Networked Embedded Systems WS 2016/17

Exercise 2: Communication

Discussion date: December 16, 2016

Task 1: Wired Communication between On-board Components

Figure **??** shows part of the functional block diagram of the Tmote Sky platform. The CC2420 radio chip and the Texas Instruments (TI) MSP430 microcontroller (MCU) communicate through an SPI bus and 6 digital input/output (I/O) lines. The radio reads or sets the state of its I/O pins with frequency f_r, as determined by its crystal oscillator. The MCU reads or sets the state of its I/O pins with frequency f_m, as determined by its internal digitally controlled oscillator (DCO). Assume the two clocks *do not drift* (i.e., f_r and f_m do not change over time), and changes in the state of an I/O pin at one component (i.e., radio or MCU) result in an *instantaneous* change in the state of the respective I/O pin at the other component.

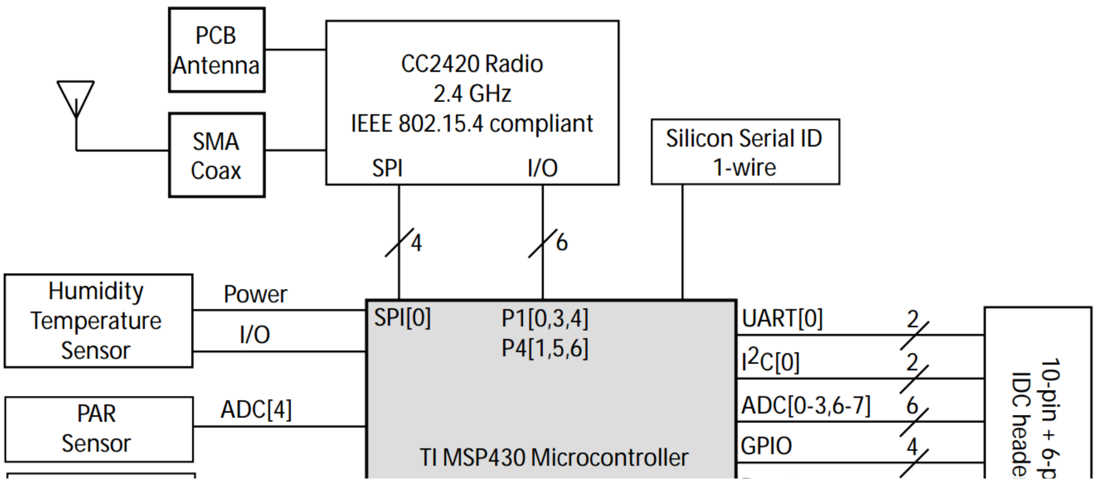

Figure 1: Part of the functional block diagram of the Tmote Sky platform.

Consider the following scenario. The radio signals to the MCU the end of a packet reception by changing the state of a specific I/O pin. As soon as the MCU detects this change, it starts to execute for a fixed number of clock ticks I (with operating frequency f_m). Immediately afterwards the MCU changes the state of a specific I/O pin in order to start a packet transmission by the radio.

(a) Determine the delay D between the end of a packet reception and the start of the next packet transmission assuming that the MCU needs to execute for $I = 100$ clock ticks, and that radio and MCU operate perfectly synchronized with frequency $f = f_r = f_m = 8$ MHz.

(b) Now assume that radio and MCU run asynchronously with frequency $f = f_r = f_m = 8\,$MHz. Determine the delay D for the case that the MCU needs to execute for $I = 100$ clock ticks.

(c) Now assume that radio and MCU run asynchronously with frequencies $f_r = 8\,$MHz and $f_m = 4\,$MHz. Determine all possible values of the delay D when the MCU executes for $I = 100$ clock ticks. Support your answer by providing an analytical expression for D as a function of f_r and f_m, among others.

(d) Assume that radio and MCU run asynchronously with frequencies $f_r = 8\,$MHz and $f_m = 2^{22}\,$Hz $= 4,194,304\,$Hz. How many possible values can the delay D take when the MCU executes for $I = 100$ clock ticks? Is it possible to reduce the number of possible values for the delay D by letting the MCU execute for a few more clock ticks (e.g., by inserting `NOP`s into the code executed by the MCU, where one `NOP` takes exactly one clock period $1/f_m$ to execute)? If so, determine the smallest number of clock ticks greater than 100 for which the number of possible values of the delay D is minimal.

Task 2: Wireless Communication between Low-power Devices

Two Tmote Sky devices, one sender and one receiver, exchange packets using their IEEE 802.15.4 compliant CC2420 radios. Figure **??** shows the frame format of an IEEE 802.15.4 packet as defined by the standard. The synchronization header (SHR) is automatically generated by the radio hardware. The frame length field (i.e., the PHY header) specifies the number of bytes in the MAC protocol data unit (MPDU); however, the most significant bit of the frame length field is reserved and should be set to zero. Many communication stacks do not use the full MAC layer format. Instead, their MPDU only consists of the MAC payload and the frame check sequence (FCS); that is, the space typically reserved for the MAC header (MHR) can be used to accommodate a larger MAC payload. The FCS is automatically generated by the radio hardware.

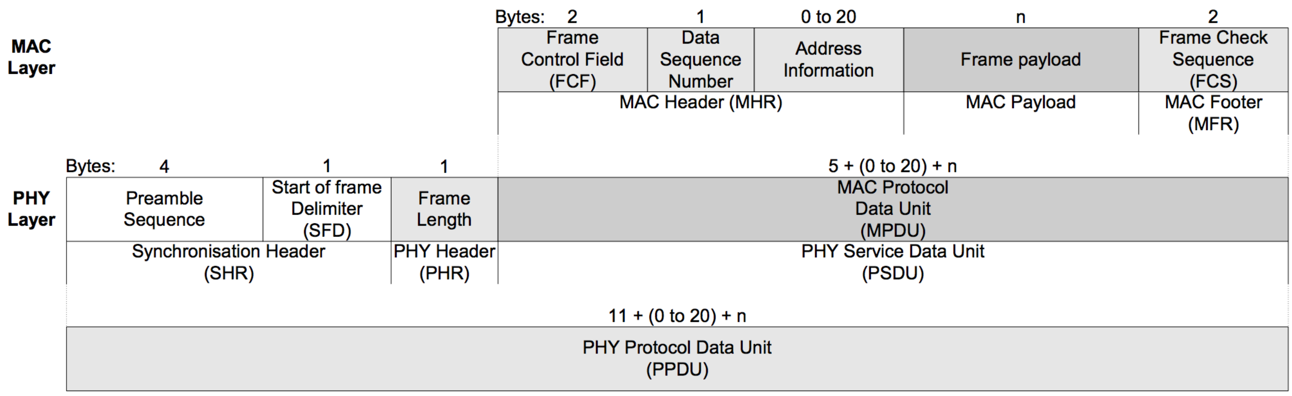

Figure 2: IEEE 802.15.4 frame format.

(a) Determine the maximum size (in bytes) of the PHY protocol data unit (PPDU). What is the maximum size of the MAC payload?

(b) The sending device wants to transmit data to the receiving device as fast as possible. The distance between the two devices is small enough so that they can communicate directly with each other. What is the maximum throughput the two devices can theoretically achieve? Keep in mind that the transmit bit rate of a IEEE 802.15.4 radio is $R = 250\,$kbit/s, and that after triggering a transmission it takes 192 μs until the radio actually starts to transmit the SHR.

(c) Now assume that the distance between sender and receiver exceeds the IEEE 802.15.4 communication range, which is typically on the order of a few tens of meters. Thus, the two devices rely on multi-hop communication, where intermediate devices relay the packets from the sender in a hop-by-hop fashion to the receiver. Assume that the number of hops in the linear multi-hop topology is smaller than the number of IEEE 802.15.4 radio channels (16). Using different channels, two devices can transmit at the same time without interfering with each other. What is the maximum multi-hop throughput the two devices (i.e., sender and receiver that are several hops apart) can theoretically achieve?

(d) Assume that sender and receiver are $H = 6$ hops apart; that is, 5 intermediate devices relay packets from the sender to the receiver. The wireless channel conditions are difficult: single-hop transmissions between any two devices succeed only with probability $p = 0.5$. To still achieve a high end-to-end reliability, devices can re-transmit each packet up to N times. A device re-transmits a packet if it does not receive an acknowledgment within a certain interval after a (re-)transmission. How many per-hop retransmissions N are needed to achieve an average end-to-end reliability higher than 99 %?

Hint: You may assume that packet (re-)transmissions are statistically independent events.

(e) To achieve a lifetime of multiple years, a device should duty-cycle its radio. Assume a device runs a sender-initiated media access control (MAC) protocol based on low-power listening (LPL). The MAC protocol is configured to regularly wake-up the radio every T_w for $T_{on} = 10$ ms to check whether there is any incoming traffic. When the radio is turned on it draws $I_{on} = 18.8$ mA, and $I_{off} = 20\,\mu$A when it is turned off. How long must the wake-up interval T_w be to achieve an estimated lifetime of 2 years (i.e., 730 days), assuming the device is powered by batteries that supply 2000 mAh at 3 V. Think about the implications on the achievable throughput.

Hint: Assume the device never sends or receives anything, it does nothing else than duty-cycling its radio. Also, neglect any effects related to battery discharge.