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Internet of things

IoT Homework
Exercise 2

Authors:
Daniel Shala - 10710181
Jurij Diego Scandola - 10709931

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1 802.15.4

Consider the following pseudocode for an ESP32-based IoT monitoring system

```
// Global Timer Handle
declare timer_handle as esp_timer_handle_t

// Initialization
function setup_camera():
    initialize_camera(QVGA)

function setup_timer():
    declare timer_config as esp_timer_create_args_t
    set timer_config.callback to process_frame
    set timer_config.name to "10_sec_timer"
    call esp_timer_create(&timer_config, &timer_handle)
    call esp_timer_start_periodic(timer_handle, 10_000_000) // 10s

function app_main():
    call setup_camera()
    call setup_timer()
    loop forever:
        delay(100 ms)

// Called every 10 seconds
function process_frame(arg):
    image = capture_camera_frame()
    person_count = estimate_number_of_people(image)
    if person_count == 0:
        payload = create_message(size=1KB)
    else if person_count == 1:
        payload = create_message(size=3KB)
    else:
        payload = create_message(size=6KB)
```

Assuming the system is operated with IEEE 802.15.4 in beacon-enabled mode (CFP only) and that the number of people present in the camera frame at any instant follows a Poisson distribution with an average rate of $\lambda = 0.15$ persons/frame:

1. Compute the Probability Mass Function of the output rate of the ESP32 $P(r = r_0)$, $P(r = r_1)$, $P(r = r_2)$, where r_0, r_1 and r_2 are the output rates when there are 0, 1, or more than 1 persons in the captured frame, respectively.

2. Based on the output rate PMF, compute a consistent slot assignment for the CFP in a monitoring system composed of 1 PAN coordinator and 3 camera nodes. Assume nominal bit rate $R = 250$ kbps, packets of $L = 128$ bytes, and 1 packet fits exactly in one slot. Compute:

    - T_s (slot time)

- Number of slots in the CFP
- T_{active}, $T_{inactive}$ and the duty cycle of the system

3. How many additional cameras can be added to keep the duty cycle below 10%?

1.1 Output Rate Probability Mass Function (PMF)

The ESP32-based IoT camera system generates data based on the number of people detected in each frame. The number of people follows a **Poisson distribution** with an average rate $\lambda = 0.15$ persons per frame. The output data rate of the node depends on how many people are detected:

- If 0 people are detected: the node sends a payload of 1 KB $\Rightarrow r_0 = 8$ kb.
- If 1 person is detected: the node sends a payload of 3 KB $\Rightarrow r_1 = 24$ kb.
- If more than 1 person is detected: the node sends a payload of 6 KB $\Rightarrow r_2 = 48$ kb.

Since the number of people k follows a Poisson distribution, the probability mass function (PMF) is:

$$P(k) = \frac{e^{-\lambda}\lambda^k}{k!}$$

Substituting $\lambda = 0.15$, we compute:

$$\begin{aligned}
P(r = r_0) &= P(0 \text{ persons}) = \frac{e^{-0.15} \cdot 0.15^0}{0!} = e^{-0.15} \approx 0.8607 \\
P(r = r_1) &= P(1 \text{ person}) = \frac{e^{-0.15} \cdot 0.15^1}{1!} = e^{-0.15} \cdot 0.15 \approx 0.1291 \\
P(r = r_2) &= P(\geq 2 \text{ persons}) = 1 - P(0) - P(1) = 1 - 0.8607 - 0.1291 = 0.0102
\end{aligned}$$

Thus, the PMF of the output rate is:

Rate	Payload (kb)	Probability
r_0	8 kb	0.8607
r_1	24 kb	0.1291
r_2	48 kb	0.0102

This PMF tells us that in the vast majority of frames (about 86%), no people are detected, resulting in the smallest data transmission (1 KB). Only about 1% of the time will the camera observe more than one person, triggering the highest output rate of 6 KB.

1.2 CFP Slot Assignment and Duty Cycle Calculation

To calculate the Beacon Interval we will take into consideration the packet size and the minimum output rate. This last one is equal to 800 bit/s, because we consider the case with one person, transmitting 1 KB of data, and the 10 s interval.

$$BI = \frac{packet\ size}{min\ output\ rate} = \frac{128 \times 8}{800} = 1,28 \text{ s}$$

The duration of a single slot (slot time T_s) depends on the data rate $R = 250$ kbps and packet size $L = 128$ bytes:

$$T_s = \frac{128 \times 8}{250 \times 10^3} = 0.004096 \text{ s} = 4.096 \text{ ms}$$

In this setup, the CFP is sized to guarantee that each node can transmit its data even in the worst-case scenario. Since the minimum expected output rate is based on a 1 KB payload every 10 seconds, we design the Beacon Interval accordingly. However, to account for the maximum possible rate of 6 KB per node, we multiply the ratio between the worst-case rate and the minimum rate (i.e., $\frac{4800}{800} = 6$) by the number of nodes (3), yielding

$$n_{CFP} = 6 \times 3 = 18 \text{ slots}$$

This ensures each node can transmit its maximum expected payload within one superframe.
Adding 1 beacon control slot, the total number of active slots becomes:

$$n_{active,slots} = 18 + 1 = 19$$

Thus, the active period is:

$$T_{active} = 19 \times T_s = 19 \cdot 0.004096 = 77.82 \text{ ms}$$

The inactive period is:

$$T_{inactive} = BI - T_{active} = 1.28 - 0.07782 = 1.202 \text{ s}$$

And the duty cycle is:

$$\text{Duty Cycle} = \frac{T_{active}}{BI} = \frac{0.07782}{1.28} = 6.08\%$$

The system remains well under a 10% duty cycle.

1.3 Maximum Number of Cameras to Keep Duty Cycle Below 10%

To determine how many additional camera nodes can be added without exceeding a duty cycle of 10%, we assume the **worst-case scenario**: every node transmits a payload of 1 KB every beacon interval. The duty cycle must remain below 10%, so:

$$\frac{T_{active}}{BI} < 0.1 \Rightarrow \frac{(18N+1)\cdot 0.004096}{1.28} < 0.1$$

Multiply both sides by 10:

$$(18N+1)\cdot 0.004096 < 0.128$$

$$18N+1 < \frac{0.128}{0.004096} \approx 31.25$$

$$18N < 30.25 \Rightarrow N < \frac{30.25}{18} \approx 1.68$$

Since N must be an integer, the maximum number of camera nodes is:

$$N = 5$$

Considering that we need 6 bits for each cam.
Therefore, the number of **additional** cameras that can be added to the system (starting from 3) is:

$$\boxed{\text{2 additional cameras}}$$