Motion Sensor and Camera Placement Design for In-home Wireless Video Monitoring Systems

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Motivation

- In-home video monitoring systems for
  - Surveillance and intruder detection
  - Elderly and infant monitoring

- What kind of devices to use?

<table>
<thead>
<tr>
<th>Small devices</th>
<th>Battery powered</th>
<th>Wireless transmission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Easy to hide</td>
<td>Easy to deploy</td>
<td>Easy to deploy</td>
</tr>
<tr>
<td>Limited field of view; cost</td>
<td>and hide</td>
<td>and hide</td>
</tr>
<tr>
<td></td>
<td>Limited energy</td>
<td>Limited bw &amp;</td>
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<td></td>
<td>&amp; system lifetime</td>
<td>transmission range</td>
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</tbody>
</table>
Motivation

- Three placement scenarios
  - Detached scenario
  - Attached scenario
  - Hybrid scenario

Motion sensors
Cameras
Motes
Outline

- Computation of coverage percentage, energy consumption and network lifetime (for all three scenarios)

- Three optimization objectives
  - $obj1$: Minimize energy consumption
  - $obj2$: Maximize network lifetime
  - $obj3$: Minimize monetary cost

- Numerical results and analysis
## Placement model

- **Placement of** $M$ **motion sensors and** $C$ **cameras**

  - The $i^{th}$ motion sensor:
    \[
    Pl_{ms} = \begin{bmatrix}
    x_{m_1} & y_{m_1} & \alpha_{m_1} \\
    \vdots & \vdots & \vdots \\
    x_{m_M} & y_{m_M} & \alpha_{m_M}
    \end{bmatrix}_{M \times 3}
    \]

  - The $j^{th}$ camera:
    \[
    Pl_{ca} = \begin{bmatrix}
    x_{c_j} & y_{c_j} & \alpha_{c_j} \\
    \vdots & \vdots & \vdots \\
    x_{c_C} & y_{c_C} & \alpha_{c_C}
    \end{bmatrix}_{C \times 3}
    \]

- **$P$** equally placed points on a flat plane:
  \[
  P = \begin{bmatrix}
  \vdots & \vdots \\
  x_{p_k} & y_{p_k} \\
  \vdots & \vdots
  \end{bmatrix}_{P \times 2}
  \]

- **Point $k$ covered by motion sensor $i$**: $Cov_{MP}(i,k) = 1$

- **Point $k$ covered by camera $j$**: $Cov_{CP}(j,k) = 1$

  \[
  \left( x_{p_k} - x_{m_i} \right)^2 + \left( y_{p_k} - y_{m_i} \right)^2 \leq R_m^2;
  \]

  \[
  \alpha_{m_i} - \frac{\theta_m}{2} \leq \arctan \left( \frac{y_{p_k} - y_{m_i}}{x_{p_k} - x_{m_i}} \right) \leq \alpha_{m_i} + \frac{\theta_m}{2}.
  \]
Detached scenario

Coverage percentage

\[
COV_{det} = \frac{1}{P} \sum_{k=1}^{P} U \left\{ \sum_{i=1}^{M} Cov_{MP}(i,k) \cdot \sum_{j=1}^{C} Cov_{CP}(j,k) \right\},
\]

\( U \{\cdot\} \) is the unit step function

\( \text{covered} \)

\( \text{not covered} \)
Detached scenario

- Energy consumption
  - Activity mode for motion sensors, cameras, transmitters and receivers

\[ E_{tot} = \frac{1}{P} \sum_{k=1}^{P} \left\{ E_{ca} \times N_{ca} (k) + E_t \times N_{ms} (k) \right\} + (E_l + E_s) \times C + (E_{ms} + E_s) \times M \]

- Activity level

\[ E_{ms} = P_{ms} \times T_{day} ; \quad E_{ca} = P_{ca} \times T_{on} \times N_{act} ; \quad E_t = P_t \times T_p \times N_{act} ; \]

\[ E_l = P_l \times T_l \times T_{day} / T_p ; \quad E_s = P_s \times T_{day} . \]
Detached scenario

- Energy consumption
  - The number of motion sensors that point $k$ can activate:
    \[ N_{ms}(k) = \sum_{i=1}^{M} Cov_{MP}(i,k) \]
  - The number of cameras that point $k$ can activate:
    \[ N_{ca}(k) = \sum_{j=1}^{C} \left( U \left\{ \sum_{i=1}^{M} \left( Tr_{MC}(i,j) \cdot Cov_{MP}(i,k) \right) \right\} \right) \]

The trigger matrix: \[ tr_{i,j} = U \left\{ \sum_{k=1}^{P} (Cov_{MP}(i,k) \cdot Cov_{CP}(j,k)) \right\} \]
Detached scenario

- **Network lifetime**
  - Defined as the lifetime of the component that depletes its battery first
  - Lifetime of the camera with the shortest lifetime

- **Detached scenario**
  - The lifetime for camera $j$: $L_{det}(j) = \frac{C_{tot}}{C_l + C_s + C_{ca}(j)}$

  \[ C_l = I_l \times 24 \times T_l / T_p, \quad C_s = I_s \times 24 \]

  \[ C_{ca}(j) = I_{ca} \times \frac{T_{on}}{T_{day}} \times 24 \times \frac{N_{pt}(j)}{P} \times N_{act} \]

  \[ N_{pt}(j) = \sum_{k=1}^{P} \left\{ \sum_{i=1}^{M} (Cov_{MP}(i,k) \cdot Tr_{MC}(i,j)) \right\} \]

  Motes share energy with cameras

  The # of points camera $j$ can be triggered
**Attached scenario**

- **Coverage percentage**

\[
COV_{att} = \frac{1}{P} \sum_{k=1}^{P} U \left\{ \sum_{i=1}^{M} \sum_{j=1}^{C} (Cov_{MP}(i,k) \cdot Cov_{CP}(j,k) \cdot Att_{MC}(i,j)) \right\}
\]
Attached scenario

- **Energy consumption**
  - No energy cost on motes
    \[ E_{tot}^+ = E_{ms} \times M + \frac{1}{P} \sum_{k=1}^{P} E_{ca} \times N_{ca}^+ (k) \]
  - The number of cameras that point \( k \) can activate:
    \[ N_{ca}^+ (k) = \sum_{j=1}^{C} \left( U \left( \sum_{i=1}^{M} (Tr_{MC}^+ (i, j) \cdot Cov_{MP} (i, k)) \right) \right) \]
    The trigger matrix: \( tr^+ (i, j) = Att_{MC} (i, j) \cdot \left( 1 - U \left( |\alpha_{m_i} - \alpha_{c_j}| - \frac{\theta_m}{2} \right) \right) \)

- **Network lifetime**
  \[ L_{att} (j) = \begin{cases} \frac{C_{tot}}{C_{ca} (j)}, & N_{act} \neq 0 \\ L_{ms}, & N_{act} = 0 \end{cases} \]
  \( L_{ms} \): lifetime of motion sensors
Hybrid scenario

Hybrid: detached cameras and attached cameras coexist

Detached camera

Attached camera

ms1

ms2

cal

cal2

Hybrid scenario

- Covered
- Not covered
Three optimization objectives

\[
\begin{align*}
\text{min} & \quad E_{tot} \\
\text{s.t.} & \quad COV \geq COV_{th} \\
\end{align*}
\]

\[
\begin{align*}
\text{max} & \quad \arg \min_{C} L(j) \\
\text{s.t.} & \quad COV \geq COV_{th} \\
\end{align*}
\]

\[
\begin{align*}
\text{min} & \quad K \\
\text{s.t.} & \quad COV \geq COV_{th} \\
& \quad \arg \min_{C} L(j) \geq L_{th} \\
\end{align*}
\]
## Devices and parameters

<table>
<thead>
<tr>
<th>Devices</th>
<th>Motion sensor</th>
<th>Mote</th>
<th>Camera</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range (m)</td>
<td>3</td>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td>Field of angle</td>
<td>90°</td>
<td>N/A</td>
<td>38°</td>
</tr>
<tr>
<td>Voltage (V)</td>
<td>2.4 – 3.6</td>
<td>2.1 – 3.6</td>
<td>9</td>
</tr>
<tr>
<td>Current (mA)</td>
<td>0.01</td>
<td>tx: 19.5, rx: 21.8</td>
<td>71.1</td>
</tr>
<tr>
<td>Power (mW)</td>
<td>0.03</td>
<td>tx: 58.5, rx: 65.4</td>
<td>640</td>
</tr>
<tr>
<td>Unit price</td>
<td>$15</td>
<td>$60</td>
<td>$60</td>
</tr>
</tbody>
</table>
Minimized energy
- Larger coverage constraint, higher energy consumption
- Use the least # of cameras to reduce overlap
- For detached scenario, low activity level: $E_{ca} \approx E_l$
- High activity level: cameras consumes much more energy.
Minimized energy

- Choose hybrid scenario
- More ms and ca for attached scenario
- Attached scenario consumes less energy at low activity level, but more energy at high activity level
  - # of cameras needed
  - Tradeoff on motes

low activity level, $COV_{th} = 70\%$

high activity level, $COV_{th} = 70\%$
Simulation results

- Cost and lifetime
  - Higher cost, longer network lifetime
  - Last for more than 3 months
  - Detached scenario costs less
  - \( \text{obj2} : \)

\[
\begin{align*}
\max_{\{PL_{ms}, PL_{ca}\}} & \quad \arg\min_C L(j) \\
\text{s.t.} & \quad COV \geq COV_{th} \\
& \quad K \leq K_{th}
\end{align*}
\]

- high activity level, \( COV_{th} = 70\% \)
Simulation results

- Cost and network lifetime

- Optimal placement strategy for \textit{obj2}:
  4 cameras detached from 2 motion sensors

Placement for optimized lifetime, \(COV_{th} = 70\%\), \(K_{th} = \$300\), high activity level
Conclusions

- Optimization of motion sensor and camera placement (coverage, energy, lifetime, cost)
- Choose the hybrid approach
- Attached scenario consumes less energy at low activity level, but more energy at high activity level
- An optimal placement strategy is given to achieve the maximum network lifetime

Future work

- Multiple cameras collaborate to localize objects
- Coverage problem with obstacles
References

THANKS!

Q & A

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