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PS-03. Fine Timing Adjustment for Application-Layer Multicast to Reduce Delay Variations of Power Grid Control Messages

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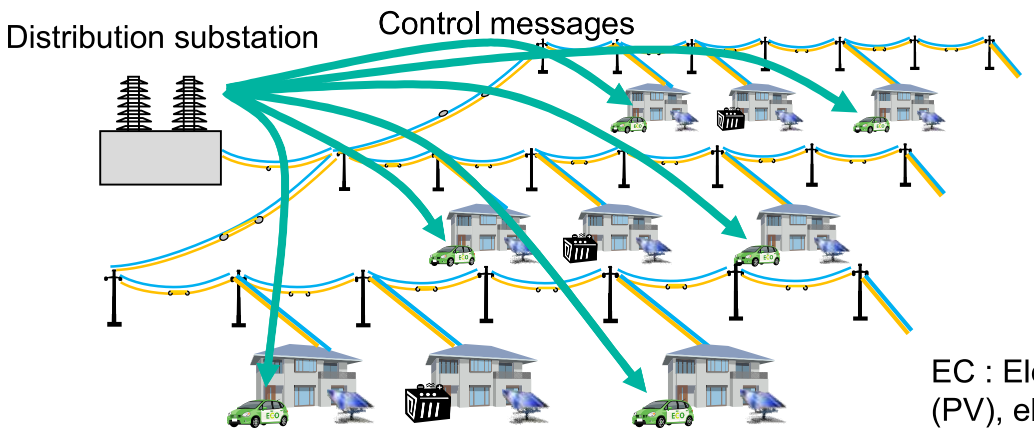
1. Background

Synchronous control of many ECs in power grids

- Power demand and supply adjustment
  - Substation controls many loads like EVs and heat pumps simultaneously for smoothing the power fluctuations generated by unstable distributed generations such as PVs.
- Distribution automation
  - The circuit breakers and line switches are controlled at the same time.

Multicast method is effective for synchronous control of ECs in power grids.



EC : Electrical components such as photovoltaic (PV), electric vehicles (EVs), heat pumps, etc.

2. Requirements and Issues of Multicast Method for Power Grid

Requirements

- Simultaneity and scalability to control many ECs at the same time.
  - The data size of control message is small.
- Short delay
  - The control messages must be delivered to the ECs within a short delay of millisecond order, without lack of information.

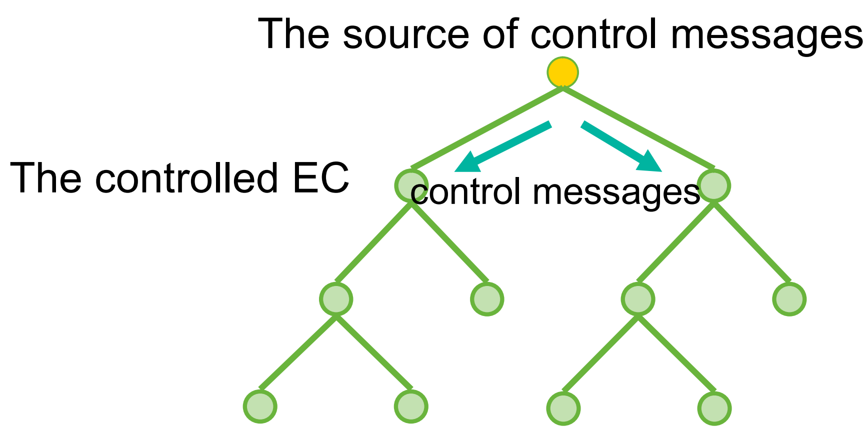
Issues

- Conventional multicasts are not designed for this purpose.
  - The conventional multicast methods emphasize throughput and scalability.
  - No method considers thousands of ECs and the millisecond order synchronous control of ECs.

3. An Application-layer Multicast Method to Reduce Delay Variations

Coexistence of scalability and simultaneity

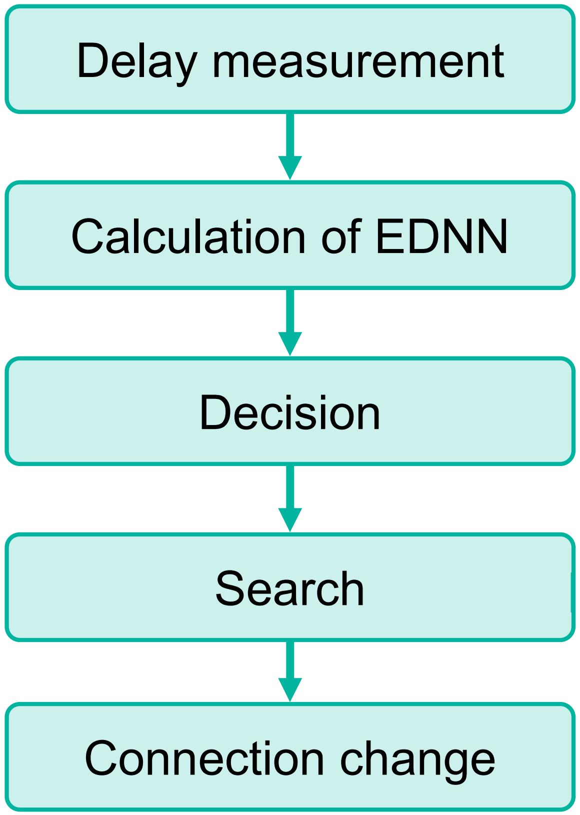
- Multicast tree for scalability
  - The source of control messages is a root node.
  - The controlled ECs are the relay nodes or leaf nodes.
  - If a new EC is added, the EC joins the multicast tree as a node.
- Tree optimization and timing adjustment for short delay and simultaneity
  - Optimization of the tree topology of an application-layer multicast to satisfy the demanded upper delay.
  - Fine timing adjustment of control messages in the application software to satisfy the demanded lower delay.

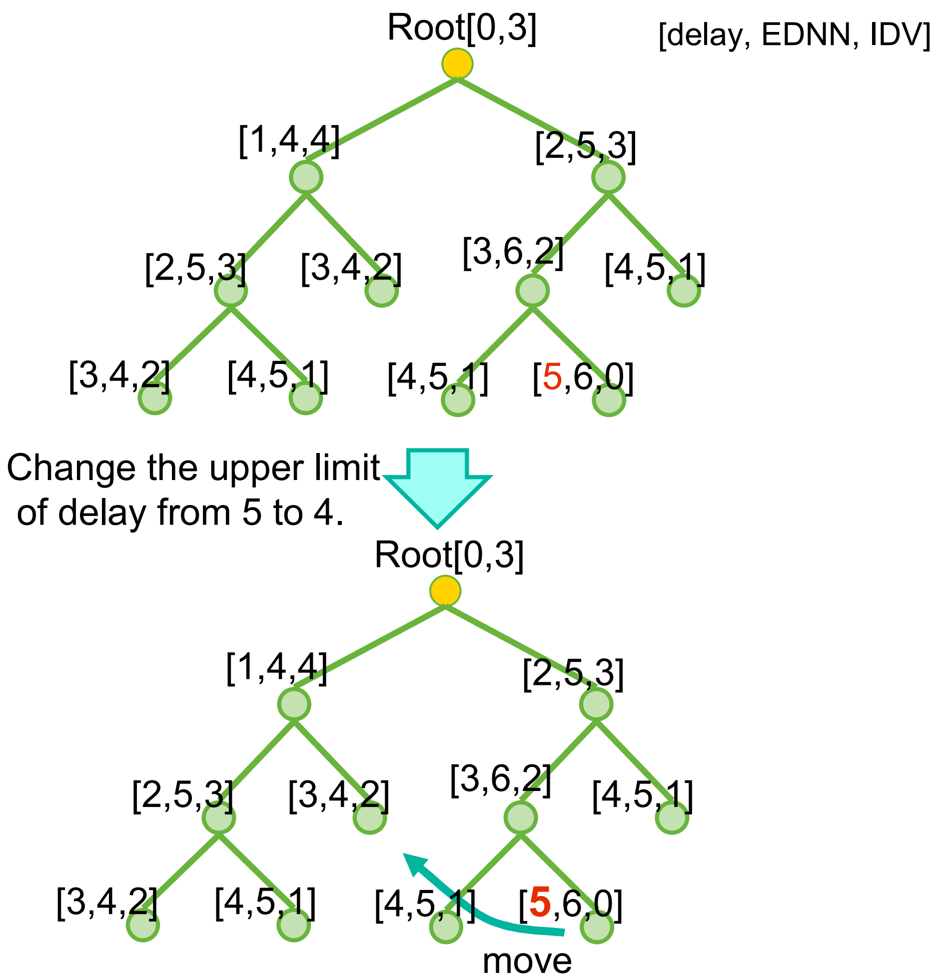


3-1. Optimization of Multicast Tree

Five steps of optimization of multicast tree to meet max delay

- Nodes outside of max delay change parent node to satisfy max delay.

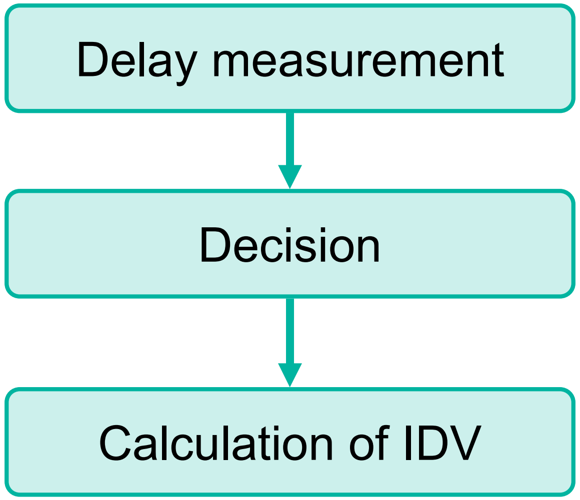


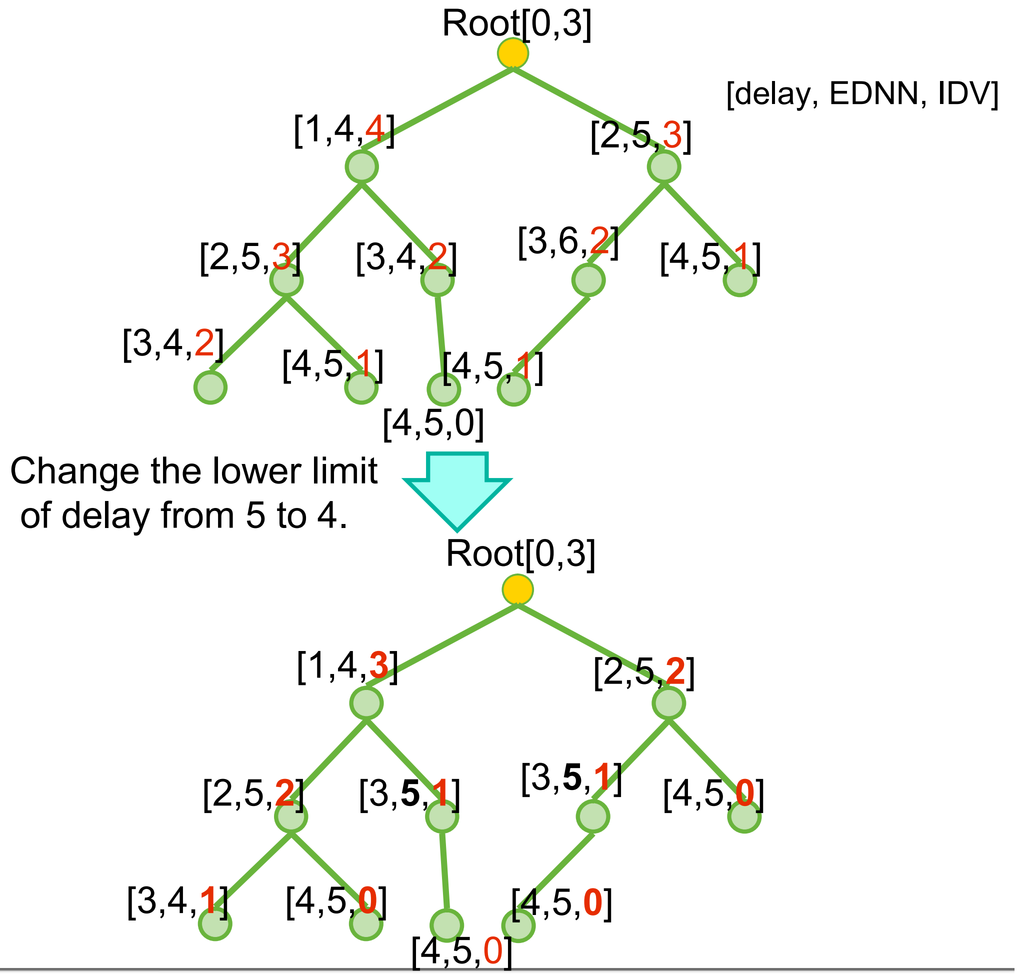


EDNN : the estimation delay of a new node
IDV : the intentional delay value

3-2. Fine timing adjustment

- Three steps for fine timing adjustment by adding intentional delay at each receiving note
  - Nodes outside of minimum delay change intentional delay to satisfy minimum delay.



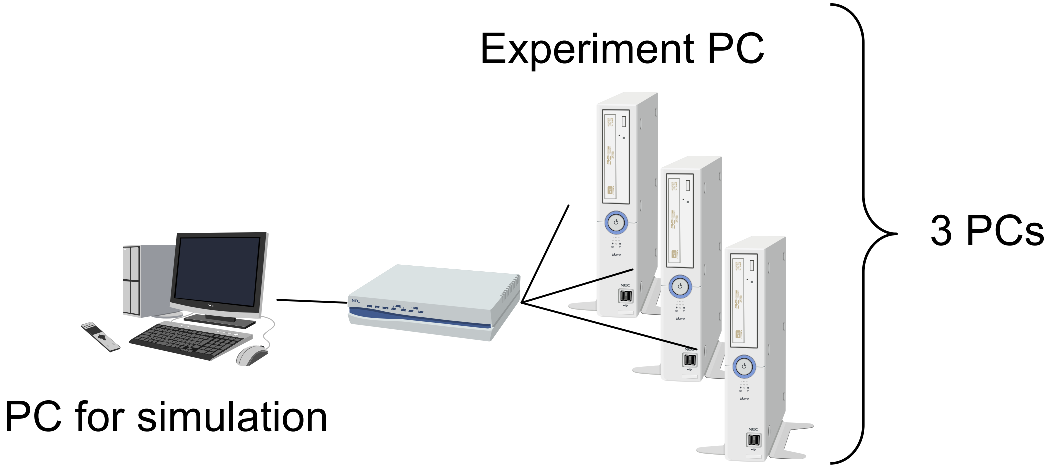


EDNN : the estimation delay of a new node
IDV : the intentional delay value

4-1. Simulation Evaluation

Simulation with

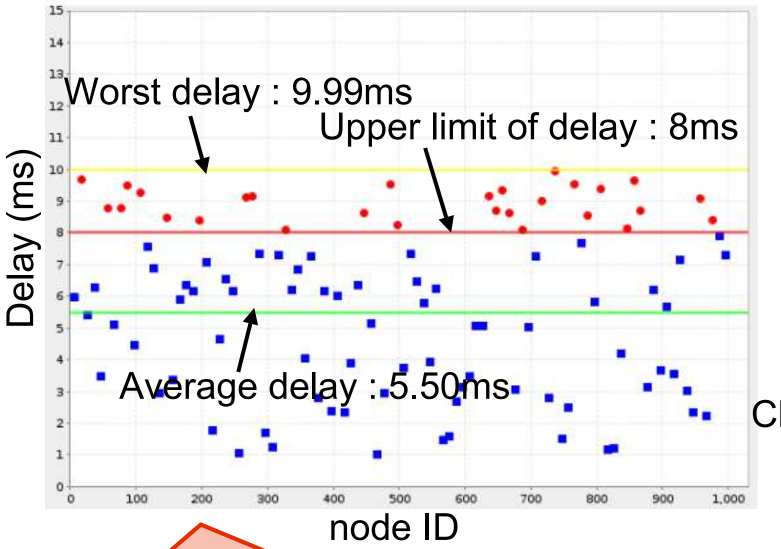
- 3 experiment PCs
  - One real node work on one PC.
- 1 PC for emulation and simulation
  - This PC emulate 997 dummy nodes.
  - This PC simulates and measures the packet transmission time of all nodes.
- One multicast tree with the real nodes and the virtual nodes.
- 1 L2 switch



4-1-1. Simulation Results (1/2)

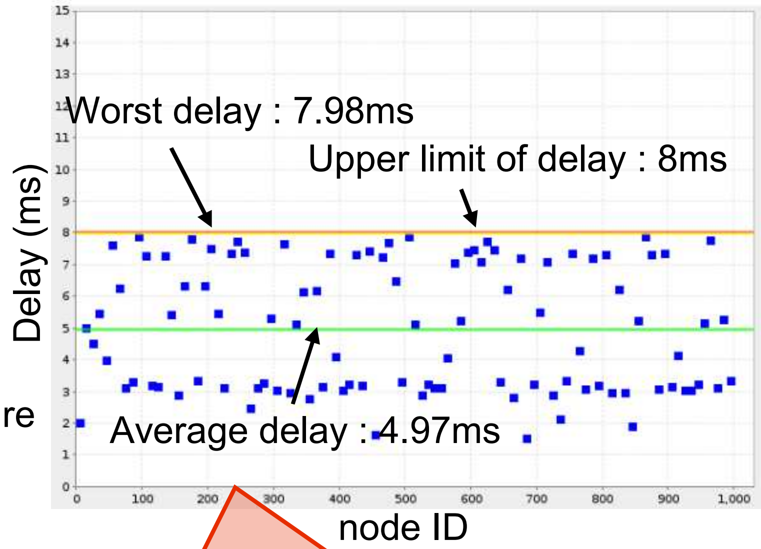
Changing the upper limit of delay from none to 8 ms.

Red circle symbols : the data outside the upper or lower limit
Blue square symbols : the data within the upper or lower limit



In star topology the variation of delay is 6.76.
There are many nodes outside the upper limit of delay.

Change tree structure



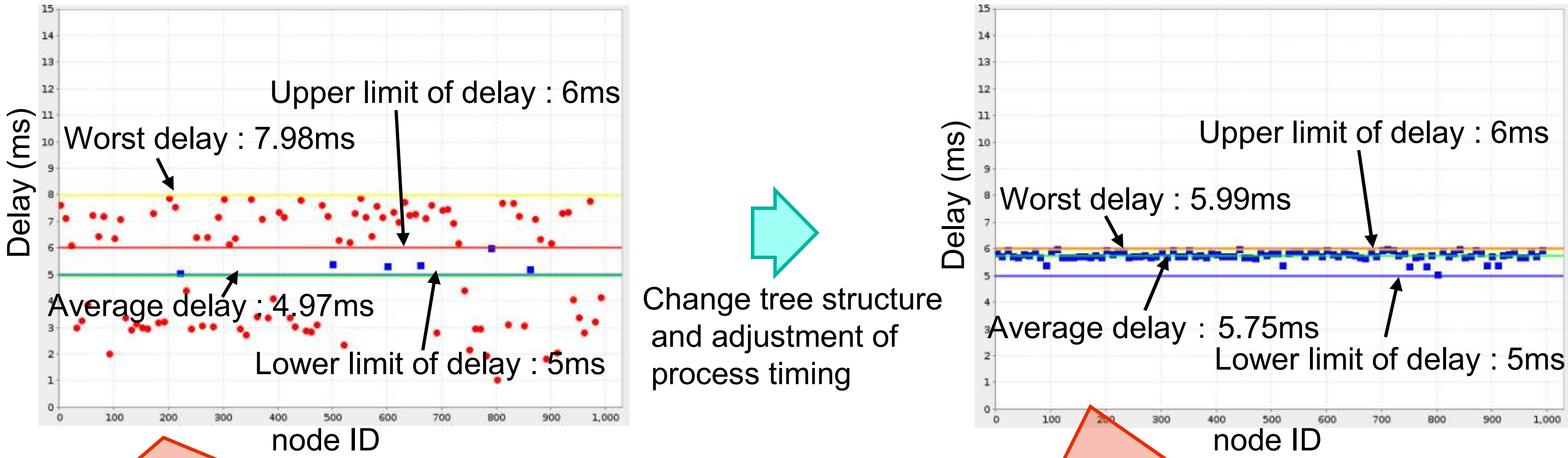
the worst delay is 7.98 ms within the upper limit of delay, and the variation of delay is 3.84.

the data of 100 randomly selected nodes was drawn.

4-1-2. Simulation Results (2/2)

- Changing the upper limit of delay from 8 ms to 6 ms and the lower limit of delay from none to 5 ms.

Red circle symbols : the data outside the upper or lower limit
Blue square symbols : the data within the upper or lower limit



There are many nodes outside of the upper and lower limits of delay.

The worst delay is 5.99 ms within the upper limit of delay, and the variation of delay is 0.02.

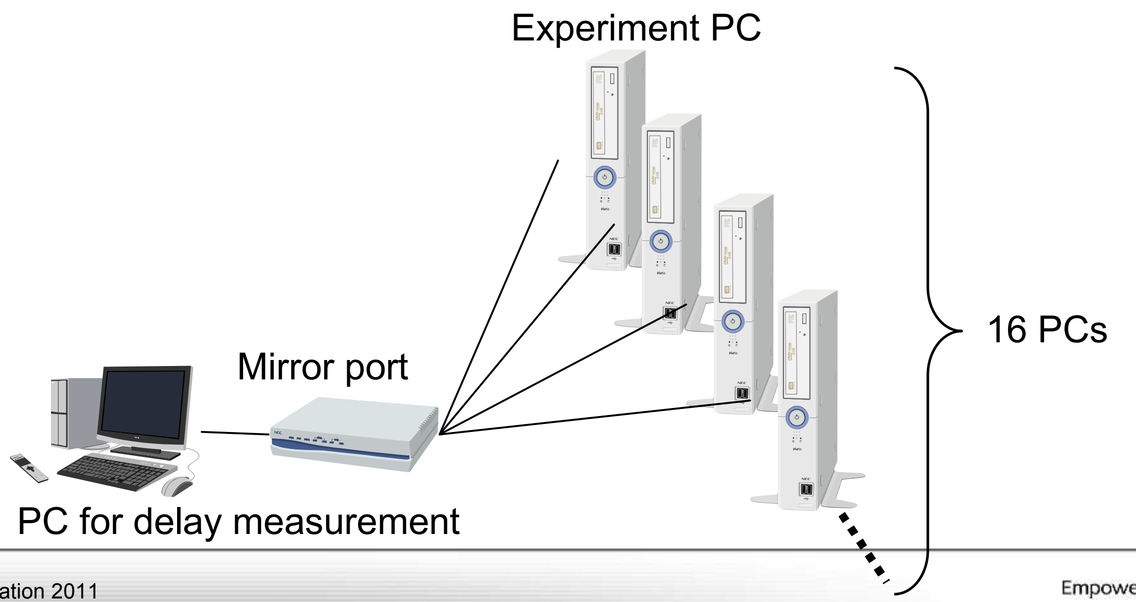
The delay variation is reduced by the proposed method in millisecond order

the data of 100 randomly selected nodes was drawn.

4-2. Delay Evaluation

Experiment with

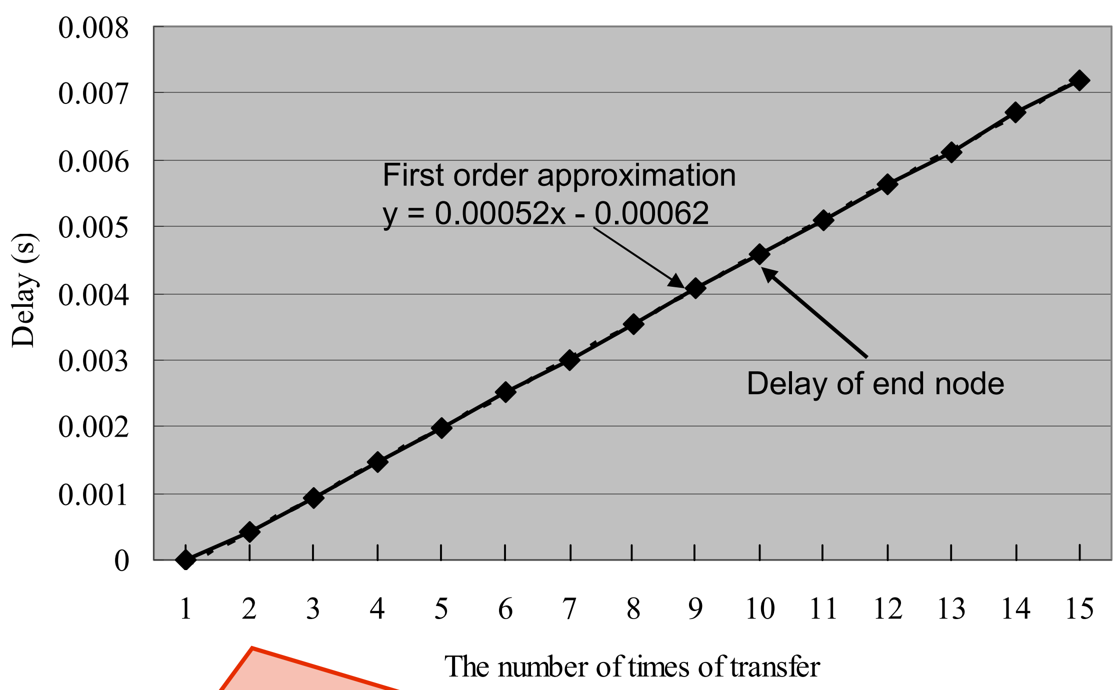
- 16 experiment PCs
  - One node work on one PC.
- 1 PC for collecting measured data
  - This PC measures the packet transmission time of all experiment PCs using the mirror port function of the L2 switch.
- 1 L2 switch with mirror port
- One multicast tree with the real nodes and the virtual nodes.

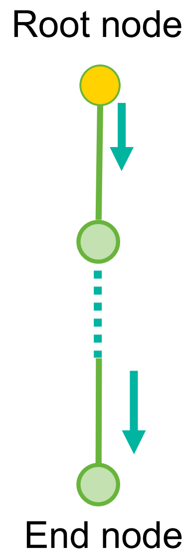


4-2-1. Results of Delay Evaluation(1/4)

Relation between the number of times of transfer and delay of end node

- The delay is defined as the period from the time when the root node sends a control message to the time when the end node receives the control message



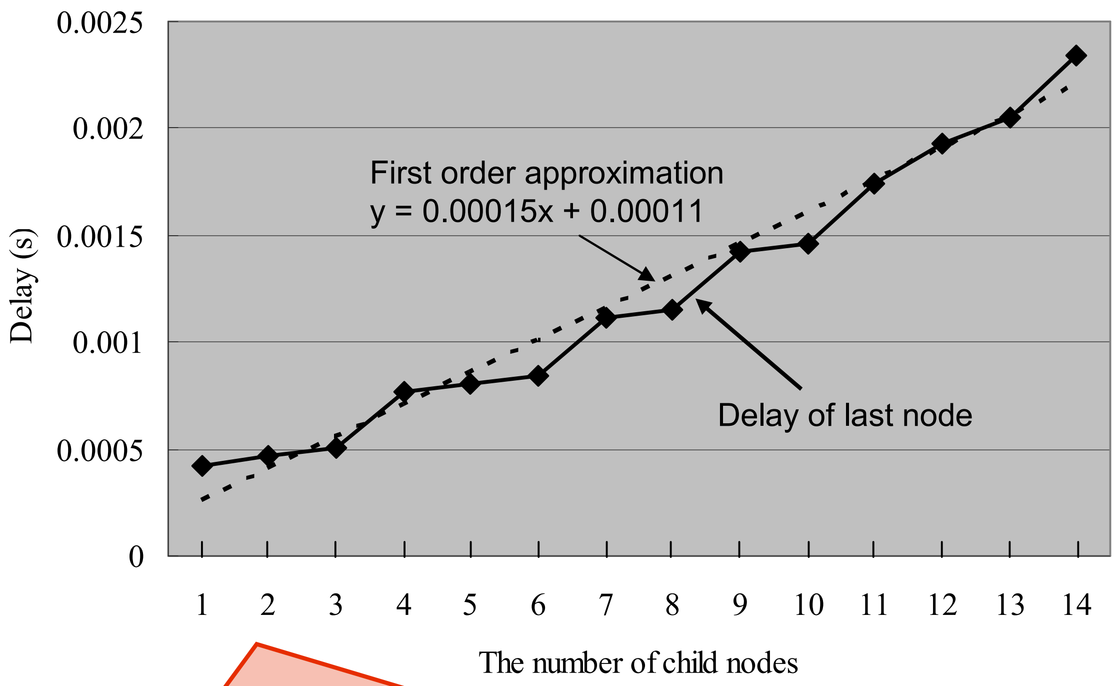


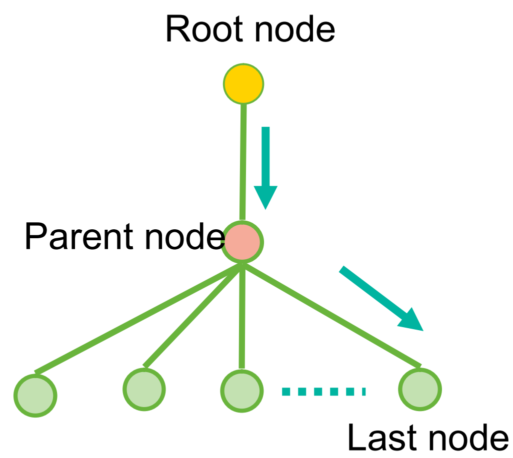
The delay at end node increases linearly with the hop count.

4-2-2. Results of Delay Evaluation(2/4)

Relation between the number of child nodes and delay of the last node

- The delay is defined as the period from the time when a node receives a control message to the time when the last child node of the node receives the control message

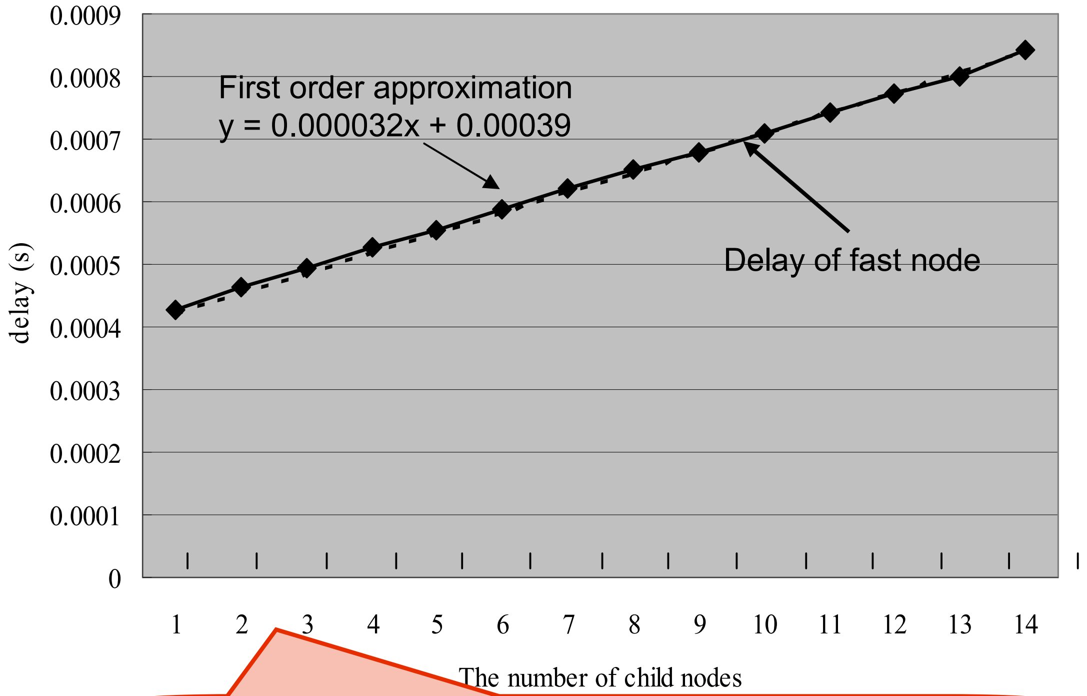


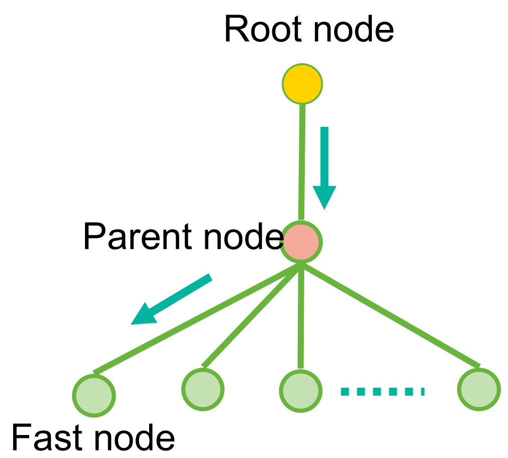


The delay at last node increases linearly with the number of child nodes.

4-2-3. Results of Delay Evaluation(3/4)

- Relation between the number of child nodes and delay of the fast child node
  - The delay is defined as the period from the time when a node receives a control message to the time when the fast child node of the node receives the control message



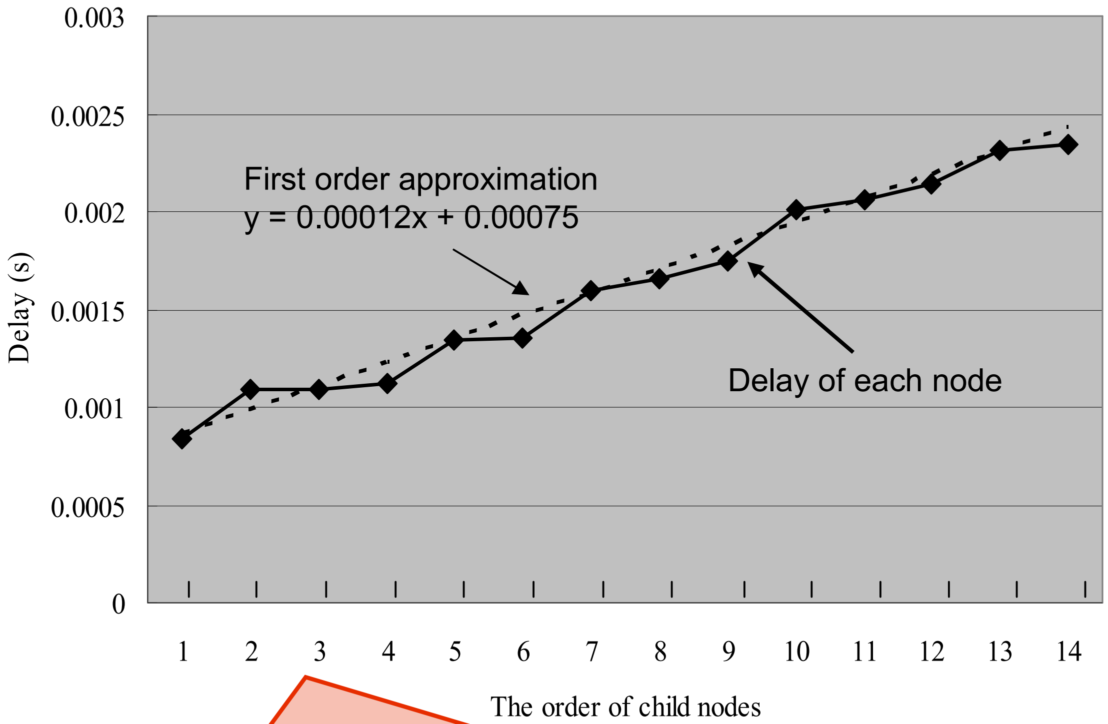


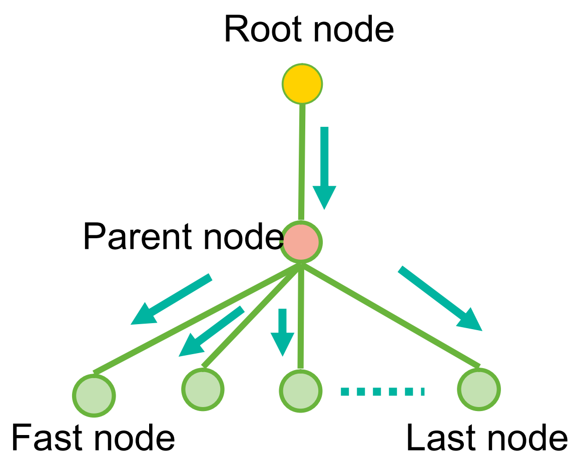
The delay at the fast node increases linearly with the number of child nodes.

4-2-4. Results of Delay Evaluation(4/4)

Relation between the order of child node and delay of each child node

- The delay is defined as the period from the time when a node receives a control message to the time when the each child node of the node receives the control message





The delay at the each node increases linearly with the order of child nodes.

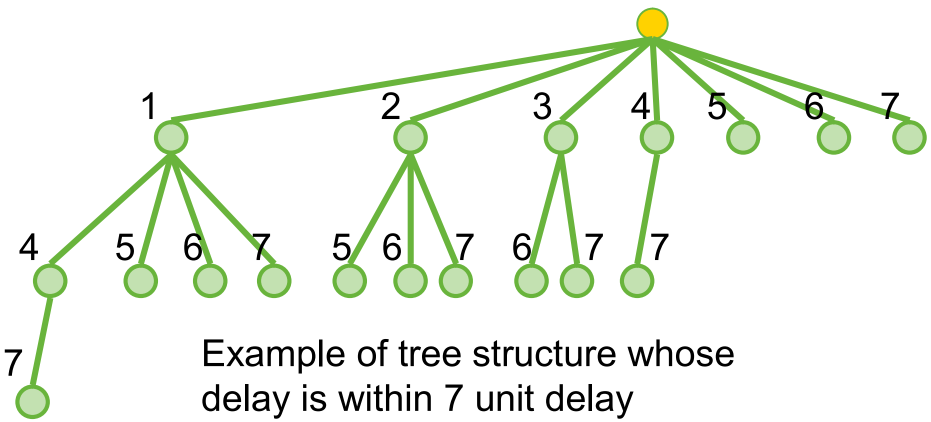
5. Discussion

- EDNN can be estimated as follows (1 unit delay is defined as the time of 0.15 - 0.17 ms. SD is delay of itself.)

$$EDNN = \begin{cases} SD+3 & \text{without child node} \\ SD+1 & \text{with child node} \end{cases} \quad (4)$$

- Worst delay

t (unit delay)	Number of nodes whose delay is whithin t
1	1
2	2
3	3
4	5
5	8
・・・	
47	83316384
48	122106096



Example of tree structure whose delay is within 7 unit delay

The prototype system can multicast the control message to over 100 million nodes within a 48 unit delay, namely within about 10 ms.

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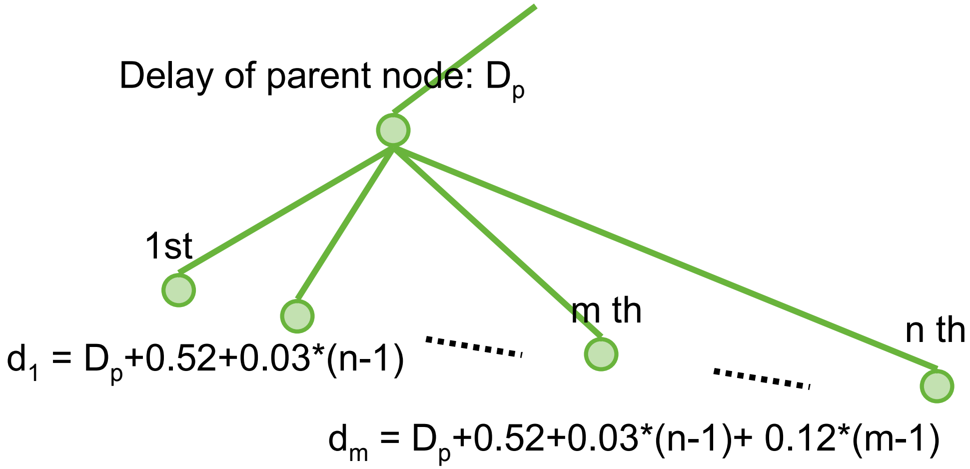
5. Discussion (cont.)

- From the results, the delay of all nodes can be estimated.
  - Let Dp be the delay of parent node, n be the number of the child nodes, and dm be the delay of the m th child node



By modeling this way, when we can not measure the delay, we can estimate the delay, EDNN and IDV of each node.

6. Conclusion

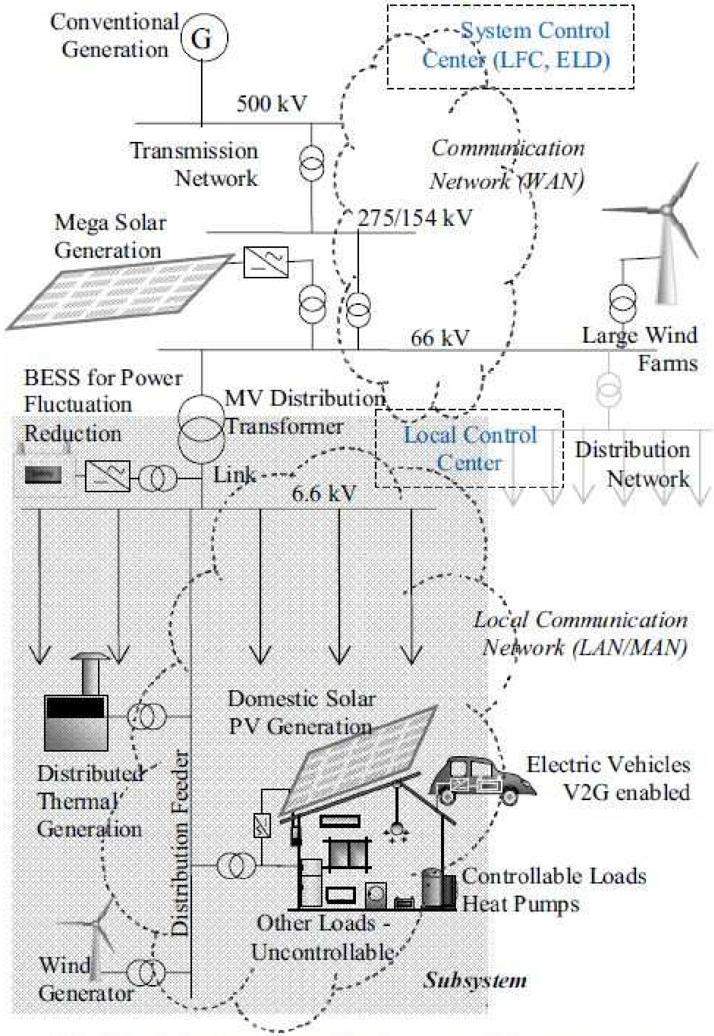
- We propose an application-layer multicast method to reduce delay variations for synchronous control of ECs.
  - Coexistence of scalability and simultaneity
    - Multicast tree for scalability
    - Tree optimization and timing adjustment for simultaneity

- Evaluation of prototype system
  - We confirmed that the proposed method has the potential of thousands order scalability and millisecond order simultaneity in the laboratory environment.

- Future works
  - Evaluation of the proposed method in real environments.

App. Example of Power Demand and Supply Adjustment

- Issues of growth of renewable energy
  - The renewable energy like PV has a negative impact on power grid because the power of renewable energy fluctuates by the weather.
- Solution for the power demand and supply adjustment by controlling the ECs in residential side.
  - The substation controls many loads like the EVs and the heat pumps simultaneously for smoothing the power fluctuations generated by unstable distributed generations such as PV.



Reference:[1]K. M. Liyanage, et al. , "Impacts of Communication Delay on the Performance of a Control Scheme to Minimize Power Fluctuations Introduced by Renewable Generation under Varying V2G Vehicle Pool Size," in Proc. of the 1st IEEE International Conference on Smart Grid Communications, pp.85-90, Oct. 2010.