Complete Automation of Future Grid for Optimal Real-Time Distribution of Renewables

Kiyoshi Nakayama, Kyle Benson,
Vahe Avagyan, Lubomir Bic, Michael Dillencourt,
Nalini Venkatasubramanian, Jack Brouwer

IEEE Smart Grid Comm 2012

What is Smart Grid?

- Concept

Making power grids intelligent
by incorporating IT technologies into a power grid

- Key Concepts
  - Incorporate natural energies such as *sunlight* from the premises like houses and factories (Renewables)
  - Integrate *Smart Intelligent Meters* with power grid

Sustainable and Reliable Autonomous Control
for Future Power Grid has been required!

Balancing problem of renewables

- A power system is transforming itself into a smart grid
  - Integrating a multitude of distributed energy resources
  - Employs automated control systems
- Essential Problem
  - To maximize the efficiency of distributed renewable energy resources
  - Power generation from fossil fuels (diesel oils), nuclear plants, among others wanted to be reduced
  - Imbalanced distribution of dispersed powers leads to blackout

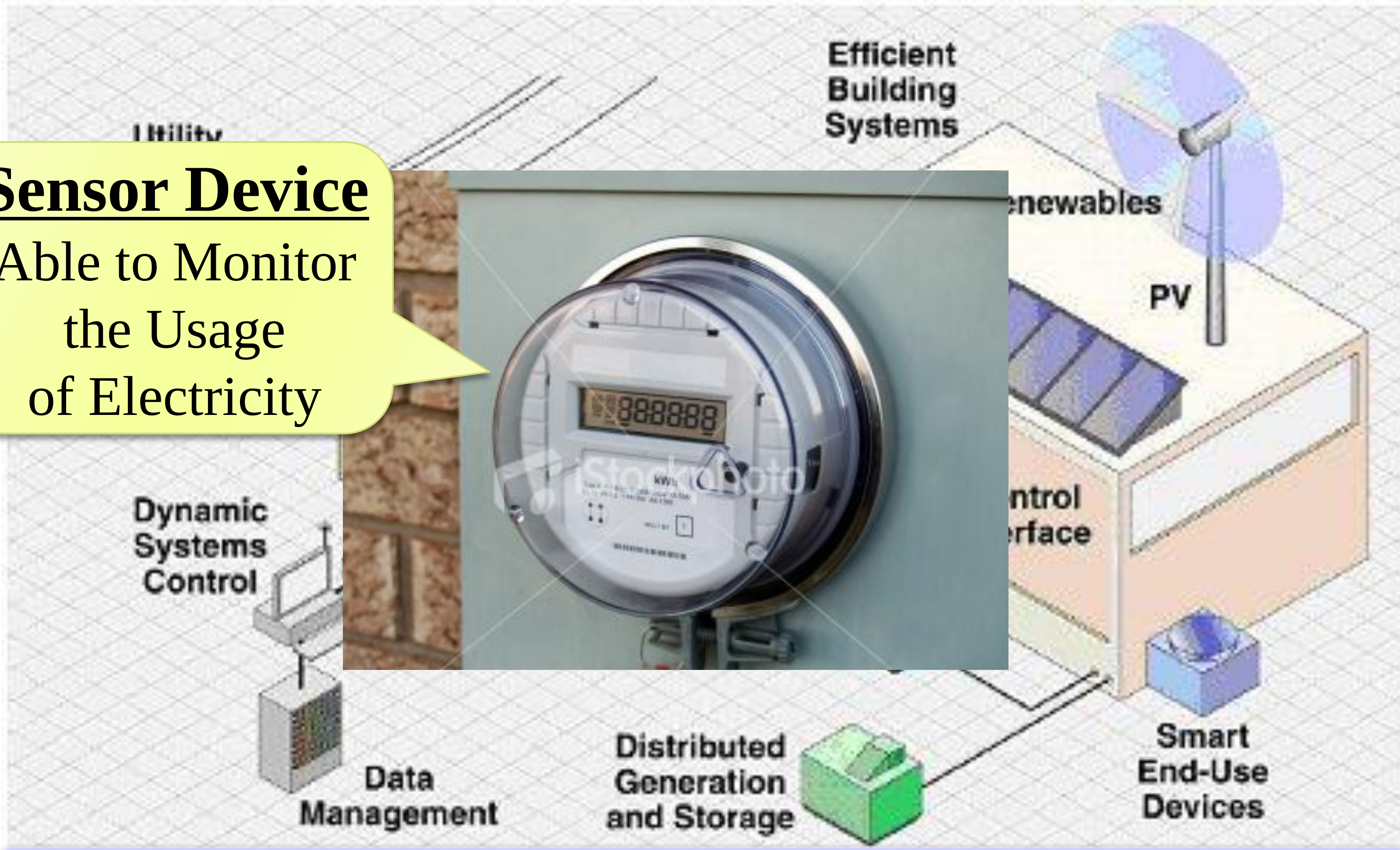
This issue leads to a balancing problem of renewables energies among dispersed power storage systems

Sustainability

The amount of electricity generated by natural energy fluctuates depending on its Intermittency and diary change of weather conditions

- Sustainable and reliable power distribution control in real time becomes difficult especially in a large-scale network
- Development of autonomous distributed architecture that can allocate dispersed renewable energy resources homogeneously is inevitable
  - To conduct high-reliable operation of future power distribution networks

Smart Meter and Communications



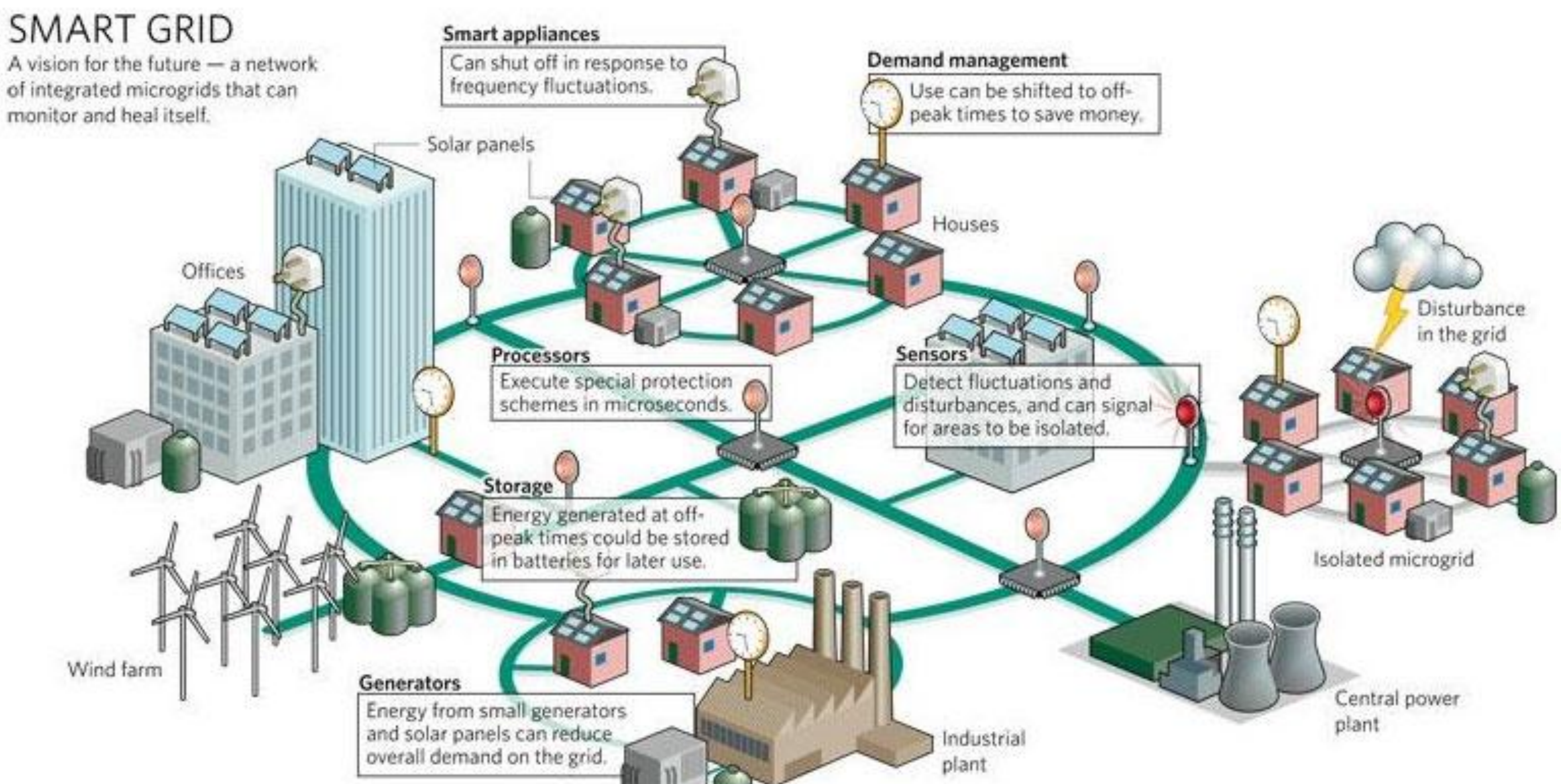
<u>Sensor Device</u>

Able to Monitor the Usage of Electricity

Smart Meters should be utilized effectively

Conception Picture of Smart Grid

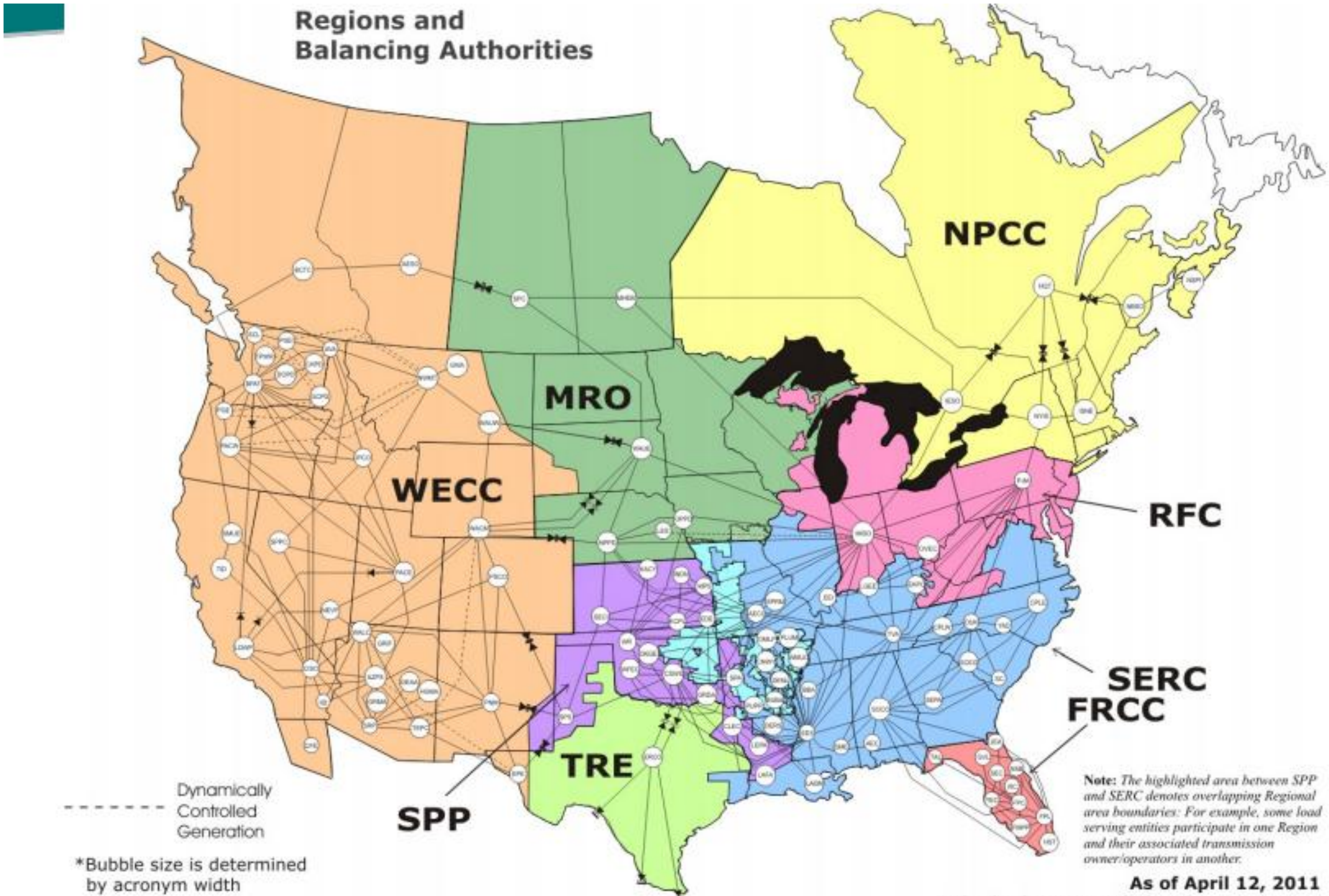
Management Constituting Loops in Mesh Networks



※A method to determine the distributed control setting of looping devices for active distribution systems

 http://vtsenvirogroup.wordpress.com/2009/05/19/you-think-youre-so-smart-grid/

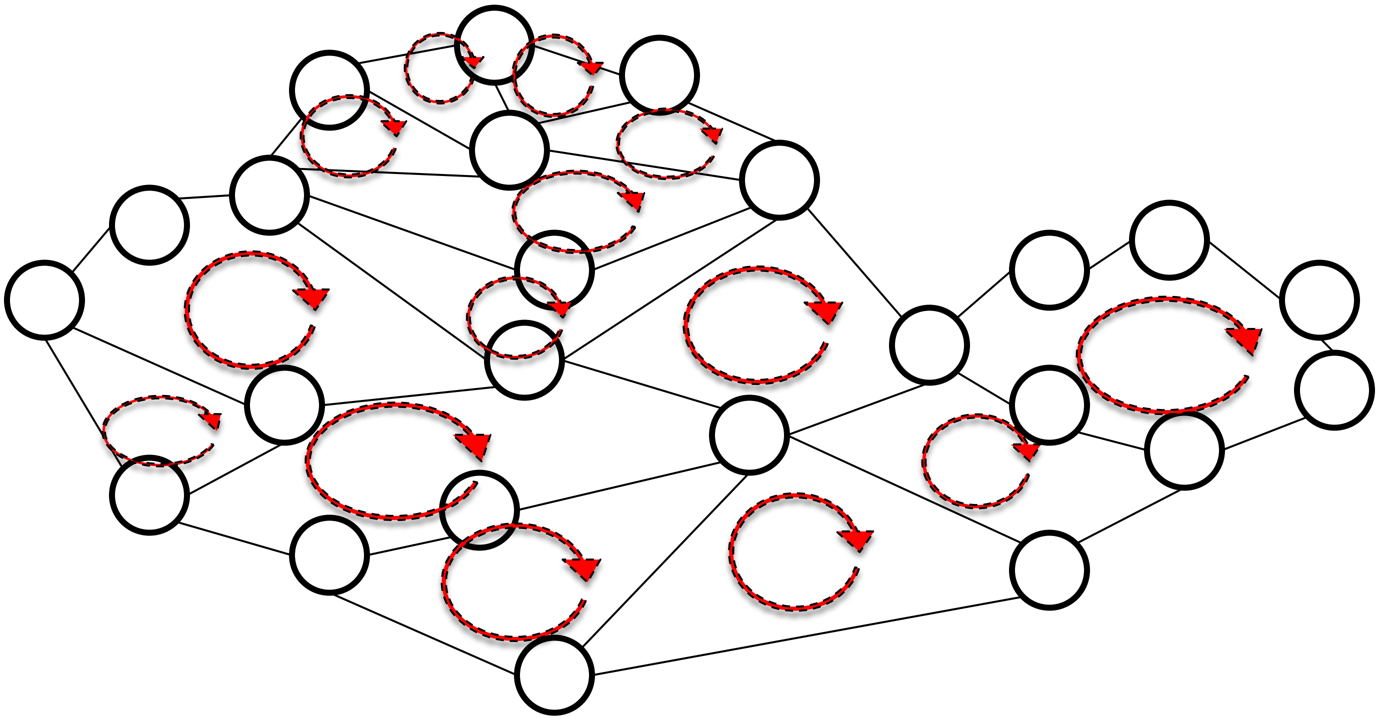
Nationwide Power Grid



http://resnick.caltech.edu/programs/smart-grid-symposium/sg-presentations/bose.pdf

Abstraction to Graph

Abstracted Form by Graph



There are many loops that underlie this kind of networks!
Loop segmentation method based on graph theory is proposed.

Tie-set Graph Theory and Distributed Control Algorithms

Since Kirchhoff's Voltage and Current Law (KVL and KCL) in 1845

Global Optimization based on Local Optimizations

Fault Tolerance Analysis

Fundamental System of Tie-sets

What are the Tie-sets?

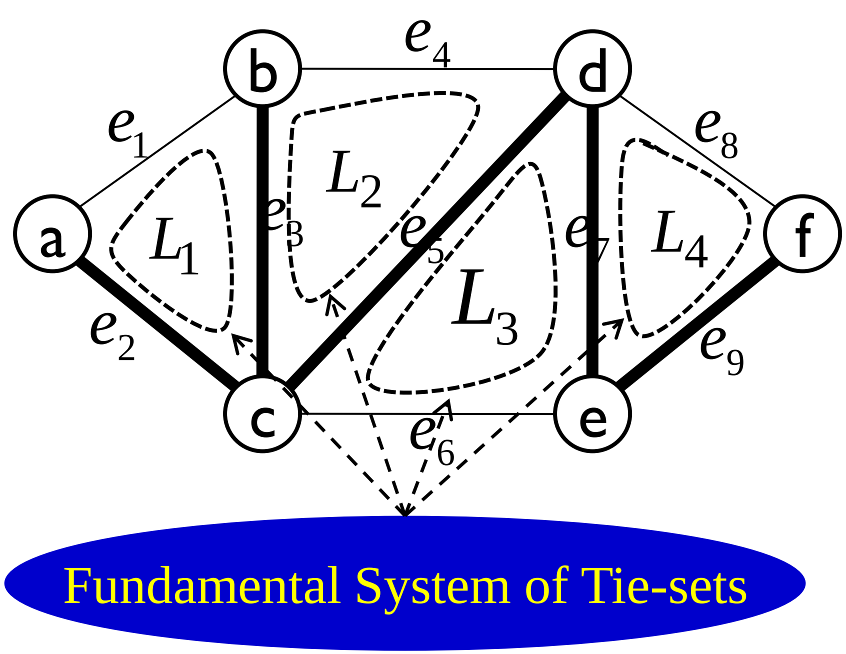
- Loop Structure of a Power Network

Tie-set Graph Theory

- Graph Theory focused on Loops

Applied to Distributed Control

Each node has Tie-set Information to which the node belong



Cover an ENTIRE Network with LOOPS !

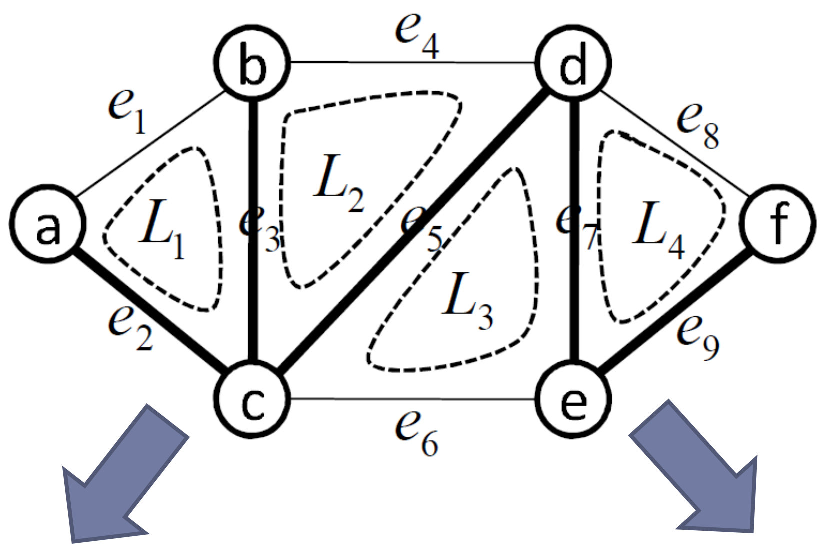
Advantages

- *Simplicity in Synchronization:* Data is exchanged within a Tie-set
- *Reduction of Electricity Loss:* Electricity is supplied within a Tie-set

Mapping Graph to Tie-set Graph

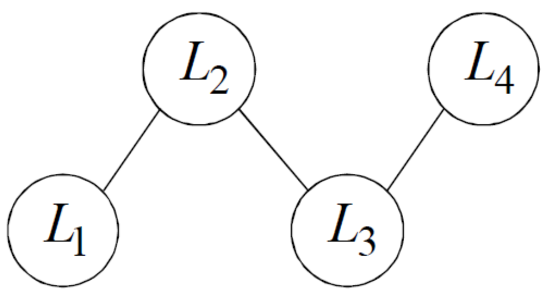
- $\underline{G} = (\underline{V}, \underline{E})$
- $\underline{V} = \{L_1, L_2, \ldots, L_\mu\}$
- $\underline{E} = \{e(L_i, L_j)\}$

- Connection Visible
- Overlapping Resources
- Communications



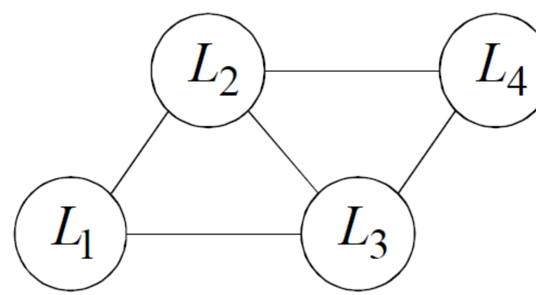
(a) e-tie-set graph.

Tie-set Graph: $\underline{G}_e = (\underline{V}, \underline{E}_e)$



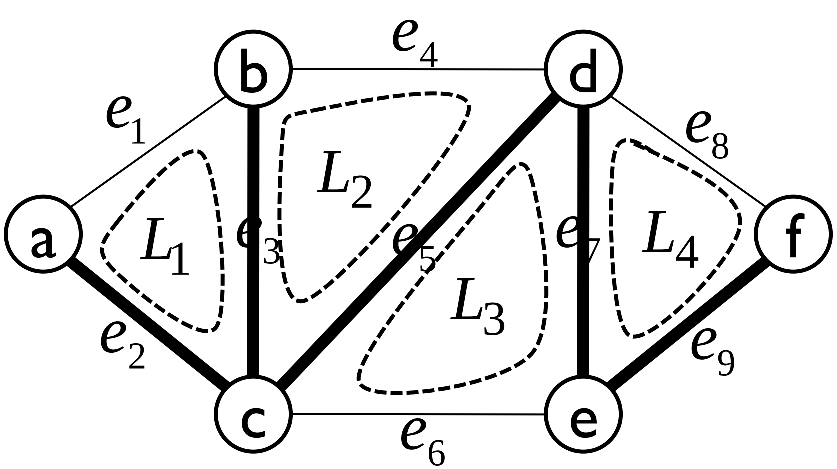
(b) v-tie-set graph.

Tie-set Graph: $\underline{G}_v = (\underline{V}, \underline{E}_v)$



State Information of a node

① Incident Links	Links connected to a node
② Adjacent Nodes	Nodes connected to a node
③ Tie-set Information	Information of tie-sets to which a node belong



Ex: State Information of node d

Incident Links : $\{e_4, e_5, e_7, e_8\}$

Adjacent Nodes : $\{b, c, e, f\}$

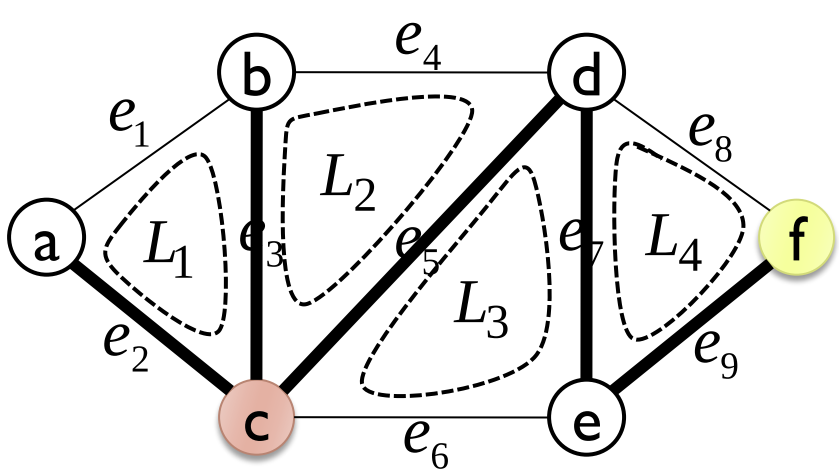
Tie-set Information : $\{L_2, L_3, L_4\}$

We had also developed an algorithm
by which each node can recognize Tie-set Information

→ *Easy network configuration for network managers*

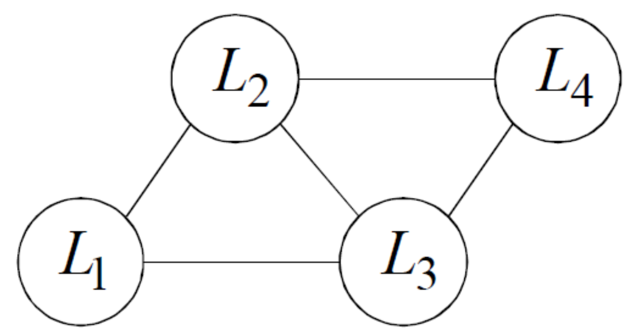
Tie-Set Leader and Communications

- There is one leader node in each tie-set L_i
- Ex. L_1: c, L_2: c, L_3: c, L_4: f
- In this case, L_1, L_2, and L_3 do not require communications. L_1, L_2, L_3 and L_4 need communications to talk each other between nodes c and f.



(b) v-tie-set graph.

Tie-set Graph: $\underline{G}_v = (\underline{V}, \underline{E}_v)$



Tie-set Agent (TA) is always checking the status of a tie-set

Optimal Real-Time Distribution of Renewable Energy Resources

Constant Balanced Allocations of Renewables in Real Time

ORDER problem

Balanced Distribution of Renewables

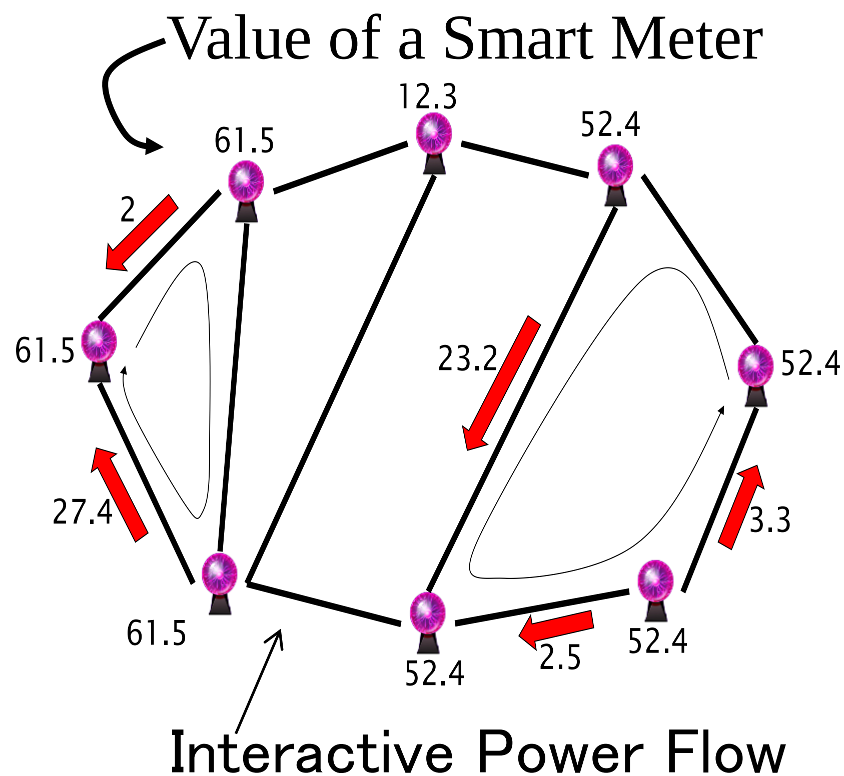
General Concept

Distributing Powers from points that have excessive power to points that have little power by adjusting generation from fossil fuels.

- Value of Smart Meters :

  → Node Power: $P_v(t)$

Power Grid

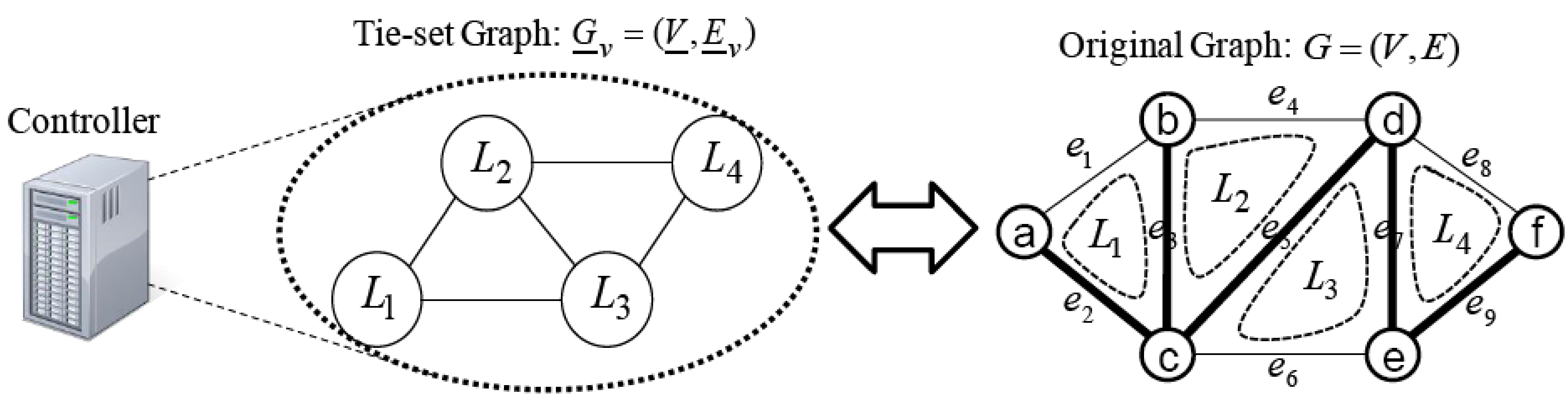


On the basis of optimization nature of tie-set graph theory

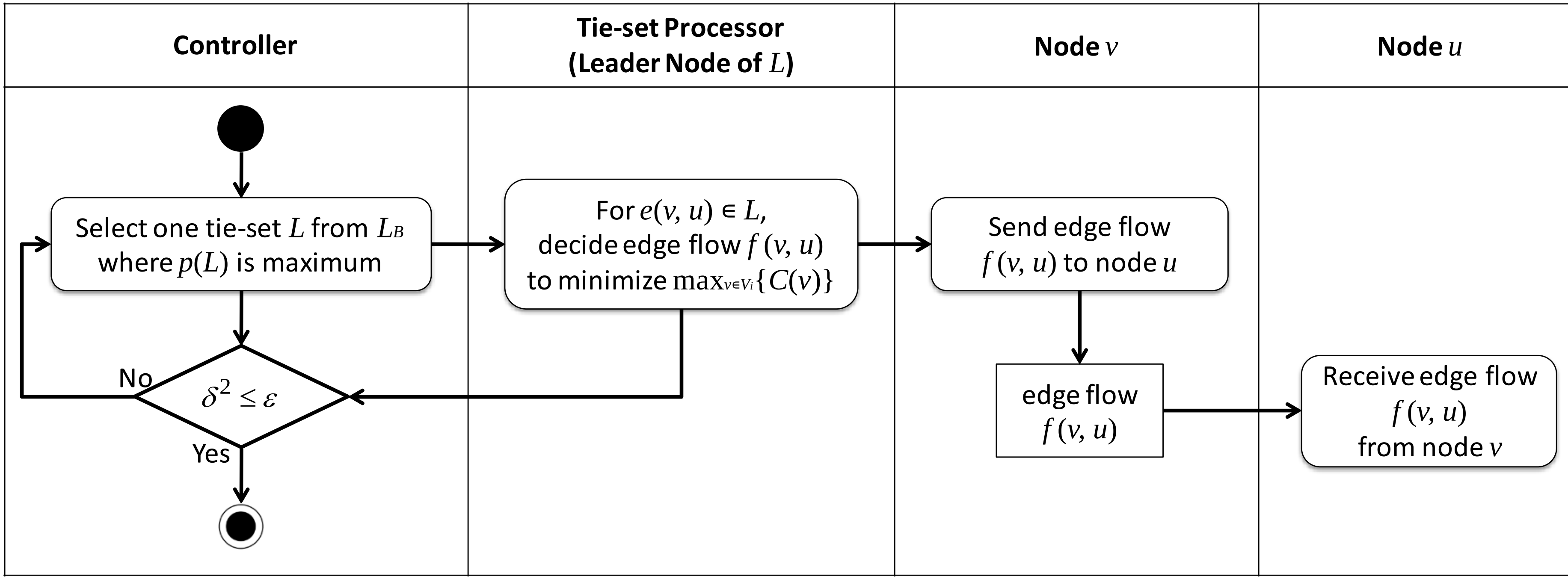
Cloud Conntrol model of a power network

The model follows the situation where controller centralizes information of smart meters in a power network.

A controller is a management system of an entire power network



Flow chart of overall processes



- $\boldsymbol{p(L)} = \textbf{Random}$

  If the value of $p(L)$ of all tie-sets is randomly assigned, the controller picks up one tie-set at random.

- $\boldsymbol{p(L) = C_{max} - C_{min}}$, $(C_{max} = \max_{v \in V}\{C(v)\}, C_{min} = \min_{u \in V}\{C(u)\})$

  This evaluation function is delta between maximum node cost and minimum node cost in a tie-set.

- $\boldsymbol{p(L) = \delta^2}$

  This evaluation function is the variance of node costs in a tie-set.

Definitions

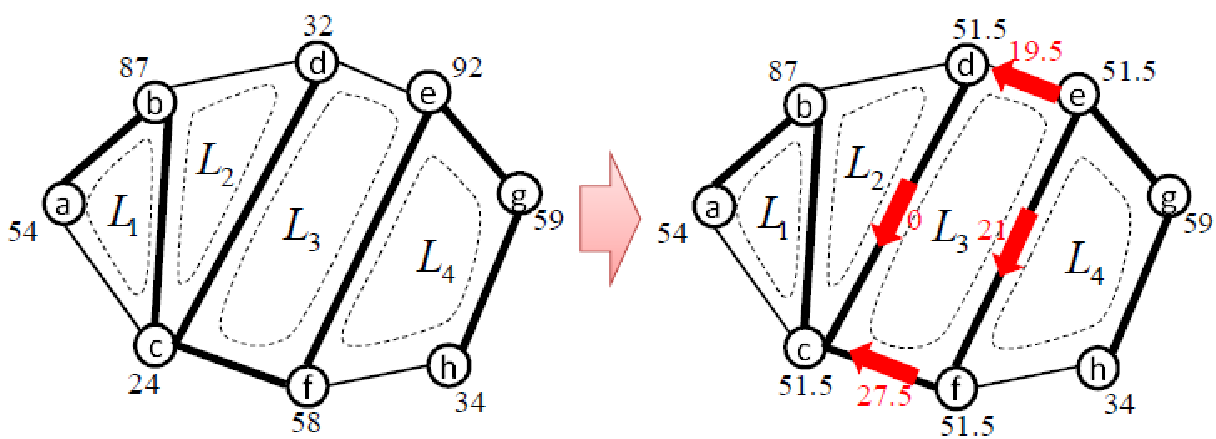
- $Pv(t)$: the amount of power (algebraic sum of power production, consumption, inflow, and outflow monitored by smart meters) that each node v possesses at time t
  - *$Pv(0)$: Initial Power*
- $Lv(t)$: load of a node v at t
- $Rv(t)$: generation by renewable energy resources
  - $Lv(t)-Rv(t)$ is often referred to as *net demand*.
  - The load L and renewable power R are both random processes
- $Dv(t)$: the amount of power that is produced by Centralized Generation Facility (CGF)

$$Pv(t) = Pv(t-1) - Lv(t) + Rv(t) + Dv(t)$$

Edge Flow (Power Flow, Load Flow)

For any two vertices *v*, *u* ($v \neq u$), let *f*(*v*, *u*, *t*) be a power flow over an edge *e*(*v*, *u*) from vertex *v* to *u* at time *t*, where if *f*(*v*, *u*, *t*) flows along the direction of an edge *e*(*v*, *u*) then *f*(*v*, *u*, *t*) > 0; otherwise *f*(*v*, *u*, *t*) < 0.

$$f(v,u,t) = F \Longrightarrow \begin{cases} P'_v(t) = P_v(t) - F \\ P'_u(t) = P_u(t) + F \end{cases}$$



ORDER Problem

ORDER Problem: For a given time sequence $\mathcal{T} = \{t\}$, each $v \in V$, and each $e(v, u) \in E$, decide the amount of power by CGF $D_v(t)$ and the edge flow $f(v, u, t)$ that satisfies the following conditions with certain threshold P_{min}.

$$\text{Minimize} \max_{v \in V} \{P_v(t)\} \tag{4}$$

$$\text{Minimize} \sum_{t \in \mathcal{T}} \sum_{v \in V} D_v(t) \tag{5}$$

$$P_v(t) \geq P_{min} \tag{6}$$

Autonomous Distributed Control for ORDER Problem (1)

- *Tie-set Agent (TA):*

  At each t, the a leader node of a tie-set, which is referred to as a System Operating (SO) point, receives a measurement vector $y(t)$ that provides information about $Pv(t)$, ($v \in V_i$) in L_i.

  - load $Lv(t)$, renewable power generation $Pv(t)$, weather forecasts, pricing info, among others than $Pv(t)$.
  - Tie-set Agent (TA) constantly navigates around on a tie-set and bring the data to a leader node with certain time interval (TI).

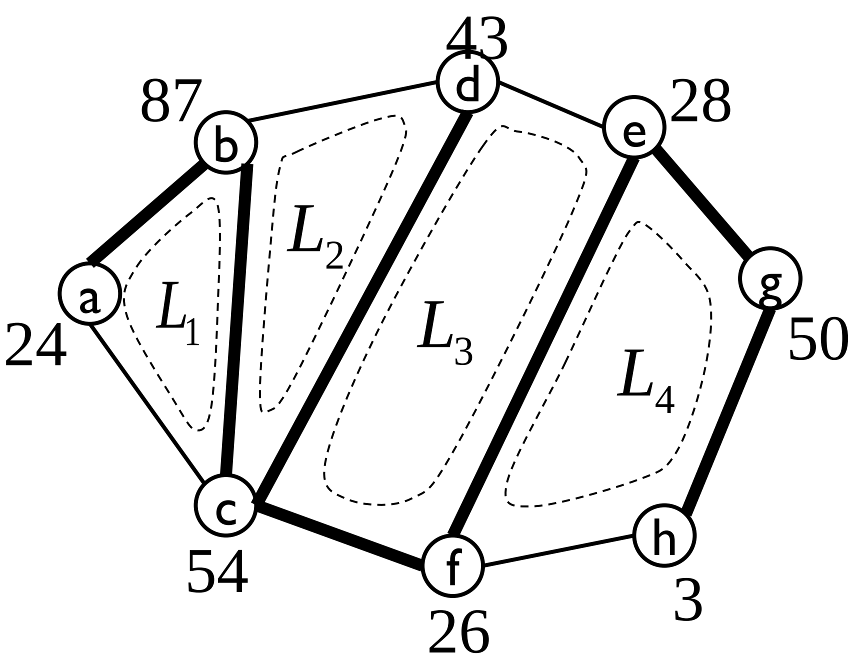
Autonomous Distributed Control for ORDER Problem (2)

- *Tie-set Evaluation Function (TEF)* $\Phi(L_i)$:
  - Function to decide the Process Priority for resources shared by several tie-sets decided based on $y(t)$

- $\Phi(L_i) = \text{Random}$
  The value of $\Phi(L_i)$ of a tie-set is randomly assigned.
- $\Phi(L_i) = P_v(t)^i_{max} - P_v(t)^i_{min}$
  Let $P_v(t)^i_{max}$ and $P_v(t)^i_{min}$ be $\min_{v \in V_i}\{P_v(t)\}$ and $\min_{v \in V_i}\{P_v(t)\}$, respectively. This TEF is the delta between the maximum power and the minimum power in a tie-set.
- $\Phi(L_i) = \sigma^2(t)$
  This TEF is the variance of $P_v(t)$, where $v \in V_i$ as defined in $\sigma^2(t) = \frac{\sum_{v \in V}(P_v(t) - \overline{P})^2}{|V|}, \left(\overline{P} = \frac{\sum_{v \in V} P_v(t)}{|V|}\right)$

Autonomous Control with TEF

- Exchanging TEF by Message Passing
- Using Flag Concept
- Parallel Optimizations are feasible



Example

In case $\Phi(L_i) = P_{max} - P_{min}$

- $\Phi(L_1) = 87 - 24 = 63$
- $\Phi(L_2) = 87 - 43 = 44$
- $\Phi(L_3) = 54 - 26 = 28$
- $\Phi(L_4) = 50 - 3 = 47$

Flag of L_1 and L_4 becomes 1

Flag of Others becomes 0

L1 and L4 conduct optimization. The procedures are constantly iterated.

Distributed Optimization Algorithm within a Tie-set

Algorithm 1 Distributed optimization algorithm in a tie-set

Step0:
Calculate the average value $\overline{P}$ of $P_v(t)$, where $v \in V_i$.
if $\overline{P} < P_{min}$ **then**
Pick a node $v_d \in V_i$, and then $P'_{v_d}(t) = P_{v_d}(t) + |V_i| \times \Delta P$, where $\Delta P = P_{min} - \overline{P}$.
Recalculate the average value $\overline{P}$.
end if

Step1:
for each node $v \in V_i$ **do**
if $P_v(t) \geq \overline{P}$ **then**
Classify $v \in V_i$ into a set of nodes X.
else if $P_v(t) < \overline{P}$ **then**
Classify $v \in V_i$ into a set of nodes Y.
end if
end for

Step2:
while $X \cup Y \neq \emptyset$ **do**
Select a node x from X, and a node y from Y arbitrarily.
if $P_x(t) - \overline{P} > \overline{P} - P_y(t)$ **then**
$f_{P(x,y)} = \overline{P} - P_y(t)$.
Update $P_y(t)$ to $\overline{P}$, and $P_x(t)$ to $P_x(t) + P_y(t) - \overline{P}$.
Remove y from Y.
else if $P_x(t) - \overline{P} > \overline{P} - P_y(t)$ **then**
$f_{P(x,y)} = P_x(t) - \overline{P}$.
Update $P_x(t)$ to $\overline{P}$, and $P_y(t)$ to $P_y(t) + P_x(t) - \overline{P}$.
Remove x from X.
else $\{P_x(t) - \overline{P} = \overline{P} - P_y(t)\}$
$f_{P(x,y)} = P_x(t) - \overline{P}$.
$P_x(t)$ to $\overline{P}$, and $P_y(t)$ to $P_y(t) + P_x(t) - \overline{P}$.
Remove x from X, and y from Y.
end if
end while

Step3:
Calculate the value of each each flow $f(v, u)$ over $e(v, u) \in L_i$ considering all flows decided above, and distribute those flows to the tie-set L_i.

Distributed Optimization Algorithm within a Tie-set (Step0)

Step0:

Calculate the average value $\overline{P}$ of $P_v(t)$, where $v \in V_i$.

if $\overline{P} < P_{min}$ **then**

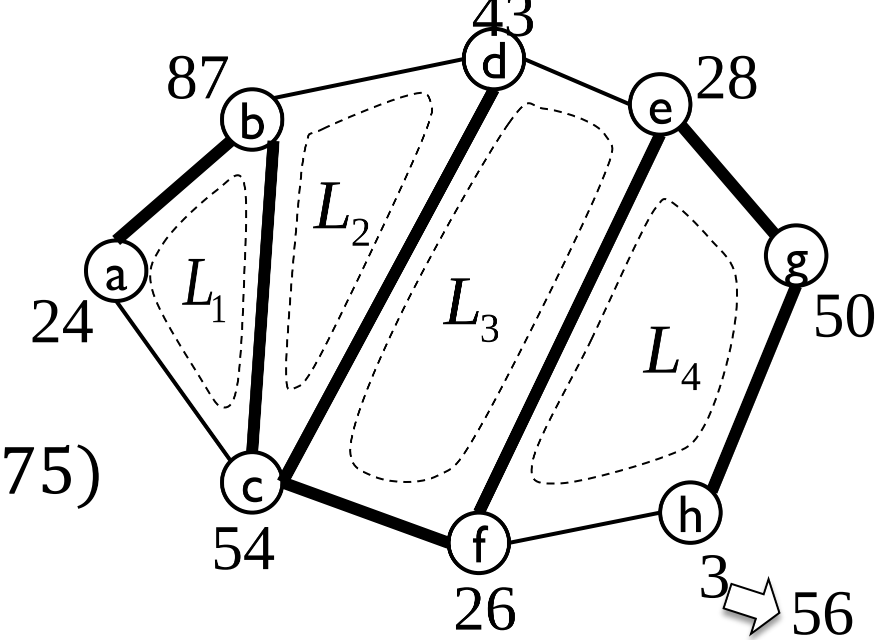
Pick a node $v_d \in V_i$, and then $P'_{v_d}(t) = P_{v_d}(t) + |V_i| \times \Delta P$, where $\Delta P = P_{min} - \overline{P}$.

Recalculate the average value $\overline{P}$.

end if

If $P_{min} = 40$

- $\bar{P} = 55\ (> 40)$ in L_1
- $\bar{P} = 26.75\ (< 40)$ in L_4
- $P_h(t) = 3 + 4 * (40 - 26.75)$
- Renewed $\bar{P} = 40$



Distributed Optimization Algorithm within a Tie-set (Step1)

Step1:

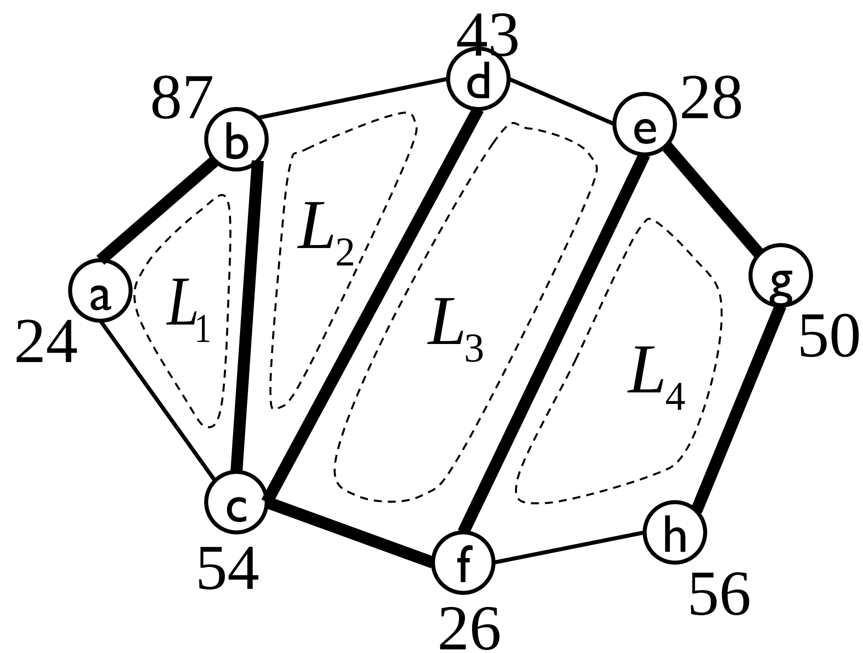
for each node $v \in V_i$ **do**
  if $P_v(t) \geq \overline{P}$ **then**
    Classify $v \in V_i$ into a set of nodes X.
  else if $P_v(t) < \overline{P}$ **then**
    Classify $v \in V_i$ into a set of nodes Y.
  end if
end for

As $\bar{P} = 55$ in L_1

- $X = \{b\}, Y = \{a, c\}$

As $\bar{P} = 40$ in L_4

- $X = \{g, h\}, Y = \{e, f\}$



Distributed Optimization Algorithm within a Tie-set (Step2)

Step2:

while $X \cup Y \neq \emptyset$ **do**

Select a node x from X, and a node y from Y arbitrarily.

if $P_x(t) - \overline{P} > \overline{P} - P_y(t)$ **then**

$f_{P(x,y)} = \overline{P} - P_y(t)$.

Update $P_y(t)$ to $\overline{P}$, and $P_x(t)$ to $P_x(t) + P_y(t) - \overline{P}$.

Remove y from Y.

else if $P_x(t) - \overline{P} > \overline{P} - P_y(t)$ **then**

$f_{P(x,y)} = P_x(t) - \overline{P}$.

Update $P_x(t)$ to $\overline{P}$, and $P_y(t)$ to $P_y(t) + P_x(t) - \overline{P}$.

Remove x from X.

else $\{P_x(t) - \overline{P} = \overline{P} - P_y(t)\}$

$f_{P(x,y)} = P_x(t) - \overline{P}$.

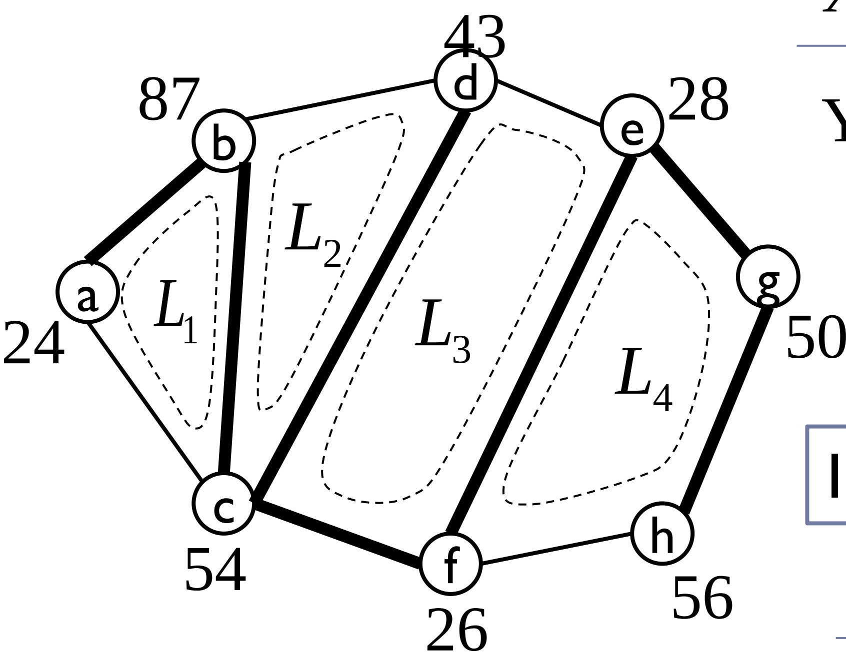
$P_x(t)$ to $\overline{P}$, and $P_y(t)$ to $P_y(t) + P_x(t) - \overline{P}$.

Remove x from X, and y from Y.

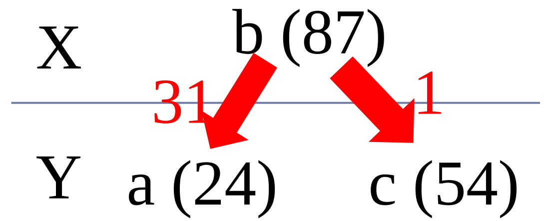
end if

end while

Distributed Optimization Algorithm within a Tie-set (Step2)



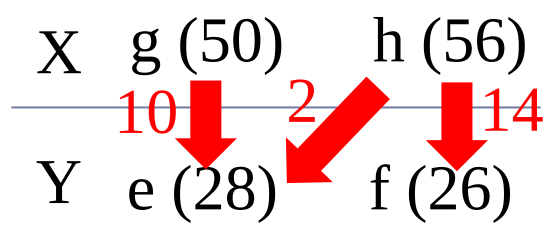
In L_1



$f(b, a) = 31$

$f(b, c) = 1$

In L_4



$f(g, e) = 10$

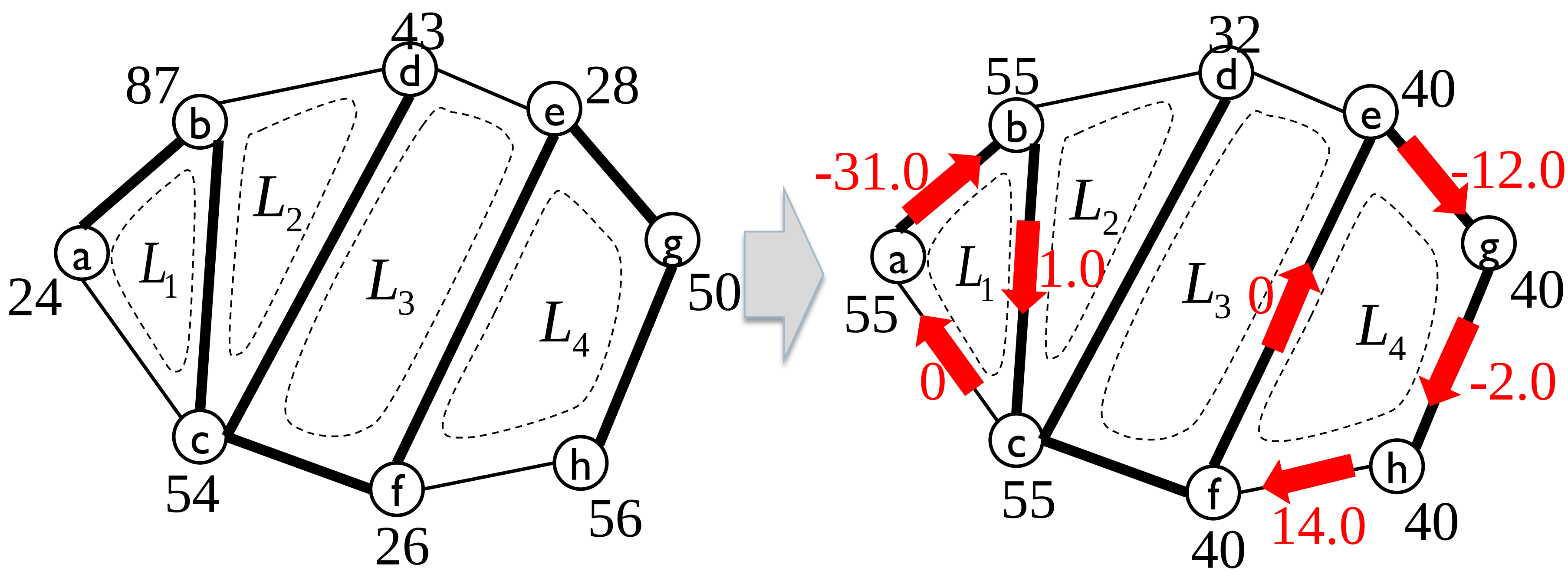
$f(h, e) = 2$

$f(h, f) = 14$

Distributed Optimization Algorithm within a Tie-set (Step3)

Step3:

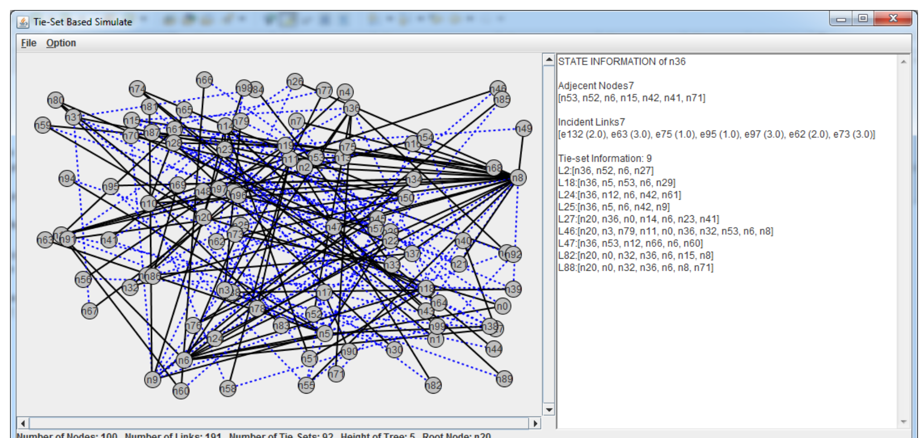
Calculate the value of each each flow $f(v,u)$ over $e(v,u) \in L_i$ considering all flows decided above, and distribute those flows to the tie-set L_i.



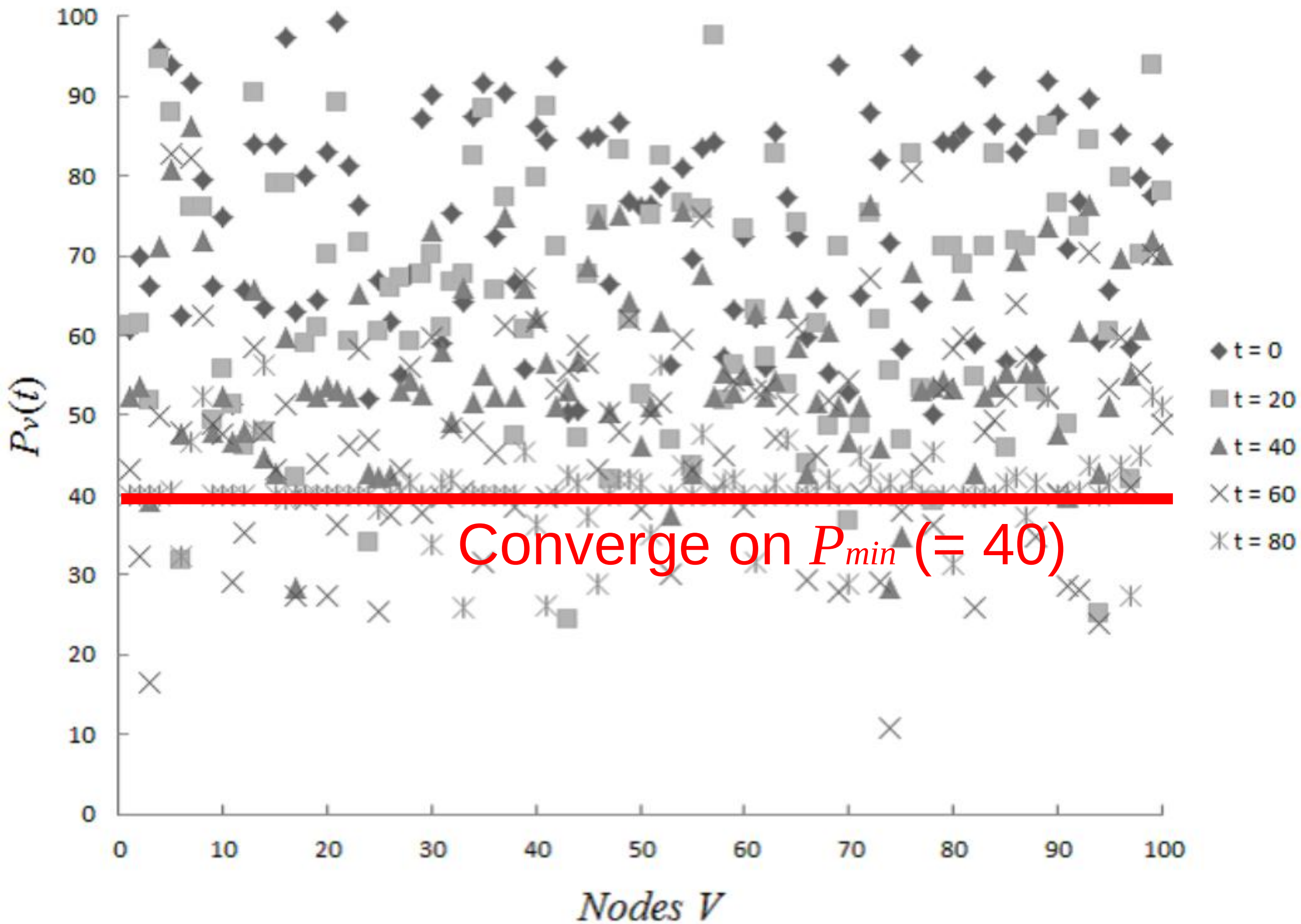
Simulations and Experiments

Simulation Conditions

- Simulation network *G* = (*V*,*E*)
  - undirected and bi-connected
  - 100 nodes and 190 links with random connection
  - Initial Power Pv(0) is assigned from 50 to 100 at random
  - Pmin = 40
  - For a given time sequence *S* = {0, 5, 10, ..., 100} [msec], *Lv*(*t*) and *Rv*(*t*) are given between 0 to 20 and 0 to 10 at random
- Behavior of Overall Convergence
- Behavior at a Node

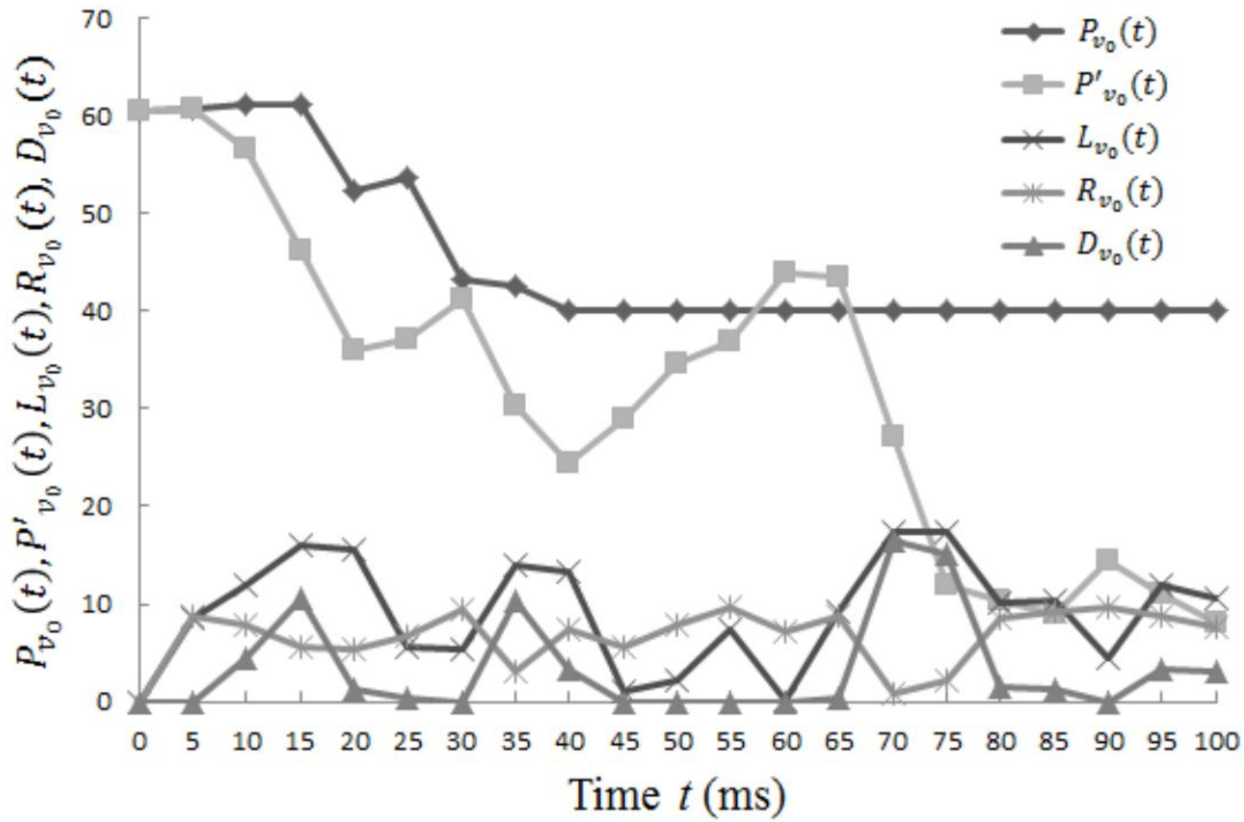


Behavior of Convergence with 100 nodes

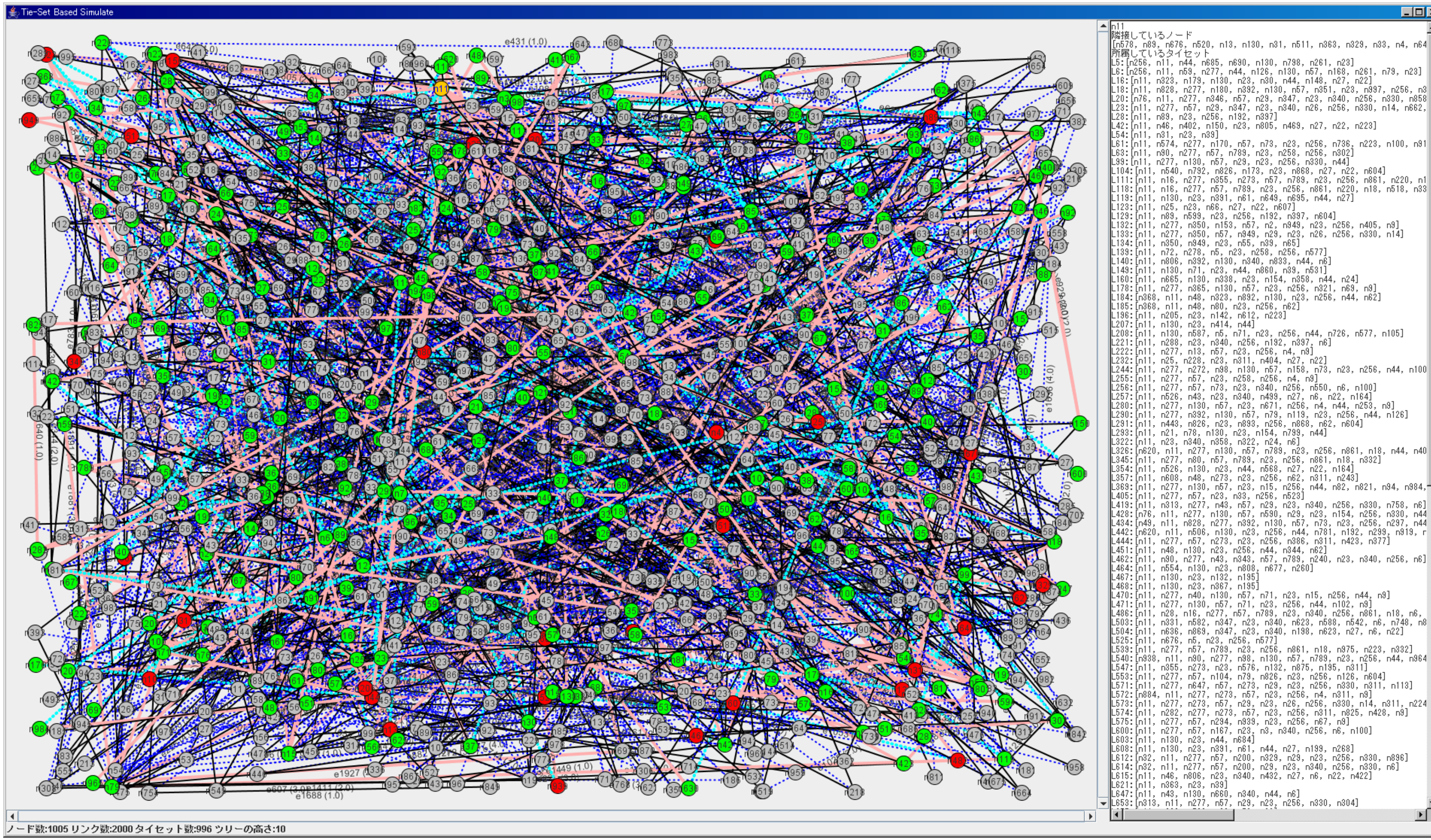


Behavior of a Node v_0

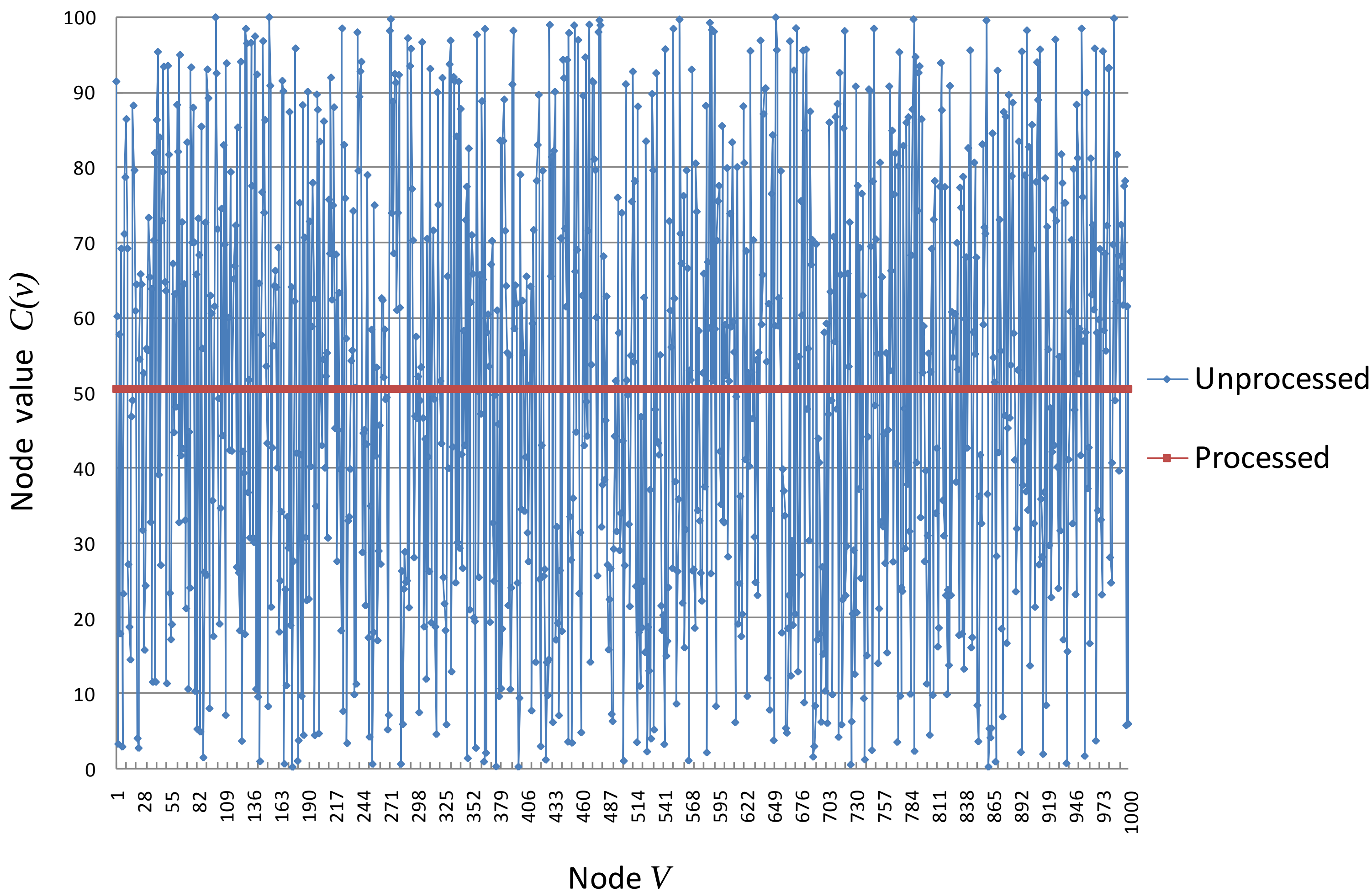
- $Pv(t) = Pv(0) - Lv(t) + Rv(t) + Dv(t)$ (With Optimization)
- $P'v(t) = Pv(0) - Lv(t) + Rv(t)$ (Without Optimization and Dv(t))



1000 node network



Convergence in 1000-node network



Conclusion

- Tie-set Graph Theory and its Distributed Algorithms are introduced as a theoretical background.
  - Tie-set Graph Theory is the logical approach to divide a graph into a set of independent loops.
- Optimal Real-Time Distribution Problem of Renewable Energy Resources (ORDER) is formulated and Autonomous Distributed Control method for ORDER is proposed.
- Simulation results of one hundred-node network demonstrate the optimal distribution of renewables and thus effectiveness of the proposed method.

Future Works

- Transmissions Loss, Conversion Loss, Error Measurement, and characteristics of Central Generation Facilities
- More Intelligent Approach
  - Measurement of Rate of Changes at a node or tie-set to design time interval to conduct optimization
- Computation of Pricing and Security
- Pragmatic Simulations
  - Experiment on a larger-scale network
  - Evaluation of TEF and its behavior
  - Feed more constraints from the energy harvesting side

Thank you for your kind attention!