FREEDM Systems Center

Distributed Control, iEMS, and On-line Battery Modeling on FREEDM Systems

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Raleigh, North Carolina

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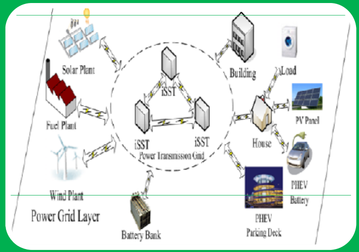
Overview

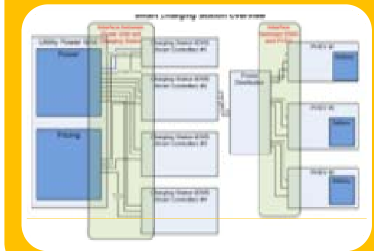
- Brief descriptions of our FREEDM and ATEC projects
  - Time-Sensitive Distributed Controls on FREEDM Systems (with Ziang Zhang)
  - Intelligent Energy Management System (iEMS) for PHEVs in Municipal Parking Deck (with Wencong Su)
  - Comprehensive Online Dynamic Battery Modeling for PHEV Applications (with Hanlei Zhang)
  - Positions on the FREEDM research roadmaps
- Consensus algorithms for a time-sensitive distributed controlled FREEDM System
  - Graph theory
  - Convergence rate
  - Time delay
- Summary and future works

Our current FREEDM and ATEC projects



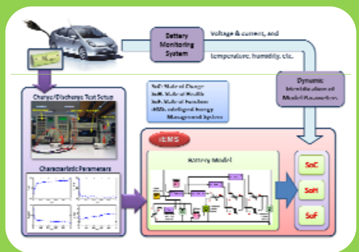
Time-sensitive distributed controls on FREEDM Systems

- Ziang Zhang
- Xichun Ying



Intelligent Energy Management System for PHEVs at A Municipal Parking Deck

- Wencong Su
- Xu Yang
- Hanlei Zhang



Comprehensive Online Dynamic Battery Modeling for PHEV Applications

- Hanlei Zhang
- Wencong Su

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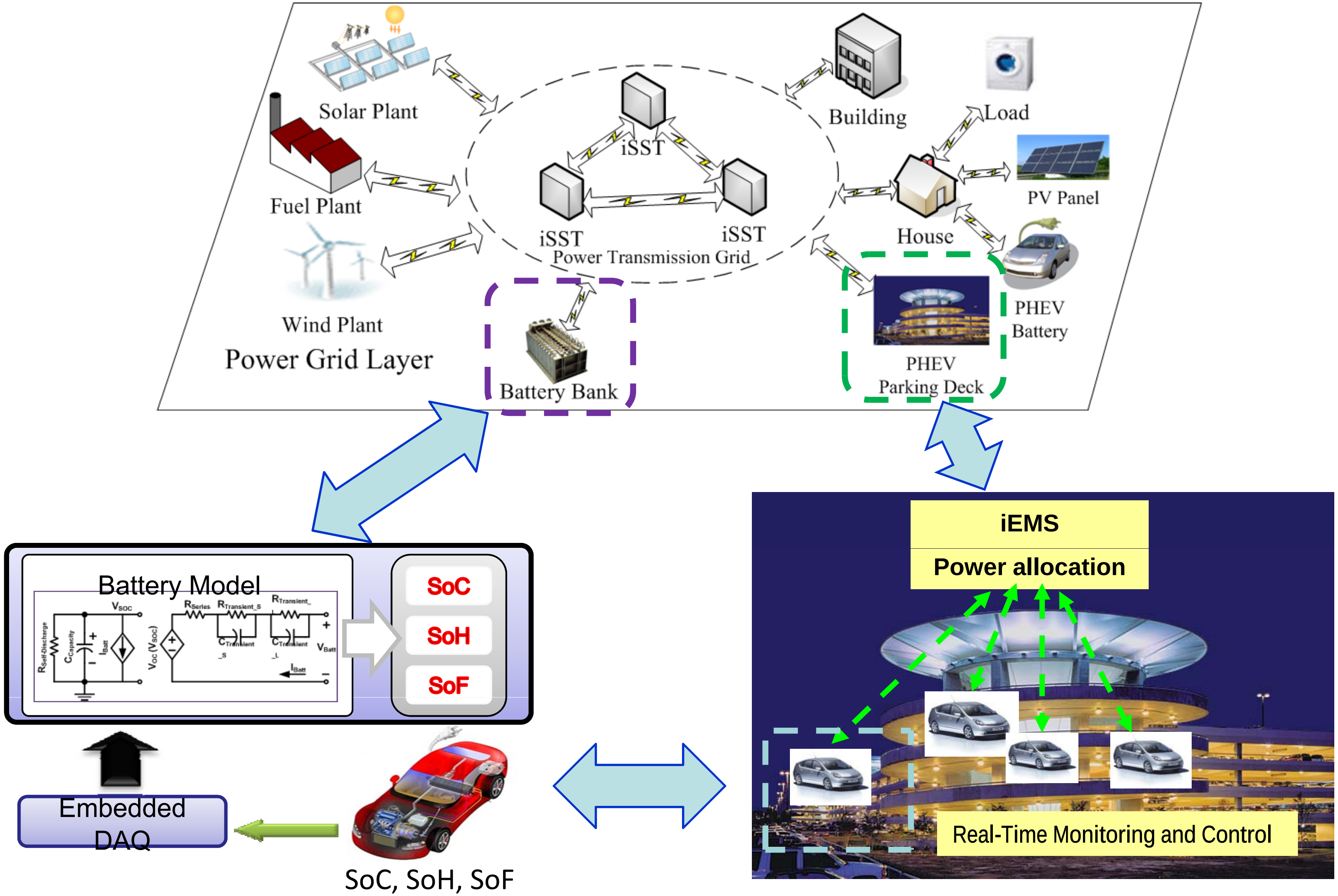
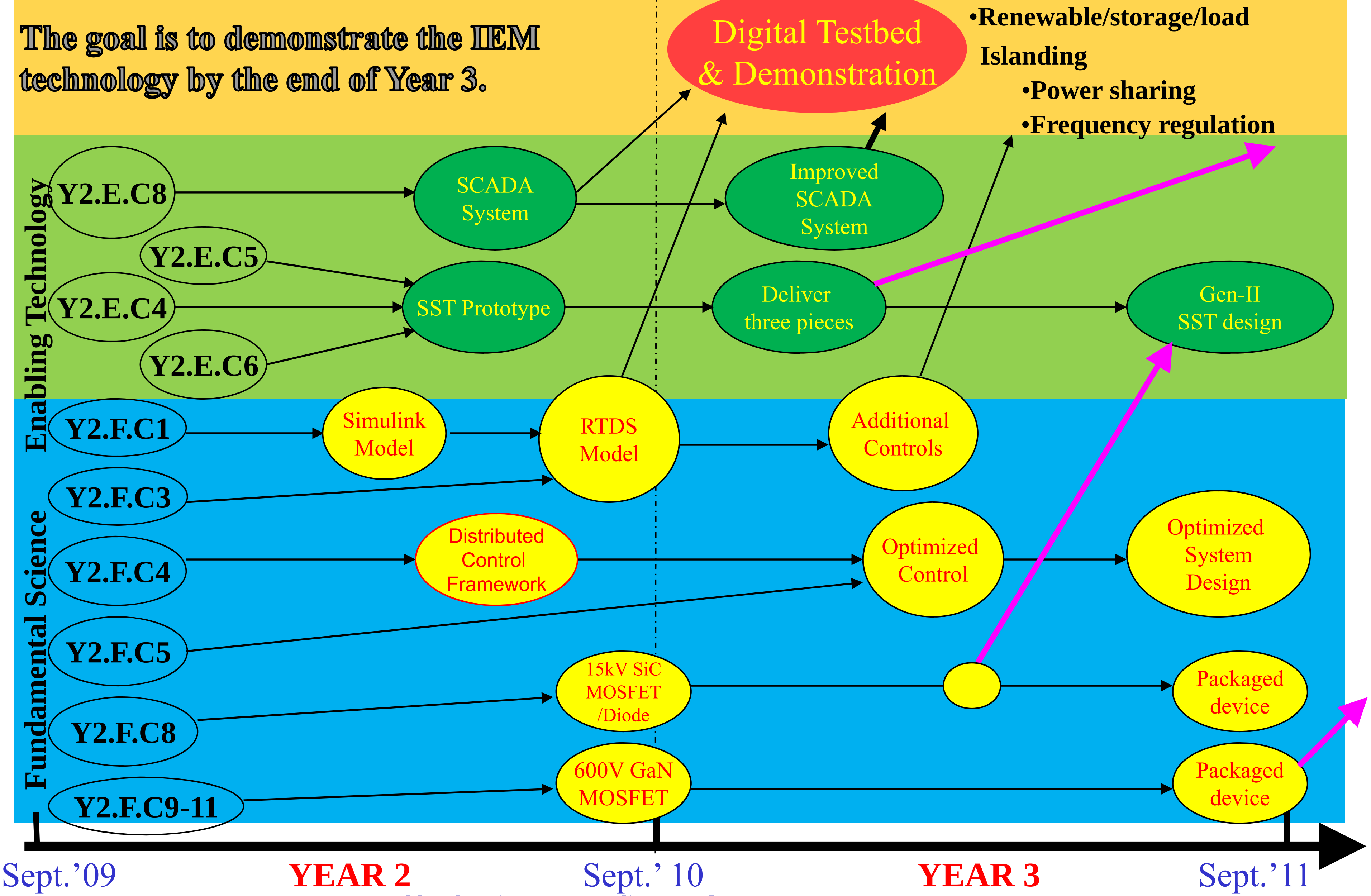
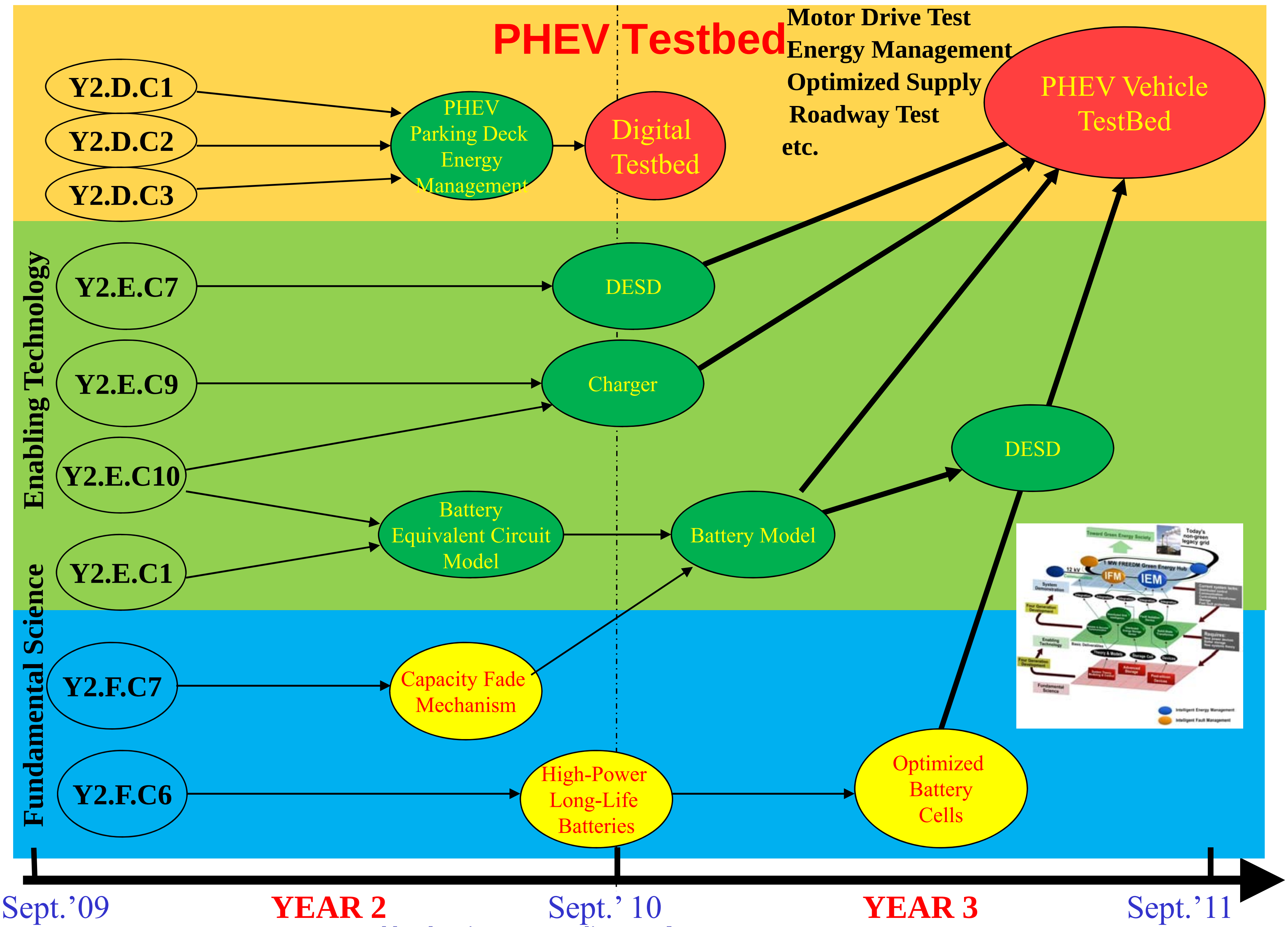
The interactions among the three projects



Digital Testbed: IEM Demonstration



Future Renewable Electric Energy Delivery and Management Systems Center



Future Renewable Electric Energy Delivery and Management Systems Center

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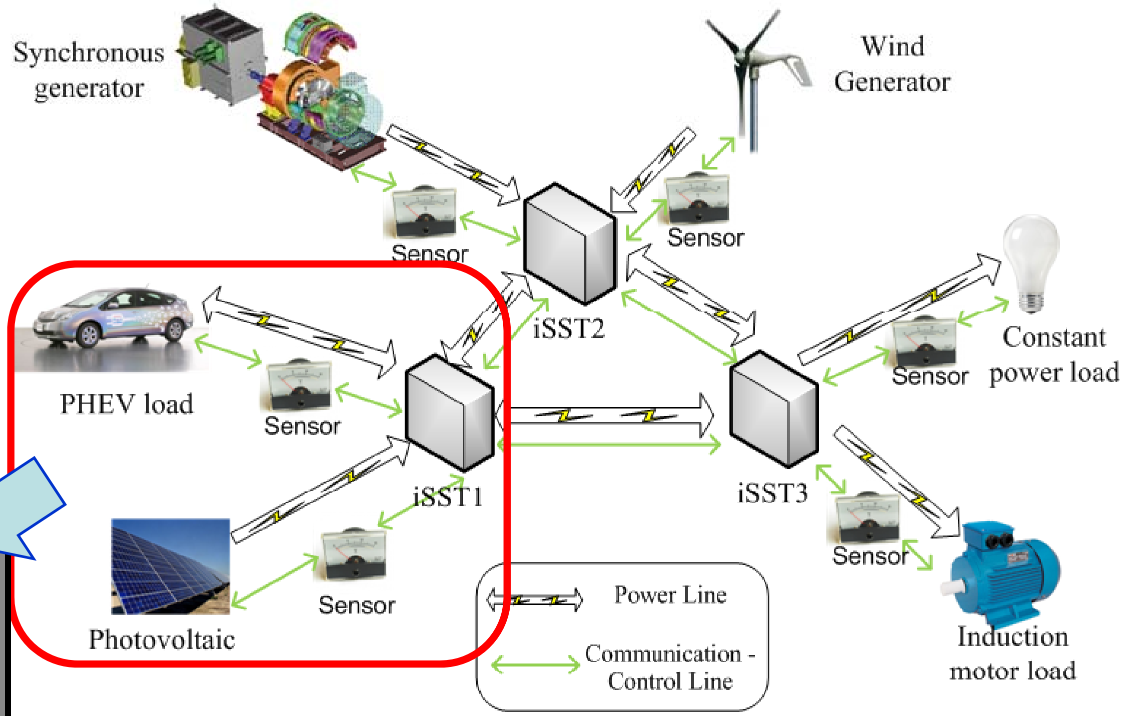
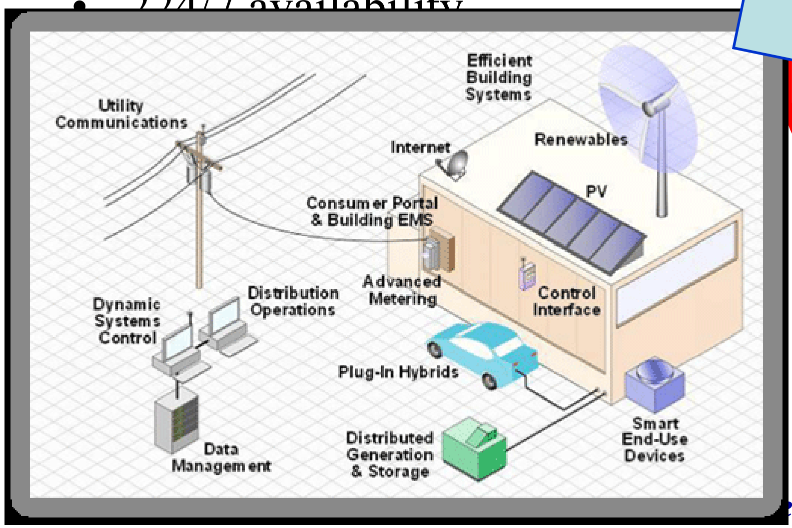
FREEDM System: a very *smart* Smart Grid

Goal of Smart Grid: ***Intelligent power delivery*** with *optimal* efficiency, effectiveness, power quality, resilience, reliably, availability, etc.

Features

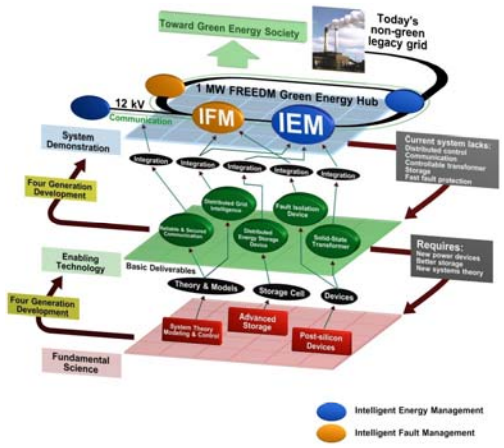
- Self healing property
- Delivery of high power quality
- Customized power usages
- Effective and efficient energyy systems
- Immunity to cyber attack
- 224/7 availability

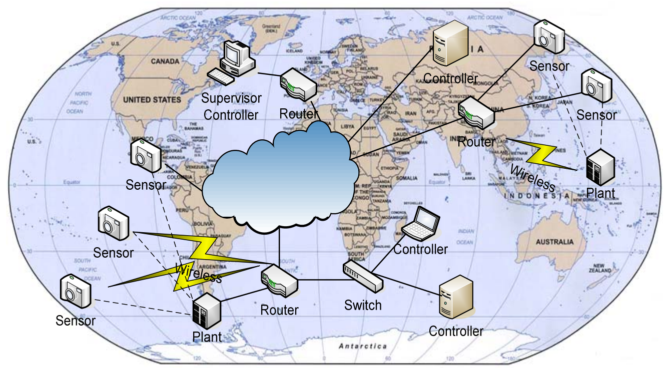




Time-sensitive distributed networked control systems (TS D-NCS)

- Enabling and enpowering individuals and small groups of sensors, actuators and controllers go global easily and seamlessly.
- Unique character – the newfound power for individuals (sensors, actuators, controllers) to collaborate/cooperate globally to solve local challenging problems (that cannot be solved otherwise)
- Provide optimized system performance with low cost through distributed information utilizations
- Enable real-time monitoring, control and operation globally with distributed local information
- Could usher in an amazing era of prosperity, innovation, and collaboration, by integrating distributed sensors, actuators, and controllers around the world.





Central Control vs. Distributed Control

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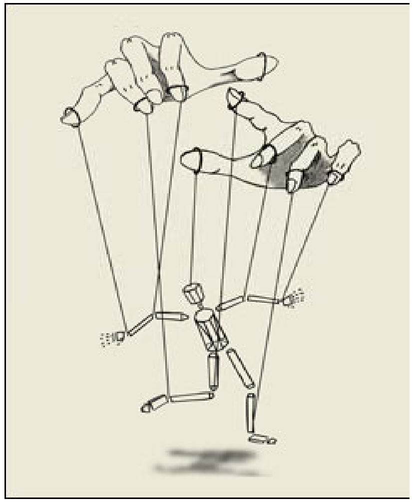

Puppet

vs.

School of fish

	Central Control	Distributed Control [1]
System	Puppets and Puppeteer	School of fish
Controller	Puppeteer (Single)	Fish (Multiple)
Information available to the controller	Puppeteer know the position of every part of puppet (Global)	Each fish only know the position of neighbors (Local)
Control Goal	Keep certain pattern of style and moving around	Keep certain pattern of shape and moving around

- Iain D. Couzin, Jens Krause, Nigel R. Franks and Simon A. Levin, "Effective leadership and decision-making in animal groups on the move", *Nature* 433, 513-516 (3 February 2005)
- …

Central control vs. distributed control -2

	Central Controlled System	Distributed Controlled System
Pros	• Control algorithm is relatively simple • …	• Relieved the computational burden for a single controller • Ease of heavy data exchange demand • Single point of failure will not necessarily affect the others • Controllers do not need the entire system state information • …
Cons	• Computational limitation of central controller • Communication limitation of central controller • Single point of failure will affect the entire system • …	• Only part of the system states are available to each distributed controller • Normally need complex algorithms and designs • …
Usages	Normally more appropriate for systems with simple control	Normally more appropriate for large-scale systems need sophisticated control

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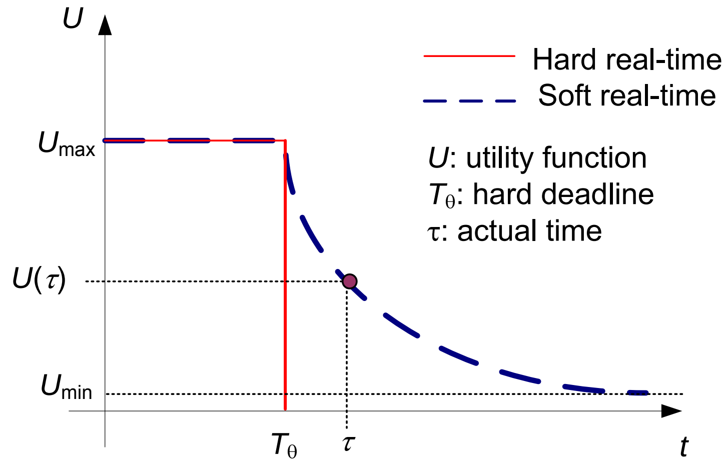
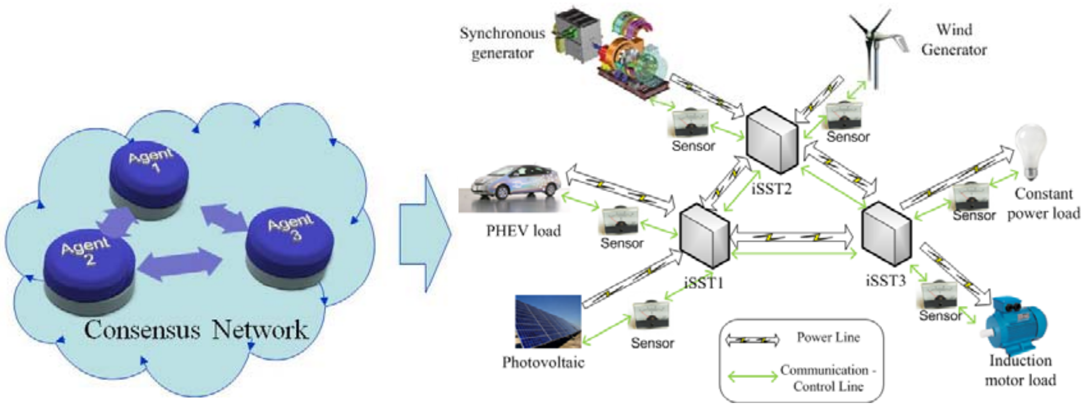
Time-sensitive distributed network control systems challenges

- Time-sensitive applications/ Time delay issues
  - Hard real-time control
  - Soft real-time control
  - Non real-time control
- Resource constraints (e.g., bandwidth, generation)/ resources allocation issues
- Data-sensitive applications/ Security issues
- …



- M.-Y. Chow, S. Chiaverini, and C. Kitts, "Guest Editorial on Focused Section on Mechatronics in Multi Robot Systems," IEEE Transactions on Mechatronics, vol. 14, pp. 133-140, April 2009, pp. 133-140.
- R. A. Gupta and M.-Y. Chow, "Networked Control Systems: Overview and Research Trends," forth coming, accepted for publication in IEEE Transactions on Industrial Electronics, October 2009.
- …



Time-sensitive Distributed Controls on FREEDM Systems

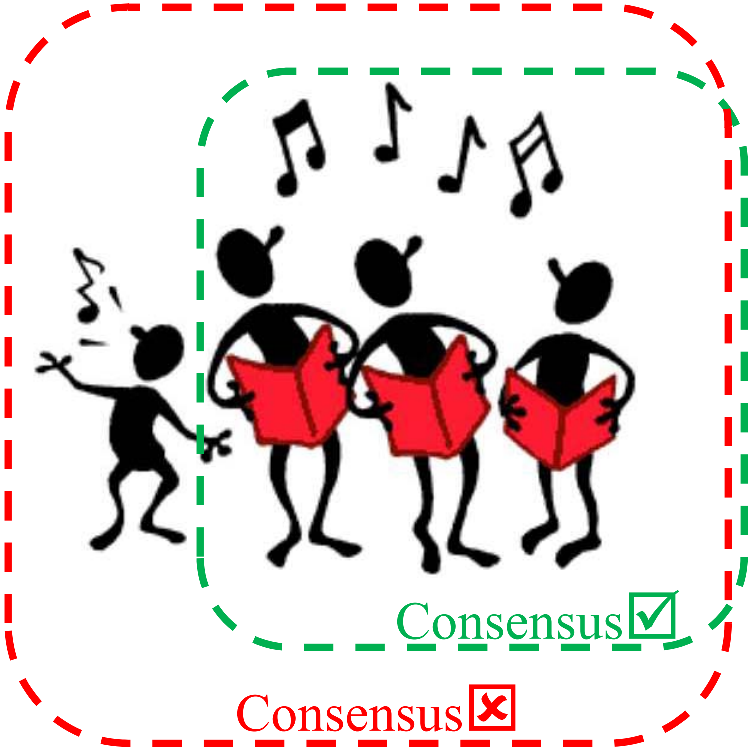
Phase I : Consensus Algorithms

RA: Ziang Zhang (John)
Department of Electrical and Computer Engineering
North Carolina State University
Raleigh, North Carolina

What is consensus?

Consensus☑ [1]

A school of fish



Chorus

Goal: swimming towards one same direction

Goal: Synchronize the melody

[1]. Larissa Conradt and Timothy J. Roper, “Consensus decision making in animals”, Trends in Ecology & Evolution, Volume 20, Issue 8, August 2005, Pages 449-456.

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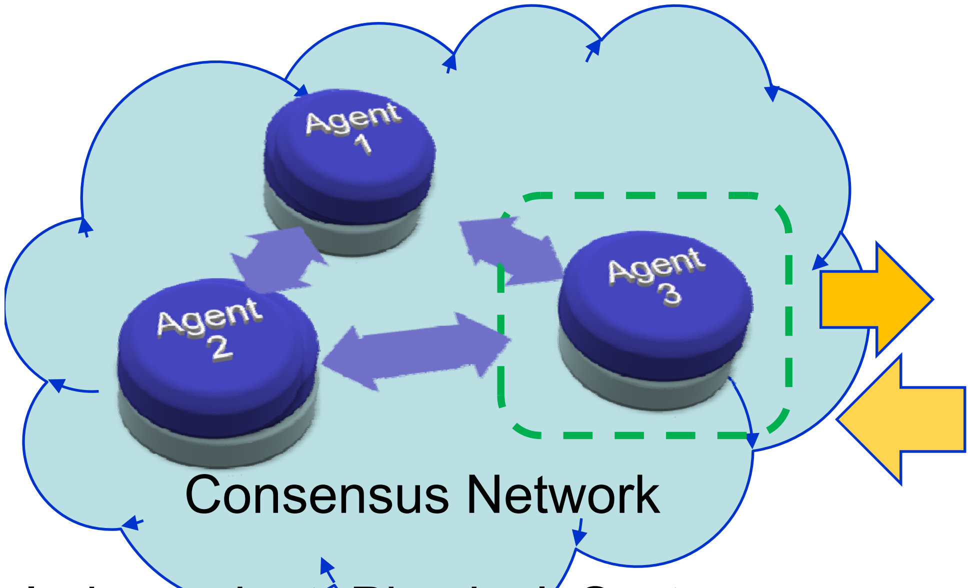
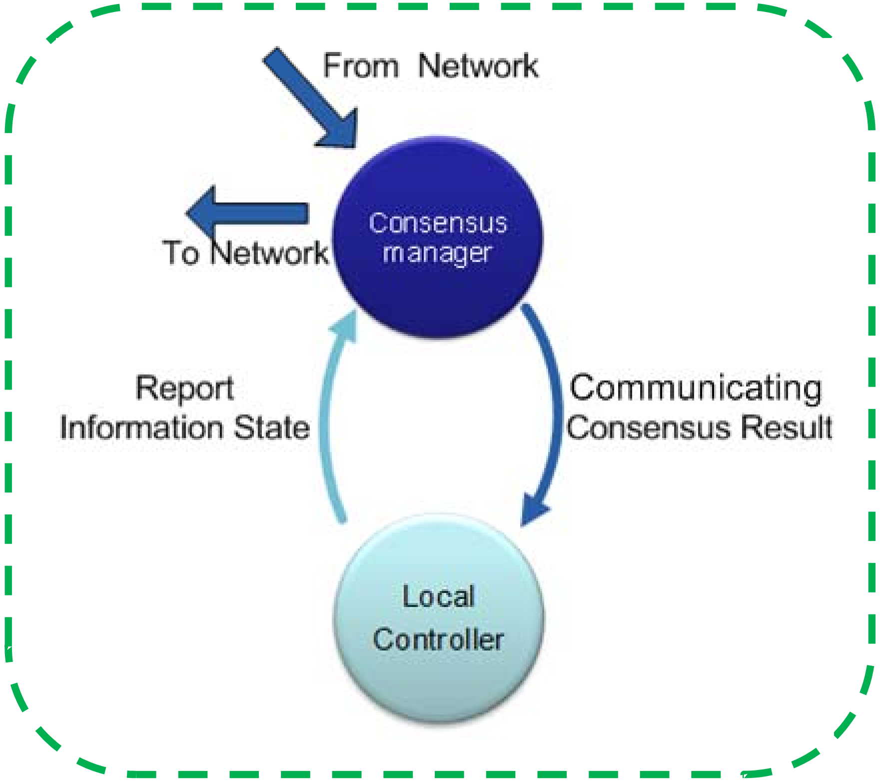
How can consensus be reached?





Independent Physical Systems
Each of them follow their own dynamic

A sufficient condition for reach consensus: If there is a directed spanning tree* exists in the communication network, then consensus can be reached. [1]

*Spanning tree: a minimal set of edges that connect all nodes

[1] Wei Ren Randal W. Beard Ella M. Atkins , “A Survey of Consensus Problems in Multi-agent Coordination”, 2005 American Control Conference June, 2005. Portland, OR, USA

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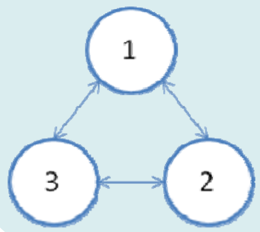
Consensus algorithm based modeling

- Adjacency matrix of a finite graph *G* on n vertices is the *n* × *n* matrix where the entry a_{ij} is the number of edges from vertex *i* to vertex *j*, a_{ij} =0 represent that agent *i* cannot receive information from agent *j*

Example:



$$A = \begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix}$$

Adjacency matrix

- Consensus problem modeling
  - Local information state ξ_i
  - First-order system $\dot{\xi}_i = \xi_i, i = 1, \ldots, n$
- Consensus algorithm:

	Scalar From	Matrix Form
Continuous	$\dot{\xi}_i = -\sum_{j=1}^{n} a_{ij}(\xi_i - \xi_j), i = 1, \ldots, n$	$\dot{\xi} = -L_n \xi$
Discrete	$\xi_i[k+1] = \sum_{j=1}^{n} d_{ij}\xi_j[k], i = 1, \ldots, n$	$\xi[k+1] = D_n \xi[k]$

Where L_n is the Laplacian matrix associated with A,

and D_n is Row-stochastic matrix associated with A.

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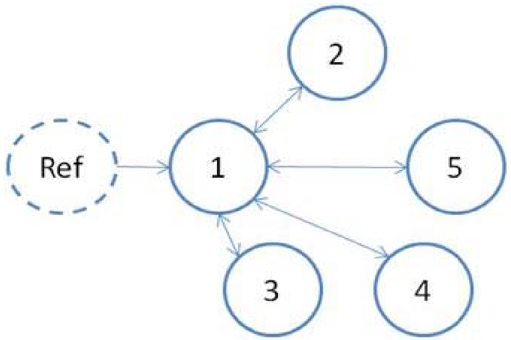
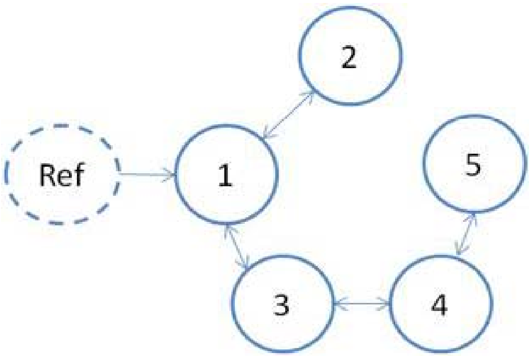
Consensus algorithm performance

- Consensus performance with different network topology - Step inputs as load references



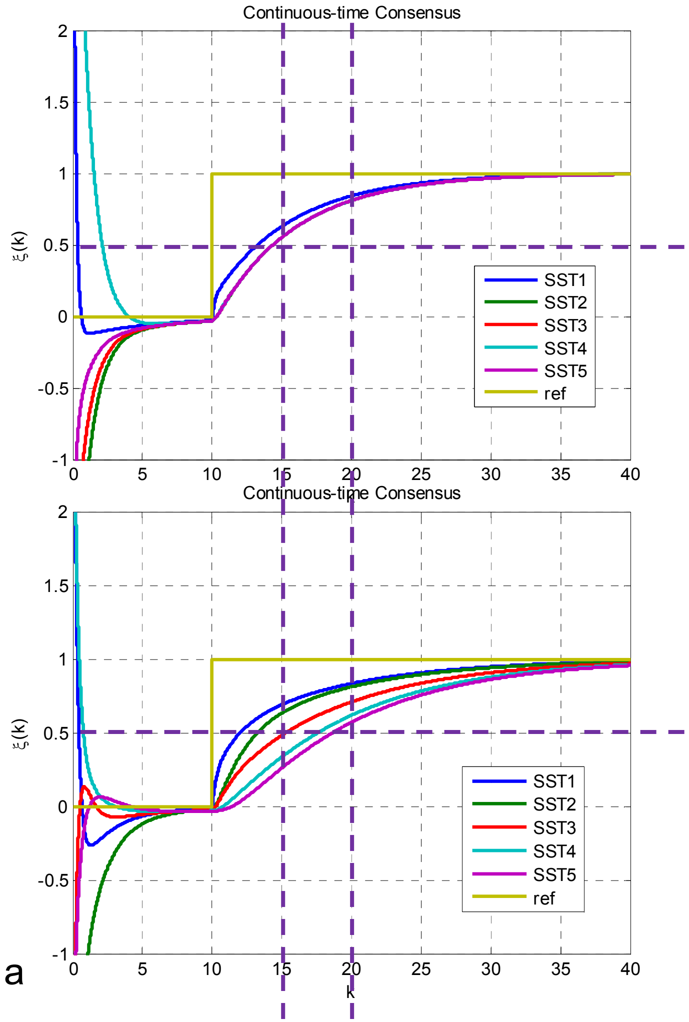
$$L = \begin{bmatrix} 4 & -1 & -1 & -1 & -1 \\ -1 & 1 & 0 & 0 & 0 \\ -1 & 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 1 & 0 \\ -1 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Algebraic connectivity $\lambda_2 = 1$



$$L = \begin{bmatrix} 2 & -1 & -1 & 0 & 0 \\ -1 & 1 & 0 & 0 & 0 \\ -1 & -1 & 2 & 0 & 0 \\ 0 & 0 & -1 & 2 & -1 \\ 0 & 0 & 0 & -1 & 1 \end{bmatrix}$$

Algebraic connectivity $\lambda_2 \approx 0.38$

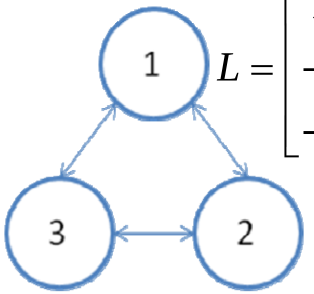


Algebraic connectivity λ_2 : The algebraic connectivity of a graph G is the second-smallest eigenvalue of the Laplacian matrix of G.

Consensus algorithm based modeling

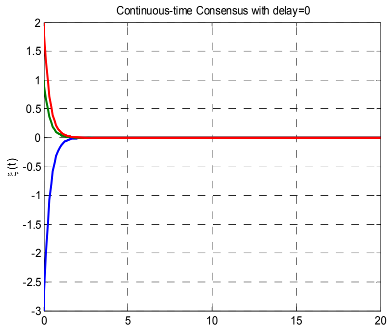
- Consensus test with time-delay τ

$$\dot{\xi}(t) = -L\xi(t-\tau)$$

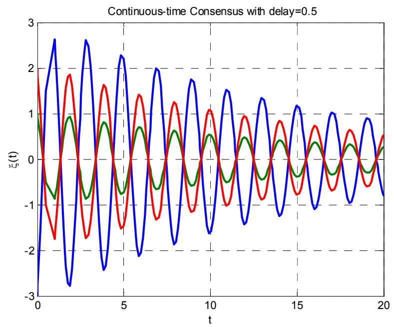


$$L = \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}$$

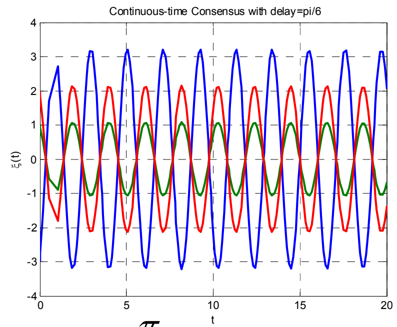
$\lambda_2 = 3, \lambda_n = \lambda_3 = 3$



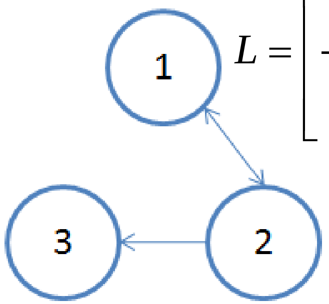
$\tau = 0$



$\tau = 0.5\,\text{sec}$

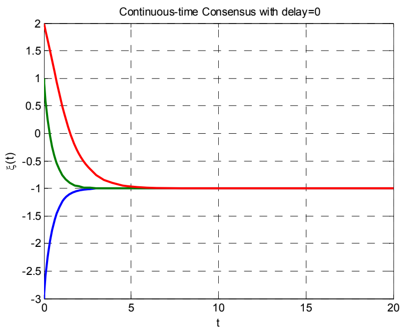


$\tau = \dfrac{\pi}{2\lambda_n} \approx 0.5236\,\text{sec}$

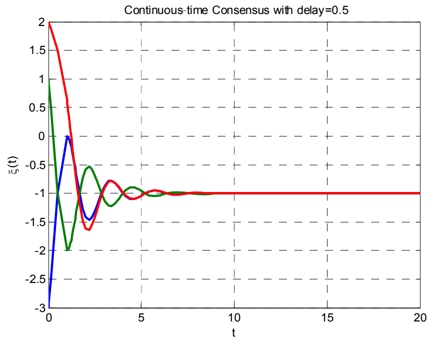


$$L = \begin{bmatrix} 1 & -1 & 0 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix}$$

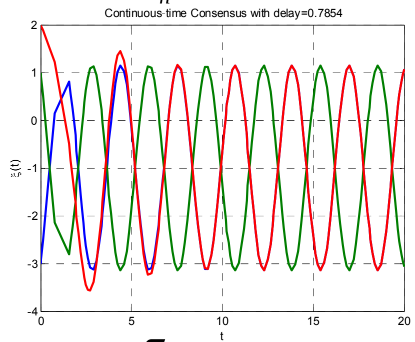
$\lambda_2 = 1, \lambda_n = 2$



$\tau = 0$



$\tau = 0.5\,\text{sec}$



$\tau = \dfrac{\pi}{2\lambda_n} \approx 0.7854\,\text{sec}$

λ_2 : Algebraic Connectivity

λ_n : Largest eigenvalue of L

A sufficient condition for convergence [1] of the consensus algorithm above is that $\tau < \dfrac{\pi}{2\lambda_n}$

[1] Reza Olfati-Saber and Richard M. Murray, *"Consensus Problems in Networks of Agents With Switching Topology and Time-Delays"*, IEEE TRANSACTIONS ON AUTOMATIC CONTROL, VOL. 49, NO. 9, SEPTEMBER 2004

Current work: Application of consensus algorithms on FREEDM systems

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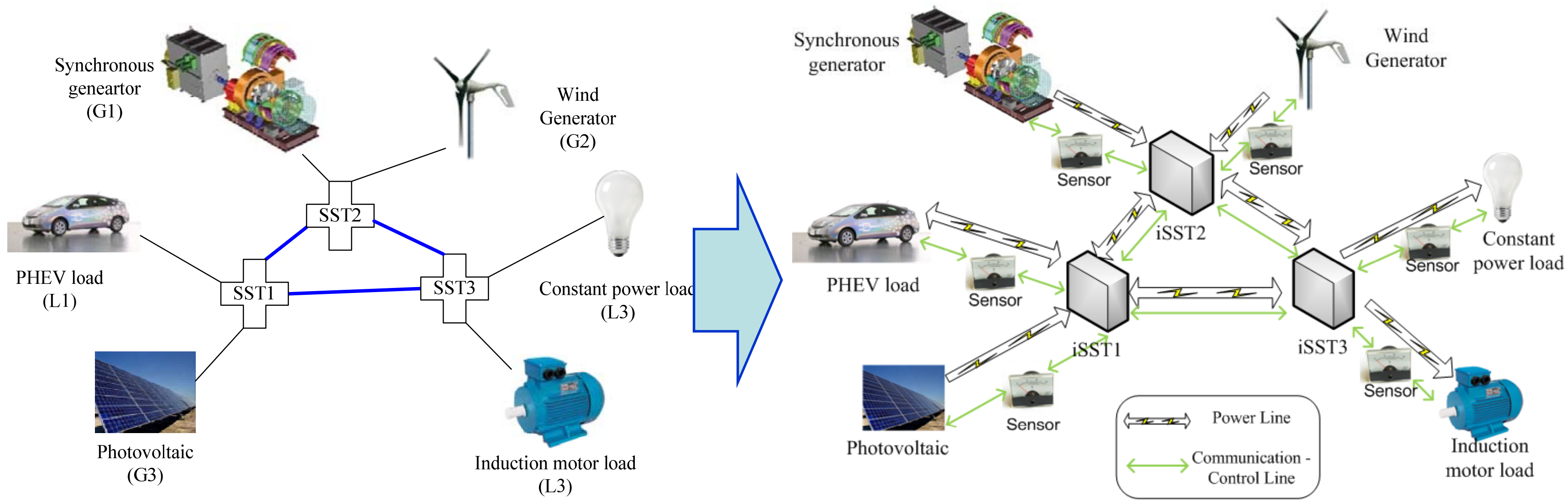

- Formulate the consensus algorithms for the FREEDM systems with both continuous time models and discrete event models
- Design high performance and reliable consensus algorithms for FREEDM systems
- Interacting with other groups
  - NCSU (communication network resilience, delay, reconfiguration, NCSU green hub models, distributed control algorithms – Dr. Mueller, Dr. Jiang, Dr. Baran)
  - MST (MST FREEDM testbed, load balancing algorithms – Dr. McMillin, Dr. Crow)
  - ASU (SST models, optimization – will establish closer interactions)

Publication: Ziang Zhang, Mo-Yuen Chow, “Consensus Algorithms for a Distributed Controlled FREEDM System”, FREEDM Annual Conference, May 2010

Some future works of the projects

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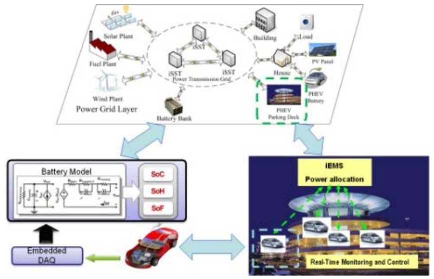
- Time-Sensitive Distributed Controls on FREEDM Systems
  - Develop consensus algorithms under separated power network and communication network
  - Develop other distributed control algorithms
  - Analyze and develop distributed controls to handle time-delay
  - Analyze and develop adaptive sampling strategies and distributed bandwidth allocation algorithms to handle bandwidth limitation
  - Collaborate with other FREEDM teams to demonstrate the distributed control algorithms on the FREEDM testbeds
  - …
- Intelligent Energy Management System (iEMS) for PHEVs in Municipal Parking Deck
  - Integrate the comprehensive battery models from the Battery Monitoring System Development and Deployment project into the iEMS
  - Interact with the Distributed Control of FREEDM system project on using some of the developed distributed control algorithms for iEMS
  - Collaborate with the Bi-directional electric vehicle supply equipment project to implement distributed control algorithms
  - Use the architect developed by Optimization of the power delivery architecture project to develop related communication network requirements and control requirements/constraints
  - Demonstrate iEMS algorithm on the PHEV testbed
  - …

Some future works of the projects – cont.

- Comprehensive Online Dynamic Battery Modeling for PHEV Applications
  - Develop online model parameter identification algorithms to properly identify the model characteristic parameters in *real time*
  - Design appropriate *State of Charge* (SoC), *State of Health* (SoH), and *State of Function* (SoF) measures to infer proper battery performances serving the iEMS and other FREEDM projects
  - Collaborate with other ATEC teams to implement the algorithms on the actual PHEV testbed
  - Collaborate with the distributed control group to provide proper battery bank real-time models
  - …
- Continue and expand interactions with other FREEDM and ATEC teams
- Enhance the interactions with industrial partners
- Reach out to new companies
- …



Thank you!

Acknowledgements: These works were partially supported by the National Science Foundation (NSF) under Award Number EEC-08212121.

Comprehensive Online Dynamic Battery Modeling

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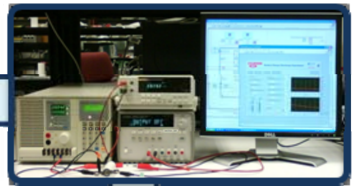
Objective

- Develop models and algorithms that can adapt to different types of batteries, their actual conditions, and their operating environments based on the in-situ measurements on the battery.
- Design appropriately State of Charge, State of Health and State of Function measures to infer proper battery performances.

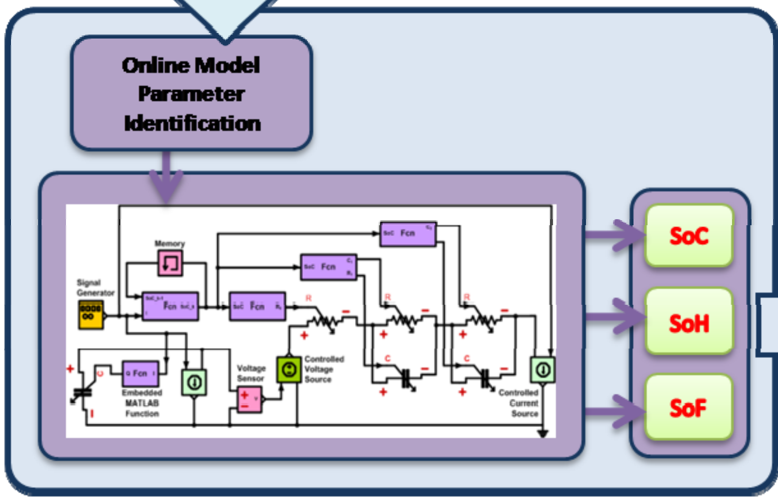
Battery Monitoring System



Motivation

- Battery states information helps to enable optimal control over the battery charging/discharging process, providing essential information for iEMS to allocate power optimally.

Voltage & current
Temperature, humidity, etc.



SoC: State of Charge
SoH: State of Health
SoF: State of Function

Challenges

- Battery relaxation effect
- Battery hysteresis effect
- Environmental effect, such as temperature, humidity, etc.
- Aging effect

Intelligent Energy Management System (iEMS)

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Related Works in Battery Model Area

Battery Models	Pros	Cons
Input-output mapping [1]	• Easy to obtain model parameters	• Can not reflect system dynamics
EIS-based model [2]	• Can be accurate in finding the model parameters	• Special instrument is required • Battery must be tested offline
Transient response mapping [3]	• Predict battery SoC • Reflect the battery dynamics partially	• v_t (i_L) dynamics modeling need to be improved • No hysteresis effect considered
Dynamic online model [4-6] (our model)	• Accurate under dynamic load condition • Suitable for online PHEV application	Require research on: • Relaxation and hysteresis effect modeling • Online parameter identification algorithm development

References

[1] O. Tremblay, L. Dessaint and A. Dekkiche, "A generic battery model for the dynamic simulation of hybrid electric vehicles", in Proceedings of Vehicle Power and Propulsion Conference, VPPC 2007. IEEE, pp. 284-289.

[2] S. Buller, M. Thele, R. Doncker and E. Karden, "Impedance-based simulation models of super-capacitors and Li-ion batteries for power electronic applications," *IEEE Transactions on Industry Applications,* vol. 41, 2005, pp. 742-747.

[3] M. Chen and G. Rincon-Mora, "Accurate electrical battery model capable of predicting runtime and I-V performance," *IEEE Transactions on Energy Conversion,* vol. 21, 2006, pp. 504-511.

[4] H. Zhang and M. Chow, "Comprehensive dynamic battery modeling for PHEV applications," in Proceedings of Power & Energy Society General Meeting, IEEE, 2010.

[5] H. Zhang and M. Chow, "Comprehensive dynamic battery model serving a municipal parking deck intelligent energy management system (iEMS)," submitted to the second FREEDM Annual Conference, 2010.

[6] H. Zhang and M. Chow, "Dynamic battery model including battery relaxation and hysteresis effect for PHEV applications," submitted to the 36th Annual Conference of the IEEE Industrial Electronics Society, IEEE IECON10, 2010.

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Dynamic battery model including battery relaxation and hysteresis effect

- Use series connected RC parallel circuits to model the battery relaxation effect

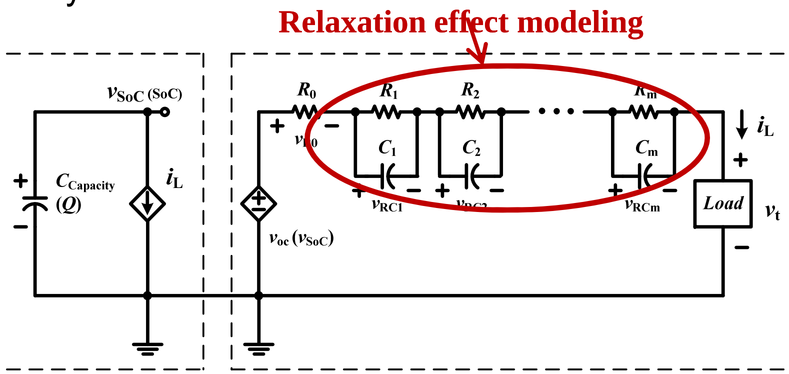

Fig. 1. The equivalent circuit of a battery cell.

- Heuristically, more RC circuits provides better model accuracy

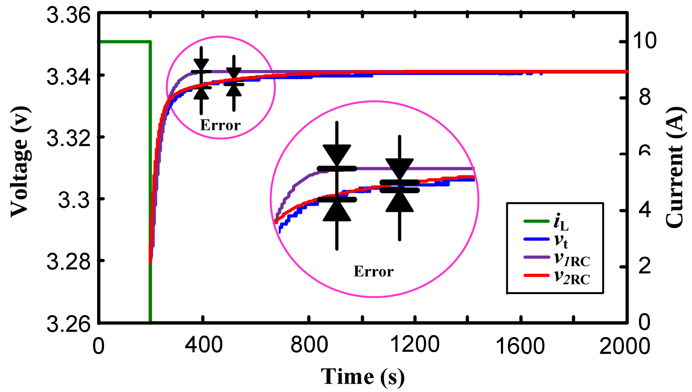

Fig. 2. Relaxation effect modeling with one RC circuit and two RC circuits.

- Use 2-norm and infinity norm to quantify the model accuracy

$$\|\boldsymbol{e}\|_2 = \left(\sum_{i=1}^{n} |e_i|^2\right)^{\frac{1}{2}}$$

$$\|\boldsymbol{e}\|_\infty = \max\ (\ |e_1|,\ |e_2|,\ \dots,\ |e_n|\ ).$$

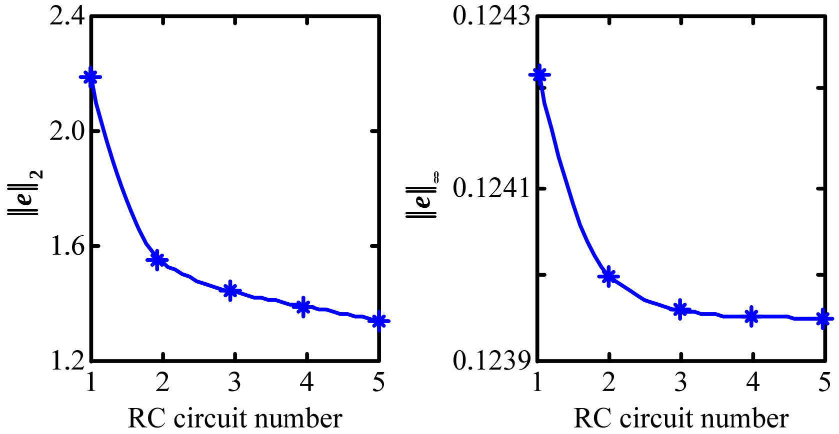

Fig. 3. Modeling error with different RC circuit number.

- On the other hand, more RC circuits also increase model computational complexity
- We need to balance between accuracy and complexity according to the application requirement

Automatic Remote Battery Charge/Discharge Web Based Workstation

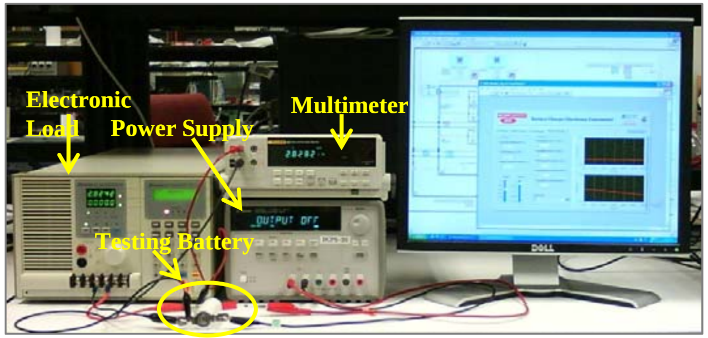

Fig. 1. The Lithium-ion battery cell and the testing instruments.

- Real time controlled battery charge discharge experiments
- Automatic battery charge discharge with user defined load profile
- Friendly GUI interface to real time battery measurements
- Basic platform for online model parameter identification with in-situ battery measurements

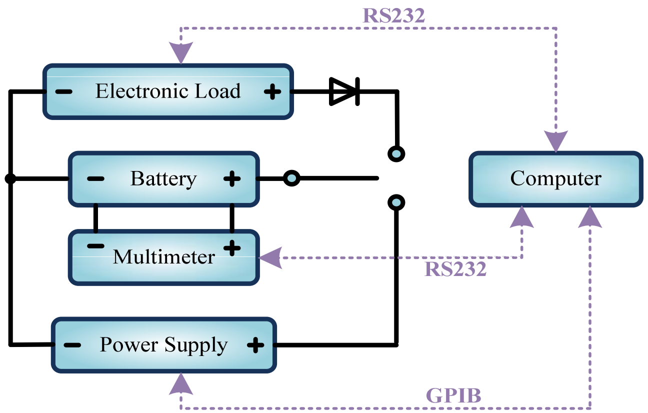

Fig. 2. Electrical connection and communication links.

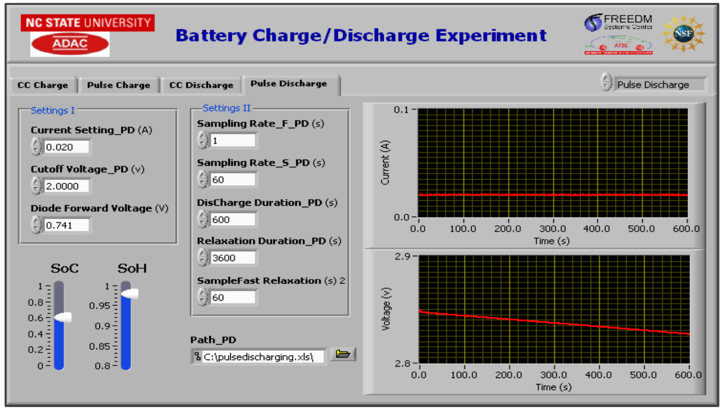

Fig. 3. Graphic user interface of the battery charge/discharge workstation.

Related publications

1. H. Zhang and M. Chow, "Comprehensive dynamic battery modeling for PHEV applications," in Proceedings of Power & Energy Society General Meeting, IEEE, 2010.
2. H. Zhang and M. Chow, “Comprehensive dynamic battery model serving a municipal parking deck intelligent energy management system (iEMS),” in Proceedings of the second FREEDM Annual Conference, 2010.
3. H. Zhang and M. Chow, “Dynamic battery model including battery relaxation and hysteresis effect for PHEV applications,” submitted to the 36th Annual Conference of the IEEE Industrial Electronics Society, IEEE IECON10, 2010.

Intelligent Energy Management System for PHEVS at a Municipal Parking Deck

FREEDM Systems Center

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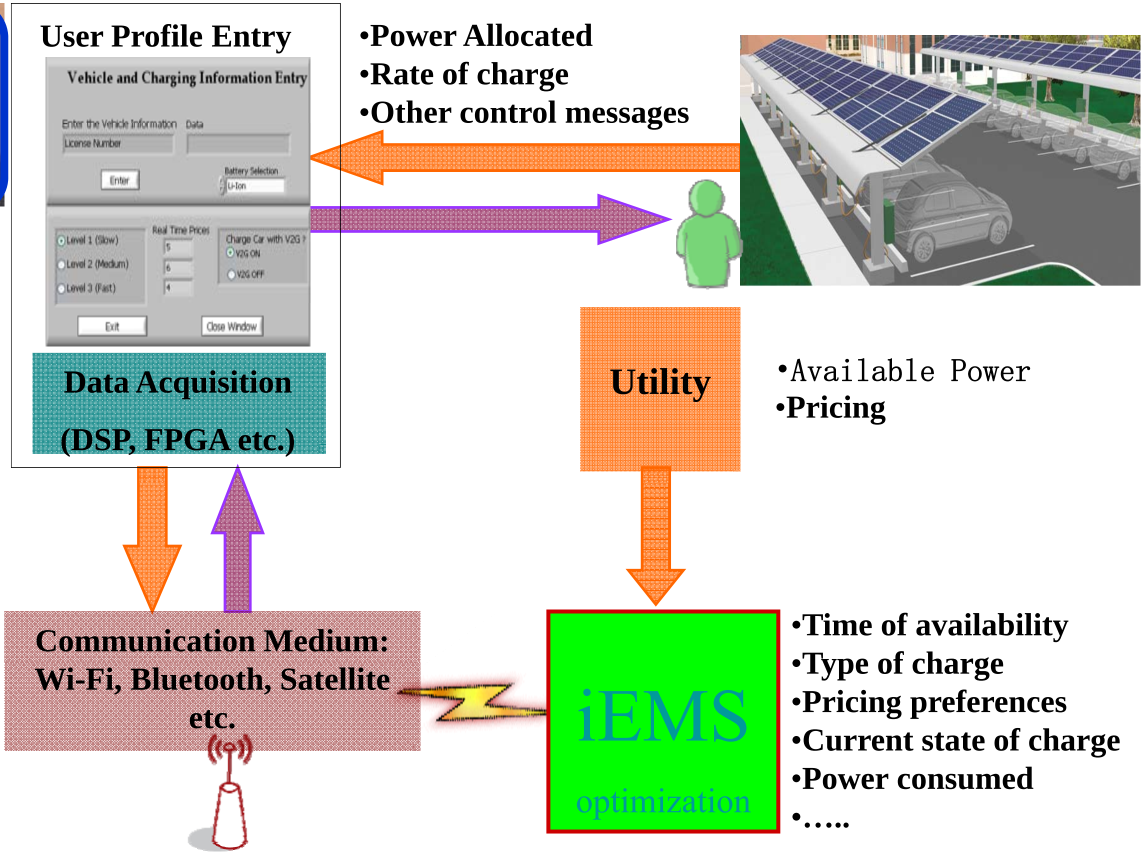


Objective

• To develop an Intelligent Energy Management System (iEMS) architecture to achieve the optimal power allocation to PHEVs at a municipal parking deck and also allow for Vehicle-to-Grid (V2G) technology.

Challenge

- A large variation of the arrival and department time of PHEVs into a PHEV parking deck
- The number of PHEVs in a parking deck at a time has a large variation with limited amount power supplied from utilities.
- Need Low cost and effective communications with sufficient bandwidth to pass information among PHEVs and the controllers to effectively perform the charging and discharging
- Need effective optimal charging/discharging controller algorithms to work seamlessly with utilities and PHEV customers under large uncertainties, and make decisions in real-time with limited bandwidth to communicate among all the entities

Intelligent Energy Management System for PHEVS at a Municipal Parking Deck

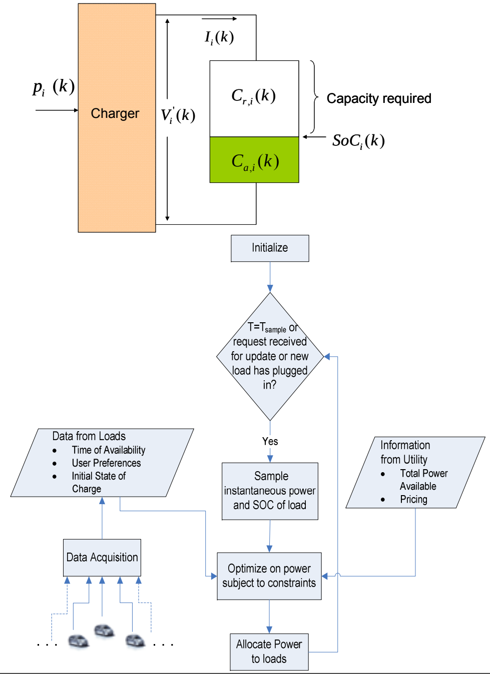
Priority Based Allocation Formulation

Motivation: Would like all vehicles *SoC* high to prevent starvation of any vehicle

$$\min_{p} J(k) \quad \text{where} \quad J(k) = -\sum_{j}\sum_{i} w_i(k) SoC_i(k+j)$$

and **p**: allocated power for each car at time *k*, i.e., $p_i(k)$ for $i \in [1, \ldots, N]$

$$C_{r,i}(k) = (1 - SoC_i(k)) \cdot C_i$$

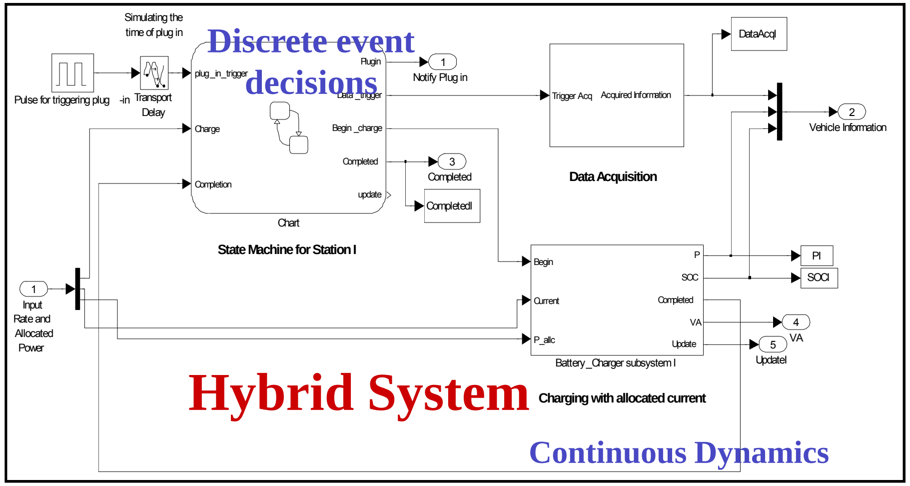


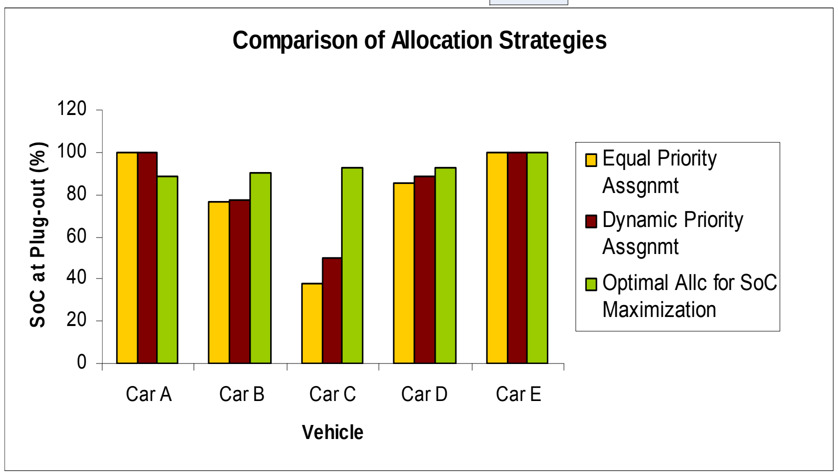
$w_i(k)$: the priority assigned for to vehicle *i* at time step *k*

Currently, we *a*ssign priorities based on capacity required and time remaining:

where α_1 and α_2 are weighting coefficients.

$$w_i(k) = \alpha_1 C_{r,i}(k) + \alpha_2 \frac{1}{T_{r,i}(k)}$$





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Intelligent Energy Management System for PHEVS at a Municipal Parking Deck

Highlights:

- Have prototyped iEMS algorithms on a PHEV Municipal Parking Deckin Matlab/Simulink
- Have developed a Graphical User Interface in Labview to conceptualize the system operation
- Have investigated the communication network with ZigBee

Current Work and Expected Milestones:

- Further developing iEMS architecture along with implementation in FREEDM and ATEC demonstration testbed in Matlab/Simulink and Labview.
- Simulating real-world parking deck scenarios with random vehicles arrivals, initial PHEVs states, time of availability using Monte Carlo method.
- Integrating the iEMS and demand side management programs into the existing testbed to alleviate the peak load demand.

Related Publication:

1) P. Kulshrestha, L. Wang, M.-Y. Chow, and S. Lukic, ***"Intelligent Energy Management System Simulator for PHEVs at Municipal Parking Deck in a Smart Grid Environment,"*** in Proceedings of IEEE Power and Energy Society General Meeting, Calgary, Canada, 2009. (invited)
2) P. Kulshrestha, K. Swaminathan, M.-Y. Chow, and S. Lukic, ***"Evaluation of ZigBee Communication Platform for Controlling the Charging of PHEVs at a Municipal Parking Deck,"*** in Proceedings of IEEE Vehicle Power and Propulsion Conference, Dearborn, Michigan, U.S.A, Sept 7-11, 2009.
3) W. Su, M.-Y. Chow, ***"An Intelligent Energy Management System for PHEVs Considering Demand Response,"*** in Proceedings of 2010 FREEDM Annual Conference, Tallahassee, Florida, U.S.A, (Submitted)
4) W. Su, M.-Y. Chow**, *"Evaluate Intelligent Energy Management System for PHEVs Using Monte Carlo Method,"*** (Draft)