Chapter 6 Interfacing

Introduction

- Embedded system functionality aspects
  - Processing
    - Transformation of data
    - Implemented using processors
  - Storage
    - Retention of data
    - Implemented using memory
  - Communication
    - Transfer of data between processors and memories
    - Implemented using buses
    - Called interfacing

Outline

- Interfacing basics
- Microprocessor interfacing
  - I/O Addressing
  - Interrupts
  - Direct memory access
- Arbitration
- Hierarchical buses
- Protocols
  - Serial
  - Parallel
  - Wireless

A simple bus

- Wires:
  - Uni-directional or bi-directional
  - One line may represent multiple wires
- Bus
  - Set of wires with a single function
    - Address bus, data bus
  - Or, entire collection of wires
    - Address, data and control
    - Associated protocol: rules for communication
Embedded Systems Design: A Unified Hardware/Software Introduction, (c) 2000 Vahid/Givargis

**Ports**

- Conducting device (metal) on periphery
- Connects bus to processor or memory
- Often referred to as a port
  - Actual pins on periphery of IC package that plug into socket on printed-circuit board
  - Sometimes metallic balls instead of pins
  - Today, metal “pads” connecting processors and memories within single IC
- Single wire or set of wires with single function
  - E.g., 12-wire address port

**Basic protocol concepts**

- Actor: master initiates, servant (slave) respond
- Direction: sender, receiver
- Addresses: special kind of data
  - Specifies a location in memory, a peripheral, or a register within a peripheral
- Time multiplexing
  - Share a single set of wires for multiple pieces of data
  - Saves wires at expense of time

**Timing Diagrams**

- Most common method for describing a communication protocol
- Time proceeds to the right on x-axis
- Control signal: low or high
  - May be active low (e.g., go_low, go or go_L)
  - Use terms assert (active) and deassert
  - Asserting go_L means go=0
- Data signal: not valid or valid
- Protocol may have subprotocols
  - Called bus cycle, e.g., read and write
  - Each may be several clock cycles
- Read example
  - rd/wr set low, address placed on addr for at least t_min time before enable asserted, enable triggers memory to place data on data wires

**Basic protocol concepts: control methods**

- Master asserts req to receive data
- Servant puts data on bus within time t_min
- Master receives data and deasserts req
- Servant ready for next request

- Master asserts req to receive data
- Servant puts data on bus and asserts ack
- Master receives data and deasserts req
- Servant ready for next request

**Strobe protocol**

**Handshake protocol**
A strobe/handshake compromise

Microprocessor interfacing: I/O addressing

- A microprocessor communicates with other devices using some of its pins
  - Port-based I/O (parallel I/O)
    - Processor has one or more N-bit ports
    - Processor’s software reads and writes a port just like a register
    - E.g., P0 = 0xFF; v = P1.2; -- P0 and P1 are 8-bit ports
  - Bus-based I/O
    - Processor has address, data and control ports that form a single bus
    - Communication protocol is built into the processor
    - A single instruction carries out the read or write protocol on the bus

ISA bus protocol – memory access

- ISA: Industry Standard Architecture
  - Common in 80x86’s
- Features
  - 20-bit address
  - Compromise strobe/handshake control
    - 4 cycles default
    - Unless CHRDY deasserted – resulting in additional wait cycles (up to 6)

Compromises/extensions

- Parallel I/O peripheral
  - When processor only supports bus-based I/O but parallel I/O needed
    - Each port on peripheral connected to a register within peripheral that is read/written by the processor
- Extended parallel I/O
  - When processor supports port-based I/O but more ports needed
    - One or more processor ports interface with parallel I/O peripheral extending total number of ports available for I/O
    - E.g., extending 4 ports to 6 ports in figure
Types of bus-based I/O:
memory-mapped I/O and standard I/O

- Processor talks to both memory and peripherals using same bus – two ways to talk to peripherals
  - Memory-mapped I/O
    - Peripheral registers occupy addresses in same address space as memory
      - e.g., Bus has 16-bit address
        - lower 32K addresses may correspond to memory
        - upper 32K addresses may correspond to peripherals
  - Standard I/O (I/O-mapped I/O)
    - Additional pin (M/IO) on bus indicates whether a memory or peripheral access
      - e.g., Bus has 16-bit address
        - all 64K addresses correspond to memory when M/IO set to 0
        - all 64K addresses correspond to peripherals when M/IO set to 1

Memory-mapped I/O vs. Standard I/O

- Memory-mapped I/O
  - Requires no special instructions
    - Assembly instructions involving memory like MOV and ADD work with peripherals as well
    - Standard I/O requires special instructions (e.g., IN, OUT) to move data between peripheral registers and memory
- Standard I/O
  - No loss of memory addresses to peripherals
  - Simpler address decoding logic in peripherals possible
    - When number of peripherals much smaller than address space then high-order address bits can be ignored
      - smaller and/or faster comparators

ISA bus

- ISA supports standard I/O
  - /I/O distinct from /MEMR for peripheral read
    - /I/O used for writes
  - 16-bit address space for I/O vs. 20-bit address space for memory
  - Otherwise very similar to memory protocol

A basic memory protocol

- Interfacing an 8051 to external memory
  - Ports P0 and P2 support port-based I/O when 8051 internal memory being used
    - Those ports serve as data/address buses when external memory is being used
      - 16-bit address and 8-bit data are time multiplexed; low 8-bits of address must therefore be latched with aid of ALE signal
A more complex memory protocol

- Generates control signals to drive the TC55V2325FF memory chip in burst mode
  - Addr0 is the starting address input to device
  - GO is enable/disable input to device

Microprocessor interfacing: interrupts

- What is the address (interrupt address vector) of the ISR?
  - Fixed interrupt
    - Address built into microprocessor, cannot be changed
    - Either ISR stored at address or a jump to actual ISR stored if not enough bytes available
  - Vectored interrupt
    - Peripheral must provide the address
    - Common: when microprocessor has multiple peripherals connected by a system bus
  - Compromise: interrupt address table

- Suppose a peripheral intermittently receives data, which must be serviced by the processor
  - The processor can poll the peripheral regularly to see if data has arrived – wasteful
  - The peripheral can interrupt the processor when it has data
- Requires an extra pin or pins: Int
  - If Int is 1, processor suspends current program, jumps to an Interrupt Service Routine, or ISR
  - Known as interrupt-driven I/O
  - Essentially, “polling” of the interrupt pin is built-into the hardware, so no extra time!
Interrupt-driven I/O using fixed ISR location

1(a): µP is executing its main program
1(b): P1 receives input data in a register with address 0x8000.

Interrupt-driven I/O using fixed ISR location

2: P1 asserts Int to request servicing by the microprocessor

3: After completing instruction at 100, µP sees Int asserted, saves the PC’s value of 100, and sets PC to the ISR fixed location of 16.

4(a): The ISR reads data from 0x8000, modifies the data, and writes the resulting data to 0x8001.
4(b): After being read, P1 deasserts Int.
Interrupt-driven I/O using fixed ISR location

5: The ISR returns, thus restoring PC to 100+1=101, where \( \mu P \) resumes executing.

Interrupt-driven I/O using vectored interrupt

1(a): \( \mu P \) is executing its main program.

2(a): \( \mu P \) is executing its main program.

2(b): \( \mu P \) jumps to the address on the bus (16).

Int: \( \mu P \) is executing its main program.

I(b): \( \mu P \) receives input data in a register with address 0x8000.

2: \( \mu P \) asserts Int to request servicing by the microprocessor.

1: After completing instruction at 100, \( \mu P \) sees Int asserted, saves the PC’s value of 100, and asserts Inta.

The ISR there reads data from 0x8000, modifies the data, and writes the resulting data to 0x8001.

3: \( \mu P \) asserts Int to request servicing by the microprocessor.

5(a): \( \mu P \) receives input data in a register with address 0x8000.

3a: After completing instruction at 100, \( \mu P \) sees Int asserted, saves the PC’s value of 100, and asserts Inta.

The ISR returns, thus restoring PC to 100+1=101, where \( \mu P \) resumes executing.
Interrupt-driven I/O using vectored interrupt

3: After completing instruction at 100, µP sees Int asserted, saves the PC's value of 100, and asserts Inta

4: P1 detects Inta and puts interrupt address vector 16 on the data bus

5(a): PC jumps to the address on the bus (16). The ISR there reads data from 0x8000, modifies the data, and writes the resulting data to 0x8001.

5(b): After being read, P1 deasserts Inta.

6: The ISR returns, thus restoring the PC to 100+1=101, where the µP resumes
Interrupt address table

- Compromise between fixed and vectored interrupts
  - One interrupt pin
  - Table in memory holding ISR addresses (maybe 256 words)
  - Peripheral doesn’t provide ISR address, but rather index into table
    - Fewer bits are sent by the peripheral
    - Can move ISR location without changing peripheral

Direct memory access

- Buffering
  - Temporarily storing data in memory before processing
  - Data accumulated in peripherals commonly buffered
- Microprocessor could handle this with ISR
  - Storing and restoring microprocessor state inefficient
  - Regular program must wait
- DMA controller more efficient
  - Separate single-purpose processor
  - Microprocessor relinquishes control of system bus to DMA controller
  - Microprocessor can meanwhile execute its regular program
    - No inefficient storing and restoring state due to ISR call
    - Regular program need not wait unless it requires the system bus

Additional interrupt issues

- Maskable vs. non-maskable interrupts
  - Maskable: programmer can set bit that causes processor to ignore interrupt
    - Important when in the middle of time-critical code
  - Non-maskable: a separate interrupt pin that can’t be masked
    - Typically reserved for drastic situations, like power failure requiring immediate backup of data to non-volatile memory
- Jump to ISR
  - Some microprocessors treat jump same as call of any subroutine
    - Complete state saved (PC, registers) – may take hundreds of cycles
  - Others only save partial state, like PC only
    - Thus, ISR must not modify registers, or else must save them first
    - Assembly-language programmer must be aware of which registers stored

Peripheral to memory transfer without DMA, using vectored interrupt
Peripheral to memory transfer without DMA, using vectored interrupt

1(a): µP is executing its main program

1(b): P1 receives input data in a register with address 0x8000.

Peripheral to memory transfer without DMA, using vectored interrupt

2: P1 asserts Int to request servicing by the microprocessor

Peripheral to memory transfer without DMA, using vectored interrupt

3: After completing instruction at 100, µP sees Int asserted, saves the PC’s value of 100, and asserts Inta.

Peripheral to memory transfer without DMA, using vectored interrupt (cont’)

4: P1 detects Inta and puts interrupt address vector 16 on the data bus.
Peripheral to memory transfer *without* DMA, using vectored interrupt (cont’)

S(a): \( \mu \text{P} \) jumps to the address on the bus (16). The ISR there reads data from 0x8000 and then writes it to 0x0001, which is in memory.

S(b): After being read, P1 de-asserts Int.

Peripheral to memory transfer with DMA (cont’)

1(a): \( \mu \text{P} \) is executing its main program. It has already configured the DMA ctrl registers.

1(b): P1 receives input data in a register with address 0x8000.

2: \( \mu \text{P} \) asserts Dreq to request control of system bus.

2: DMA ctrl asserts Dreq and requests servicing by DMA ctrl.

2(a): DMA ctrl asserts Dreq and requests servicing by DMA ctrl.

3: \( \mu \text{P} \) de-asserts Dreq and resumes control of the bus.

3: P1 asserts Dreq to request control of system bus.

Peripheral to memory transfer *without* DMA, using vectored interrupt (cont’)

6: The ISR returns, thus restoring PC to 100+1=101, where \( \mu \text{P} \) resumes executing.

Peripheral to memory transfer with DMA

1(a): \( \mu \text{P} \) is executing its main program. It has already configured the DMA ctrl registers.

1(b): P1 receives input data in a register with address 0x8000.
Peripheral to memory transfer with DMA (cont’)

2: P1 asserts req to request servicing by DMA ctrl.

3: DMA ctrl asserts Dreq to request control of system bus

Peripheral to memory transfer with DMA (cont’)

4: After executing instruction 100, µP sees Dreq asserted, releases the system bus, asserts Dack, and resumes execution. µP stalls only if it needs the system bus to continue executing.

Peripheral to memory transfer with DMA (cont’)

5: DMA ctrl (a) asserts ack, (b) reads data from 0x8000, and (c) writes that data to 0x0001.

(Meanwhile, processor still executing if not stalled!)

Peripheral to memory transfer with DMA (cont’)

6: DMA de-asserts Dreq and ack completing the handshake with P1.
Arbitration: Priority arbiter

- Consider the situation where multiple peripherals request service from single resource (e.g., microprocessor, DMA controller) simultaneously - which gets serviced first?
  - Priority arbiter
    -- Single-purpose processor
    -- Peripherals make requests to arbiter, arbiter makes requests to resource
    -- Arbiter connected to system bus for configuration only

Arbitration using a priority arbiter

1. Microprocessor is executing its program.
2. Peripheral1 needs servicing so asserts Inta.
3. Priority arbiter asserts Inta.
4. Microprocessor stops executing its program and stores its state.
5. Priority arbiter asserts Ireq1.
6. Microprocessor asserts Iack1 to acknowledge Peripheral1.
7. Peripheral1 puts its interrupt address vector on the system bus
8. Microprocessor jumps to the address of ISR read from data bus, ISR executes and returns
9. (and completes handshake with arbiter)
10. Microprocessor resumes executing its program.

Types of priority
- Fixed priority
  -- each peripheral has unique rank
  -- highest rank chosen first with simultaneous requests
  -- preferred when clear difference in rank between peripherals
- Rotating priority (round-robin)
  -- priority changed based on history of servicing
  -- better distribution of servicing especially among peripherals with similar priority demands

ISA bus DMA cycles

DMA Memory-Write-Req Cycle

DMA Memory-Read-Req Cycle
Arbitration: Daisy-chain arbitration

- Arbitration done by peripherals
  - Built into peripheral or external logic added
    - req input and ack output added to each peripheral
- Peripherals connected to each other in daisy-chain manner
  - One peripheral connected to resource, all others connected “upstream”
  - Peripheral’s req flows “downstream” to resource, resource’s ack flows “upstream” to requesting peripheral
  - Closest peripheral has highest priority

Network-oriented arbitration

- When multiple microprocessors share a bus (sometimes called a network)
  - Arbitration typically built into bus protocol
  - Separate processors may try to write simultaneously causing collisions
    - Data must be resent
    - Don’t want to start sending again at same time
      - statistical methods can be used to reduce chances
- Typically used for connecting multiple distant chips
  - Trend – use to connect multiple on-chip processors

Example: Vectored interrupt using an interrupt table

- Fixed priority: i.e., Peripheral 1 has highest priority
- Keyword “at_” followed by memory address forces compiler to place variables in specific memory locations
  - e.g., memory-mapped register in arbiter, peripherals
- A peripheral’s index into interrupt table is sent to memory-mapped register in arbiter
- Peripherals receive external data and raise interrupt
Multilevel bus architectures

- Don’t want one bus for all communication
  - Peripherals would need high-speed, processor-specific bus interface
    - excess gates, power consumption, and cost; less portable
  - Too many peripherals slows down bus
- Processor-local bus
  - High speed, wide, most frequent communication
  - Connects microprocessor, cache, memory controllers, etc.
- Peripheral bus
  - Lower speed, narrower, less frequent communication
  - Typically industry standard bus (ISA, PCI) for portability
- Bridge
  - Single-purpose processor converts communication between busses

Advanced communication principles

- Layering
  - Break complexity of communication protocol into pieces easier to design and understand
  - Lower levels provide services to higher level
    - Lower level might work with bits while higher level might work with packets of data
  - Physical layer
    - Lowest level in hierarchy
    - Medium to carry data from one actor (device or node) to another
- Parallel communication
  - Physical layer capable of transporting multiple bits of data
- Serial communication
  - Physical layer transports one bit of data at a time
- Wireless communication
  - No physical connection needed for transport at physical layer
Parallel communication

- Multiple data, control, and possibly 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

Serial communication

- Single data wire, possibly also control and power wires
- Words transmitted one bit at a time
- Higher data throughput with long distances
  - Less average capacitance, so more bits per unit of time
- Cheaper, less bulky
- More complex interfacing logic and communication protocol
  - Sender needs to decompose word into bits
  - Receiver needs to recompose bits into word
  - Control signals often sent on same wire as data increasing protocol complexity

Wireless communication

- Infrared (IR)
  - Electronic wave frequencies just below visible light spectrum
  - Diode emits infrared light to generate signal
  - Infrared transistor detects signal, conducts when exposed to infrared light
  - Cheap to build
  - Need line of sight, limited range
- Radio frequency (RF)
  - Electromagnetic wave frequencies in radio spectrum
  - Analog circuitry and antenna needed on both sides of transmission
  - Line of sight not needed, transmitter power determines range

Error detection and correction

- Often part of bus protocol
- Error detection: ability of receiver to detect errors during transmission
- Error correction: ability of receiver and transmitter to cooperate to correct problem
  - Typically done by acknowledgement/retransmission protocol
- Bit error: single bit is inverted
- Burst of bit error: consecutive bits received incorrectly
- Parity: extra bit sent with word used for error detection
  - Odd parity: data word plus parity bit contains odd number of 1’s
  - Even parity: data word plus parity bit contains even number of 1’s
  - Always detects single bit errors, but not all burst bit errors
- Checksum: extra word sent with data packet of multiple words
  - E.g., extra word contains XOR sum of all data words in packet
Serial protocols: I²C

- I²C (Inter-IC)
  - Two-wire serial bus protocol developed by Philips Semiconductors nearly 20 years ago
  - Enables peripheral ICs to communicate using simple communication hardware
  - Data transfer rates up to 100 kbits/s and 7-bit addressing possible in normal mode
  - 3.4 Mbits/s and 10-bit addressing in fast-mode
  - Common devices capable of interfacing to I²C bus:
    - EPROMS, Flash, and some RAM memory, real-time clocks, watchdog timers, and microcontrollers

I²C bus structure

Serial protocols: CAN

- CAN (Controller area network)
  - Protocol for real-time applications
  - Developed by Robert Bosch GmbH
  - Originally for communication among components of cars
  - Applications now using CAN include:
    - elevator controllers, copiers, telescopes, production-line control systems, and medical instruments
  - Data transfer rates up to 1 Mbit/s and 11-bit addressing
  - Common devices interfacing with CAN:
    - 8051-compatible 8592 processor and standalone CAN controllers
  - Actual physical design of CAN bus not specified in protocol
    - Requires devices to transmit/detect dominant and recessive signals to/from bus
    - e.g., ‘1’ = dominant, ‘0’ = recessive if single data wire used
    - Bus guarantees dominant signal prevails over recessive signal if asserted simultaneously

Serial protocols: FireWire

- FireWire (a.k.a. 1-Link, Lynx, IEEE 1394)
  - High-performance serial bus developed by Apple Computer Inc.
  - Designed for interfacing independent electronic components
    - e.g., Desktop, scanner
  - Data transfer rates from 12.5 to 400 Mbit/s, 64-bit addressing
  - Plug-and-play capabilities
  - Packet-based layered design structure
  - Applications using FireWire include:
    - disk drives, printers, scanners, cameras
  - Capable of supporting a LAN similar to Ethernet
    - 64-bit address:
      - 10 bits for network ids, 1023 subnetworks
      - 6 bits for node ids, each subnetwork can have 63 nodes
      - 48 bits for memory address, each node can have 281 terabytes of distinct locations
Serial protocols: USB

- USB (Universal Serial Bus)
  - Easier connection between PC and monitors, printers, digital speakers, modems, scanners, digital cameras, joysticks, multimedia game equipment
  - 2 data rates:
    - 12 Mbps for increased bandwidth devices
    - 1.5 Mbps for lower-speed devices (joysticks, game pads)
  - Hierarchical star topology can be used
    - One USB device (hub) connected to PC
    - Hub can be embedded in devices like monitor, printer, or keyboard or can be standalone
    - Multiple USB devices can be connected to hub
    - Up to 127 devices can be connected like this
  - USB host controller
    - Manages and controls bandwidth and driver software required by each peripheral
    - Dynamically allocates power downstream according to devices connected/disconnected

Parallel protocols: PCI Bus

- PCI Bus (Peripheral Component Interconnect)
  - High performance bus originated at Intel in the early 1990’s
  - Standard adopted by industry and administered by PCISIG (PCI Special Interest Group)
  - Interconnects chips, expansion boards, processor memory subsystems
  - Data transfer rates of 127.2 to 508.6 Mbits/s and 32-bit addressing
    - Later extended to 64-bit while maintaining compatibility with 32-bit schemes
  - Synchronous bus architecture
  - Multiplexed data/address lines

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
    - If clock speed of bus is X, transfer rate = 16 x X bits/s
  - 32-bit addressing

Wireless protocols: IrDA

- IrDA
  - Protocol suite that supports short-range point-to-point infrared data transmission
  - Created and promoted by the Infrared Data Association (IrDA)
  - Data transfer rate of 9.6 kbps and 4 Mbps
  - IrDA hardware deployed in notebook computers, printers, PDAs, digital cameras, public phones, cell phones
  - Lack of suitable drivers has slowed use by applications
  - Windows 2000/98 now include support
  - Becoming available on popular embedded OS’s
Chapter Summary

- Basic protocol concepts
  - Actors, direction, time multiplexing, control methods
- General-purpose processors
  - Port-based or bus-based I/O
  - I/O addressing: Memory mapped I/O or Standard I/O
  - Interrupt handling: fixed or vectored
  - Direct memory access
- Arbitration
  - Priority arbiter (fixed/rotating) or daisy chain
- Bus hierarchy
- Advanced communication
  - Parallel vs. serial, wires vs. wireless, error detection/correction, layering
  - Serial protocols: FC, CAN, FireWire, and USB; Parallel: PCI and ARM.
  - Serial wireless protocols: IrDA, Bluetooth, and IEEE 802.11.

Wireless protocols: Bluetooth

- Bluetooth
  - New, global standard for wireless connectivity
  - Based on low-cost, short-range radio link
  - Connection established when within 10 meters of each other
  - No line-of-sight required
    - e.g., Connect to printer in another room

Wireless Protocols: IEEE 802.11

- IEEE 802.11
  - Proposed standard for wireless LANs
  - Specifies parameters for PHY and MAC layers of network
    - PHY layer
      - Physical layer
      - Handles transmission of data between nodes
      - Provisions for data transfer rates of 1 or 2 Mbps
      - Operates in 2.4 to 2.4835 GHz frequency band (RF)
      - Or 300 to 428,000 GHz (IR)
    - MAC layer
      - Medium access control layer
      - Protocol responsible for maintaining order in shared medium
      - Collision avoidance/detection