Knowing the air you breath - the Signal Processing way

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Knowing the Air ...

Economic Times, 2017

Delhi pollution: Air quality dips sharply ahead of Diwali

(Business Today 06 Nov)

Not just Delhi, 70 Indian cities reel under air pollution

(Down To Earth 05 Nov)

Clean air is a human right: WHO

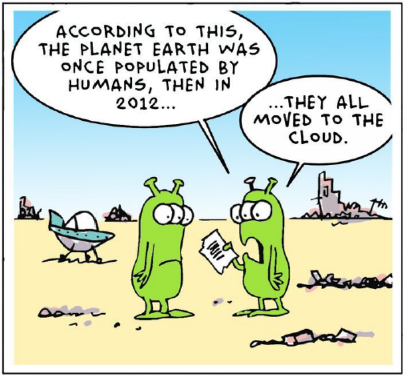
(Down To Earth 02 Nov)

Investments in Engineering

- Centre of Excellence for Research on Clean Air (CERCA) set up in IIT Delhi
- Number of ground based air quality (AQ) stations increased by Pollution Control Boards
- Sprinklers and artificial rains sought as options to help settle particulate matter (PM)
- **Deficits** in present AQ measurement/sensing
  - Ground station equipments require regular repair
  - Stations mostly concentrated in industrial belts
  - Average error in PM monitoring between 10-26 %

Signal Analytics for Rescue

- With emergence of IoT devices, shift has been from 'ground to the cloud'



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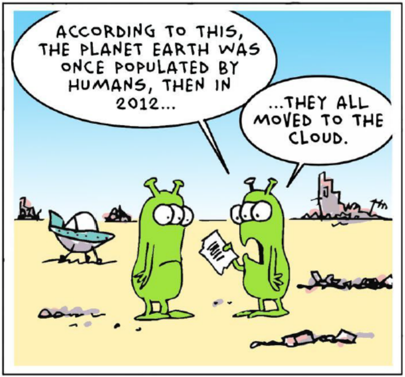
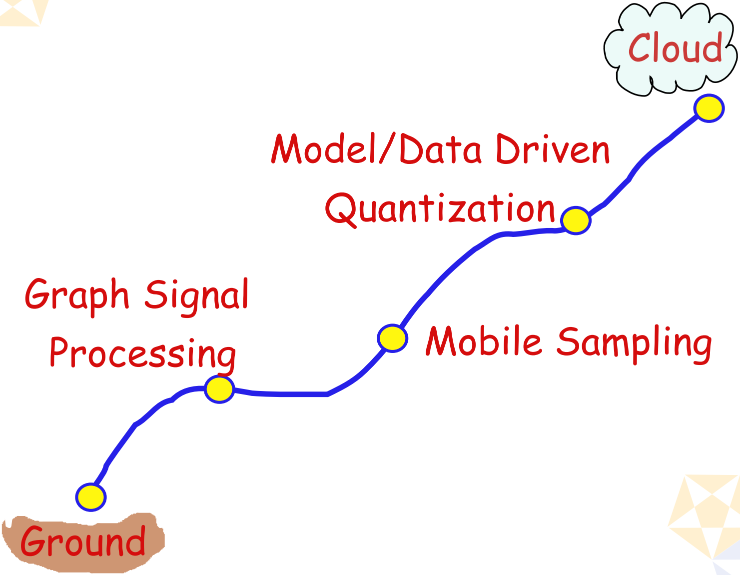


Data has become all pervasive due to smart devices

Roadmap to the Cloud



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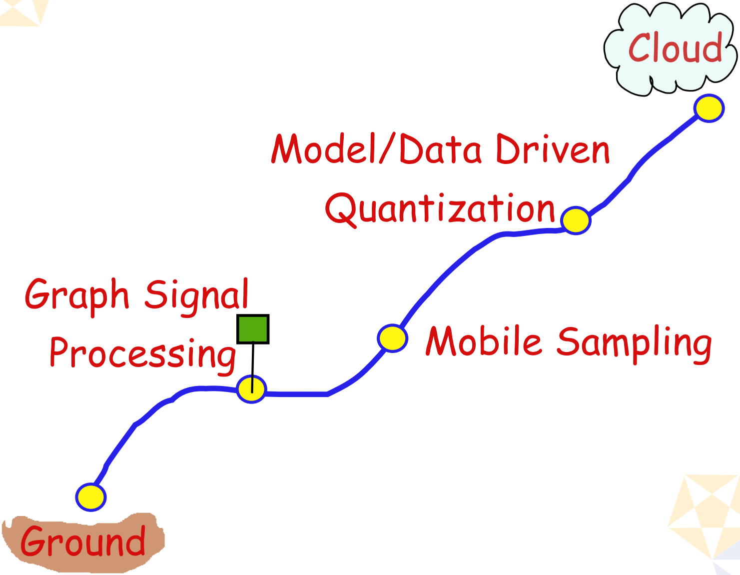
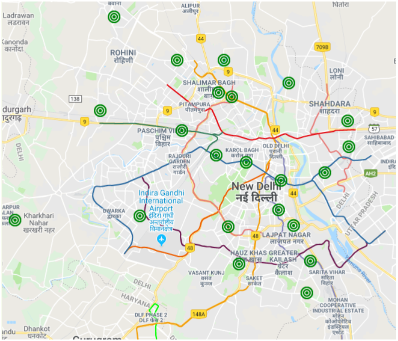


Graph SP : Basics

- Each station is a node on graph



- $\mathcal{G}(V, E, W)$; edges represents correlation (distance)
- At any time t, graph signal is a vector $\vec{f}$
- $\vec{f}$ represents and snapshot of (say) PM 2.5 measurement
- An example of the edge weights is;

$$W_{i,j} = \begin{cases} \exp\left(\frac{\text{dist}(i,j)^2}{2\theta^2}\right) & \text{if dist}(i,j) \leq \kappa \\ 0 & \text{otherwise.} \end{cases}$$

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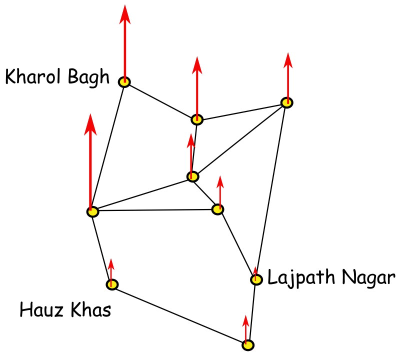

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Spectral is better?

- Like in classical signal processing, we can define a Graph Fourier Transform [Shuman-Narang-Frossard-Ortega-Vandergheynst'13]
- (The Graph Laplacian) $\mathcal{L} := D - W$
  - Laplacian is positive semi-definite
  - Eignenvalues are bounded $0 := \lambda_0 \leq \lambda_1 \leq \cdots \leq \lambda_{N-1} := \lambda_{\mathsf{max}}$
  - Corresponding eigenvectors are frequency vectors (increasing zero crossings); $\vec{u}_0, \vec{u}_1, \cdots, \vec{u}_{N-1}$
- GFT is defined as;

$$\widehat{f}(\lambda_l) := \left\langle \vec{f}, \vec{u}_l \right\rangle$$

Recent trends...

- Graph Filtering: helps in denoising, ensuring sparsity, localization (zooming)
- Graph Wavelet Transforms : multiresolution analysis of graphs, sparse representations [Narang-Ortega'12]
- Spatio-Temporal Processing : deals with time variation of the graph signal. Joint space-time transforms are studied
- Graph Learning : learning graph weights from (training) data [Dong-Thanou-Frossard-Vandergheynst'16]

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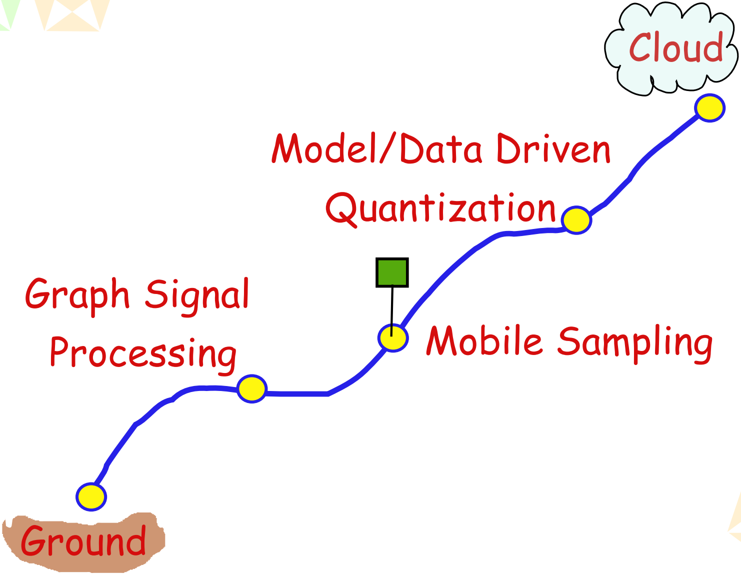
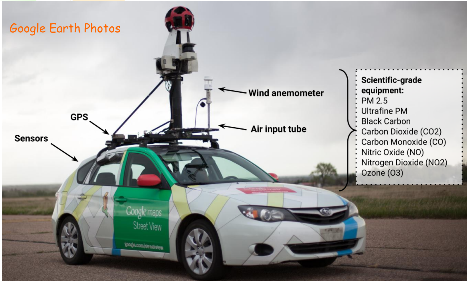


Sampling Spatial Fields



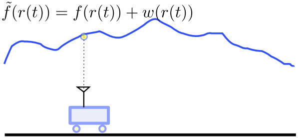
http://www.pigeonairpatrol.com

- Sensors are mounted on vehicles or birds to collect large amounts of data
- Mobile Sampling comes with measurement noise/ delay, but a large number of samples would come to the rescue !

A familiar Bandlimited model

- To start, model assumes time-invariance and limited bandwidth [Unnikrishnan-Vetterli'13]

- Let sampling vehicle have uniform velocity; $r(t) = u + vt$



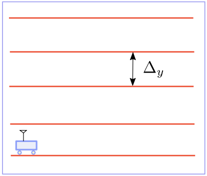
- 1-D Field: BW $\in [-\rho, \rho]$; time domain signal will see a bandwidth of $[-v\rho, v\rho]$

- (Nyquist-Shannon Sampling):

$$\widehat{f}(x) = \sum_{j \in \mathbb{Z}} s(jT) \frac{vT\rho}{\pi} \text{sinc}\left(\frac{\rho(x - jvT)}{\pi}\right)$$

More into practice

- 2-D Field: BW: $[-\rho, \rho] \times [-\rho, \rho]$.
- 2-D mobile sampling results in lower mean-square error than static sampling approach



Other Extensions:

- Sampling high dimensions using lower dimension manifolds [Unnikrishnan-Vetterli'13]
- Location unaware sampling [A. Kumar'17]
- Sampling of spatio-temporal fields [ongoing]

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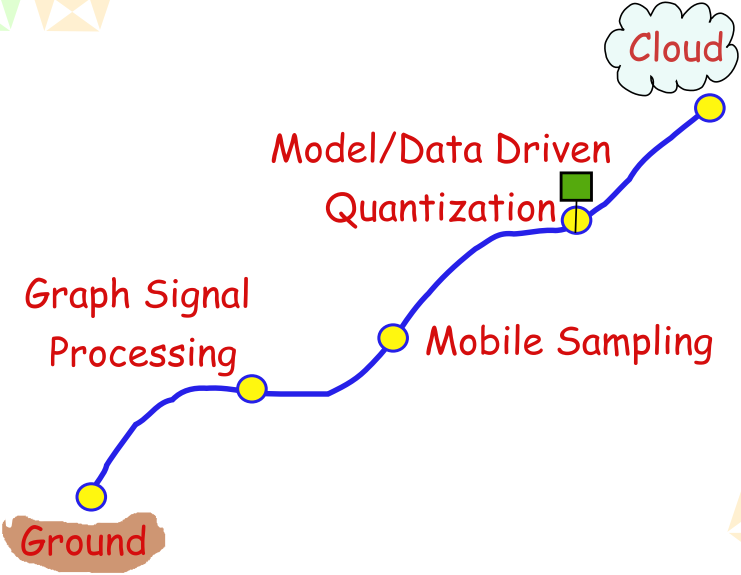
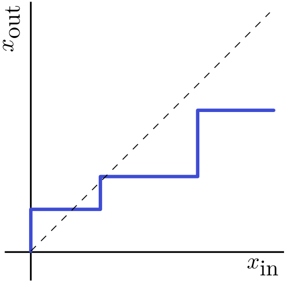
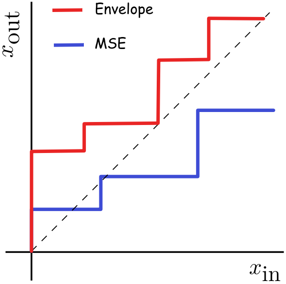


Envelope to the cloud

- Traditional mean square error quantizer (a.k.a Lloyd-Max quantizer) will not provide reliable approximation

- A comparative picture:





- Envelope quantization applicable in protection region database (TV whitespace), weather monitoring

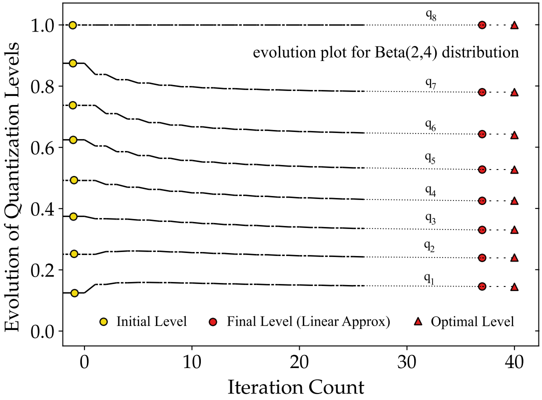
Drive using Model

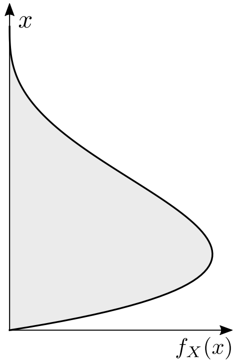
- Model driven approaches assumes the probability density is known
- Cost function (mean square error) optimization

$$\min_{Q(.)} \quad \text{MSE}(Q(X), X) \quad \text{subject to } Q(X) \geq X$$

- 1-parameter/ scalar quantization [Anavangot-Kumar'18]
  - Using localized MSE optimization a recursive algorithm is developed
  - In low computational settings, using piecewise-linear approx can be applied
  - Algorithm is shown to have exponential (error) decay rate and global optimality

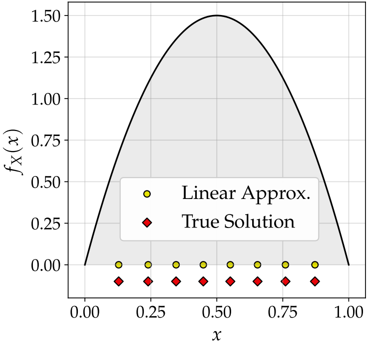
Alternating Recurrence



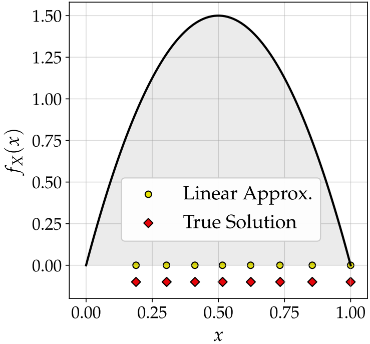


Algorithm details on the board

In simulation



ALM for symmetric Beta(2,2)



AEQ for symmetric Beta(2,2)

- Approximate Lloyd-Max (ALM) uses MSE cost (unconstrained)
- Approximate Envelope Quantizer (AEQ) uses envelope constrained MSE

Driven by data

- For traditional MSE; Learning Vector Quantization (LVQ) and K-means are popular
- Data driven envelope quantization approaches are not straight extensions
- High-dimensional quantization can be challenging

Summary... On cloud 9

- We discussed three state-of-the-art signal processing methods for analyzing sensor data
- Statistical learning tools are expected to dominate in each case
- Modern sensor technology and signal acquisition need to be reliable and power efficient

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Thank you!