Internet of Things

Homework: exercise n. 2

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Exercise text

Consider the following pseudocode for a 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 $\lambda = 0.15$ people/frame

1. Compute the Probability Mass Function of the output rate of the ESP32 $\mathrm{P}(r = r_0)$, $\mathrm{P}(r = r_1)$, $\mathrm{P}(r = r_2)$, where r_0, r_1 and r_2 are the output rates when there are 0, 1 or more than 1 people 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, 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 Expected rate probability

We are first aiming at using the standard Poisson's distribution density function to determine the expected number of people per frame, outlining therefore the expectations for each available data rate.

To do this, with N being the number of people per frame, we will distinguish among the cases for $N = 0$, $N = 1$ and $N \geq 2$.

Given the average rate $\lambda = 0{,}15$ people/frame of a Poisson distribution, the corresponding density function is, traditionally:

$$P_\lambda(n) = \frac{\lambda^n}{n!} \cdot e^{-\lambda}$$

Which results in:

$$P(r = r_0) = P(N = 0) = \frac{0{,}15^0}{0!} \cdot e^{-0{,}15} = 1 \cdot e^{-0{,}15} = 0{,}861$$

$$P(r = r_1) = P(N = 1) = \frac{0{,}15^1}{1!} \cdot e^{-0{,}15} = 0{,}15 \cdot e^{-0{,}15} = 0{,}129$$

$$P(r = r_2) = P(N \geq 2) = 1 - P(N = 0) - P(N = 1) = 0{,}010$$

In which we outlined the last case resulting from the remainder of the first two, as it includes all the scenarios in which the number of people per frame is ≥ 2, also relying on standard probability properties.

2 The complete monitoring system

2.0.1 Pseudocode analysis

The attached pseudocode describes a sketch of the behaviour of an overall monitoring algorithm.

The nodes, therefore, outline a periodic timer-based cycle, which involves the collection of a new frame from the connected camera capture device, which is then parsed, estimating the number of people present.

The payload is then formed, according to a dimensioning rule which imposes its size being 1 kB (the minimum) for the case where $N = 0$ and 6 kB (the maximum) for the case where $N \geq 2$.

Ultimately, the periodic timer restarts, analyzing a new frame every 10 seconds.

2.0.2 Computation

Given $R = 250\ kb/s$ and $L = 128\ Bytes$ from the text, we add the details related to the periodic capturing and monitoring algorithm, which underlines $d = 10\ seconds$ as the cyclic monitoring period.

As shown during the exercise lectures, the nominal data rate (R) stems from:

$$R = \frac{L}{T_S} \Rightarrow T_S = \frac{L}{R} = \frac{128 \cdot 8\ bits}{250 \cdot 1000\ bits/second} = 4{,}096\ ms$$

In which we shown that the Time Slot duration can be easily derived by computing the inverse formula.

In a similar way, the equivalent data rate (r) uses the minimum data rate as its reference, declaring, of course, subsequent ones as multiples of the reference one.

This translates to requiring:

$$r = \frac{min(l_i)\ \forall i \in [0, 1, 2]}{d} = \frac{1000 \cdot 8\ bit}{10\ seconds} = 800\ bits/s$$

In which l_i represent the payload length (or size) in the three possible cases ($N = 0,\ 1\ or\ \geq 2$).

This allows us to compute the inverse formula of r, outlining ultimately the BEACON INTERVAL value:

$r = \frac{L}{BI} \Rightarrow BI = \frac{L}{r} = \frac{128 \cdot 8\ bits}{800\ bits/s} = 1{,}28\ seconds$

When planning for the slot allocation, we cannot consider anything else than the worst-case scenario: even if, as commented earlier, the probability of having 3 camera nodes in the system detecting more than 1 person is very low, it still represents a theoretical possibility.

In such a case, we would need to allocate the space for the maximum payload size ($6\ kB$) to all the nodes. Each node will therefore use $\frac{r_x}{r} = \frac{6 \cdot r}{r} = 6$ slots in the worst case.

Moreover, the system's active state includes only the COLLISION FREE PART, for which the assigned GUARANTEED TIME SLOTS will ultimately be:

$$N_{CFP} = \sum_{x=0,\ 1,\ 2} \frac{r_x}{r} = 3 \cdot \frac{6 \cdot r}{r} = 18 \text{ slots.}$$

In which we outlined the worst case when considering 3 monitoring nodes.

ACTIVITY and INACTIVITY periods will immediately follow:

$T_{ACTIVE} = (18 + 1) \cdot T_S = 19 \cdot T_S = 77{,}824\ ms$

In which we considered an additional slot for the BEACON message.

$T_{INACTIVE} = BI - T_{ACTIVE} = 1{,}28\ seconds - 0{,}078\ seconds = 1{,}202\ seconds$

From which we derive, ultimately:

$$D_{\%} = \frac{T_{ACTIVE}}{T_{ACTIVE} + T_{INACTIVE}} = \frac{T_{ACTIVE}}{BI} = 6{,}08\ \%$$

In which we highlighted the use of both ACTIVE and INACTIVE parts of the BEACON INTERVAL.

Being the duty cycle lower than the targeted one (10%), there may still be room for fitting new camera nodes.

3 Additional camera nodes

Let's now point our resolution towards the targeted duty cycle:

$D_{\%} \leq 10\%$, which of course translates to requiring $T_{ACTIVE} \leq 128\ ms$.

Let's now call t the total number of TIME SLOTS (T_S) that can be fit in the ACTIVE period, as a whole and rewrite T_{ACTIVE} consequently.

$T_{ACTIVE} = (t + 1) \cdot T_S \leq 128\ ms$

$$t \leq \left\lfloor \frac{128\ ms}{T_S} - 1 \right\rfloor = \left\lfloor \frac{128\ ms}{4{,}096\ ms} - 1 \right\rfloor = 30 \text{ slots.}$$

In our current implementation, 18 slots are presently being occupied by the worst case scenario, as shown earlier.

Therefore, we can use the additional $30 - 18 = 12$ TIME SLOTS remaining for the additional camera nodes.

Assuming, as before, to adopt the worst case scenario, we can ultimately compute the allowed number of camera nodes which may fit into the monitoring system by assigning them all of the remaining TIME SLOTS.

This translates to:

$$N_{CFP} = \left\lfloor \sum \frac{r_x}{r} = n \cdot \frac{6 \cdot r}{r} = n \cdot 6 \right\rfloor = 12$$

With n being the number of allowed additional camera nodes.

Resulting in:

$$n = \left\lfloor \frac{12}{6} \right\rfloor = 2$$

The number n of additional allowed camera nodes is therefore 2.