FireFly Mosaic: A Vision-Enabled Wireless Sensor Networking System

Anthony Rowe　　**Dhiraj Goel**　**Raj Rajkumar**

Dept. of Electrical & Computer Engineering

Carnegie Mellon University, U.S.A.

{agr,dgoel,raj}@ece.cmu.edu

Electrical & Computer ENGINEERING

1

Outline

- **Motivation**
  - Assisted Living
  - Vision as a Sensor
- FireFly Mosaic
- System Performance
- Home Activity Clustering

Electrical & Computer ENGINEERING

Aging Population

- 2000 US Census: 10 Million People over 65 Live Alone
  - Expected to more than double by 2050

- $70,912 per year for a private room in a nursing home ($194 per day)

- $25.32 per hour for in-home aid

- Quality of Life
  - People want to stay at home and enjoy their normal routine

- Similar trends in Europe (e.g. Italy) and Asia (e.g. Japan)

Where Can Technology Assist?

- Monitor Daily Patterns
  - Generate Sanitized Reports for Doctors and Caretakers

- Monitor Home Environment
  - Is the oven on? Is the temperature okay?

- Track Medication and Use

- Fall Detection

- Continual Medical Monitoring

Vision-Enabled Wireless Sensor Networks (WSN)

- ## Images Provide Extremely Rich Information
  - Local processing provides more than just an image

- ## Multiple Cameras Provide:
  - Greater Sensing Area Coverage
  - Increase Decision Confidence based on mutual information
  - Helps Address Occlusion (View Obstruction) Problems

Electrical & Computer
ENGINEERING

5

Vision-Enabled WSN Challenges

- ## Vision Challenges
  - Color Constancy, Dynamic Lighting, Object Recognition, etc

- ## System Challenges
  - Limited Bandwidth
  - Limited Power
  - Group Coordination
  - Fusing Multiple Sensor Inputs

Electrical & Computer
ENGINEERING

6

Outline

- Motivation
- FireFly Mosaic
  - Hardware Components
  - System Primitives
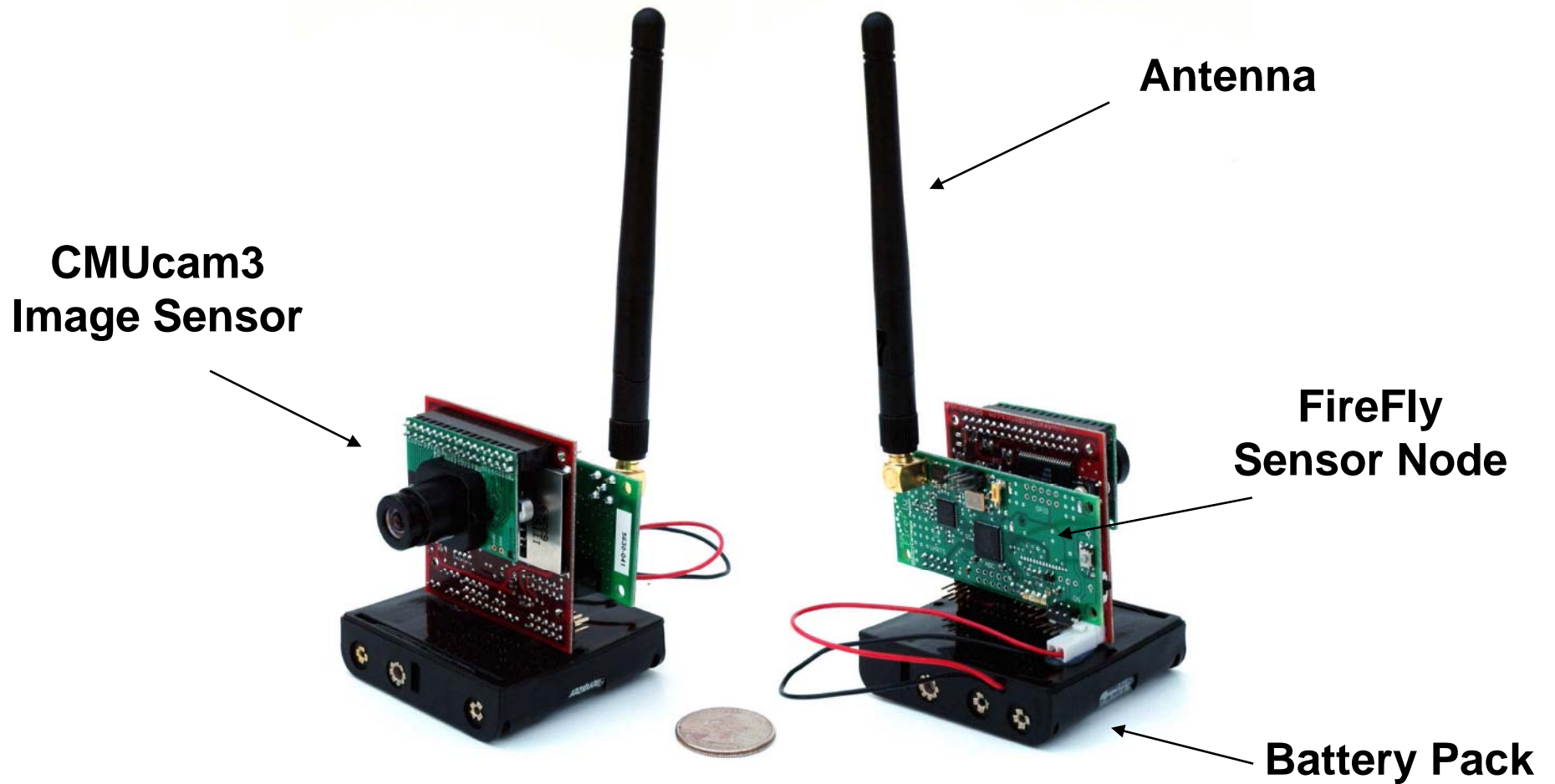- System Performance
- Home Activity Clustering

Electrical & Computer ENGINEERING

FireFly Mosaic Architecture

Wearable Mobile Device

Software Services

External Network

Gateway Device

FireFly Sensor Node

Image Sensor Node
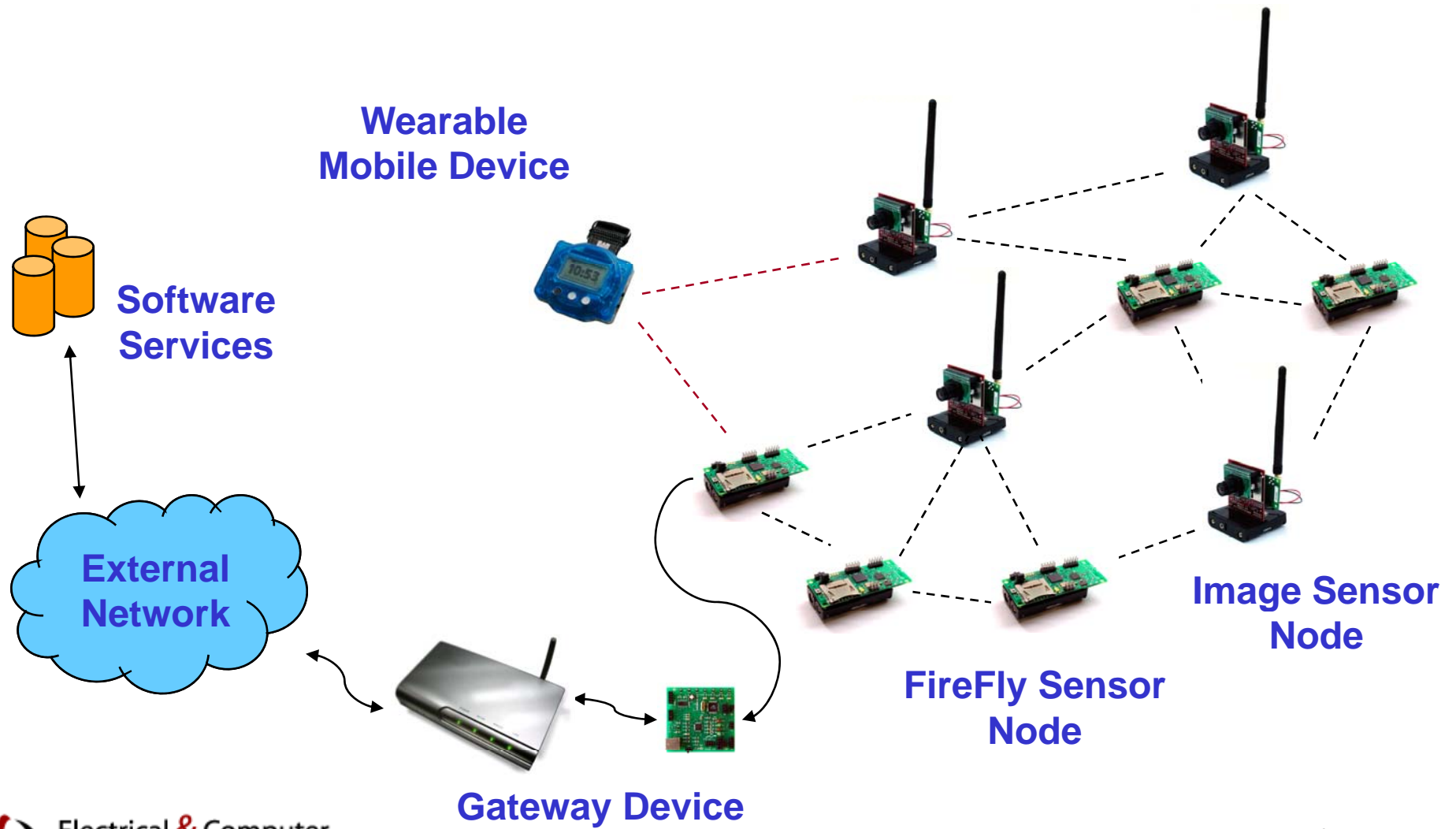
Sensor Network Description

- FireFly Sensor Node
  - ATmega1281, 8K Ram, 128K Rom
  - CC2420, 802.15.4 Radio

- Nano-RK RTOS (www.nano-rk.org)
  - Priority-based Fully Preemptive Operating System
  - Reservations
  - Open Source / Plain Vanilla C

- RT-Link
  - TDMA Link Layer Protocol
    - Collision Free TX and RX slots
  - Software Time Synchronization

Light

3 Axis Acceleration

PCB Antenna

Temperature

Audio

MiniSD slot

Electrical & Computer ENGINEERING

9

FireFly Mosaic Node

Antenna

CMUcam3 Image Sensor

FireFly Sensor Node

Battery Pack

Electrical & Computer
ENGINEERING
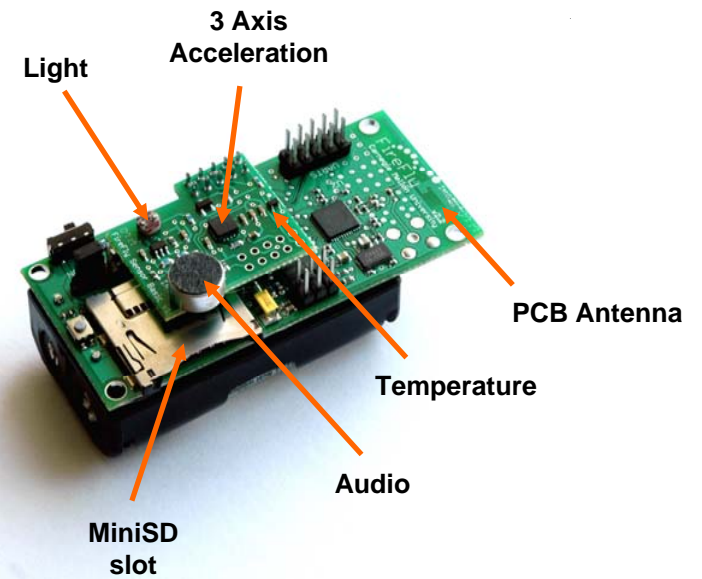
CMUcam3 Image Sensor

- 60 MHz ARM7TDMI Processor

- 64K RAM, 128K Flash

- 352 x 288 RGB Images

- Open-Source Image Processing Library
  - Color Blob Tracking, Frame Differencing, Convolutions, Histograms, Color Space Conversion, Down Sampling, Template Matching, JPEG compression

- Commercially Available
  - USA, Canada, France, Germany, Italy, England, Sweden, Finland, Czech Republic, Singapore and Spain

Electrical & Computer
ENGINEERING

11

Software Stack

FireFly Node

Activity Reporting

Sensing

Network Mgmt.

RT-Link Layer

Nano-RK RTOS

ATmega1281 8-bit MCU

802.15.4

CMUcam3

Activity Clustering

CC3 Image Libs

60 MHz ARM7 MCU

FIFO

CMOS Camera

Electrical & Computer ENGINEERING
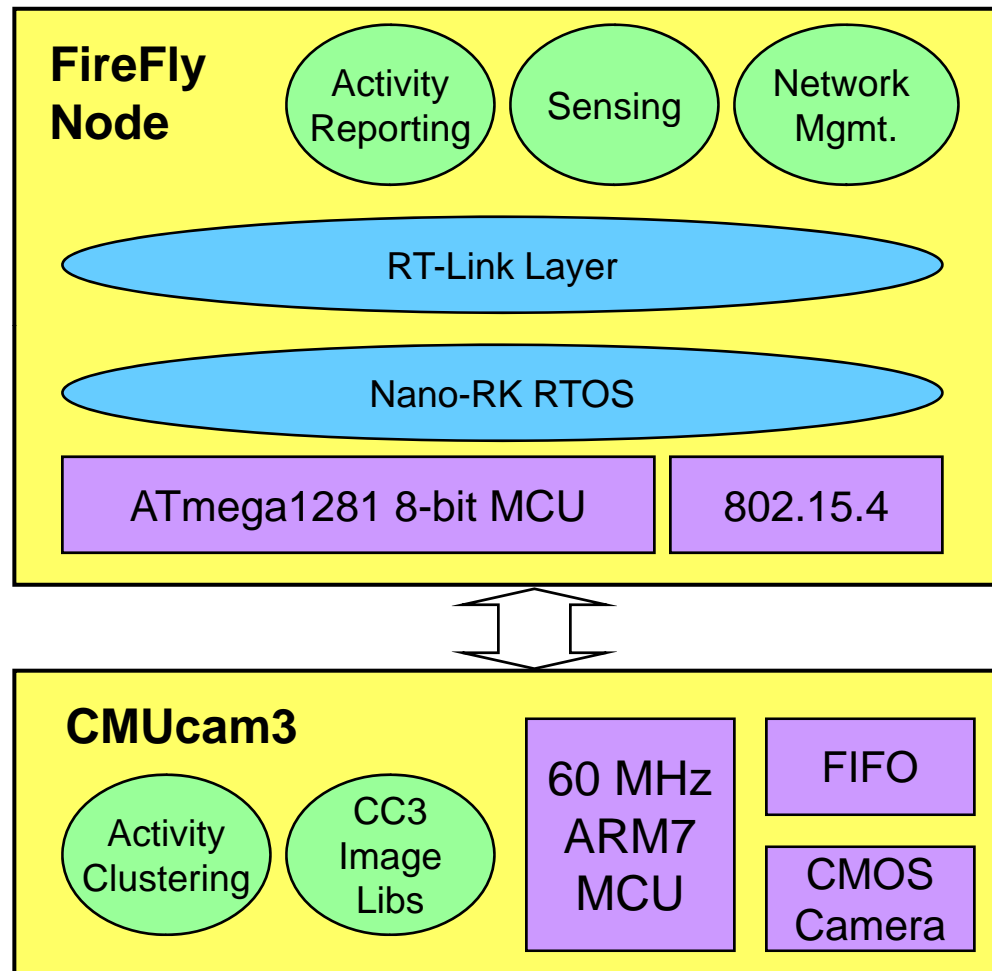
FireFly Mosaic Primitives

- Camera Connectivity Graphs

- Camera-Centric TDMA Scheduling Heuristics
  - Based on Camera Connectivity Graphs

- Time Synchronization Primitives

- Image Processing Tools
  - Image Transfer
  - Multiple Camera Image Region Correlation

Electrical & Computer
ENGINEERING

13

Camera Network Graphs (CNG)
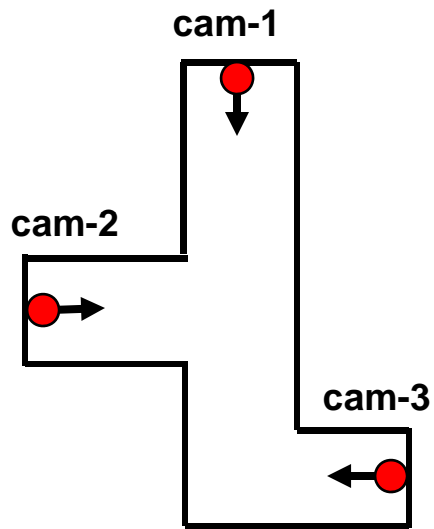
Physical View
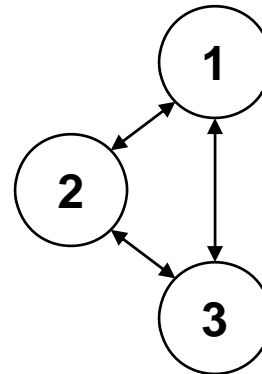
Non-Overlapping CNG
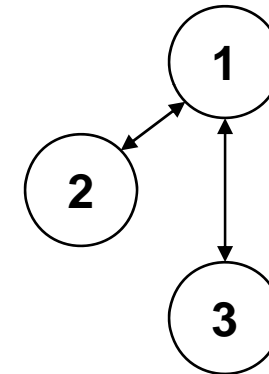
Shared View CNG

Communication Scheduling
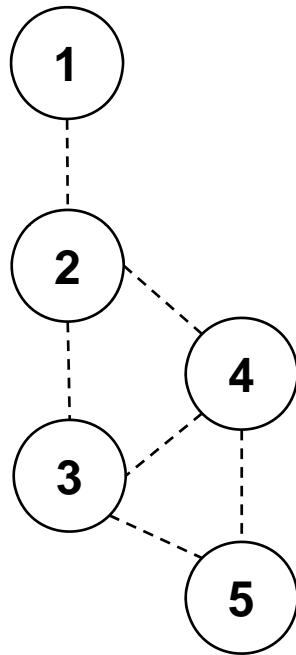
Communication Graph
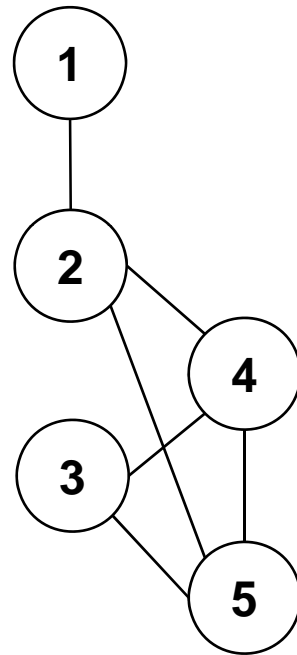
Camera Network Graph
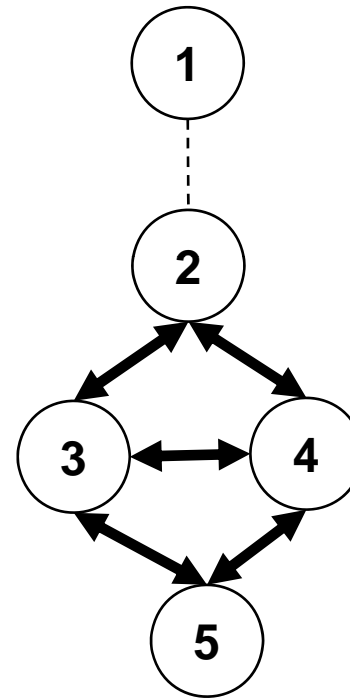
Camera Cluster Communication
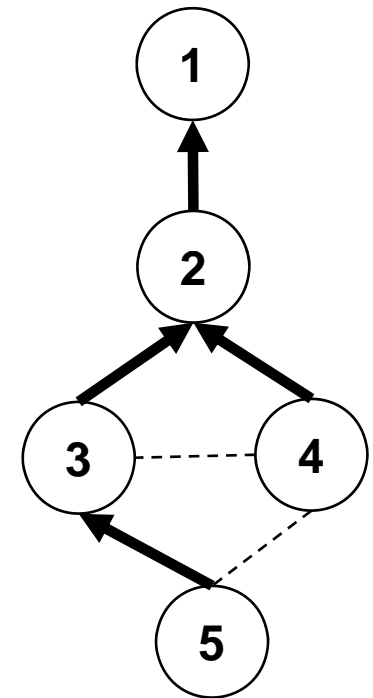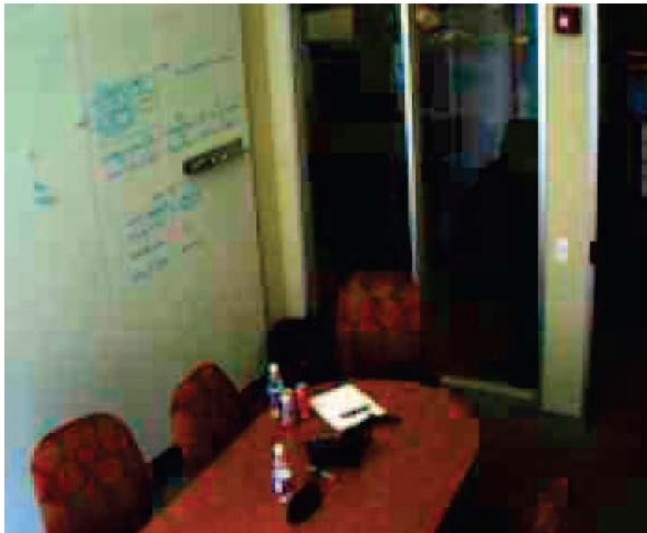
Upstream Result Communication

Outline

- Motivation
- FireFly Mosaic
- System Performance
  - Timing Jitter
  - Image Transfer Quality and Frame Rate
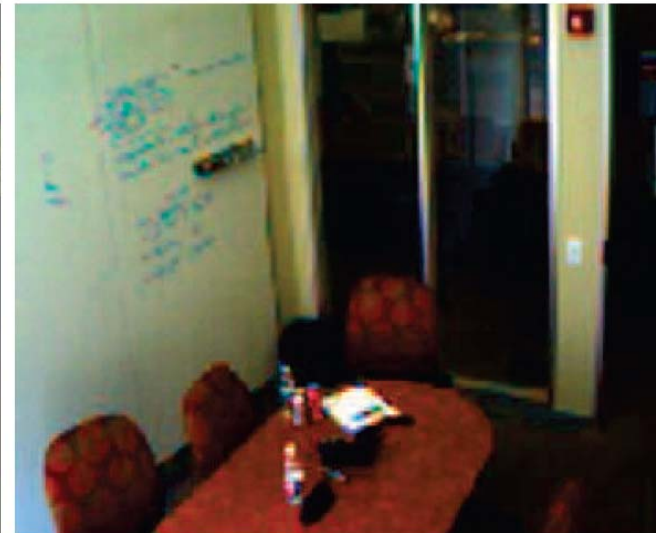 - Energy Distribution
- Home Activity Clustering

Electrical & Computer
ENGINEERING

Timing Jitter
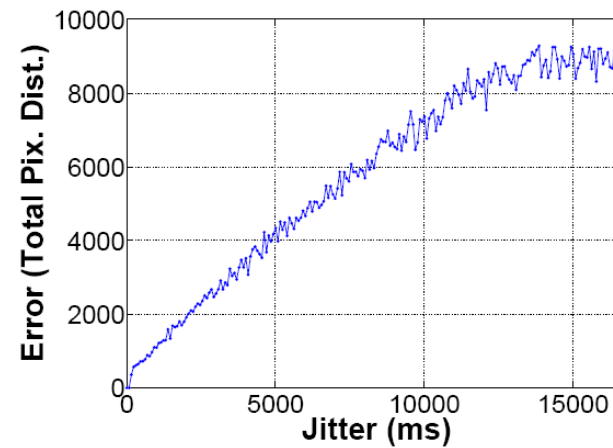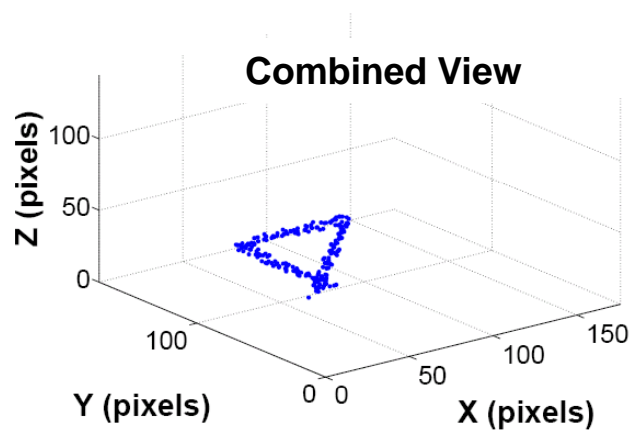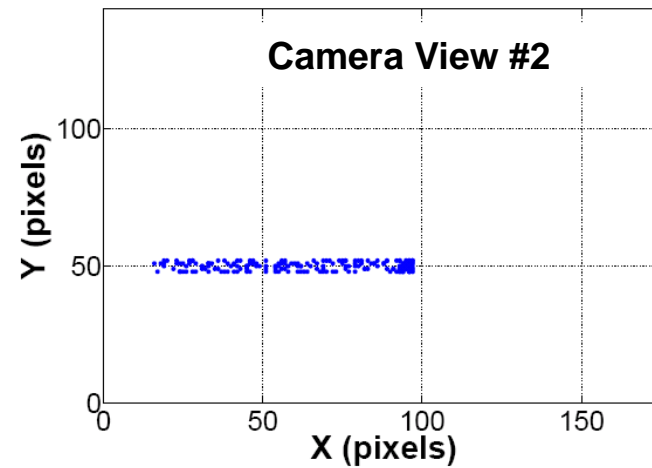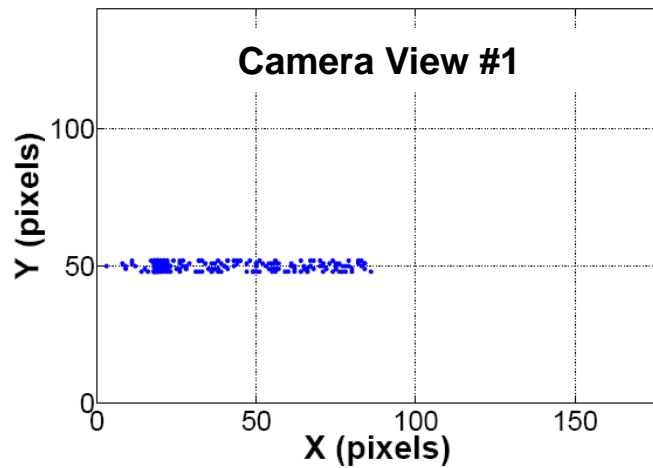
Sending Images

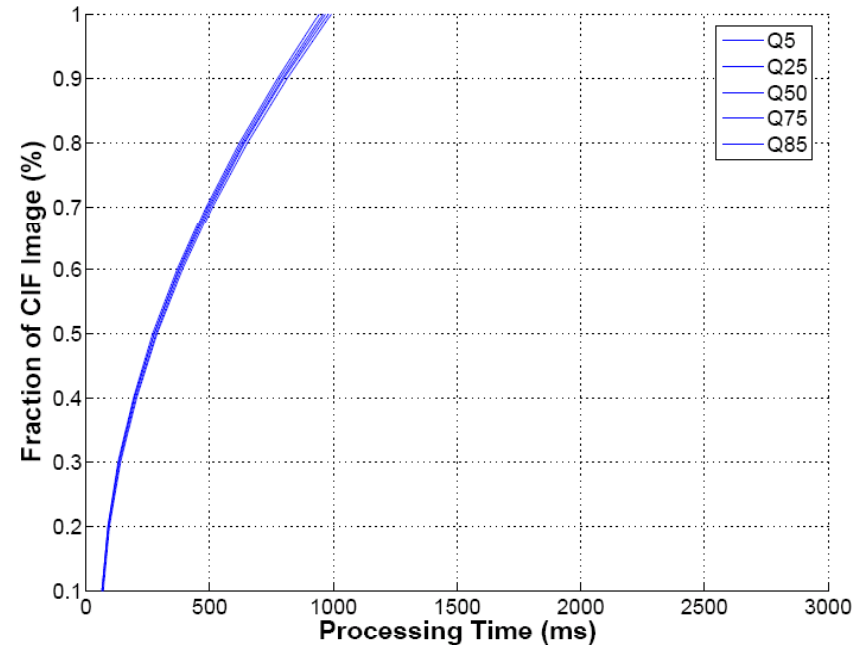- If I want to send an image, what is the best resolution, compression level and network rate?

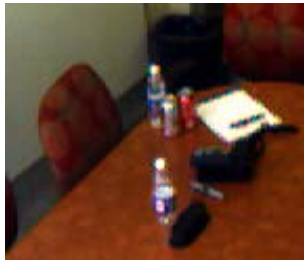**1 sec**   **2.5 sec**

CPU vs Network Bandwidth
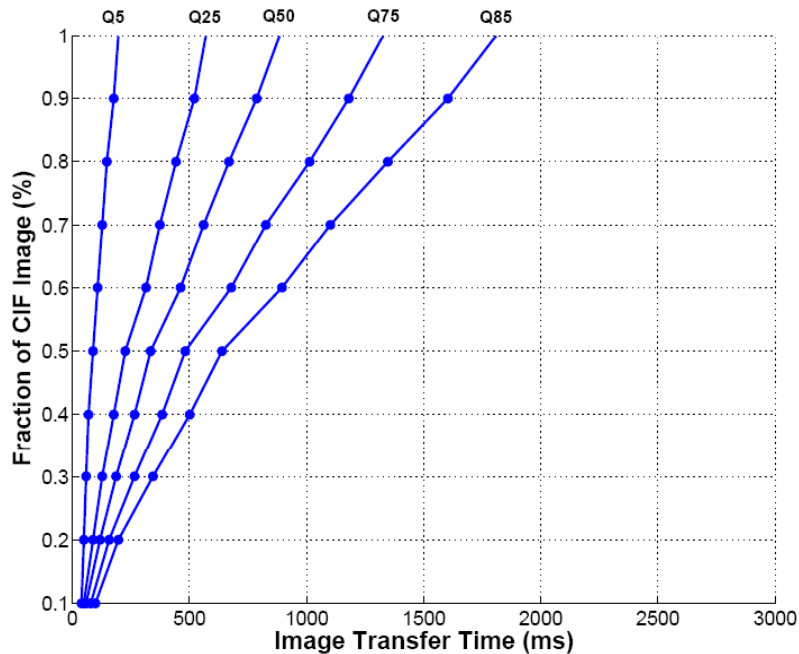
Network Transmit Time

(Assuming No MAC Overhead)

JPEG Compression Time

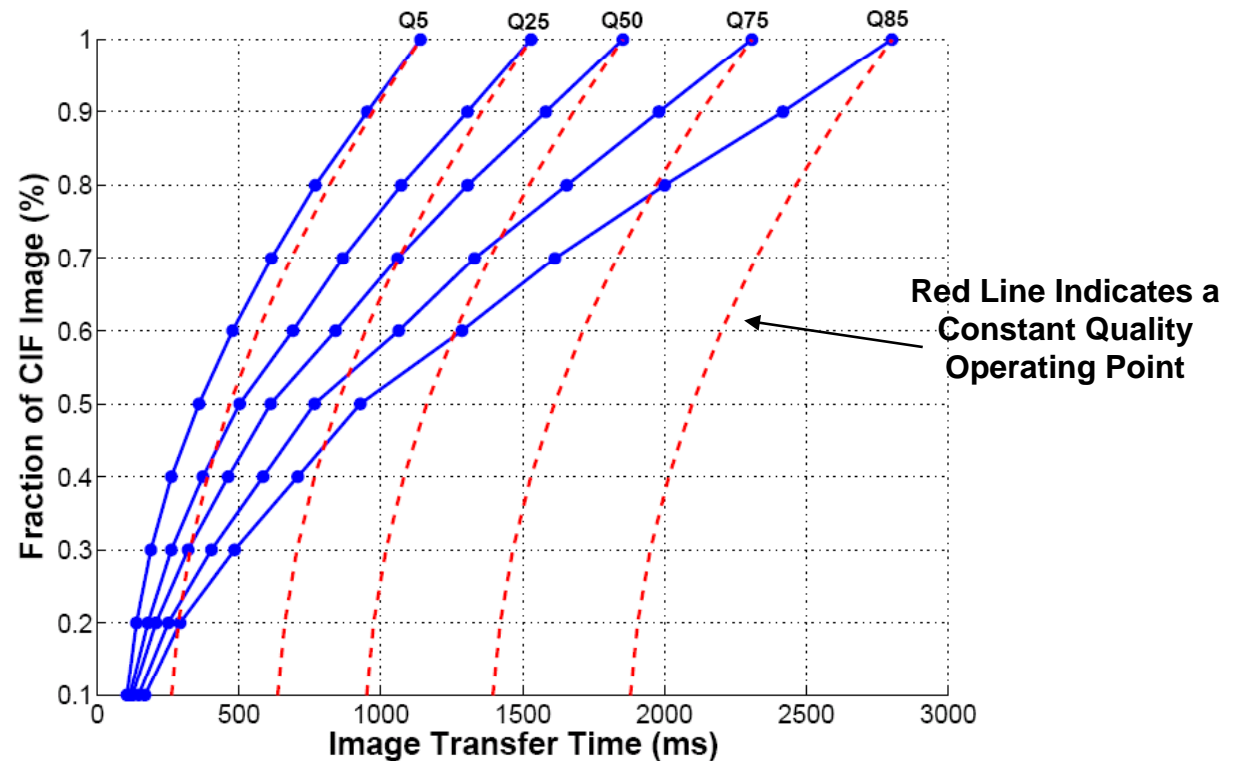# Image Transfer Given CPU and Network Timing Parameters

Q85
.5 FPS

Q50
1 FPS

Q5
4 FPS

Given a quality level, a compression and resolution can be found for minimal image transmit time.

20

Energy Distribution

	Active (mW)	Idle (mW)	Sleep (mW)
ARM7 Core	108	10	0.25
ARM7 Peripherals	49.5	2	0.01
Frame Buffer	171	52	n/a
CMOS Camera	125	5	n/a
MMC	13.2	1	n/a
ATmega1281	6.6	0.02	0.02
CC2420	66.0	15	0.01
Total	572.3	132.52	0.29

Camera sensor consumes 2x the radio active power

Outline

- Motivation
- FireFly Mosaic
- System Performance
- Home Activity Clustering

Home Activity Clustering

- ## Automatically Learn Activities
  - Cooking, Cleaning, Sleeping, Watching TV, Working, etc

- ## Monitor Transitions between Activities

- ## Easy Setup and Training
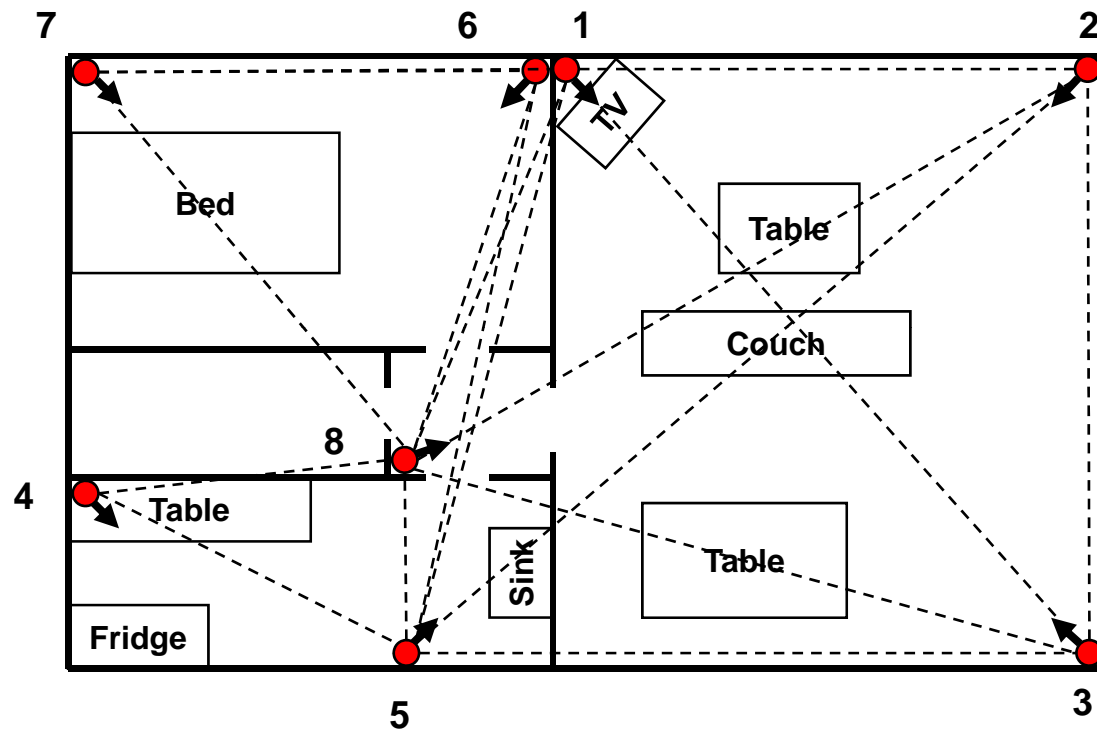 - Cameras Placed "Arbitrarily"

Home Activity Clustering

1) Generate Camera Network Graph with Correlated Image Regions

2) Gaussian Mixture Model (GMM) Motion Detection

3) Local Activity Clustering

4) Global Activity Cluster Merging

5) Generate Model

Electrical & Computer
ENGINEERING

Deployment in an Apartment

Data Collection:

- 8 nodes

- 1 Day of Training

- 3 Days of Data Collection

Correlate Camera Regions
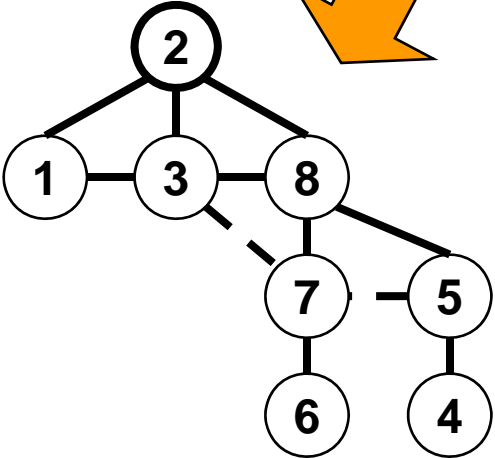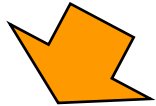
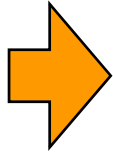# Communication Scheduling

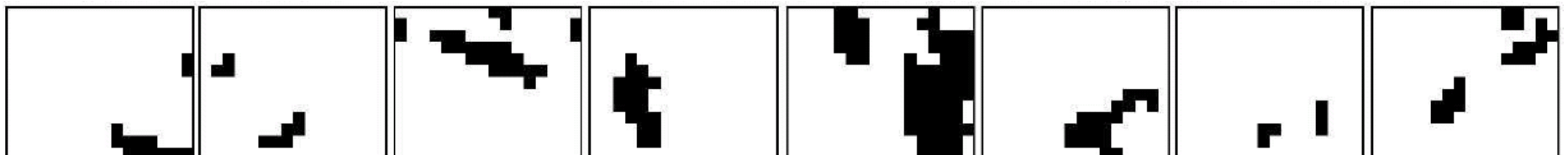| Node	TX	RX
Node 1	1 | 17	0,2 | 16
Node 2	0	1,2 | 15,16,17
Node 3	2 | 16	0,6 | 14,15
Node 4	9	1,7
Node 5	7 | 11	4,6,9
Node 6	10	5
Node 7	5 | 13	3,4,8,10 | 12
Node 8	3,4,6,8 | 12,14,15	0,2,5,7 | 11,13

27

Activity Detection
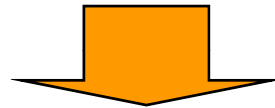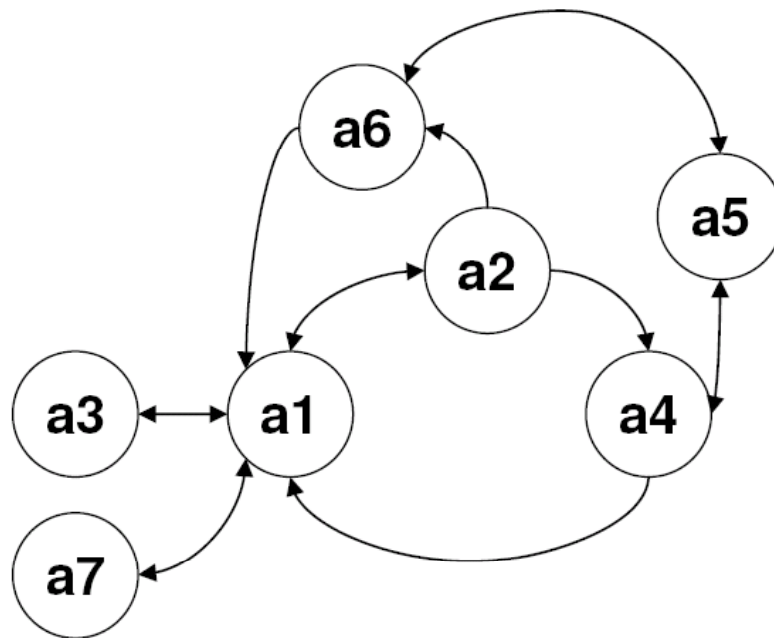

**Gaussian Mixture Model
Background Subtraction**
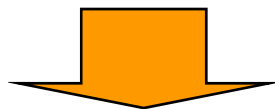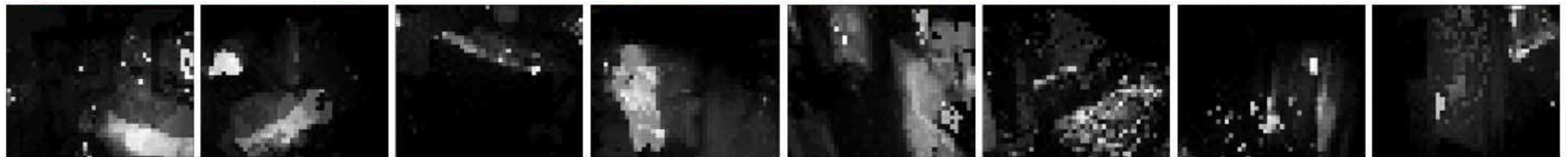
**Down Sampling and Connected
Component Analysis**

Activity Clustering Sample Results

State	Labeled Action
a1	Sitting on Couch
a2	Working at Table
a3	Television
a4	Working at Sink
a5	Bag Moving on Door
a6	Sleeping in Bed
a7	Checking Gateway CPU

Conclusions

- CMOS Camera Sensors are Becoming Cheaper and Consume Less Power

- Low-Cost Microcontrollers are Getting Powerful Enough to Perform Useful Local Image Processing

- Tightly Coordinated Application-Specific Sensor Network Communication Can Enable More Sophisticated Sensing

- Sensor Networking Systems Hold Great Potential for Assisted-Living Applications
  - *Demonstrated using FireFly Mosaic*

Questions?