Hierarchical State Estimation Using Phasor Measurement Units

Ali Abur
Northeastern University

Benny Zhao (CA-ISO) and Yeo-Jun Yoon (KPX)

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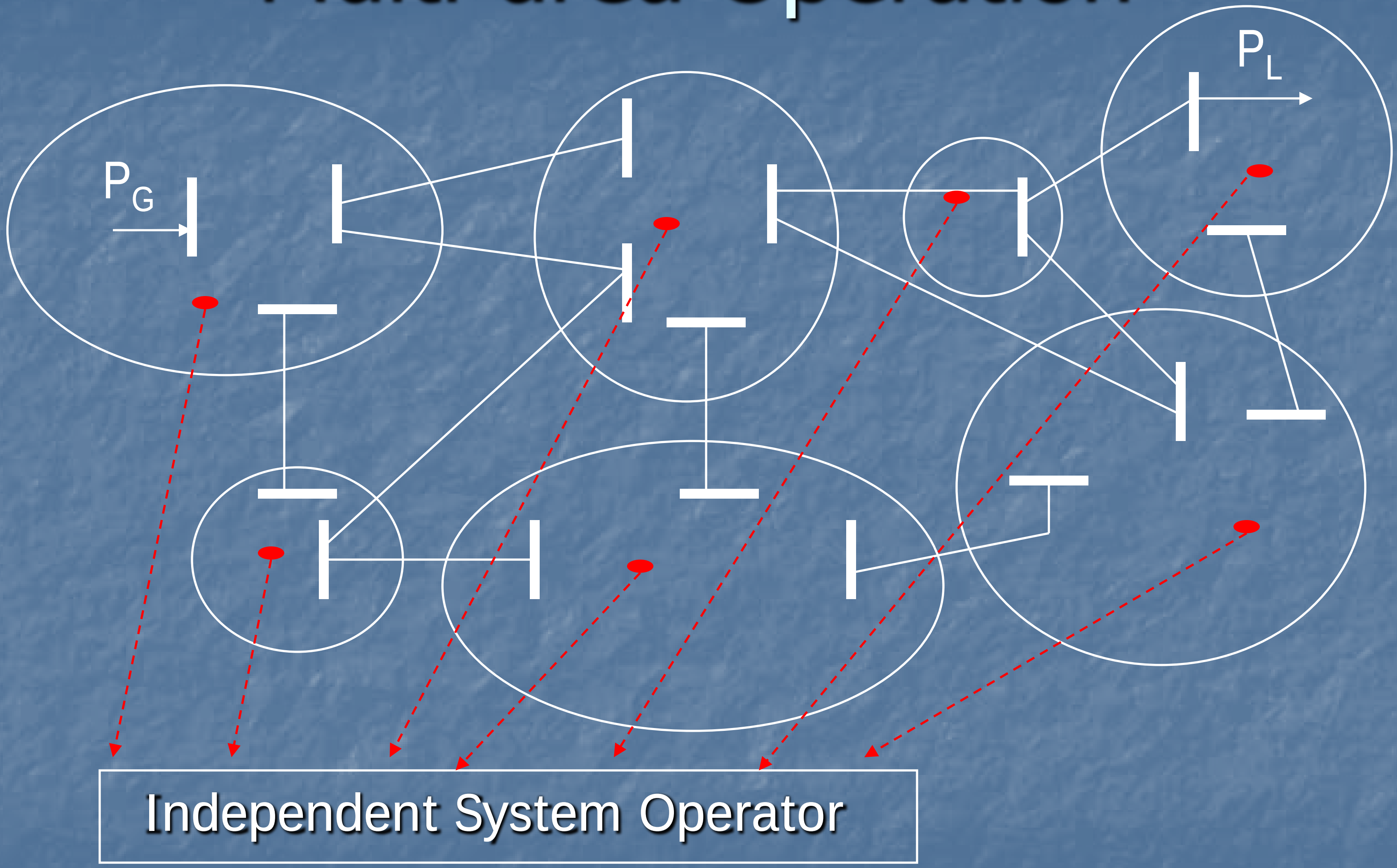
Multi-area Operation



Challenge: How to monitor the system state?

- Centralized / Flat Solution:
  - Data intensive.
  - Dimension grows with system size (areas).
  - Data base/format must be standardized.
  - Large amounts of data and measurements must be exchanged between areas and ISO.
  - Vulnerable to disturbances to the central or any one of the area SCADA systems.

Challenge: How to monitor the system state?

- Hierarchical Solution:
  - Each area uses its own data.
  - Problem size does not grow significantly with number of areas.
  - Each area has its own SE and Data-base.
  - Limited number of data and measurements must be exchanged between areas and ISO.
  - Partial system monitoring is possible during individual area failures.

Problem Statement and Constraints

- Areas are reluctant to share network data and measurements due to competition.
- Overall system state must be estimated based on limited measurements from each area.
- Gross errors (bad data) in measurements must be detected, identified and corrected even if they appear at the area boundaries.
- If the entire system is not observable, all states associated with the observable islands will have to be estimated.

State Estimation Problem

$$\text{Minimize } J(x) = r^T R^{-1} r$$

$$\text{Subject to } z = h(x) + r$$

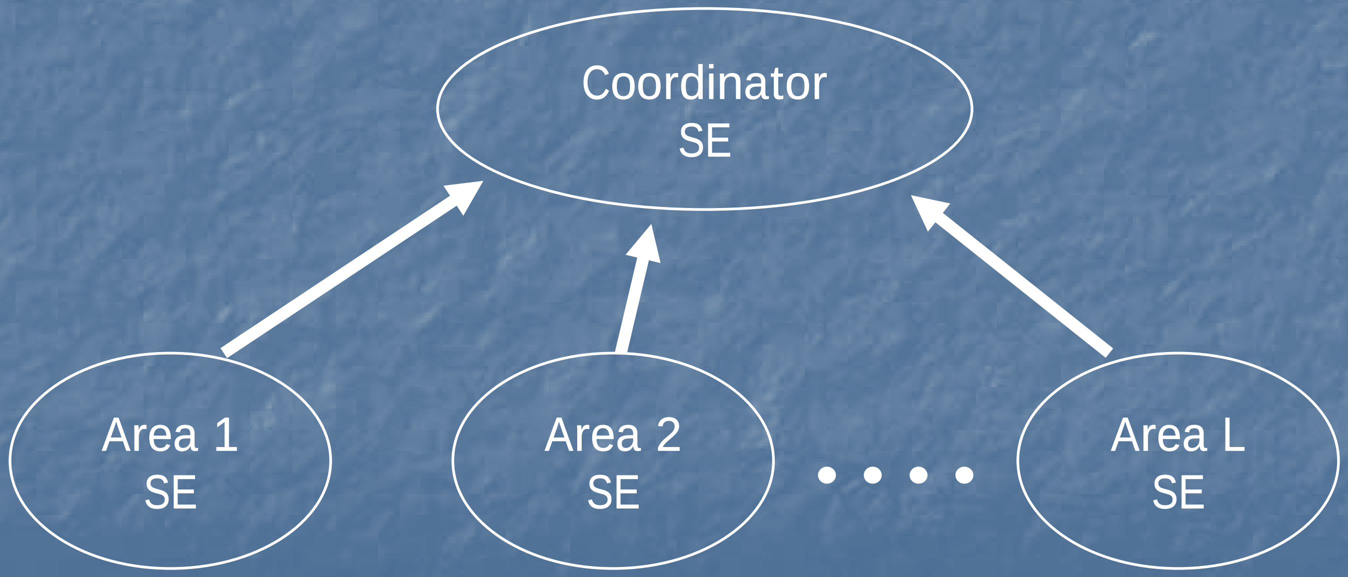
R is the covariance of measurement errors.

h(x) is the estimated value of z.

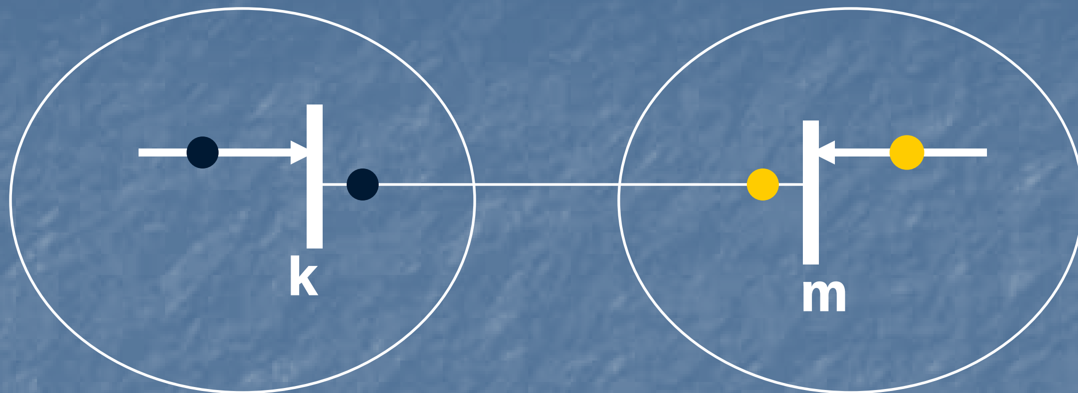
x is the estimated state vector.

Hierarchical State Estimation

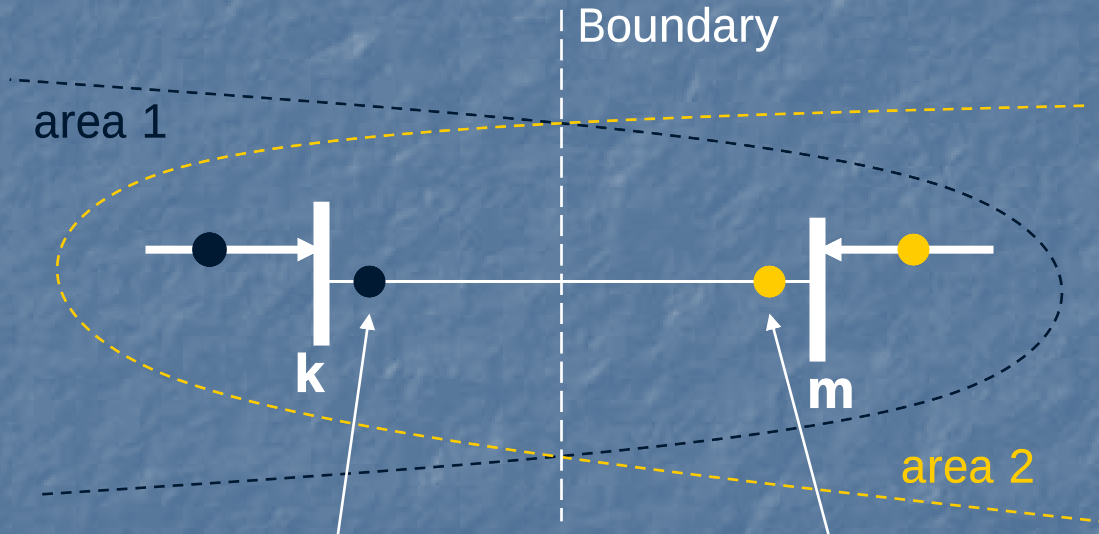
- Each area SE estimates its own state.
- Coordinator SE
  - merges the solutions, and
  - processes bad data for boundary measurements.



Measurement Decomposition



P_k: unusable
P_m: unusable
P_{km}: unusable
P_{mk}: unusable

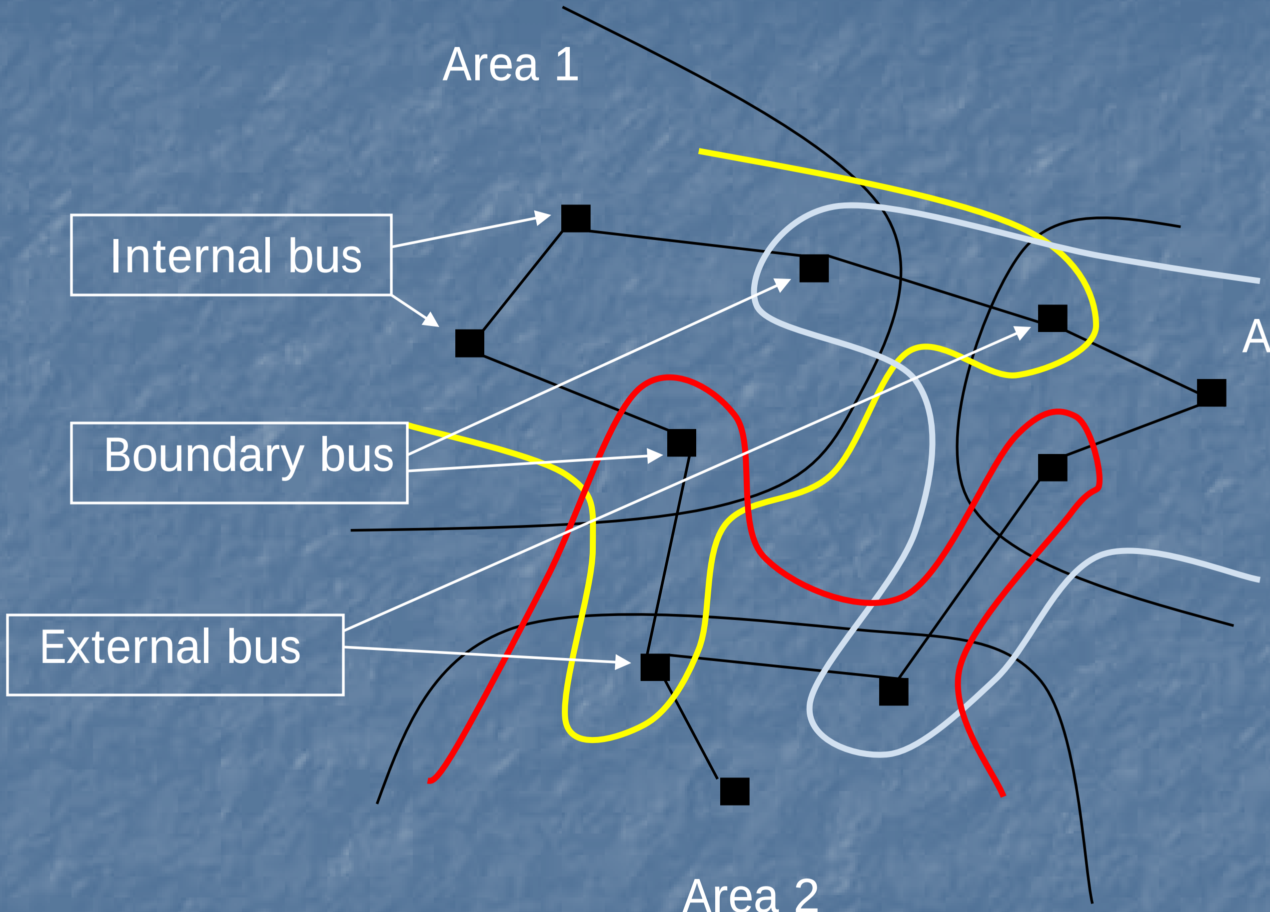


May not be available to area 2.

May not be available to area 1.

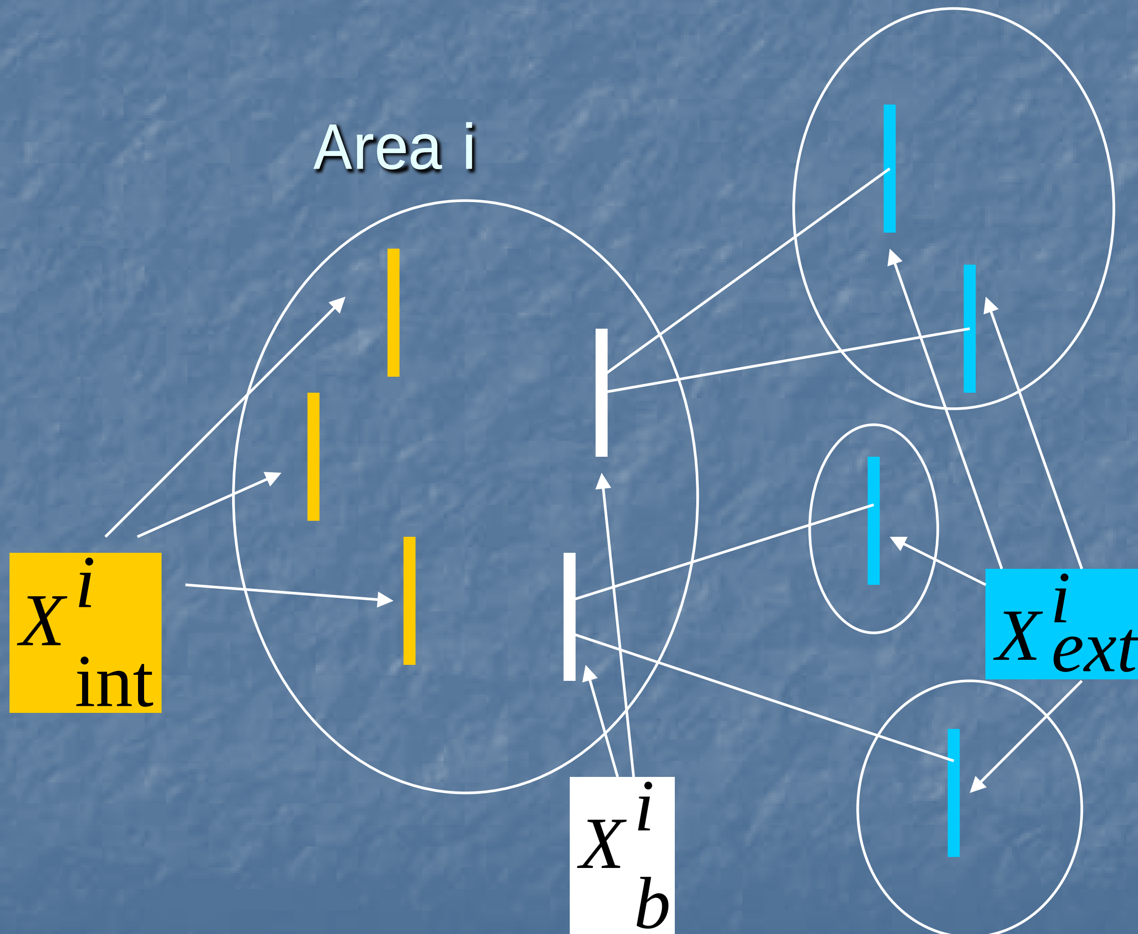
P_k: unusable by 2
P_m: unusable by 1

Proposed Decomposition



Proposed Decomposition

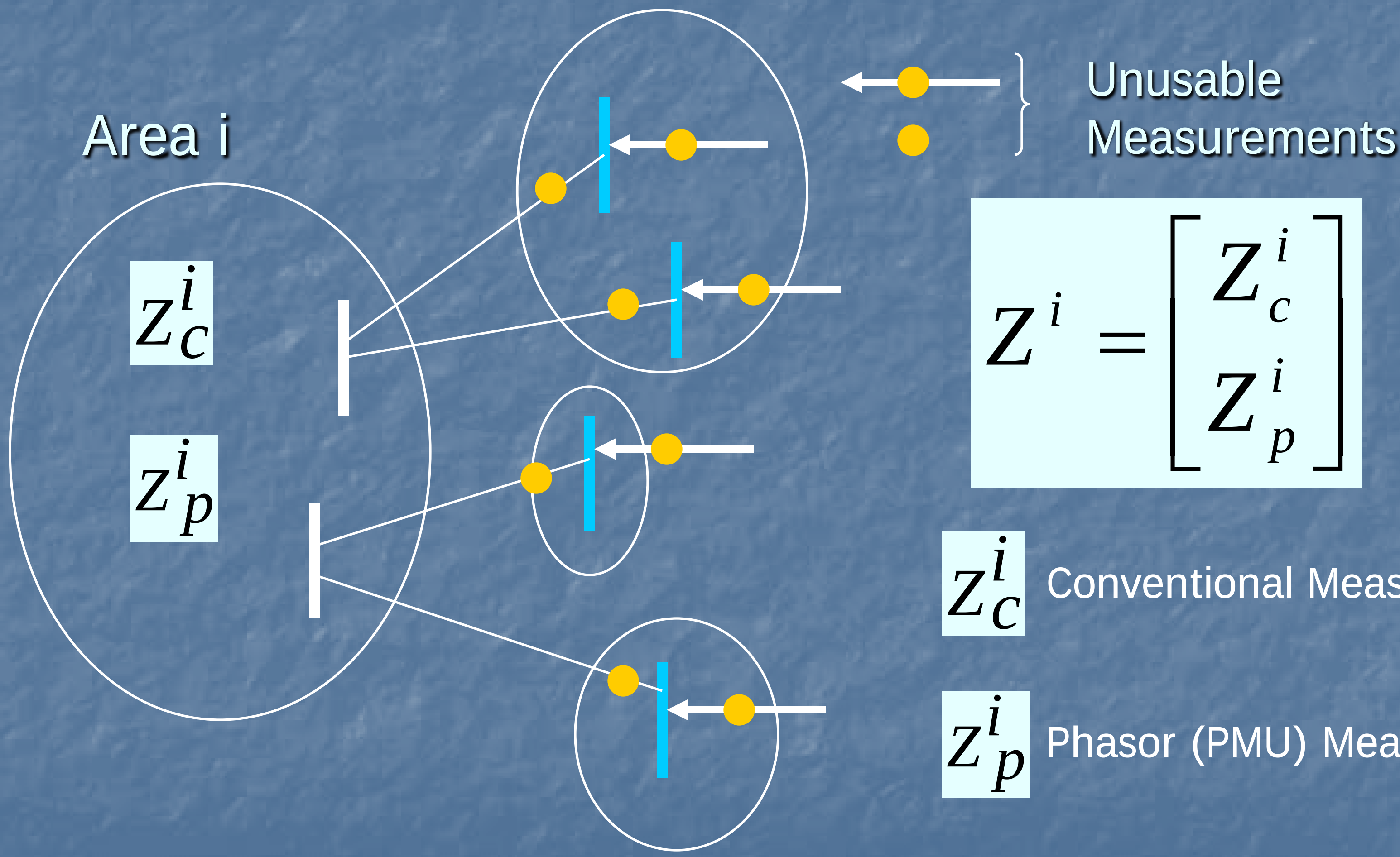
Define the state vector for each area i:



$$X^i = \begin{bmatrix} X^i_{\text{int}} \\ X^i_b \\ X^i_{ext} \end{bmatrix}$$

Proposed Decomposition

Measurement vector for each area i:



$$Z^i = \begin{bmatrix} Z_c^i \\ Z_p^i \end{bmatrix}$$

z_c^i Conventional Measurements

z_p^i Phasor (PMU) Measurements

Properties of z^i

- Should render an observable area.
- External boundary buses may or may not be observable.
- Redundancy must be sufficient to make the internal bad data detectable and identifiable. Else, employ optimal meter placement [1] methods to address this problem.

[1] Magnago, F.H. and Abur, A., "Unified Approach to Robust Meter Placement against Bad Data and Branch Outages,"
IEEE Trans. on Power Systems, Vol.15, No.3, August 2000, pp.945-949.

Area i State Estimation

Minimize $\sum_{j=1}^{m} \frac{1}{\sigma_j^2} (r_j^i)^2$

Subject to $z_j^i = h_j(\hat{x}^i) + r_j^i \quad 1 \le j \le m_i$

where:

$e_j^i \propto N(0, \sigma_j^2)$

m_i: number of measurements in z^i

$\hat{z}_j^i = h_j(\hat{x}^i)$ estimated measurement

$\hat{x}^i = \begin{bmatrix} \hat{x}_{int}^i \\ \hat{x}_b^i \\ \hat{x}_{ext}^i \end{bmatrix}$ estimated state

Measurements Received and Used by the Coordinator's SE

- Each area state estimates are treated as pseudo-measurements with the following distribution:

$$N(\hat{x}^i, \Lambda^i)$$

where:

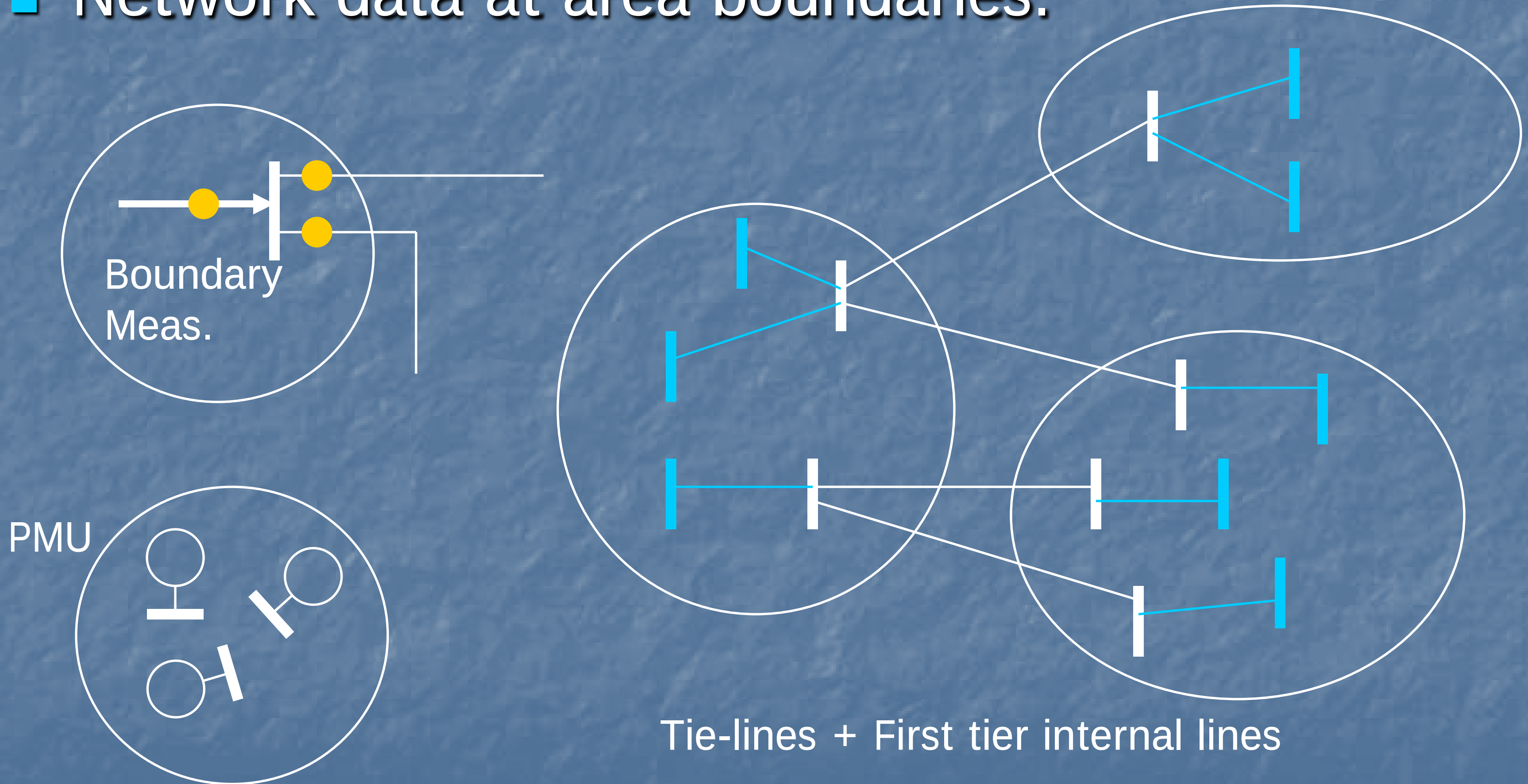
$$\Lambda^i = \left[G^i\right]^{-1}$$

$$G^i = \left[H^i\right]^T \left[R^i\right]^{-1} \left[H^i\right]$$

$$\left[H^i_{jk}\right] = \partial h_j / \partial x^i_k$$

$$R^i = \text{cov}(e^i)$$

- Boundary measurements from each area Z_b^i.
- Any available PMU measurements from area i, Z_p^i.
- Network data at area boundaries.



Coordinator's SE

$$\text{Minimize} \sum_{j=1}^{k} \frac{1}{R_{jj}} (r_j)^2$$

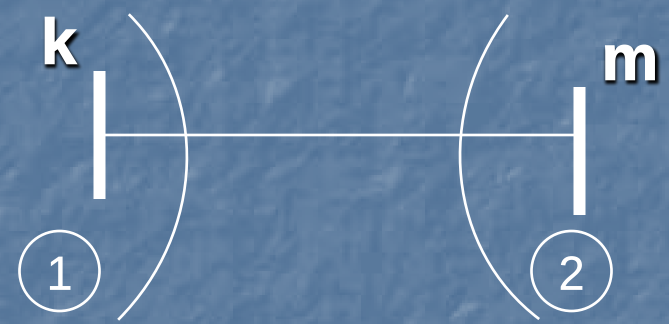
$$\text{Subject to } z_j = h_j(\hat{x}_b) + r_j \quad 1 \le j \le k$$

$$e_j \propto \begin{cases} N(0,\sigma_j^2) & \text{boundary measurements} \\ N(0,\sigma_{pj}^2) & PMU \text{ measurements} \\ N(0,\Lambda_{jj}) & \text{area state estimates} \end{cases}$$

$$R_{jj} = diag\{\mathrm{cov}(e_j)\}$$

$$X_b = \begin{bmatrix} x_b^1 \\ \vdots \\ x_b^L \end{bmatrix} \qquad Z_j = \begin{bmatrix} \hat{x}^1 \\ \hat{x}^2 \\ \vdots \\ \hat{x}^L \\ z_b^1 \\ \vdots \\ z_b^L \\ z_p^1 \\ \vdots \\ z_p^L \end{bmatrix}$$

Note:
Multiple pseudo-measurements for the boundary states.

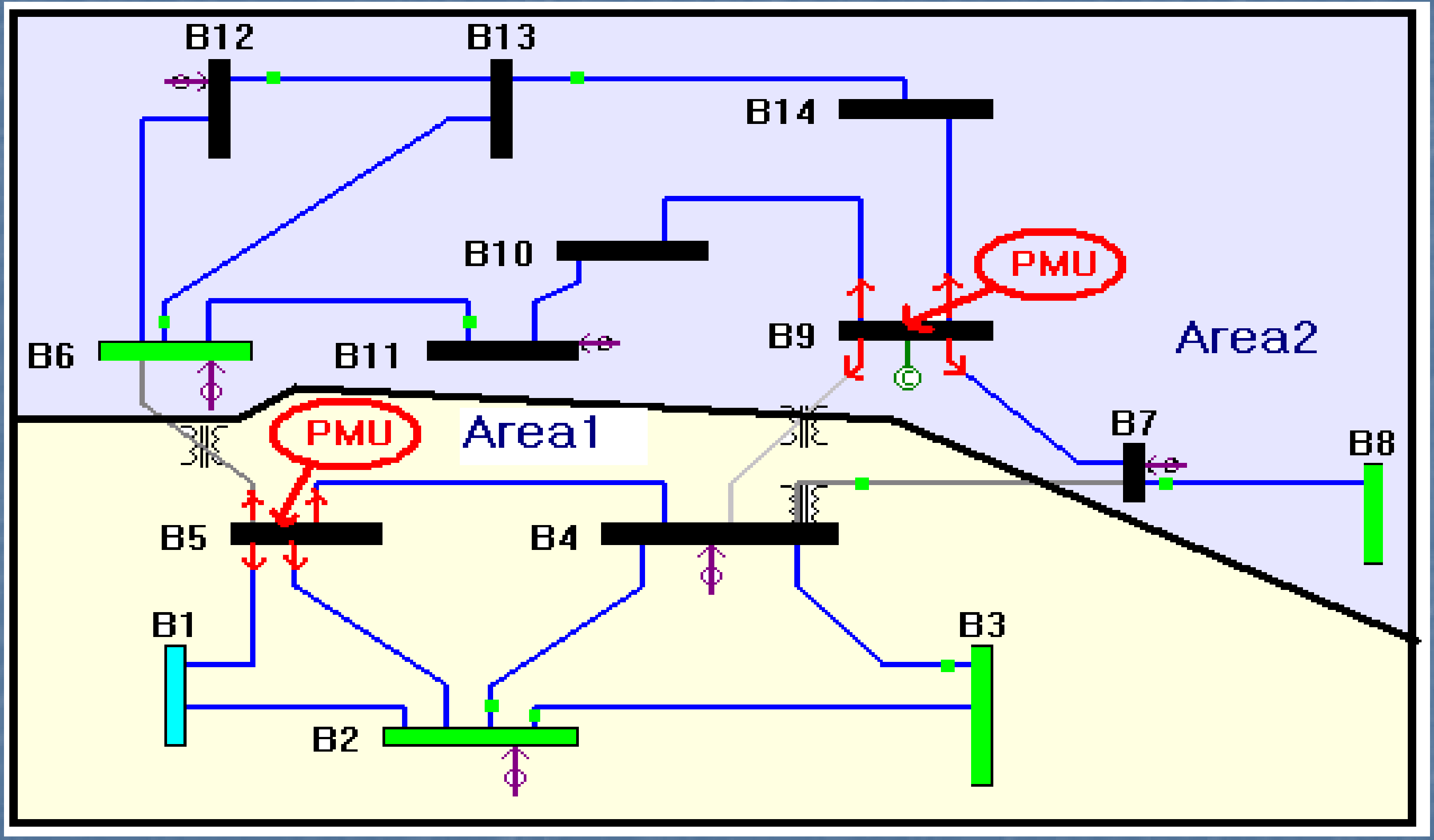


$$\hat{x}_k^1, \quad \hat{x}_k^2, \quad \hat{x}_m^1, \quad \hat{x}_m^2$$

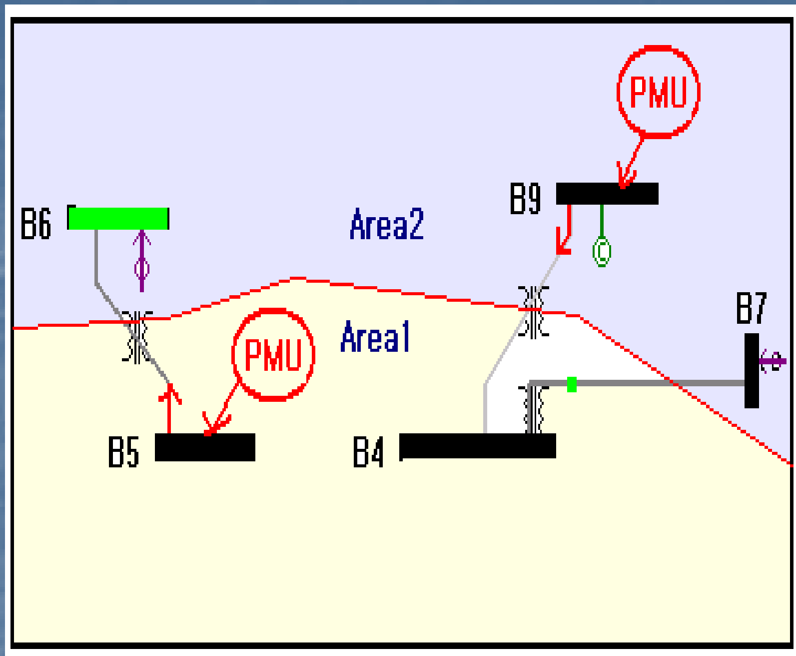
Properties

- No boundary measurements are discarded.
- All detectable / identifiable bad data are detected and identified.
- PMU measurements are effectively used, but not required for this scheme to work.
- Areas do not share network data (internal system details) or intermediate iteration results. They only provide boundary network model and measurements and their estimated states.

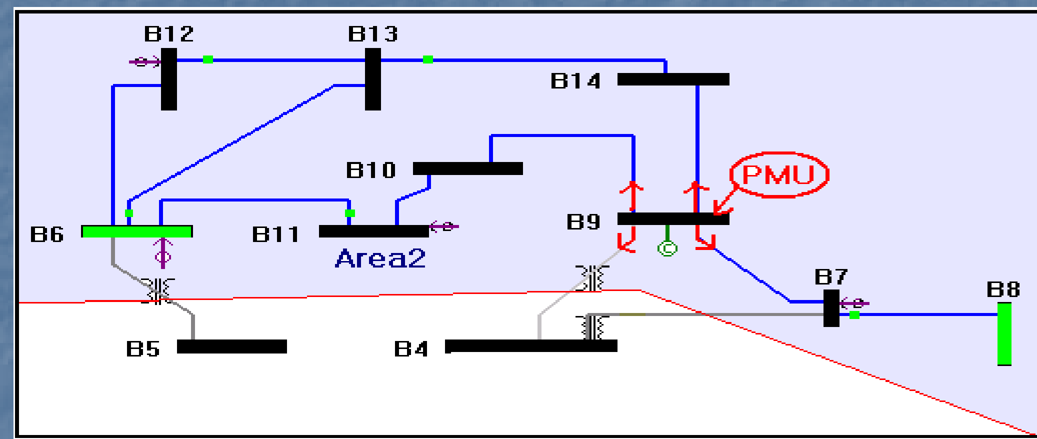
IEEE 14 Bus System : Two Area Example



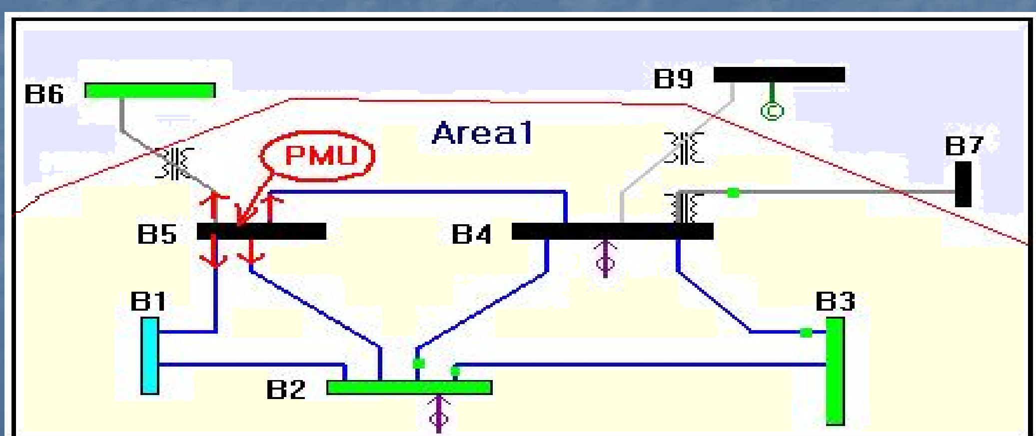
COORDINATOR



AREA 2



AREA 1



Estimation Results with Gaussian errors (No Bad Data)

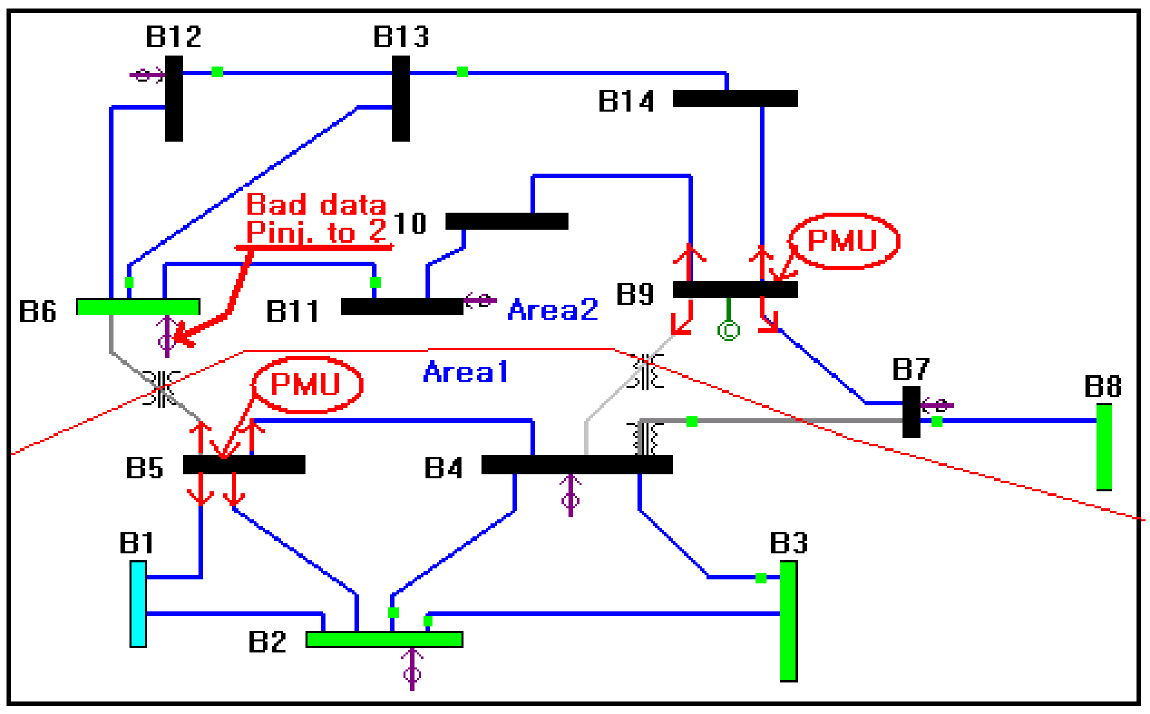
-Measurements-

	Inj.	Flow	Volt.Mag	Phase	I-real	I-imag	Boundary	External
Integrated	12	18	2	2	8	8		
Area 1	4	8	1	1	4	4		
Area2	8	10	1	1	4	4		
Coordinator	6	2	2	2	8	8	10	10
Error S.D.	0.01	0.008	0.004	0.0001	0.001	0.001	Computed	Computed

-Estimation Results-

	Degrees of Freedom	Chi-Square limit	Objective function J(x)	Largest Normalized Residual
Integrated	21	38.93	23.38	1.7791
Area1	6	16.81	2.52	1.3218
Area2	6	16.81	9.09	1.8095
Coordinator	24	42.98	33.25	2.1457

Bad Data Processing (P$_{inj}$ at Bus 6)



Note that P_6 becomes "critical" after decomposition.

➔ Bad data can not be detected by the SE of area 2.

Bad Data Identification Results

Area 2 SE

Chi-square limit (0.99%)	16.8
Objective function J(x)	4.0

Measurement Type	Largest Normalized Residual
I-real (9,10)	1.8095
I-imag (9,7)	1.8073
I-real (9,14)	1.6774
…	…

Coordinator SE

Chi-square limit (0.99%)	42.9
Objective function J(x)	27965

Measurement Type	Largest Normalized Residual
Pinj (6)	146.43
I-real (5,6)	117.54
Qinj (6)	94.3880
…	…

Conclusions

- A hierarchical state estimation approach is proposed.
- The main advantage of the proposed set up is that individual area state estimators can operate independently and do not have to share network data or measurements with any neighbors.
- Coordination is accomplished via a central coordinator, such as an ISO, which receives state estimation solutions from individual areas and coordinates them.

Conclusions …

- Coordinator also carries out bad data processing function in order to detect missed bad data by individual area estimators due to the reduced redundancy at area boundaries during individual area estimations.
- Having PMU measurements greatly facilitates but are not required for the hierarchical solution.