FIWEX: Compressive Sensing Based Cost-Efficient Indoor White Space Exploration

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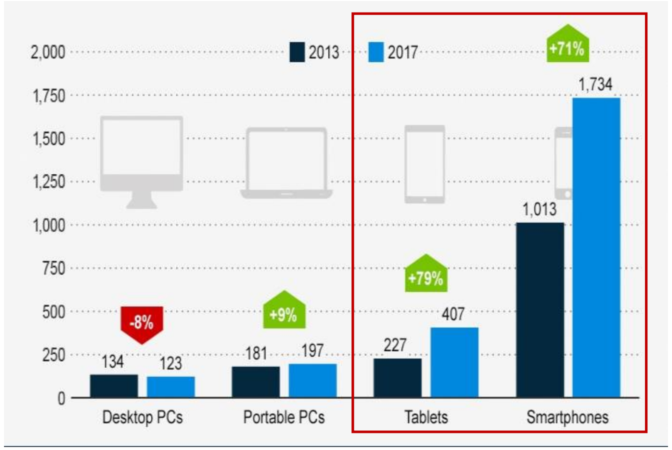
Outline

- Motivation
- Indoor White Space Measurement
- System Design
  - System Model
  - Data Reconstruction
  - Sensor Deployment
- Evaluation
- Summary

Explosive Wireless Data Demand

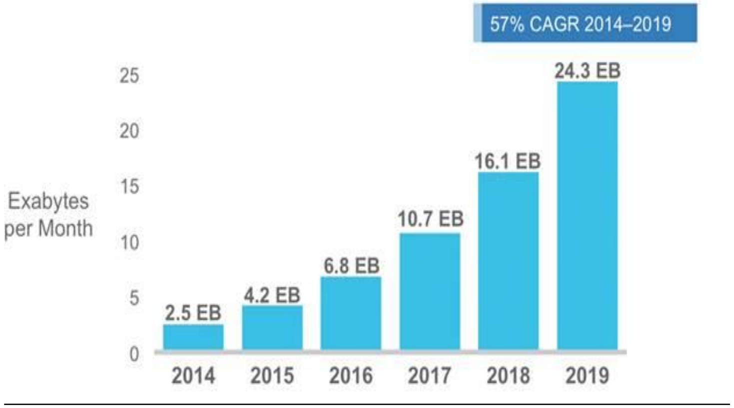
The fast development of wireless networks and mobile communication leads to the explosive wireless traffic growth

Smartphone sales broke the billion barrier in 2013



Source: The International Data Corporation (IDC)

Cisco Forecasts the global wireless data traffic will reach about 24 EB per month in 2019

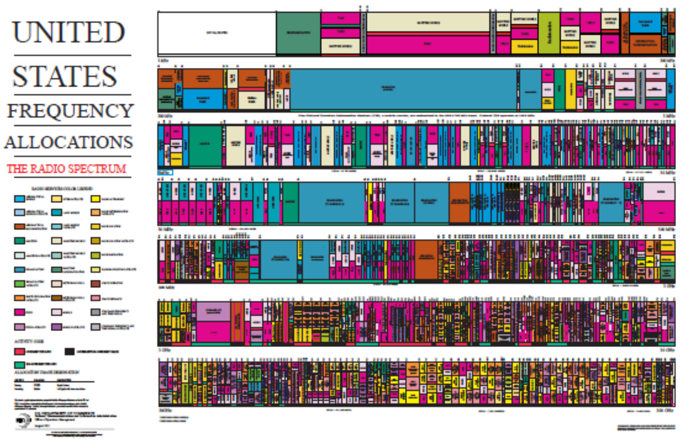


Source: Cisco VNI Mobile, 2015

Low Spectrum Utilization

- Most licensed spectrums are underutilized.

United States frequency allocation



http://www.ntia.doc.gov

Average spectrum occupancy by band in Chicago and New York

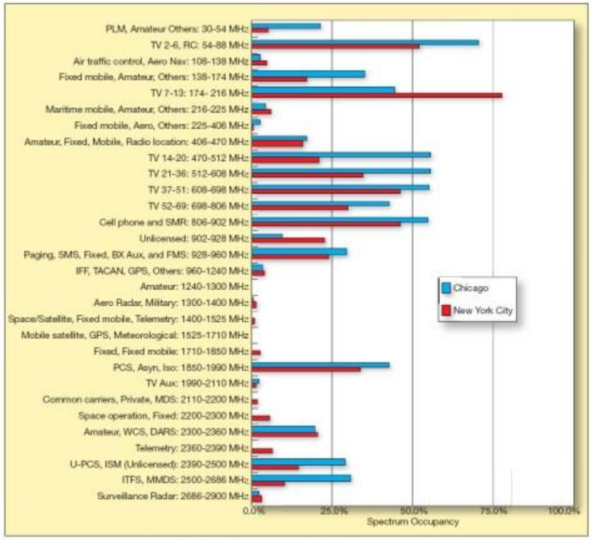


Figure 1. Spectrum measurements in New York City and Chicago conducted by Shared Spectrum.

http://defenseelectronicsmag.com

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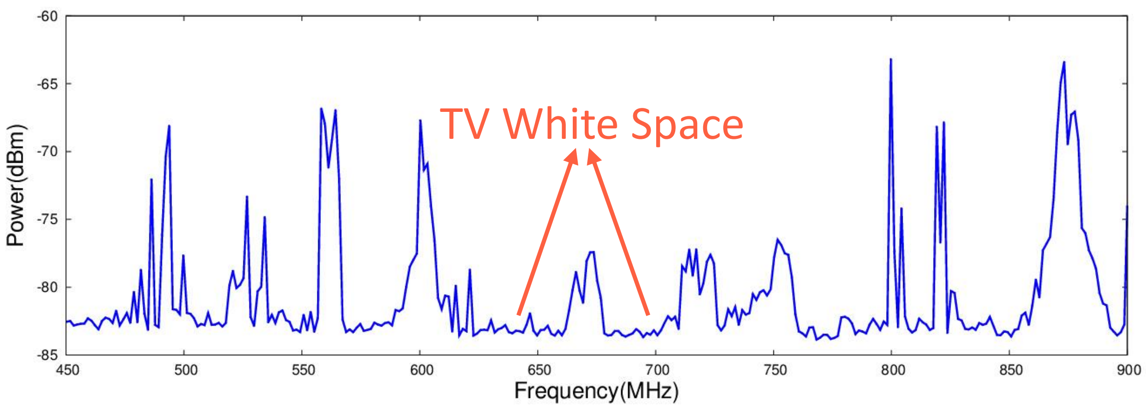
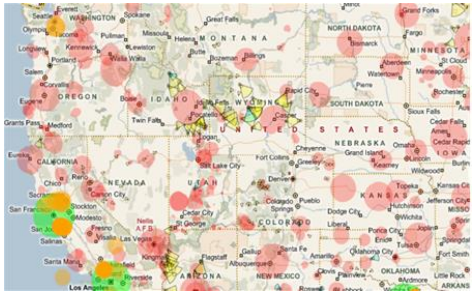
White Spaces

- FCC (Federal Communications Commission) allowed unlicensed devices to use locally unoccupied TV channels.
- Not interfere with the licensed devices.





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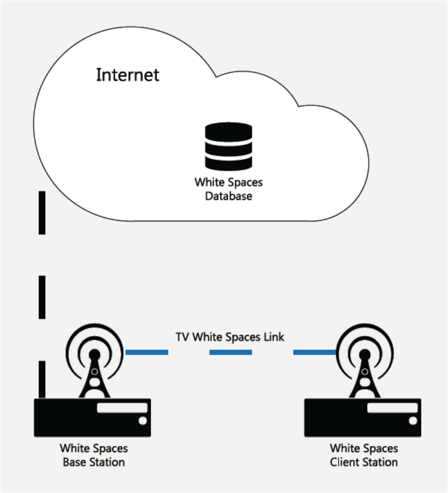
Outdoor White Space Exploration

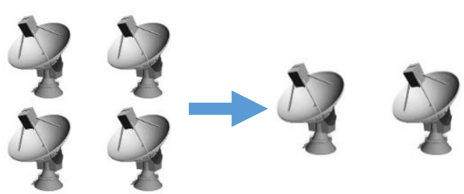
- Most of the prior work focus on the outdoor white space exploration.
- Geo-location database approach



Indoor White Space Exploration

- WISER is the first indoor white space exploration mechanism. (MobiCom’13)

- Can we improve the efficiency of WISER? YES！



Less RF Sensors

Higher system performance

Contributions

- How to reduce the number of sensors?
  - Compressive sensing
  - Smart use of Strong channels
  - Channel dependency and location dependency

- How to deploy these sensors?
  - K-medoids clustering based sensor deployment

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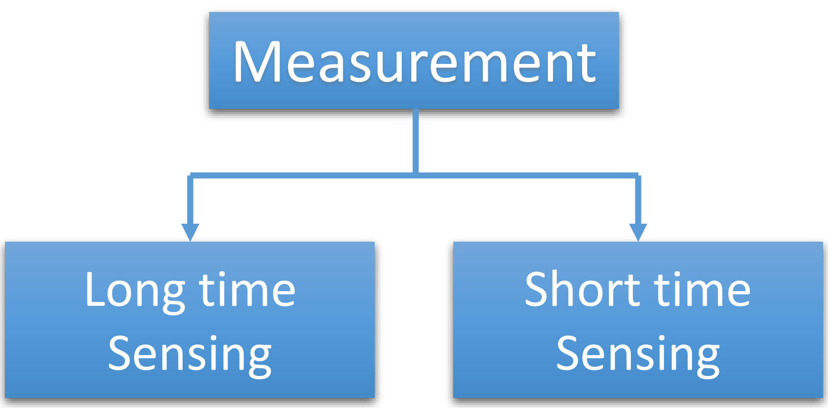
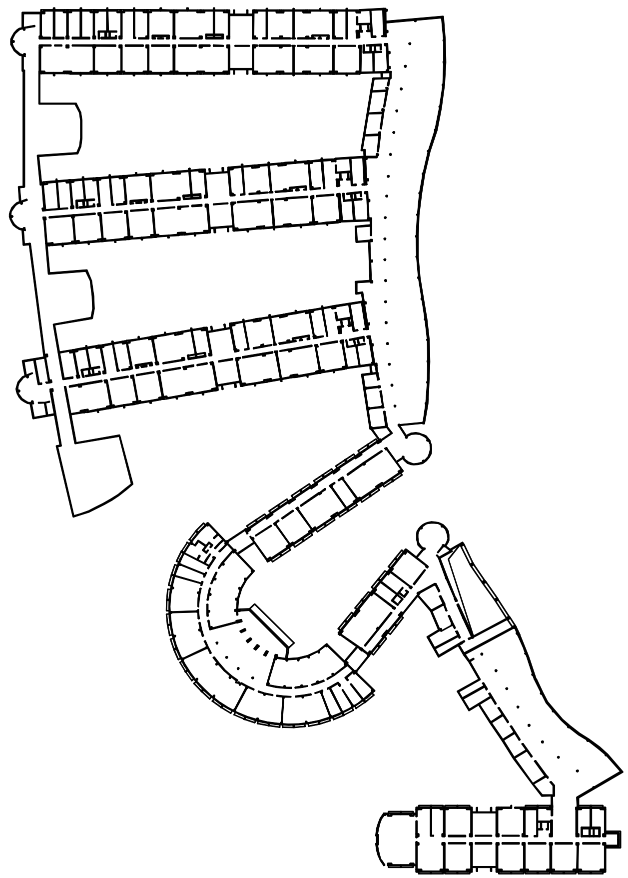
Measurement Setup

- Measurement setup
  - Digital TV channels (45)
  - Energy detection
  - 3rd floor of the SEIEE building



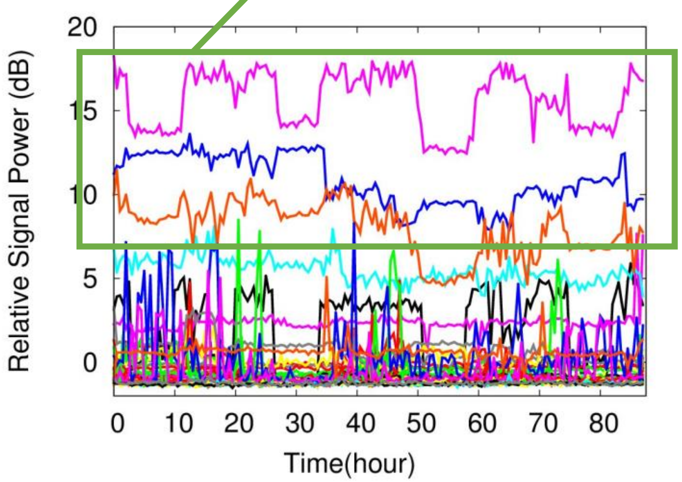


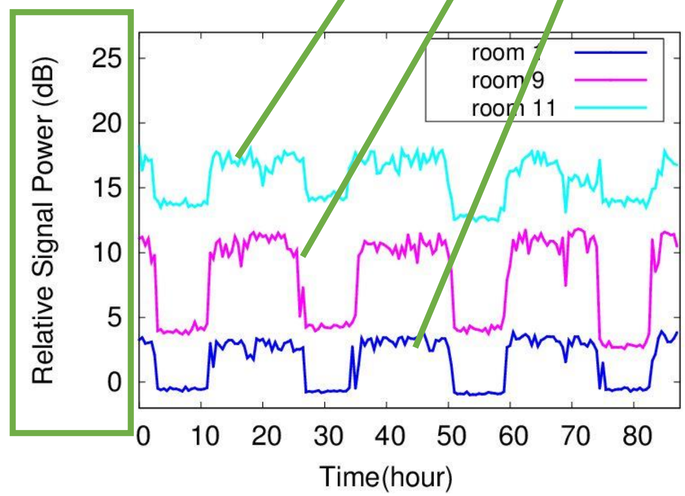
Long-Time Sensing

- 20 USRP with each in a room
- Measure a total time of 87.5 hours

A single channel may have different strength at different locations.

Strong Channels





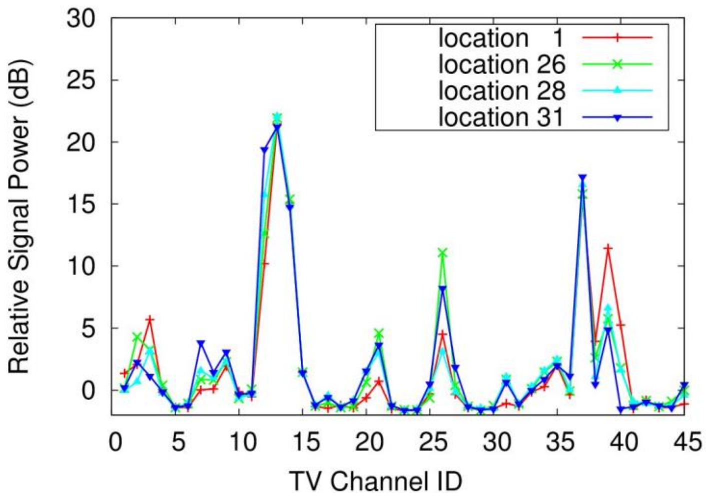
Short-Time Sensing

- Measure the power of 45 channels at all 67 locations using a movable cart
- Perform 14 rounds of sensing in a period of 2 weeks.
- We get 14 Measurement Matrices (67×45)

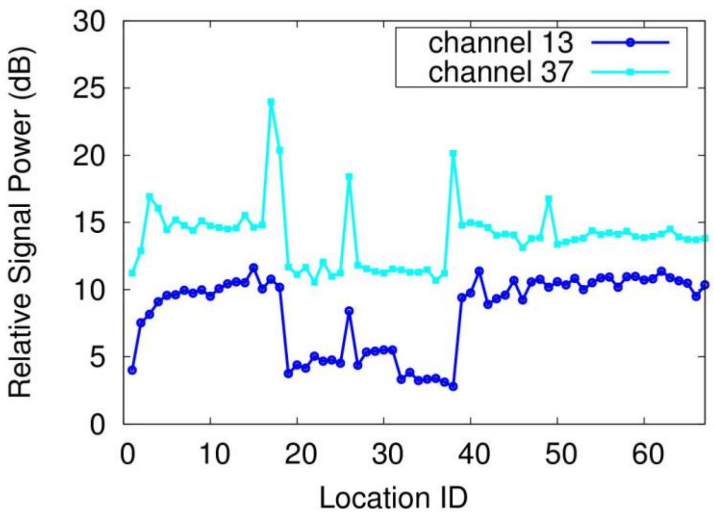
$$\begin{array}{cc} & \text{Channels (45)} \\ \text{Locations (67)} & \begin{bmatrix} M_{1,1} & M_{1,2} & \cdots & M_{1,44} & M_{1,45} \\ M_{2,1} & M_{2,2} & & M_{2,44} & M_{2,45} \\ \vdots & & \ddots & & \vdots \\ M_{66,1} & M_{66,2} & \cdots & M_{66,44} & M_{66,45} \\ M_{67,1} & M_{67,2} & & M_{67,44} & M_{67,45} \end{bmatrix} \end{array}$$

Location & Channel Dependence

- Short-time sensing help us to explore the location dependence and channel dependence of indoor white space.



Signal strength of all channels are similar at four different locations

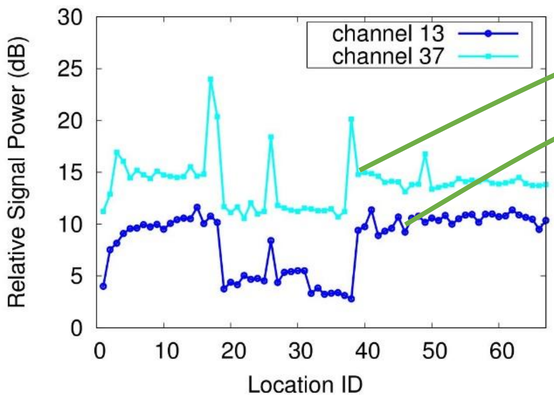


The difference between signal strength of two channels at all locations are almost fixed.

Location & Channel Dependence

- Euclidean distance based Similarity description

Not Enough!



$$\begin{bmatrix} \cdots & M_{1,13} & \cdots & M_{1,37} & \cdots & M_{1,45} \\ \cdots & M_{2,13} & & M_{2,37} & \cdots & M_{2,45} \\ & \vdots & \ddots & & \vdots & \\ \cdots & M_{66,13} & & M_{66,37} & \cdots & M_{66,45} \\ \cdots & M_{67,13} & \cdots & M_{67,37} & \cdots & M_{67,45} \end{bmatrix}$$

Linearly Dependent

Measurement Summary

	Prior Work	Our Work
Strong Channel	All locations share same set of strong channels	Different location have different strong channels
Channel (location) relationship	Euclidean distance	Linear dependence

⇩

Improve the system performance

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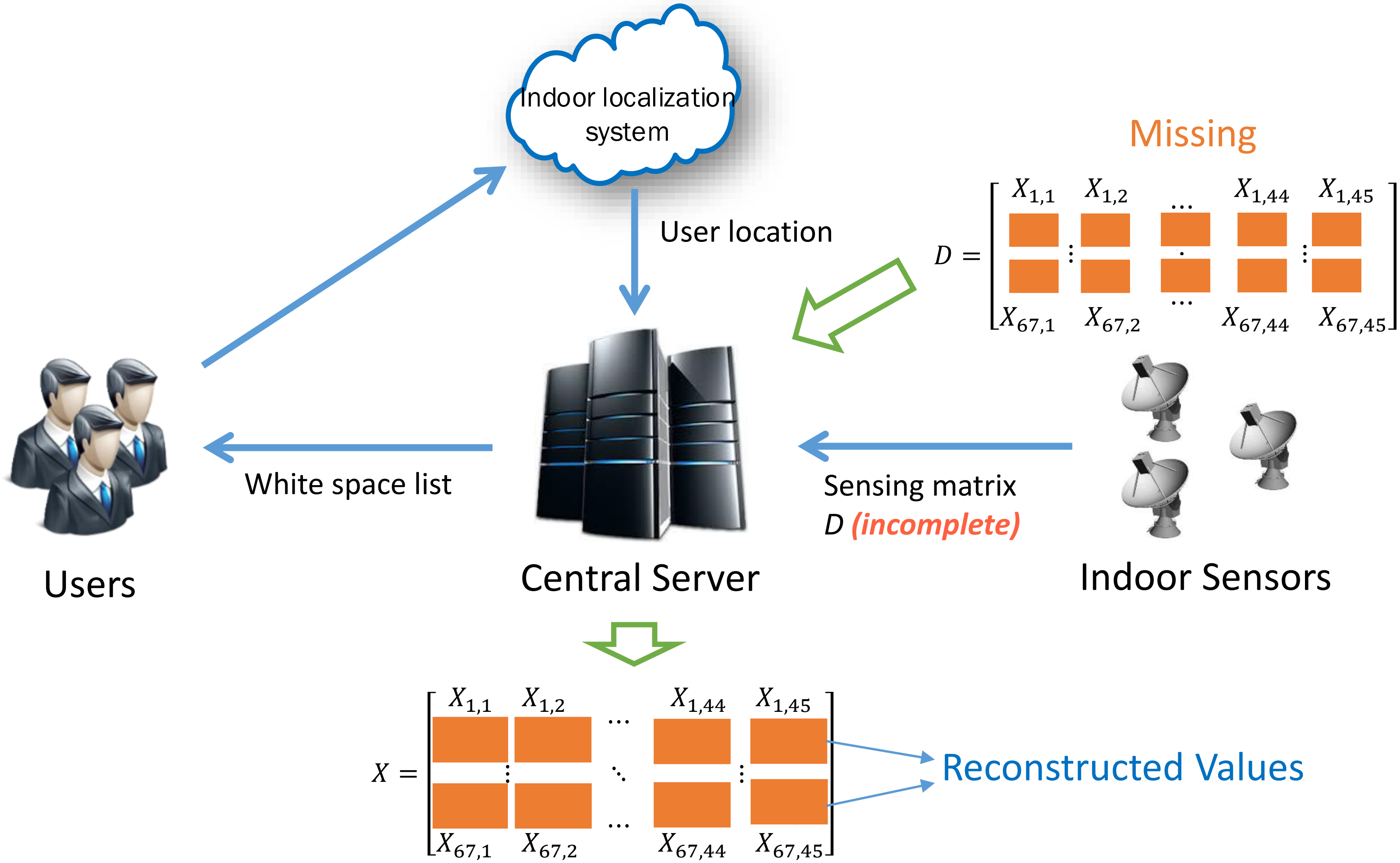
System Model



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Problem

$$D = \begin{bmatrix} X_{1,1} & X_{1,2} & \cdots & X_{1,44} & X_{1,45} \\ & \vdots & & \vdots & \\ X_{67,1} & X_{67,2} & \cdots & X_{67,44} & X_{67,45} \end{bmatrix} \xrightarrow{?} X = \begin{bmatrix} X_{1,1} & X_{1,2} & \cdots & X_{1,44} & X_{1,45} \\ X_{2,1} & X_{2,2} & & X_{2,44} & X_{2,45} \\ \vdots & & \ddots & & \vdots \\ X_{66,1} & X_{66,2} & \cdots & X_{66,44} & X_{66,45} \\ X_{67,1} & X_{67,2} & \cdots & X_{67,44} & X_{67,45} \end{bmatrix}$$

Incomplete　　　　　　　　Complete

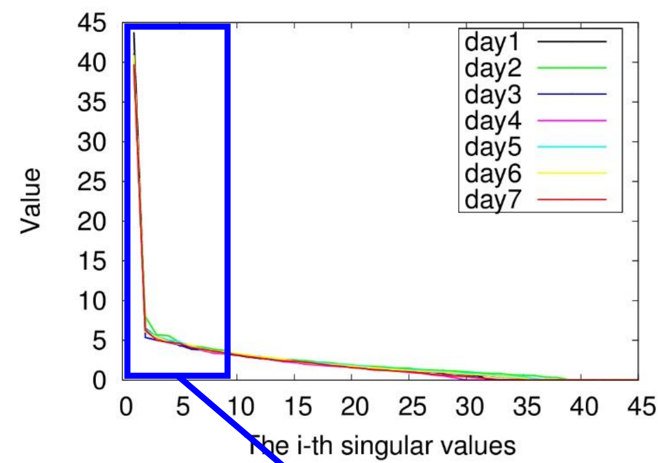
Constrains: $B \circ X = D$

- '$\circ$' refers to Hadamard Product, element-wise product
- $B(i,j) = 1 \Leftrightarrow X(i,j)$ exists in *D*.
- D is the direct measurement matrix.

Given B and D, how to calculate X?

Compressive Sensing

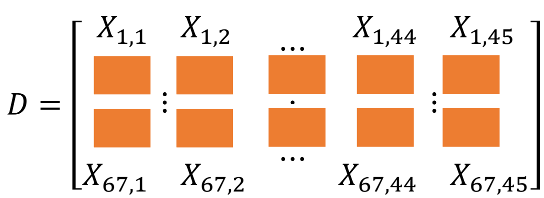
- X is low rank
  - Matrix with low rank feature can reconstructed with a high accuracy.



The top 25% singular values contribute most of the energy.

- Challenge

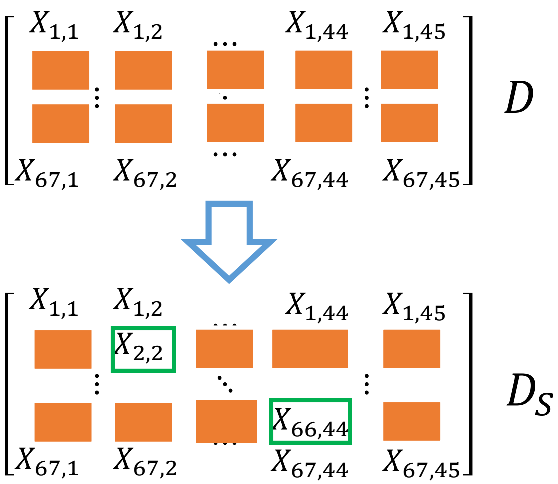
  Compressive sensing can not deal with Line-wise missing value.



Line-wise missing values

Strong Channel

- Different location have different strong channels.
- Add strong channels to measurement matrix D.



Missing value

Strong channel

- Objective Function:

$$Minimize$$

$$\underbrace{\|B_S \circ (LR^T) - D_S\|_F^2}_{\textit{fitting error}} + \underbrace{\lambda(\|L\|_F^2 + \|R\|_F^2)}_{\textit{Low-rank approximation}}$$

Location-Channel Dependence

- Every row (column) of X can be approximated as the linear combination of other correlated rows (columns)
- Matrix expression

$PX - P_0 \approx 0$ (Location dependence)

$XC - C_0 \approx 0$ (channel dependence)

Minimize

$$\|B_S \circ (LR^T) - D_S\|_F^2 \quad \text{// fitting error}$$
$$+ \lambda(\|L\|_F^2 + \|R\|_F^2) \quad \text{// low-rank approximation}$$
$$+\|P(LR^T) - P_0\|_F^2 \quad \text{// location dependence}$$
$$+\|(LR^T)C - C_0\|_F^2 \quad \text{// channel dependence}$$

Can be easily solved using *Alternative Least Square* method!

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Sensor Deployment

Question: Given *N* sensors, how to deploy them?

- Location dependence
- Deploy sensors at “independent” locations

Clustering based sensor deployment

Given N sensors → Cluster all locations into N groups → Deploy a sensor at the center of each group

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Evaluation

- Methodology
  - 7 data sets for training; 7 data sets for testing

- Metrics
  - False Alarm Rate (FA Rate)

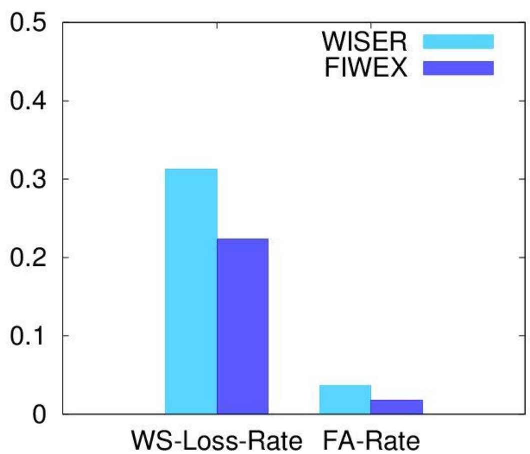
$$\frac{\#\ of\ channels\ misidentified\ as\ vacant}{\#\ of\ system\ identified\ vacant\ channels}$$

  - White Space Loss Rate (WS Loss Rate)

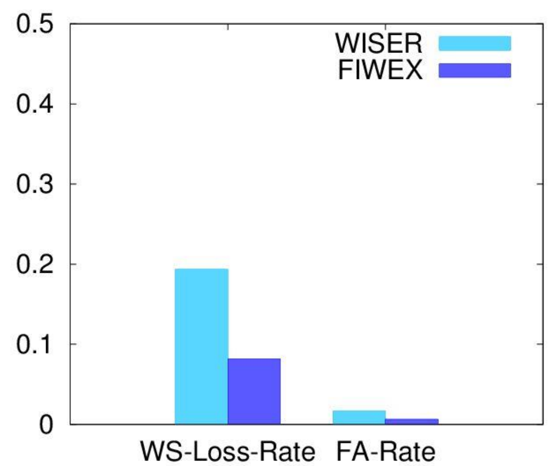
$$\frac{\#\ of\ channels\ misidentified\ as\ occupied}{total\ \#\ of\ actually\ vacant\ channels}$$

Comparison With WISER

- FIWEX outperforms the existing mechanism : WISER, when the sensor number is 10 and 30.



10 sensors



30 sensors

Comparison With WISER

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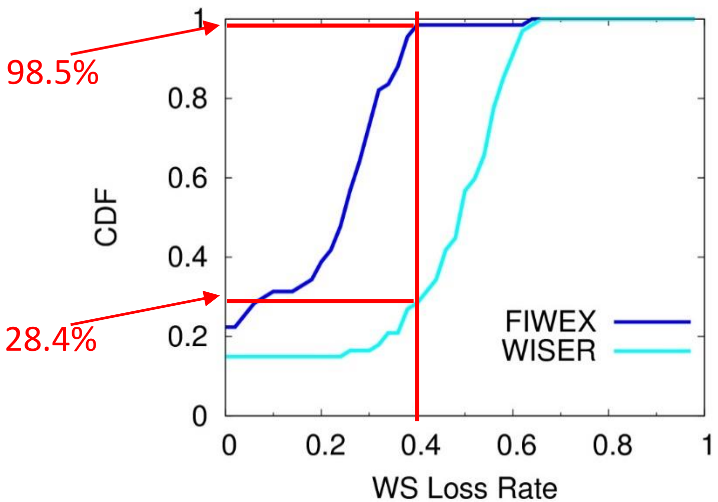
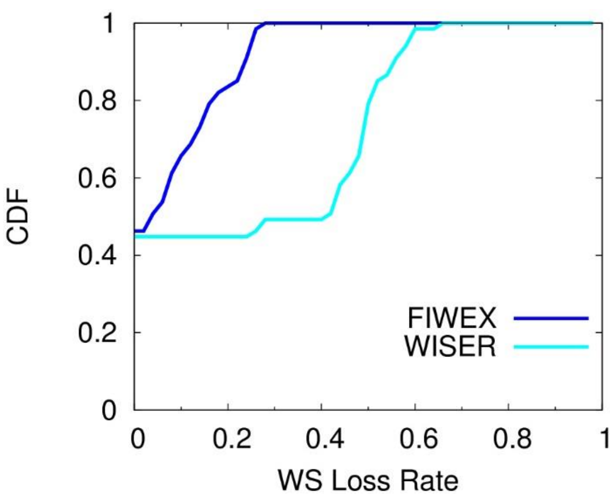


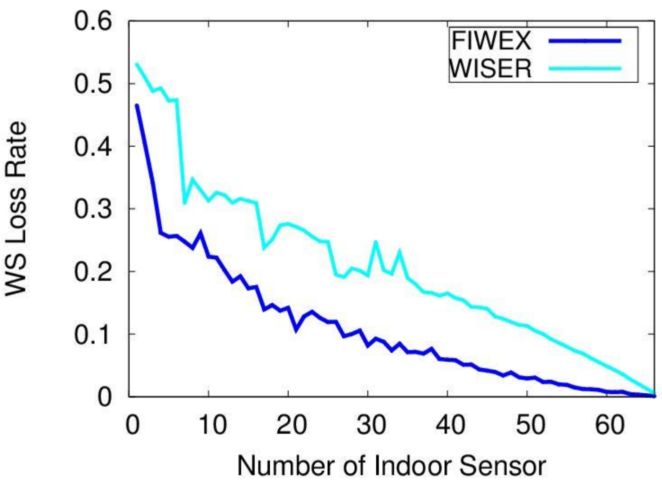
10 sensors



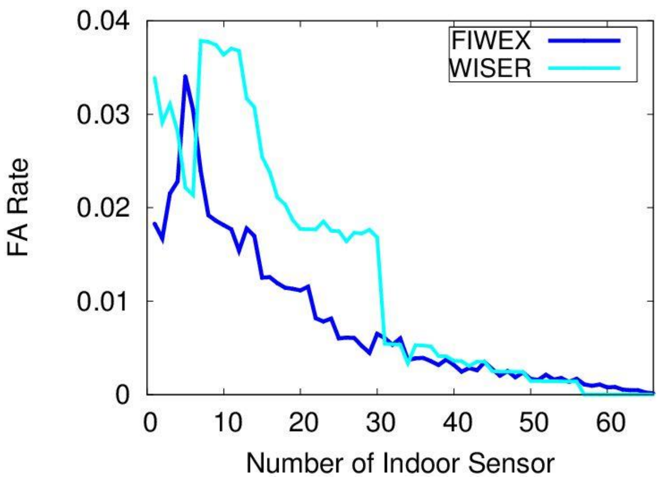
30 sensors

Performance On The Number Of Sensors

- FIWEX outperforms WISER in most cases.



47.8% performance improvement



38.4% performance improvement

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Summary

- We perform indoor white space measurements in a real building to study the characteristics of indoor white space.
- We proposed a cost-efficient indoor white space exploration mechanism – FIWEX.

Thank You!