Emerging Needs for Evolving Hybrid Energy Cyber-Physical System (e-CPS)

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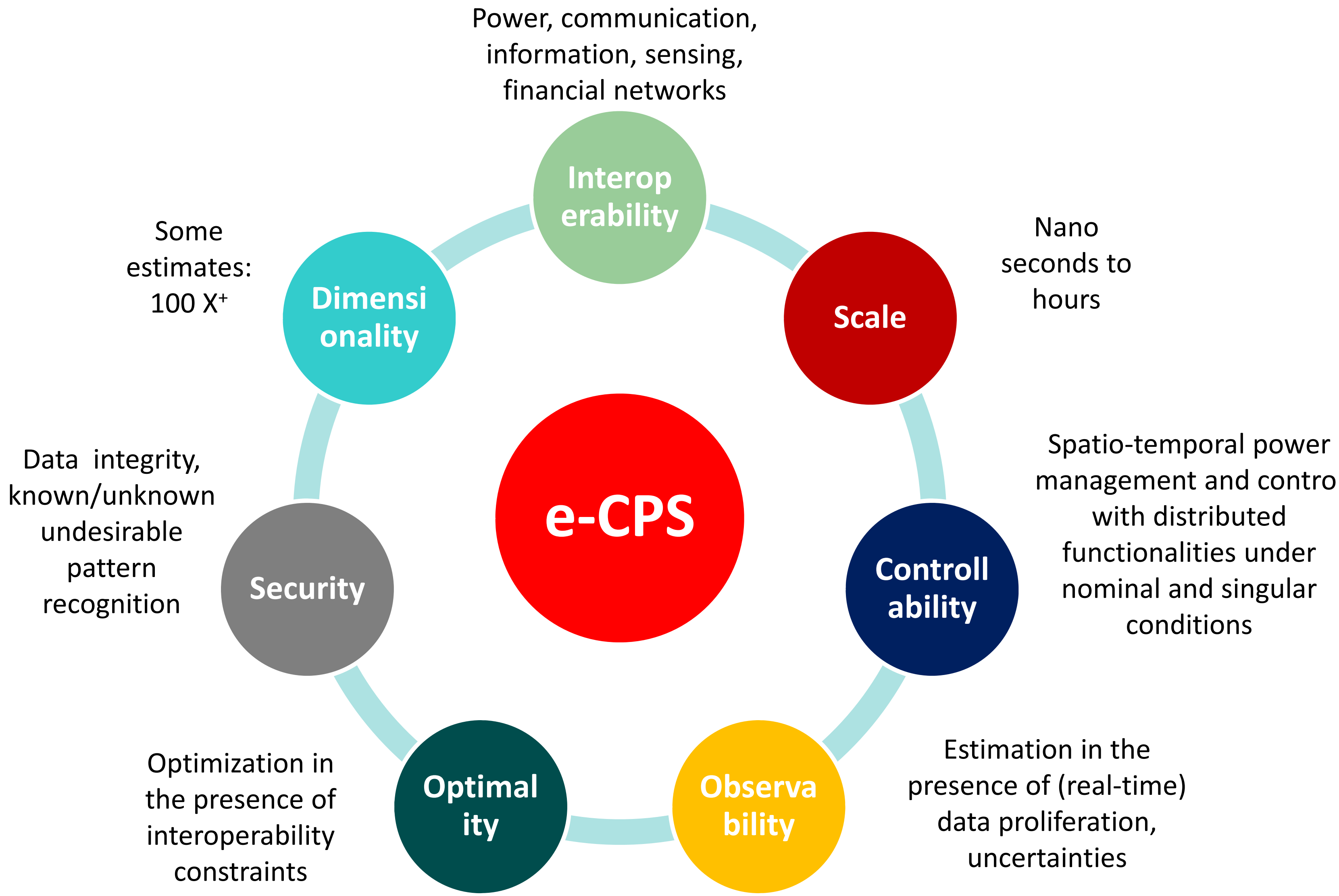
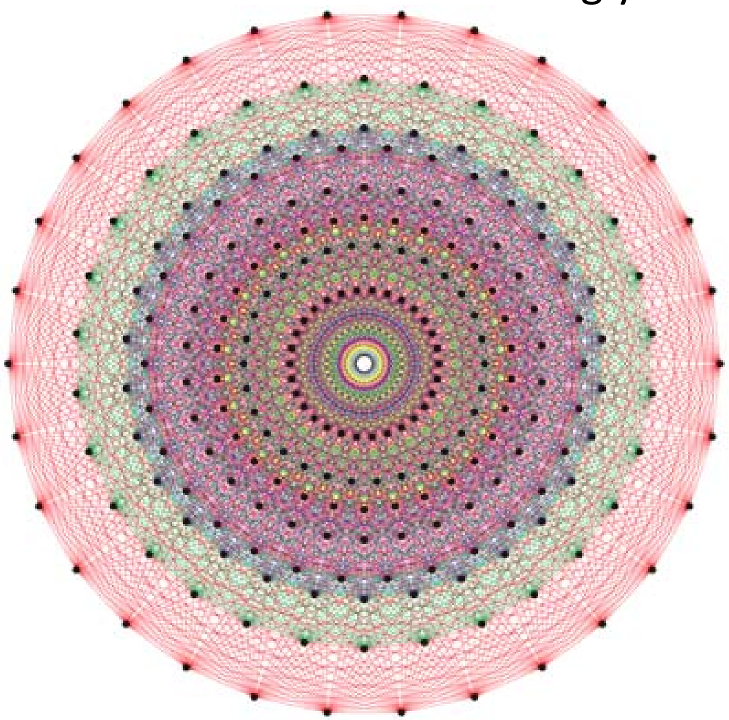
Challenges of e-CPS

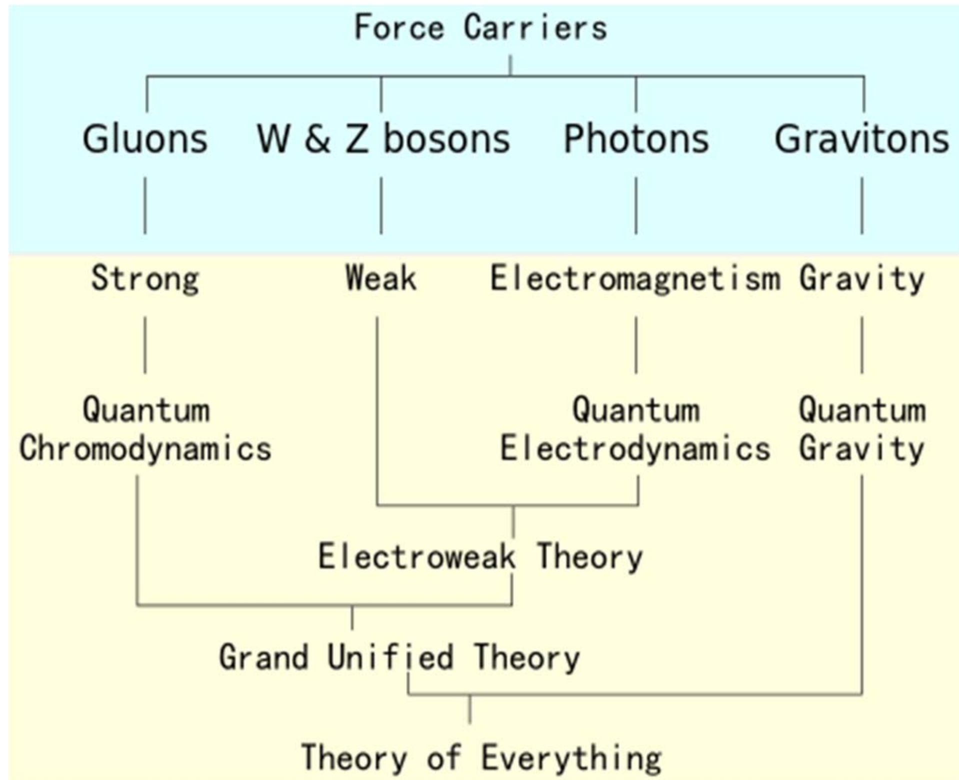


e-CPS: Great, but how do we tackle the giant?

Think of a “slightly” bigger giant:
The Universe
which works so amazingly



E^8: A theory of everything



“Understanding the interplay between small and large is the key to the solution”

Courtesy John Stembridge/Atlas of Lie Groups Project

e-CPS modeling challenges

- Unified dynamical modeling that captures hybrid, functional, event-driven, and stochastic dynamics with cross-disciplinary inter-dependencies

- Representation of multi-scale, multi-dimensional, and nonlinear spatio-temporal dynamics at varying levels of abstraction, granularity and aggregation

- Generalized approach(es) to contingency, stability, robustness, and reliability analyses that is (are) scalable, seamless, computationally efficient, and can provide offline and real-time measure and predictions

e-CPS control challenges

- Optimal networked-control to sustain distributed operation under communication-network's capacity and power-network's stability bounds in the presence of nodal and network uncertainty, stochasticity, and destabilization

- Jointly optimize control of the power network over the communication network and control of the information-flow network itself

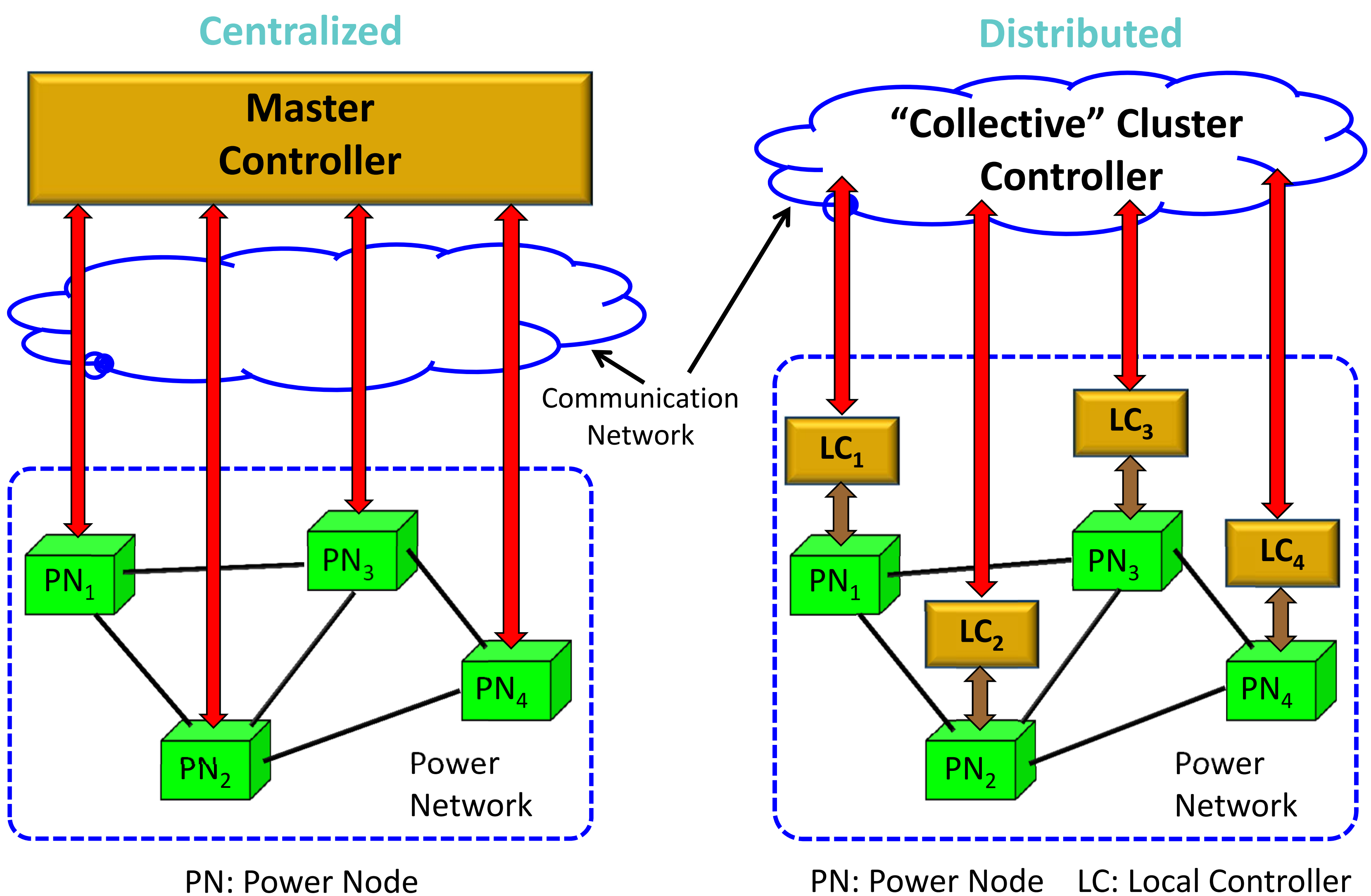
- Unification of event-driven control, protection using rapid solid-state switching, and distributed coordination

- Robustness of control in the presence of uncertainty in the truthfulness and accurate representation of the measured/ estimated data

Few Illustrations ….

Illustration 1

Network architectures for control of inverters



Control distribution

Centralized Control

Cost:

$$J = \left(X^* - X\right)^T P \left(X^* - X\right)$$

$$X^* = g(X)$$

Constraints:

$$X(t_0 + T_w) = f\left(X(t_0), \{\alpha_i\}_{i=1-h}, T_w, \{A_i\}_{i=1-h}, \{B_i\}_{i=1-h} \right),$$

$$X(t_0 + T_w) \le X_{max},$$

$$\sum_{i=1}^{h} \alpha_i = 1, \text{ and } 0 < \alpha_i < 1$$

Cost and Constraint Decomposition

Module 1

Cost: $\left(X_1^* - X_1\right)^T P_1 \left(X_1^* - X_1\right)$ $\quad X_1^* = g_1'(X_1, D_1)$

Constraints:

$$X_1(t_0 + T_{w_1}) = f_1\left(X_1(t_0), \{\alpha_{1_i}\}_{i=1-h_1}, T_{w_1}, \{A_{1_i}\}_{i=1-h_1}, \{B_{1_i}\}_{i=1-h_1}, W_1 \right),$$

$$X_1(t_0 + T_{w_1}) \le X_{1max},$$

$$\sum_{i=1}^{h_1} \alpha_{1_i} = 1, \text{ and } 0 < \alpha_{1_i} < 1$$

⋮

Module *N*

Cost: $\left(X_N^* - X_N\right)^T P_N \left(X_N^* - X_N\right)$ $\quad X_N^* = g_N'(X_N, D_N)$

Constraints:

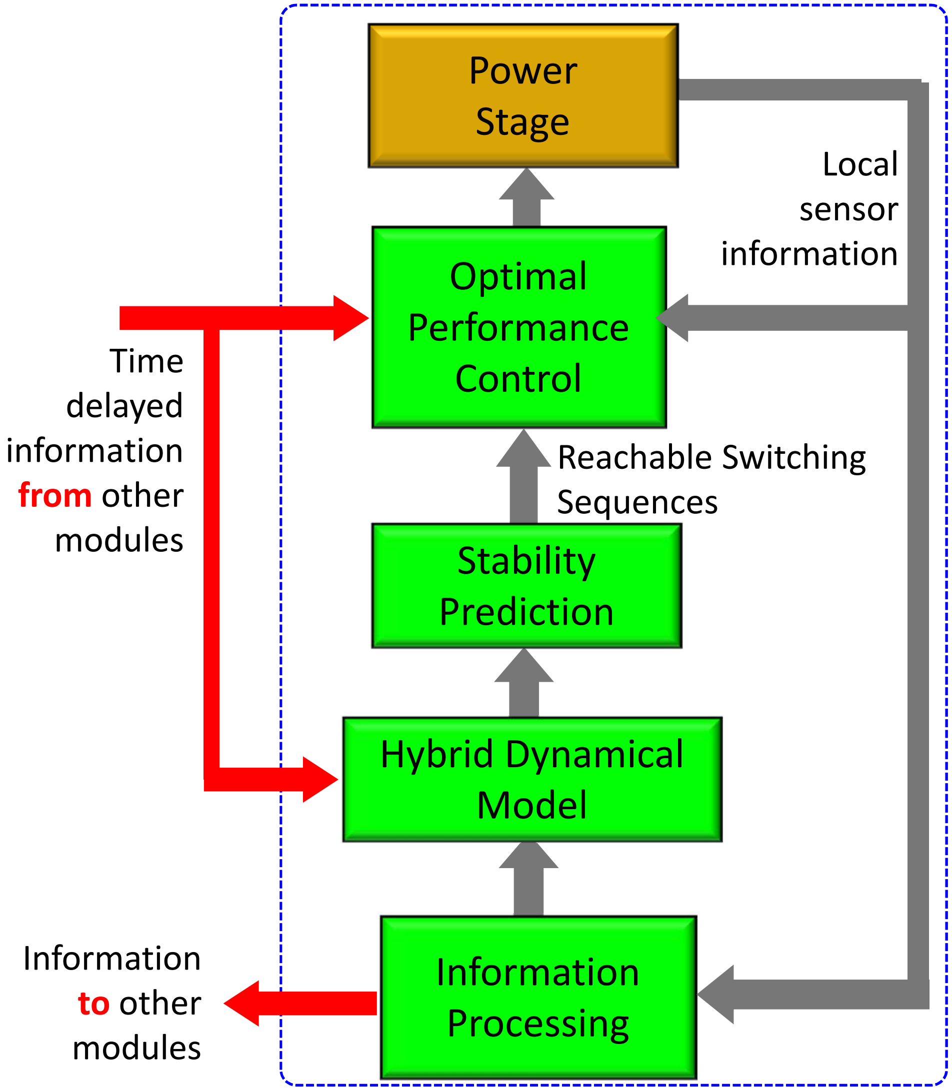
$$X_N(t_0 + T_{w_N}) = f_N\left(X_N(t_0), \{\alpha_{N_i}\}_{i=1-h_N}, T_{w_N}, \{A_{N_i}\}_{i=1-h_N}, \{B_{N_i}\}_{i=1-h_N}, W_N \right),$$

$$X_N(t_0 + T_{w_N}) \le X_{N max},$$

$$\sum_{i=1}^{h_N} \alpha_{N_i} = 1, \text{ and } 0 < \alpha_{N_i} < 1$$

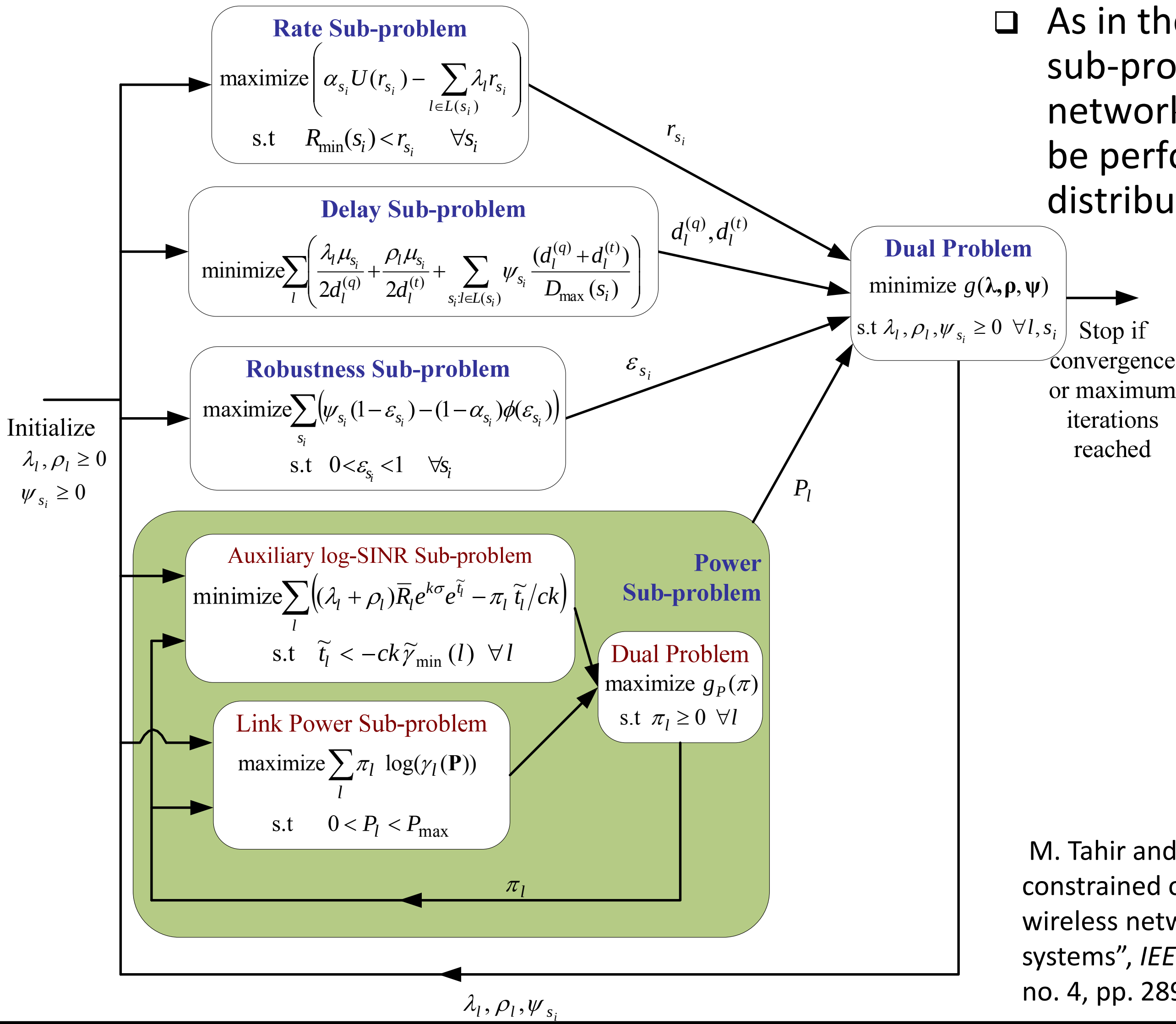
S.K. Mazumder, K. Acharya, and M. Tahir, “Joint optimization of control performance and network resource utilization in homogeneous power networks”, *IEEE Transactions on Industrial Electronics*, vol. 56, no. 5, pp. 1736-1745, 2009.

Module power control for distributed implementation



S.K. Mazumder and K. Acharya, "Multiple Lyapunov function based reaching criteria for orbital existence of switching power converters", *IEEE Transactions on Power Electronics*, vol. 23, no. 3, pp. 1449-1471, 2008.

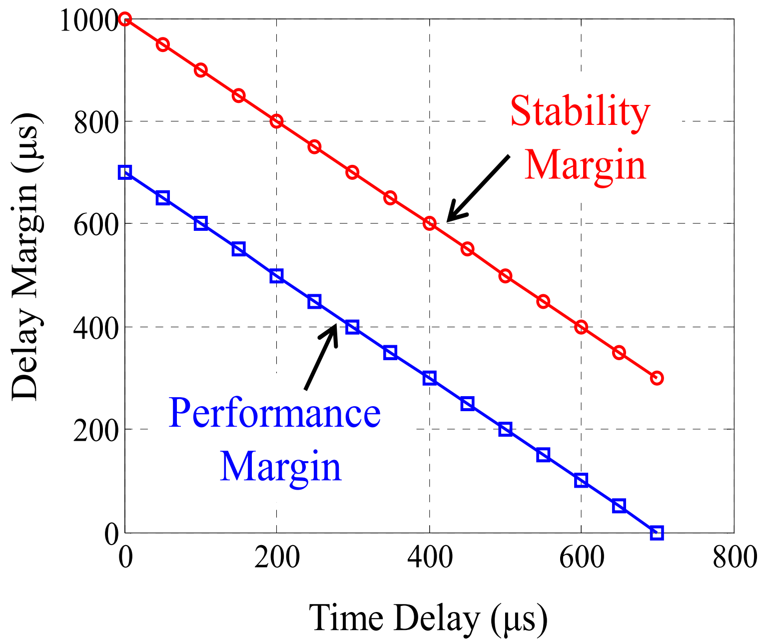
Communication network throughput optimization



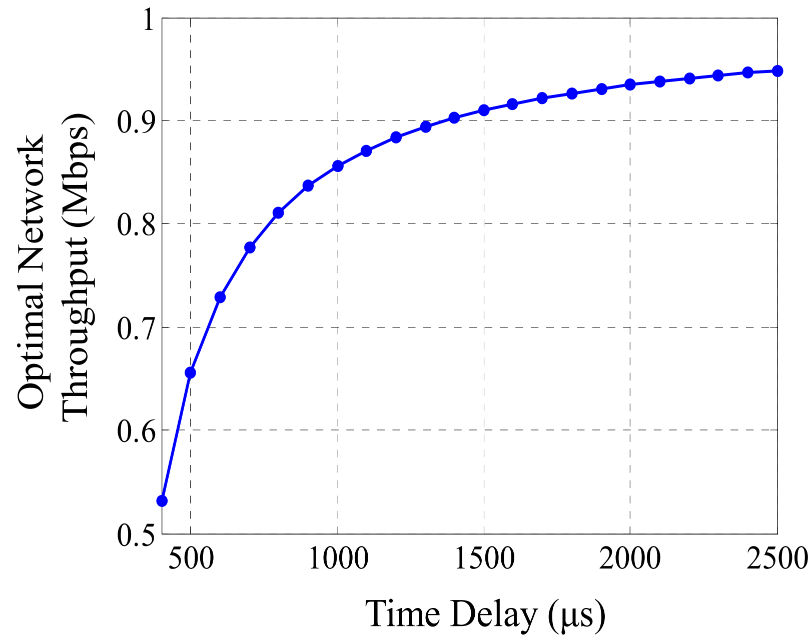
- As in the case of the control sub-problem, communication network optimization can also be performed centrally or in a distributed manner

M. Tahir and S.K. Mazumder, “Delay constrained optimal resource utilization of wireless networks for distributed control systems”, *IEEE Communication Letters*, vol. 12, no. 4, pp. 289-291, 2008.

Non-cooperative control-communication scenario



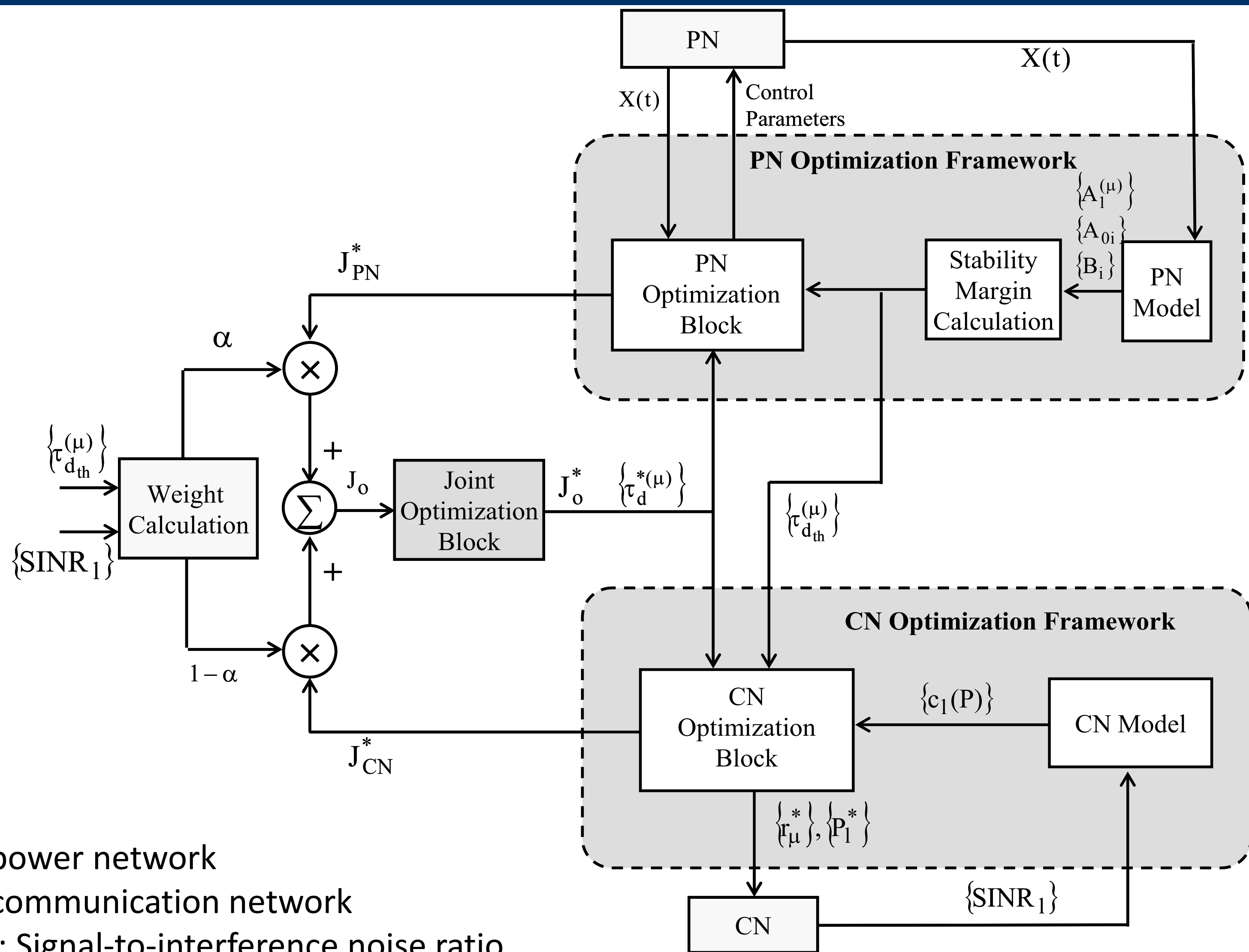
Variations of the stability and performance margins in terms of delay margin



Achievable optimal network throughput as a function of the network time delay

Tradeoff, with regard to network time delay, between control performance and stability and resource utilization of the communication network

Joint optimization



PN: power network
CN: communication network
SINR: Signal-to-interference noise ratio

Results (centralized vs. distributed control)

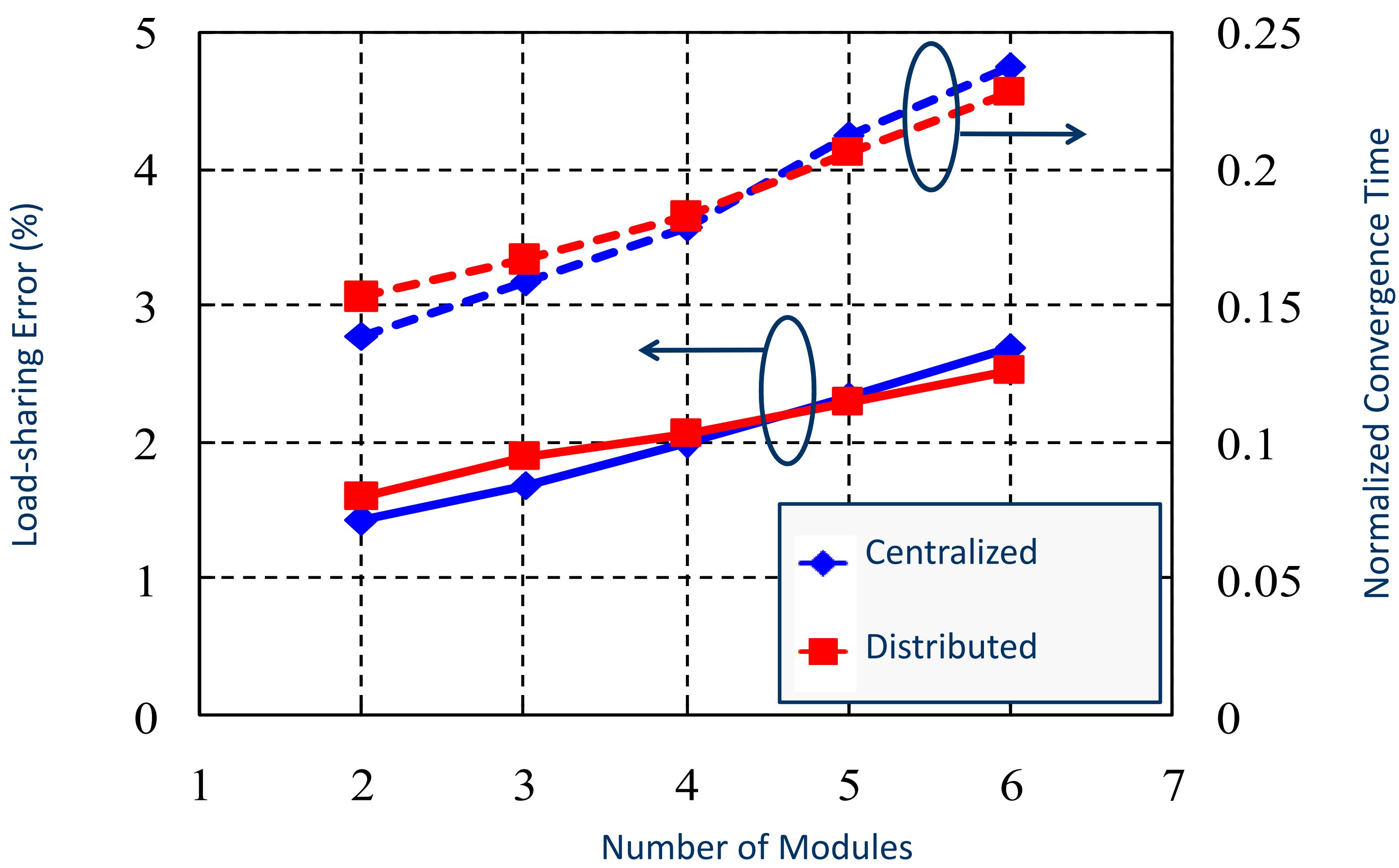
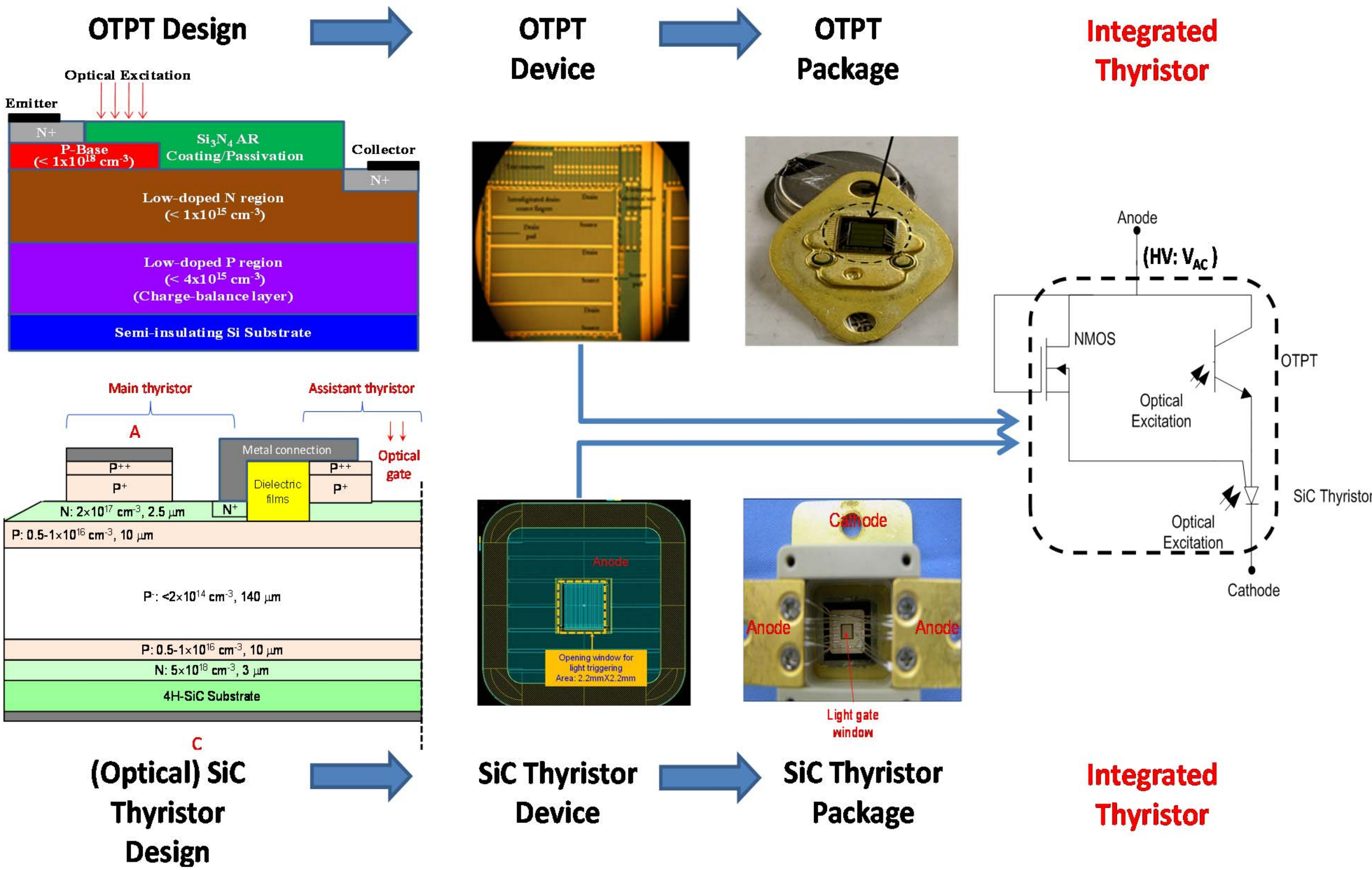


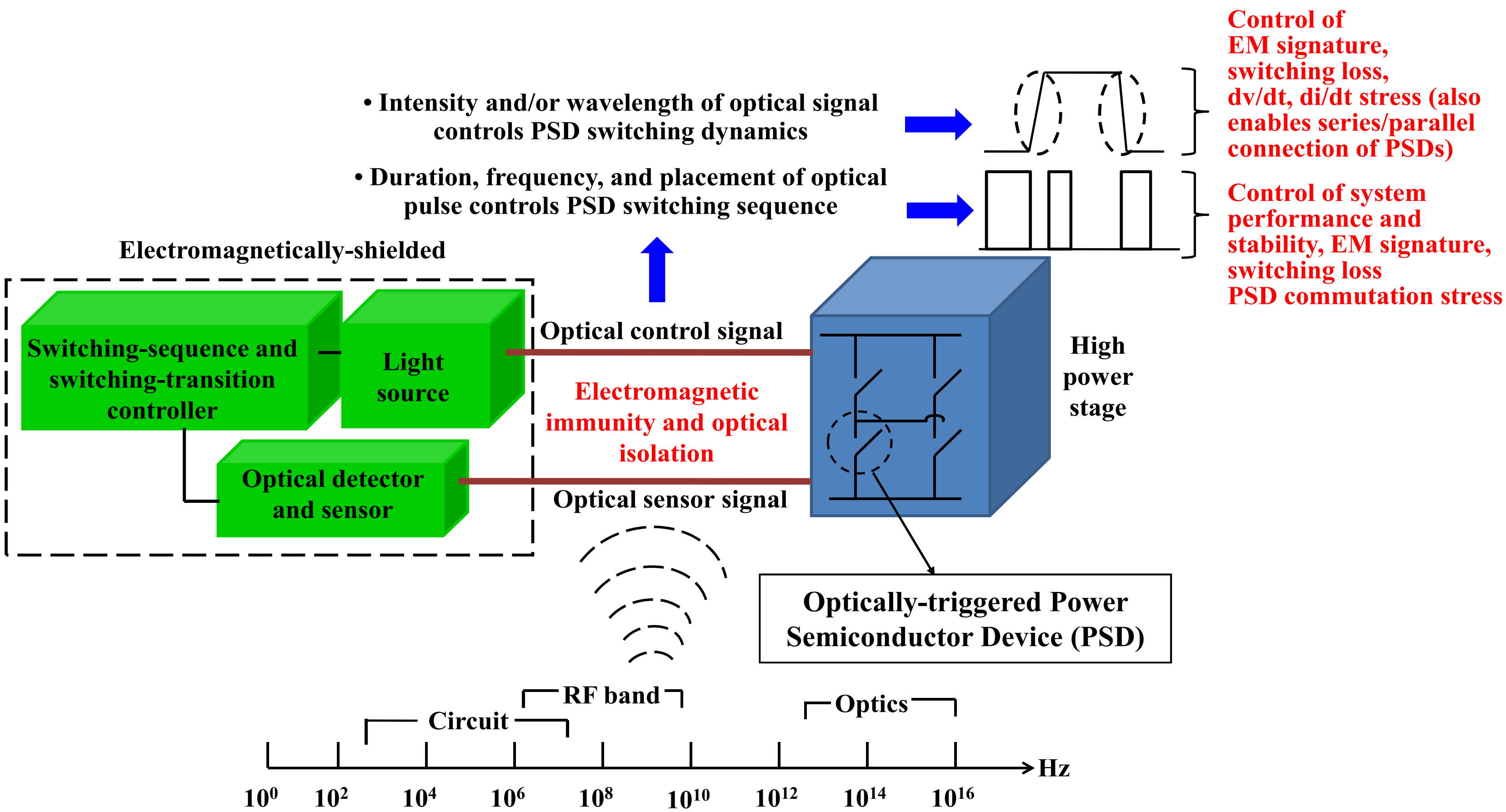
Illustration 2

World's first all-optical 15-kV/10-kHz/2-kA SiC ETO

ARPA-E project – Collaboration between UIC, Silicon Power, Cree



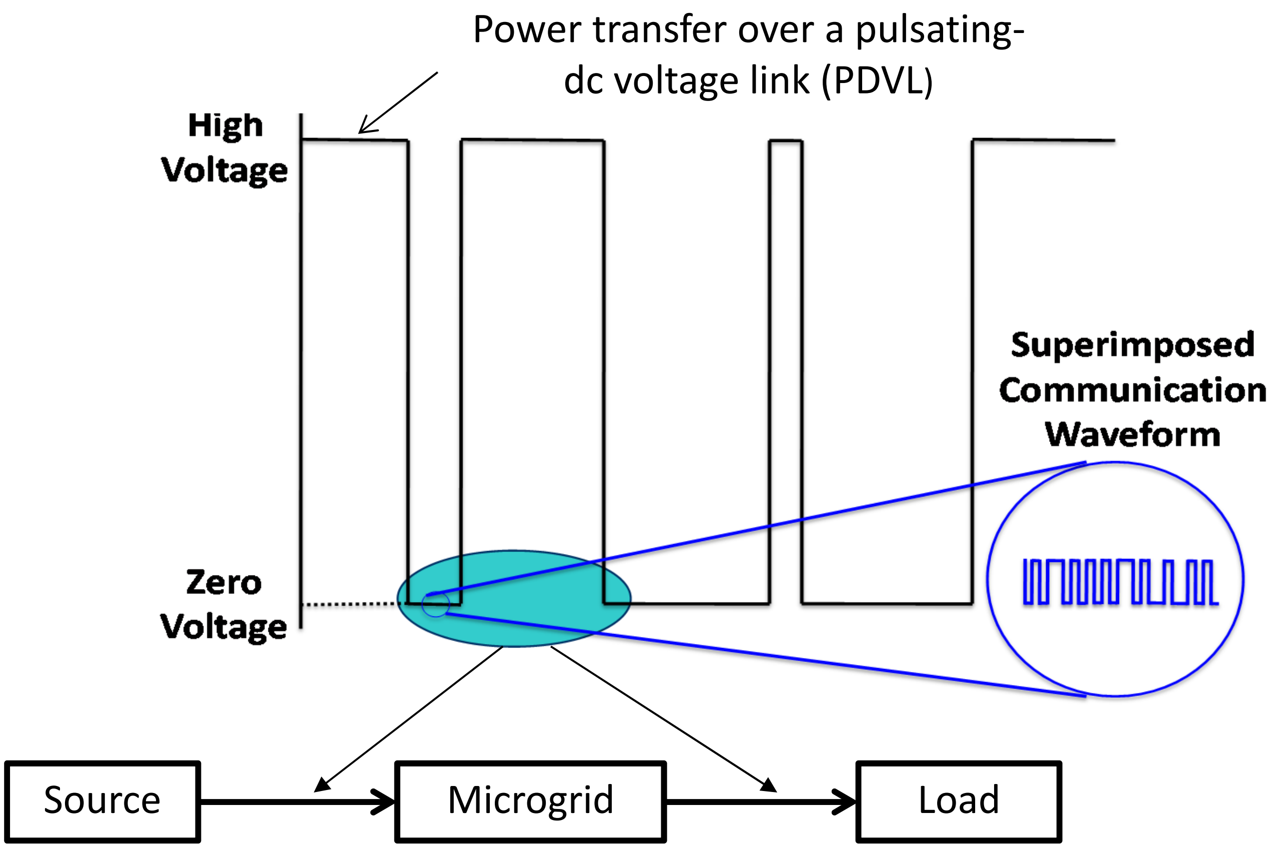
Control of system at device level



Dynamic control of device dynamics for rapid fault mitigation, power quality, and multi-scale power management

Illustration 3

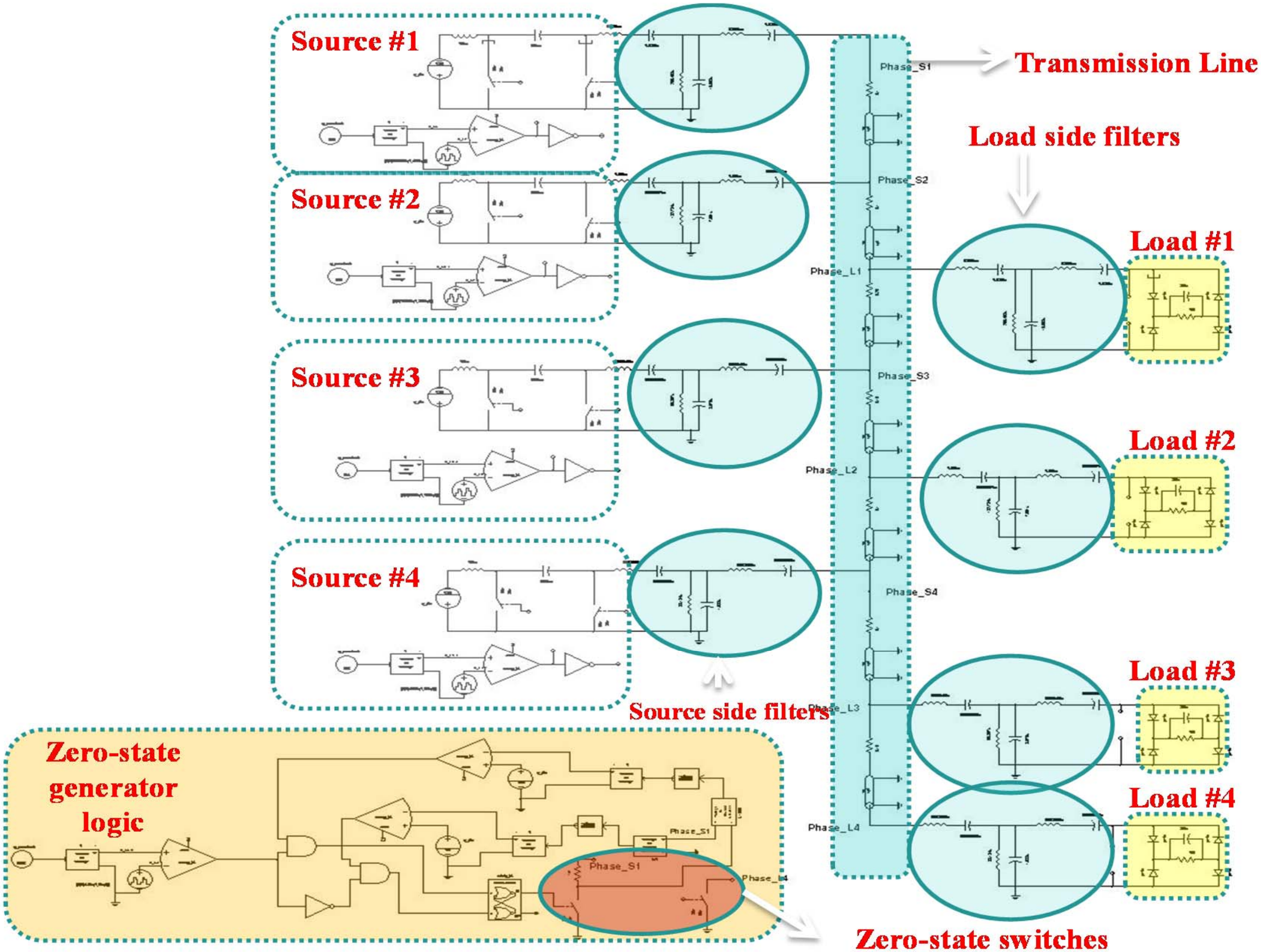
Boolean microgrid*



Discretized power and data delivery

* Patent pending

A simple realization for discretized power flow



Thank You!

Elementary to composite particles