocol options
  - Break in the cable splits the bus

  - May be a poor choice for fiber optics due to problems with splitting/merging
  - Was prevalent for early desktop systems
  - Is used for most embedded control networks

4

Star Network Topologies

- **Star**
  - Can emulate bus functions
    - Easy to detect and isolate failures
    - Broken wire only affects one node
    - Good for fiber optics
    - Requires more wiring; common for current desktop systems
  - Broken hub is catastrophic
  - Gives a centralized location if needed
    - Can be good for isolating nodes that generate too much traffic

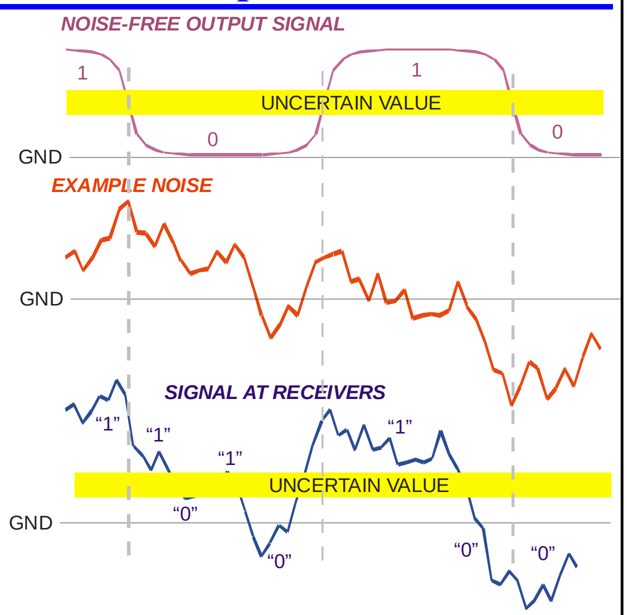


- **Star topologies increasing in popularity**
  - Bus topology has startup problems in some fault scenarios
  - Safety critical control networks moving to dual redundant star (Two independent networks, each network having star topology)

5

Hardware Connection Techniques

- **Circuits need to assert "HI" and "LO" on a physical bus**
  - Example:
    HI = 5 volts
    LO = 0 volts



- **Noise immunity is important**
  - Isolate noise on any single node from carrying over to network
  - Prevent noise on network from affecting nodes

6

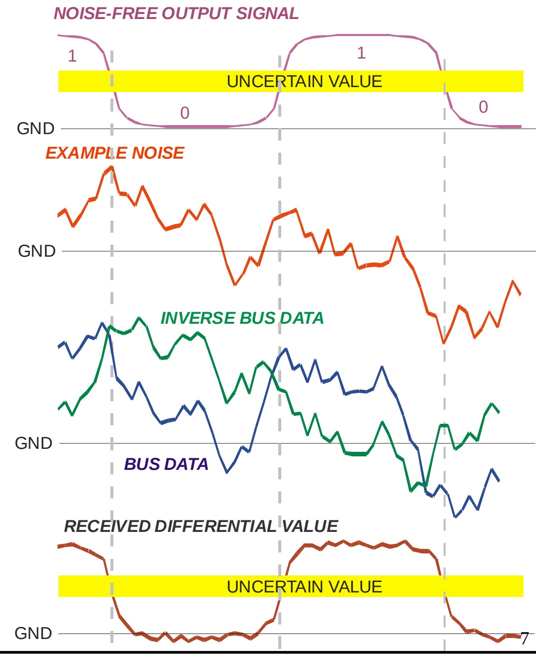
Differential Drivers To Suppress Noise

- **Send both Data and Inverse Data values on a 2-wire bus**
  - Example:

    DATA — HI = 5 volts, LO = 0 volts

    Inverse DATA — HI = 0 volts, LO = 5 volts

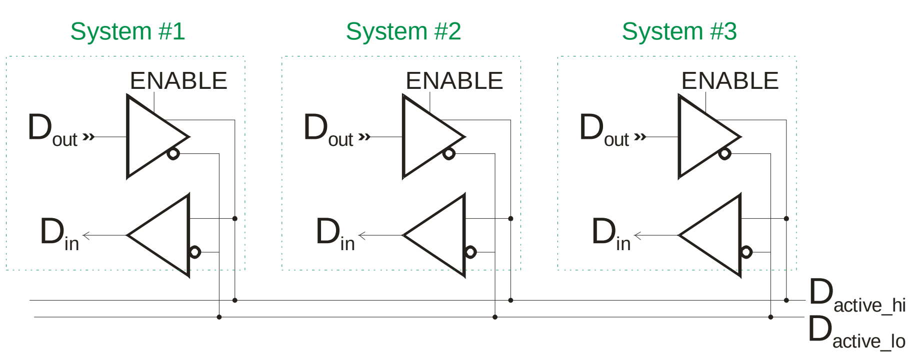
  - Receiver subtracts two voltages
    - Eliminates common mode voltage bias
    - Leaves any noise that affects lines differently



7

RS-485 Is A Common Multi-Master Bus

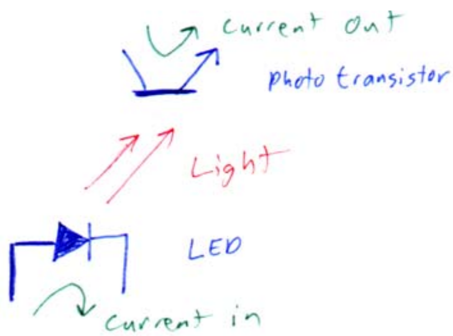
- **Used in industrial control networks (e.g., Modbus; Profibus)**
  - RS-422 differential drivers; high speed + good range (10 Mb/s @ 12 meters)
  - Add terminators to reduce noise
  - Make sure that exactly one system has its output enabled at a time!
    - Often it is "master/slave" – one system tells each other system when its turn comes



8

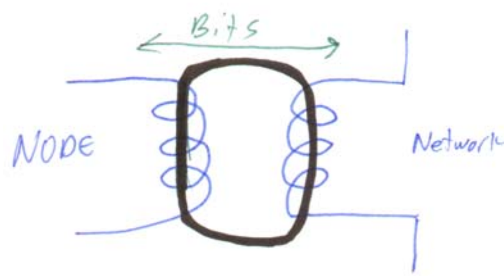
Optical Isolators For Voltage Spikes

- **Big noise spikes can cause damage to connected nodes**
  - Want isolation to help with very sharp, big spikes
- **Optical isolators provide a physical "air gap"**
  - LED illuminates when provided with current
  - Photo-transistor conducts when LED shines IR light on it
  - Two sets for each node – one set for transmit; a second set for receive
- **Provides excellent isolation**
  - No physical connection – just photons crossing a gap
  - LED saturates, preventing over-drive
  - Still subject to noise
  - Network must have its own power supply for receive LEDs
- **Supports bit dominance**
  - If LED sticks "on" network is disrupted



What About Voltage Spikes & Stuck Nodes?

- **"Stuck" nodes are a problem**
  - If a node sticks at transmitting a "low" or "high", can disable entire network
- **One common solution: current-mode transformer coupling**
  - AC component of bit edges crosses transformer
  - DC component of stuck nodes is ignored
  - Transformer's inductance protects against spikes
  - Current mode operation improves noise rejection
  - Commonly used in flight controls
- **BUT, limitations**
  - Can't do bit dominance
  - Collision detection very difficult
  - Transformer "droop" requires frequent data edges
  - Signals must be DC balanced (equal "hi" and "lo" energy)



Encoding Styles

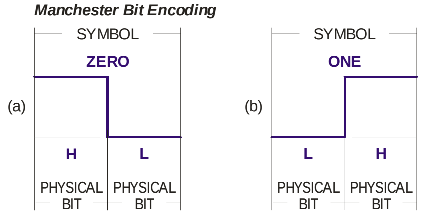
- **RZ – Return to Zero encoding**
  - Encoding ensures that signal returns to “zero” every so often
  - Forces edges every bit or two by simple encoding rules
    - Makes it easy to synchronize receivers to bit stream
    - Makes it easy to use transformer coupling
- **NRZ – Non-Return to Zero encoding**
  - Attempts to improve efficiency by just sending bit values without guaranteed edges
  - But, lack of edges makes it difficult to synchronize receivers
    - We’ll discuss ways around that problem
    - And makes use with transformer coupling difficult
- **Notes:**
  - Both encodings are subject to bit flips, even with differential transmitters
  - We’re using “physical bits” to represent HI/LO values
    - Symbols (“data bits”) might take one or more physical bits, depending on encoding

11

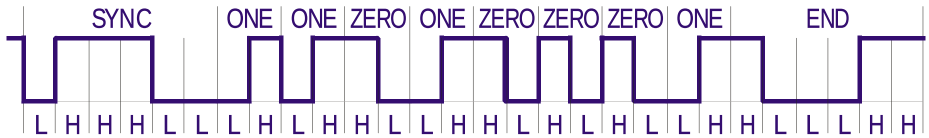
Basic Bit RZ Encoding - Manchester

- **Manchester Encoding**
  - Data encoded by transition from high-to-low or low-to-high
  - Guaranteed transition in every bit – but worst case bandwidth is 2 edges per bit
  - Errors require inverting adjacent pairs of physical bits

Manchester Bit Encoding



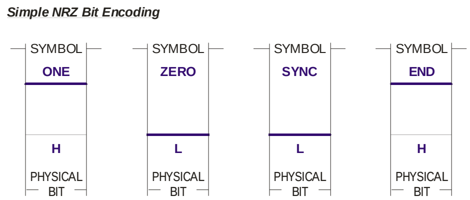
Manchester Encoding Example: 1101 0001

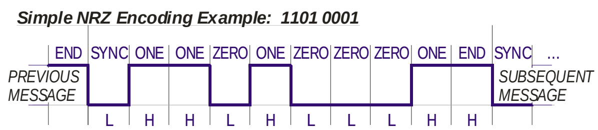


12

Non-Return to Zero (NRZ) Encoding (see 18-348)

- **Send a Zero as LO; send One as HI**
  - Worst case can have all zero or all one in a message – no edges in data
  - Simplest solution is to limit data length to perhaps 8 bits
    - SYNC and END are opposite values, guaranteeing two edges per message
    - This is the technique commonly used on computer serial ports / UARTs
  - Bandwidth is one edge per bit
    - But no guarantee of frequent edges





13

Generic Message

START	HEADER	PAYLOAD	ERROR DETECTION	END

- **Start symbol**
  - Designates start of a message and lets receiver sync to incoming bits
- **Header**
  - Global priority information (which message gets on bus first?)
  - Routing information (source, destination)
- **Payload (Data)**
  - Application- or high-level-standard defined data fields (often only 1-8 bytes)
- **Error detection**
  - Detects corrupted data (e.g., using a CRC)
- **End**
  - Designates end of message

14

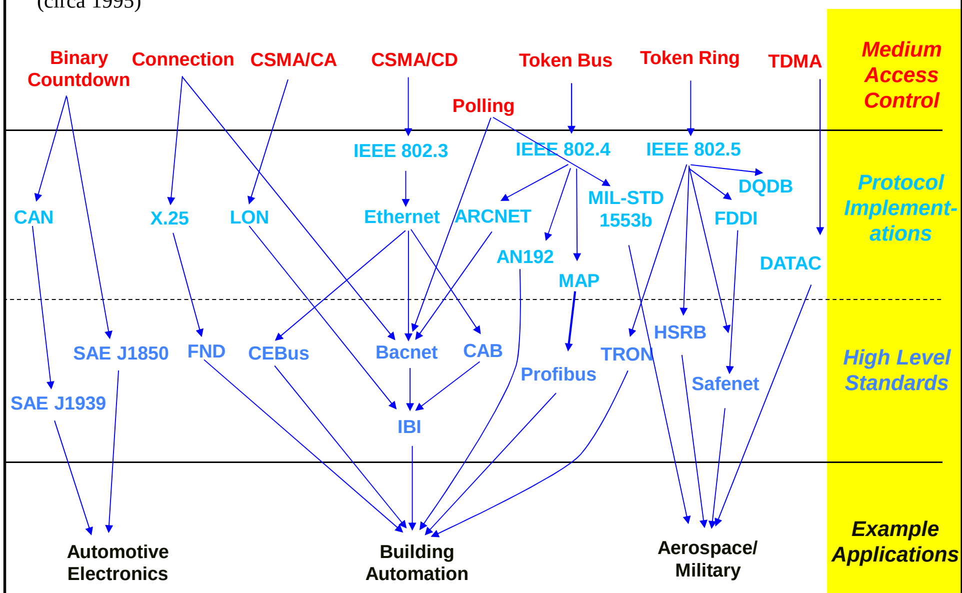
Central Issue: Message Priority

- **Local priority**
  - Each node transmits its highest priority message *when it gets a turn on the bus*
  - Or, it can implement some form of round-robin message transmission, etc.
- **Global priority**
  - Which node gets the next turn on the bus?
  - Could be a function of round-robin selection of nodes
  - Could be a function of the node's inherent priority
  - Could be a function of the priority of the highest message on the node -- a "global message priority" scheme
- **Fundamental tension:**
  - Reducing latency for high-priority nodes/messages
    vs.
  - Ensuring fairness/no starvation for low-priority nodes/messages

15

Embedded Protocol Family Tree

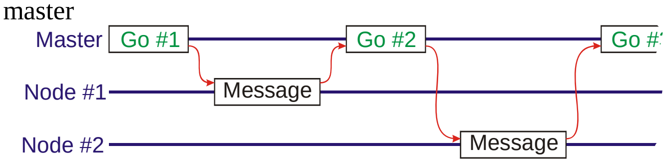
(circa 1995)



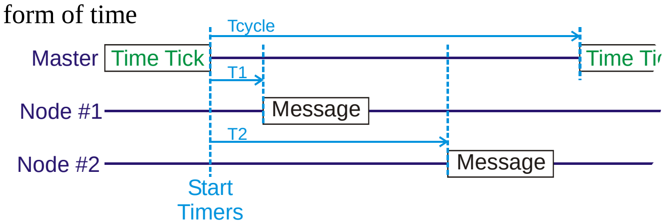
16

Coordination: Bus Master Approach

- **Bus Master can poll for messages & wait for response**
  - Problem: missing/slow slave
    - Master uses worst-case timeout waiting for response
    - If slave gets confused/is late, protocol fails
  - Problem: broken master

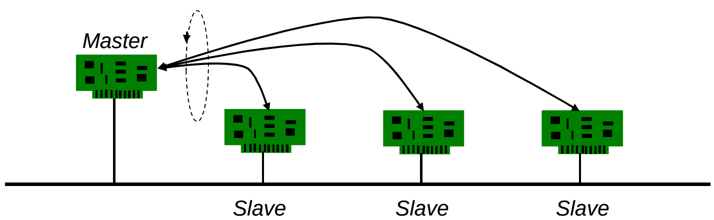


- **Master can send a time tick – TDMA**
  - Other nodes select response time from that time tick
  - Then becomes a form of time slice/time slot protocols (discussed later)



17

Polling



- **Operation**
  - Centrally assigned Master polls the other nodes (slaves)
  - Non-master nodes transmit messages when they are polled
  - Inter-slave communication through the master
- **Examples**
  - MIL-STD-1553B, 1773, Profibus, Bacnet, AN192

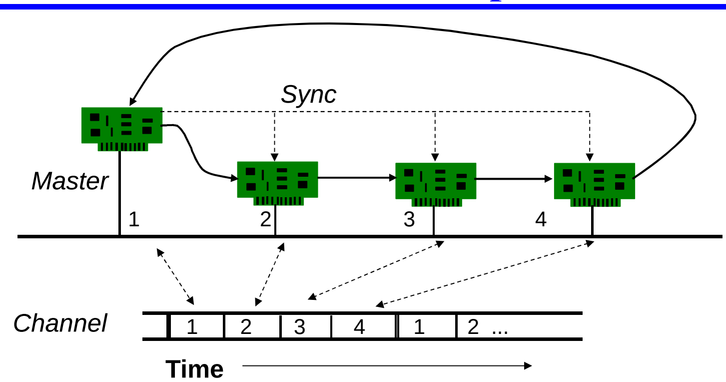
18

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 fixed during installation (not robust)
    - Or, master must discover nodes during reconfiguration
  - Prioritization is local to each node
    - But, can use centralized load balancing
    - Polling need not be in strict order; it could be, for example:
      1, 2, 1, 3, 4, 1, 5, 1, 3, 1, 6, …(repeats)

19

TDMA - Time Division Multiplexed Access



- **Operation**
  - Master node sends out a frame sync to synchronize clocks
  - Each node transmits during its unique time slot
- **Examples**
  - Satellite Networks, DATAC, TTP, static portion of FlexRay

20

TDMA Tradeoffs

- **Advantages**
  - Simple protocol to implement
  - Deterministic response time
  - No wasted time for Master polling messages

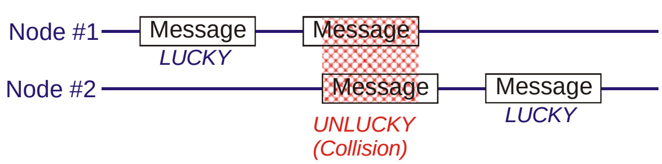
- **Disadvantages**
  - Single point of failure from the bus master
  - Wasted bandwidth when some nodes are idle
  - Requires stable clocks
  - Network size fixed during installation (not robust)
  - Prioritization is local to each node
    - (can use centralized load balancing)

- **Variation: Variable Length TDMA (~Implicit Token)**
  - Unused time slices are truncated to save time
  - More efficient use of bandwidth
  - Used in FlexRay Dynamic Segment

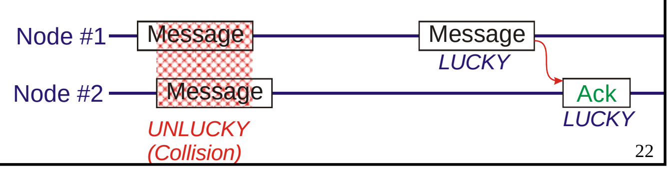
Coordination: Transmit and Hope (CSMA)

(CSMA = Carrier Sense Multiple Access)

- **Send a message and hope it made it**
  - Useful for satellites & systems with no collision detection
  - Vulnerable for entire time a message is transmitting
  - No direct way to know if message was delivered successfully



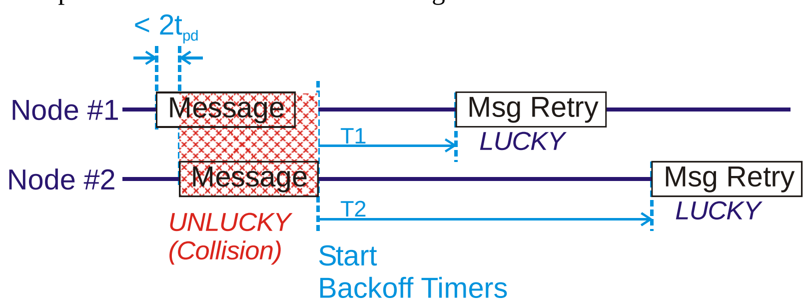
- **Send a message and wait for a response saying you made it**
  - *IMPLICIT* collision detection
  - Response might not make it even if message makes it
  - Iterate until some node pair gets lucky *twice* in a row



Transmit And Collide (CSMA/CD)

- **Transmit message; if you get lucky network transitions to "active"**
  - If you get unlucky, you get a collision event
  - Vulnerability window is about 2 t_{pd}
    - (Two propagation delays along length of network)

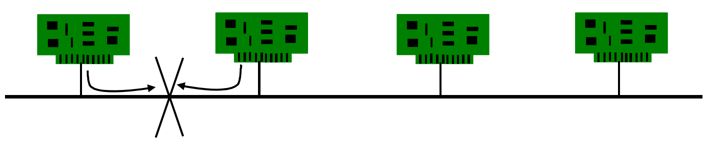
- **After collision, back off a certain time**
  - Amount of time to back off should vary with network load
  - Repeated collisions result in increasing backoff times



23

CSMA/CD

- **Carrier Sense Multiple Access / Collision Detection**



- **Operation**
  - A node waits for an idle channel before transmitting
  - Collisions can occur if two or more nodes transmit simultaneously
  - If a collision is detected, the nodes stop transmitting
    - Resolve contention using random backoff algorithm (2x longer interval each retry)

- **Examples**
  - Ethernet, IEEE 802.3, Bacnet, CAB, CEBus

24

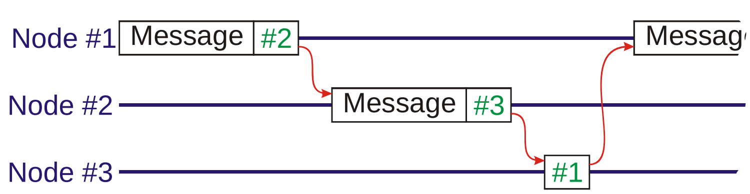
CSMA/CD Tradeoffs

- **Advantages**
  - Small latency for low traffic load
  - Network initialization/configuration is not required
  - Node can enter or leave the network without any interruption
  - Supports many nodes
  - Probabilistic global prioritization is possible
  - Extensive installed base and support
- **Disadvantages**
  - Designed for aperiodic traffic - not ideal for synchronized control loops
  - Collision detection is an analog process which is not always practical
  - Unbounded individual message latency
  - Poor efficiency under heavy loads
- **What about newer systems that promise "Real Time Ethernet"?**
  - Uses a deterministic point-to-point switch – no shared wire

25

Coordination: Explicit Tokens

- **"Token" value says which node is transmitting and/or should transmit next**
  - Token holder = OWNER; only the owner may transmit
  - Master/slave polling is a special form where token is passed by master and returned to master by slave
  - Problems: Lost token / Duplicated token(s) / Who starts?



Token passes to next node according to # field.

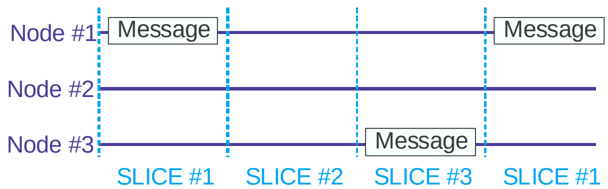
- **Token passed as node number or other similar value**
  - May be tacked on to end of data-bearing message
  - Can be either node # that has token or node # that gets token next
  - Null messages with tokens must be passed to prevent network from going idle

26

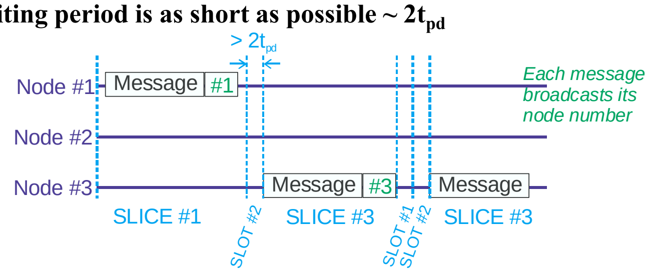
Coordination: Implicit Tokens

- **Length of waiting period is used as a time-domain implicit "token"**
  - Owner of bus determined by what time it is instead of explicit token message

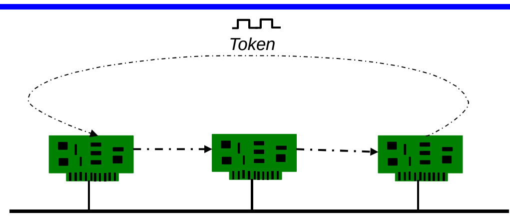
- **Time *slices* -- waiting period is a whole message long**
  - TDMA, TTP



- **Time *slots* -- waiting period is as short as possible ~ $2t_{pd}$**
  - CSMA/CA



Token Bus



- **Operation**
  - A token signal is passed from a node to node on a bus (virtual ring)
  - Only the token holder has permission to access the media

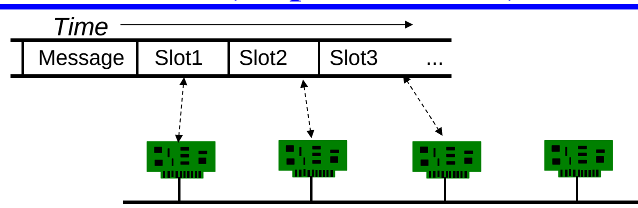
- **Examples**
  - IEEE 802.4, Arcnet, AN192, MAP, Profibus

Token Bus Tradeoffs

- **Advantages**
  - Bounded latency for real-time control applications
  - High throughput during heavy traffic
  - On-the-fly reconfiguration
- **Disadvantages**
  - Token passing latencies under light traffic conditions
  - Prioritization local to each node
  - Lengthy reconfiguration process
  - Token initialization, loss, and duplication recovery overhead
  - Collisions may occur during initialization and reconfiguration
  - Complex protocol (especially at MAC sublayer)
- **Token bus was popular for a while, but is used less often now**

29

CSMA/CA (Implicit Token)

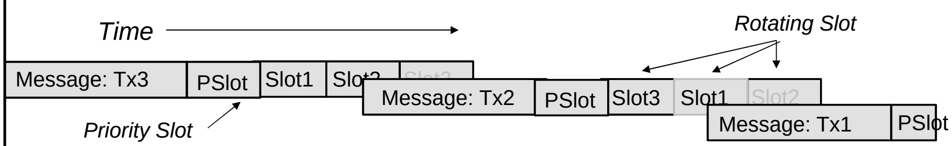


- **Operation**
  - IDLE: Active station transmits immediately
  - After each message, reserve S slots for N nodes

    IMPORTANT: Slots are normally idle – ***they are time intervals, not signals!***
  - BUSY: Transmit during your assigned slot
    - If S=N, no collisions - known as **Reservation CSMA**
    - If S<N, statistical collision avoidance
- **Example**
  - Echelon LONTalk

30

CSMA/CA Slot Strategies



- **One or more Priority slots (Pslots)**
  - Always in the same order after the message
  - Used for global prioritization – high priority messages
  - Each slot belongs to exactly one transmitter with a priority message
  - Could be multiple: Pslot0, Pslot1, Pslot2 assigned per message type
- **Multiple Rotating slots**
  - Rotating order based on last message sender – enables fairness
  - Generally one per transmitter, shared among all non-priority messages
- **Each slot is a few bit times – long enough for signal propagation**
  - Slots are time intervals and ***NOT SIGNALS***
    - ***Slot is "no signal" unless a message starts transmitting in it***
  - *When transmitter has a message to send, it starts during its slot time*

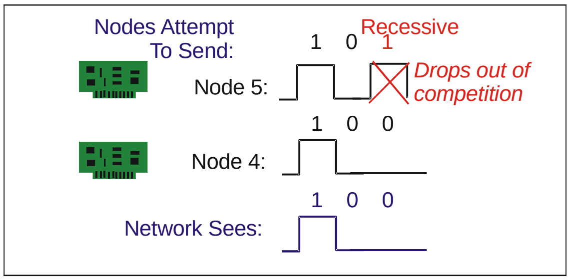
31

CSMA/CA Tradeoffs

- **Advantages**
  - Small latency for light traffic
  - Good throughput under heavy traffic
  - Global prioritization through fixed slots – prioritized implicit token passes
  - Bounded latency through rotating slots – non-prioritized implicit token passes
- **Disadvantages**
  - Restarting time slots from an idle bus can be difficult
    - Send dummy messages to avoid idle state
  - Collisions can occur
  - Node complexity in mapping Sth slot to Nth node
- **You'll see more of this in the FlexRay lecture**

32

Binary Countdown (Bit Dominance)



- **Operation**
  - Each node is assigned a unique identification number
  - All nodes wishing to transmit compete for the channel by transmitting a binary signal based on their identification value
  - A node drops out the competition if it detects a dominant state while transmitting a passive state
  - Thus, the node with the *LOWEST* identification value wins
- **Examples**
  - CAN, SAE J1850

33

Binary Countdown Tradeoffs

- **Advantages**
  - High throughput under light loads
  - Local and global prioritization possible
  - Arbitration is part of the message - low overhead
- **Disadvantages**
  - Propagation delay limits bus length (2 t_{pd} bit length)
  - Unfair access - node with a high priority can "hog" the network
  - Poor latency for low priority nodes
- **You'll see more on binary countdown in the CAN lecture**
  - Don't worry about exactly how this works until that lecture

34

EMULATION

- **You can use one protocol to emulate another**

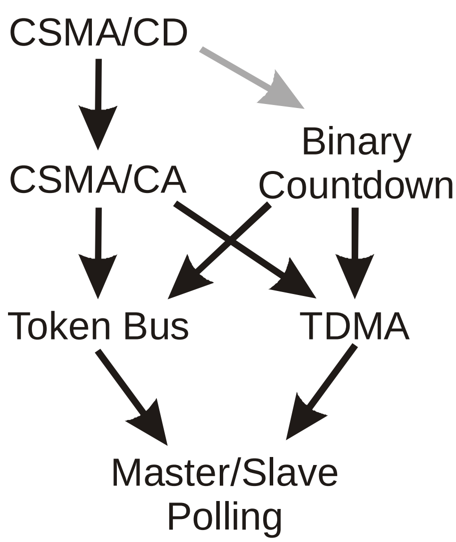
- **Use Ethernet (CSMA/CD) to emulate:**
  - Master/slave polling – slaves only respond when polled
  - Token bus – use explicit token messages; application only transmits when it has the token
  - TDMA – slaves measure time from message from master and transmit appropriately

- **But, there is no free lunch**
  - “Slot” time involves round-trip through OS – longer than a couple bit times
  - “Slice” time must account for CPU/OS jitter, not just HW oscillator drift

35

Emulation Capability Lattice

- **Protocols higher in picture can emulate protocols lower in picture**
  - Example: you can pass a token around on a CAN network in software



36

Wireless Networks

- **Strength is installation flexibility**
  - No wiring harnesses to install (except for power)
  - Can make/break networks without physical connections
  - Can have overlapping/interacting/hierarchical networks (e.g., Bluetooth)
- **Weakness is potential unreliability for critical operations**
  - Geometry may introduce standing waves/fading
  - Conflicts with other wireless systems (EMC = ElectroMagnetic Compatibility)
  - Interference from RF emitters (EMI = ElectroMagnetic Interference)
  - Limited spectrum space
  - Where does a wireless node get its power – who changes the batteries?
  - ***In general, unsuitable for use in critical applications that aren't fail-safe!***
- **Also, cost**
  - Bluetooth is getting cheap enough to be in consumer electronics
  - But has to be able to beat a piece of copper and a plastic connector
  - And that cost has to include power supply strategy

37

Key Overall Tradeoff Issues

- **Protocols are optimized for different operating scenarios**
  - Collision-based
    - High number of possible transmitters
    - Low number of *active* transmitters
    - Arbitration overhead proportional to activity
    - In worst case (every node active) network can effectively crash
  - Token-based, Time-multiplexed & Polled
    - Moderate number of *total* transmitters
    - Handles worst case activity without a problem
    - Arbitration overhead relatively constant
  - Binary countdown
    - Moderately large number of message types
    - Arbitration overhead constant
    - Global prioritization (*but* no mechanism for fairness)

38

Review

- **General embedded network issues**
  - Dynamic tension among efficiency, latency, determinism
- **Classes of protocols**
  - Time-multiplexed (polled/time-triggered)
  - Token (implicit/explicit)
  - Binary countdown
  - You should know all protocol type names and general operating principles
- **General tradeoff overview**
  - Global vs. local priority (and, priority vs. fairness)
    - Think about it – what does each protocol do about global prioritization?
  - Efficiency vs. dynamic flexibility
    - Think about it – what does each protocol do to minimize overhead if messages aren't uniformly distributed?
  - Wired vs. wireless

39

Supplemental Material

Protocol Tradeoffs Revisited

- **Bit encoding**
  - Self-clocking schemes are simpler, but require more bandwidth
  - Bit-stuffed schemes require extra bits for stuffing, result in nondeterministic message lengths
- **Collision-based protocols**
  - An unbounded number of collisions results in unbounded worst-case latency
    - Idea: use collision to signal start of a reservation CSMA protocol – works well
  - In general not constrained by bit speed/network length ratio (but IS constrained by message speed/network length ratio)
- **Bit dominance/binary countdown protocols**
  - Excellent efficiency
    - But must have compatible network medium
  - Constrained by network bit speed/network length ratio

41

Protocol Tradeoffs Revisited – 2

- **Implicit Token / Time-based protocols**
  - Longer timed intervals potentially waste bandwidth
    - Unused slices on TDMA
  - Any timed interval requires an accurate oscillator at each node
    - Worst for TDMA
    - Relevant to CSMA/CA as well
  - Constrained by bit speed/network length ratio
- **Explicit Token-based/handshake protocols**
  - Consumes bandwidth for token passing
    - Master/Slave polling the worst – individual polling message
    - Token bus OK under heavy load if token pass combined with transmission
    - Token ring is better, but requires special topology
  - Does not require precise oscillators, especially if used with self-clocking bits
  - Not specifically constrained by bit speed/network length ratio
    - But bus topologies are inefficient if network is longer than a whole message time

42

Protocol Tradeoffs Revisited – 3

- **Local priority**
  - Flexible, straightforward to implement
- **Global priority – requires consensus of nodes to determine winner**
  - Bit dominance does this "for free"
  - Implicit tokens approximate this by very fast (implicit) token pass to all nodes
  - Token ring approximates this by very fast (explicit) token pass to all nodes
  - Explicit token/handshake protocols in general have a difficult time doing this
- **Global fairness – requires ability to send non-prioritized messages**
  - Bit dominance must use emulation of another protocol to do this (e.g., polling)
  - Implicit tokens do this by using rotating slots
  - Explicit tokens do this as part of token passing – no additional charge

43

Alternative Networks

- **Optical Fiber**
  - Excellent noise immunity
  - Very high bandwidth

  - Expensive to connect/splice
  - Expensive emitter/receiver
  - Needs separate power wiring
- **Free-space optical (*e.g.*, infrared)**
  - Potential alternative for small enclosed systems
  - No wires (except for power)
  - Good for benign confined environments (e.g., TV remotes)

  - Relatively low bandwidth
  - Transceiver costs still a bit high (but being driven by palmtop PC market)
  - Still need to get power to nodes

44