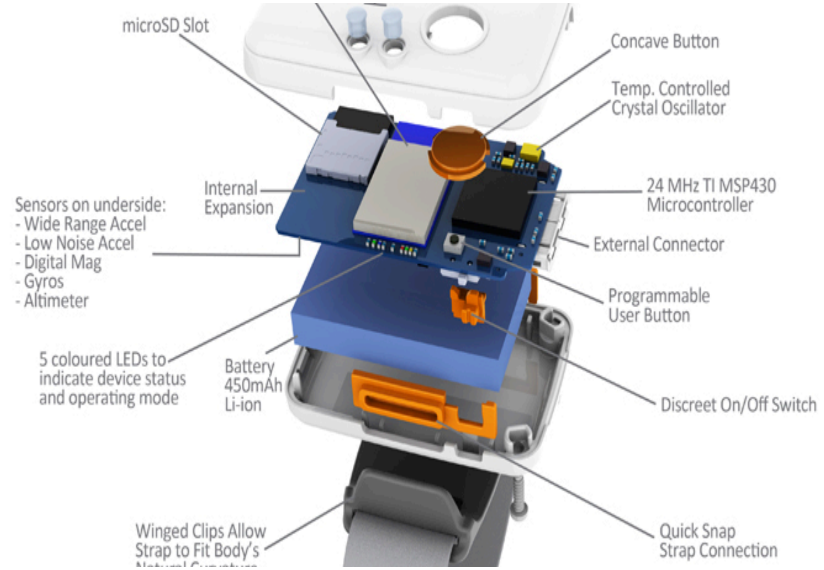
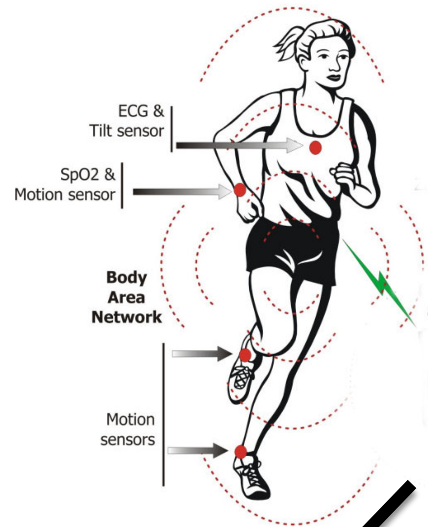
Cyber-physical System

- Cyber-Physical system coupling bio-sensors on people and wireless networks
- **Goals:** provide real-time monitoring of health and behavior, enable feedback via adaptive and personalized interventions
- New decision-making problems
  - sensing, communication, control
- **Challenges:** sensor & data heterogeneity; sensor & coordinator energy constraints; sensing & communication are state dependent; decentralized decision-making

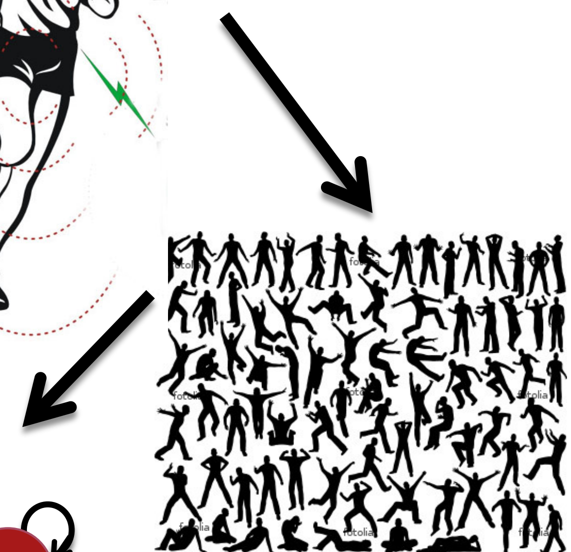


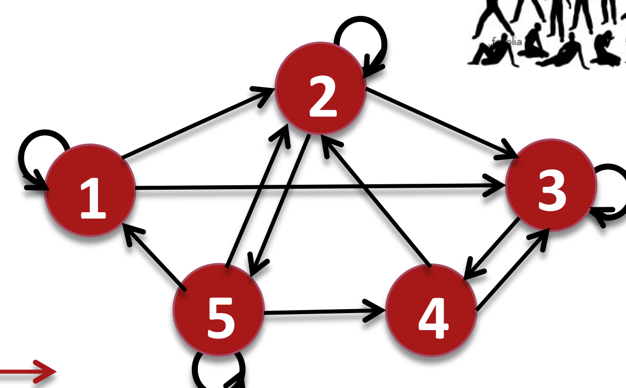
Wireless body area sensing network

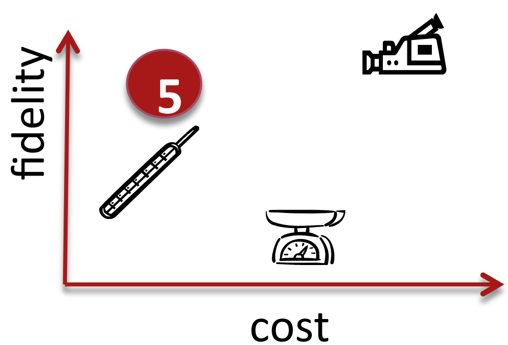
- What physical state are you in?
  - Walking, running, sitting
- **Heterogeneous** on-body sensors
- The challenge
  - **Mobile phone is energy bottleneck**
  - Sensors are heterogeneous in cost
  - Fidelity is state/sensor dependent

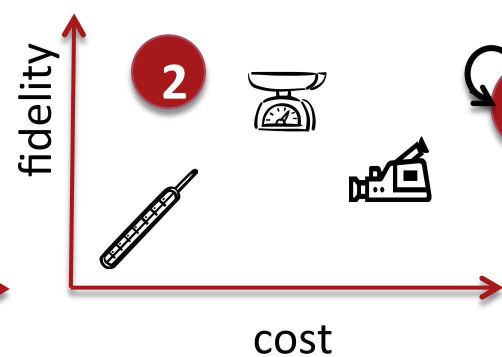


Jovanov et al. Journal of NeuroEngineering and Rehabilitation 2005





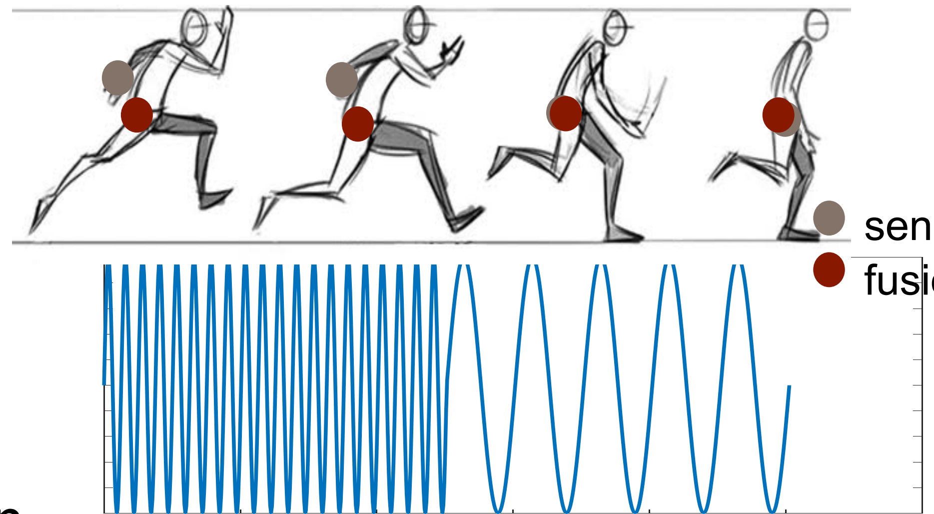


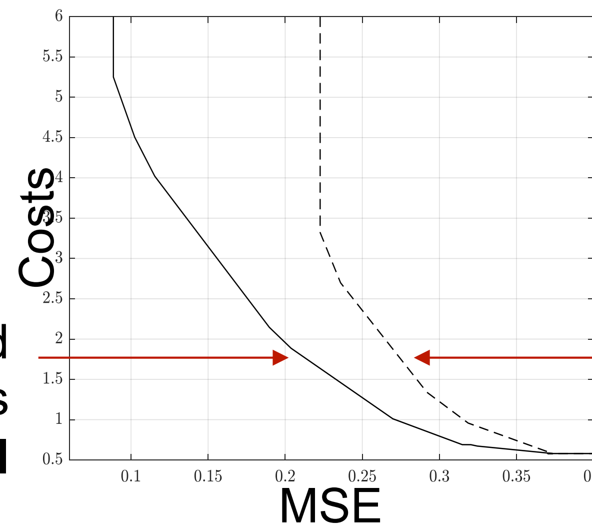


Improved Active Tracking – Sensor Allocation

USC Viterbi

- To demodulate signals from different sensors need channel state information (CSI)
- CSI is system/state dependent
- → CSI carries information about system state
- Cost versus estimation error
  - CSI does not add to **cost**
  - Strongly improves error

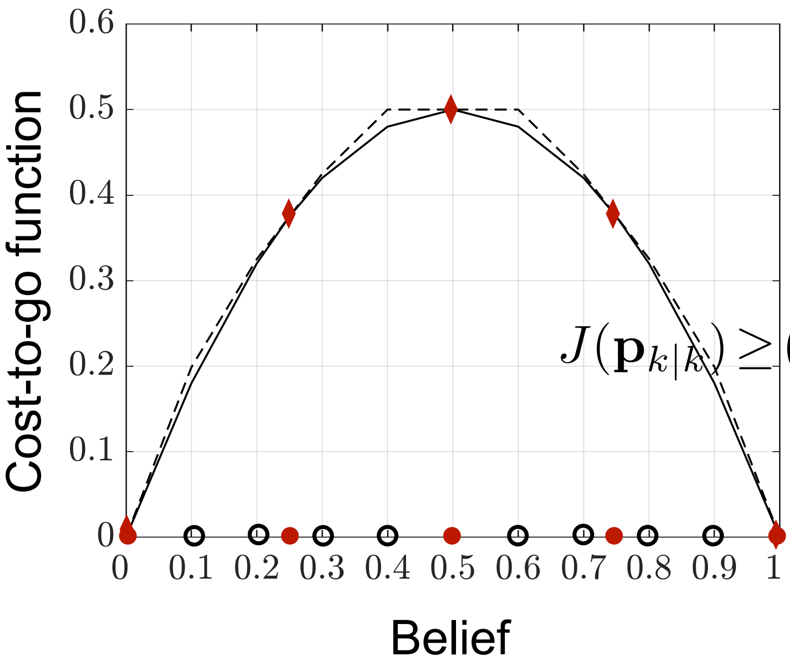




Technical Contributions

- Problem originally posed as Partially Observable Markov Decision Process problem
  - Discretize, convert to MDP
- Can convert multidimensional optimization in multiple single dimensional optimizations via partial belief computation
  - No loss in performance/optimal
  - Lower complexity
- Can show convexity of cost-to-go function
  - Enables derivation of tight lower bound
  - Only a subset of conditional beliefs needed to compute lower bound
  - Suggests new (lower complexity) probabilistic strategy
- Closed form expression for lower complexity belief update
- ISIT 2016, full paper submitted to IEEE Transactions on Signal Processing

Convexity and Associated Bounds



- Consider a basis of beliefs

$$\mathbf{p}_{k|k} = \sum_{i=1}^{n} \nu_i \mathbf{b}_{k|k}^{(i)}$$

- Convexity enables bound:

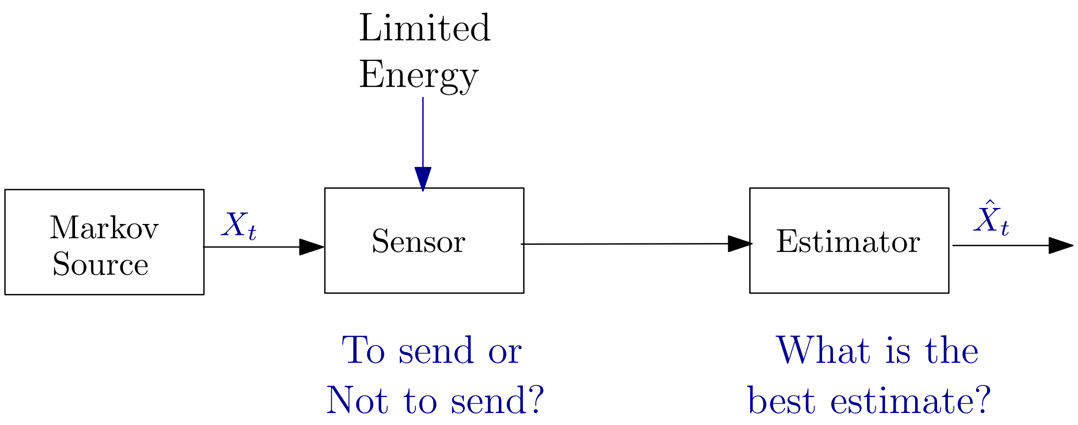
$$J(\mathbf{p}_{k|k}) \geq (1-\lambda)\Delta(\mathbf{p}_{k|k}) + \sum_{i=1}^{n} \nu_i \left(J(\mathbf{b}_{k|k}^{(i)}) - (1-\lambda)\Delta(\mathbf{b}_{k|k}^{(i)})\right)$$

- Only compute cost for some conditional beliefs, else use bound
- → Tight bounds
- New probabilistic strategy

$$\mathbb{P}(\mathbf{u}_k|\mathbf{p}_{k|k}) = \begin{cases} \delta_{\mathbf{u}_k, \arg\min_{\mathbf{u}} \{K(\mathbf{p}_{k|k}, \mathbf{u})\}}, & \text{if } \mathbf{p}_{k|k} \in \mathcal{B}, \\ \sum_{i=1}^{n} \nu_i \delta_{\mathbf{u}_k, \arg\min_{\mathbf{u}} \{K(\mathbf{b}_{k|k}^{(i)}, \mathbf{u})\}}, & \text{otherwise}, \end{cases}$$

Min-max estimation with signaling

- **Key objectives:** Keep the worst possible estimation error small at all time instants.

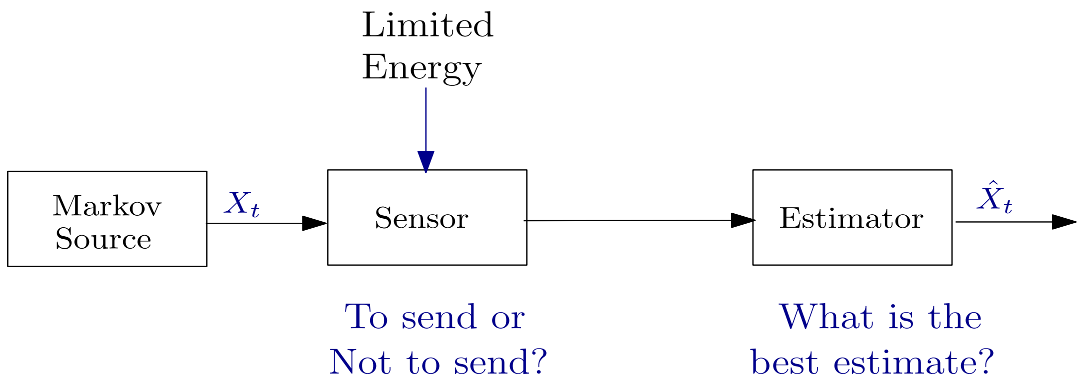


- Minimize the worst case instantaneous estimation cost

$$max_X max_t |X_t - \hat{X}_t|$$

- The sensor has a hard constraint on number of transmission allowed.
- Optimal trade-off between energy utilization and estimation quality
- Possibility of signaling/implicit communication: No transmission conveys information to the estimator.

Min-max estimation with signaling



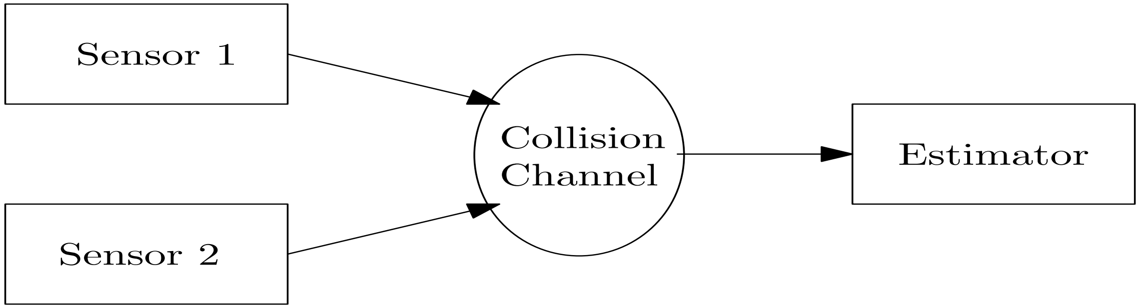
- **Main results**: Under certain symmetry properties about the source uncertainty:
  - The globally optimal estimate is the most recently received source value.

$$\hat{X}_t = \begin{cases} X_t & \text{if transmitted,} \\ \hat{X}_{t-1} & \text{if not transmitted.} \end{cases}$$

  - The globally optimal transmission strategy is an energy-based threshold rule:

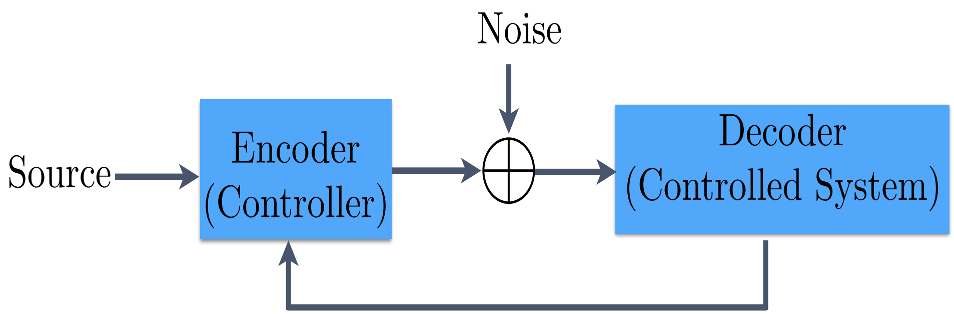
$$U_t = \begin{cases} Transmit & \text{if } |X_t - \tilde{X}_t| > Th(E_t), \\ Don't & \text{if } |X_t - \tilde{X}_t| \leq Th(E_t). \end{cases}$$

Estimation over the collision channel



- Limited energy sensors sharing a communication channel.
- Simultaneous transmissions cause collision.
- Trade-offs between energy utilization, channel utilization and estimation qualities of the two measurements.
- Problem of decentralized dynamic resource sharing.
- Initial observations: From one sensor's perspective, the problem resembles communication over a packet-drop channel.
- Ongoing work: Characterization of optimal transmission strategies.

Real-time communication and coordination



- How can we characterize source and channel models that allow for zero-error communication in real time?
- Related to a coordination problem: How can two agents communicating over an imperfect channel agree on a common decision?
- A simple sufficient condition for zero error communication/coordination with Markov or IID sources over memoryless channels: Fewer possible source/decision values than the single-shot zero-error capacity.
- The above condition is necessary for sources that are conditionally IID given the common information at the encoder and the decoder.