Design of Distributed Algorithm in WSNs for Engineering Applications

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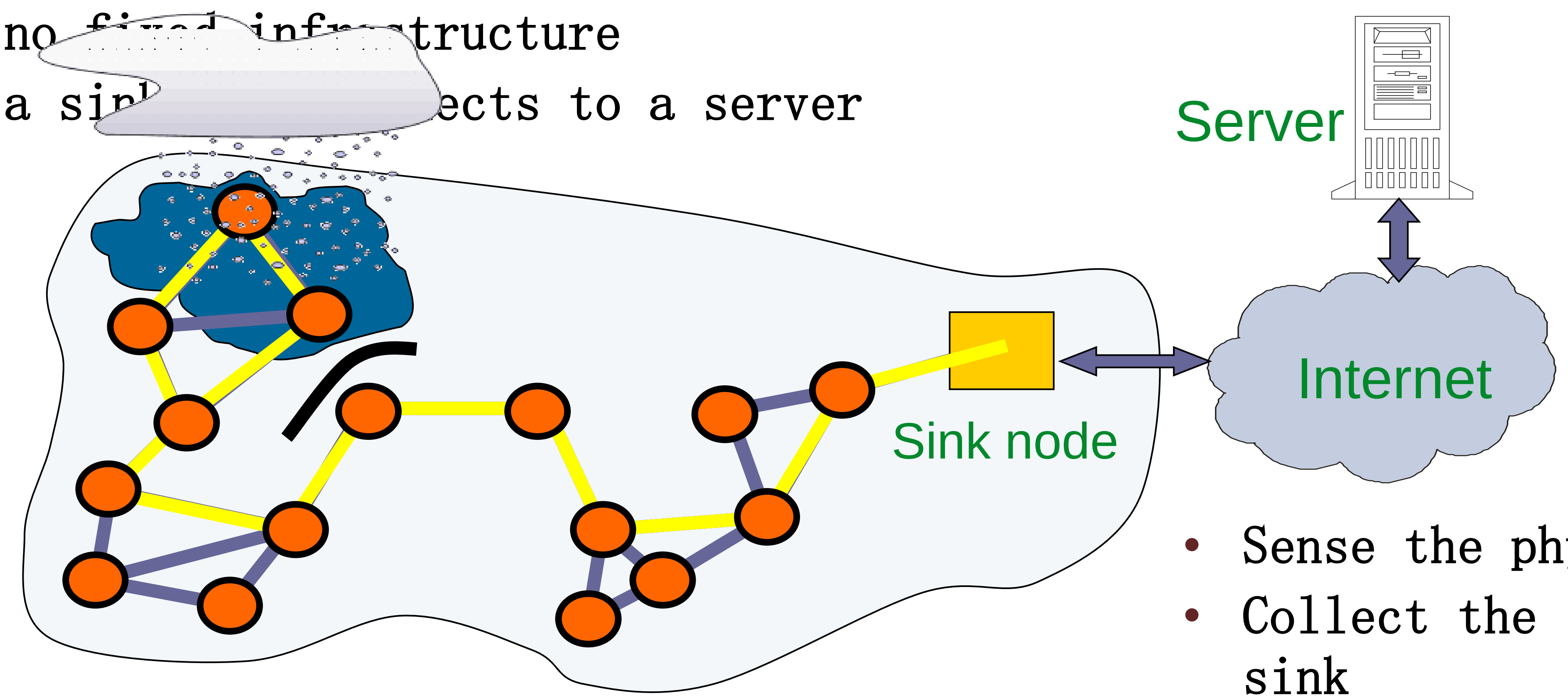
Outline

- Wireless sensor networks
- In-network processing:
  - existing solutions and drawbacks
- A structured approach to designing distributed algorithms in engineering applications of WSNs.
- Our work on WSN-based SHM

Wireless Sensor Networks (WSN)

- WSN consists of a large number of smart sensors nodes.
  - nodes are attached sensors and communicate through wireless c connections
  - nodes can be mobile or stationary
  - no fixed infrastructure
  - a sin ects to a server

- MCU: 12MIPS
- Power: 0dBm or 1dBm
- Frequency: 2.4G/830M/433MHz
- Data rate: 250k/80k/20kbps



- Sense the physical phenomenon
- Collect the information to sink
- Process it to get relevant results

Applications of WSN

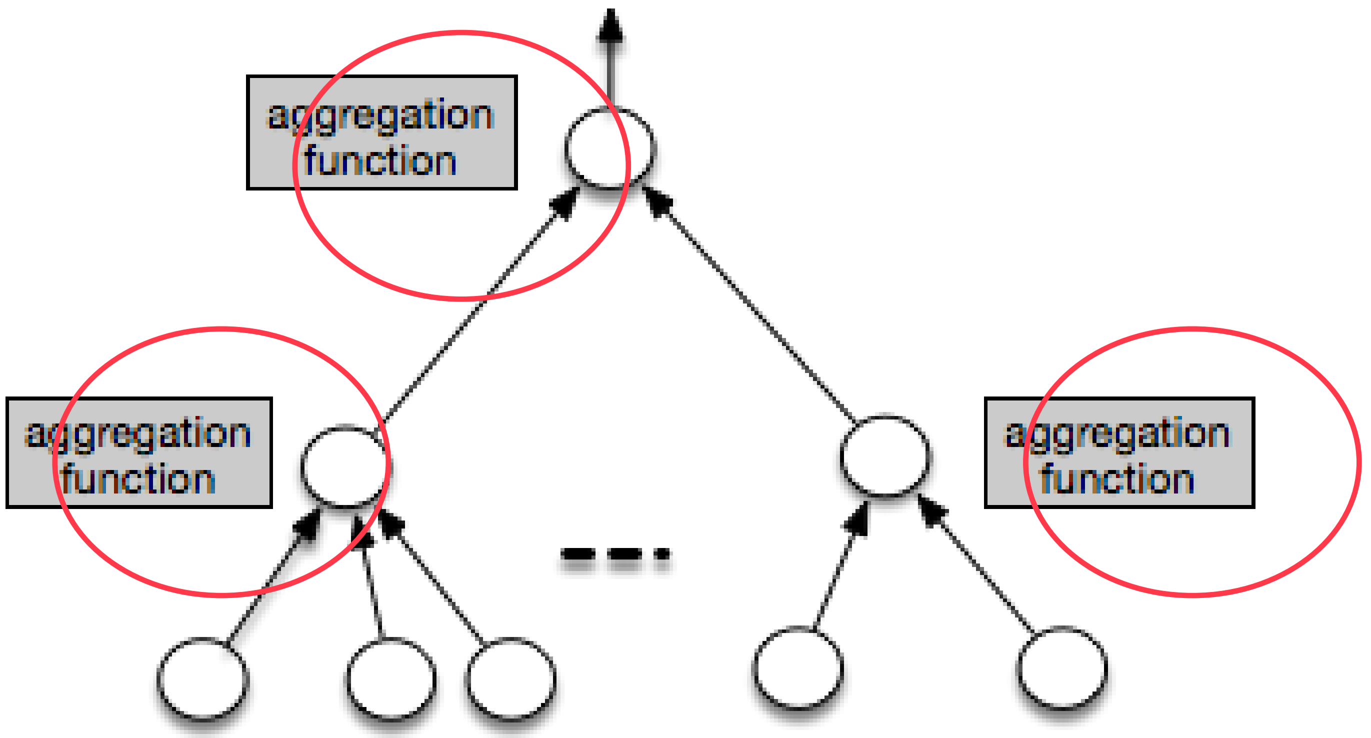
In-network Processing

- For applications where the amount of sensory data or the scale of the network is large, collecting massive raw data to the sink node for (centralized) processing is infeasible:
  - Sensor nodes are much more limited in power, memory, and computational capacities
  - Communication consumes a lot of battery power
  - Centralized processing takes longer time
- In-network processing: data sensed is processed by sensor nodes themselves, while being transmitted to the sink.
  - facilitating a distributed, collaborative approach to computation

In-network Processing in WSN
the data aggregation approach

- Data aggregation: the process of aggregating the data from multiple sensors to eliminate redundant transmission

- Two steps to design data aggregation in WSN
  - Design an appropriate aggregation function
  - Design a routing/scheduling protocol



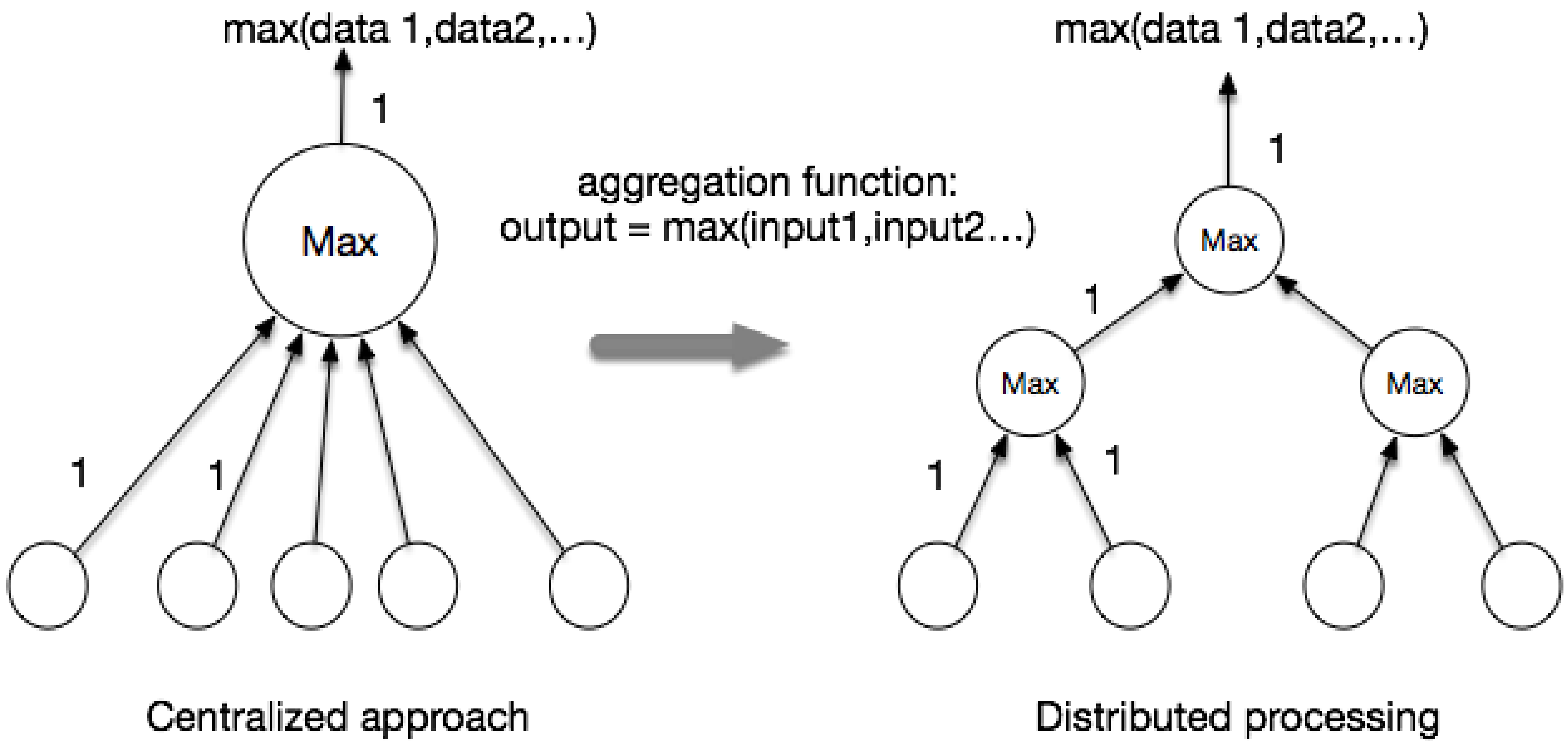
Aggregation Function

- Aggregation function: on receiving multiple data, how a sensor node processes the data so as to achieve the same final results as in the centralized approach.

- Types of aggregation functions:
  - *Constant output size*: an intermediate sensor aggregates multiple incoming packets into a single outgoing packet (Examples: Max, Min, Average…)
  - *Dynamic output size*: the size of the output changes with the inputs (e.g., two types of correlation model: self-coding, foreign coding…)

Example of Aggregation Function

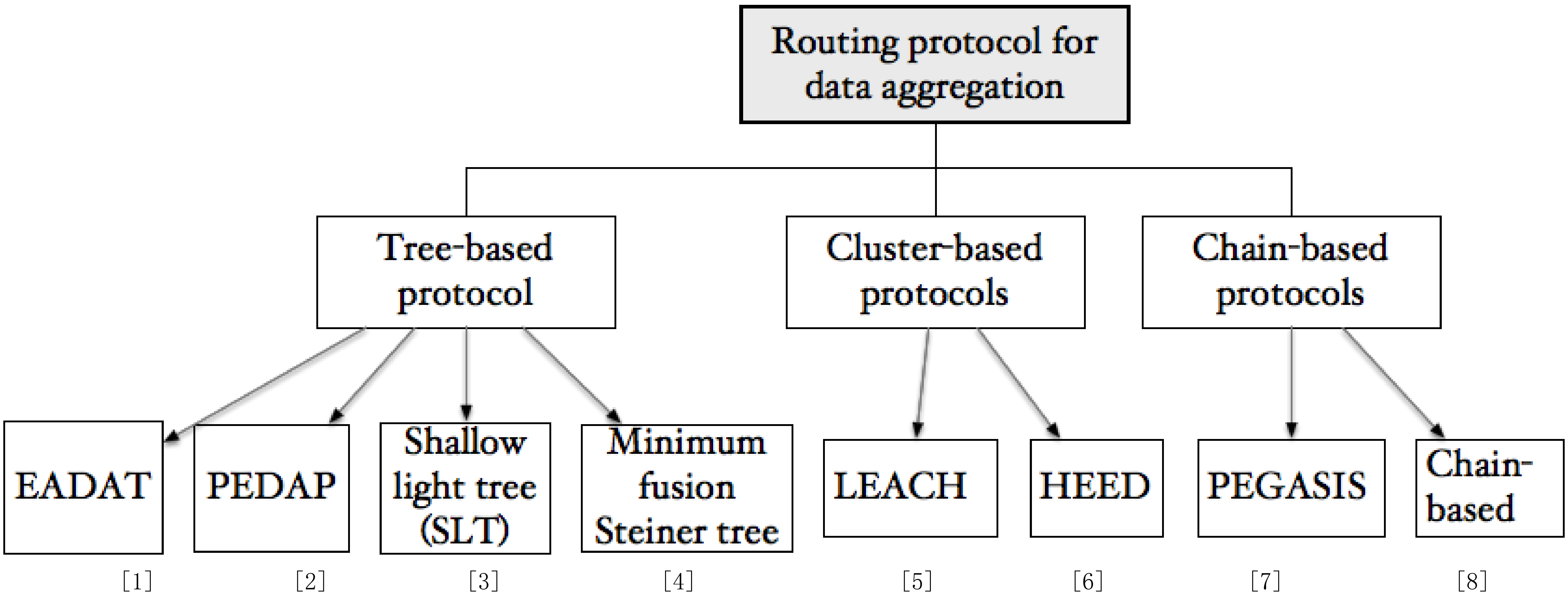
- Design the aggregation function for calculating the maximum value of all the sensor nodes in the network



Aggregation Routing Protocols

- Routing protocol: the aggregation paths from source nodes to the destination nodes
- Problem formulation
  - **Given**: a network model, and the aggregation function
  - **Objective**: to design a routing protocol to achieve some objectives such as maximizing system lifetime, minimizing energy consumption/latency,…

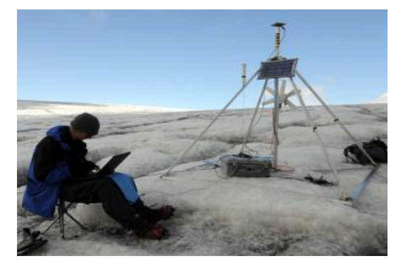
Aggregation Routing Protocols

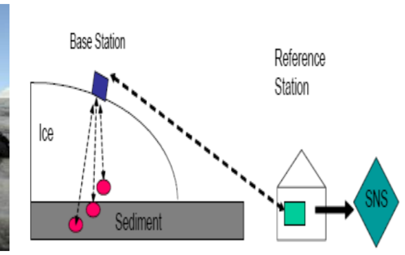


[1] M. Ding, X. Cheng and G. Xue, "Aggregation Tree Construction in Sensor Networks," 2003 IEEE 58th Vehic. Tech. Conf., vol. 4, no. 4, Oct. 2003, pp. 2168–72.
[2] H. O. Tan and I. Korpeoglu, " Power Efficient Data Gathering and Aggregation in Wireless Sensor Networks," SIGMOD Record, vol. 32, no. 4, Dec. 2003, pp. 66–71.
[3] Luo H, Luo J, Liu Y, et al. Adaptive data fusion for energy efficient routing in wireless sensor networks[J]. Computers, IEEE Transactions on, 2006, 55(10): 1286-1299.
[4] Anandkumar A, Tong L, Swami A, et al. Minimum cost data aggregation with localized processing for statistical inference INFOCOM 2008.
[5] Heinzelman W B, Chandrakasan A P, Balakrishnan H. An application-specific protocol architecture for wireless microsensor networks. TWC, 2002
[6] Younis O, Fahmy S. HEED: a hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks[J]. TMC, 2004, 3(4): 366-379.
[7] Lindsey S, Raghavendra C S. PEGASIS: Power-efficient gathering in sensor information systems. Aerospace conference proceedings, 2002.
[8] K. Du, J. Wu and D. Zhou, " Chain-based protocols for data broadcasting and gathering in sensor networks," Inte'l Parallel and Distributed Processing Symp, April 2003

Different Types of WSN Applications

- Environmental monitoring, forest fire monitoring, etc.





- Characteristics:
  - Low sampling frequency (per min/hour) ⟶ small amount of data
  - Simple computation (max, min, average) ⟶
    - algorithms are lightweight.
    - in-network processing is relatively easy

Limitations of Existing Data Aggregation in WSNs

- Targeting at conventional applications of WSNs (e.g. environmental monitoring), and design of in-network processing is relatively straightforward.

- Accordingly, the aggregation function is generally assumed to be handily available, and the focus is put on designing aggregation routing protocols.

- Assumptions for routing protocols
  - using the data aggregation can always obtain the same result as the centralized approach
  - each sensor node has unlimited computation capability

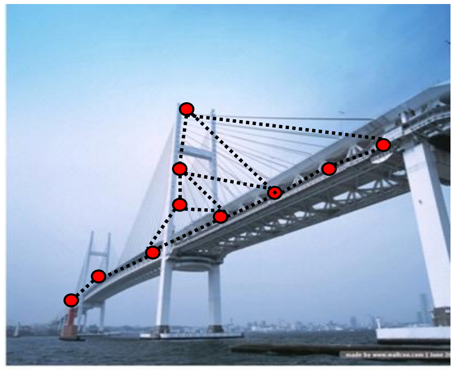
However, many engineering applications of WSNs have unique properties that make the design of data aggregation difficult

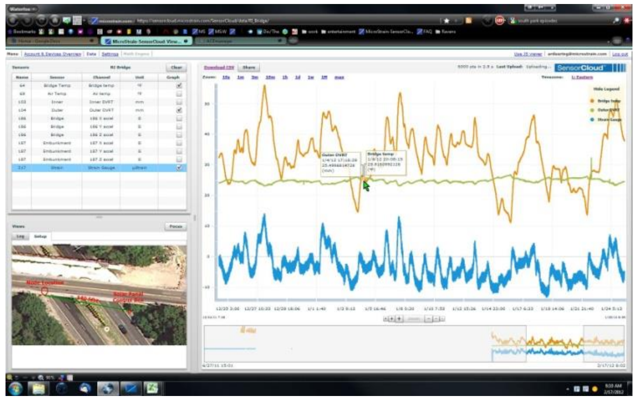
Engineering applications of WSNs:

Monitoring important status, properties or parameters of objects/systems in applications of civil, mechanical, and electrical engineering, etc.

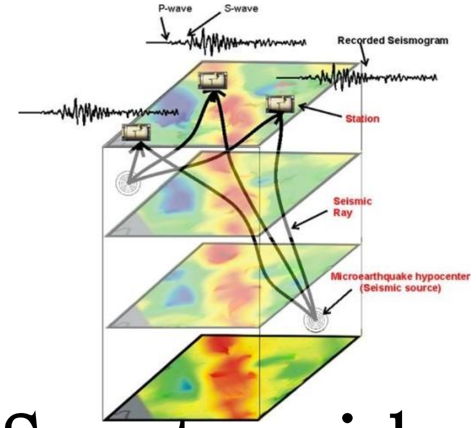
Engineering Applications of WSNs

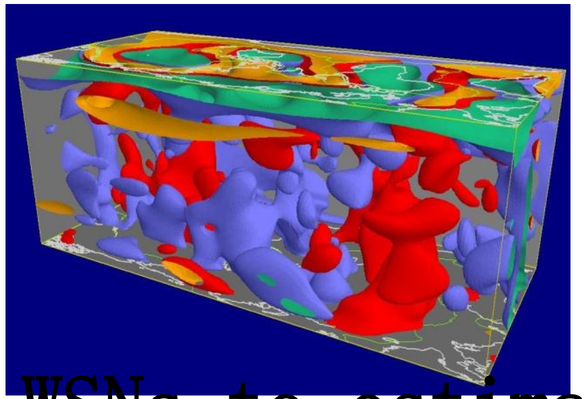
- Structural Health Monitoring (SHM): using WSNs to identify healthy condition of infrastructures





- Seismic tomography:using WSNs to identify inner structure condition of seismic region

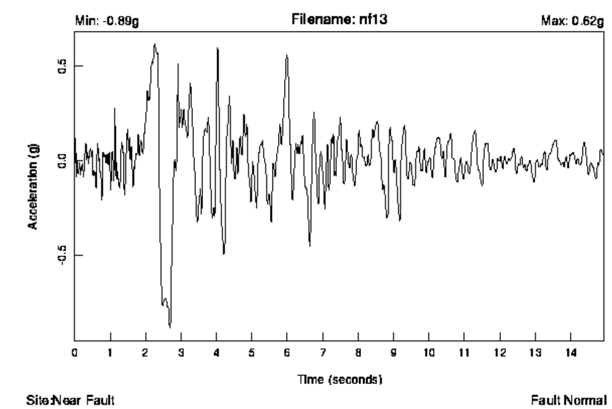




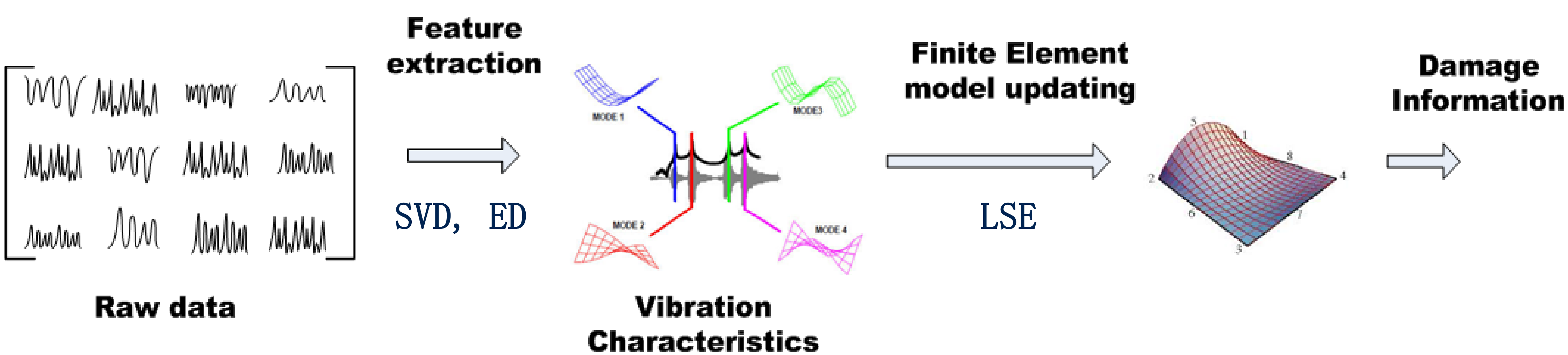
- Smart grid: using WSNs to estimate state in smart grid

Engineering Applications
Structural Health Monitoring

- Data intensive : acceleration data sampled at x00Hz~x000Hz



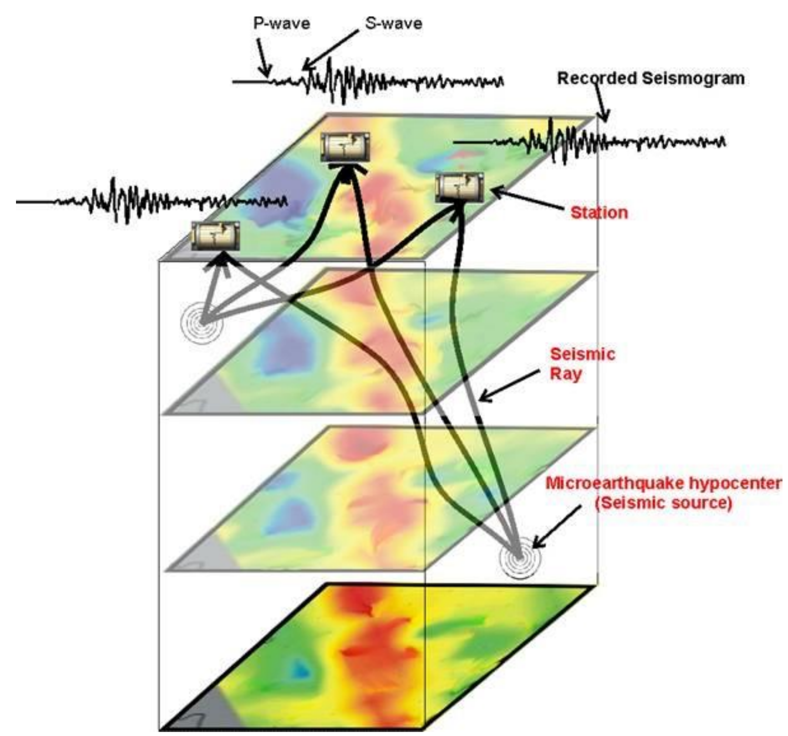
- “Heavy” computation: based on complex matrix computation



Engineering Applications
Seismic Tomography

- Data intensive :

  acceleration data sampled at x00Hz~x000Hz



- "Heavy" computation: least square estimation

$$\begin{bmatrix} A_1 \\ A_2 \\ \vdots \\ A_N \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \\ \vdots \\ S_M \end{bmatrix} = \begin{bmatrix} t_1 \\ t_2 \\ \vdots \\ t_N \end{bmatrix}$$

$\begin{bmatrix} A_1 \\ A_2 \\ \vdots \\ A_N \end{bmatrix}$ the distance of p-wave in each grid (known)

$\begin{bmatrix} S_1 \\ S_2 \\ \vdots \\ S_M \end{bmatrix}$ speed in each grid (tbd)

$\begin{bmatrix} t_1 \\ t_2 \\ \vdots \\ t_N \end{bmatrix}$ travel time (known)

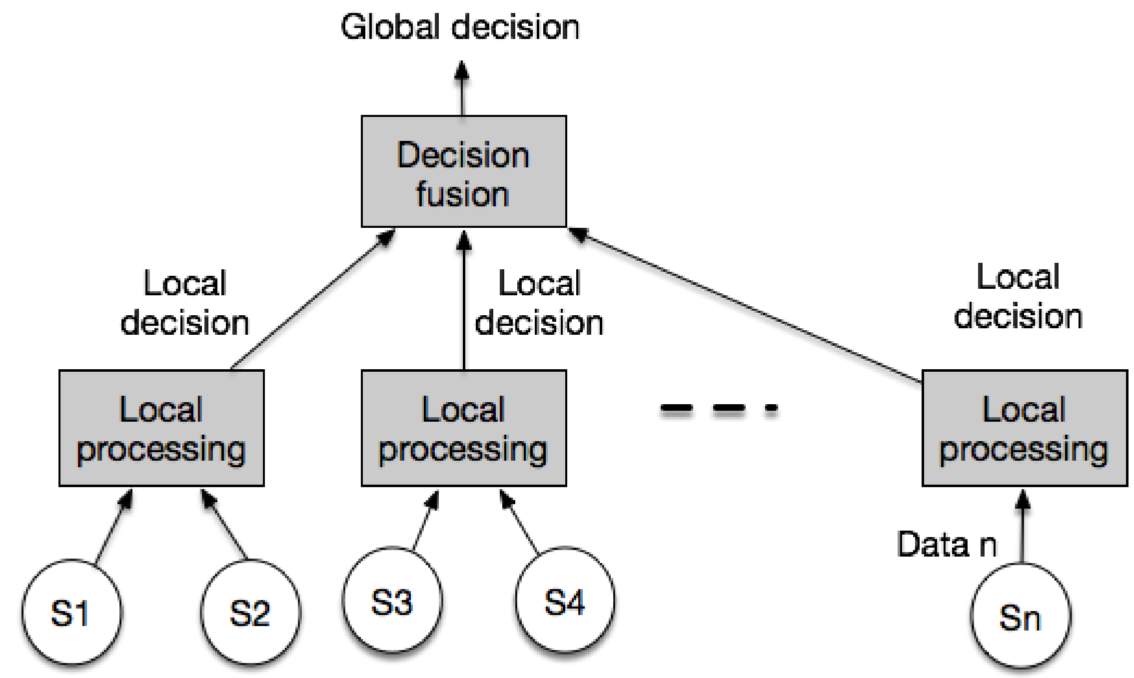
Engineering Applications
Summary

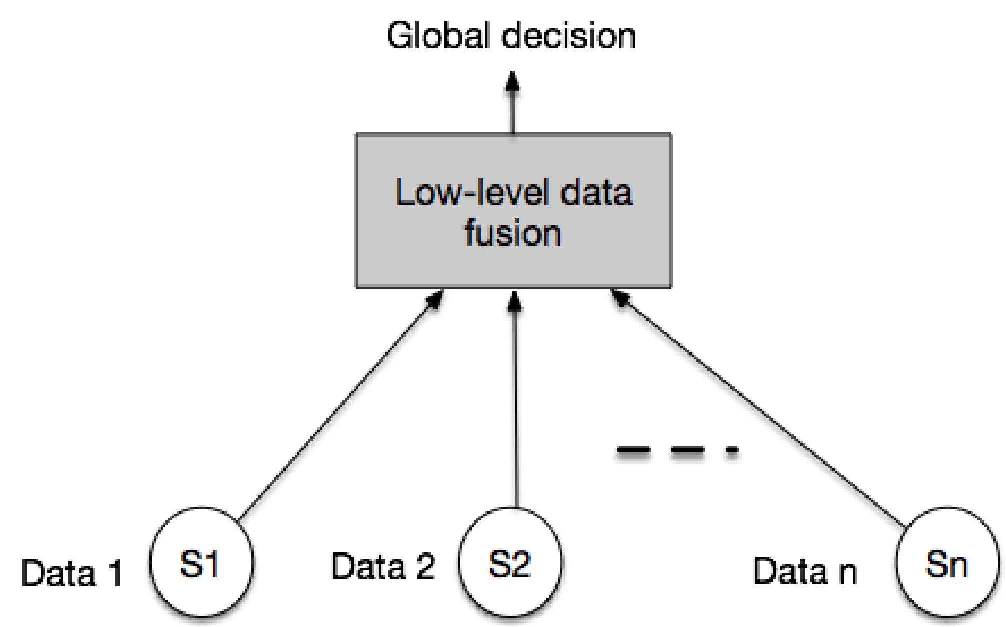
- Data-intensive: not feasible to transmit raw data, so in-network processing is necessary

- Algorithms are complex:
  - **Computation intensive**: implementing in-network processing may be in-feasible or cost for a sensor node
  - **Data-level collaboration of sensors:** Low level data fusion from different sensors: designing an aggregation function is not trivial

Low and High Level Data Fusion

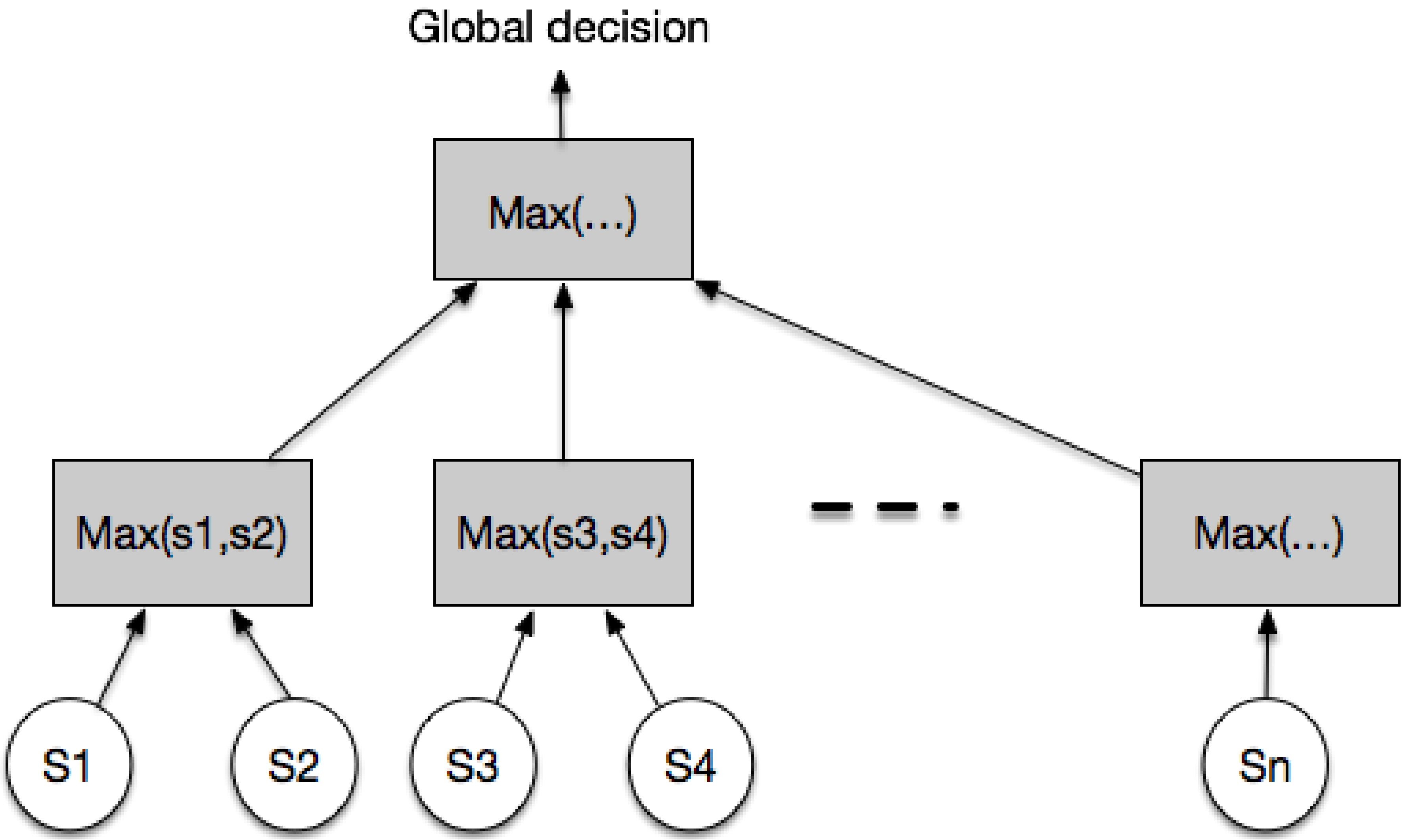
- High level fusion: each sensor node can make a decision based on its own or neighbors' data, local decisions can be combined afterwards.
  - Decision level fusion
  - Feature level fusion
- Low level fusion: final decision can only be made after collecting data from all the sensor nodes





High-Level Data Fusion

- Obtaining the maximum value within a WSN



Low-level Data Fusion

- The Eigensystem Realization Algorithm(ERA) in SHM
- Implements singular value decomposition of a matrix H: H=SVD

$$H = \begin{bmatrix} y(1) & y(2) & \cdots & y(p) \\ y(2) & y(3) & \cdots & y(p+1) \\ \vdots & \vdots & \vdots & \vdots \\ y(q) & y(q+1) & \cdots & y(p+q+1) \end{bmatrix}$$

Hankel data matrix H

$$y(k) = \begin{bmatrix} y^1(k) \\ y^2(k) \\ \vdots \\ y^m(k) \end{bmatrix} \begin{matrix} \text{data from sensor 1} \\ \text{data from sensor2} \\ \\ \text{data from sensor m} \end{matrix}$$

each element involves data from multiple nodes

- When calculating S,V,and D, data from all the sensor nodes are involved simultaneously

Algorithms with Low-level Data Fusion

- Large matrix with data from multiple sensor nodes
- Naive distributed algorithms would require data from different sensor nodes being exchanged frequently
  - Algorithm complexity would be very high and generally cannot be implemented with sensor nodes.
  - Designing distributed version for these algorithms is challenging!

Requirements of Algorithm Design

- **Communication efficiency**: without collecting raw data to a center, reducing wireless transmissions.
- **Computation efficiency**: able to be implemented in resource-limited wireless nodes.
- **High accuracy**: able to achieve the similar quality as the centralized algorithms.

Algorithm Design Steps

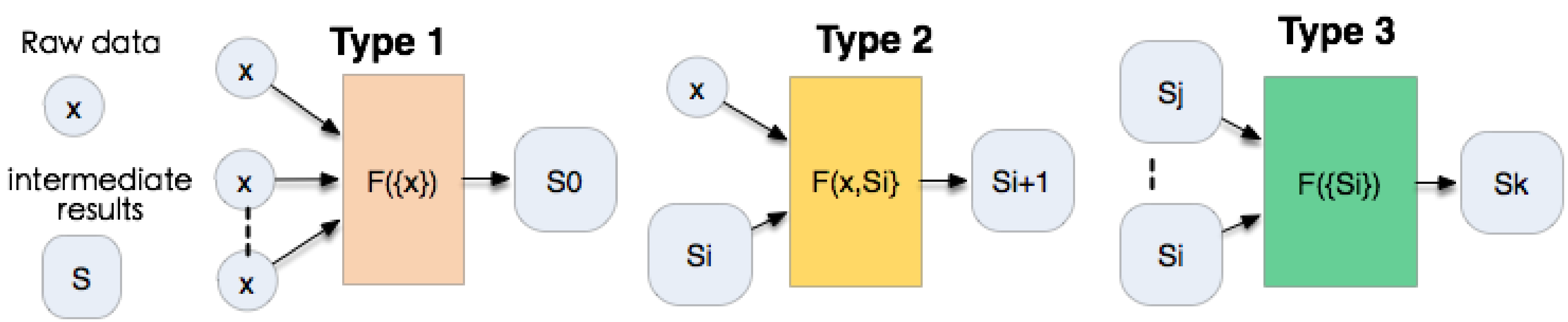
- **Step 1: design appropriate aggregation functions for these algorithms**

- **Step 2:** select appropriate type of routing structure

- **Step 3:** design optimal routing protocols under various constraints

Basic Aggregation Functions

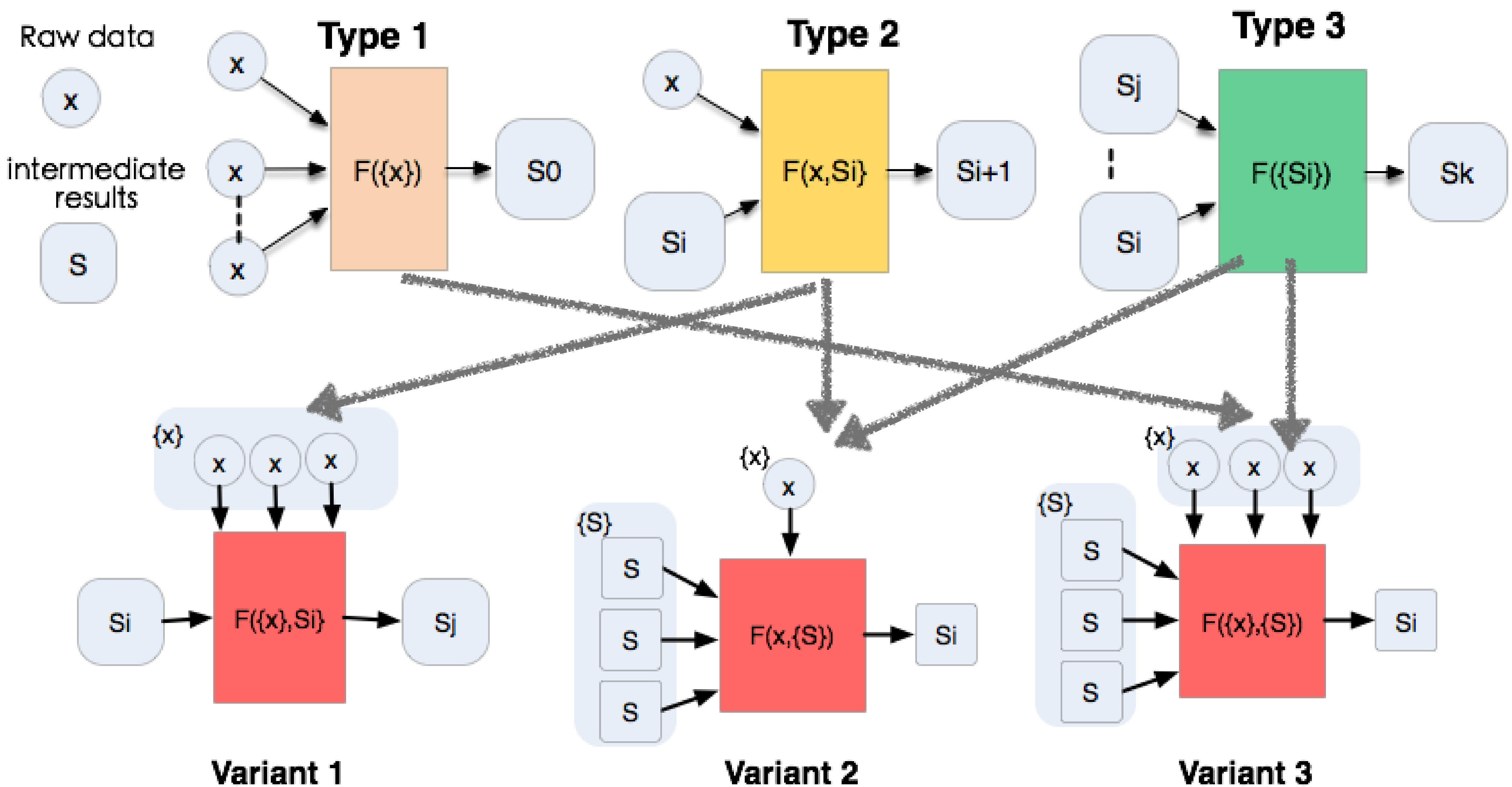
- Type 1: Combining multiple raw data
- Type 2: Combining a single raw data with an intermediate result
- Type 3: Combining multiple intermediate results



F({x}) F(x, si) F({si})

Composite Aggregation Functions

F({x}) F(x, si) F({si})



F(si, {x}) F({si}, x) F({si}, {x})

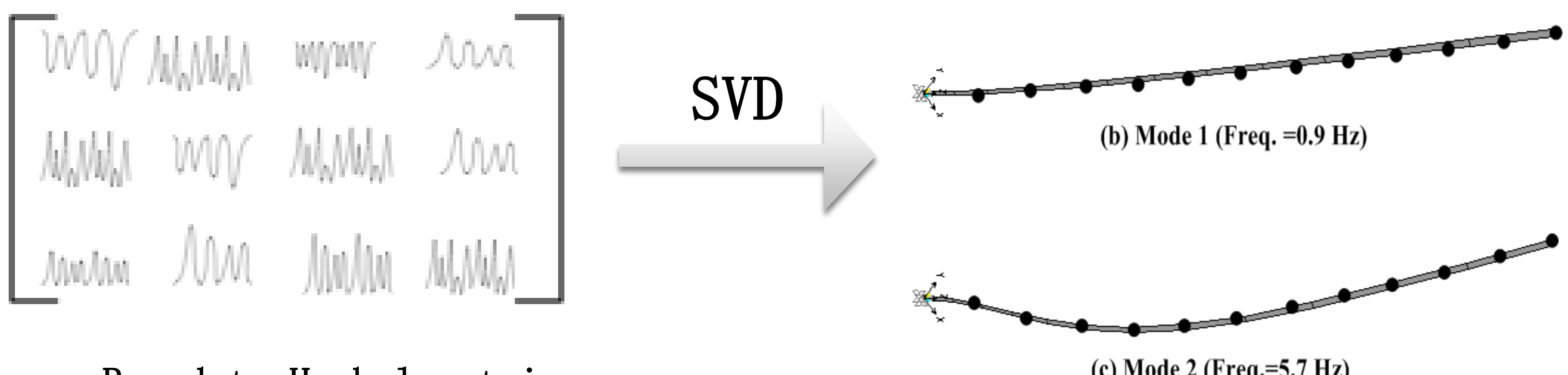
How to identify basic aggregation functions for complicated algorithms?

- Generally algorithm-specific
- But two approaches may help
  - Divide and conquer
  - Incremental algorithm

Approach 1: Divide and Conquer

- Example: the ERA algorithm for SHM, whose objective is to obtain mode shape of a structure

ERA:



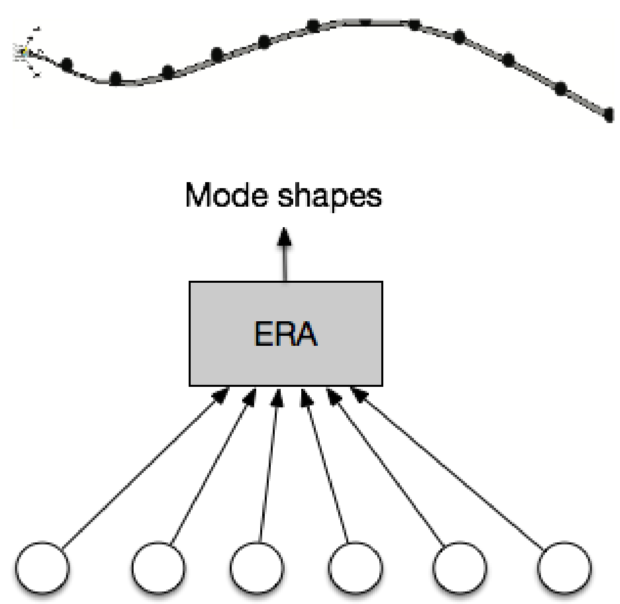
Raw data Hankel matrix

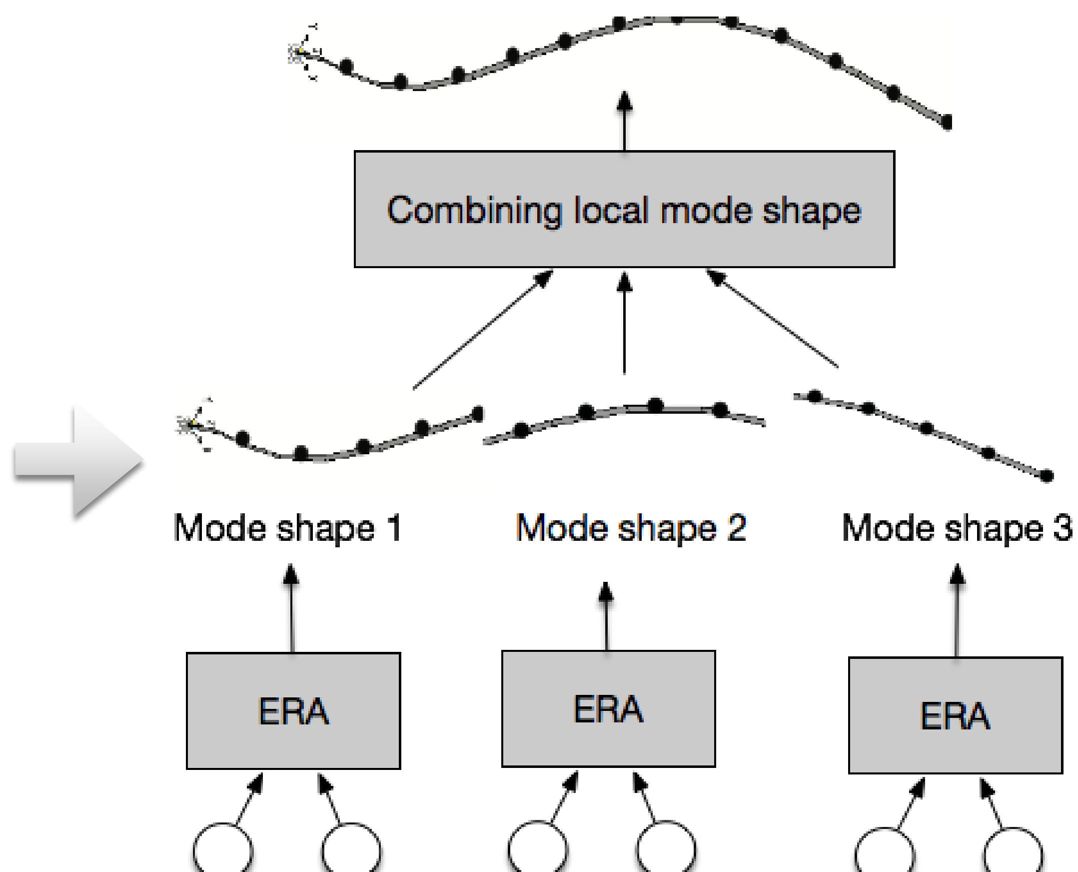
- Mode shapes: vibration pattern of a structure – used for damage detection, structural modeling, etc.

Designing Distributed ERA

- Adopt the 'divide and conquer' approach to identify mode shape in a distributed manner

Centralized ERA

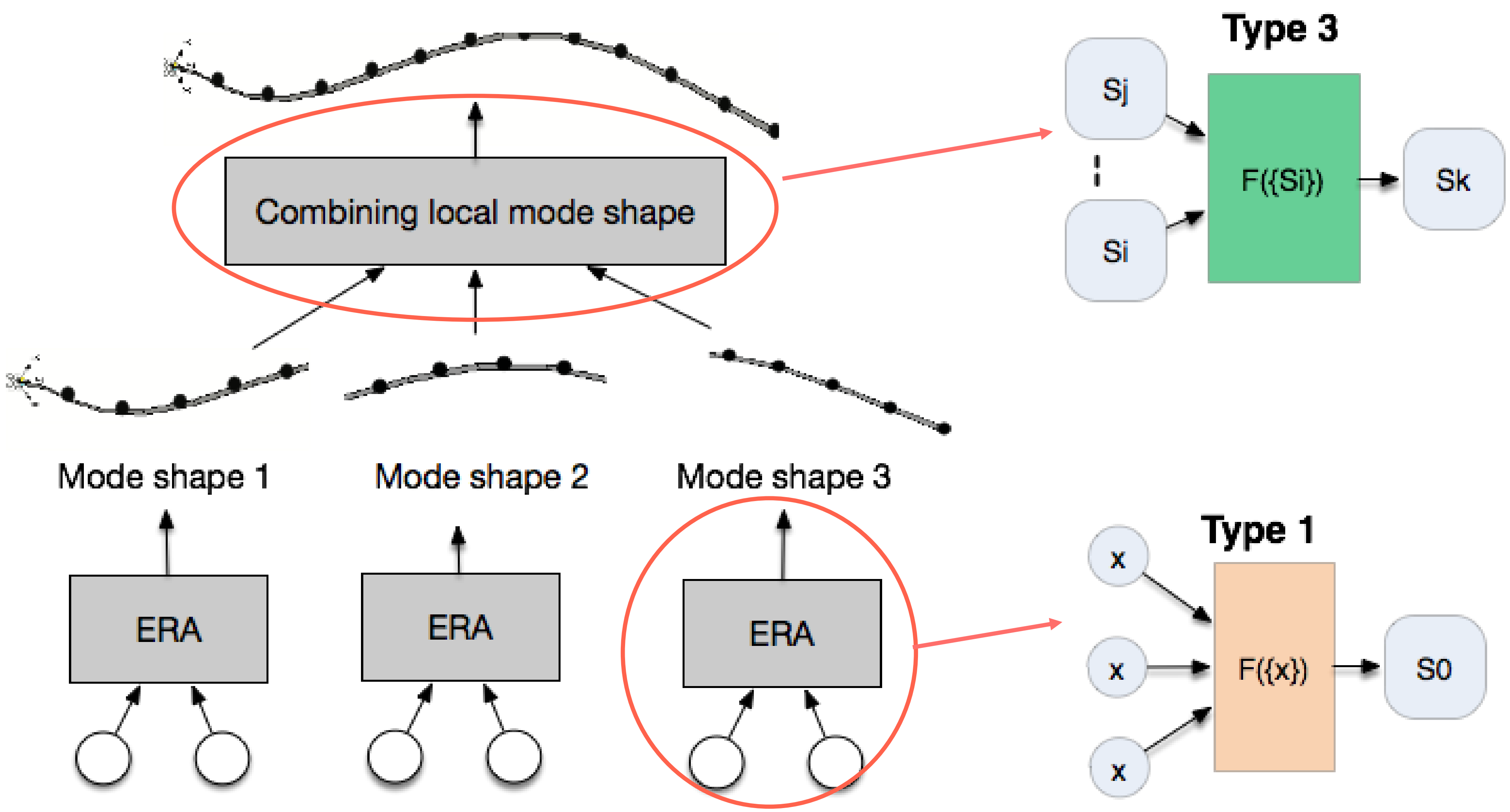




- Partitioning the network into clusters.
- CH in each cluster identifies local mode shapes
- Local mode shapes are assembled afterwards based on the least square estimation (LSE)

Aggregation Function for the Distributed ERA

- Divide and conquer approach: we can identify two basic aggregation functions of Type 1 and Type 3

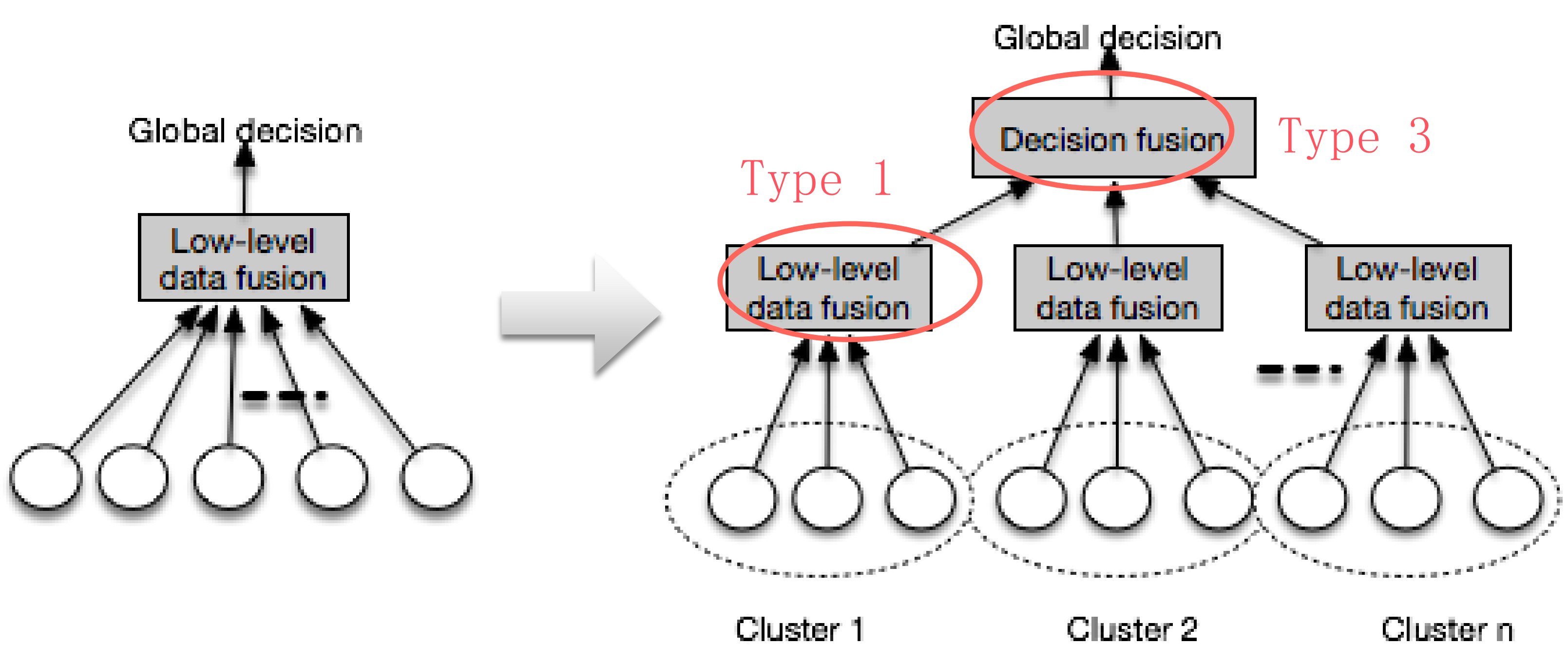


How multiple intermediate results are combined? Via LSE

How multiple raw data are combined? Via ERA

Generalizing the Approach

- Key idea: Transform low-level data fusion to high-level fusion, the feature-level fusion



- Divide sensor nodes into clusters
- Low-level data fusion within each cluster
- Fusing results from all clusters

- This approach generates two aggregation functions of type 1 and type 3

Generalizing the Approach

Examples:

- Subspace identification (SI) and
- Frequency domain decomposition(FDD)
  - Classic algorithms for identifying modal parameters (including mode shapes and natural frequencies in SHM) based on SVD.

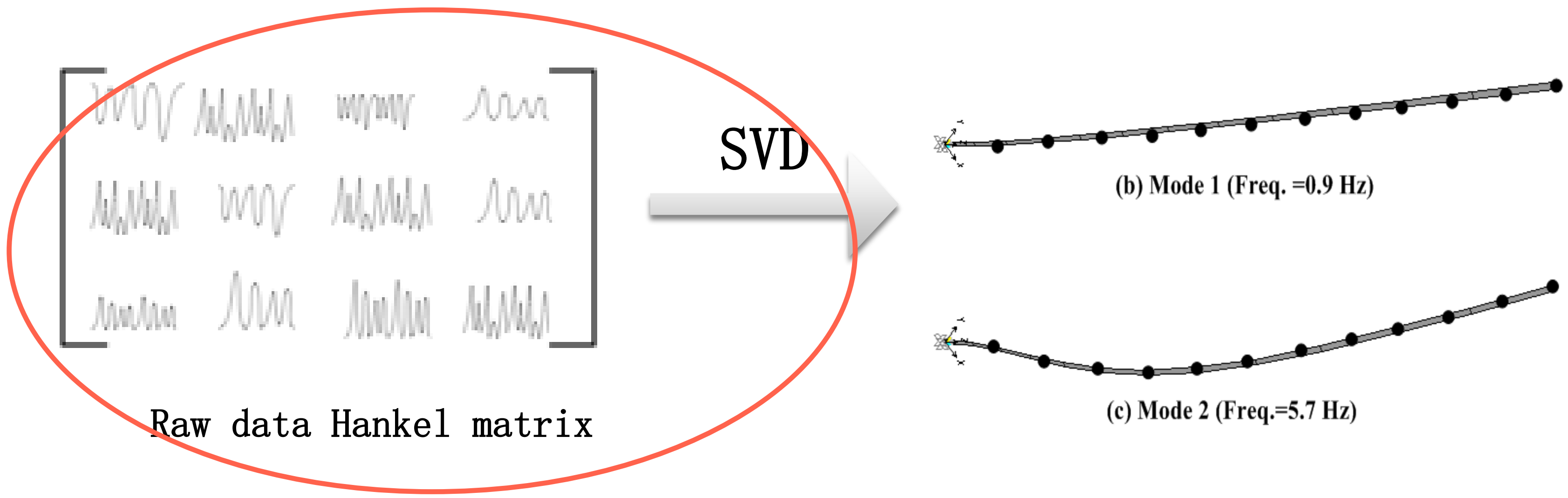
Approach 2: Incremental Algorithms

- Given a sequence of input, find a sequence of solutions that build incrementally while adapting to the changes in the input

Transform Centralized Algorithms to Incremental Algorithms

- Example: the ERA algorithm for SHM, used to obtain mode shape of a structure

ERA:



- Can we implement distributed ERA by designing an incremental version of the SVD?

Incremental SVD

- Calculate the U, S, V of the initial input data matrix A

$$[\mathbf{A}] = USV^T$$

- Then update U, S, V using the new data T

$$\begin{bmatrix}\mathbf{A}\\ \mathbf{T}\end{bmatrix}$$

- Result is the same as calculating the USV using data matrix

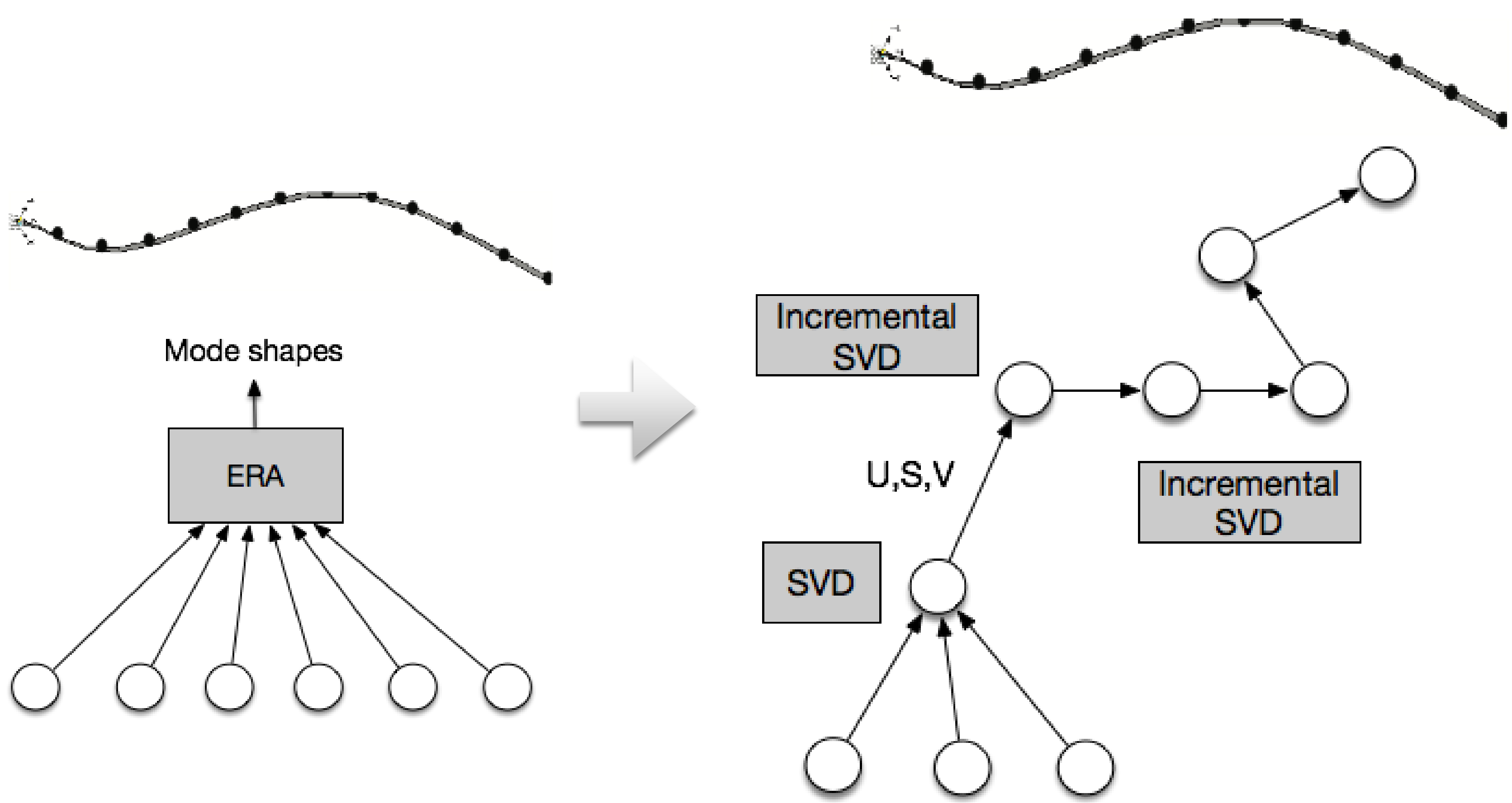
$$\begin{bmatrix}\mathbf{A}\\ \mathbf{T}\end{bmatrix} = U^{'}S^{'}V'$$

Zha and H. Simon, “On updating problems in latent semantic indexing,” SIAM Journal on Scientific Computing, vol. 21, p. 782, 1999

Designing Distributed ERA

- Adopt incremental SVD to identify mode shape in a distributed manner

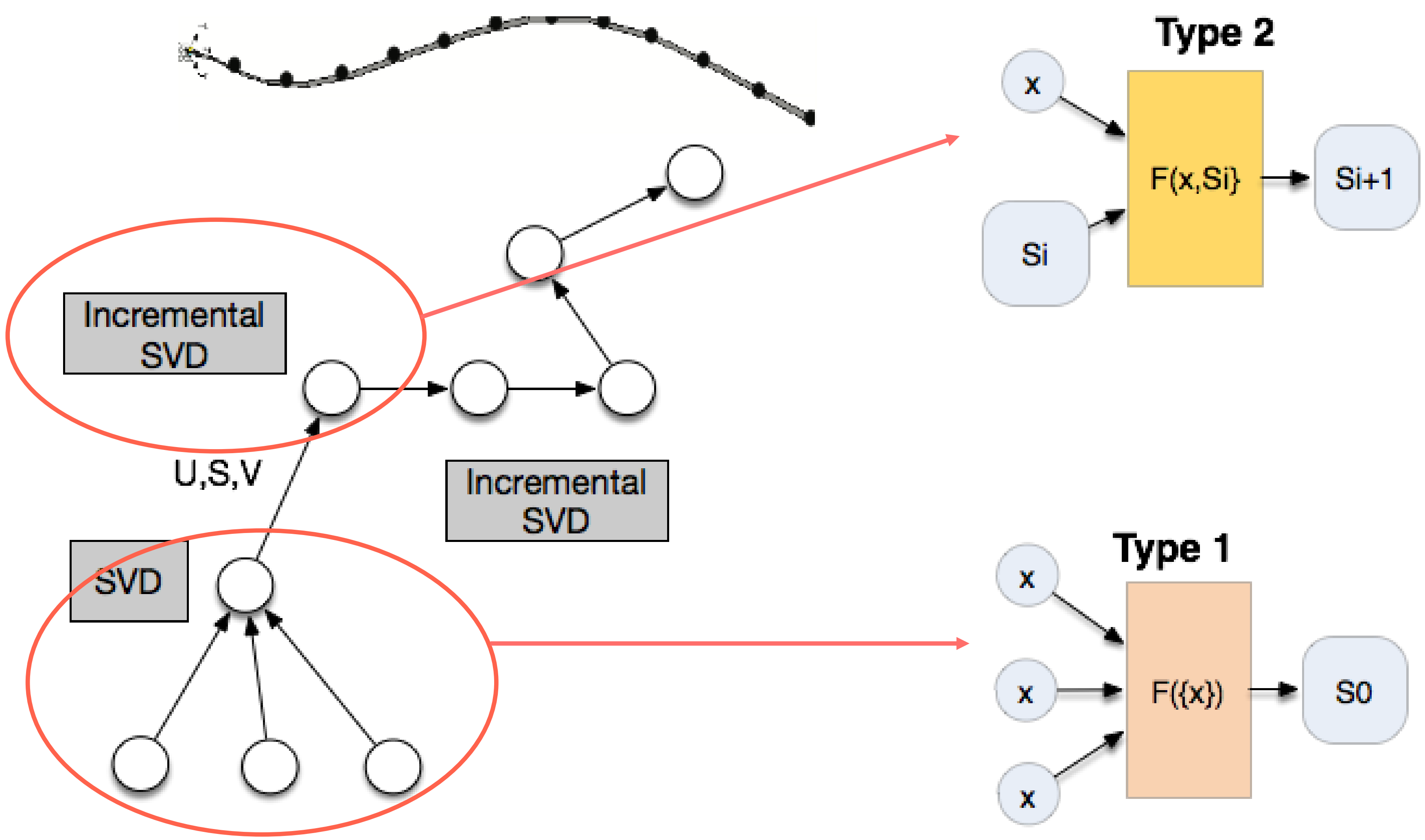
Centralized ERA Distributed ERA



- Implement the SVD based on initial sets of data from a few sensor nodes
- The results of SVD (U,S,V) travel in the network, and will be incrementally updated when meet any node on the route.

Aggregation Function for the Distributed ERA

- Incremental updating approach: we can identify two basic aggregation functions of Type 1 and Type 2

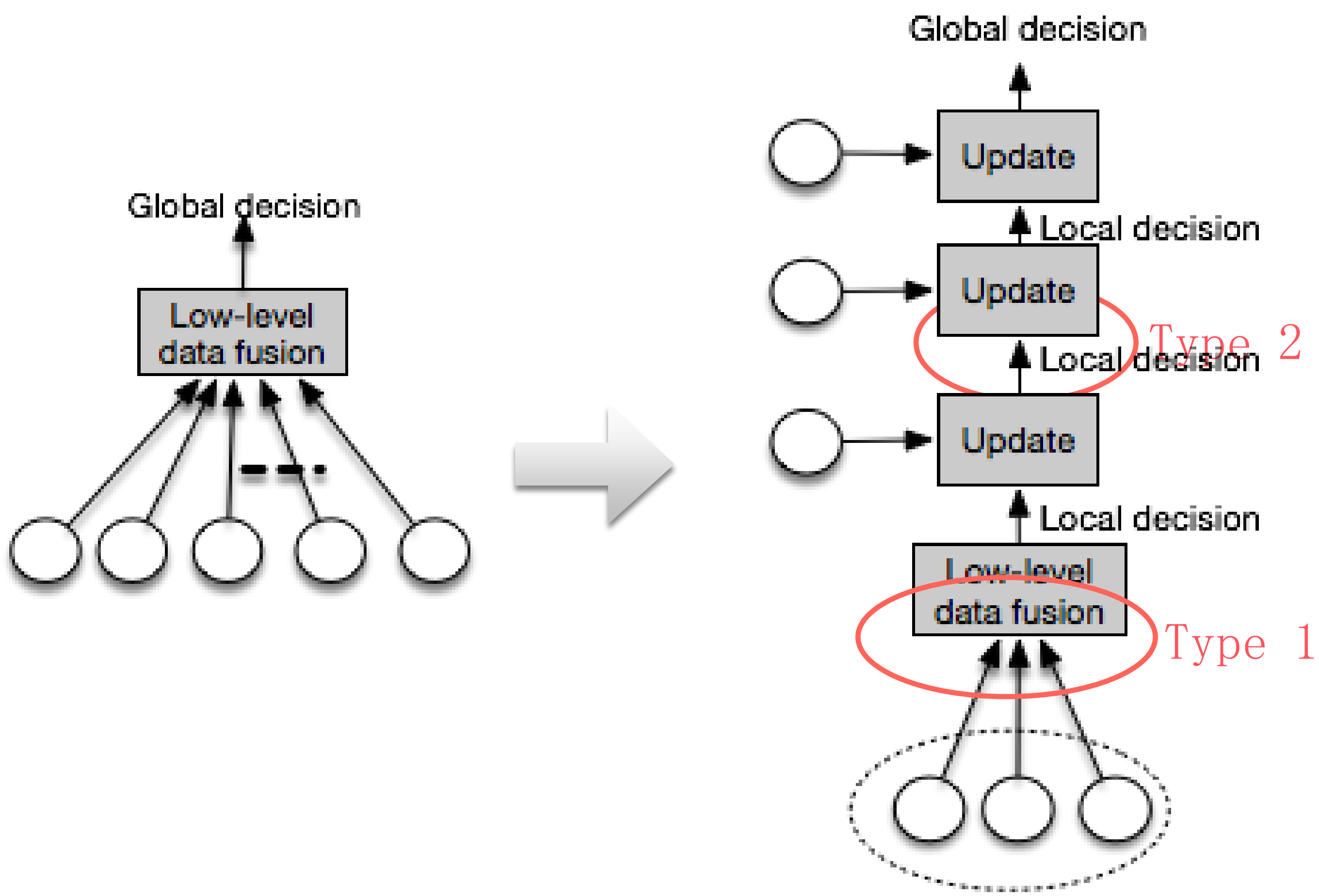


How a single raw data can be combined with an intermediate result

How multiple raw data are combined? Via SVD

Generalizing the Approach

- Key idea: result is updated incrementally along a path in the network



- Part of the raw data are utilized to obtain a preliminary result
- The result is updated when passing every node in the network

- This approach generates two aggregation functions of type 1 and type 2

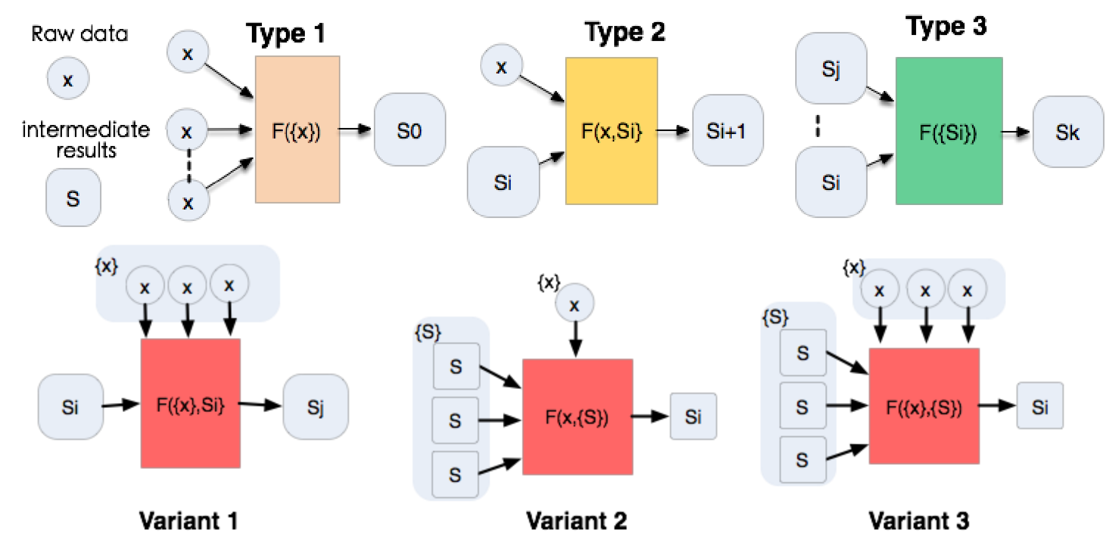
Generalizing the Approach

Examples:

- Subspace identification (SI) and
- Frequency domain decomposition(FDD)
  - Classic algorithms for identifying modal parameters (including mode shapes and natural frequencies in SHM) based on SVD.
- Least square estimation
  - Smart grid and volcanic tomography)

Designing Aggregation Functions Summary

- Three basic aggregation functions and the variants



- Design aggregation functions using (1) divide and conquer and (2) incremental algorithms.

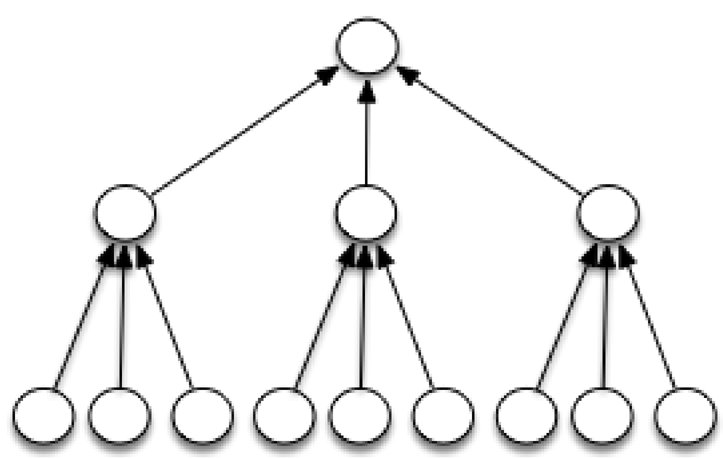
- Comparison of the two approaches
  - Divide and conquer: relatively easy but cannot guarantee accuracy
  - Incremental algorithm: guarantee accuracy but may not be handy available

Algorithm Design Steps

- **Step 1**: design appropriate aggregation functions for these algorithms
- **Step 2: select appropriate type of routing structure**
- **Step 3:** design optimal routing protocols under various constraints

Types of Routing Protocols

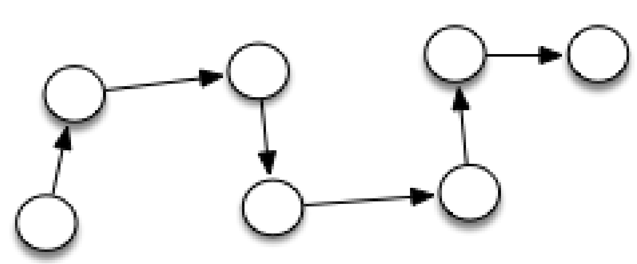
Cluster-based



Features:

- Nodes are divided into clusters, and CHs obtain local results
- Local results from different clusters are combined only once
- Example: distributed ERA using divide and conquer

Chain-based

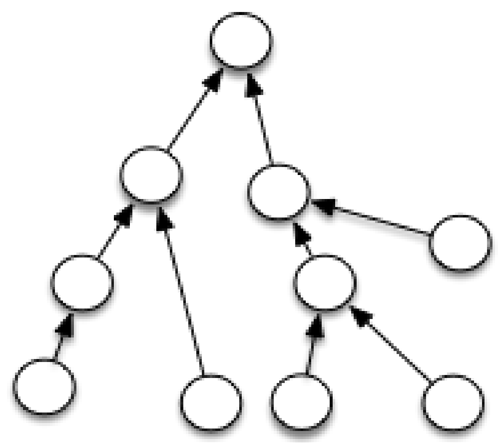


Features:

- Information is updated incrementally along a Hamiltonian path in the network
- Example: distributed ERA using incremental SVD

Types of Routing Protocols

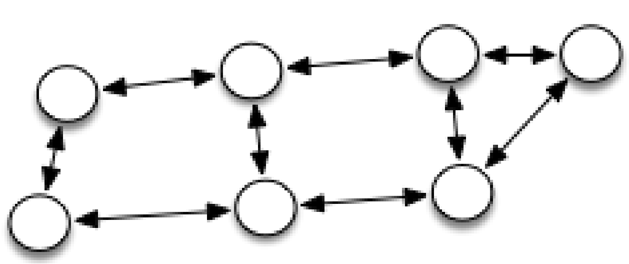
Tree-based



Features:

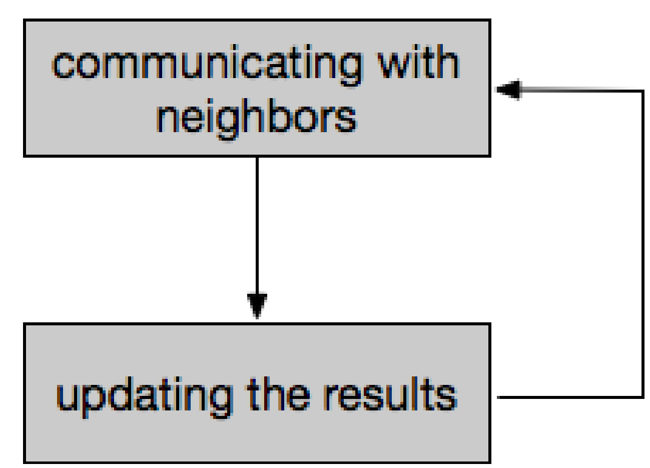
- Leaf nodes send raw data to parents
- Non-leaf nodes collect raw data/intermediate results from their children, process them and send the results to their parents

Diffusion-based



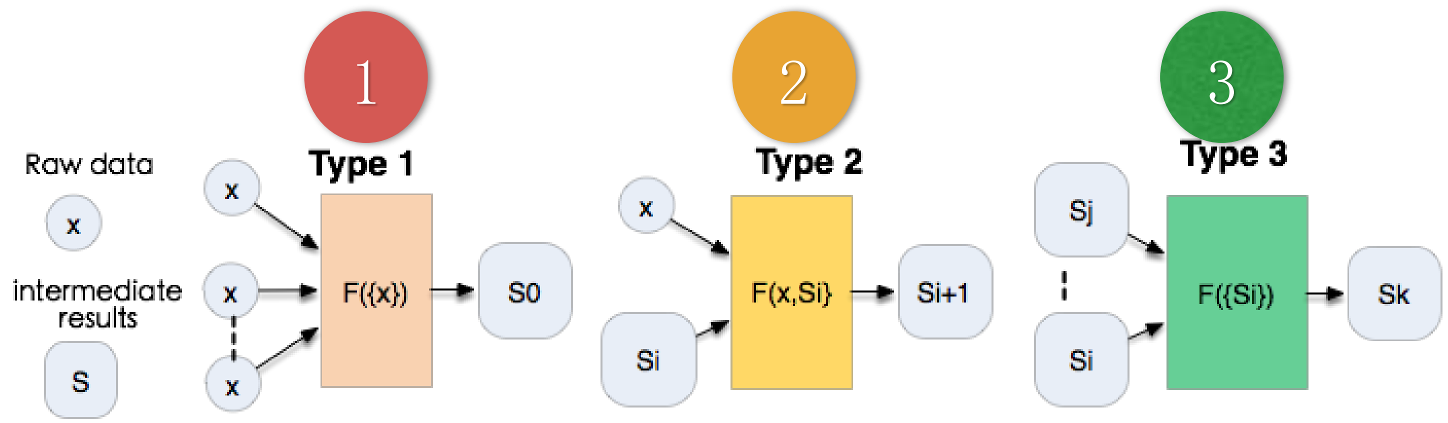
Features:

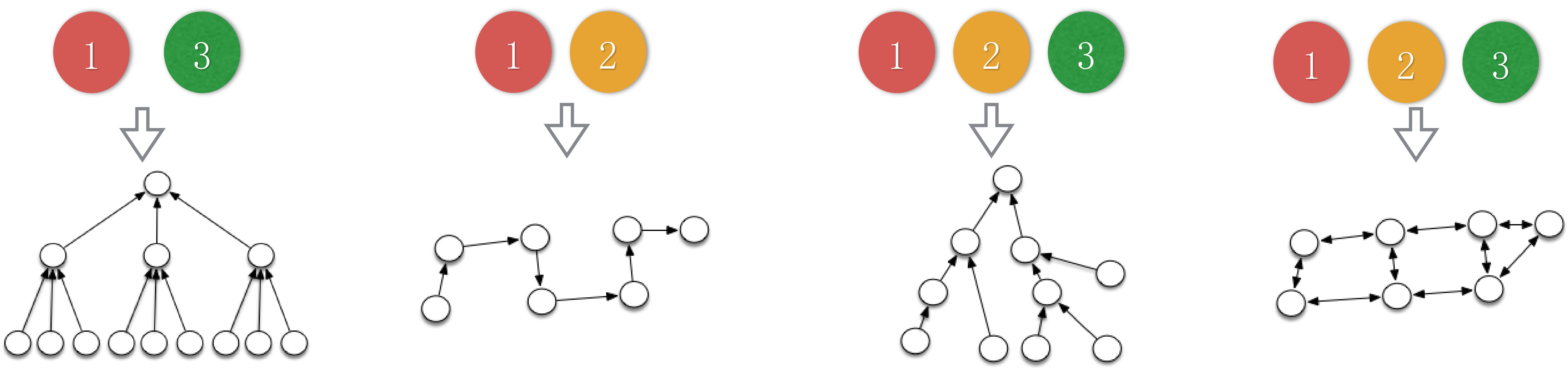
- each node keeps communicating with neighbors and updating the results.
- Example: LSE



Selecting Routing Structure

The routing structure can be chosen according to the available aggregation functions





Cluster-based Chain-based Tree-based Diffusion-based

Algorithm Design Steps

- **Step 1**: design appropriate aggregation functions for these algorithms
- **Step 2**: select appropriate type of routing structure
- **Step 3: design optimal routing protocols under various constraints**

Design Optimal Routing Protocols

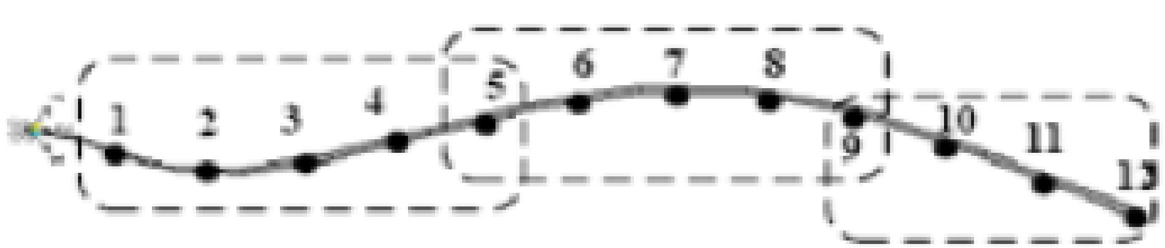
- Given aggregation functions and type of routing protocols, designing the optimal routing protocol is generally an optimization problem and, in most cases, is NP hard:
  - Optimal clustering
  - Hamiltonian path
  - Spanning trees

- Existing routing protocols did not consider constraints from real applications:
  - Constraint on accuracy of results
  - Constraint on node’ s capability
  - …

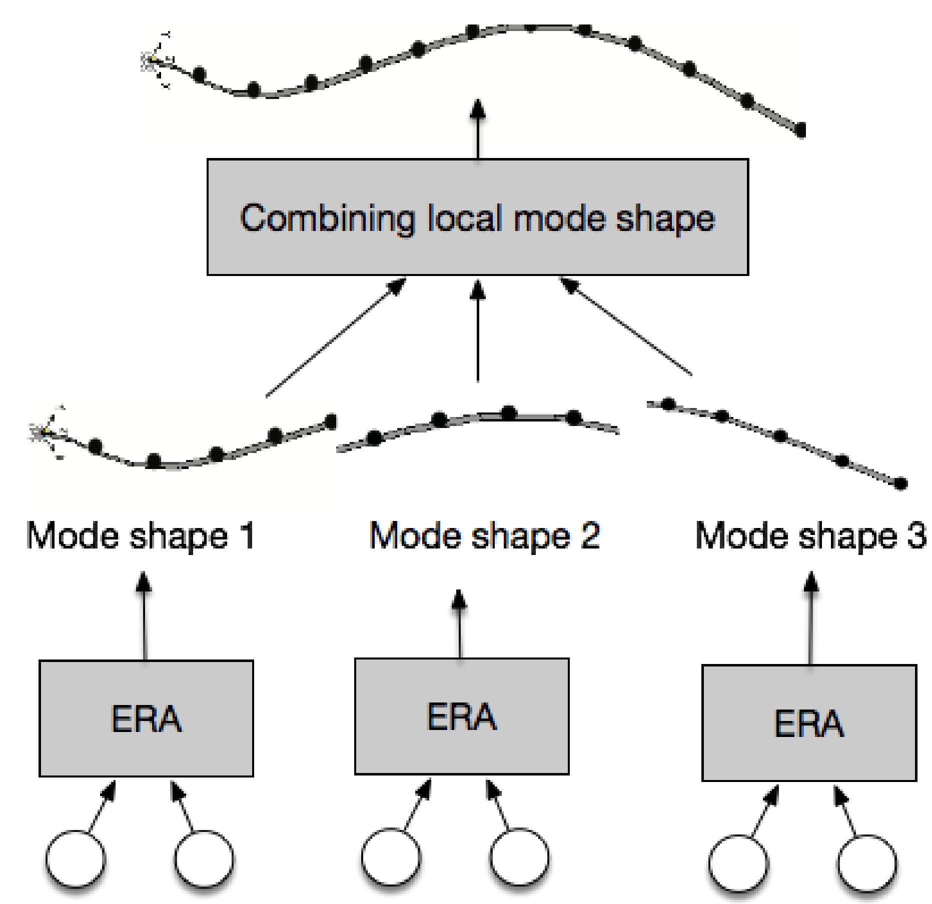
Constraints for Routing Protocols

- example of distributed ERA using clusters

- Nodes are divided into clusters and mode shapes from different clusters are assembled together.
- However, to combine local mode shapes, clusters must overlap.
- In addition, nodes in each cluster must be large enough to obtain accurate local result



Distributed ERA based on clusters



Constraints for Routing Protocols

– example of distributed ERA using clusters

- Given: the network model and energy consumption model
- Objective: divide the deployed sensor nodes into a number of clusters such that the overall energy consumption is minimized
- Subject to (constraints):
  - Clusters overlap and connected
  - Cluster size >p for damage detection quality

Our Work on WSN-based SHM

Energy Efficient Clustering for WSN-based SHM

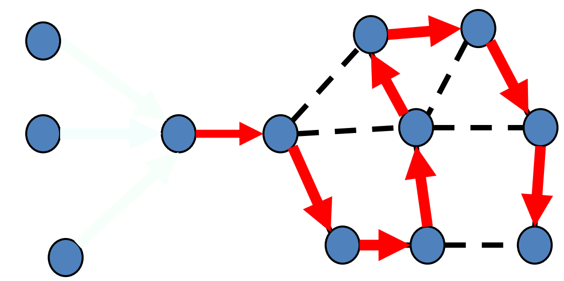
- Cluster-based ERA
- Using “divide and conquer” to generate aggregation functions.
- Clustering routing structure
- Optimal clustering by considering network model, system model, clustering constraints

Xuefeng Liu, Jiannong Cao, Steven Lai, Chao Yang, Hejun Wu, Youlin Xu, “Energy Efficient Clustering for WSN-based Structural Health Monitoring”, 30th IEEE International Conference on Computer Communications (INFOCOM 2011), April 10 - 15, 2011, Shanghai, China.

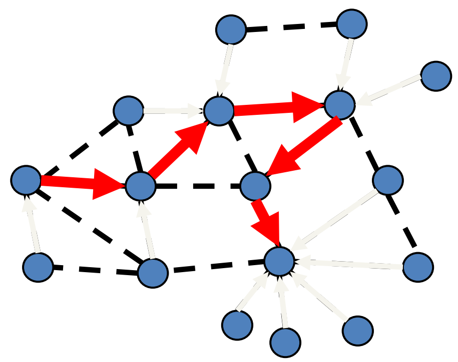
High Quality SHM using WSN

- High quality distributed ERA
  - Using “incremental SVD’ as the first step to generate aggregation functions.
  - Different routing architectures including chain-based and tree-based.
  - Optimal routing by considering network model, system model, computation capability and cost.

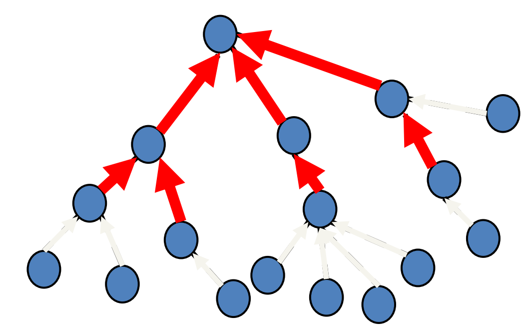
a Hamiltonian path



a connected dominating set



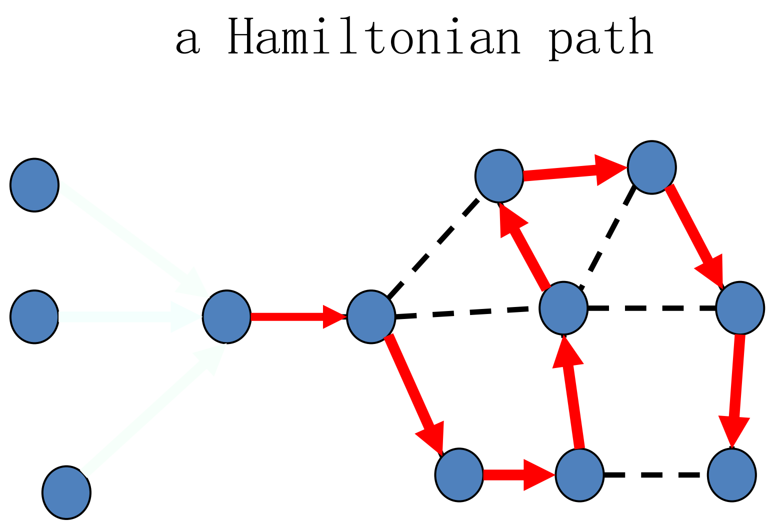
a shortest path tree

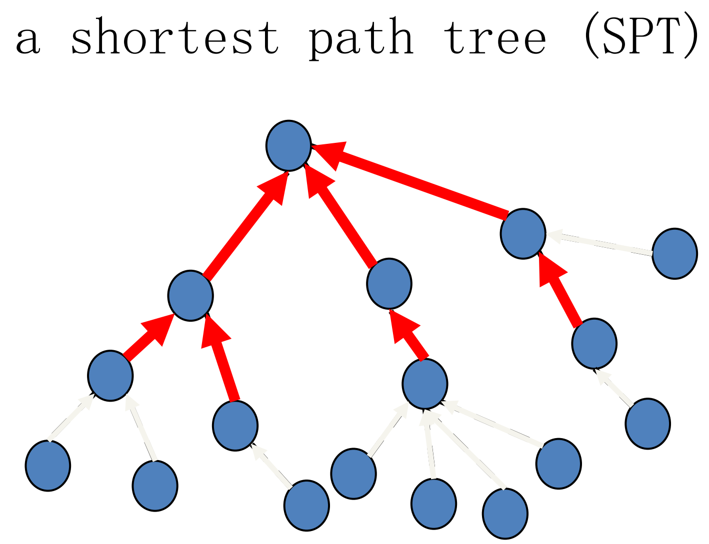


Xuefeng Liu, Jiannong Cao, Wenzhan Song, Shaojie Tang, “Distributed Sensing for High Quality Structural Health Monitoring using Wireless Sensor Networks”, 33rd IEEE Real-Time Systems Symposium (IEEE RTSS-2012), Dec 5-7, 2012. San Juan, Puerto Rico.

Xuefeng Liu, Jiannong Cao, Wen-Zhan Song, Peng Guo, Zongjian He, “Distributed Sensing for High-Quality Structural Health Monitoring using WSNs”, IEEE Transactions on Parallel and Distributed Systems (TPDS), 26(3): 738-747 2015.

Energy-efficient Least Squares Estimation in WSNs





- Updating along a Hamiltonian path will have less energy consumption, but largest delay
- Updating along a SPT will have higher energy consumption, but with minimum delay
- A tradeoff between Hamiltonian path and SPT

Wanyu Lin, Jiannong Cao, Xuefeng Liu, "E3: Towards energy-efficient distributed least squares estimation in sensor networks", IEEE 22nd International Symposium of Quality of Service (IWQoS 2014), 2014. Hong Kong, China. pp. 21-30

Related Publications

Xuefeng Liu, Jiannong Cao, Wenzhan Song, Shaojie Tang, “Distributed Sensing for High Quality Structural Health Monitoring using Wireless Sensor Networks”, 33rd IEEE Real-Time Systems Symposium (IEEE RTSS-2012), Dec 5-7, 2012. San Juan, Puerto Rico.

Xuefeng Liu, Jiannong Cao, Steven Lai, Chao Yang, Hejun Wu, Youlin Xu, “Energy Efficient Clustering for WSN-based Structural Health Monitoring”, 30th IEEE International Conference on Computer Communications (INFOCOM 2011), April 10 - 15, 2011, Shanghai, China.

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Xuefeng Liu, Jiannong Cao, Shaojie Tang, Peng Guo, “A Generalized Coverage-Preserving Scheduling in WSNs: a Case Study in Structural Health Monitoring”, The 33nd IEEE International Conference on Computer Communications (INFOCOM 2014), April 27-May 2, 2014 - Toronto, Canada.

Xuefeng Liu, Jiannong Cao, Shaojie Tang, “Fault Tolerant Complex Event Detection in WSNs: A Case Study in Structural Health Monitoring”, 32nd IEEE International Conference on Computer Communications (INFOCOM 2013), April 14-19, 2013 - Turin, Italy.

Md Zakirul Alam Bhuiyan, Jiannong Cao, Guojun Wang, Xuefeng Liu, “Energy-Efficient and Fault-Tolerant Structural Health Monitoring in Wireless Sensor Networks”, 31st IEEE International Symposium on Reliable Distributed Systems (SRDS’12), Oct. 8 - 11, 2012. Irvine, California, US

Wanyu Lin, Jiannong Cao, Xuefeng Liu, “E3: Towards energy-efficient distributed least squares estimation in sensor networks”, IEEE 22nd International Symposium of Quality of Service (IWQoS 2014), May 26-27, 2014. Hong Kong, China. pp. 21-30

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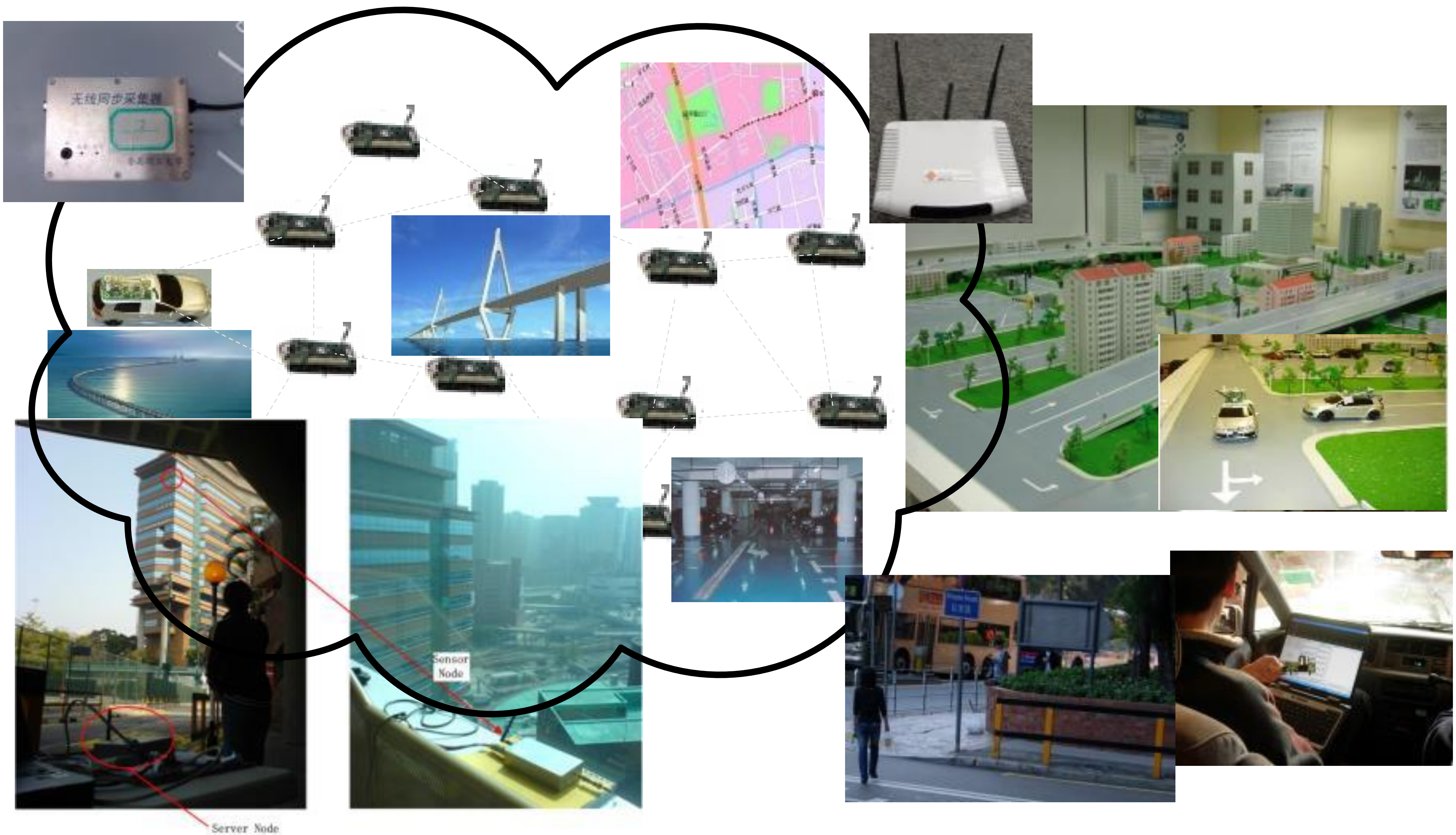
Intelligent Services with Wireless Sensor Networks



Summary

- Engineering applications of WSN are data-intensive and require data-level collaboration among the sensor nodes
- Designing distributed algorithms is challenging
- In-network processing via data aggregation is a widely used approach
- We developed a systematic and structured method to designing distributed WSN engineering algorithms

thank you!