Energy-efficient Cross-camera Communication for Classification with Overlapping Field-of-View

ECE M202A: Embedded Systems, Fall 2021
Final Project Presentation
https://zutierrez.github.io/ecem202a_project/report

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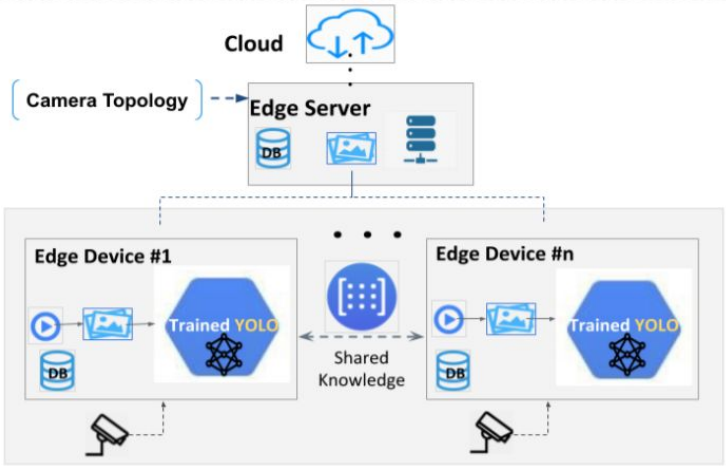
State-of-the-Art and Prior Research

CONVINCE: Collaborative Cross-Camera Video Analytics at the Edge

1) Collective entity of cameras capture takes advantage of **spatio-temporal** correlations
2) **Knowledge sharing** to conserve power

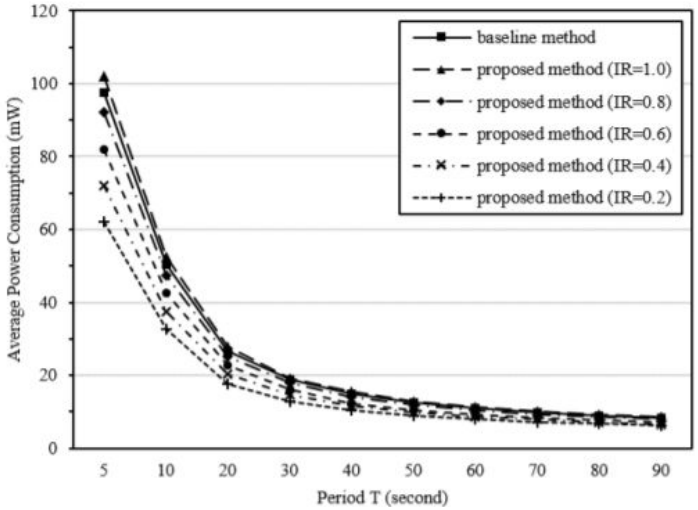


CONVINCE Framework Overview
(H. B. Pasandi and T. Nadeem)

State-of-the-Art and Prior Research

CamThings: IoT Camera with Energy-Efficient Communication by Edge Computing based on Deep Learning

1) Only **images of interest** are transmitted to Cloud
2) **Frequency** of image capture is adjusted
3) Edge computing based on **DNNs**



Improved Power Consumption via CamThings Framework
(J. Lim, J. Seo, and Y. Baek)

Overall Project Goals and Specific Aims

To optimize ***power consumption*** of multi-camera image classification using cross-camera communication.

Strategies:

1) Reducing the rate of capture
2) Transmitting only images of interest
3) Preventing redundant image transmission

Accomplishments

- Deployed machine learning model on edge-computing device
  - Arduino classified images using MobileNet V1 and TensorFlow Lite
- Arduino-Arduino cross-communication
  - Transmitted/received classified object labels between devices
- Arduino-to-WiFi-device image transmission
  - Transmitted images from the Arduino to the host device (computer)
- Analysis of power consumption for different scenarios
  - Found voltage and current draw of Arduino for multiple cases

Image Collecting and Model Training

Datasets: 128x128 images of Faces (Flickr-Faces-HQ) and other miscellaneous objects (Linnaeus 5)

Image Processing: 96x96 crop and data augmentation

128x128 image 96x96 image

MobileNet V1 0.1: 53.2K RAM and 101K ROM (default settings and optimizations)

87% accuracy on test set, **20** training cycles, 1,000 human samples, 1,000 unknown → Transfer Learning

- **Speed:** inference time < 300 ms on average
- **Low Compute:** Runs on Arduino Nano 33 BLE Sense with 256KB (nRF52840)
- **Compatibility with Arduino Nano:** lightweight library for edge devices

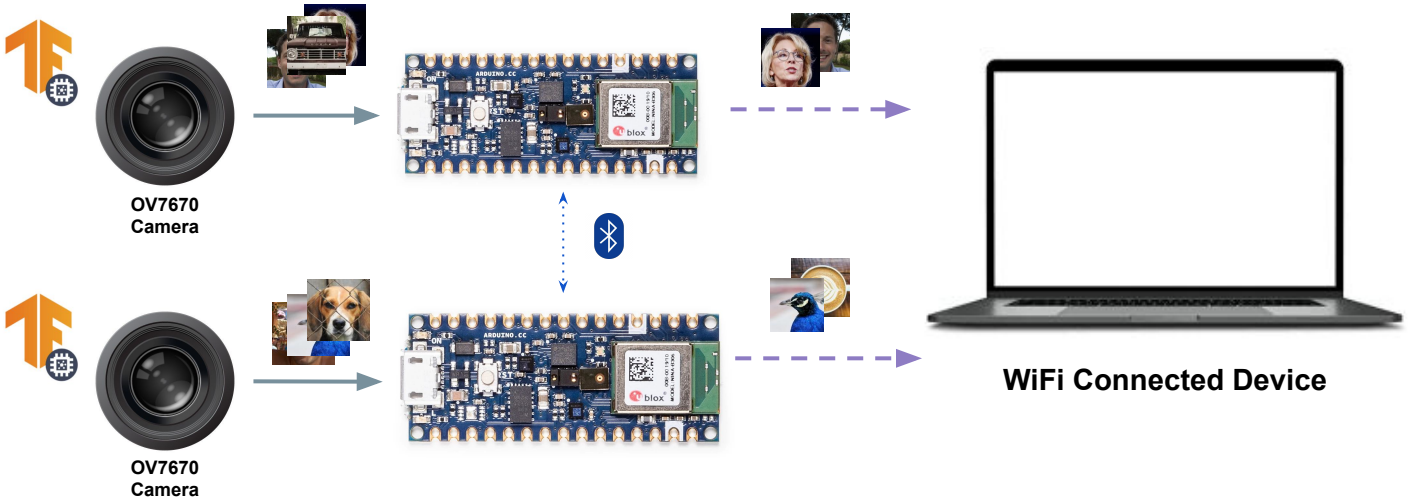
Cross-Camera Communication via BLE

- BLE 5 Characteristics and Constraints:
  - BLE 5 has practical net data rate of around 1.4 Mbps
  - Central Peripheral Model for Data Sharing
  - Constant advertisement of data over connection requires additional power
  - Images (280x320) are too large for BLE so label are transmitted in their place

- Arduino-Arduino communication
  - Central device sends classified label (integer value) to the peripheral device, which can prevent redundant transmissions to cloud

Hardware System Overview:

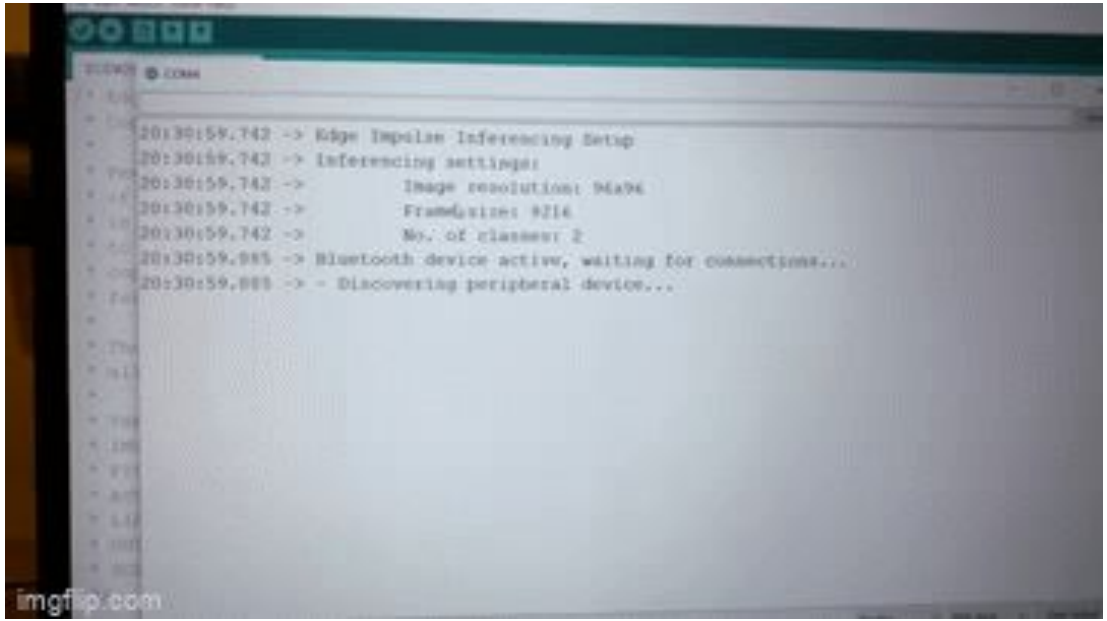
Arducam OV7670, 0.3 MP Camera Module
Arduino Nano 33 BLE Sense



Classification and Communication

Model Performance: 51 ms inference, 66.1k Peak RAM, 107.7K Flash

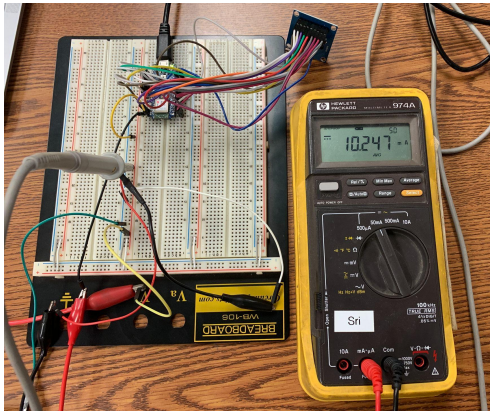
BLE Communication: Arduino 0.314 ms Inference and Label Sharing

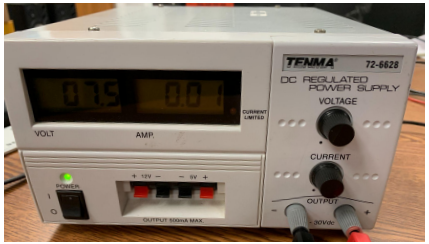


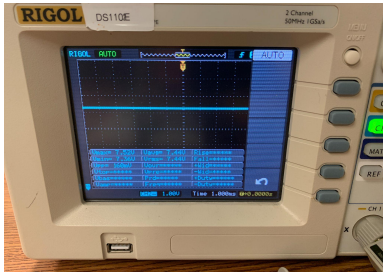
BLE Communication Demonstration: Arduino Nano 33 BLE Sense Central Device advertises label to Peripheral Device

Evaluation Set Up

- TENMA Power Supply
  - V = 7.5V (supply > 5.0V selected to override USB voltage)
  - USB current contamination
- RIGOL DS1102E Oscilloscope
  - Used to measure voltage
- HP974A Multimeter
  - Inserted in series to measure current
- 4 Evaluation Cases
  - Base case
  - Classification only
  - Classification with Bluetooth
  - Image transmission







Lab Instruments for Power Analysis:
Evaluation Setup and Methods

Evaluation and Results (Case 0)

“Reset” Arduino Program

- Average Current = 9.0mA

“Blink” Arduino Program

- Without USB: 17.38mA / 19.88 mA
- With USB: 17.36 mA / 19.83 mA

```
// the setup function runs once when you press reset or power the board
void setup() {
  // initialize digital pin LED_BUILTIN as an output.
  pinMode(LED_BUILTIN, OUTPUT);
}

// the loop function runs over and over again forever
void loop() {
  digitalWrite(LED_BUILTIN, HIGH);   // turn the LED on (HIGH is the voltage level)
  delay(1000);                       // wait for a second
  digitalWrite(LED_BUILTIN, LOW);    // turn the LED off by making the voltage LOW
  delay(1000);                       // wait for a second
}
```

Code Snippet: Arduino Blink Program for Base Power Consumption

→ USB current contamination is negligible (< 0.1 mA)

Evaluation and Results (Case 1)

Image Classification Model Program

- Instantaneous Current:
  - **Task Flow:** Taking photo (2s) → inference (0.3s) → Delay (2s)
  - 26.8mA → 27.8mA → 24.3mA
- Average Current = ~26 mA

```
20:51:28.054 -> Inferencing settings:
20:51:28.054 ->         Image resolution: 96x96
20:51:28.054 ->         Frame size: 9216
20:51:28.054 ->         No. of classes: 2
20:51:28.054 ->
20:51:28.054 -> Starting inferencing in 2 seconds...
20:51:30.057 -> Taking photo...
20:51:33.241 -> Predictions (DSP: 10 ms., Classification: 328 ms., Anomaly: 0 ms.):
20:51:33.241 ->     person:     0.000000
20:51:33.241 ->     unknown:    0.996094
```

Evaluation and Results (Case 2)

Classification + BLE Communication Program

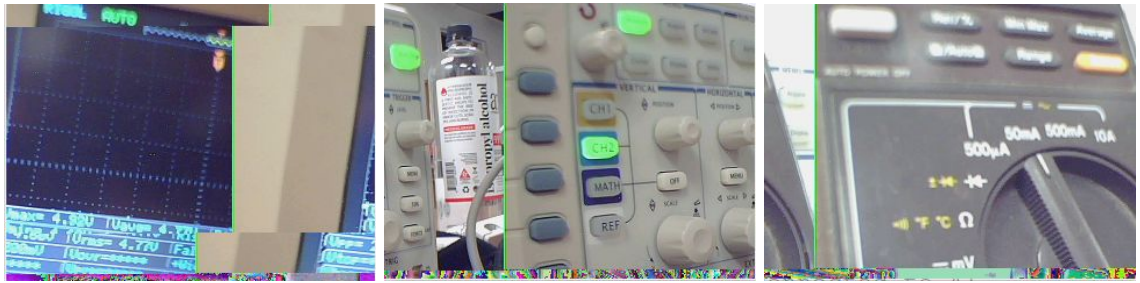
- Instantaneous Current:
  - **Task flow:** searching → connect → delay → take photo/inference → disconnect/reconnect
  - 13.3 mA → 10.3 mA → 28-29 mA → 31-32 mA → 20-21 mA
- Average Current:
  - **Before BT connection:** 13.3 mA
  - **After BT connection:** 28 mA

```
20:31:39.343 -> - Connecting to peripheral device...
20:31:39.416 -> * Connected to peripheral device!
20:31:39.416 ->
20:31:39.416 -> - Discovering peripheral device attributes...
20:31:40.658 -> * Peripheral device attributes discovered!
20:31:40.658 ->
20:31:40.658 -> * Device connected and starting inference!!
20:31:40.658 ->
20:31:40.658 ->
20:31:40.658 -> Starting inferencing in 2 seconds...
20:31:42.641 -> Taking photo...
20:31:46.214 -> Predictions (DSP: 18 ms., Classification: 584 ms., Anomaly: 0 ms.):
20:31:46.214 ->     person:     0.000000
20:31:46.214 ->     unknown:    0.996094
20:31:46.214 -> Choosing Label... - UNKNOWN detected
20:31:46.214 -> * Writing value to eventImage characteristic: 0
20:31:46.253 -> * Writing value to gesture_type characteristic done!
20:31:46.253 ->
20:31:46.253 -> * Device connected and starting inference!!
```

Evaluation and Results (Case 3)

Images Transmission from Arduino to WiFi Device Program

- Average Current:
  - **Idle**: 25 mA
  - **Take photo:** 29 mA
  - **Transmit photo binary:** 27 mA



Final Results: Power Consumption Summary

- V_avg consistent in all cases
  - V_avg = 7.44V (over 10 ms), Vpk-pk = 120-160 mV
- USB current contamination is negligible

Case	Task	Min Current	Max Current	Avg. Current	Avg. Power
0	Reset	-	-	9 mA	**68 mW**
1	Classification	24.3 mA	27.8 mA	26 mA	**195 mW**
2	Classification + BLE	10 mA	32 mA	28 mA	**210 mW**
3	Image Transmission	-	-	27 mA	**203 mW**

Conclusions and Discussion

- Summary: Given a 50% redundancy rate, only 0.74% reduction in power consumption
  - **Total energy per frame = 35.9 mAh**
  - **Energy saved per frame = 0.267 mAh**
- This method does not significantly reduce power consumption in a 2-camera system executing on-board image classification and BLE communication in real time
- Reducing image transmissions by eliminating redundancies does not yield significant energy savings such that it compensates for power consumption of BLE communication
  - **BLE energy per frame = 2.58 mAh**
- Image classification & image transmission have similar power consumption (27-28 mA)
- Taking photos results in highest current spike (31-32 mA)

Challenges

Arduino Nano 33 BLE Sense Limitations

- **Low memory:** an lightweight model was necessary to avoid reaching memory capacity
- **Low processing power:** slow image capture and transmission during runtime (1 second)
- **Compilation speed:** large file took several minutes

OV7670 Camera Limitations

- **Low image quality:** tradeoffs made to switch to lower resolution camera decreased inference accuracy during execution at the edge
- **Unreliable connection:** images often became corrupted after several successful images. One camera produced constantly blurry images.

BLE Communication Issues

- **Unexpected disconnection:** Arduinos successfully connected but frequently lost connection due to memory constraints of running image classification model in conjunction with constant BLE advertising
- **Low throughput:** BLE 5 cannot send full image data in one transmission, images had to be split up into packets

Improvements & Future Work

Improvements:

- Utilize portable WiFi device (such as RPi) instead of computer as fog layer device
- Train model for finer granularity of on-device image classification (i.e. black dog vs. white dog)
- Improve latency and throughput by optimizing neural network architecture while maintaining low power consumption

Future Work:

- Develop overlapping field-of-view algorithm
- Analyze power consumption with portable power supply (battery) in real-life case study

References

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7. Edge Impulse CLI: *https://docs.edgeimpulse.com/docs/cli-installation*
8. ArduCAM Repository: *https://github.com/ArduCAM/Arduino*

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