Communication Systems for Wide Area Monitoring and Control Applications

Alstom grid, June 11 2014

Lars Nordström
larsno@kth.se

PSMIX Group
KTH – Royal Institute of Technology
Stockholm, Sweden

Lars Nordström – in brief

2011 *Professor Information Systems for Power System Control*

2008 *Assoc. Professor, KTH*

2006 *Director of EKC² – Swedish Centre on Electric Power*

2004 *Researcher at KTH, Program manager ICT for Power program*

2002 *CEO & Founder LB Software – mobile GIS software*

1998 *Consulting AU-System (SCADA, Control Systems)*

Senior Member IEEE

Member CIRED, Cigre

IEC TC57 Sweden chairman, IEC Strategic Smartgrid group member

EU Task force Smartgrids expert group member

PI/Co-PI for 1,5 MEUR annual

Two start-ups in Demand response & Information Modeling

100+ publications

- *Wide Area Monitoring & Control*
- *Distributed control*
- *Demand Response*

Father of three great kids!

www.ee.kth.se/psmix

Outline

- PSMIX @ KTH
- Wide Area Monitoring and Control
- Information & Communication Systems
  - Application requirements
  - System models
- Two case studies
  - State aware data delivery service
  - Adaptive PDC waiting-time

KTH – Royal Institute of Technology,

- ***Established 1827 in Stockholm***
- ***KTH in numbers:***

  800 Faculty

  2200 Research, tech & admin staff

  1800 PhD Students,

  13000 M.Sc &.B.Sc. students
- ***Focus Areas:***

  Energy, Life Science, Materials, ICT & Transportation

KTH VETENSKAP OCH KONST

THE WORLD UNIVERSITY RANKINGS

#34 Technical University

School of Electrical Engineering

- *One of ten schools at KTH*
- *EE School in numbers*
  - *70 Faculty across 10 departments*
  - *230 PostDocs & PhD Students*
  - *800 BSc & MSc Students.*
- *Focus areas*
  - *Power Systems, Power Electronics, Control Systems, Signal Processing, Communication Systems*

QS WORLD UNIVERSITY RANKINGS

#31 Electrical Engineering

Power groups at EE School

Power markets, system performance and regulation

Söder, Hesamzadeh, Amelin,

Power system stability and control, Hybrid AC/DC system control and operation

Ghandhari, Vanfretti, Berggren(ABB)

Communication & Control for Power Systems, Cybersecurity, Distributed control

Nordström, Ekstedt, Ericsson (SvK), Wang(ABB)

Power System reliability, Reliability centered asset management

Bertling, Hilber

Power Electronics, Multi-level converter technologies, HVDC applications

Nee, Norrga, Harnefors (ABB)

Electric drives for hybrid applications, permanent magnet drives, electric traction,

Wallmark, Soulard, Leksell, Östlund, Dijkhuisen(ABB)

Multiphysics modeling, EMC electromagnetic compatibility, lightning

Thottapillill, Månsson, Becerra, Norgren

Highvoltage, Insulation materials, Electromagnetic modeling,

Engdahl, Edin

Power Systems Management & Related Information Exchange

Group lead: Nordström
Affiliated: Ekstedt, Ericsson(SvK), Wang (ABB)
Post-Docs: Saleem, Chenine
7 PhD students + 2 Industrial PhD @ ABB
8 MSc Students

Research Areas:

- Reliable and High-performing ICT infrastructures
- Distributed Control of Power Systems
- Novel Market Models for Active Power Systems

Educational Activities:

- Communication & Control for Power Systems
- Computer Applications in Power Systems
- Circa 20 Masters & Bachelor projects annual

Funding:
1,2 MEUR Annual
58% External
Main sources:
FP7, Swedish Energy Agency ABB, SvK.

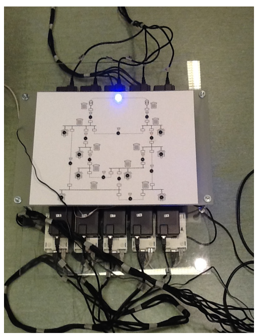
Collaboration & Funding

- ***ValueFlex***, *project on Demand response flexibility forecasting and decision support 100 k€,*
- ***DISCERN***, *EU FP7 observability and controllability of active distribution grids, 2013-2016, 400 k€*
- ***Grid4EU*** *EU FP7 Active Low Voltage grids, 200k€*
- *Real-time control of* ***Hybrid AC/DC grids****, 400 k€*
- ***Swegrids*** *– Swedish centre for Smart Grids and Energy storage,1200k€.*

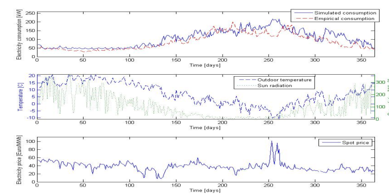
- ***INSTINCT***, *ICT Solutions for Active Distribution Networks and Customer Interaction 150 k€*
- ***Stronggrid***, *Transmission system control and security. 280 k€*
- ***Vinnova*** *project on ICT Architectures for Smartgrids and Electric Storage, 300 k€*
- ***STandUP*** *Strategic Research Area on Renewable Energy and Smart grids, 1000 k€*

Recent Highlights

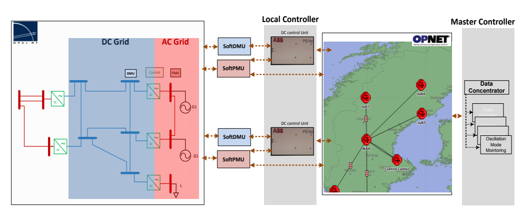
Implemented a distributed algorithm for self-healing grids using wireless communication. Article in revision for IEEE Transactions



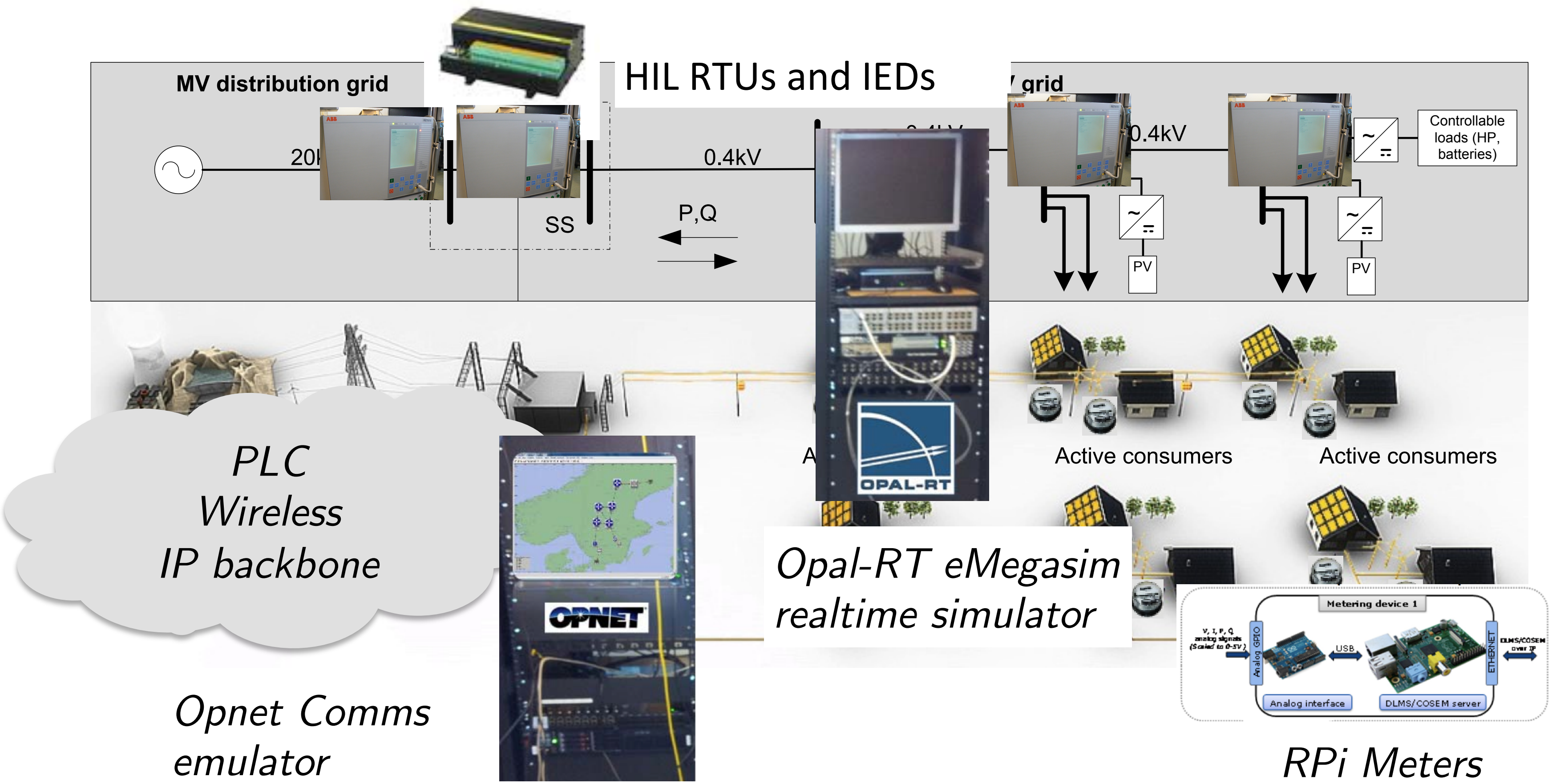
Markov chain based residential flexibility forecasting for demand response developed, and tested in Smartgrids Gotland demo project Article in revision for Elsevier Journal



Multi-agent control strategy for DC voltage control in MT-HVDC grids, published and introduced to ABB, presently implementing prototype in ABB controllers.



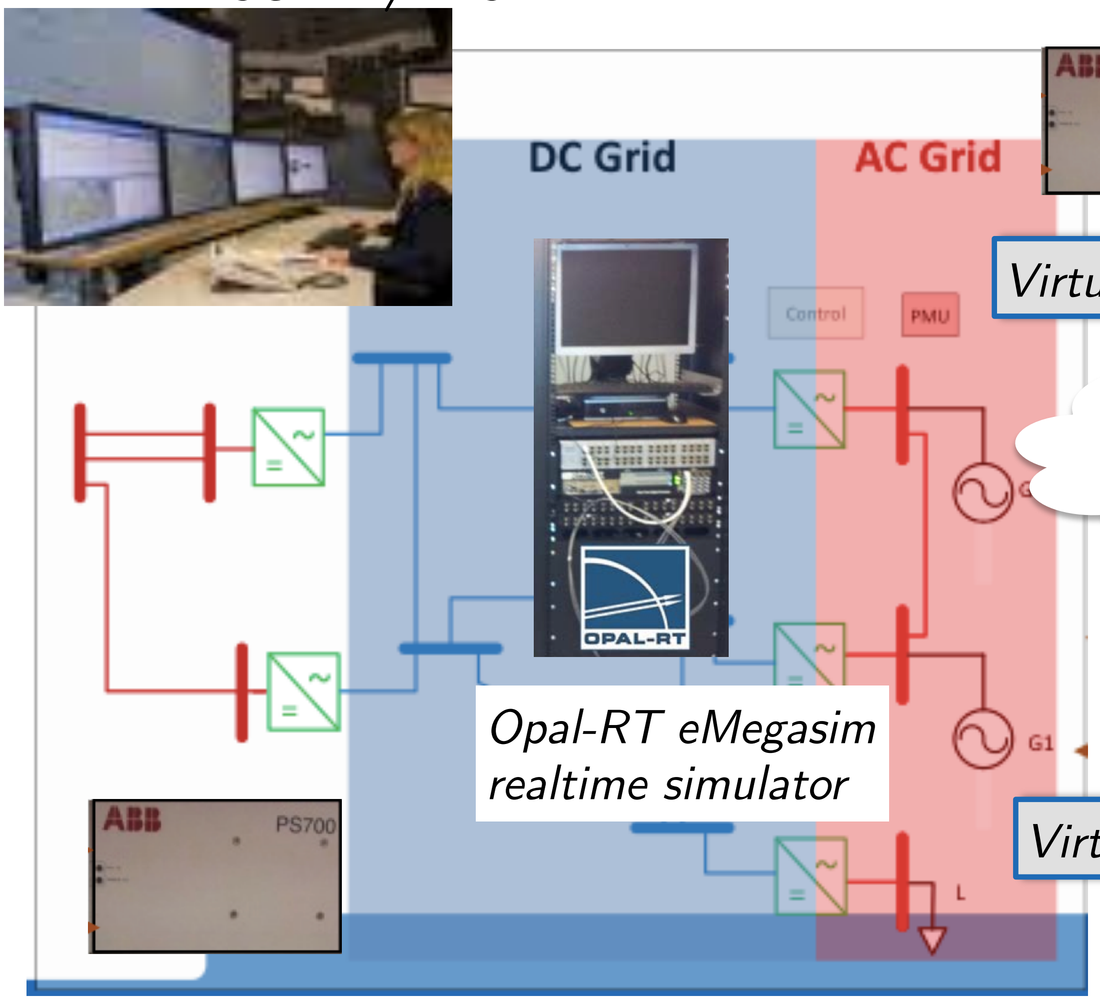
Research infrastructure – Distribution



Research infrastructure - Transmission

ABB Network Manager SCADA/EMS

ABB HVDC controllers EtherCAT I/O



Virtual PMU

Opal-RT eMegasim realtime simulator

Virtual MU

Fibre IP backbone

Opnet Comms emulator

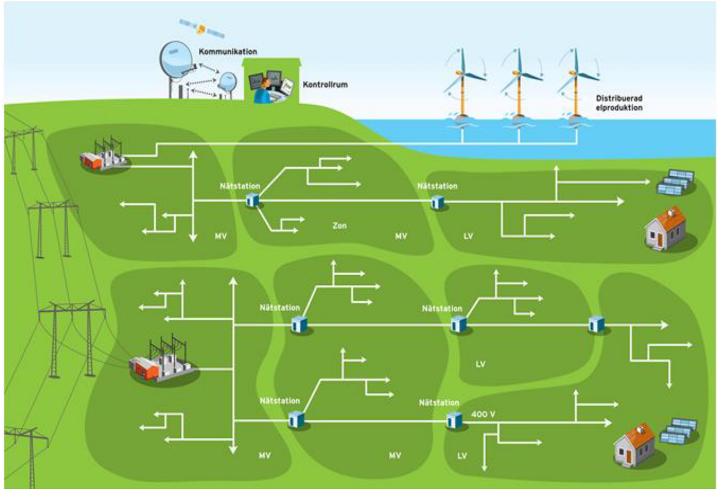
Research Infrastructure – Smartgrids Gotland

Maximise Wind utilisation, minimise export to mainland

Consumer engagement via price incentives directly to smart devices

Improve power quality (interruptions and voltage)

Cost reductions at utility and minimised risk for QoS failure charges



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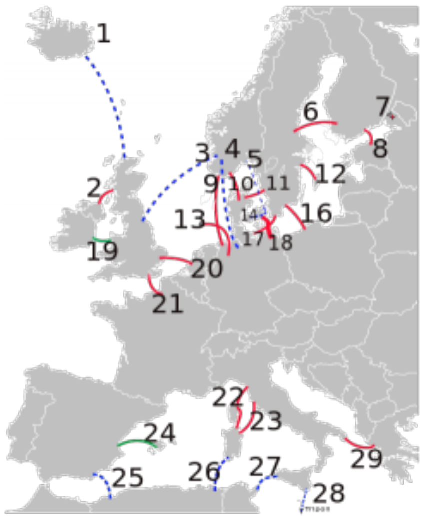
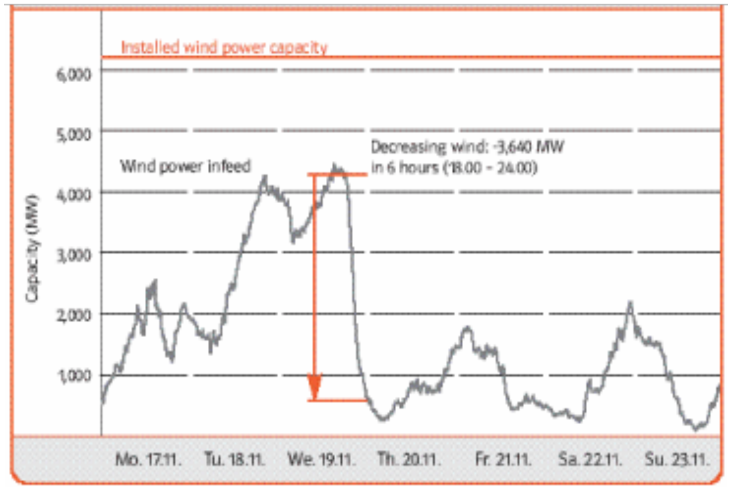
Transmission level challenges

Increased market coupling leads to larger variations in power flow



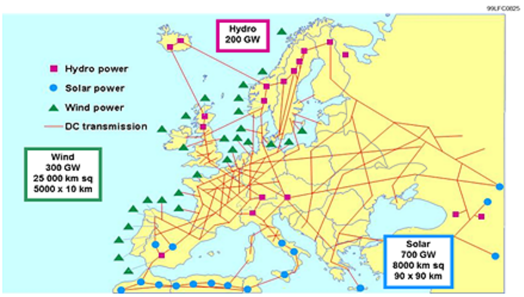
Source: Tintazul, Maix, J JMesserly;



E.On Netz (2004), *Wind Report 2004.*

Inherent variability of supply and power flow increases stress to the system

Large amounts of renewables not in close proximity to load centers.

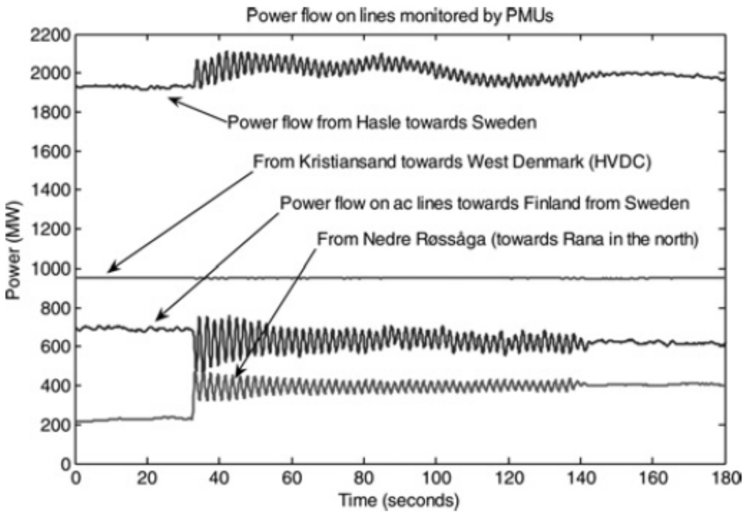


Source: Gunnar Asplund, Elways AB

Power Oscillations in the Nordic system

- *Oscillations are present*
  - *N Finland - S Norway*
  - *S Norway - Swe/Den*
  - *North Norway - Finland*
- *Event in August 2007*
  - *Low load, Hydro production in N&W Norway*
  - *3,9 GW export (30%)*
- *Increased levels of Wind power impacts damping*

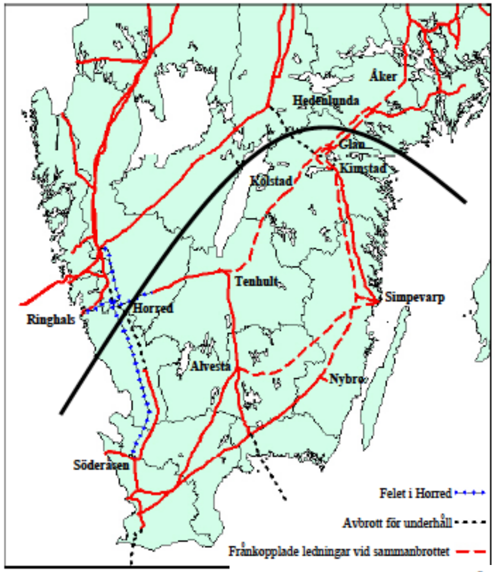
Frequency, Hz	Damping, %	Observability (mode shape)
0.33	4.34	inter-area mode, observable as power oscillations between Finland and South Norway
0.48	2.34	inter-area mode, observable as power oscillations between and South Norway and Sweden/Denmark
0.54	2.21	local area mode, observable in northern Norway
0.76	1.40	local area mode, observable in western Norway

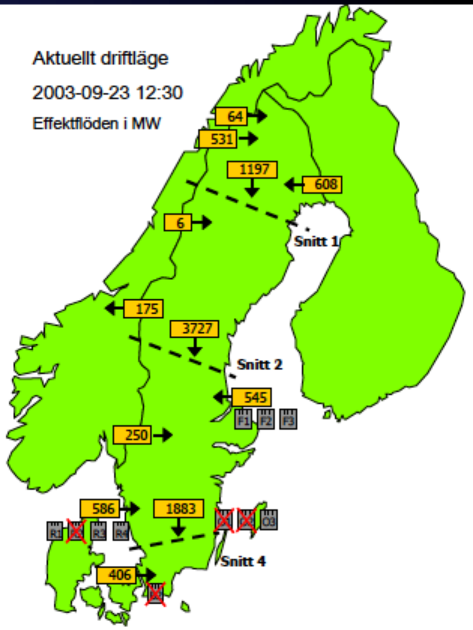


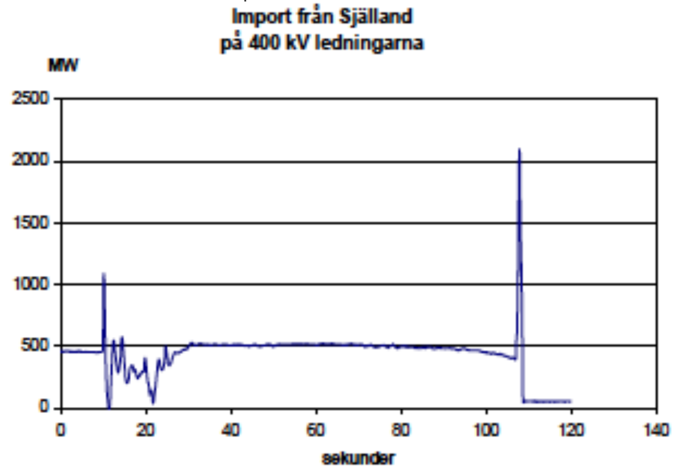
P. Korba and K. Uhlen, "Wide-area monitoring of electromechanical oscillations in the Nordic power system: practical experience," IET Gener. Transm. Distrib., vol. 4, no. 10, p. 1116, 2010.

Nordic black-out Sept 2003

- *Nuclear station trip caused increase in North to South power flow.*
- *Subsequent Double-busbar fault resulted in loss of 2 additional Nuclear stations & lines*
- *Only two 400 kV N-S line remained*
- *Voltage dropped <0,8 p.u. Protection separated SE Sweden*





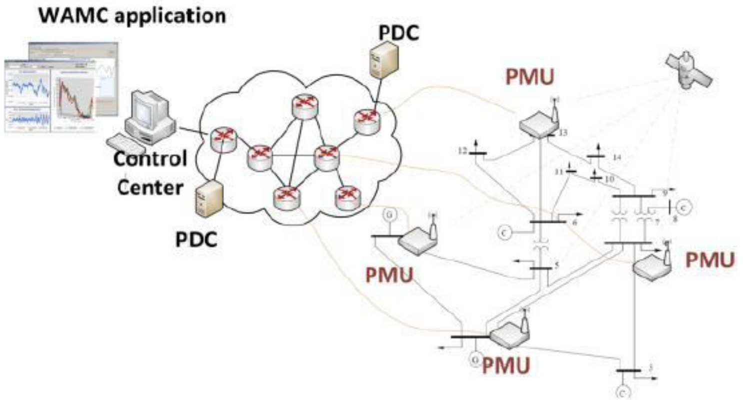


WAMC[1] Applications

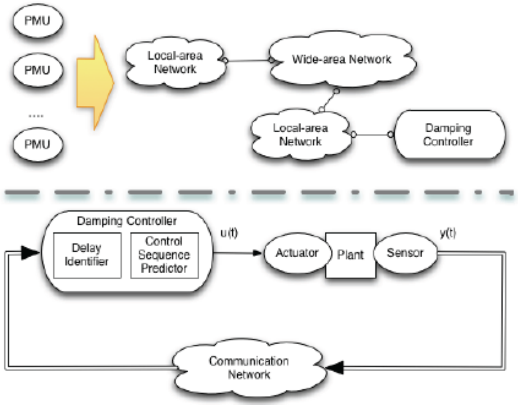
- *Candidate for managing transmission system challenges*
- *Fundamental concept:*

  Synchronized real-time data available through a high-performance communication system to provide system-wide early warning and control.

Central applications



Local application using remote data



1: A Dear child has many names: WAMS, WAMPAC, WAMC, WAPS, WAP, RAS

Central vs. Local Applications

Central applications

- State Estimation
  - Augmented with PMUs
  - PMU only SE
- Wide Area Sit. Awareness
  - Visualisation
  - Early warning
- Voltage Stability Analysis
- Post-fault analysis

Local appl w/remote data

- FACTS device control
  - Oscillation damping
  - Voltage control
- Special Protection Schemes
  - Anomaly detection
  - Intelligent Load shedding

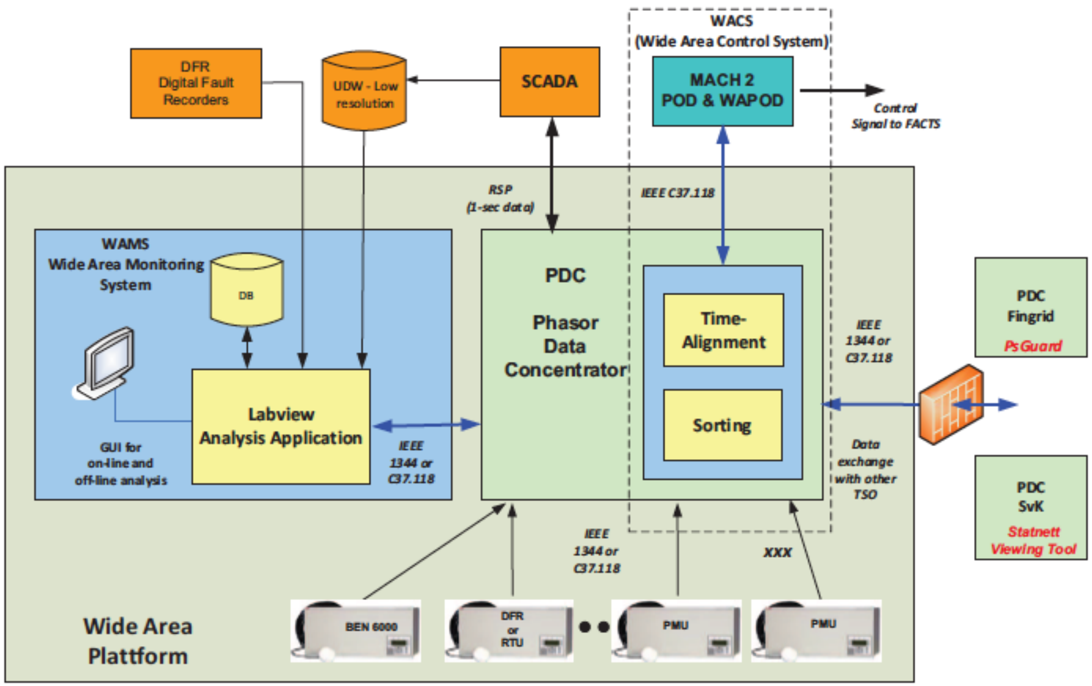
D. E. Bakken, A. Bose, C. H. Hauser, S. I. Edmond, D. E. Whitehead, and G. C. Zweigle, “Smart Generation and Transmission with Coherent , Real-Time Data,” Pullman, WA, 2010

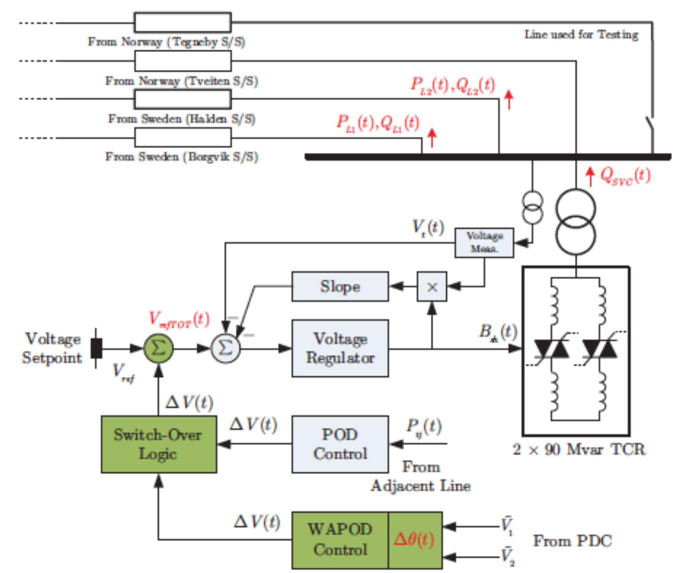
M. Zima, M. Larsson, P. Korba, C. Rehtanz, and G. Andersson, “Design Aspects for Wide-Area Monitoring and Control Systems,” Proc. IEEE, vol. 93, no. 5, pp. 980–996, May 2005.

A. G. Phadke and J. S. Thorp, “Communication needs for Wide Area Measurement applications,” in 2010 5th International Conference on Critical Infrastructure (CRIS), 2010, pp. 1–7.

NORDIC example

- POD controller in S Norway
- Intended for Voltage control modified for POD & WA-POD
- Uses local P or remote V phasors

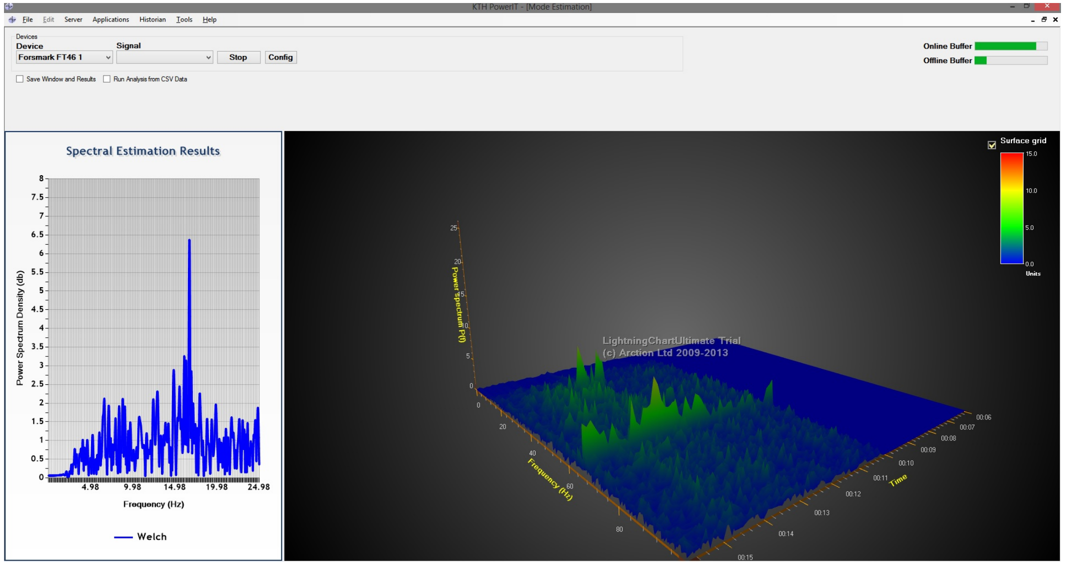




K. Uhlen, L. Vanfretti, M. M. De Oliveira, A. B. L. Member, V. H. Aarstrand, and J. O. Gjerde, "Wide-Area Power Oscillation Damper Implementation and Testing in the Norwegian Transmission Network," in IEEE Power & Energy Society General Meeting, 2012, pp. 1–7.

SvK – Sub Synchronous Resonance

- SSR Visualisation at Swedish Grid (SvK)
- OpenPDC connected to subset of PMUs in grid
- Non-commercial R&D platform for application prototyping



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WAMC & ICT

- *WAMC systems (of all types) are dependent on the non-functional characteristics of the underlying Information & Communication Systems*

- *A series of studies have been made on communcation system requirements*

- *All concluding that:*

  "It depends on the application"

QoS normalization

- *QoS requirements normalization at WSU*
- *Summarizing a set of QoS requirements*
- *Very useful, but weaker on Interoperability & Cybersecurity*

Table 1: Normalized Values of QoS+ Parameters

Difficulty (5:hardest)	Latency (msec)	Rate (Hz)	Criticality	Quantity	Geography	Deadline (Bulk traf.)
5	5–20	240–720+	Ultra	Very High	Across a grid or multiple ISOs	<5 sec.
4	20–50	120–240	Highly	High	Within an ISO/ RTO	1 min.
3	50–100	30–120	Medium	Medium	Between a few utilities	1 hr.
2	100–1000	1–30	Low	Low	Within a single utility	1 day
1	>1000	<1	Very Low	Very Low (serial)	Within a substation	>1 day

D. E. Bakken, A. Bose, C. H. Hauser, S. I. Edmond, D. E. Whitehead, and G. C. Zweigle, "Smart Generation and Transmission with Coherent , Real-Time Data," Pullman, WA, 2010.

Application Requirements Summary

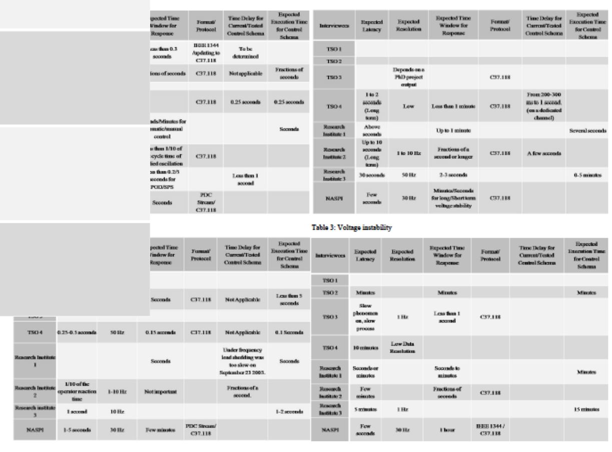
Table 2: Diversity of Data Delivery of Selected Power Application Families

a		Traditional State Estimation	Direct State Measurement	Operator Displays	Catch Up for Operator Displays	Distributed Wide-Area Control	Distribute SIPS	Synchronous Distributed Control	Renewable Gen. Islanding Control	Transient Stability	Ancillary Services	Automated Contingency Drill-Down	Post-Event (Analysis	Research
Paper Section		3.1	3.1	3.2	3.2	3.3	3.4	3.5	3.6	3.7	3.7	3.8	3.9	3.9
Loop Entity		P	P	P	P	C	C	C	C	C	C	P	P	P
In[i] (most difficult input)	Kind	SS	SS	SS	Co	SS	SS	SS	SS	SS	SS	SS	Co	Co
	Lat.	1–2	1–2	1	1	2–4	4–5	2–4	2-3	5	1	1	1	1
	Rate	1–2	1–2	2–3	—	2–3	5	1-2	2–3	—	—	2–3	—	—
	Crit	1-5	1-5	1-5	1–2	5	5	5	4-5	5	1–3	5	1-5	1-5
	Quan	3–5	1–2	3–5	1–2	3–5	2–4	1-3	1-3	1–2	1–5	3–5	5	1-5
	Geog	5	1-5	5	5	1–5	1–5	1–5	2-3	4-5	3–5	3–4	3–5	3–5
	Dline	—	—	—	5	—	—	—	—	—	—	—	2–3	1
Out[j] (most difficult output)	Kind	SS	SS	SS	Bu	Co	Co	Co	Co	Co	SS	SS	Bu	Bu
	Lat.	1–2	1–2	1	—	3-5	5	3-5	3–5	5	1–2	1	—	—
	Rate	1–2	1–2	1	—	—	—	—	—	—	1–2	2–3+	—	—
	Crit	3	3	3	1–2	5	5	5	5	5	1–3	5	1–2?	1
	Quan	3–5	1–2	1	2–4	1-2	1	1	1	1	1	3–5	5	5
	Geog	1–2+	1–3+	1	1–2+	1–5	1–5	1–5	2-3	3–5	2	3–4	5	5
	Dline	—	—	—	5	—	—	—	—	—	—	—	2–3	1
NASPInet Class		—	B	D	—	B	A	A	A	A	A	D	C	E

Nordic TSO Survey

Survey of requirements across Nordic TSOs

Interviewees	Expected Latency	Expected Resolution	Expected Time Window for Response	Format/ Protocol	Time Delay for Current/Tested Control Schema	Expected Execution Time for Control Schema
TSO 1		10 Hz	Less than 0.3 seconds	IEEE 1344 /updating to C37.118	To be determined	
TSO 2	Less than 2 seconds	10 Hz	Fractions of seconds	C37.118	Not applicable	Fractions of seconds
TSO 3						
TSO 4	0.25-2 or 3 seconds	10/50 Hz for online/offline applications		C37.118	0.25 seconds	0.25 seconds
Research Institute 1	Seconds		Seconds/Minutes for automatic/ manual control			Seconds
Research Institute 2	Fractions of seconds	Above 10 Hz	Less than 1/10 of the cycle time of studied oscillation	C37.118		
Research Institute 3	1 second	50 Hz	Less than 0.2/5 seconds for POD/SPS		Less than 1 second	
NASPI	1-5 seconds	10 Hz	Seconds	PDC Stream/ C37.118		

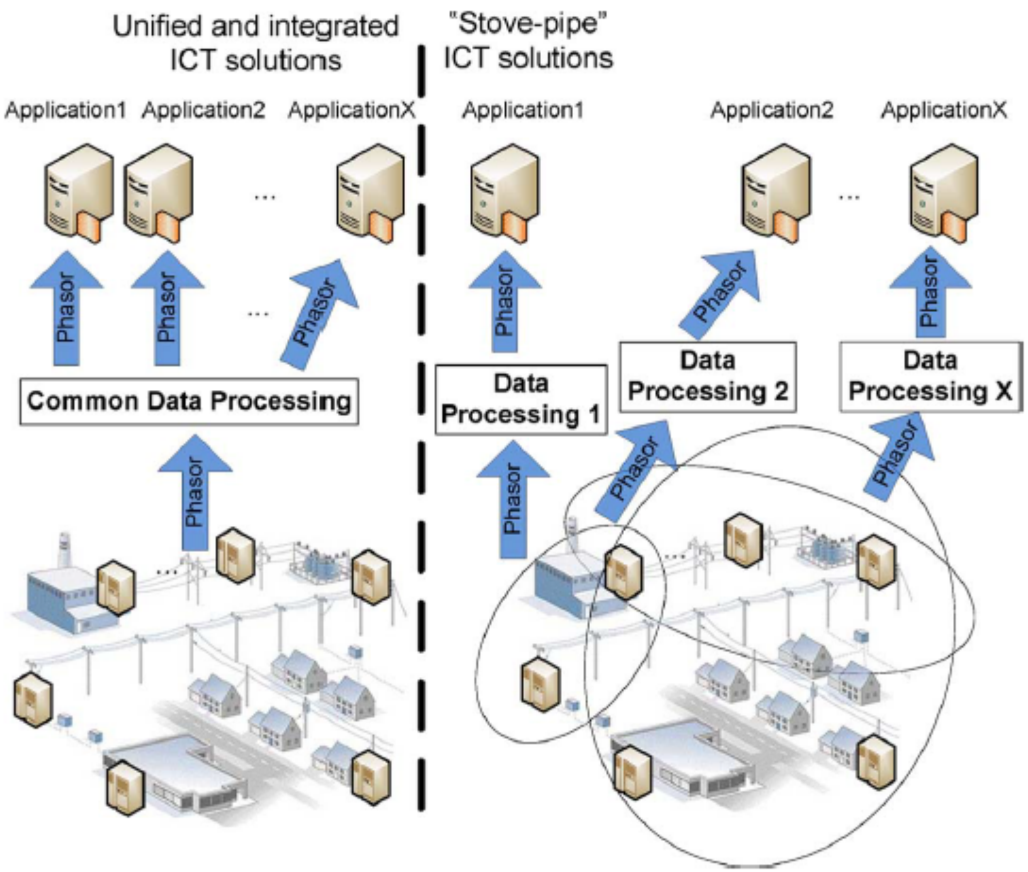


M. Chenine, K. Zhu, and L. Nordström, "Survey on priorities and communication requirements for PMU-based applications in the Nordic Region," in IEEE PowerTech, 2009, pp. 1–8.

Architectures for WAMC applications

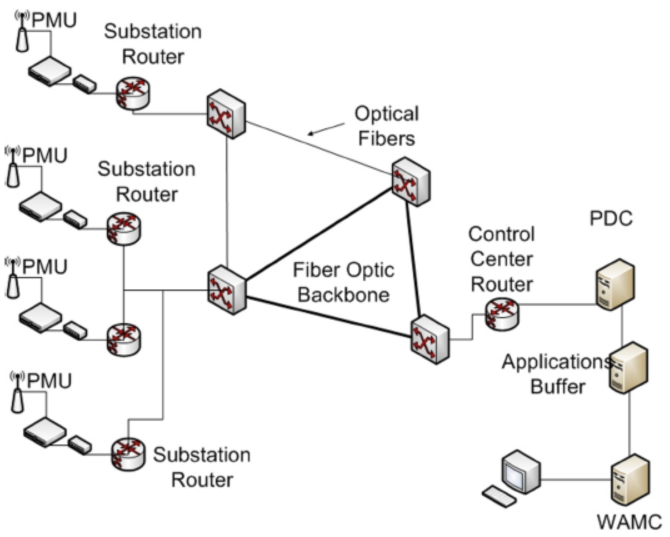
- *What is really the problem?*
- *Dedicated fibre solves it all!*

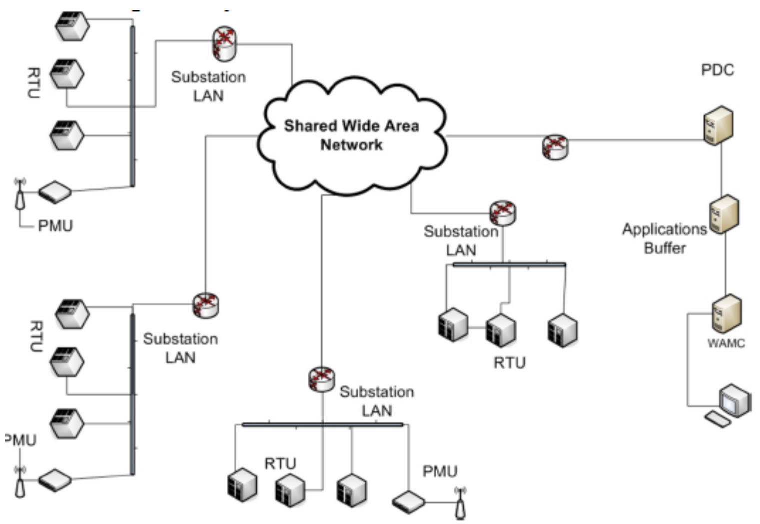
- *Shared IP networks is the future*
- *Multi application support is a must*
- *Shared architecures comes with compromises*



Outline

Dedicated vs Shared network models





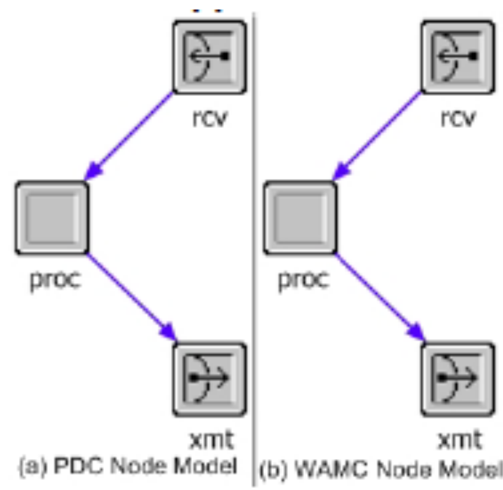
- Dedicated fibre channels
- N*64 kbps
- Core network of SDH switches
- SAS router for LAN access
- C37.118 encapsulated in IP

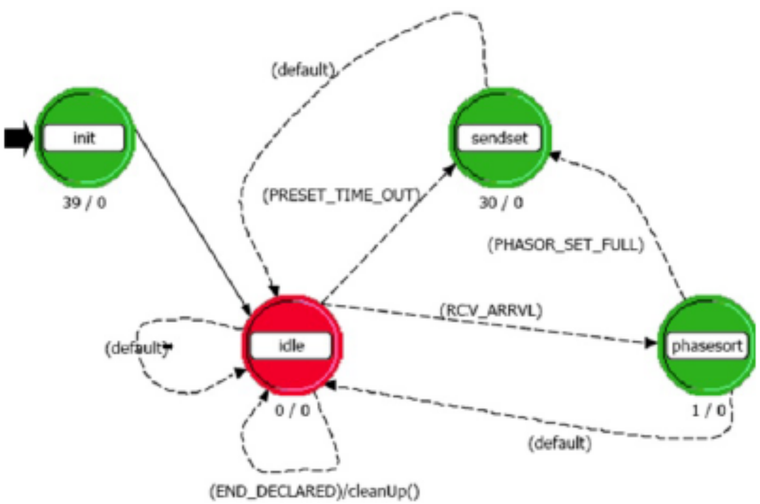
- Shared TCP/IP network
- Varying backgorund traffic up to 70% of capacity
- Core network of routers
- SAS router for LAN access
- C37.118 encapsulated in TCP/IP

M. Chenine and L. Nordström, "Modeling and Simulation of Wide-Area Communication for Centralized PMU-Based Applications," IEEE Trans. Power Deliv., vol. 26, no. 3, 2011.

PMU & PDC models in Opnet

- *Developed models in Opnet*
  - *PMU & Data sink (WAMC)*
  - *PDC sorting algorithm*





$$T_i = T_{SSi} + T_{WANi} + 2T_{CCi} + T_{PDCi}$$

$$T_{SSi} = T_{CCi} << T_{WANi}$$

$$T_i = T_{WANi} + T_{PDCi}$$

$$T_{PDCi} = T_{sort} + Min(T_w | T_{TO})$$

Completeness versus Delay

- *Analysis of completeness of dataset vs additional delay casued by PDC waiting (or Time-out setting)*

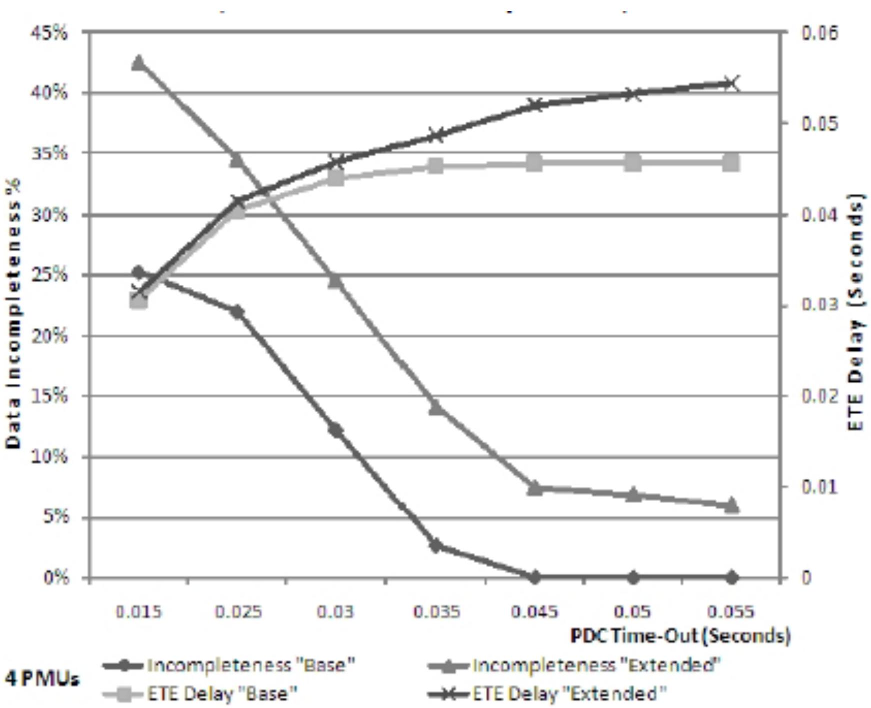


Figure 8: 4 PMUs scenarios

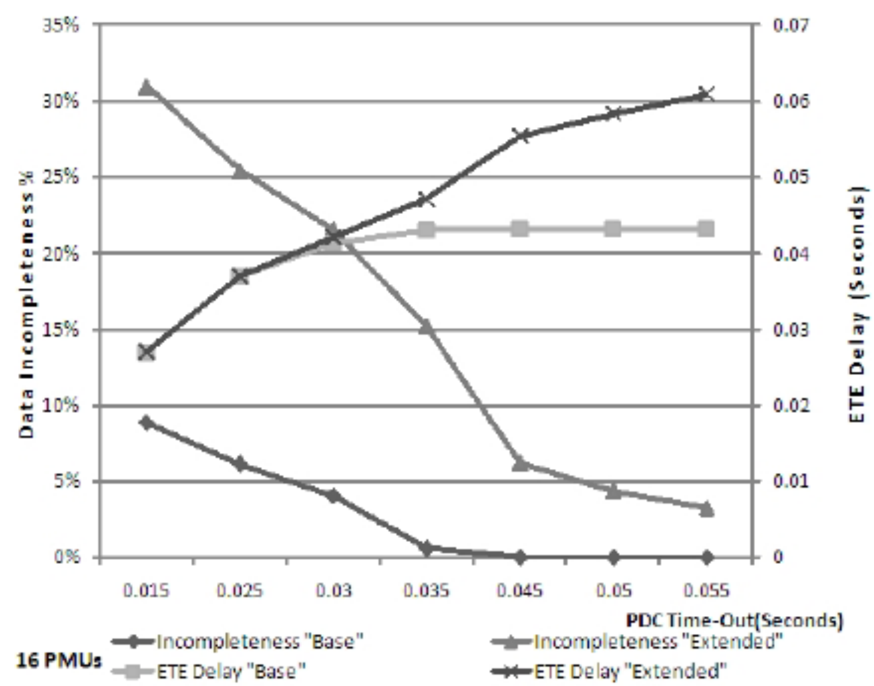
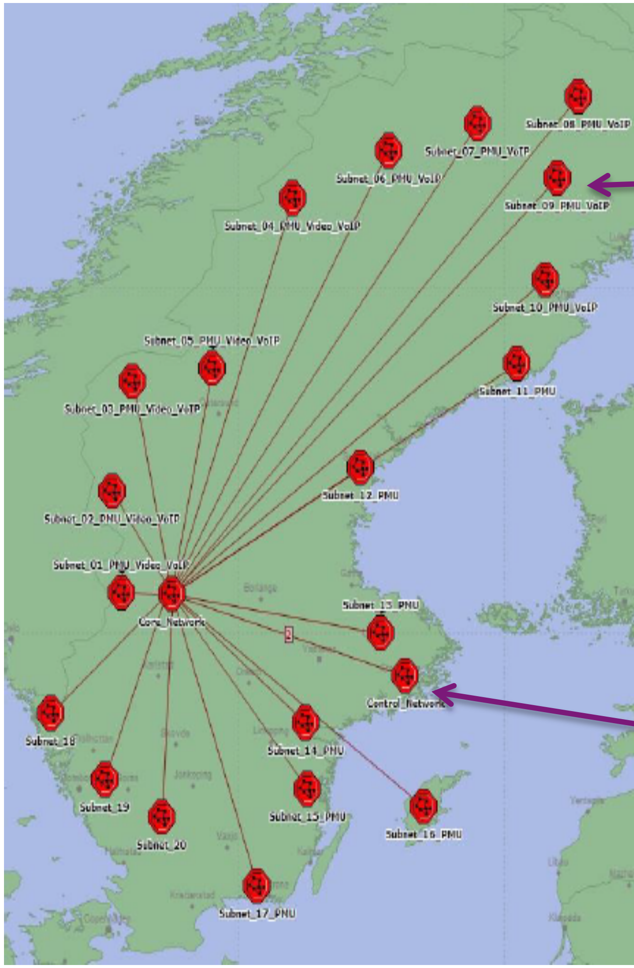
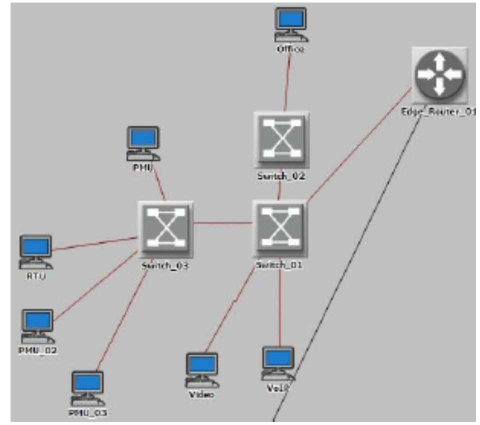


Figure 10: 16 PMUs scenarios

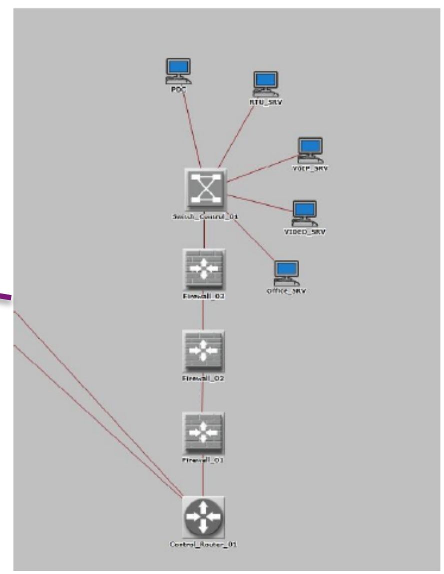
[1] M. Chenine and L. Nordström, "Investigation of communication delays and data incompleteness in multi-pmu wide area monitoring and control systems," in International Conference on Electric Power and Energy Conversion Systems (EPECS), 2009, pp. 1–6.

Opnet Modeller – QoS w TCP/IP





Substation with traffic sources,
PMU, RTU, VoIP, Video, etc



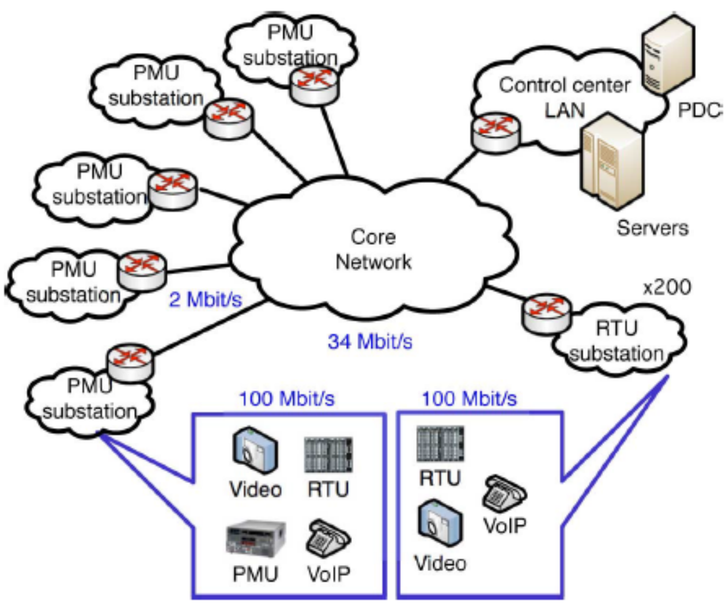
Control Centre with traffic sinks,
PDC, SCADA, VoIP, Video

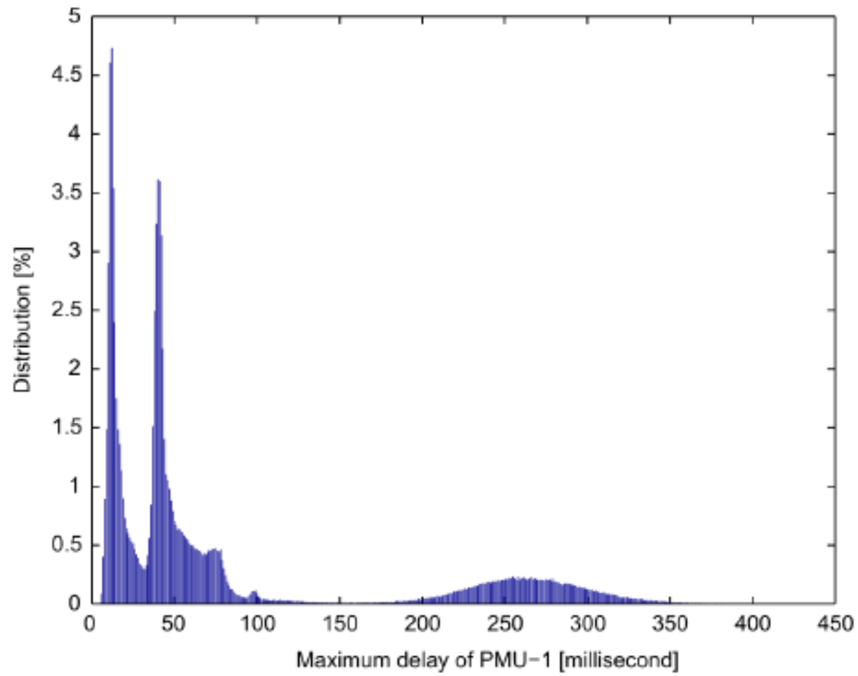
Studies include TCP & UDP
Various QoS schemes

B. Johansson, "Traffic Modeling and Evaluation of QoS schemes in Wide Area Monitoring System," M.Th, KTH - Royal Institute of Technology, 2013.

Empirical data from a Nordic TSO

- *Data series with actual delay collected during 61 days*
  Nov 2012-Jan 2013





e.g. Delay histogram PMU-1

K. Zhu, M. Chenine, L. Nordström, S. Holmström, and G. Ericsson, "Design Requirements for Wide-Area Damping System: Using Empirical Data from a Utility Network," IEEE Trans. Smart Grid, vol. 5, no. 2, pp. 829 – 838, 2014.

Goodness of fit study

- A number of potential distributions evaluated usig Akaike Information Criterium

  Normal, Log-normal, Exponential, Poisson, Weibull, Gamma, Generalised Pareto and Tri-modal

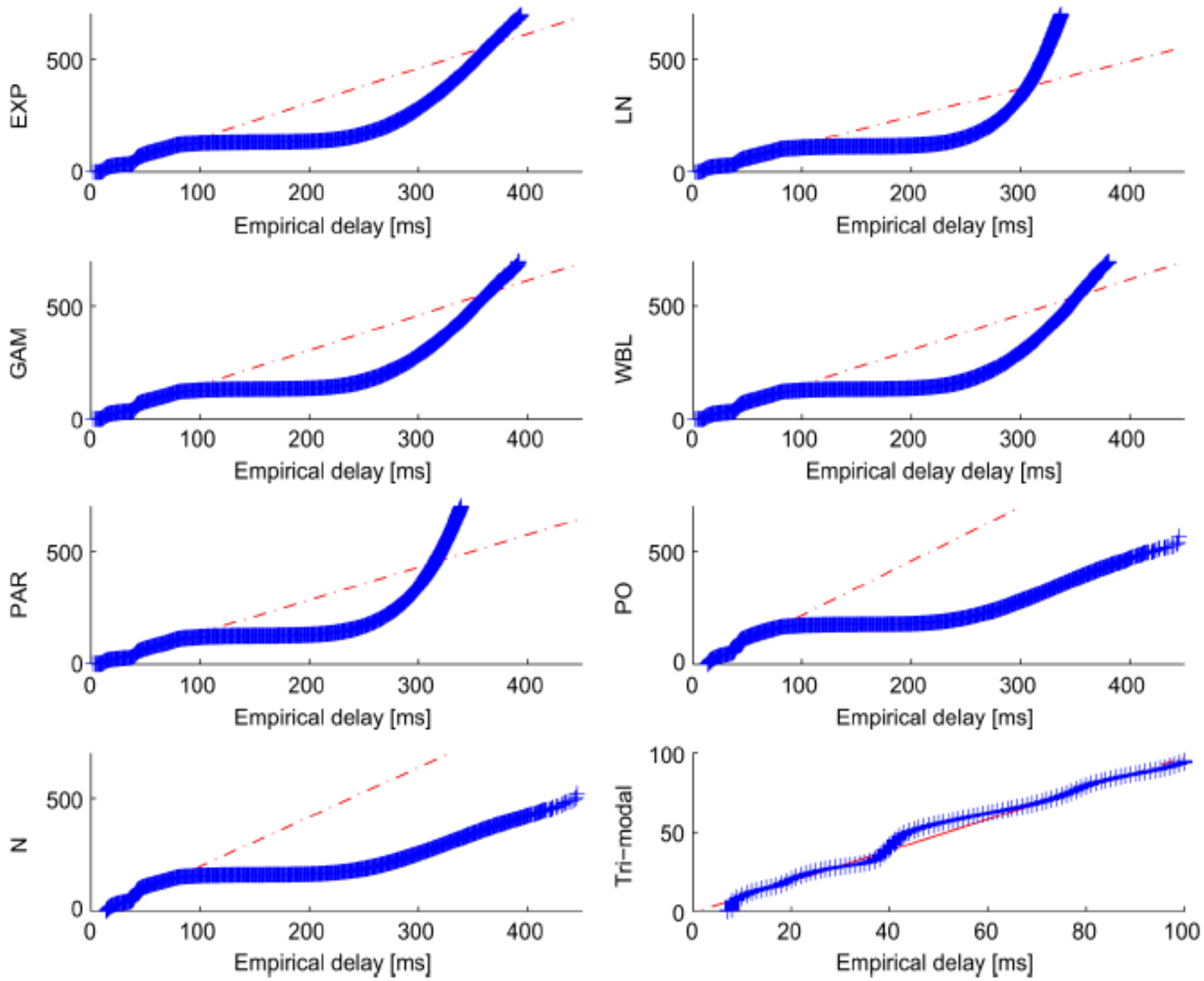
$$AIC = -2ln(L) + 2k$$

L = maximized likelihood function, k = number of parameters.

TABLE IV
AIC SCORES OF THE TESTED DISTRIBUTIONS AGAINST THE MAXIMUM PMU DELAY PROFILES

PMU	EXP	LN	WBL	GAM	PAR	PO	N	Tri-modal
1	5,044,000	4,950,000	5,040,000	5,044,000	5,024,000	5,152,000	5,373,000	**4,765,000**
2	4,884,000	4,839,000	4,999,000	5,026,000	4,932,000	4,911,000	5,282,000	**4,727,000**
3	5,033,000	4,763,000	4,943,000	4,929,000	4,900,000	4,917,000	5,219,000	**4,707,000**
4	5,013,000	4,819,000	5,207,000	5,165,000	4,913,000	4,996,000	5,233,000	**4,688,000**
5	5,441,000	5,298,000	5,467,000	5,511,000	5,501,000	5,464,000	5,612,000	**5,197,000**
6	5,106,000	4,867,000	4,892,000	5,087,000	4,955,000	4,935,000	5,102,000	**4,809,000**
7	5,483,000	5,321,000	5,521,000	5,433,000	5,672,000	5,700,000	5,723,200	**5,237,000**
8	5,537,000	5,335,000	5,430,000	5,844,500	5,519,000	5,411,000	5,699,000	**5,236,000**

Tri-modal distribution wins



Summary

- *Requirements all depend on application*
- *Plenty of studies and data available*
- *System models in Opnet (NS2, NS3 etc) allow co-simulations for controller validation*
- *Empirical data and delay probability distributions can be used for controller design*

  Tri-modal distribution provides good match for emipirical results.

Outline

- PSMIX @ KTH
- Wide Area Monitoring and Control
- Information & Communication Systems
    - Application requirements
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- Two case studies
    - State aware data delivery service
    - Adaptive PDC waiting-time

Between a rock and a hardplace

- Given the inevitable dependancy on a less than perfect (at least deterministically perfect) ICT infrastructure, what can be done?

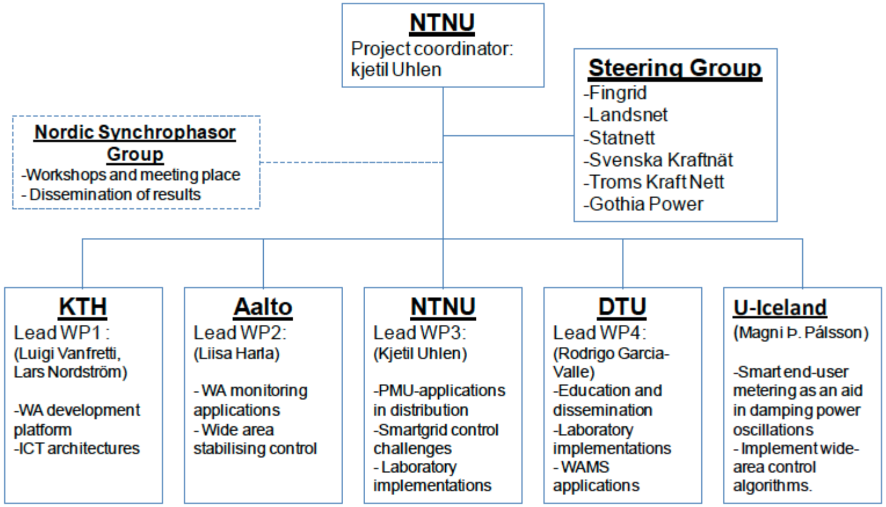
- Design controllers that adapts to ICT delays
- Design ICT systems that adapts its delays

Stronggrid project

- Develop innovative applications that will enable operation and control of the Nordic power grid more reliably and with better information about security margins.
- Develop a research platform comprised by a power systems emulator (software and hardware labs), PMUs, PDCs and specialized software.
- Develop a set of software interfaces allowing PMU-data application development, and implementation.

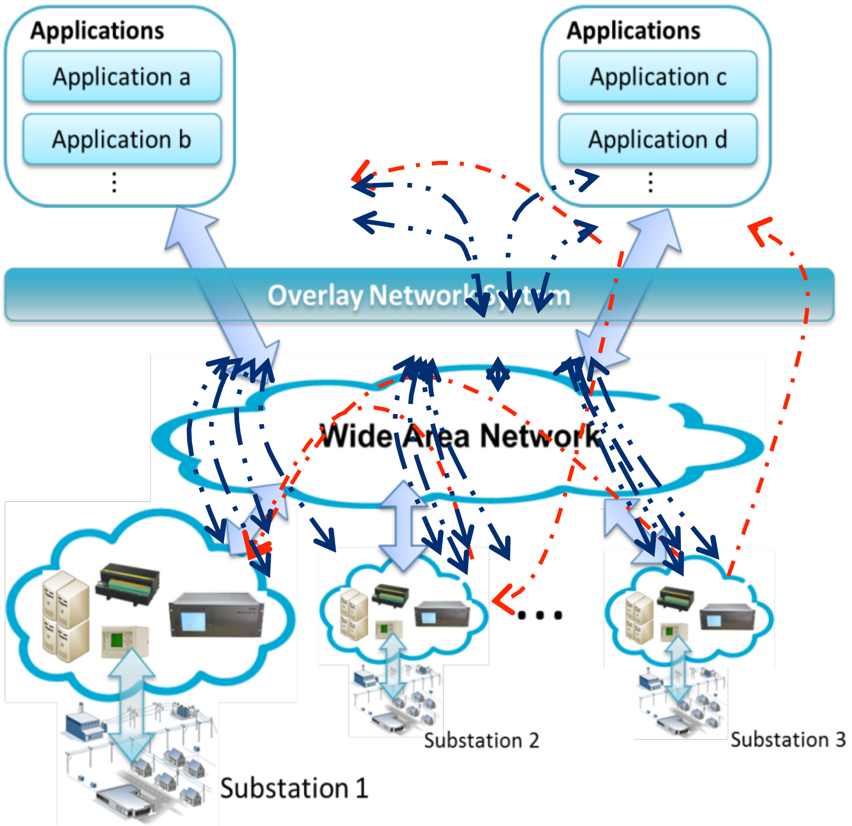
STRONgrid
nart Transmission Grids Operation and Control
KTH - NTNU - AALTO - DTU - UI

Sustainable Energy Systems 2050
NORDIC ENERGY RESEARCH PROGRAMME



Novel ICT Architectures

Peer-to-Peer Architecture

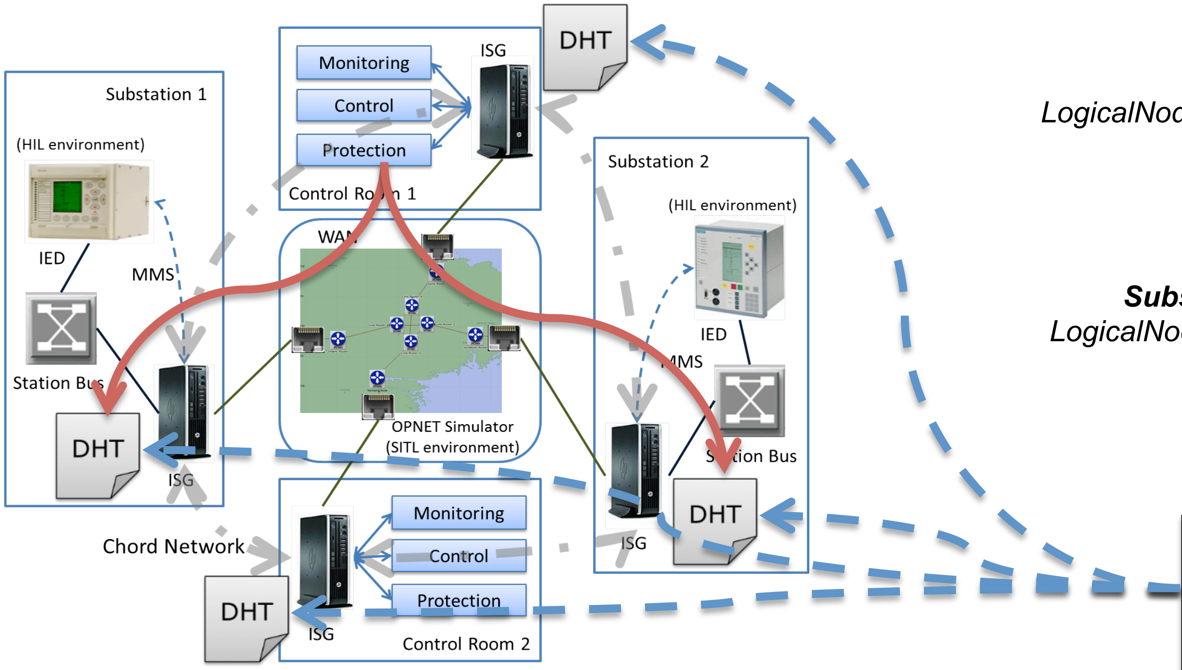


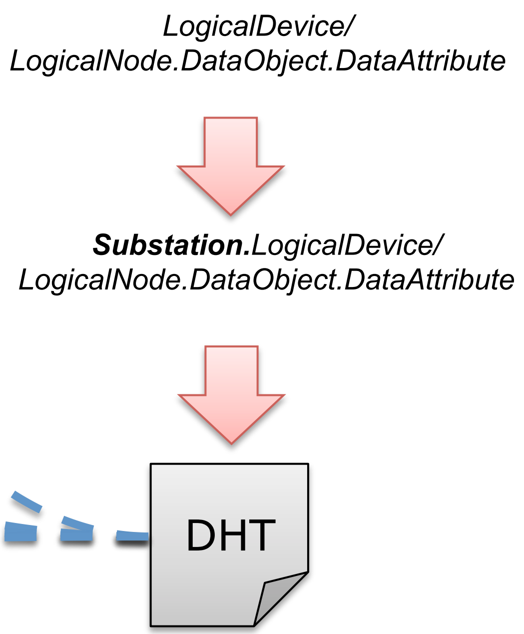
- *Enable seamless access to measurements at abstract level for applications*
- *Robust and high performance data lookup*
- *Quality of Service aware data delivery*
- *Enable applications to switch between separate data sources to enable robust control.*

Y.Wu, L. Nordström, A.Saleem, K.Zhu, N. Honeth, M. Armendariz , "Perspectives on Peer-to-Peer Data Delivery Architectures for Next Generation Power Systems". in Proceedings of ISAP 2013, Tokyo, Japan.

DHT for 61850 access across WANs

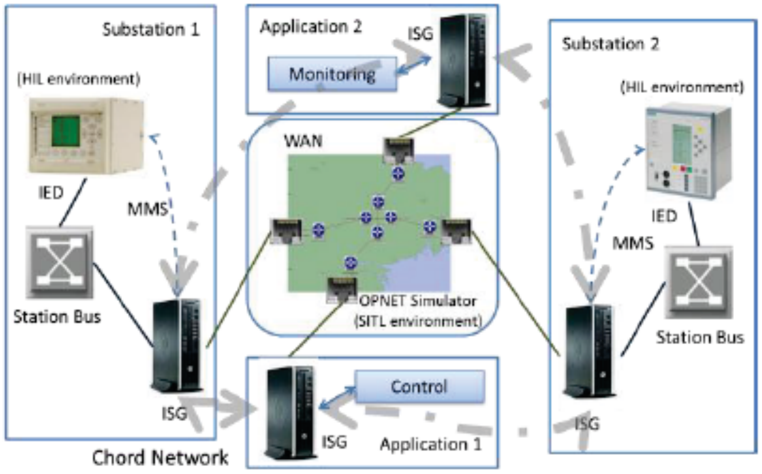
- *Available measurements (as IEC61850 Logical Nodes) at a participating IED is registered in Peer to Peer network*
- *Application queries Local iRouter (Intelligent Gateway) shares data, look-up made via Distributed Hash Table.*
- *Measurements from participating IEDs available across WAN through sharing in local ISG*

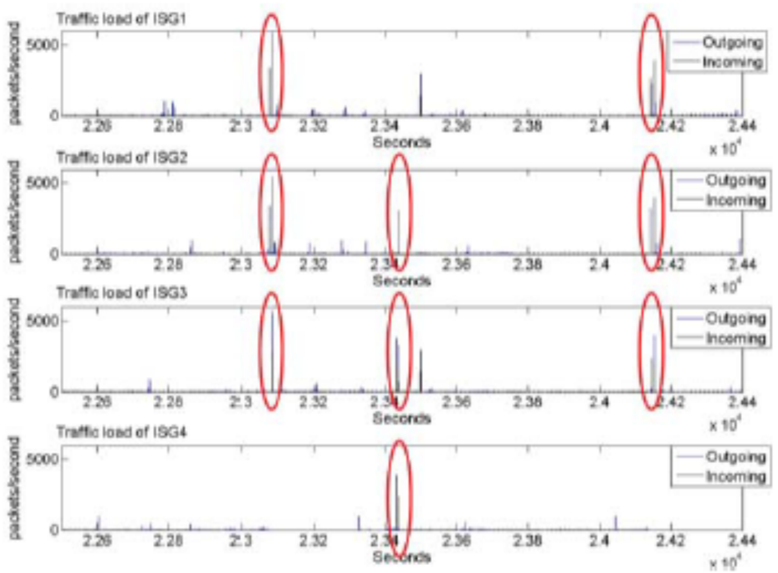




DHT using Chord

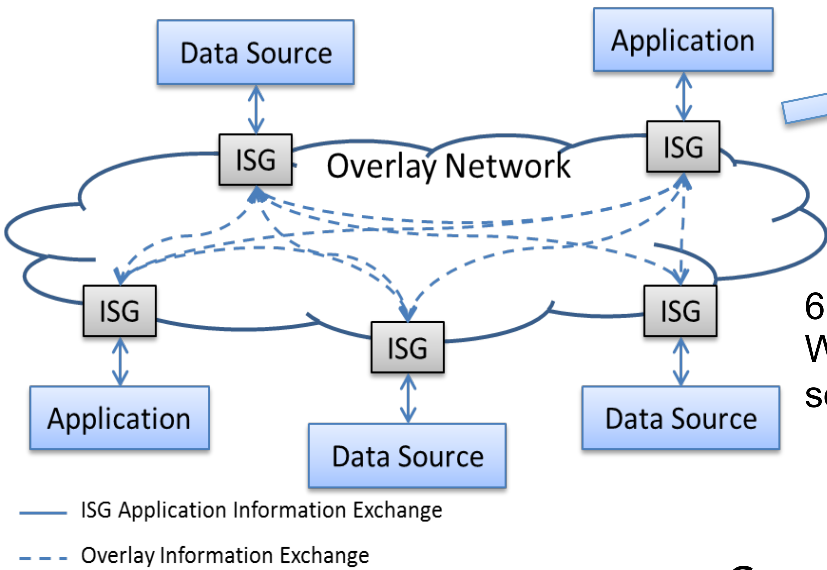
- Chord network setup to manage DHT sharing
- After initilisation a redundant DHT created.
- Stable at 40 p/s
- When ISGs leave or enter, traffic spikes emerge



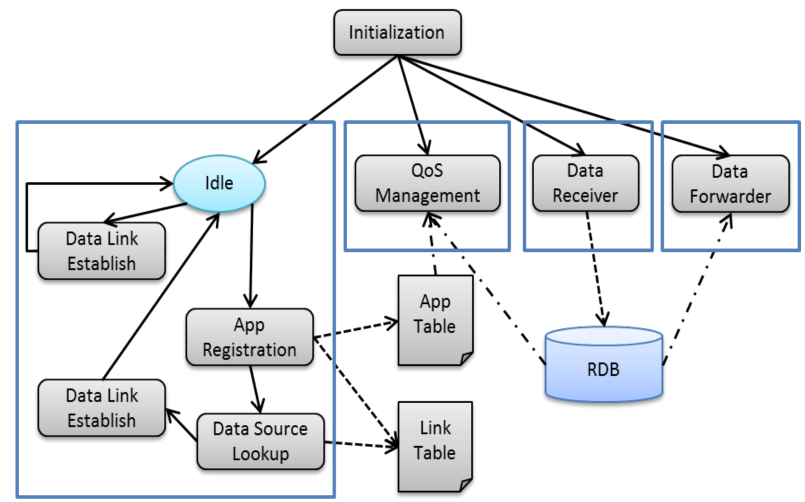


Stateful Data Delivery Service

➢ *Application interface – Stateful Data Delivery Service*

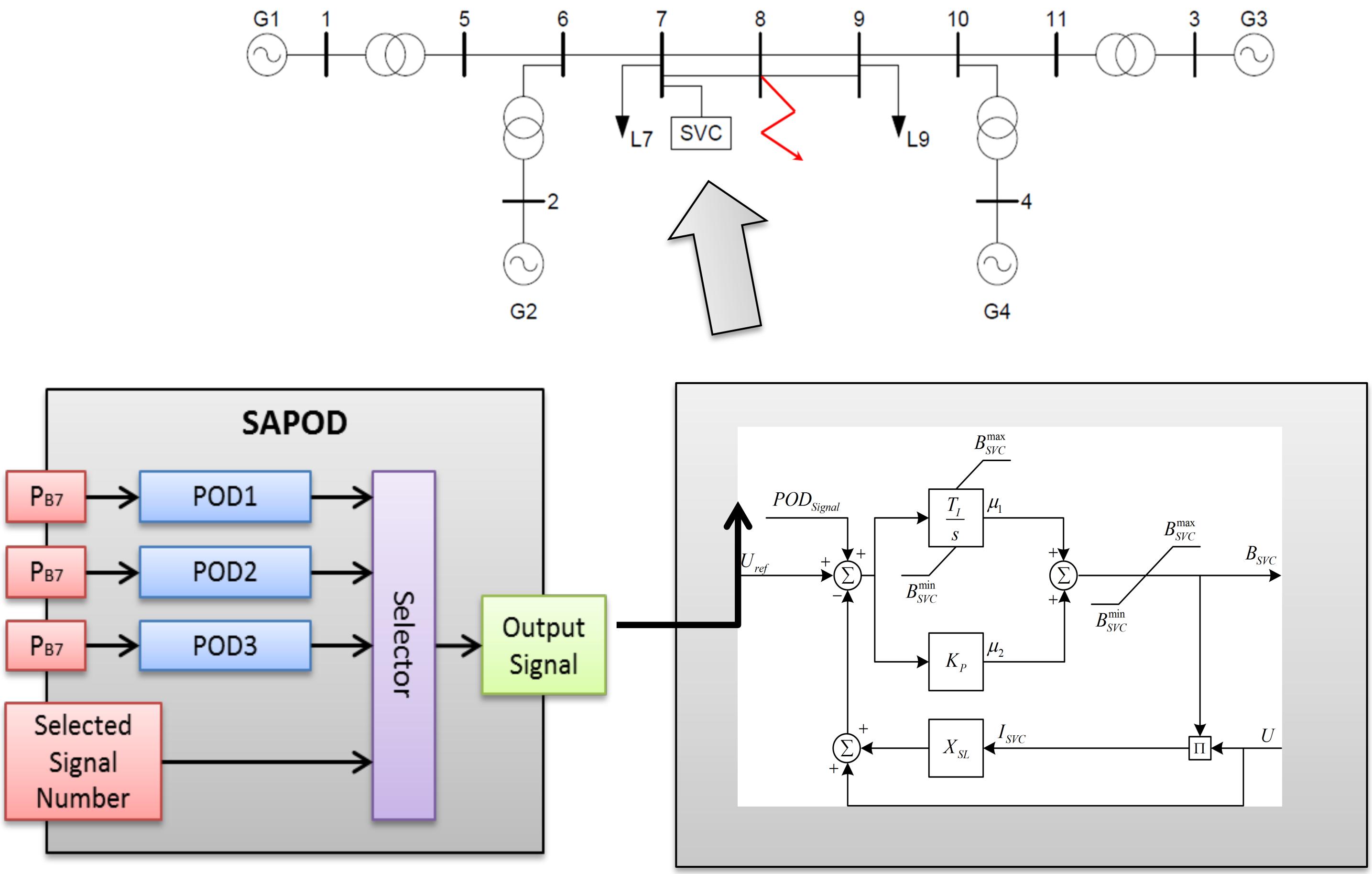


61850 over WAN solution



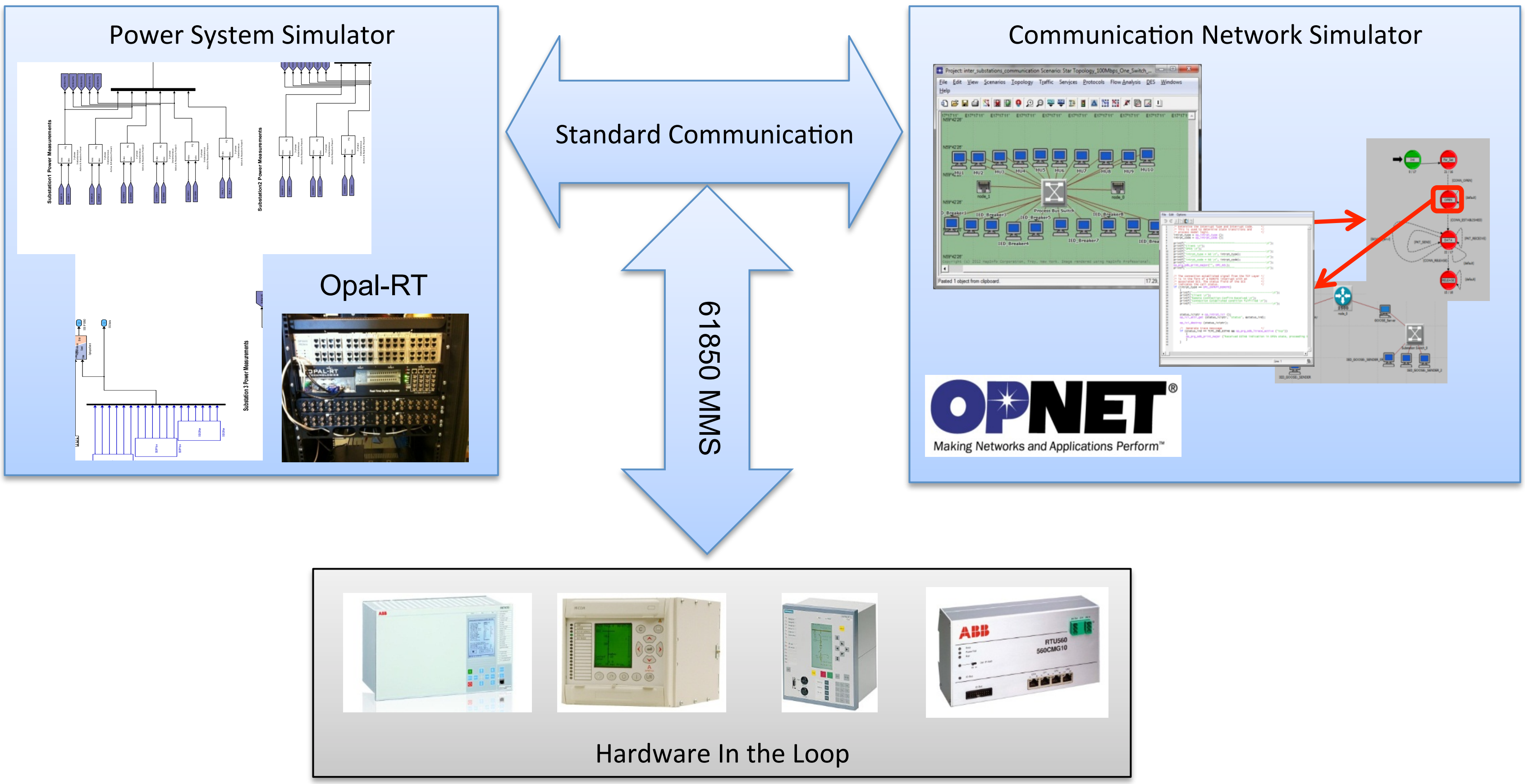
Stateful data delivery service

- *Application QoS registers requirement*
- *DDS monitors QoS online*
- *QoS guaranteed to the application*



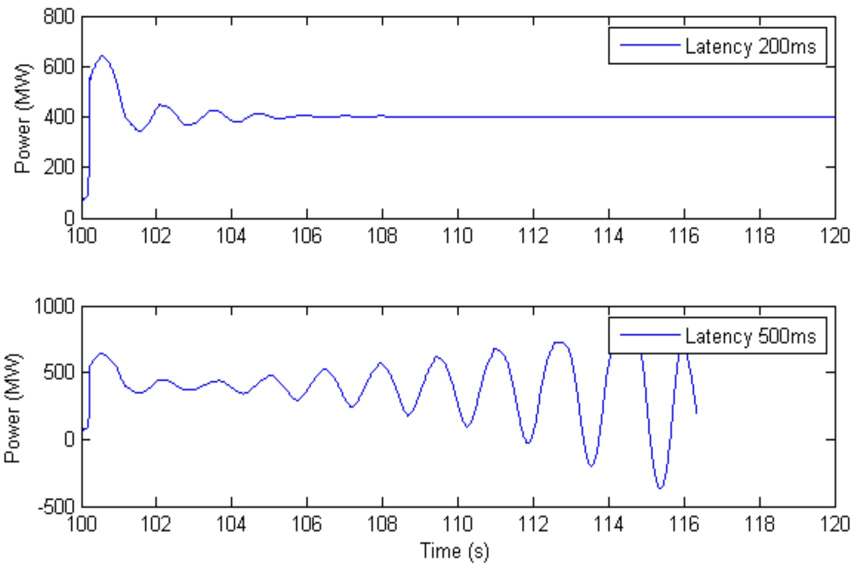
Yiming, W, Babazadeh B., Nordström L. ”Stateful Datadelivery service for Wide Area monitoring adn control applications” In proceedings of ToSG – Workshop on Trustworthiness of the Smartgrid,, Atlanta, Georgia, USA June 2014.

Laboratory Test platform

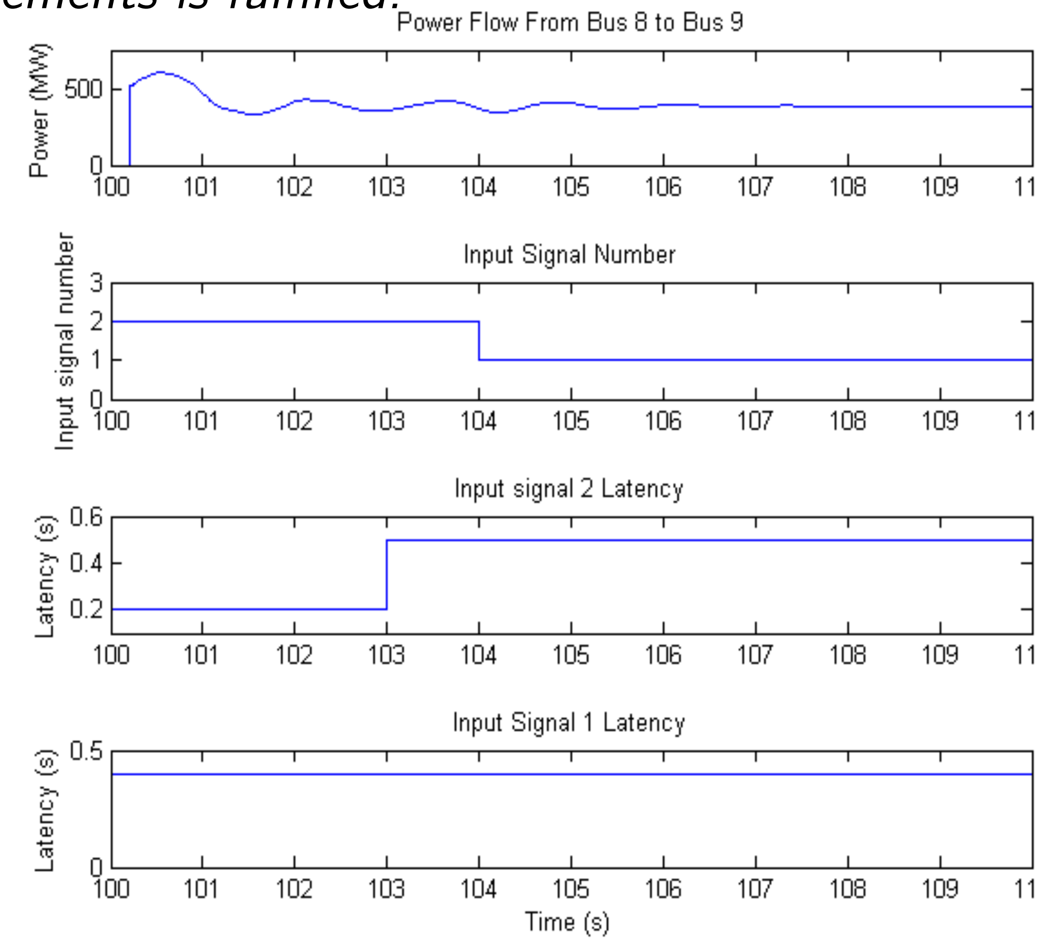


Proof of concept – real-time simulations

- *Scenario: Controller uses Powerflow at buses 7, 8 or 9 as input.*
- *SDDS monitors delays, and supplies data according to application's priorities as long as delay requirements is fulfilled.*



System stability at varying latency



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Making delay's predictable

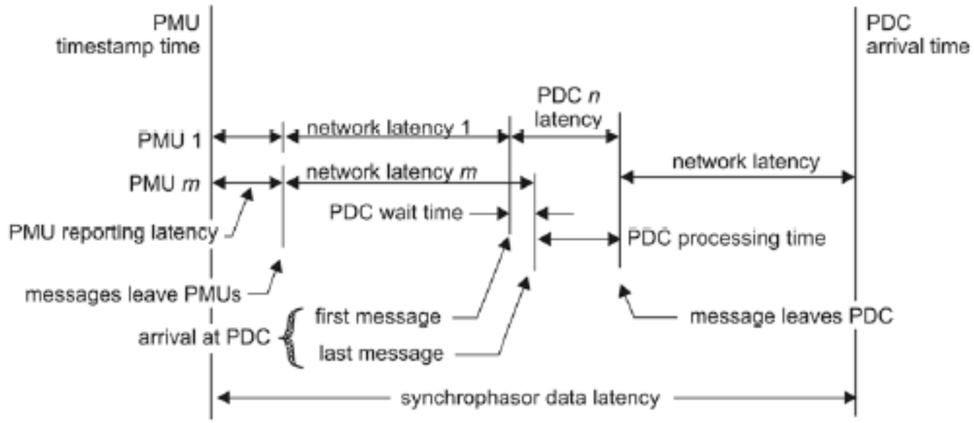
- For POD controllers, communication delays can be compensated in the controller.
- Time delay corresponds to phase shift input, if known, it can be compensated.

- So, why not make the delay predictable?

IEEE C37.244 standard

- *Guide for Phasor Data Concentrator Requirements covering among others:*

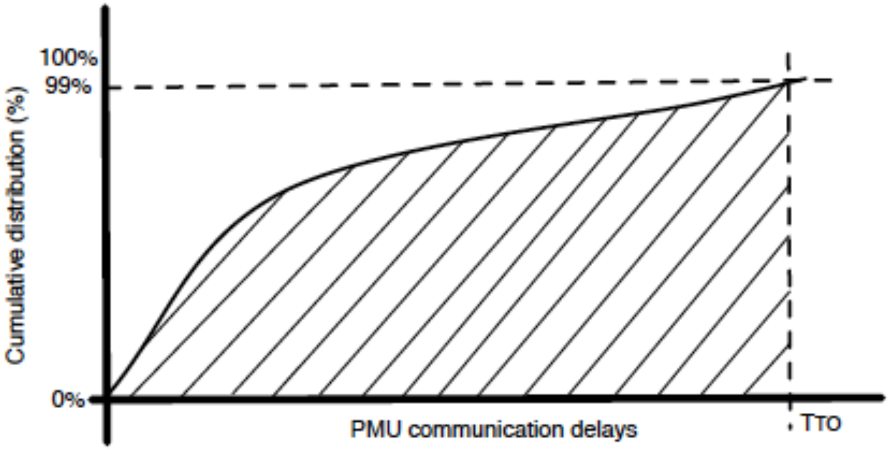
  Data Aggregation, Data forwarding, Data latency, Reporting rate conversion etc.



- *Does not cover the ability so set desired latency.*

PDC adaptive waiting time

- By creating model of the pdf of the PMU delays, we can estimate optimal timeout for the PDC , and thereby smooth the delay.



1) Collect PMU communication delays in a memory
2) Estimate PMU communication delay distribution based on the accumulated historical information
3) Determine the PDC wait time by referring the desired packet loss rate to the identified statistical distribution model of the PMU communication delays
4) Buffer PMU data frames until the calculated PDC wait time passes
5) Erase the memory and repeat the step 1)

K, Zhu, S, Rahimi, L. Nordström, Z, Boming ”Configuration of Phasor Data Concentrators as Adaptive Delay Buffers in Wide-Area Damping Control System” In review (2nd revision) for IEEE Transactions

Summary

- *WAMC applications depend significantly on the communication system performance*
- *For performance, architecture of solution is more important than actual physical or computing delay*
- *Adapting controllers to Communication variations by abstracting the Communication system to the application offers some solutions*
- *Alternately, adapting the communication latency to fit the controllers*