Compressed Sensing Signal and Data Acquisition in Wireless Sensor Networks and Internet of Things

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Introduction and Motivation

- WSNs and IoT based signal/data acquisition
  - Sparseness of Information
  - Heterogeneous networks and networked things
- Motivation
  - Low-cost data acquisition system
  - Resolution, sensitivity and reliability of data compression in IoT
  - Adaptive sparse representation and recovery
Compressed Sensing (1)

- **Condition of Compressed Sensing**
  - Compressible of signal/data
  - Sparse representation
  \[ x = \sum_{i=1}^{n} \theta_i \psi_i \quad \text{or} \quad \theta = \Psi^T x, \]
  - Random measurements
  - Coherence of two vectors
  \[ \mu = \max_{i,k} |\langle \phi_i, \psi_k \rangle| . \]
Compressed Sensing (2)

- **k-RIP Condition**
  \[
  (1 - \delta_k) \frac{m}{n} \|x\|_2^2 \leq \|\Phi x\|_2^2 \leq (1 + \delta_k) \frac{m}{n} \|x\|_2^2.
  \]

- **Recovery Algorithm**
  - RIP guarantees near optimal recovery
    \[
    \min_{\theta} \|\theta\|_p \text{ s.t. } y = \Phi \Psi \theta
    \]
  - Existing recovery algorithms:
    (BP, MP, OMP, StOMP, CoSaMP, SP)
Compressed Sensing (3)

- Noise Model and Recovery Accuracy

\[
\arg \min_{\theta} \| y - \Phi \Psi \theta \|_2^2 + \lambda_2 \| \theta \|_1.
\]

\[
\rho = \frac{||x - \bar{x}||_2^2}{n}.
\]
CS-Based Framework in WSNs and IoT (1)

- CS IoT (CSI)
  - CS information end-node (CSIE), which aims to reduce the number of samples without losing the essential information;
  - Compressed data delivery scheme, which aims to minimize the received data distortion and communication burden;
  - Information recovery at fusion center(s)
Signal/Data Acquisition Model

- Node-Dependent Signal/Data Acquisition

\[ y = Ax + \epsilon \]

- benefits:
  1) reduce number of samples;
  2) reduce communication burden;
  3) reduce the computation cost at nodes
CS-Based Framework in WSNs and IoT (4)

- Cooperative Signal/Data Acquisition between nodes:

\[
\mathbf{y} = [y_1, \cdots, y_m]^T = \sum_{j=1}^{n} A_{i,j} x_j
\]

- Consensus Algorithm based Signal/Data Acquisition over Networks:

\[
\begin{aligned}
\mathbf{y}_a &= \Phi \mathbf{A} \mathbf{x} + \mathbf{\epsilon}_a \\
\min_{\mathbf{x}} \sum_{i \in \mathcal{N}_a} \left( y_i - x_{i}^{(i)} - \sum_{k \in \mathcal{N}_s \cup \mathcal{N}_i} A_{k,i} x_{k}^{(i)} - \sum_{j \in \mathcal{N}_a} A_{k,i} x_{j}^{(j)} \right)^2 \\
\text{s.t. } &x_{i}^{(i)} \geq 0, \forall i \in \mathcal{N}_a, \\
&x_{k}^{(i)} \geq 0, \forall k \in \mathcal{N}_s \cup \mathcal{N}_i.
\end{aligned}
\]
Sparse Representation

- CSIE samples the original information and then deliver the samples through CSI;

- Advantages:
  1) it runs on thin node of IoT;
  2) it takes the advantage of the temporal correlation between continuous data matrices
CS-Based Framework in WSNs and IoT (6)

- Illustration of the compressibility of network

(a) Monitoring scenario.

(b) Sparse representation of monitoring data.
Noise Model, Communication Load, and Recovery Accuracy

- Input noise
  \[ y = A(x + \epsilon) \quad \epsilon \sim \mathcal{N}(0, I_n) \]

- Probability of a packet in error
  \[ P_E = 1 - (1 - P_e)^L \]

- Average arrival rate
  \[ \sigma = \frac{N(1 - e^{\eta^T})e^{-2N\eta^T_p}(1 - P_E)}{T} \]
The number of useful packets

\[ \text{Prob} \{ K(\eta, T) = k \} = P_K(k; \eta, T) = \frac{(\eta T)^k}{k!} e^{-\sigma T}. \]
Adaptive Cluster Sparse Representation and recovery algorithm

Step 1) Estimate the residual of each iteration.
Step 2) Compute the best clusters $C_{k,c}$ support set of the errors (index set).
Step 3) Merge the strongest support set.
Step 4) Reconstruct the signals according to the given support sets.
Step 5) Prune $x$ and compute residual for the next round.
Performance Evaluation

- Node-Dependent Signal Acquisition

(a) Original map and (b) reconstructed map with ACSRA algorithm.
Performance Evaluation (2)

- **ECG Signal Acquisition and Recovery**
  - ECG dataset is available:
    http://www.cs.ucr.edu/eamonn/discords
  - $k=128$, the length of signal is 2048, $M = [256, 384]$
  - only 18.75% of the original data needs to be transmitted over network.

<table>
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<tr>
<th>No.</th>
<th>ECG Datasets</th>
<th>Size($N$)</th>
<th>Recovery Error</th>
<th>CPU Time (s)</th>
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<td>chfdb1</td>
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</tr>
</tbody>
</table>
Performance Evaluation (3)

- Comparison with GPSR, LASSO, and OMP

- $k=74$, the length of signal is 2048, $M = 512$
Summary and Conclusions

- We formulate the problem of data acquisition based on CS in IoT and WSNs.
- A CS-based information acquisition framework is proposed for IoT, which involves the compressed sampling at IoT end nodes, information transmission over IoT, and accurate data recovery at FC.
- By taking the correlation of sensing data over IoT and WSNs into consideration, an adaptive sparse representation and corresponding signal reconstruction algorithm are proposed that offer a higher accuracy and lower computational complexity compared with preexisting group/cluster sparse reconstruction algorithm.
Reference (1)

Reference (2)

- S. Kumar, B. Kadow and M. Lamkin "Challenges with the introduction of radio-frequency identification systems into a manufacturer's supply chain for a pilot study", Enterprise Inf. Syst., vol. 5, no. 2, pp.235 -253 2011.
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