Correlation-Aware Protocol Design for Wireless Multimedia Sensor Networks

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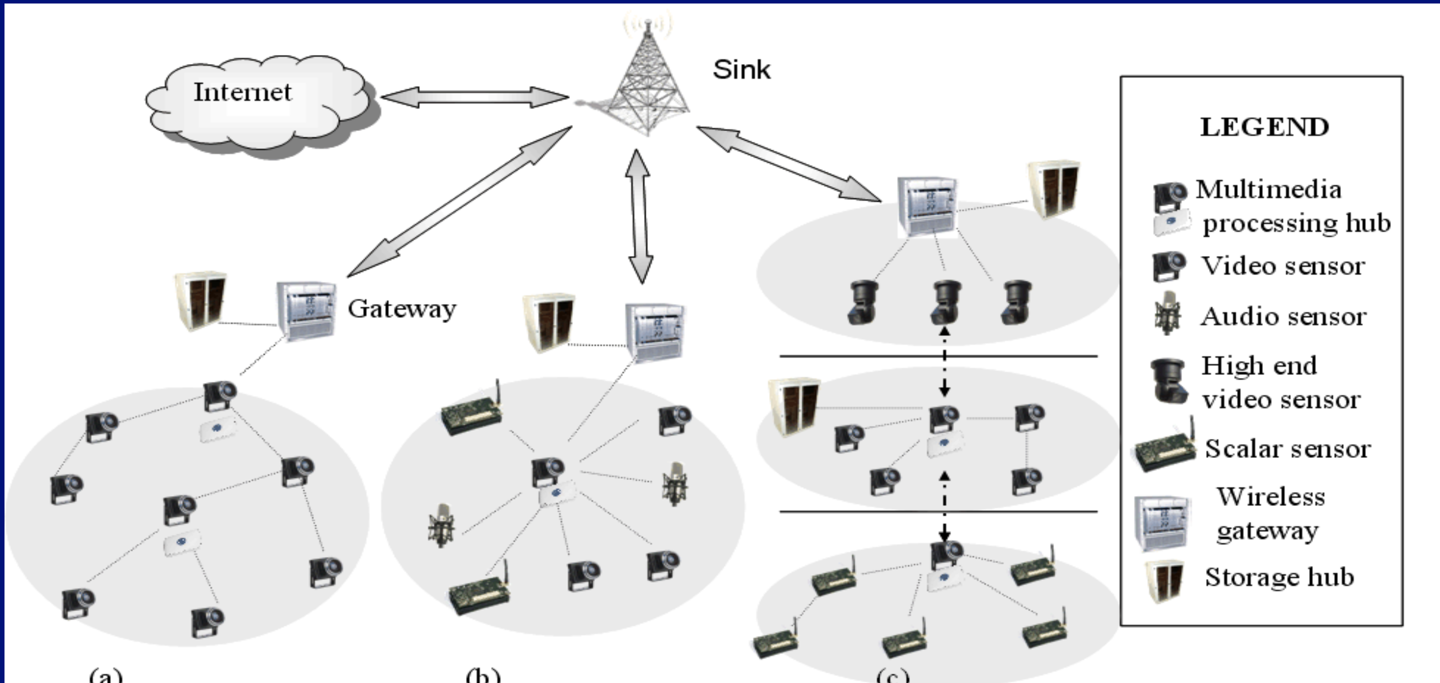
Outline

- Introduction to WMSNs
- Spatial correlation for visual information in WMSNs
  - Correlation function
  - Entropy-based analytical framework
  - Correlation and coding efficiency
- Correlation-aware routing protocol design
- Future works

Wireless Multimedia Sensor Networks



(a)
Single-tier flat, homogeneous sensors, distributed processing, centralized storage

(b)
Single-tier clustered, heterogeneous sensors, centralized processing, centralized storage

(c)
Multi-tier, heterogeneous sensors, distributed processing, distributed storage

Wireless Multimedia Sensor Networks

- Quality of Service (QoS) requirements
  - Delay, jitter, packet loss ratio, and distortion bounds
- High bandwidth demand
  - Audio, video, and scalar data traffics
  - Visual information is especially bandwidth-demanding
- Resource constraints
  - Limited power, processing and storage capability

Features of Sensor Networks

- Application patterns
  - Query driven
  - Event driven
- Communication protocols for sensor networks
  - Data-centric routing and data aggregation
  - ESRT: event-to-sink reliable transport
  - CC-MAC: spatial correlation based collaborative MAC
  - Most of them are designed for scalar data

Multimedia In-Network Processing

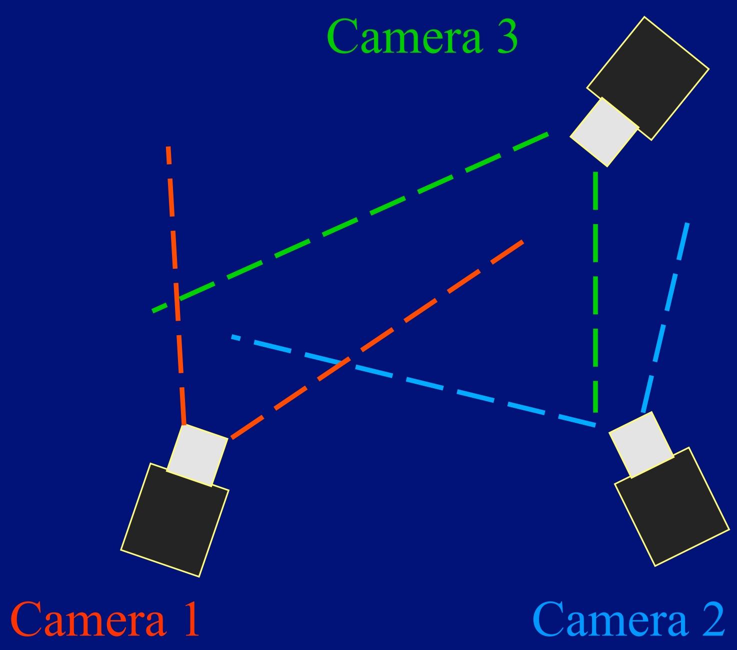
- Filter uninterested data
- Merge correlated data from multiple views, multiple resolutions
- Image processing algorithms
  - No theoretical model for image contents
  - Application-specific
  - Complicated and needs considerable processing energy

Research Goals

- Study the correlation characteristics of visual information in WMSNs
  - Application-independent, avoiding specific image processing algorithms
  - Low computation and communication costs
- Design efficient communication protocols for WMSNs
  - Exploit the correlation characteristics
  - Under QoS constraints

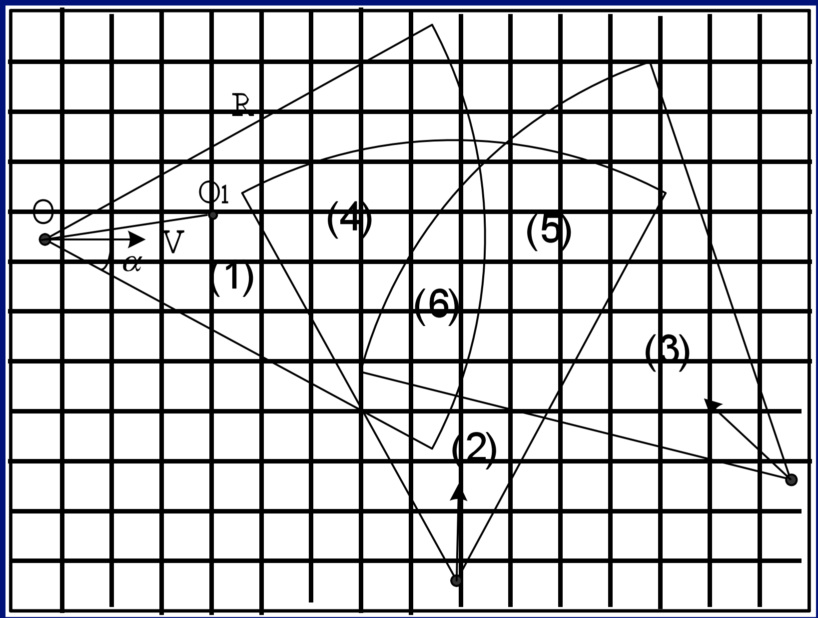
Spatial Correlation of Video Sensors

- There exists correlation among the visual information observed by cameras with overlapped field of views (FoV).
  - Directional sensing
  - 3-D to 2-D projection
  - Complicated overlapping patterns



Spatial Correlation Model (I): Correlation Function

- **Area partitions**
  - FoV parameters: (O,R,V,α)
  - Divide the FoVs into several partitions, such that each partition belongs to the FoVs of the same set of cameras.
  - Discrete grid based algorithm

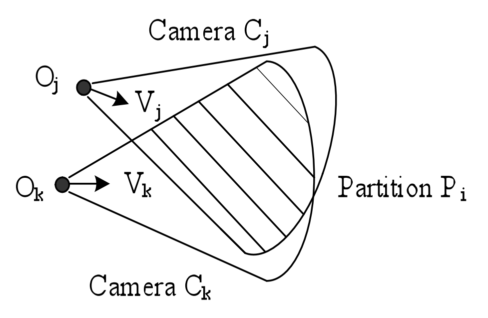


Spatial Correlation Model (I): Correlation Function

R. Dai and I.F. Akyildiz, "A Spatial Correlation Model for Visual Information in Wireless Multimedia Sensor Networks", IEEE Transactions on Multimedia, Oct. 2009.

- Spatial correlation coefficient between the observations at two cameras

$$\rho_{j,k} = F\left(f_j, f_k, O_j, O_k, \vec{V}_j, \vec{V}_k, P_i\right)$$



  - Derived from the *projection model* of cameras
  - The spatial correlation coefficient is a function of the two cameras' focal lengths (f), locations (O), sensing directions (V), as well as the location of the overlapped area (P).

Spatial Correlation Model (II): Entropy-Based Framework

R. Dai and I.F. Akyildiz, "Joint Effect of Multiple Correlated Cameras in Wireless Multimedia Sensor Networks", in Proc IEEE ICC 2009, Jun. 2009.

- In a WMSN, each camera can provide a certain amount of information to the sink.
- If multiple cameras transmit their observed visual information to the sink, and they are correlated with each other, how much information can be gained at the sink?
- Estimate the *joint entropy* of multiple correlated cameras.

Spatial Correlation Model (II) - Entropy-Based Framework

- Given an area of interest, the amount of information provided by a single camera is: $H(X_i)$
  - Can be easily estimated at each camera.

- The amount of information from multiple cameras:

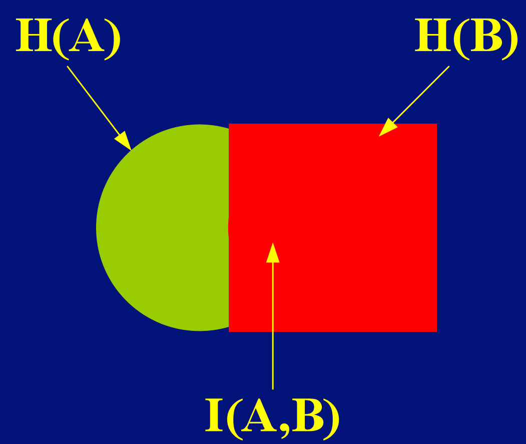
  joint entropy $H(X_1, X_2, \ldots, X_N)$
  - Related to joint probability distributions of the sources
  - Intuitively, if the images from these cameras are less correlated, they should provide more information.

Spatial Correlation Model (II): Entropy-Based Framework

- Joint entropy of two sources:

$$H(A,B) = H(A) + H(B) - I(A;B)$$
$$= (1 - \frac{1}{2}ECC)(H(A) + H(B))$$

where $ECC = \frac{2I(A;B)}{H(A)+H(B)}$



ECC is the normalized entropy correlation coefficient; not easy to be obtained.

Spatial Correlation Model (II): Entropy-Based Framework

- Our solution for joint entropy estimation:

$$H(A,B) \approx (1-\frac{1}{2}\rho_{A,B})(H(A)+H(B))$$

- Conditional entropy:

$$H(B\,|\,A) = H(A,B) - H(A) \approx (1-\frac{\rho_{A,B}}{2})H(B) - \frac{1}{2}\rho_{A,B}H(A)$$

- For multiple correlated cameras $\{X_1, X_2, ..., X_N\}$
  Estimate the joint entropy $H(X_1, X_2, ..., X_N)$

Spatial Correlation Model (II): Entropy-Based Framework

- Form a dependency graph of the cameras $\{X_1, X_2, ..., X_N\}$
  Assuming that each camera is dependent on the camera that is most correlated with it.

- For example, five cameras have a dependency graph as $X_1 \rightarrow X_3 \rightarrow X_5$, $X_2 \rightarrow X_4$
- Their joint entropy is estimated as follows:

$$H(X_1, X_2, ..., X_5) = H(X_1) + H(X_3 | X_1) + H(X_5 | X_3) + H(X_2) + H(X_4 | X_2)$$

Joint Compression/Coding Efficiency

P. Wang, R. Dai and I.F. Akyildiz, "Collaborative Data Compression Using Clustered Source Coding for Wireless Multimedia Sensor Networks", submitted for conference publication, Jul. 2009.

- Perform joint source coding among multiple correlated sensors to reduce the traffic injected into the network.

- Joint entropy serves as the lower bound of the total coding rates of multiple nodes.

$$\sum_{n=1}^{N} R_i \geq H(X_1, X_2, \ldots, X_N)$$

Estimation of Joint Coding Efficiency

- We can estimate the efficiency of joint coding from our correlation model. Define an estimated joint coding efficiency as

$$\eta_H = 1 - \frac{H(X_1, \cdots, X_N)}{H(X_1) + \cdots + H(X_N)}$$

- From practical coding experiments on the observed images, we can obtain the actual joint coding efficiency:

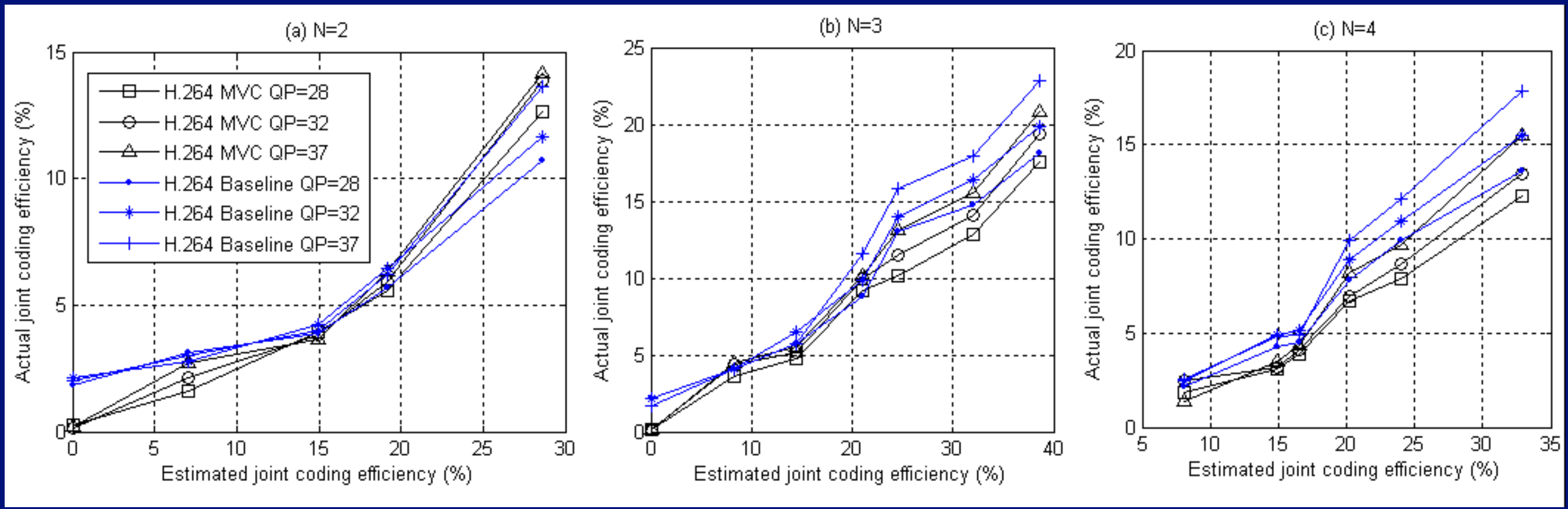
$$\eta_R = 1 - \frac{R(X_1, \cdots, X_N)}{R(X_1) + \cdots + R(X_N)}$$

Validation of Estimated Joint Coding Efficiency

- Verify the estimated coding efficiency by comparing it to the actual coding efficiency
- Comparisons are given under different parameters
  - Different numbers of cameras (N=2,3,4)
  - Two coding schemes from H.264 standards: "Baseline Profile" and "Multi-View Coding (MVC) extension"
  - Coding parameters: three quantization steps (QP=28, 32, and 37)

Validation of Estimated Joint Coding Efficiency

- The actual joint coding efficiency increases as the estimated efficiency increases.
- The estimated efficiency can efficiently predict the coding efficiency of different video coders.



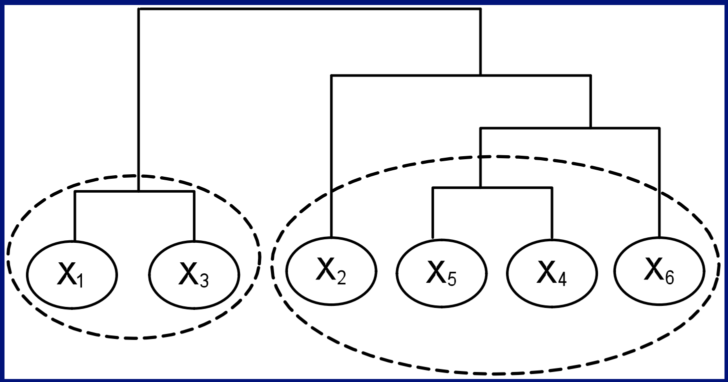
Correlation-Aware QoS Routing

R. Dai, P. Wang, and I.F. Akyildiz, "Correlation-Aware QoS Routing for Wireless Video Sensor Networks", in preparation, 2009.

- Joint source coding among correlated nodes
  - Can estimate the joint coding efficiency from the correlation model
  - Reduce the video data volume by joint coding between sensors
- Event or query driven applications
  - Video sensors with large overlapped FoVs tend to report the same event and generate traffic concurrently.

Correlated Groups of Video Sensors

- Form correlation groups of video sensors in a network
  - Cluster the video sensors with large overlapped FoVs into a groups
  - Hierarchical clustering
  - Metric for clustering: the overlapped ratio of FoVs (r) between two sensors.



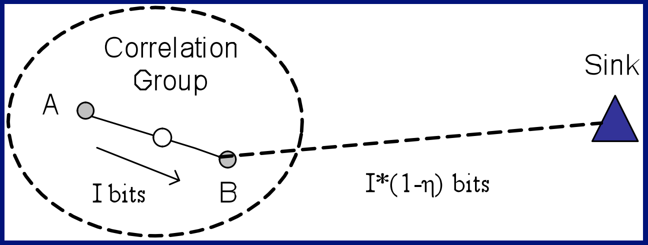
Routing with Joint Source Coding

- Features of the video streams generated at a sensor
  - Periodical intra coded reference frames (I frames): high data rate
  - Inter coded frames (P,B frames): lower data rate.
  - For the I frames with high data rates, joint source coding can be further applied to reduce the traffic.

Routing with Joint Source Coding

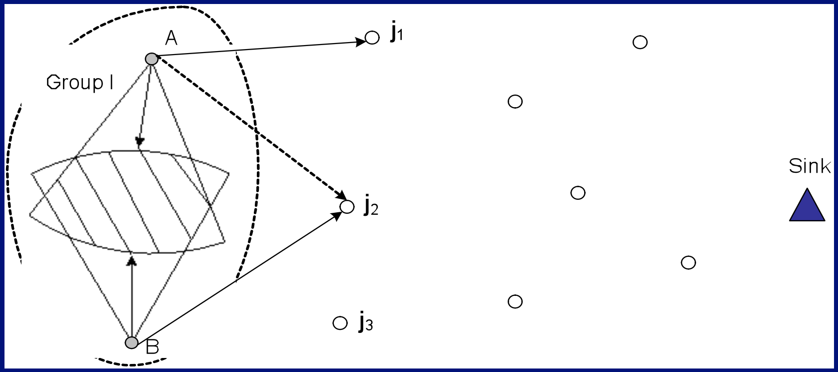
- **Sensor A can select sensor B for differential coding**
  - Estimated differential coding efficiency: η
  - Estimated size of the intra frame at A: I (bits)
  - Estimated saved bits from differential coding: $I^*\eta$
  - The potential energy efficiency of differential coding can be evaluated by the following *energy gain*:

$$G_E = \frac{\textit{Communication Energy of } I \cdot \eta \text{ bits}}{\text{Processing energy of differential coding}}$$



Load Balancing for Correlated Sensors

- In the following example, Sensor A and sensor B have large overlapped FoVs. However, as their sensing directions differ a lot, there is little gain from joint source coding.
- Likely to generate traffic simultaneously.
- Load balancing: try to select different paths for them.



QoS Constrained Routing Framework

- End-to-end QoS constraints
  - Delay
  - Jitter
  - Packet loss rate
- These constraints are mapped to single hop requirements
- Routing decisions: next hops should satisfy these constraints and achieve energy efficiency at the same time

Correlation-Aware QoS Routing

- Joint source coding in the routing process
  - Introduces extra processing energy and delay
  - After joint source coding, the required bandwidth reduces, and the transmission energy can be saved
- Study how to map the QoS constraints for joint source coding

Future Works

- Exploit the correlation of visual information at the MAC layer
- Propose a cross-layer solution (routing and MAC)

Thanks

Q & A