Approximate Query Service on Autonomous IoT Cameras *(MobiSys 2020)*

Mengwei Xu[1], Xiwen Zhang[2], Yunxin Liu[3] Gang Huang[1], Xuanzhe Liu[1], Felix Xiaozhu Lin[2]
[1]Peking University, [2]Purdue University, [3]Microsoft Research

Presenter: Rui Yang
Date: Oct.22, 2020

Video Analytics Apps

- Busy cross roads
- Retailing store
- Sports stadium
- Parking lots
- ...

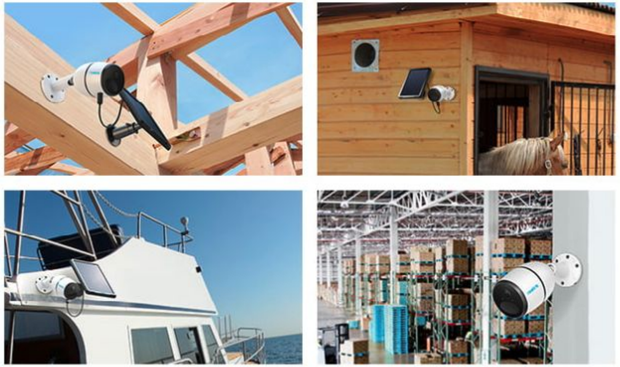
Urban, residential areas

✓ Wired electricity
✓ Good internet

Video Analytics Apps

- Busy cross roads
- Retailing store
- Sports stadium
- Parking lots
- ...

?



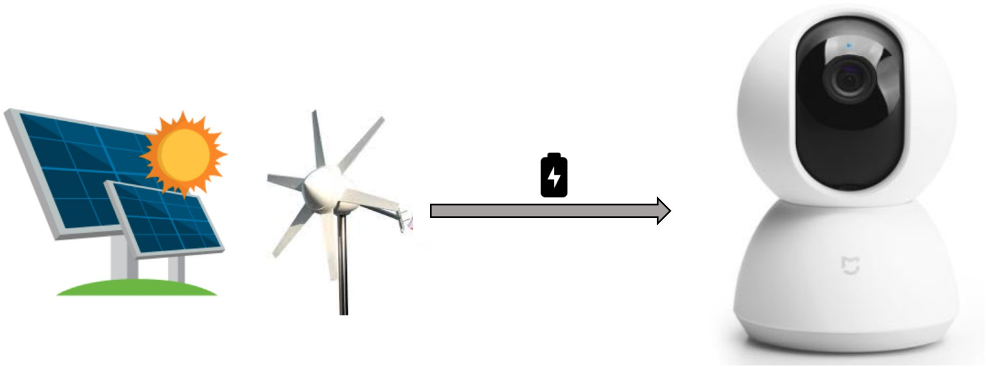
- Construction sites
- Cattle farms
- Highways
- Wildlifes
- ...

Urban, residential areas

Rural, off-grid area

Autonomous Camera

- **Energy-independent** and **Compute-independent**



Small-sized energy harvester
e.g., “10Wh today”

Commodity SoCs, RPI-like,
chargeable battery

Autonomous Camera

- **Energy-independent** and **Compute-independent**

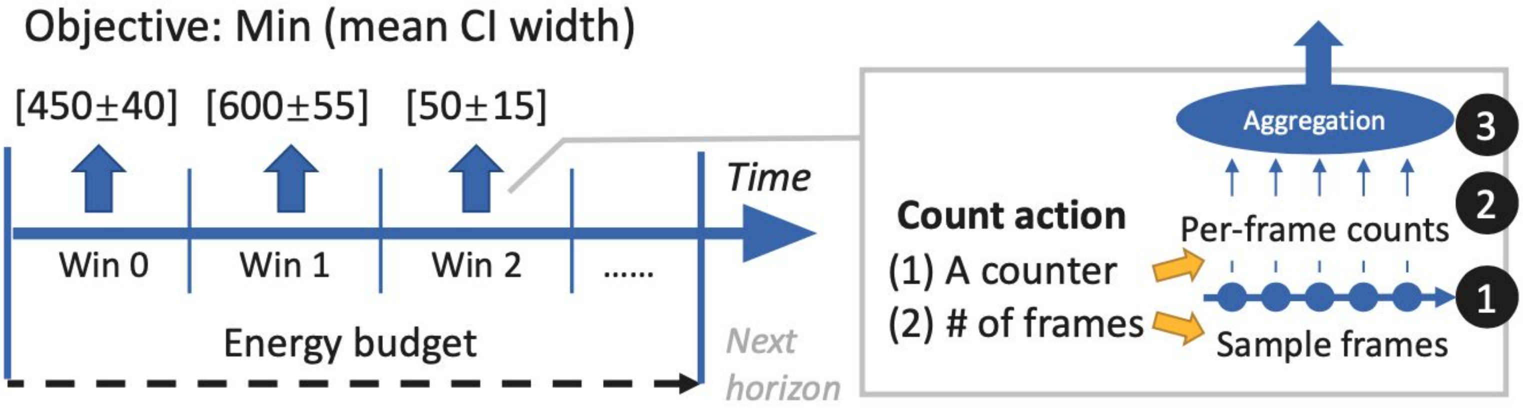
Small-sized energy harvester
e.g., “10Wh today”

Commodity SoCs, RPI-like,
chargeable battery

Concise, numerical
video summaries

Elf for Autonomous Cameras

- Target video query: object counting (with bounded error)

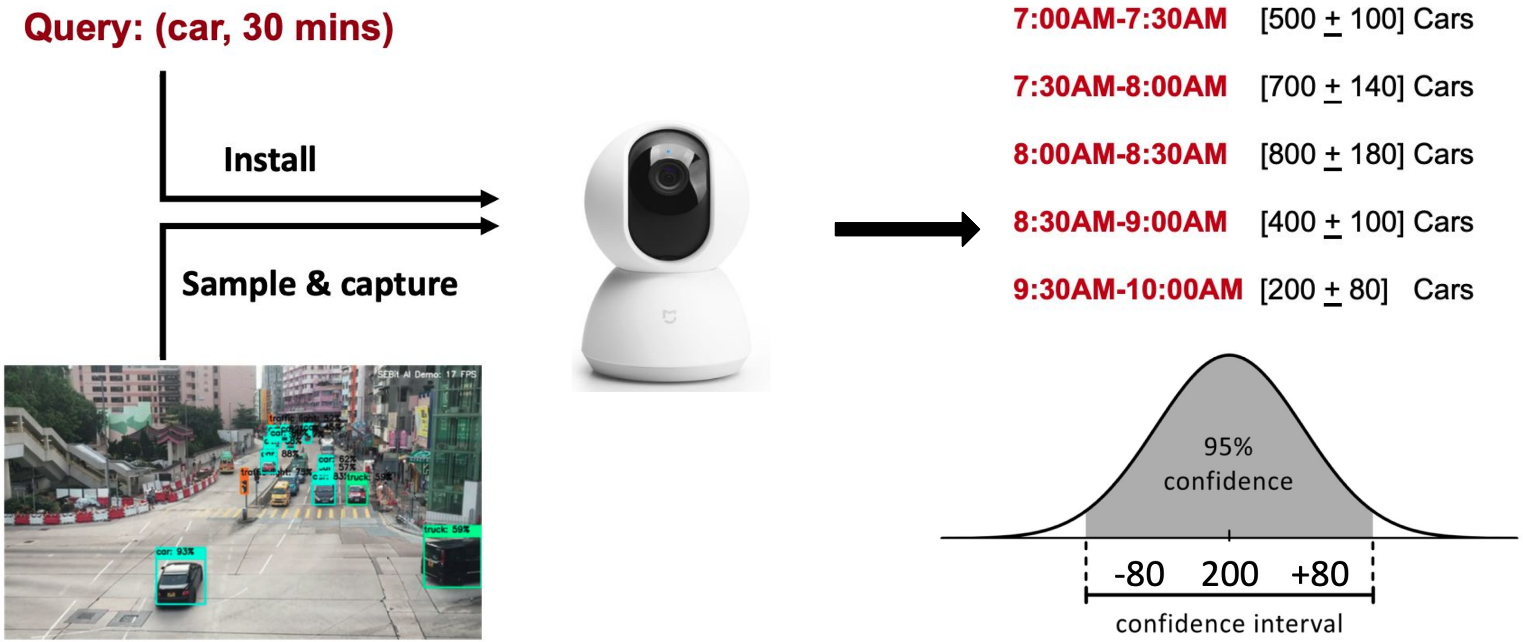


(a) A horizon

(b) A window

Elf for Autonomous Cameras

- Target video query: object counting



Elf for Autonomous Cameras

- Target video query: object counting

- The central problem: planning constrained energy for counting
  - Energy model: a budget that cannot be exceeded in a horizon (e.g., 24 hrs)
  - Target: smallest mean CI widths across all (30-min) windows in a horizon
  - Trade-offs: frame sampling and NN selections

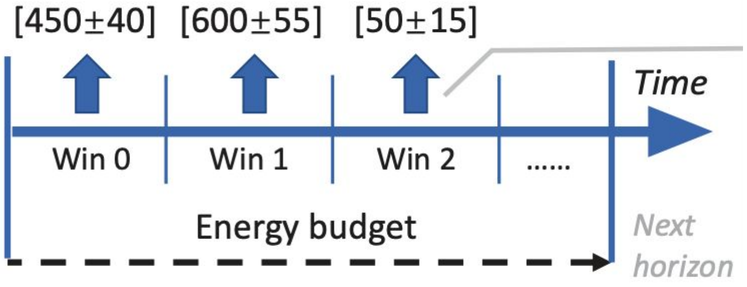
Elf for Autonomous Cameras

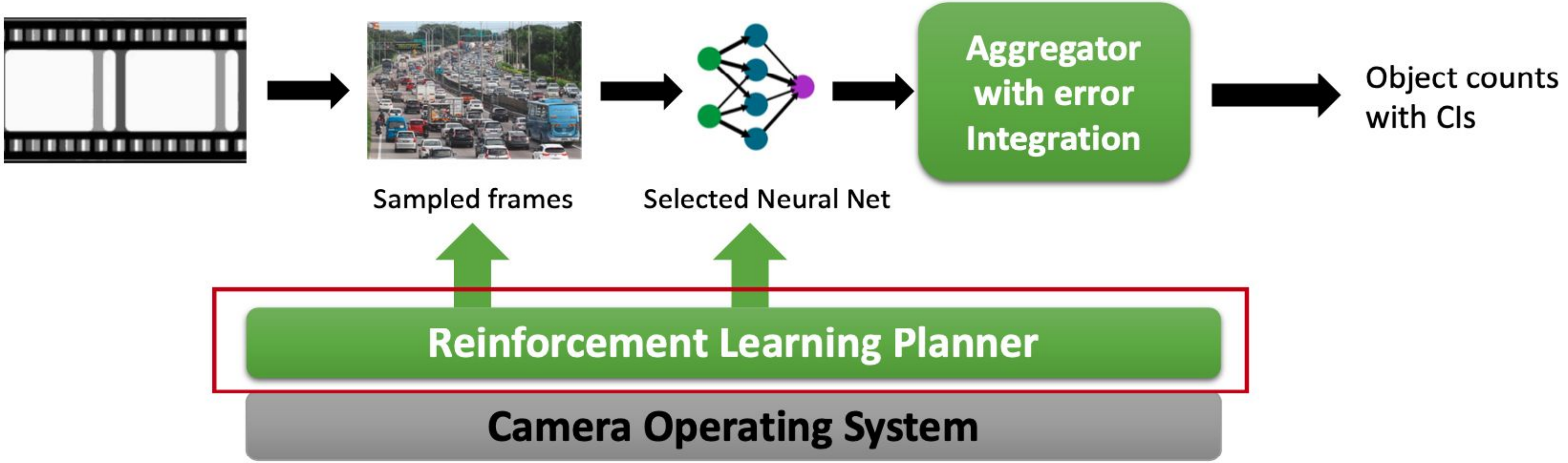
- Target video query: object counting

- The central problem: planning constrained energy for counting
    - Energy model: a budget that cannot be exceeded in a horizon (e.g., 24 hrs)
    - Target: smallest mean CI widths across all (30-min) windows in a horizon
    - Trade-offs: frame sampling and NN selections

- Solution: two main aspects:
    - Per window: characterizing count actions and outcome
    - Across windows: making joint count decisions on the go

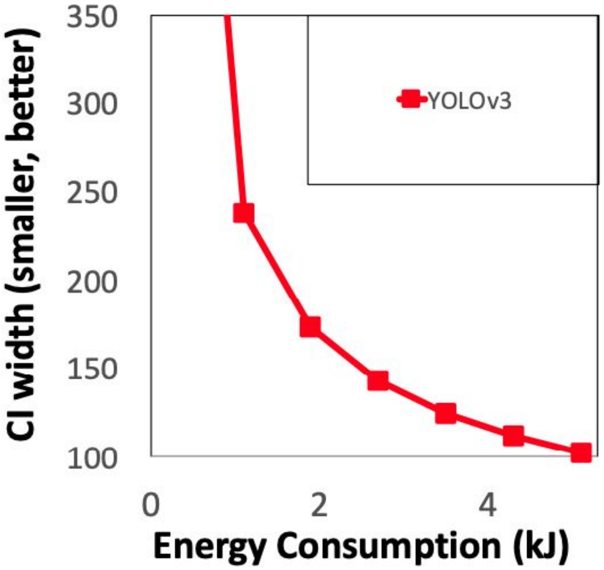
Elf Overview





Elf tech #1: per-window energy/CI fronts

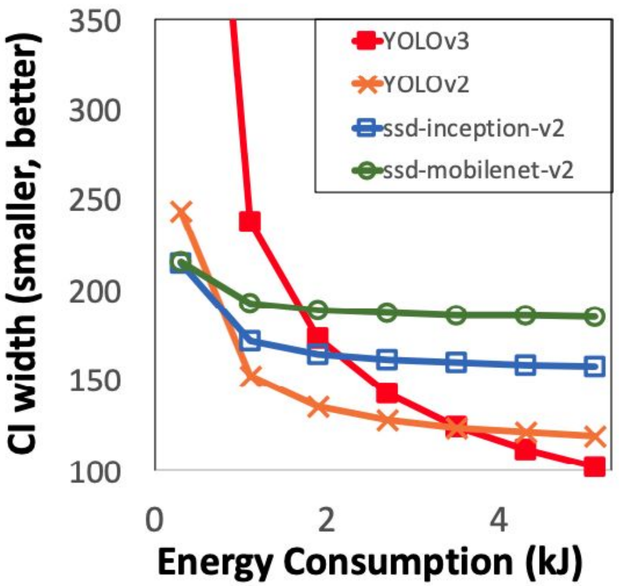
- What's the best count action for a window?
    - A *count action*: determining (1) an NN and (2) # of frames to process



Energy Consumption = E(NN) * frame_num

Elf tech #1: per-window energy/CI fronts

- What's the best count action for a window?
    - A *count action*: determining (1) an NN and (2) # of frames to process

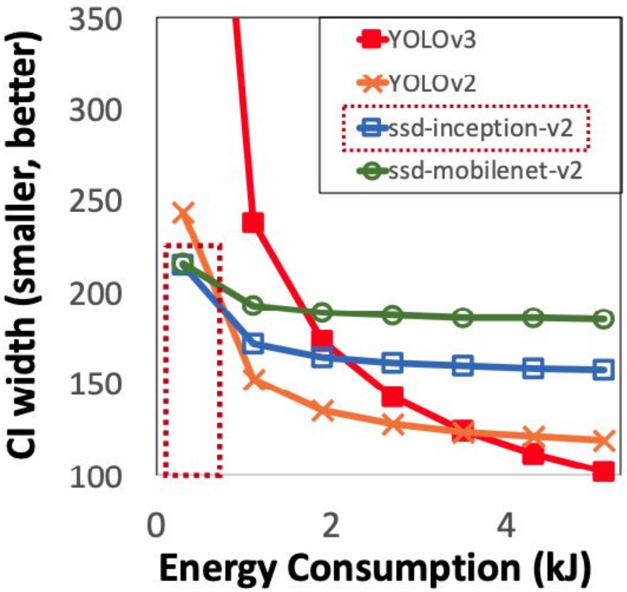


Energy Consumption = E(NN) * frame_num

NN Counters	Input	mAP	Energy
YOLOv3 (Golden, GT) [85]	608x608	33.0	1.00
YOLOv2 [84]	416x416	21.6	0.22
faster rcnn inception-v2 [86]	300x300	28.0	0.40
ssd inception-v2 [68]	300x300	24.0	0.08
ssd mobilenet-v2 [88]	300x300	22.0	0.05
ssdlite mobilenet-v2 [88]	300x300	22.0	0.04

Elf tech #1: per-window energy/CI fronts

- What's the best count action for a window?
  - A *count action*: determining (1) an NN and (2) # of frames to process

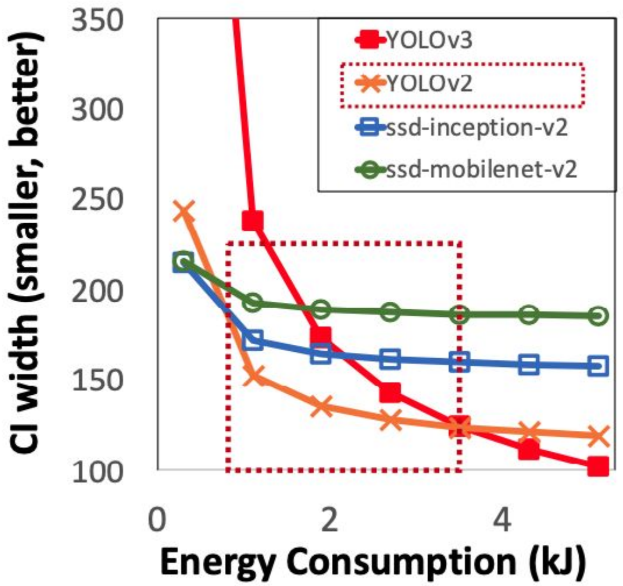


When energy is low: cheaper NNs win

- **Bottlenecked by sampling error (frame quantity)**

Elf tech #1: per-window energy/CI fronts

- What's the best count action for a window?
    - A *count action*: determining (1) an NN and (2) # of frames to process

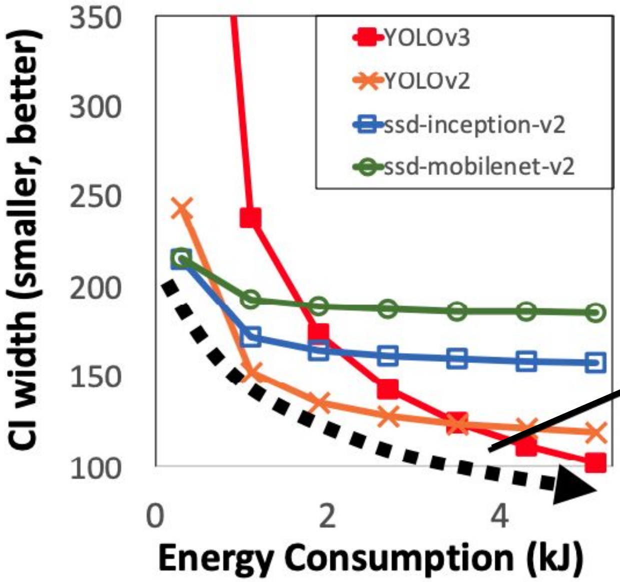


When energy is low: cheaper NNs win
- **Bottlenecked by sampling error (frame quantity)**

When energy is low: more accurate NNs win
- **Bottlenecked by NN error (frame quality)**

Elf tech #1: per-window energy/CI fronts

- What's the best count action for a window?
  - A *count action*: determining (1) an NN and (2) # of frames to process



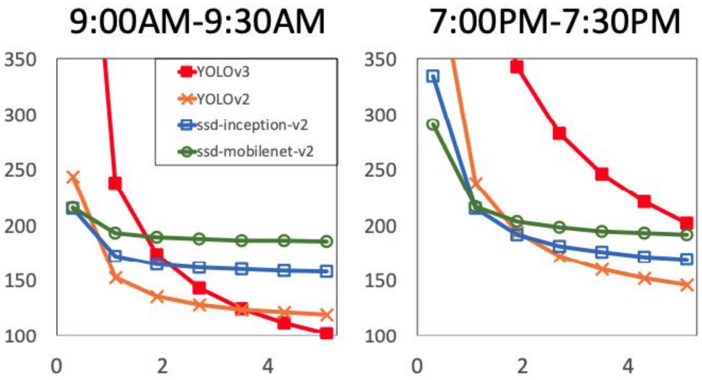
When energy is low: cheaper NNs win
When energy is low: more accurate NNs win

Energy/CI front*: the combination of all "optimal" count actions with varied energy*

- How to construct? Error integration
- Depends on the video characteristics

Elf tech #1: per-window energy/CI fronts

- What's the best count action for a window?
  - A *count action*: determining (1) an NN and (2) # of frames to process



Different windows have different energy/CI fronts

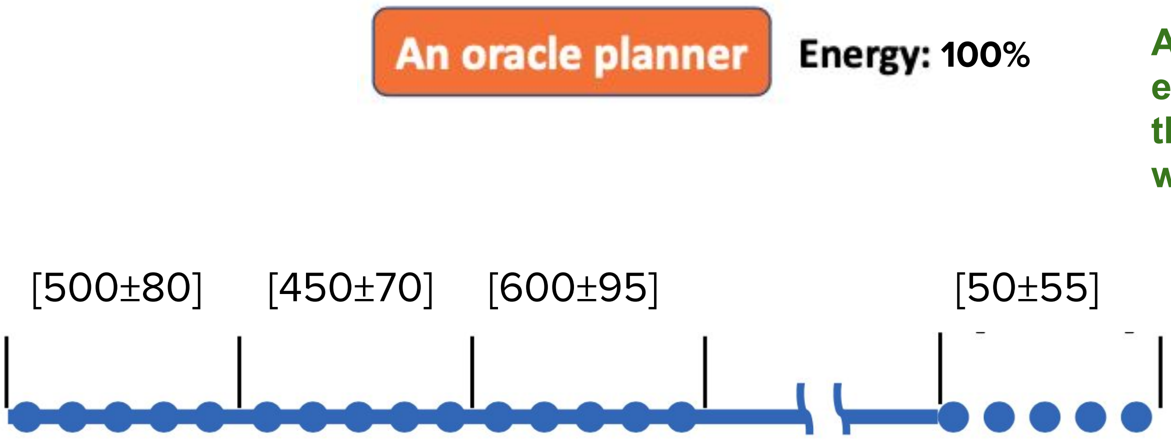
When energy is low: cheaper NNs win
When energy is low: more accurate NNs win

Energy/CI front: *the combination of all "optimal" count actions with varied energy*

- How to construct? Error integration
- Depends on the video characteristics

Elf tech #2: across-window joint planning

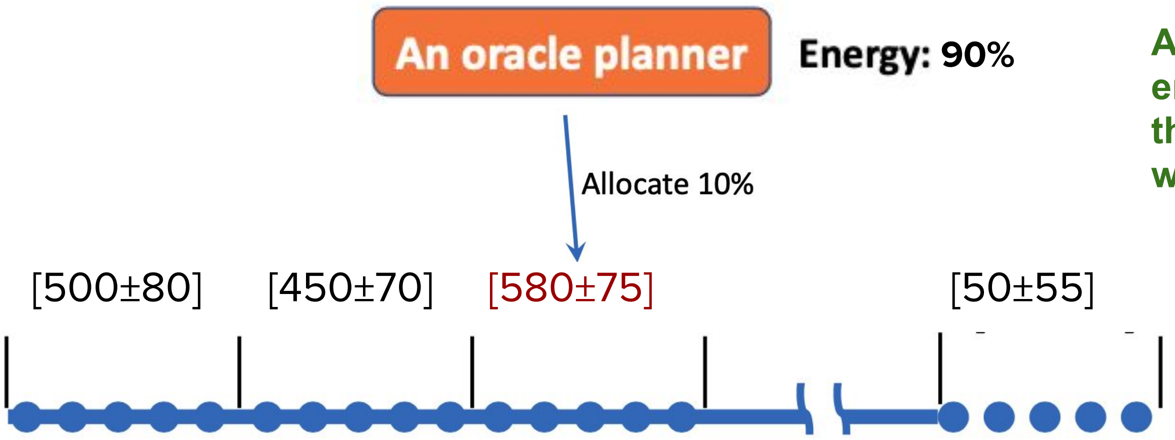
- An Oracle Planner: best performance but unrealistic
    - knows all energy/CI fronts



A greedy approach: giving energy to the window with the most benefit (i.e., CI width reduction).

Elf tech #2: across-window joint planning

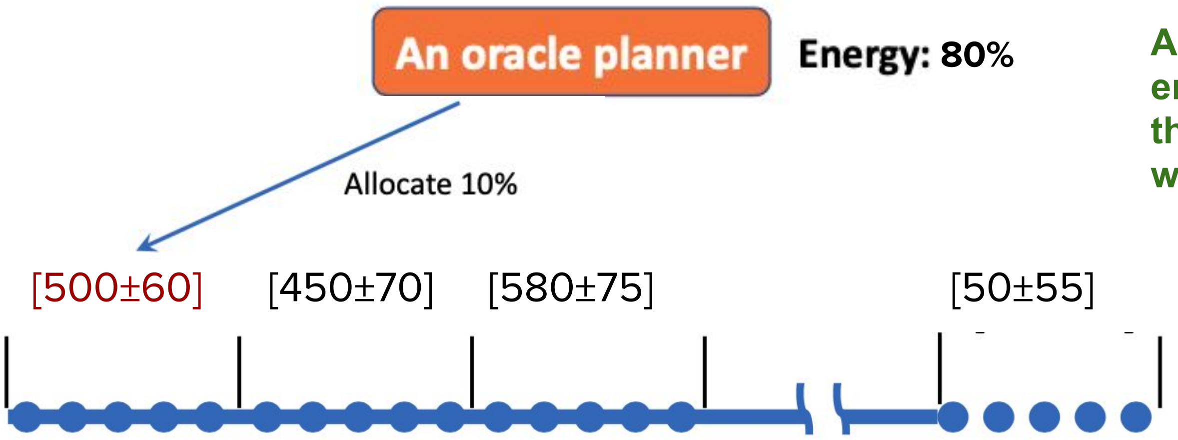
- An Oracle Planner: best performance but unrealistic
  - knows all energy/CI fronts



A greedy approach: giving energy to the window with the most benefit (i.e., CI width reduction).

Elf tech #2: across-window joint planning

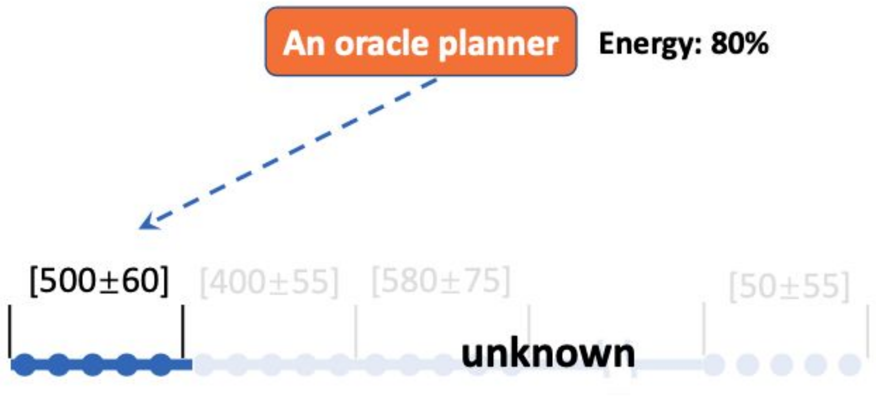
- An Oracle Planner: best performance but unrealistic
  - knows all energy/CI fronts



A greedy approach: giving energy to the window with the most benefit (i.e., CI width reduction).

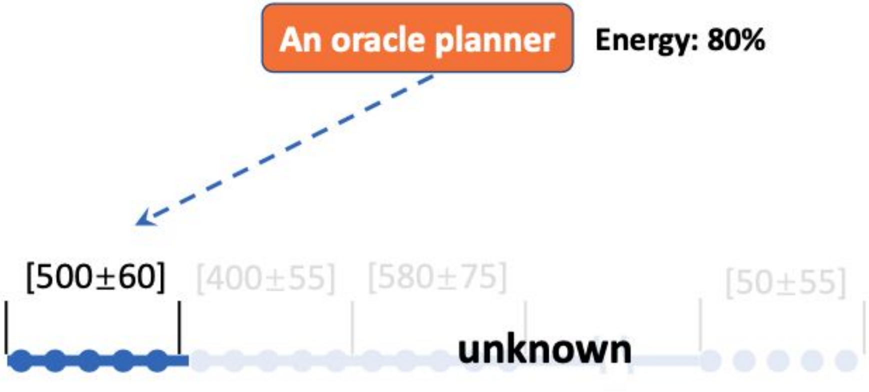
Elf tech #2: across-window joint planning

- An Oracle Planner: best performance but unrealistic
    - knows all energy/CI fronts



Elf tech #2: across-window joint planning

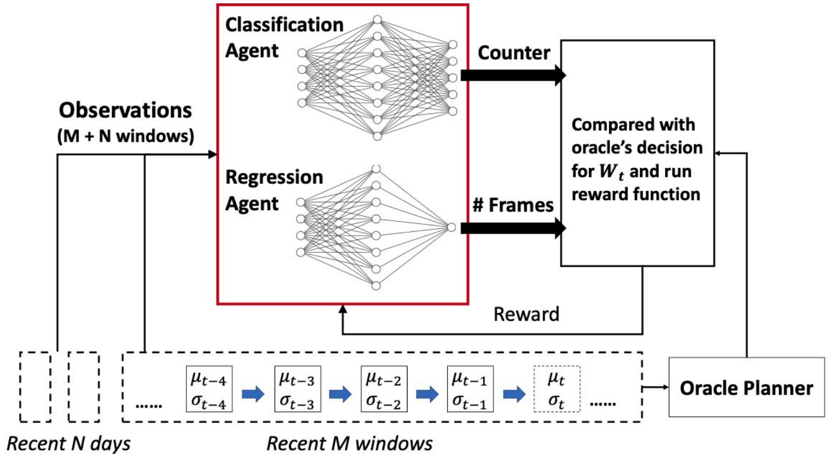
- An Oracle Planner: best performance but unrealistic
    - knows all energy/CI fronts
- Challenges:
    - Needs global knowledge (budget planning)
    - On-the-go (cannot delay, needs to provide fresh data for users)



Elf tech #2: across-window joint planning

- An Oracle Planner: best performance but unrealistic
  - knows all energy/CI fronts
  - Planned offline

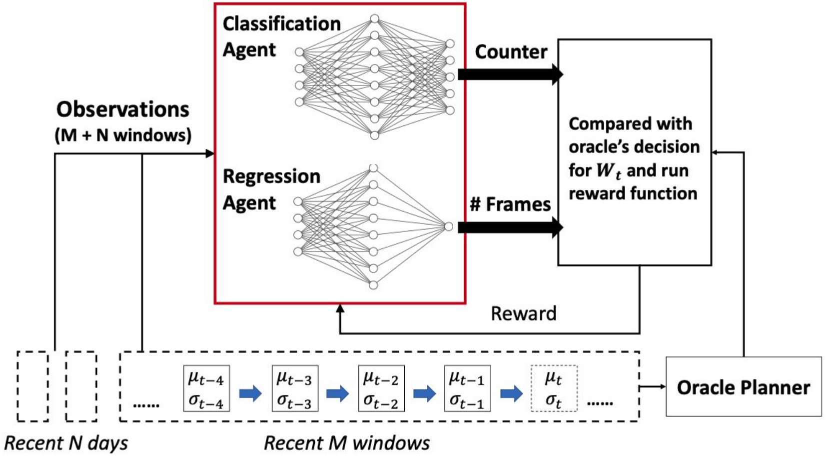
- A learning-based planner: imitating the oracle planner
  - basis: reinforcement learning
  - rationale: daily and temporal patterns



Elf tech #2: across-window joint planning

- An Oracle Planner: best performance but unrealistic
  - knows all energy/CI fronts
  - Planned offline

- A learning-based planner: imitating the oracle planner
  - basis: reinforcement learning
  - rationale: daily and temporal patterns
  - offline training -> online prediction
    - Two agents: NN selection and # of frames
    - Observations: knowledge of past windows
    - Penalty: deviation from oracle's decision



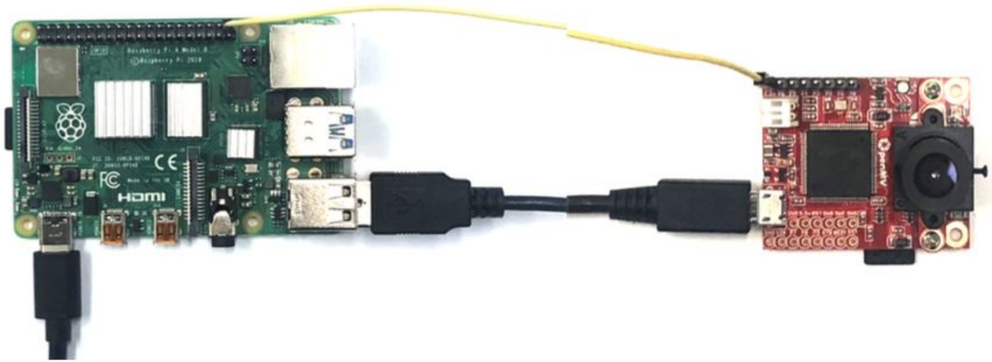
Elf tech #2: across-window joint planning

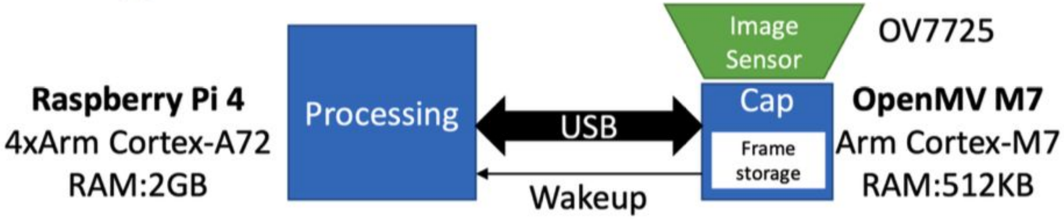
- An Oracle Planner: best performance but unrealistic
  - knows all energy/CI fronts
  - Planned offline

- A learning-based planner: imitating the oracle planner
  - basis: reinforcement learning
  - rationale: daily and temporal patterns
  - offline training -> online prediction
  - Enforce energy budget:
    - Different models for different budget level
    - Backstop design in case of no-energy
      - make reservation for future windows
      - Tuning reward functions to be conservative on energy

Elf Implementation

- Capture & processing decoupled for higher energy efficiency
    - Processing batched at the end of each window





Elf Evaluation

- Over 1,000-hr videos
  - Public, 2-week long each stream
- Baselines
  - 1. GoldenNN: most accurate NN
  - 2. UniNN: one fixed best NN
  - 3. Oracle: offline planned
- Small solar panel
  - 10Wh~30Wh per day

Auburn, AL

Hampton, NY

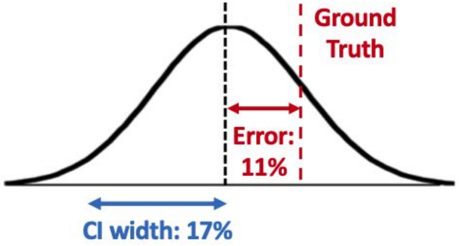
Jackson, WY

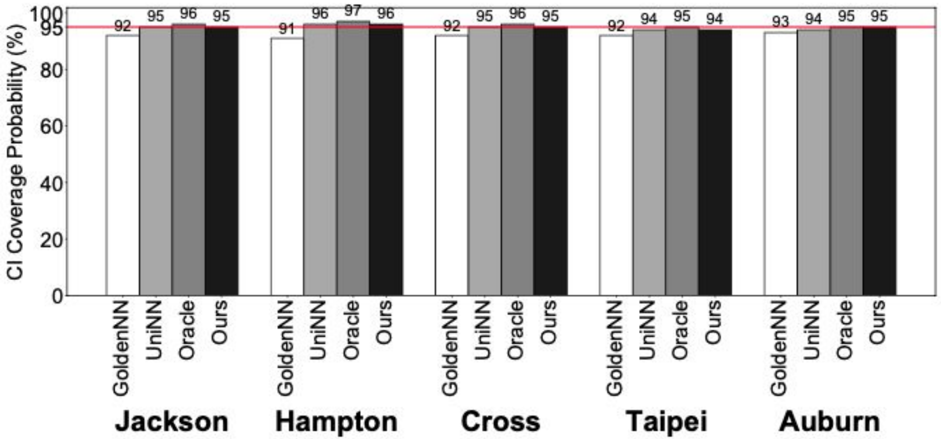
Taipei

Taipei

Elf Evaluation

- Average: 11% error, valid and 17%-width CI
    - 95% confidence level



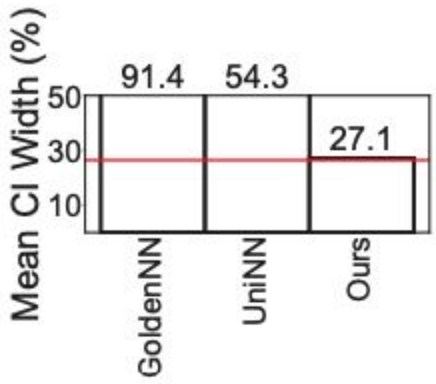


Cis cover ground truth with 95% probability (specified)

Elf Evaluation

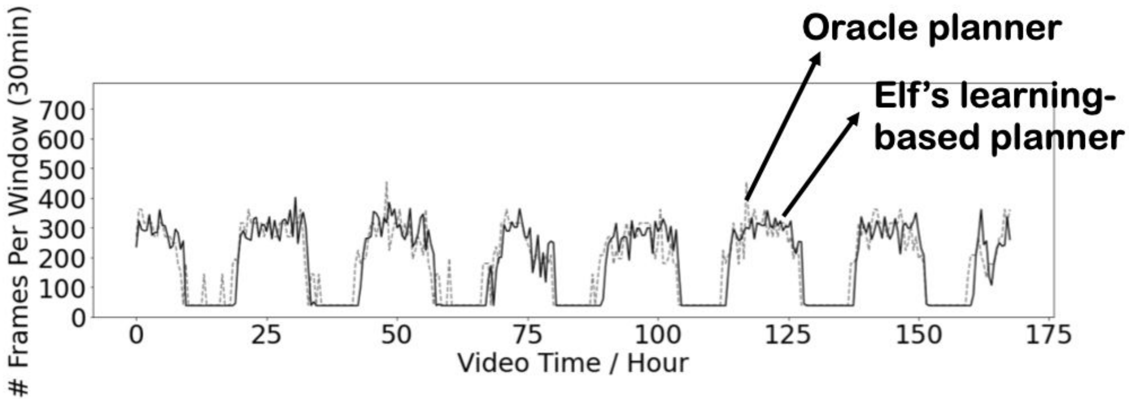
- Average: 11% error, valid and 17%-width CI
- Significant improvements over baselines in CI widths
    - The number in the table is how much Elf closer to oracle (best case)

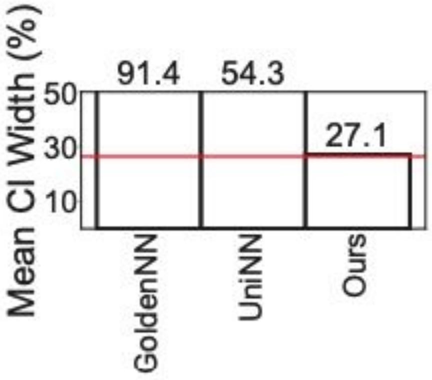
Budget (per day)	10Wh	20Wh	30 Wh
Golden NN	66.6%	59.8%	56.2%
UniNN	41.1%	16.6%	9.7%



Elf Evaluation

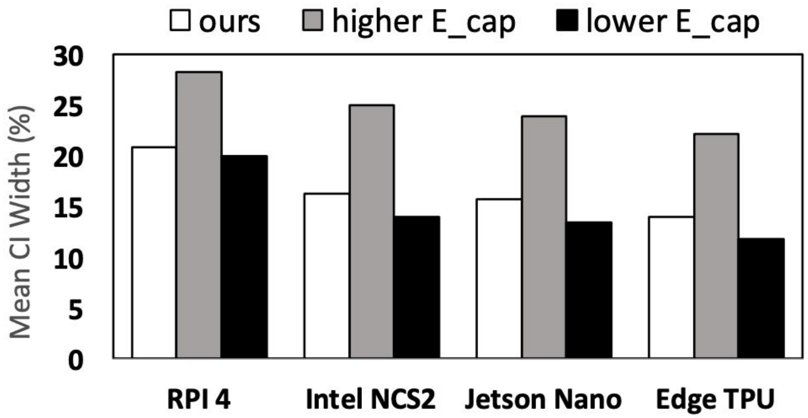
- Average: 11% error, valid and 17%-width CI
- Significant improvements over baselines in CI widths
    - The number in the table is how much Elf closer to oracle (best case)
    - Very close to oracle





Elf Evaluation

- Average: 11% error, valid and 17%-width CI
- Significant improvements over baselines in CI widths
- Very close to oracle
- What if we have AI accelerators?
    - CIs are reduced noticeably (by 22.1%–33.1%)
    - Still cannot process every frame (short of energy)



Summary

- Autonomous camera: expanding the geo-frontier of video analytics
  - Energy-independent and compute-independent
- Elf: the first runtime for autonomous camera
  - Target query: object counting
  - Key idea: count planning per- and across-windows
- Prototyped on heterogeneous hardware
- Evaluated on over 1,000-hr videos
  - 11% error, 17% CI width

Very high-level thoughts of the paper

- Pros:
    - Clear, precise problem definition, use case
    - Comprehensive discussion and consideration (design & expr)

- Cons:
    - Not exactly a bounded error. Error aggregation function looks empirical
    - Not sure how easy that can be applied to other query / problem
    - Experiments are still based on urban data

- Maybe a further topic
    - Duplicated / distinct object.

Moving computation to IoT devices

Reasons to keep it local / on-device:

- Device is becoming more powerful and chips are cheaper
- Privacy issue
- Data is becoming too large to transmit and compute with in-different cost

Challenges of IoT computation-related system

- Limited Bandwidth / Unstable wireless
  - 5g-IoT (survey)

- Limited energy
- Limited computational power

- Others:
  - Device heterogeneity
    E.g. Heterogeneous Multi-Mobile Computing (Mobisys 2019)
  - Mobile
  - Context-aware

Some big areas in IoT

- Security
  - Blockchain related (survey)
- Sensing related:
  - E.g. Localization
- Healthcare
- AI on the edge / device
- Application
- Network management, mmWave etc

Feeling some diff between system and IoT research

System: (a little more) driven by expectation (metrics)

IoT: (a little more) limited by constraints