Internet of Things
Homework

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1 Exercise 2: IoT Monitoring System Analysis

1.1 Task Summary

This exercise analyzes an ESP32-based IoT monitoring system that captures camera frames, estimates the number of people, and generates data payloads of varying sizes. The objectives are:

1. To compute the Probability Mass Function (PMF) of the output data rate of the ESP32, considering a Poisson distribution for the number of people detected.
2. To determine a consistent slot assignment for the Contention Free Period (CFP) in an IEEE 802.15.4 network with 3 camera nodes and 1 PAN coordinator. This involves calculating slot time (T_s), total CFP slots, active time (T_{active}), inactive time ($T_{inactive}$), and the system's duty cycle.
3. To calculate how many additional camera nodes can be added to the system while keeping the duty cycle below 10%.

1.2 System Parameters and Givens

The following parameters and conditions are defined for the system:

- Data processing interval: The `process_frame` function is called every 10 seconds.
- People detection: Follows a Poisson distribution with an average rate $\lambda = 0.15$ persons/frame.
- Payload sizes based on person count:
  - 0 persons: 1KB
  - 1 person: 3KB
  - >1 person: 6KB
- Network standard: IEEE 802.15.4 in beacon-enabled mode (CFP only).
- Network configuration: 1 PAN coordinator and 3 initial camera nodes.
- Nominal bit rate (R): 250 kbps.
- Packet size (L): 128 bytes (1 packet fits exactly in one slot).

1.3 1. Probability Mass Function of the Output Rate

The number of people X detected in a frame follows $P(X = k) = \frac{e^{-\lambda}\lambda^k}{k!}$ with $\lambda = 0.15$.

- $P(X = 0) = e^{-0.15} \approx 0.860708$
- $P(X = 1) = 0.15 \cdot e^{-0.15} \approx 0.129106$
- $P(X > 1) = 1 - P(X = 0) - P(X = 1) \approx 0.010186$

The output rates r_0, r_1, r_2 for payloads generated every 10 seconds are:

- $r_0(1\text{KB}) : \frac{1 \times 1024 \times 8 \text{ bits}}{10 \text{ s}} = 819.2 \text{ bps}$
- $r_1(3\text{KB}) : \frac{3 \times 1024 \times 8 \text{ bits}}{10 \text{ s}} = 2457.6 \text{ bps}$
- $r_2(6\text{KB}) : \frac{6 \times 1024 \times 8 \text{ bits}}{10 \text{ s}} = 4915.2 \text{ bps}$

Result: The PMF of the output rate r is:

- $\boxed{P(r = 819.2 \text{ bps}) = P(X = 0) \approx 0.8607}$
- $\boxed{P(r = 2457.6 \text{ bps}) = P(X = 1) \approx 0.1291}$
- $\boxed{P(r = 4915.2 \text{ bps}) = P(X > 1) \approx 0.0102}$

1.4 2. CFP Slot Assignment and System Timings

Given the nominal bit rate $R = 250$ kbps and a packet size $L = 128$ bytes $=$ 1024 bits.

Slot Time (T_s): First, I calculated the slot time:

$$T_s = \frac{L}{R} = \frac{1024 \text{ bits}}{250000 \text{ bps}} = 0.004096 \text{ s}$$

Result:

$$\boxed{T_s = 4.096 \text{ ms}}$$

Beacon Interval (BI): It is derived from the packet size ($L = 1024$ bits) and a characteristic system slowest output rate of $R_{sys\_slow} = 800$ bps:

$$BI = \frac{L}{R_{sys\_slow}} = \frac{1024 \text{ bits}}{800 \text{ bps}} = 1.28 \text{ s}$$

Slots per Camera: Next, I calculated the number of slots required per camera for a consistent assignment during the CFP. This calculation is based on a worst-case scenario where each camera needs to effectively transmit data at an average rate of $R_{cam\_wc} = 4800$ bps within the duration of one Beacon Interval ($BI = 1.28$ s). The data transmitted per camera in one BI is:

$$\text{Data per camera per BI} = R_{cam\_wc} \times BI = 4800 \text{ bps} \times 1.28 \text{ s} = 6144 \text{ bits}$$

The number of slots per camera is then:

$$\text{Slots per camera} = \frac{\text{Data per camera per BI}}{L} = \frac{6144 \text{ bits}}{1024 \text{ bits/slot}} = 6 \text{ slots}$$

CFP Configuration (3 camera nodes): With 3 camera nodes, each requiring 6 data slots:

- Total data slots for 3 nodes (Ncfp or $N_{\text{CFP\_data}}$): 3 nodes $\times$ 6 slots/node $=$ 18 slots.
  Result:
  $$\boxed{\text{Ncfp (Total data slots)} = 18 \text{ slots}}$$
- Active Time (T_{active}): This period includes the data slots for all cameras plus one additional slot for the beacon.
  $T_{active} = (N_{\text{CFP\_data}} + 1) \times T_s = (18 + 1) \text{ slots} \times 0.004096 \text{ s/slot} = 19 \times 0.004096 \text{ s} = 0.077824$ s.
  Result:
  $$\boxed{T_{active} = 77.824 \text{ ms}}$$
- Inactive Time ($T_{inactive}$): With the new BI $= 1.28$ s:
  $T_{inactive} = \text{BI} - T_{active} = 1.28 \text{ s} - 0.077824 \text{ s} = 1.202176$ s.
  Result:
  $$\boxed{T_{inactive} \approx 1.202 \text{ s}}$$
- Duty Cycle (DC): DC $= \frac{T_{active}}{\text{BI}} \times 100\% = \frac{0.077824 \text{ s}}{1.28 \text{ s}} \times 100\% = 6.08\%$.
  Result:
  $$\boxed{\text{Duty Cycle (3 nodes)} = 6.08\%}$$

1.5 3. Additional Cameras for Duty Cycle < 10%

For this analysis, I defined the active time (T_{active}) for N_{cam} cameras based solely on their cumulative data slots:

$$T_{active}(N_{cam}) = N_{cam} \times \text{slots\_per\_camera} \times T_s$$

Substituting slots_per_camera = 6:

$$T_{active}(N_{cam}) = N_{cam} \times 6 \times 0.004096 \text{ s}$$

The condition to keep the duty cycle below 10% is:

$$\frac{T_{active}(N_{cam})}{\text{BI}} < 0.10$$

Plugging in the values:

$$\frac{N_{cam} \times 0.024576 \text{ s}}{1.28 \text{ s}} < 0.10$$

This simplifies to:

$$N_{cam} \times 0.0192 < 0.10$$

From this, I calculated the limit for N_{cam}:

$$N_{cam} < \frac{0.10}{0.0192} \approx 5.208333$$

Since the number of cameras must be an integer, I determined the maximum number of cameras (N_{max}) by taking the floor of this limit:

$$N_{max} = \lfloor 5.208333 \rfloor = 5$$

I then verified the duty cycle for $N_{max} = 5$ cameras and for $N_{max}+1 = 6$ cameras:

- For 5 cameras, $T_{active}(5) = 5 \times 6 \times 0.004096 \text{ s} = 0.12288 \text{ s}$. The duty cycle is $\frac{0.12288}{1.28} \times 100\% \approx 9.60\%$.
- For 6 cameras, $T_{active}(6) = 6 \times 6 \times 0.004096 \text{ s} = 0.147456 \text{ s}$. The duty cycle is $\frac{0.147456}{1.28} \times 100\% \approx 11.52\%$.

These calculations confirm that 5 is the maximum number of cameras to keep the duty cycle below 10%.

Result:

$$\boxed{\text{Number of additional cameras that can be added} = 5 - 3 = 2}$$