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SinBerBEST | Singapore-Berkeley Building Efficiency and Sustainability in the Tropics

Thrust 3

Grid/Building cooperation through a Building Operating System

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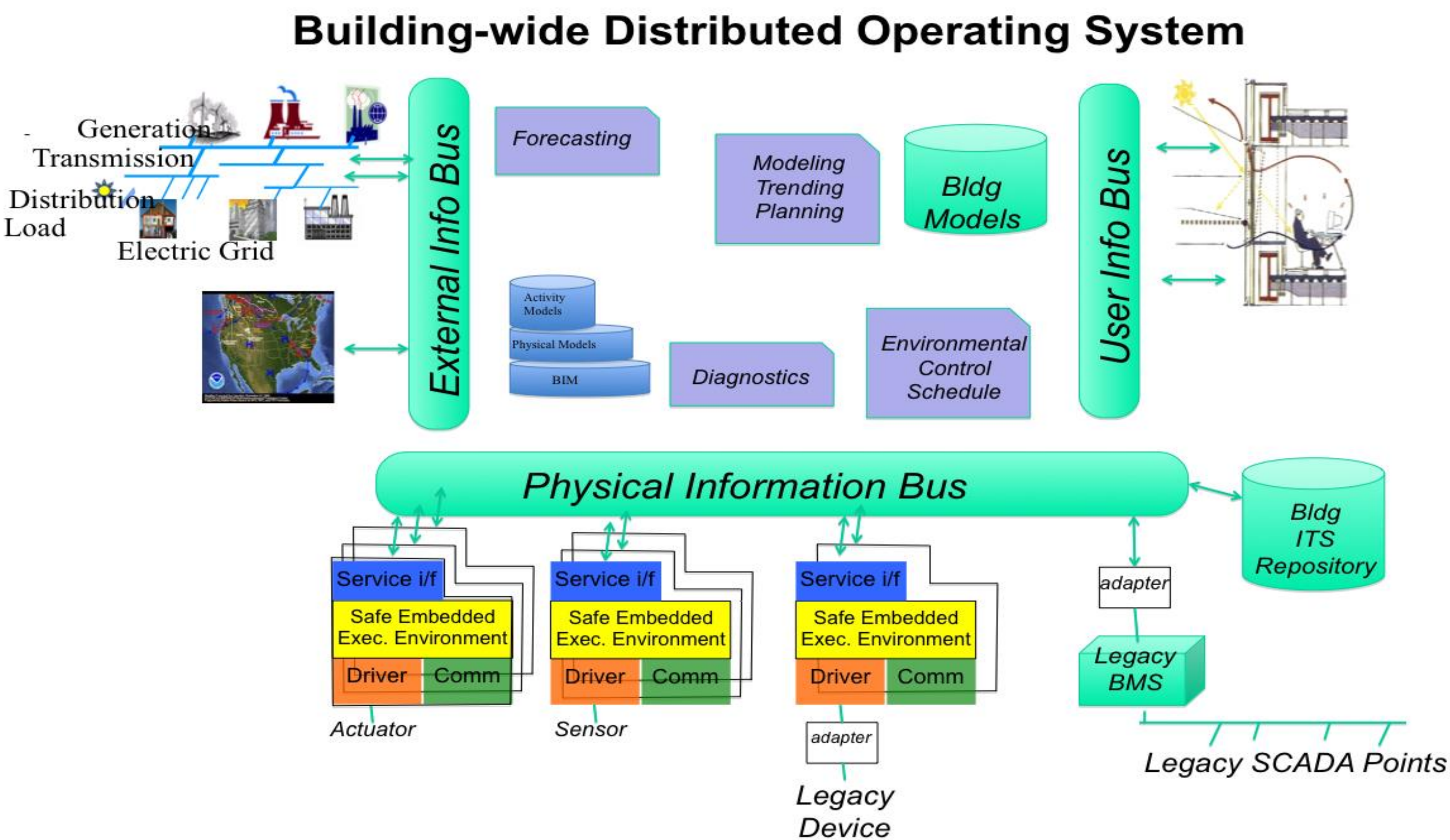
Mission Statement

Develop Foundations, Methodology and Tools to design and demonstrate a multi-scale embedded, intelligent distributed system consisting of wireless and wired networked sensors, actuators and controllers that executes a hierarchical control plan in real-time and in cooperation with building energy distribution grids and interactions with external utility grid, while adapting to system evolutions and local variations, controlling and optimizing resources.

Building Operating System

- **Objectives**: To apply new foundations and methodologies to design and demonstrate building operating systems that
  - Enable a fundamental change from oblivious consumption and isolated production to aware, agile, optimized and adaptive consumption and generation of energy in the building, particularly in the form of electrical power;
  - Provide high degree of cooperation between the building and the future extended smart power grid which incorporates intelligence into various points of consumption and generation within the building;
  - Provides critical functionality at all times, despite damages caused by accidental faults, errors, and degradations or malicious intrusions.
- **Methodologies**: Utilize and integrate pervasive instrumentation, broadly embedded intelligence, control and communication, modeling, forecasting and planning to actively manage the load buildings present to an intelligent energy distribution grid within and external to the building while also providing a comfortable and productive environment to occupants.

Concept of Building Operating System



Status of Research Team in Thrust 3

- Principal Investigators:
  - Alberto SANGIOVANNI
  - King-Jet TSENG
  - Sanjib PANDA
  - Boon Hee SOONG
  - Peter CHONG
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- Collaborators:
  - Francesco BORRELLI (UCB)
  - Gilbert FOO (NTU)
  - Jiyun ZHAO (NTU)
  - Zhili ZHOU (IBM)
  - Forrest Megger (ETH-FCL)
  - Danielle Griego (NTU)

- PhD Students:
  - Ming ZHAO
  - Krishnanand
  - Nurul Husna ARDIYANTO
  - Radha SREE
  - *1 vacancy (CAO Qi?)*

- Research Staff:
  - Guangyu JIN
  - HNIN Yu Shwe
  - Edwin CHAN
  - *2 vacancies (Mehdi?)*

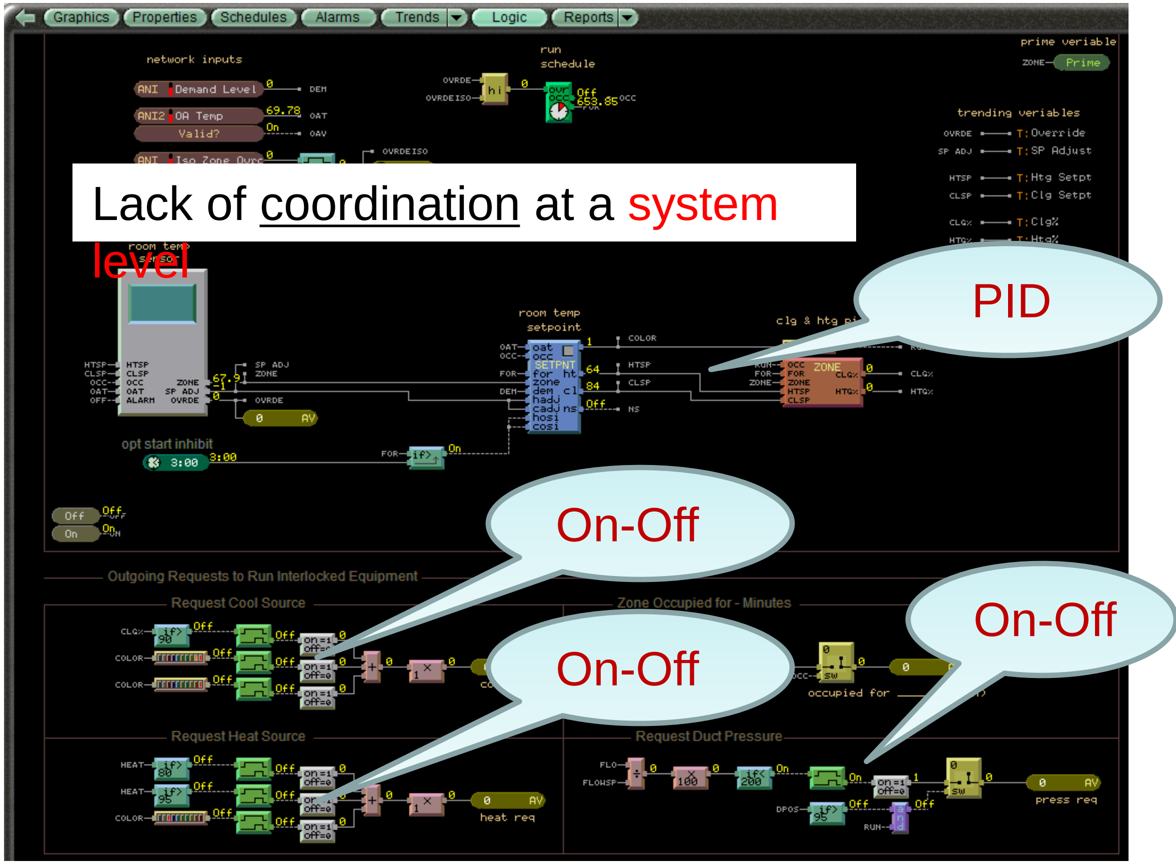
Work Packages for Jan 2012 – Mar 2013

- WP3.1: Development of Building Automation and Control (BAC) Systems
  a. Modeling and Optimal Controller Design *for HVAC System*
  b. Controller Platform Framework Setup
  c. Sensor Selection and Placement
- WP3.2: Intelligent Energy Distribution Systems in Buildings
  a. Intelligent Power Switches with Cooperative Energy Storage
  b. Hybrid DC/AC Building Power Distribution
- WP3.3: Information Networks for Smart Buildings
  a. Design and Optimization of Efficient Information Networks
  b. Energy Management Applications

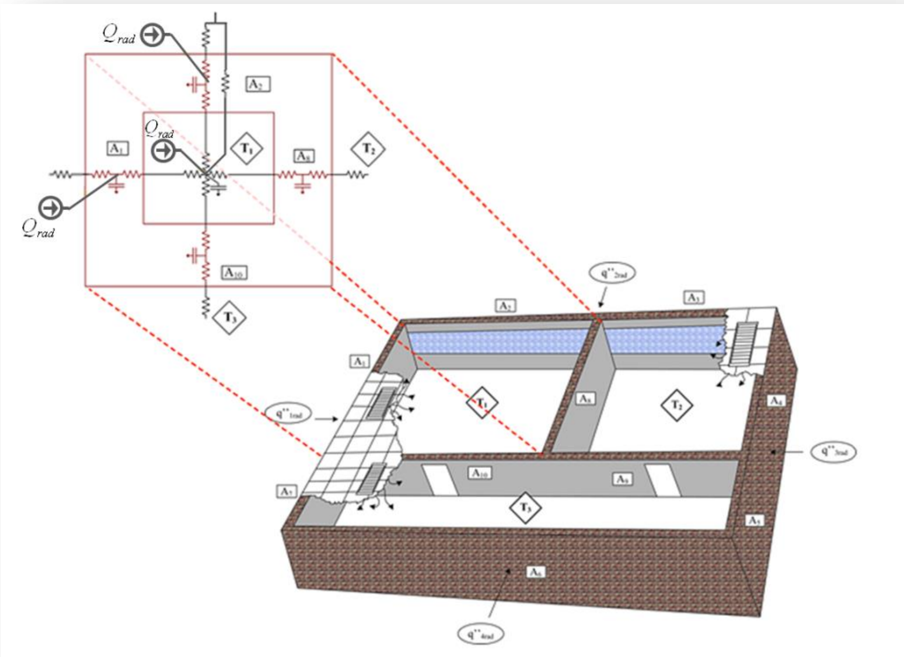
WP3.1a:Modeling and Optimal Controller Design

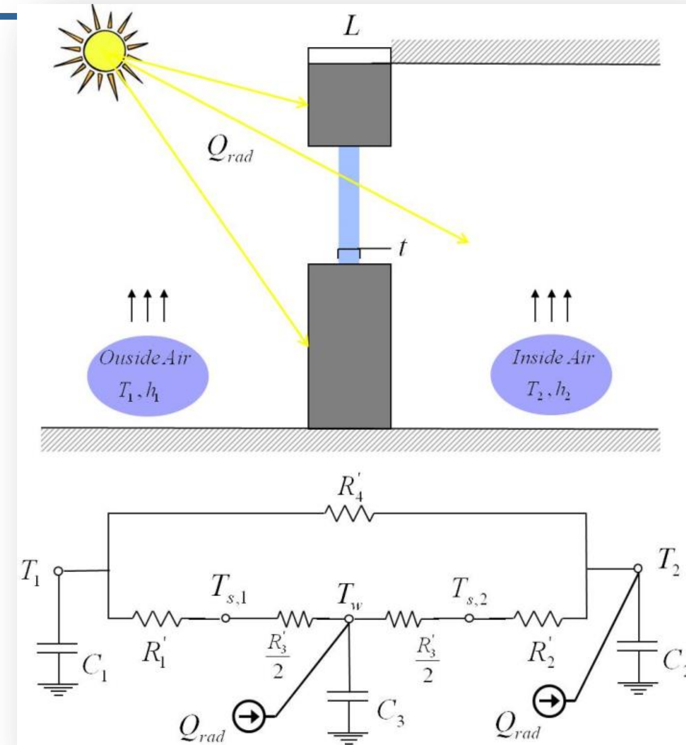
Observations:

- Control logic governing today's buildings uses simple control schemes *dealing with one subsystem at a time…*
- Local actions are determined without taking into account the interrelations among:
  - Outdoor weather conditions
  - Internal heat gains
  - Indoor air quality
  - Cooling demands
  - HVAC process components



WP3.1a:Modeling and Optimal Controller Design





Thermal and circuit model of a wall with window

$$\frac{dT_{w_i}}{dt} = \frac{1}{C_{w_i}}\left[\sum_{j\in\mathcal{N}_{w_i}} \frac{T_j - T_{w_i}}{R'_{ij}} + r_i\alpha_i A_i q''_{rad_i}\right]$$

$$\dot{x}(t) = Ax(t) + Bu(t) + d(t)$$
$$y(t) = Cx(t)$$

Energy balance equations:

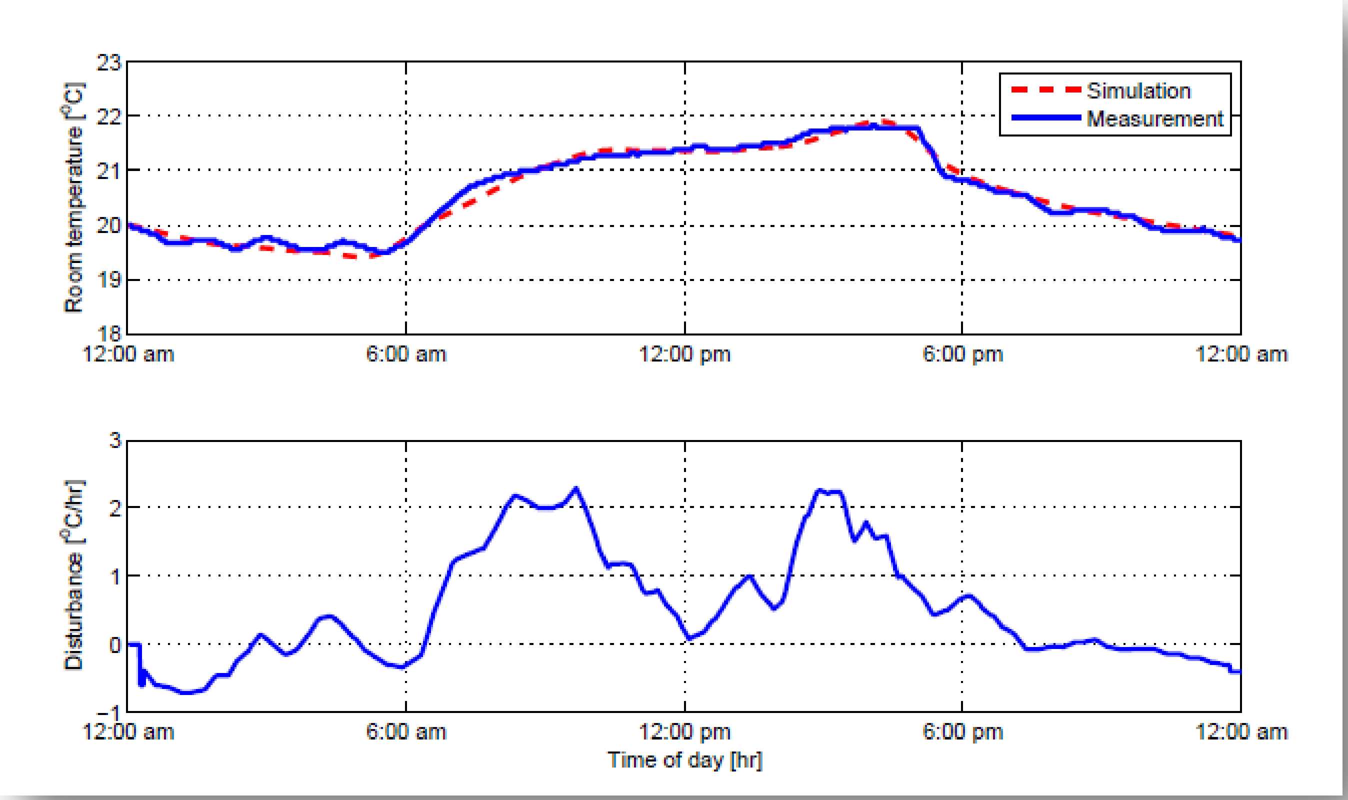
$$\frac{dT_{r_i}}{dt} = \frac{1}{C_{r_i}}\left[\sum_{j\in\mathcal{N}_{r_i}} \frac{T_j - T_{r_i}}{R'_{ij}} + \dot{m}_{r_i}c_p(T_{s_i} - T_{r_i}) + w_i\tau_{win_i}A_{win_i}q''_{rad_i} + \dot{q}_{int}\right]$$

WP3.1a:Modeling and Optimal Controller Design

Parameter and Unmodeled Dynamics Estimation

- Initial guess (ASHRAE Handbook)
- Used fmincon

- Historical Data of UC Berkeley Bancroft library,
- Conference room



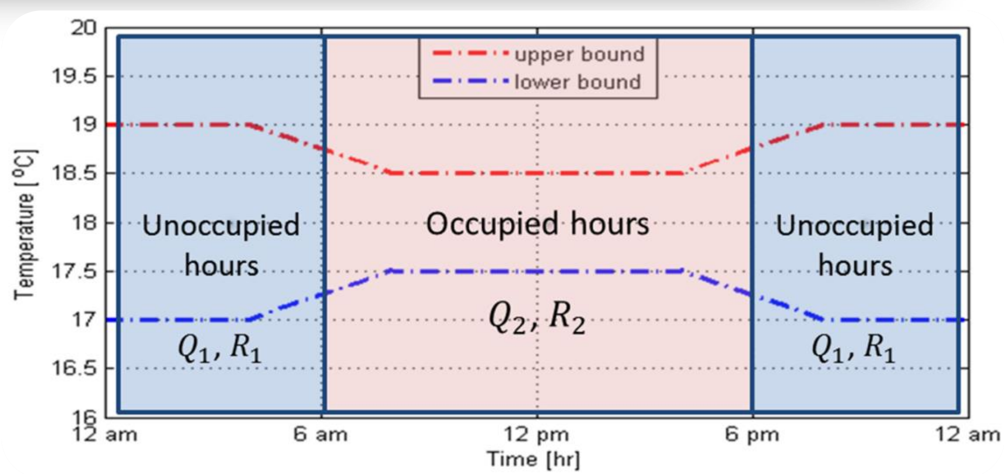
WP3.1a:Modeling and Optimal Controller Design

$$\min_{U_t,\bar{\epsilon},\underline{\epsilon}} \quad \{|U_t|_1 + \kappa|U_t|_\infty + \rho(|\bar{\epsilon}_t|_1 + |\underline{\epsilon}_t|_1)\} =$$

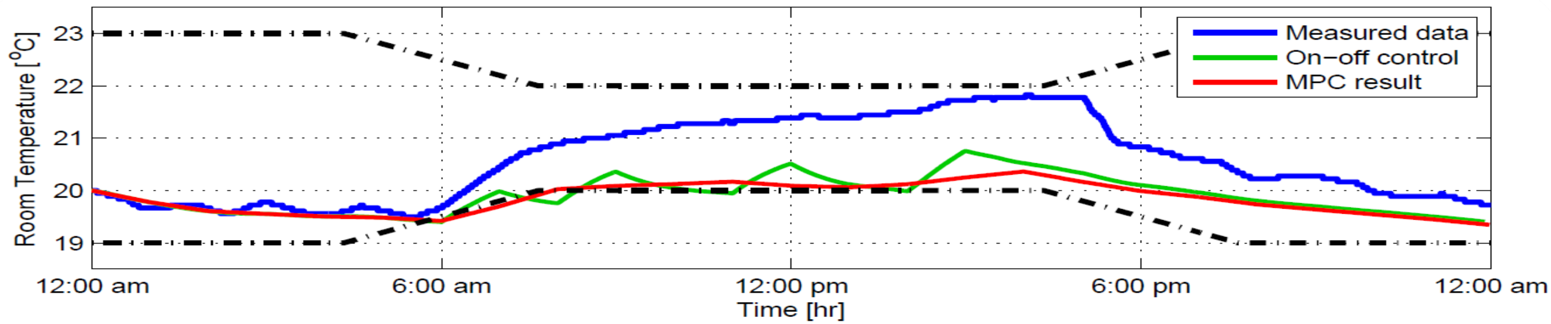
$$\min_{U_t,\bar{\varepsilon},\underline{\varepsilon}} \quad \{\sum_{k=0}^{N-1} |u_{t+k|t}| + \kappa \max(|u_{t|t}|, \cdots, |u_{t+N-1|t}|) + \rho \sum_{k=1}^{N} (|\bar{\varepsilon}_{t+k|t}| + |\underline{\varepsilon}_{t+k|t}|)\}$$

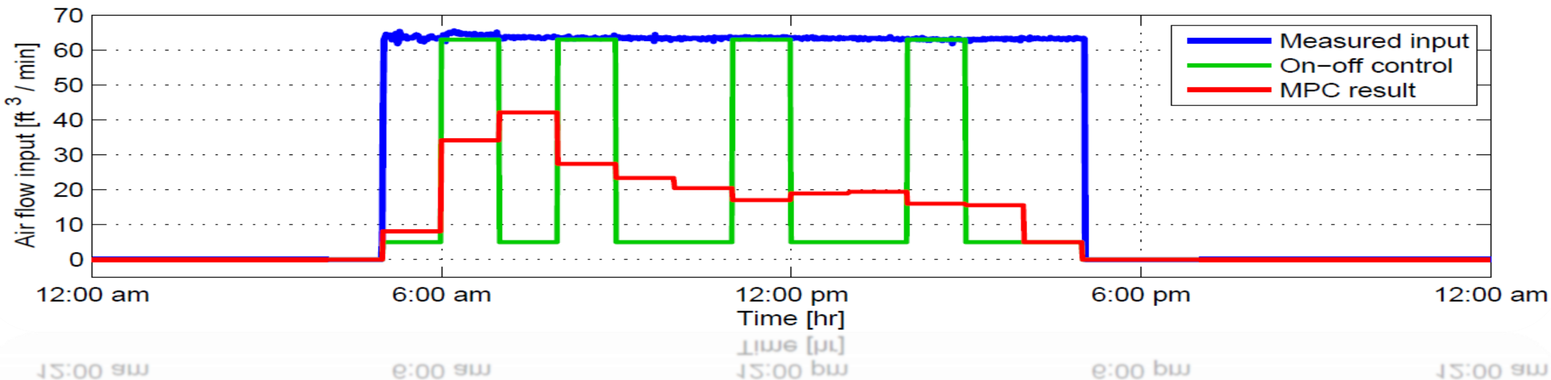
$$\begin{aligned}
\text{s.t.} \quad & x_{t+k+1|t} = Ax_{t+k|t} + Bu_{t+k|t} + Ed_{t+k|t}, && k = 0, ..., N-1 \\
& y_{t+k|t} = Cx_{t+k|t}, && k = 1, ..., N \\
& 0 \leq u_{t+k|t} \leq \overline{\mathcal{U}}, && k = 0, ..., N-1 \\
& \underline{T}_{t+k|t} - \underline{\varepsilon}_{t+k|t} \leq y_{t+k|t} \leq \overline{T}_{t+k|t} + \bar{\varepsilon}_{t+k|t}, && k = 1, ..., N \\
& \underline{\varepsilon}_{t+k|t}, \bar{\varepsilon}_{t+k|t} \geq 0, && k = 1, ..., N
\end{aligned}$$

Model predictive control



WP3.1a:Modeling and Optimal Controller Design





Controller	Total input $[ft^3]$	Peak input $[ft^3/min]$	Total energy $[kWh]$	Running time $[s]$
Original control	45360	63	12.46	-
On-off control	17520	63	4.62	1.8
MPC	14870	42	3.33	102.4

68% 66% 35% 73%

S

WP3.1b:Controller Platform Framework Setup

Co-design of Control Algorithm and Embedded Platform for HVAC Systems

Researchers Involved:

- *Mehdi Maasoumy (UCB)*
- *Qi Zhu (UCR)*
- *Cheng Li (NTU)*
- *Forrest Meggers(FCL*)*
- *Brülisauer Marcel(FCL*)*
- *Alberto Sangiovanni-Vincentelli (UCB)*

*: Future Cities Lab of ETH in Singapore

Problem statement

- The design of HVAC systems involves three main aspects:
  - Physical components and environment,
  - Control algorithm that determines the system operations based on sensing inputs,
  - Embedded platform that implements the control algorithm.

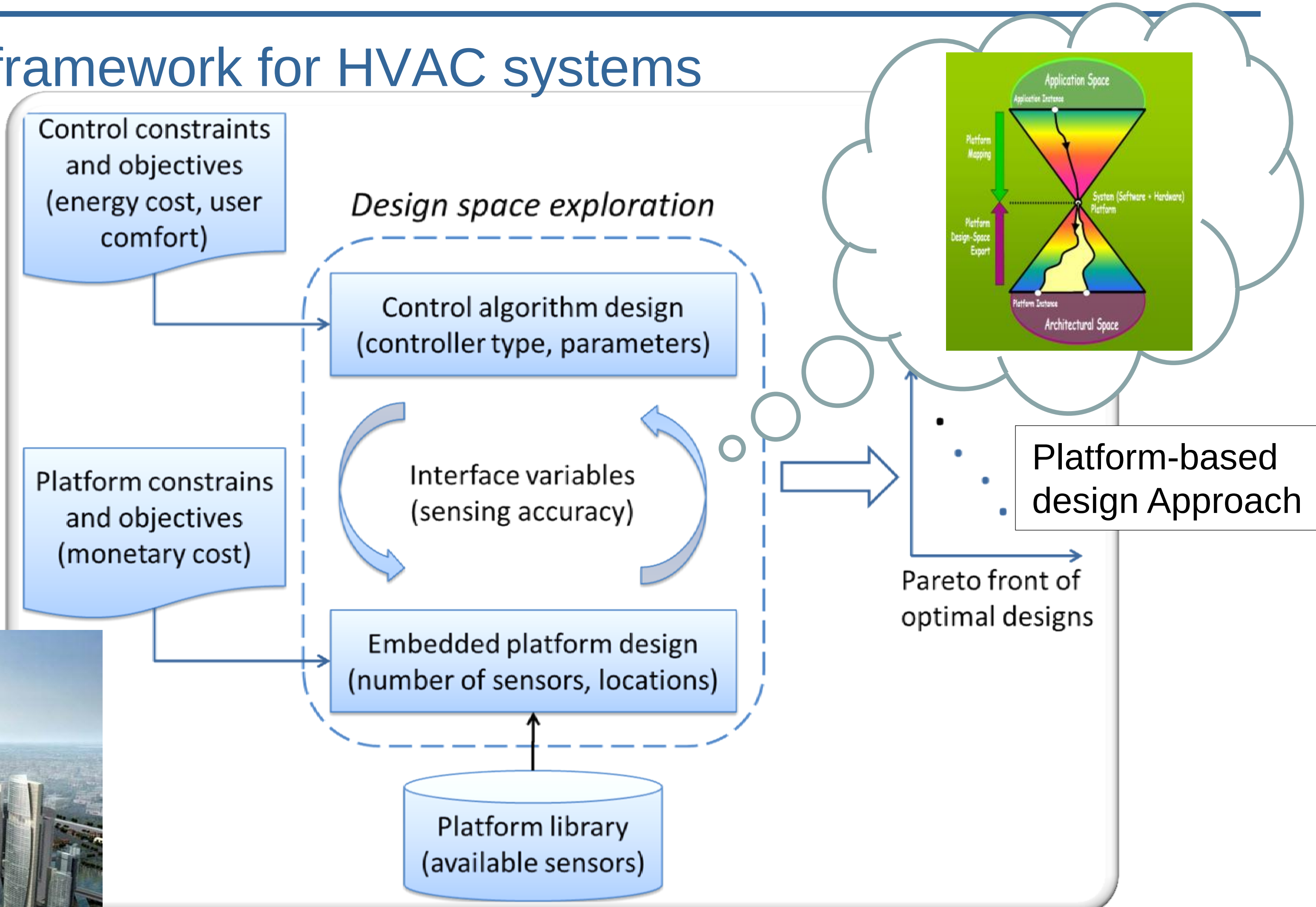
- In the traditional *top-down approach*, the design of the HVAC control algorithm is done without explicit consideration of the embedded platform.

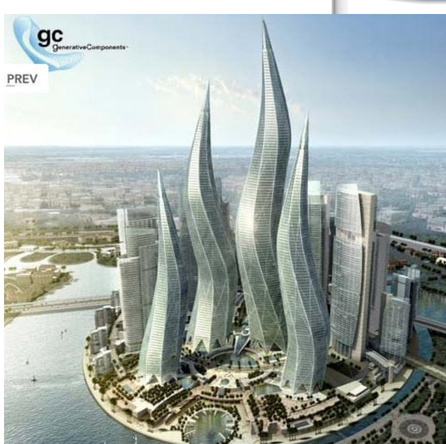
With the…

- *Employment of more complex HAVC control algorithms,*
- *Use of distributed networked platforms, and*
- *Imposing of tighter requirements for user comfort,*

The assumption that the embedded platform will always be sufficient for any control mechanism

Co-design framework for HVAC systems





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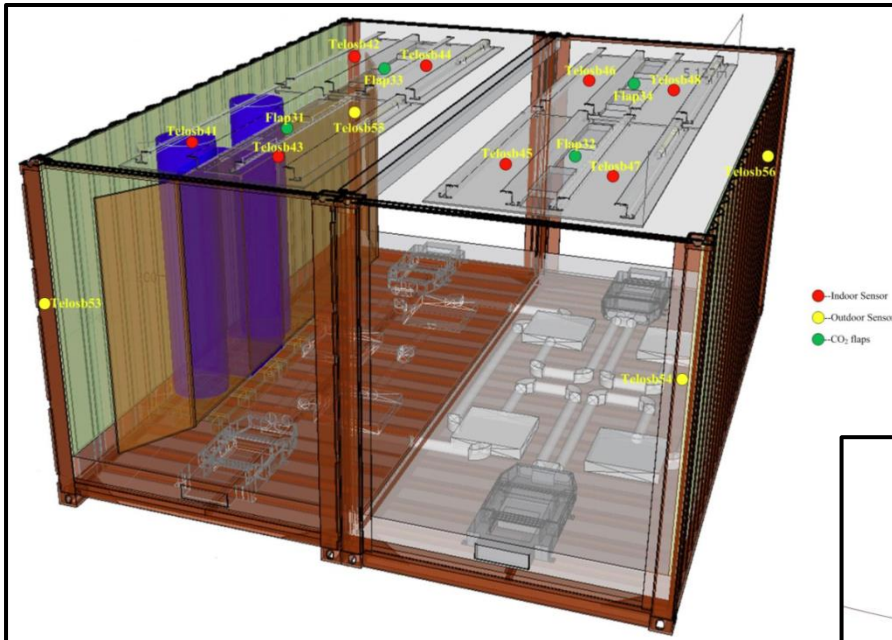


BubbleZERO Research Setup

Which is conceived as part of the Low Exergy Module development for Future Cities Laboratory (FCL) of ETH in Singapore.

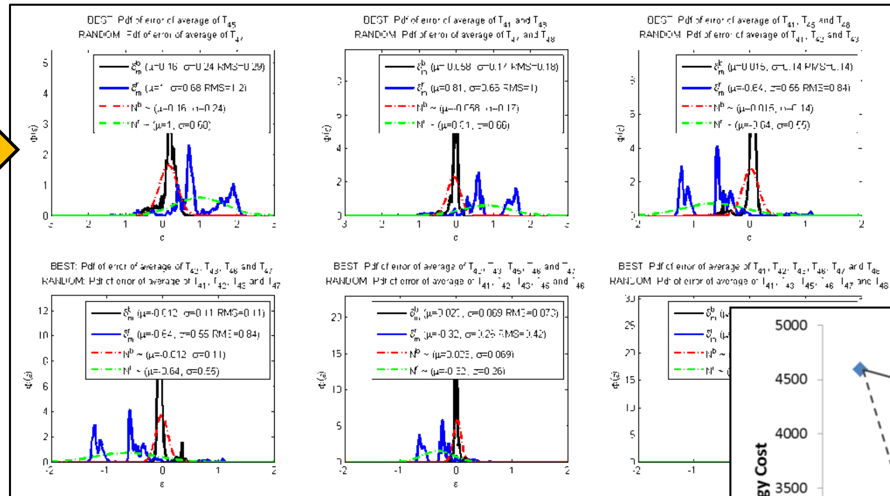
The environment sense system includes:

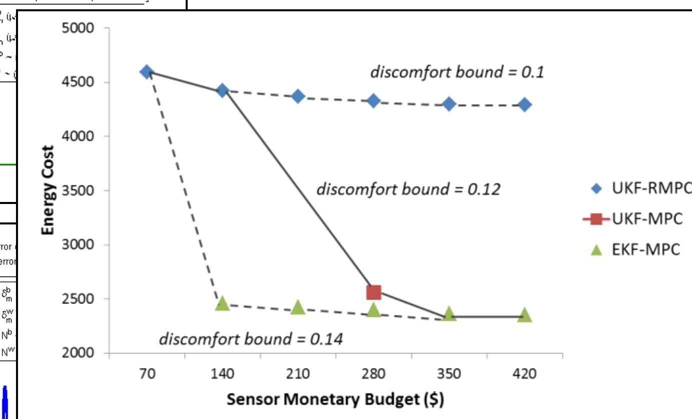
8 indoor sensors (Telosb41-48)
4 CO2 concentration sensors (flap31-34)
4 outdoor sensors (Telosb53-56)

WP3.1c: Sensor Selection and Placement

Each figure plots the *pdf* of the difference of the average of k sensor readings with the average of all 7 sensor readings. The **best**, **worst** and **random** set of sensors are selected based on their resulting Δ_{rms} error.

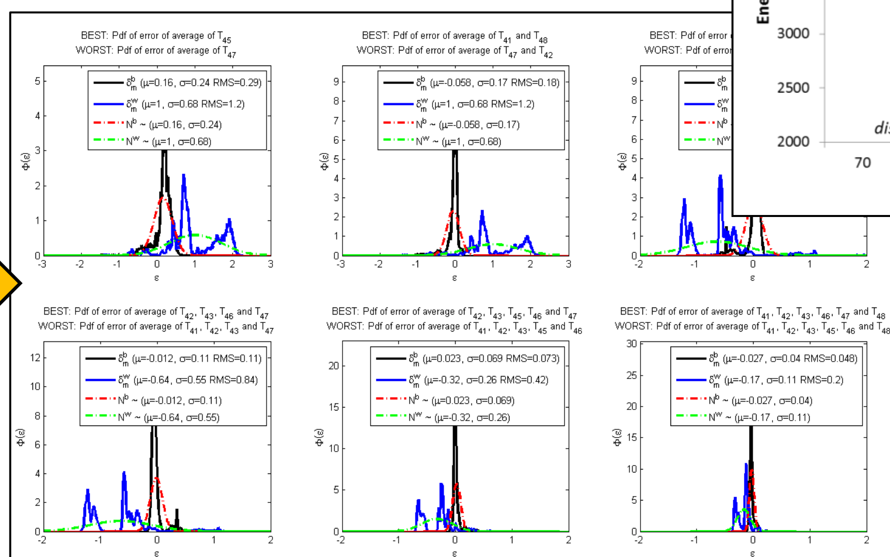
Average error of k sensors for the Minimal error set of sensors and a **random** choice of sensors.



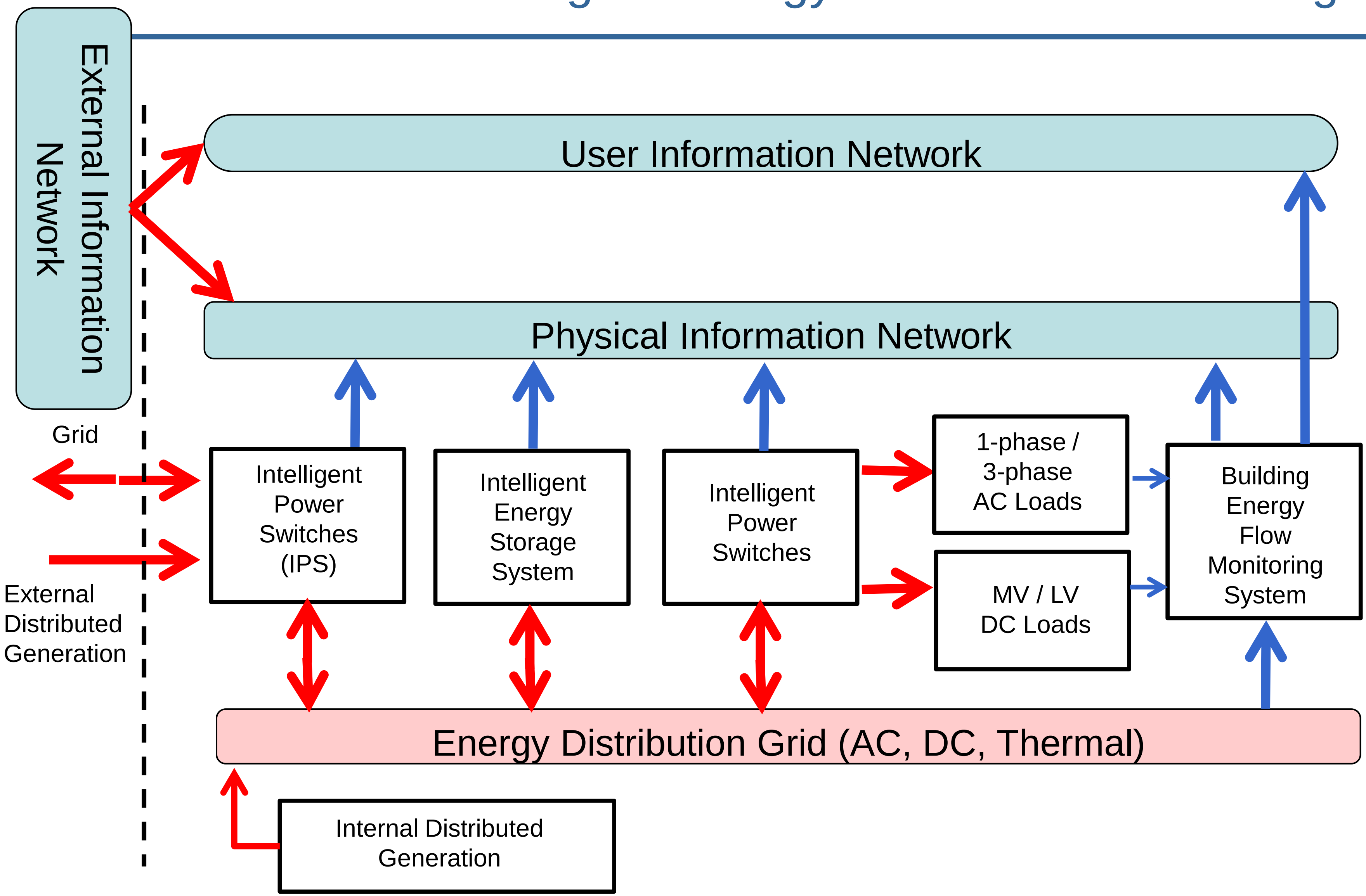


Pareto front Under Discomfort index Contraints

Average error of k sensors for the Minimal error set of sensors and the **worst** choice of sensors.

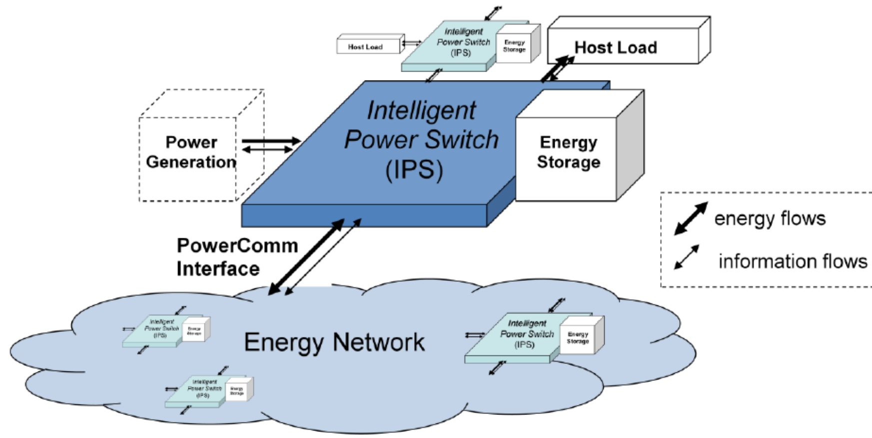


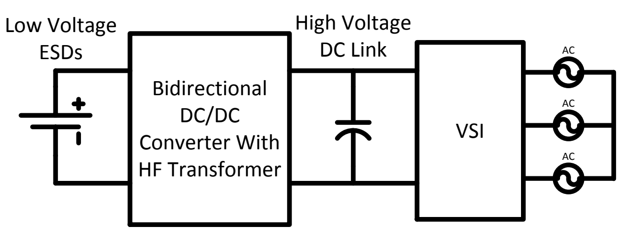
WP3.2: Intelligent Energy Distribution in Buildings

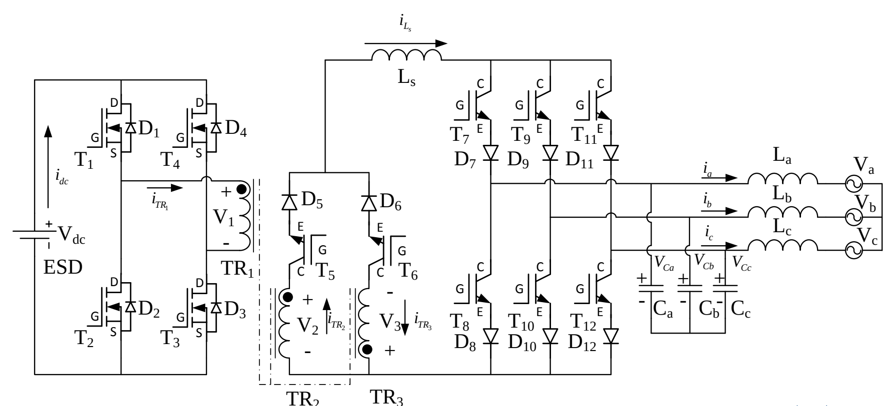


WP3.2a: Intelligent Power Switch with Cooperative Energy Storage

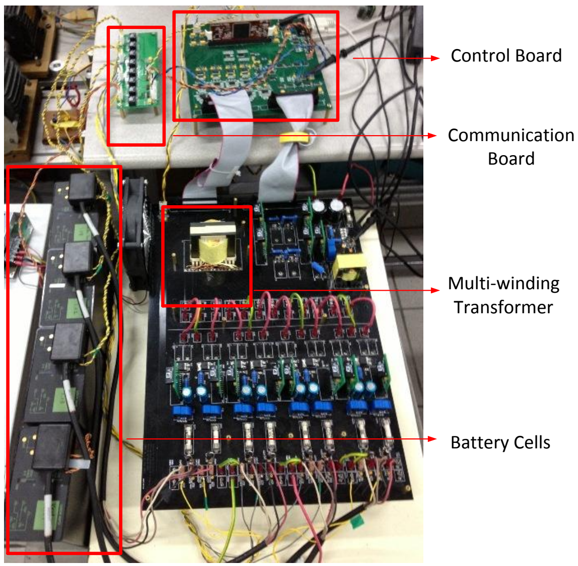
- The original concept of intelligent power switch (IPS) as in the ‘LoCal’ paper.
- IPS combines communications with a power electronic interface to manage the link between any energy source or load and the energy distribution grid.
- Block and circuit diagrams of possible *partial* implementations.
- Issues and features include:
  - Solid-state transformers for voltage translation
  - Low-loss Si-C power electronics
  - Battery cell equalization for energy storage
  - Circulating energy issue among multiple IPS
  - Resilient isolatable energy sub-network s with renewable power generation sources
  - Chemical-free energy storage
  - Power line and wireless communications
  - Energy harvesting for autonomous sensors

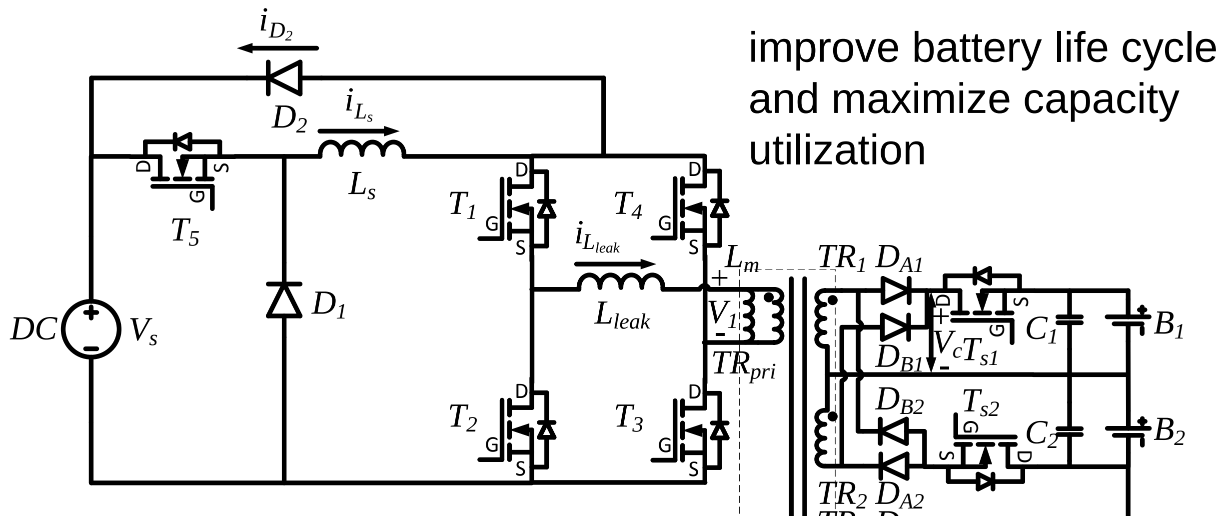


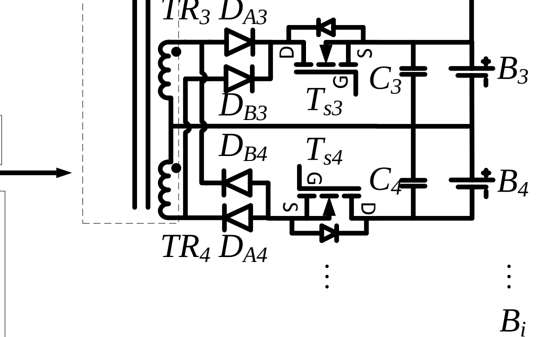




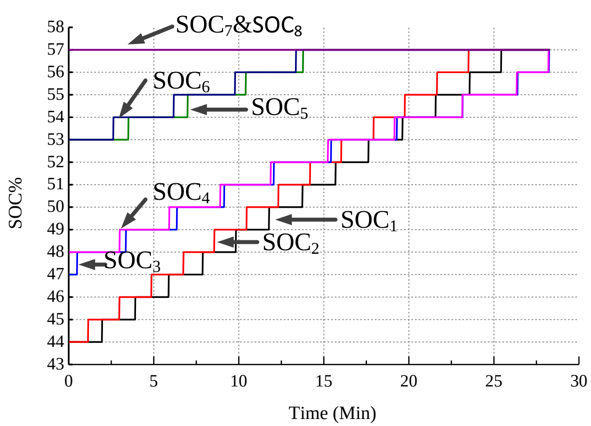
Development of cell equalizer for lithium-ion battery energy storage system

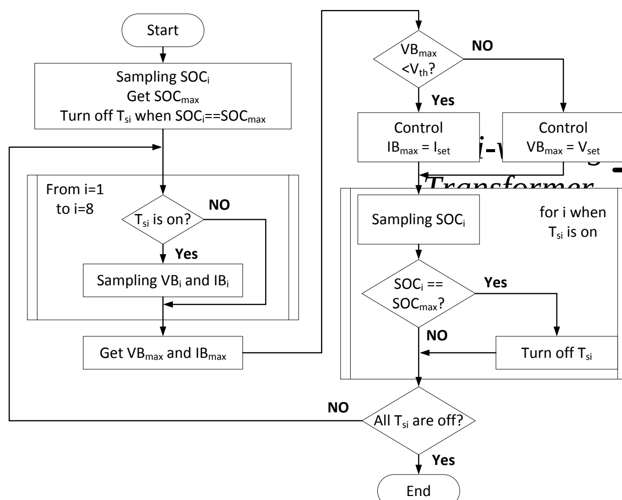




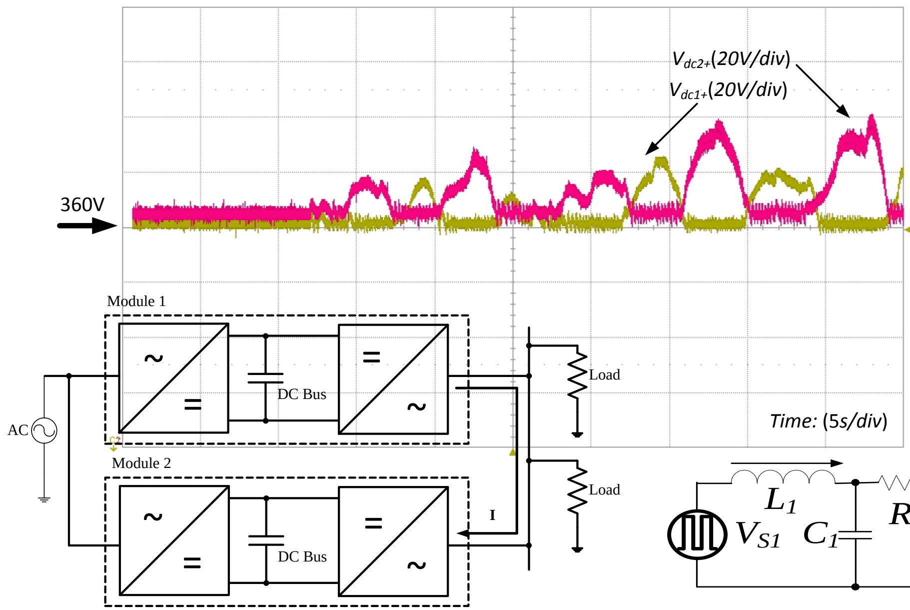


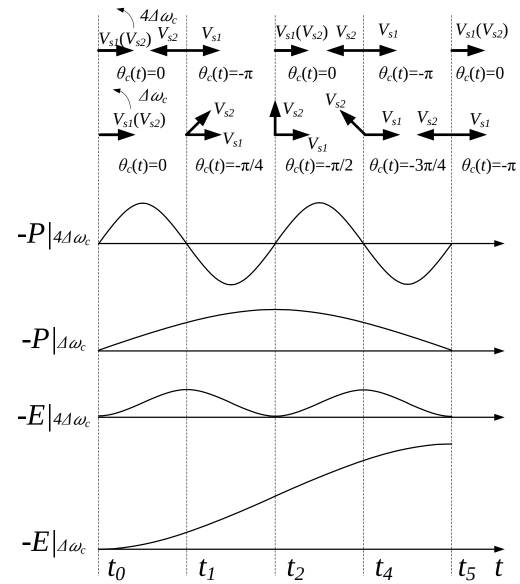
improve battery life cycle and maximize capacity utilization

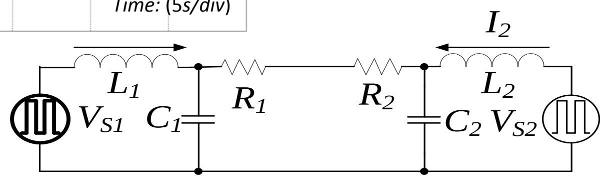




Issue of circulating energy among multiple IPS connected to the building power network



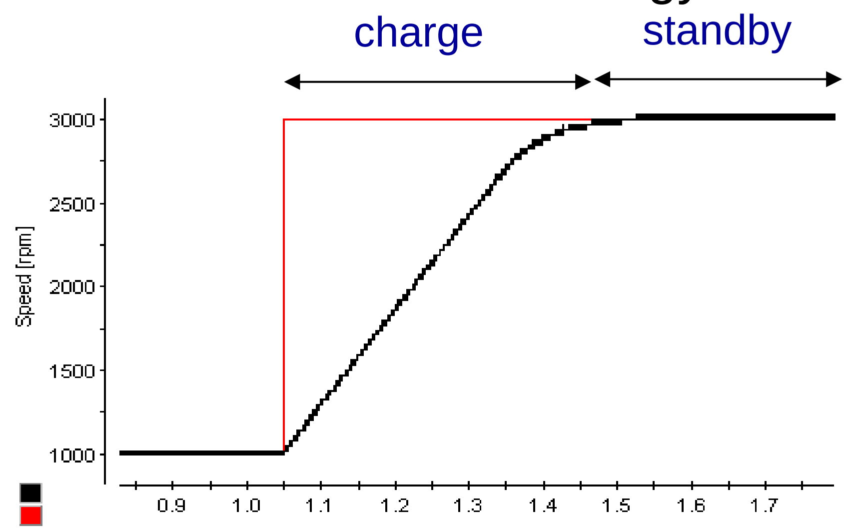


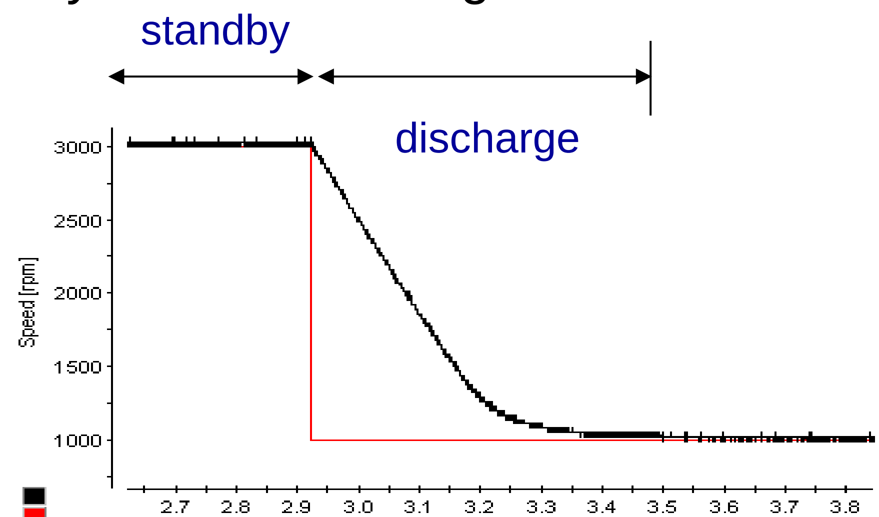


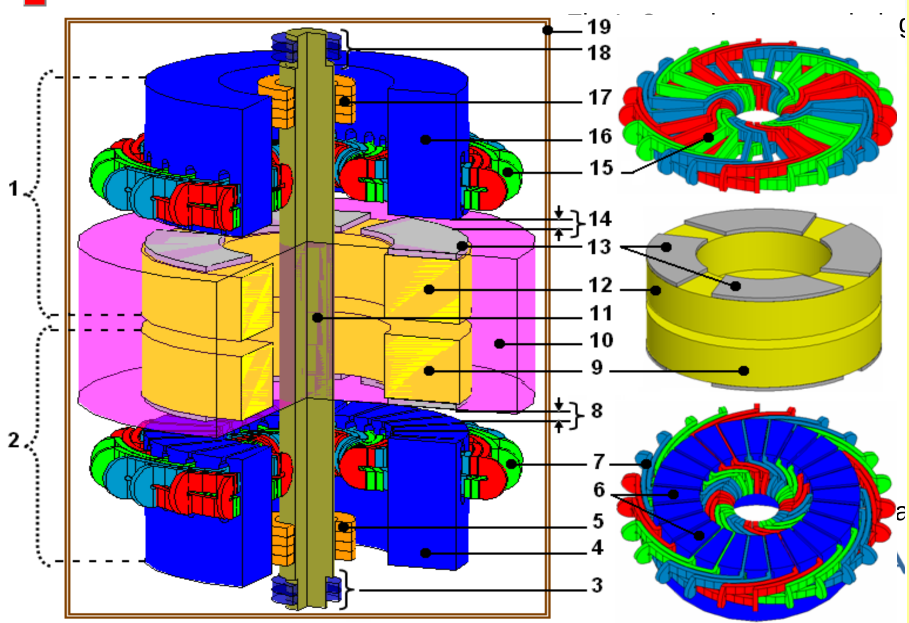
$$S_{V_{S1}}(m,n)=C_{mn}{}^{2}\cdot\left[\underbrace{-j\cdot\frac{\omega_{mn}L}{-\omega_{mn}{}^{2}L^{2}+\frac{L}{C}}+j\cdot\frac{\frac{1}{2\omega_{mn}C}}{-\omega_{mn}{}^{2}L^{2}+\frac{L}{C}}\cdot\left(1-\sin\left(\frac{\pi}{2}+m\Delta\theta_{c}\right)\right)}_{\text{Reactive Power}}+\underbrace{\frac{-\frac{1}{2\omega_{mn}C}}{-\omega_{mn}{}^{2}L^{2}+\frac{L}{C}}\cdot\cos\left(\frac{\pi}{2}-\Delta m\theta_{c}\right)}_{\text{Active Power}}\right]$$

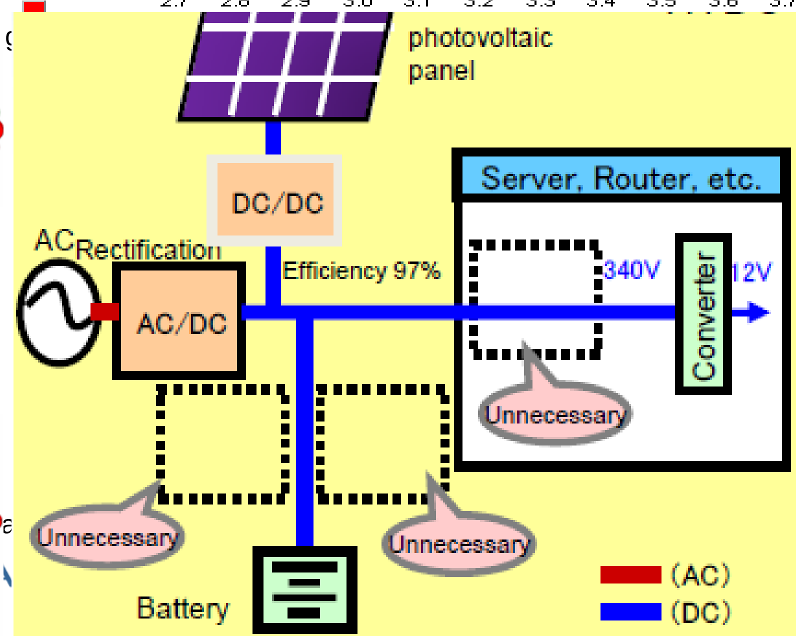
WP3.2a: Intelligent Power Switch with Cooperative Energy Storage

Chemical-Free Green Energy Storage System for Buildings – Kinetic Battery

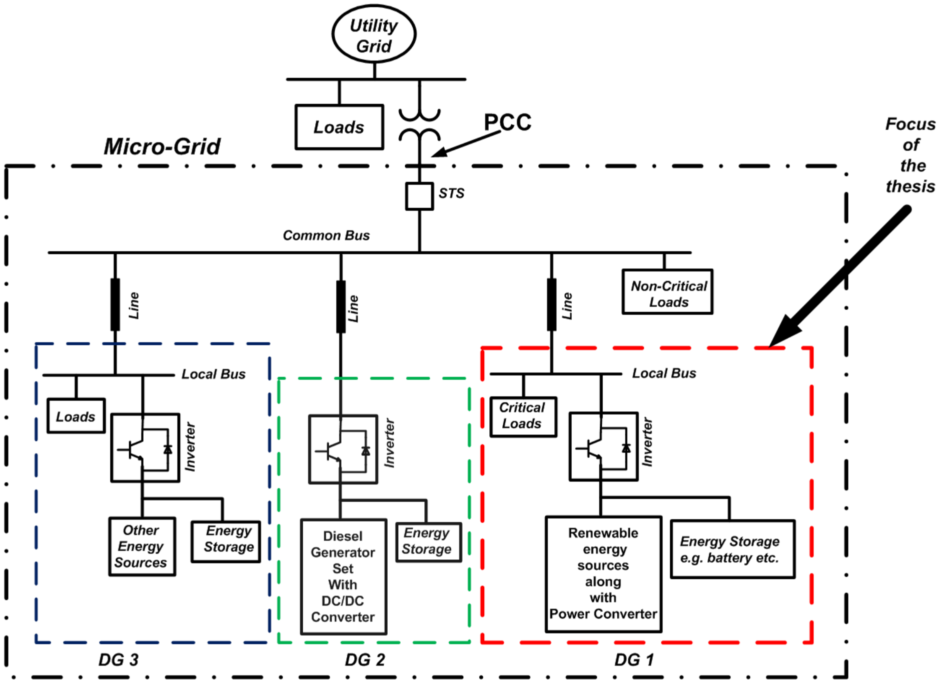








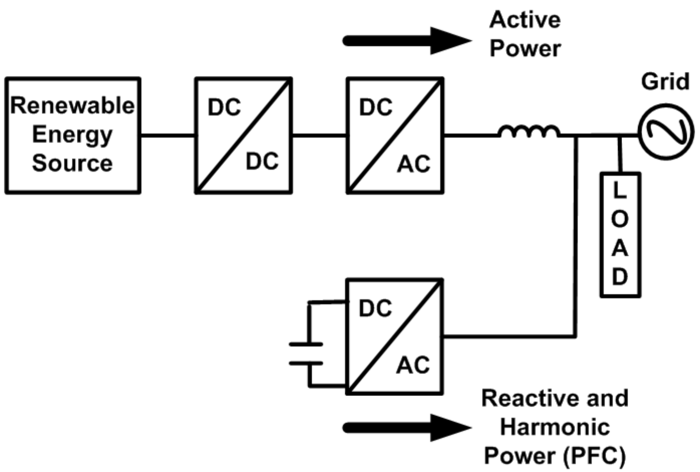
WP3.2b: Hybrid DC/AC Building Power Distribution



- Intelligent Power Switch determines grid connected or islanded operation.
- DG1, DG2 and/or DG3 can be fossil fuel based or renewable energy source based generator interfaced to common AC bus using power electronic converters.
- Main concerns of micro-grid research are : High band-width active and reactive power flow control, THD control of current drawn from common AC bus, Load voltage regulation…etc….

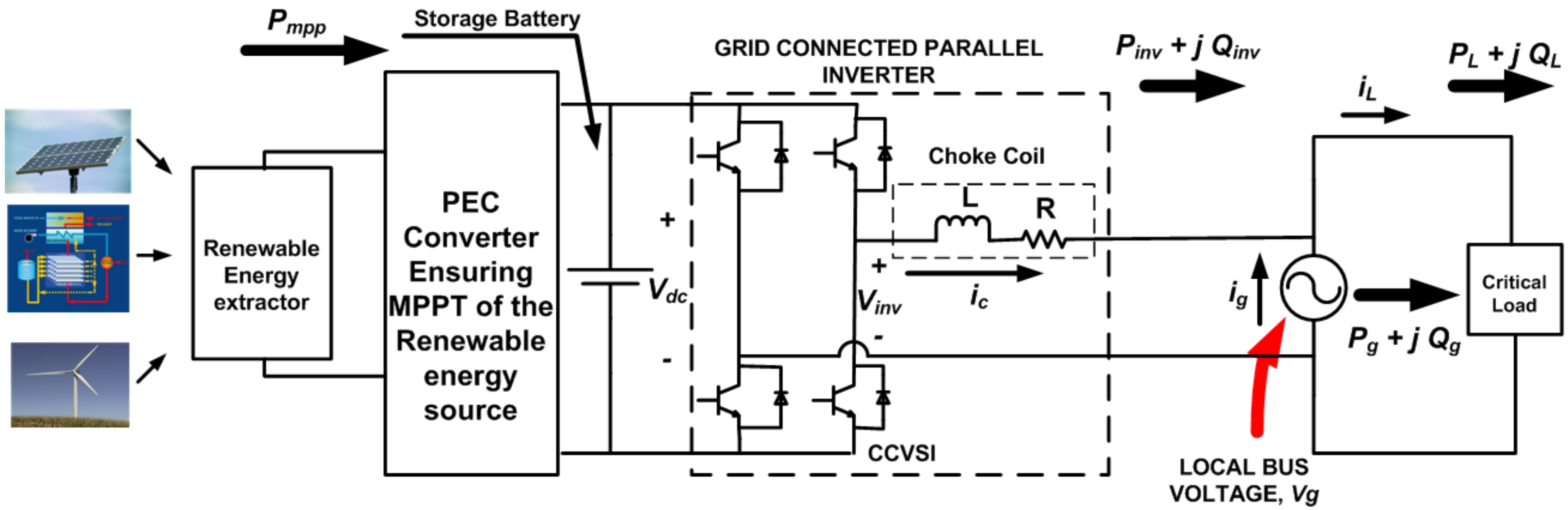
Single-phase residential application

- Parallel connected inverter is directly connected to grid to feed harvested power.
- Loads are non-linear in nature; requiring another inverter circuit to work as PFC.
- Single inverter should be designed doing both the tasks.
- Most of the synchronous frame (*d*-*q* frame) current controllers are for balanced three-phase systems; can not be directly applied in single-phase system.
- If common bus voltage has sag, swell or other types of harmonic contaminations, critical loads may malfunction; requiring a topological change in inverter configuration.



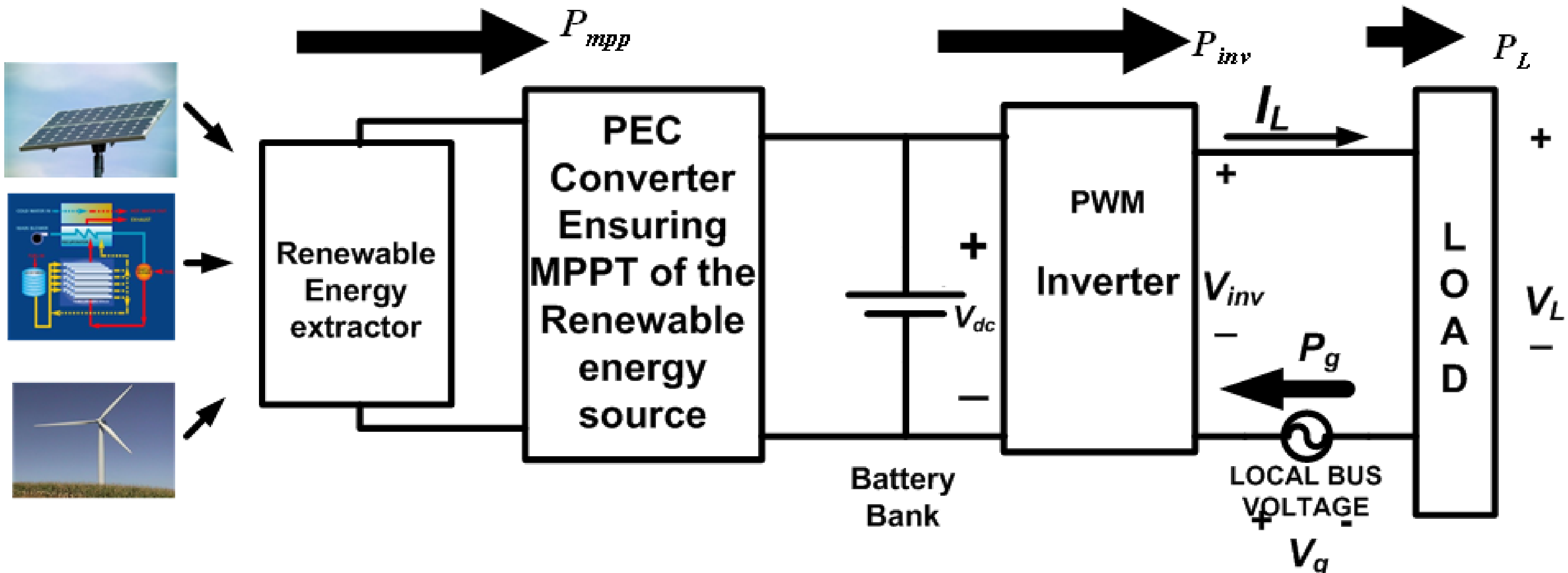
Traditional parallel connected converters with PFC operation.

Schematic: Single-phase parallel connected inverter



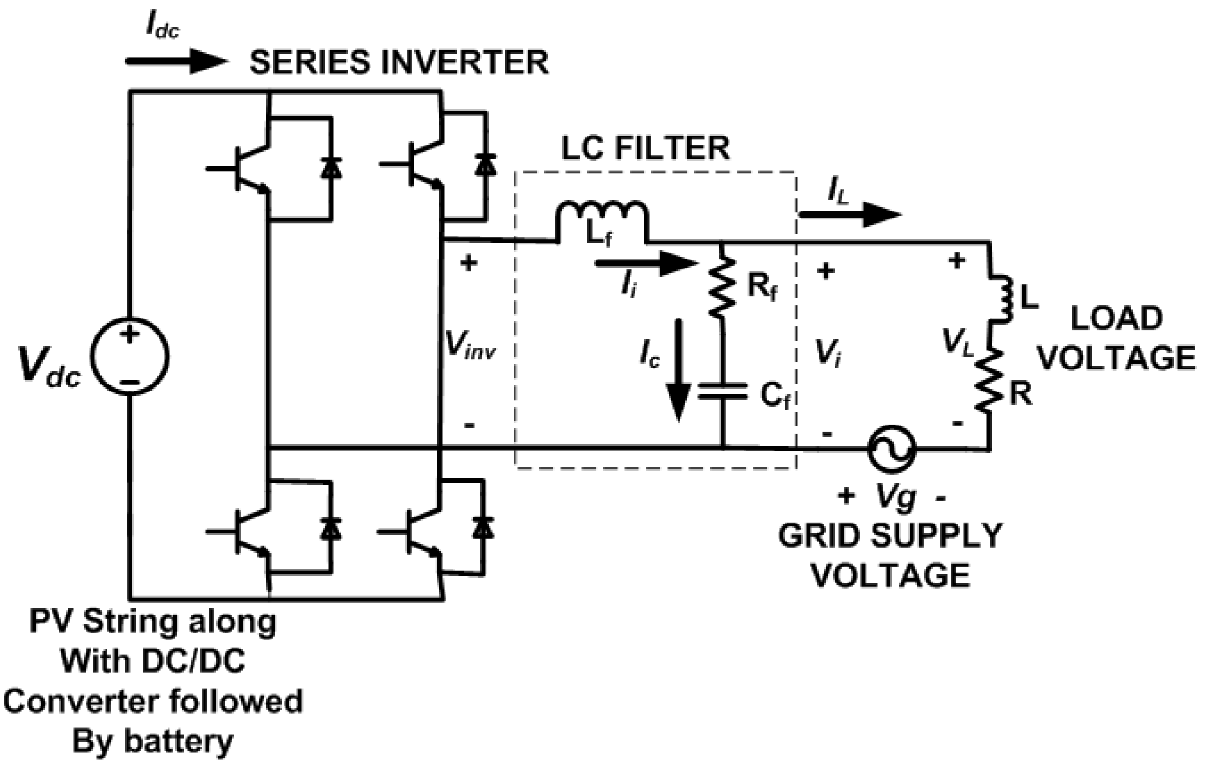
- Total load active power P_L is shared between inverter active power, P_{inv} and grid active power, P_g… i.e. $P_L = P_{inv} + P_g$
- There is a savings in power consumption from grid.
- The current drawn local bus is purely sinusoid with DPF=1.
- High-performance non-linear current controller is used for the inverter to perform two actions:
  - Active power flow control
  - THD control of grid current

WP3.2b: Hybrid DC/AC Building Power Distribution

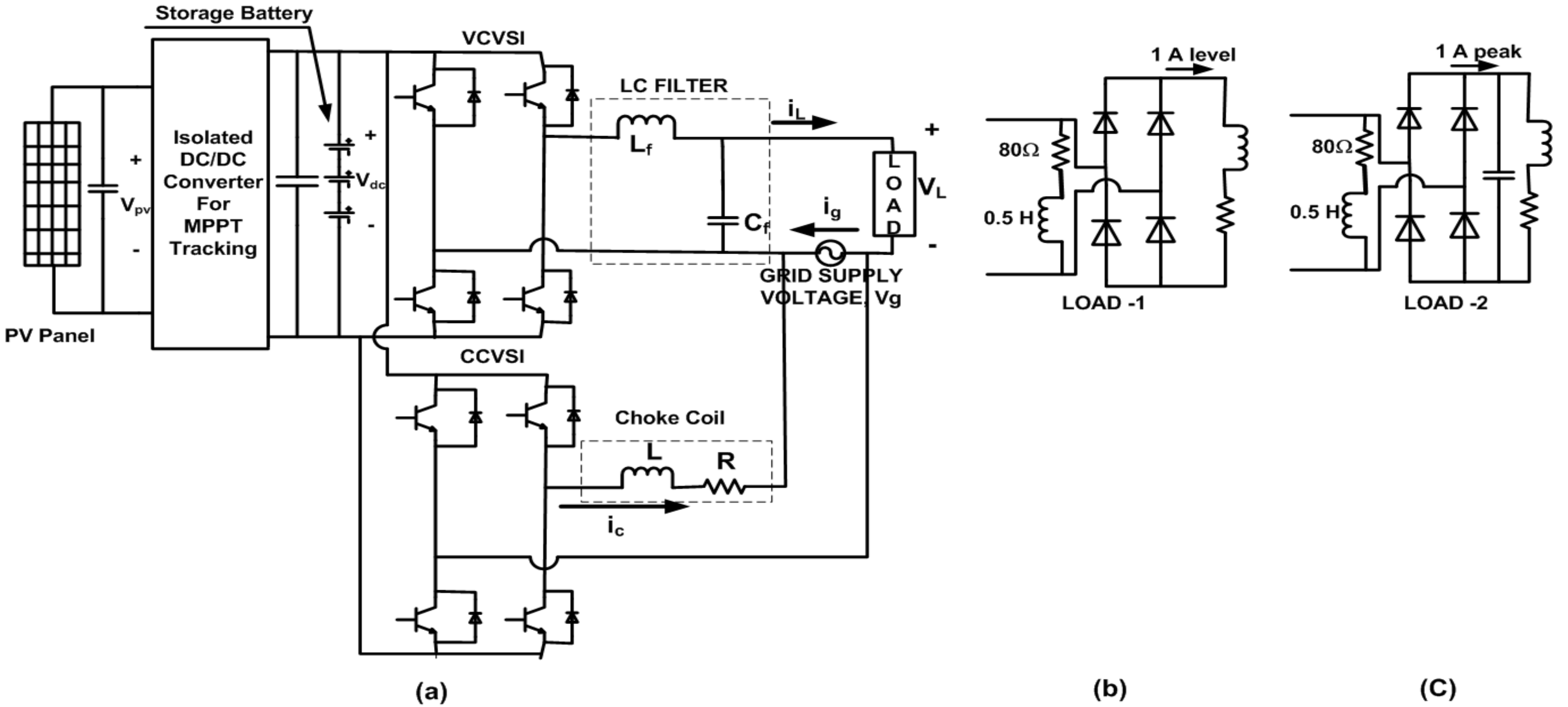


- Total load active power P_L is shared between inverter active power, P_{inv} and grid active power, P_g… i.e. $P_L = P_{inv} + P_g$
- There is a savings in power consumption from grid.
- The current drawn local bus is leading voltage even at the presence of lagging pf load.
- The load voltage V_L is pure sinusoid and at rated value even if grid has sag, swell or harmonic contamination.
- Inverter voltage, V_{inv} is added vectorially with grid voltage, V_g to control load voltage, V_L.
- THD control of load voltage.

Schematics of the series inverter circuit topology

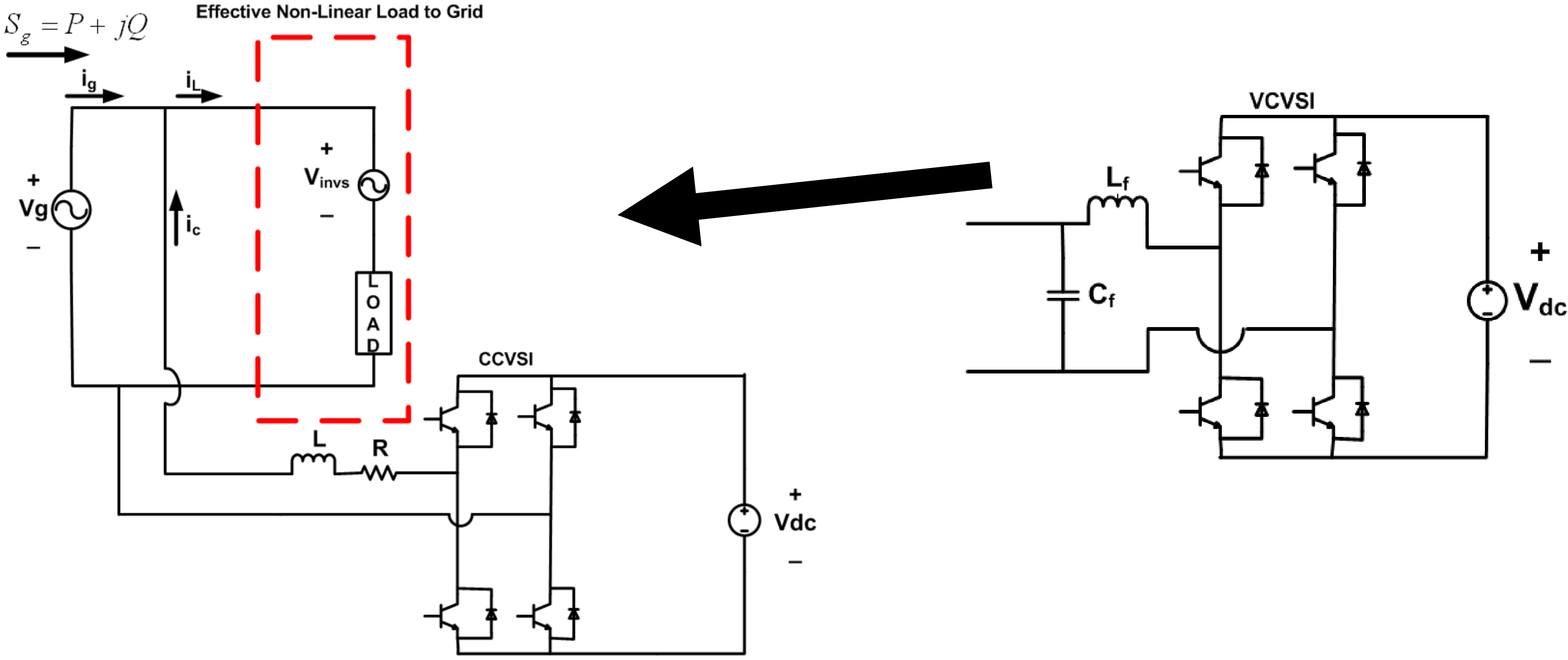


Single phase hybrid connected PV inverter topology



- **Series inverter is used to regulate the load voltage.**
- **Parallel inverter is used to control grid active as well as reactive power along with grid current THD control**

Hybrid connected PV inverter topology



WP3.2b: Hybrid DC/AC Building Power Distribution

- A single-phase *p-q* theory based current reference generation approach for a single-phase parallel connected inverter is proposed so that the single inverter is able to control grid active and reactive power flow as well as shaping the grid currents.

- A *Lyapunov function* based current controller is proposed so that single inverter is able to track the current ensuring *power flow control* and *THD control.*

- A single-phase series connected inverter control strategy is proposed ensuring grid active power flow control as well as stabilizing load voltage under grid voltage sag, swell, harmonic contamination as well as frequency drift.

- A *Spatial Iterative Learning Controller (SILC*) is designed to do the voltage regulation and power flow efficiently.

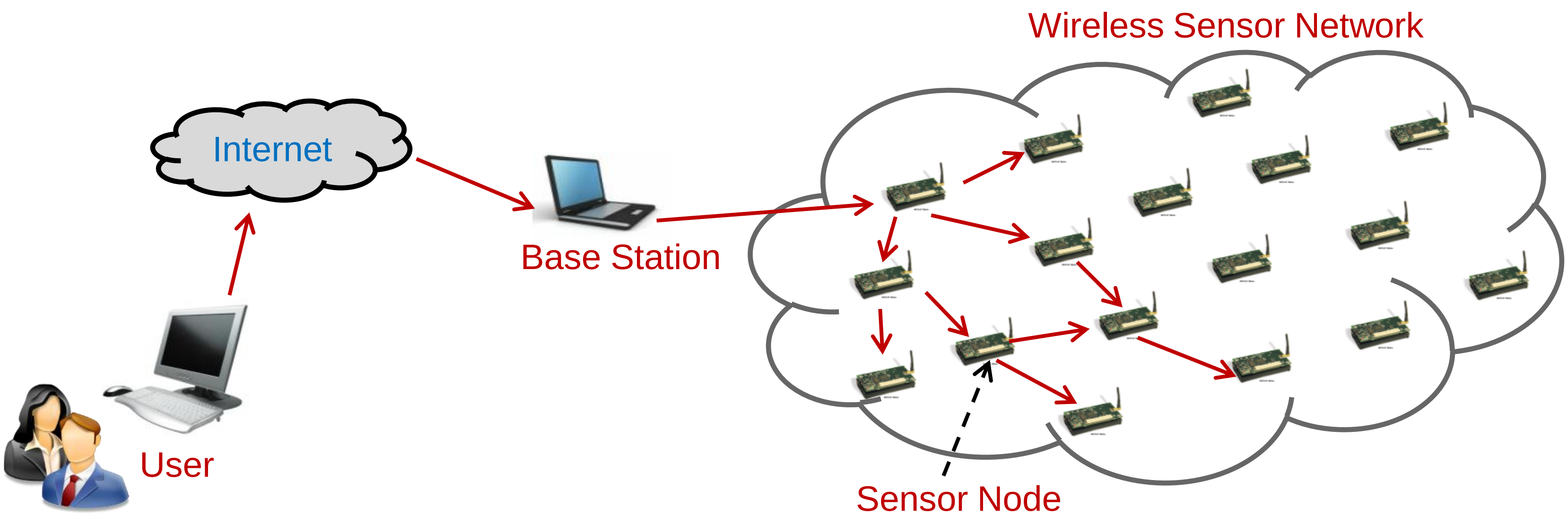
WP3.3: Information Networks for Smart Buildings

- WP3.3a: Design and Optimization
  - Design of wireless sensor network architecture
  - Integration of WSN into BMS
  - Incorporation with smart grid framework
  - Optimized adoption of communication technologies
- WP3.3b: Applications for Energy Efficient Buildings
  - Intra-building energy demand response management

Wireless Sensor Network (WSN)

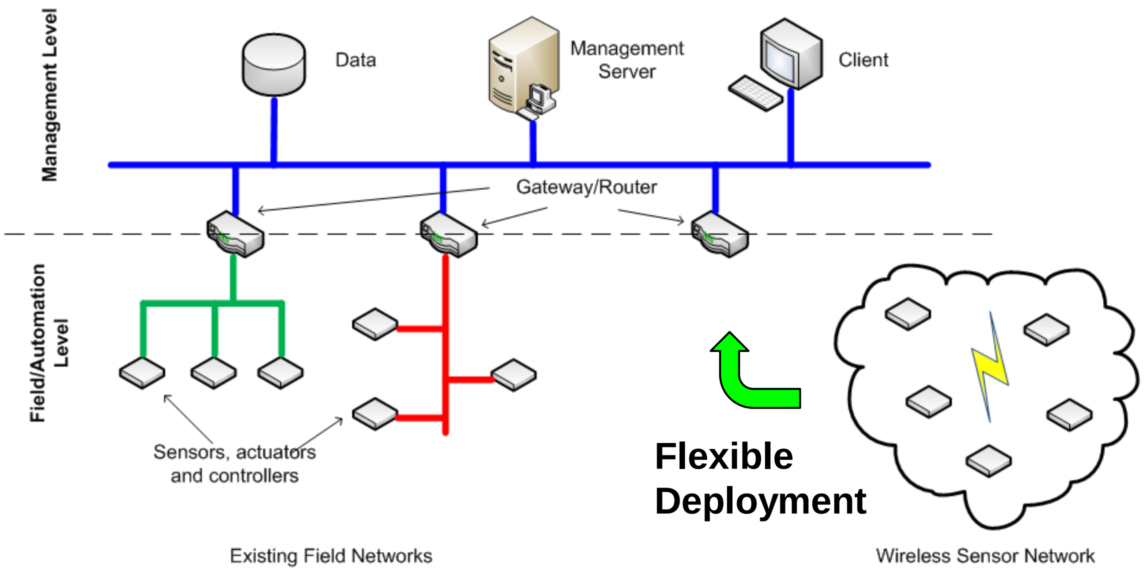
➢ **What is WSN?**

- The WSN used in smart building management systems consists of different types of sensor nodes measuring parameters such as temperature, humidity, light, asphyxiating gases/smoke, occupancy, and power consumption.



Integration of Wireless Sensor Network

- Building Management Systems (BMS) are used for managing and controlling electrical and mechanical systems, such as lighting, ACMV, and vertical transportation, in buildings.
- Flexibility of WSN-based system makes it a promising solution to augmenting existing building's BMS for better sensing capability and facilitating energy-efficient building automation.
- Issues: interoperability and interfacing with existing BMS standards and legacy devices

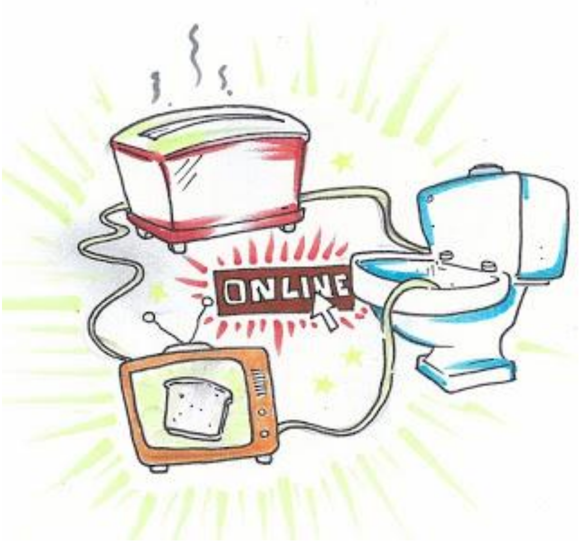


Internet of Things (IoT)

- IoT involves with a huge number of tiny, battery-powered, independent and intelligent things/objects to do the followings:

	technologies we need
Talk to each other	Communications
Perform one or several tasks	Hardware/electronics
Make decision	Optimization/Control theory Data/video analytics

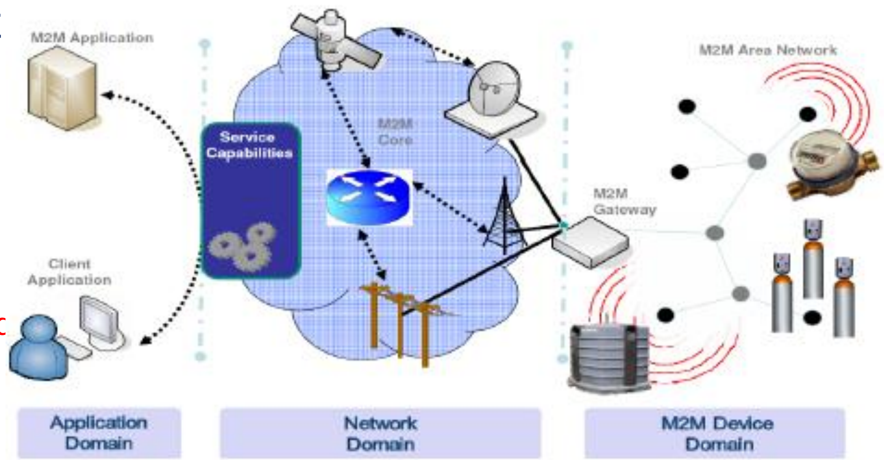
- What are these things/objects?
  - RFID
  - Wireless sensors
  - Smart phones
  - RFID sensor
  - NFC



Machine-to-Machine Communication (M2M)

➢ What is M2M?

- M2M means no human intervention whilst devices are communicating end-to-end.
  - Machine to Machine
    - Keywords:physical sensors and actuators;
  - Machine to Machine
    - Keywords:hardware; protocols; end-to-end delay and reliability
  - Machine to Machine
    - Keywords:middleware, software, application



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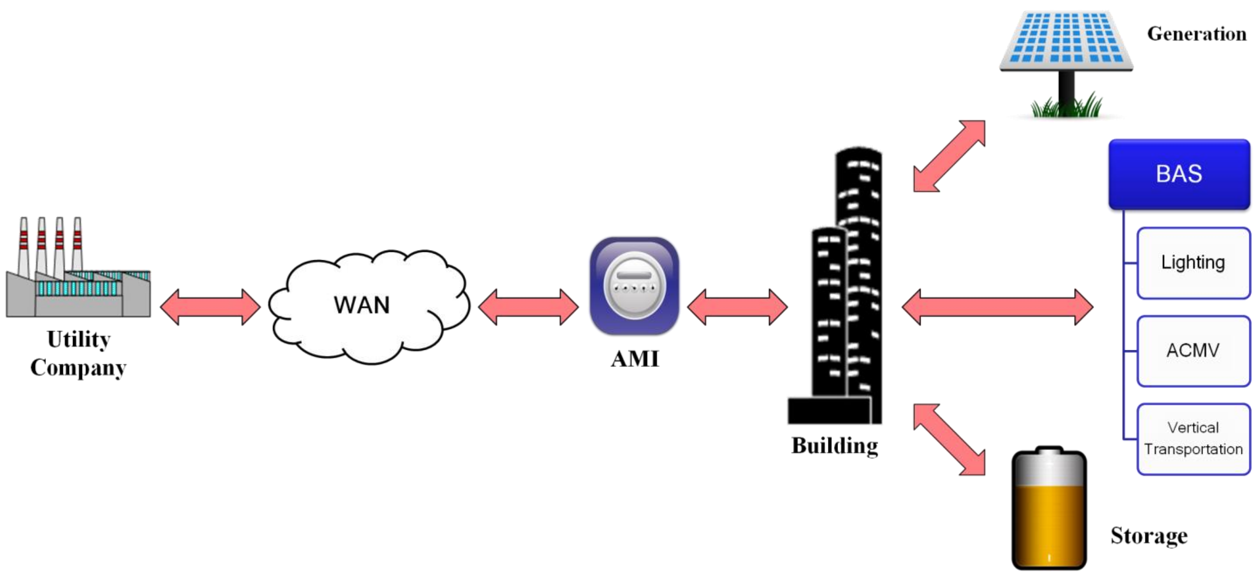
- What are the characteristics of M2M?
  - Multitude
  - Variety
  - Invisibility
  - Criticality
  - Intrusiveness

Design with Smart Grid Framework

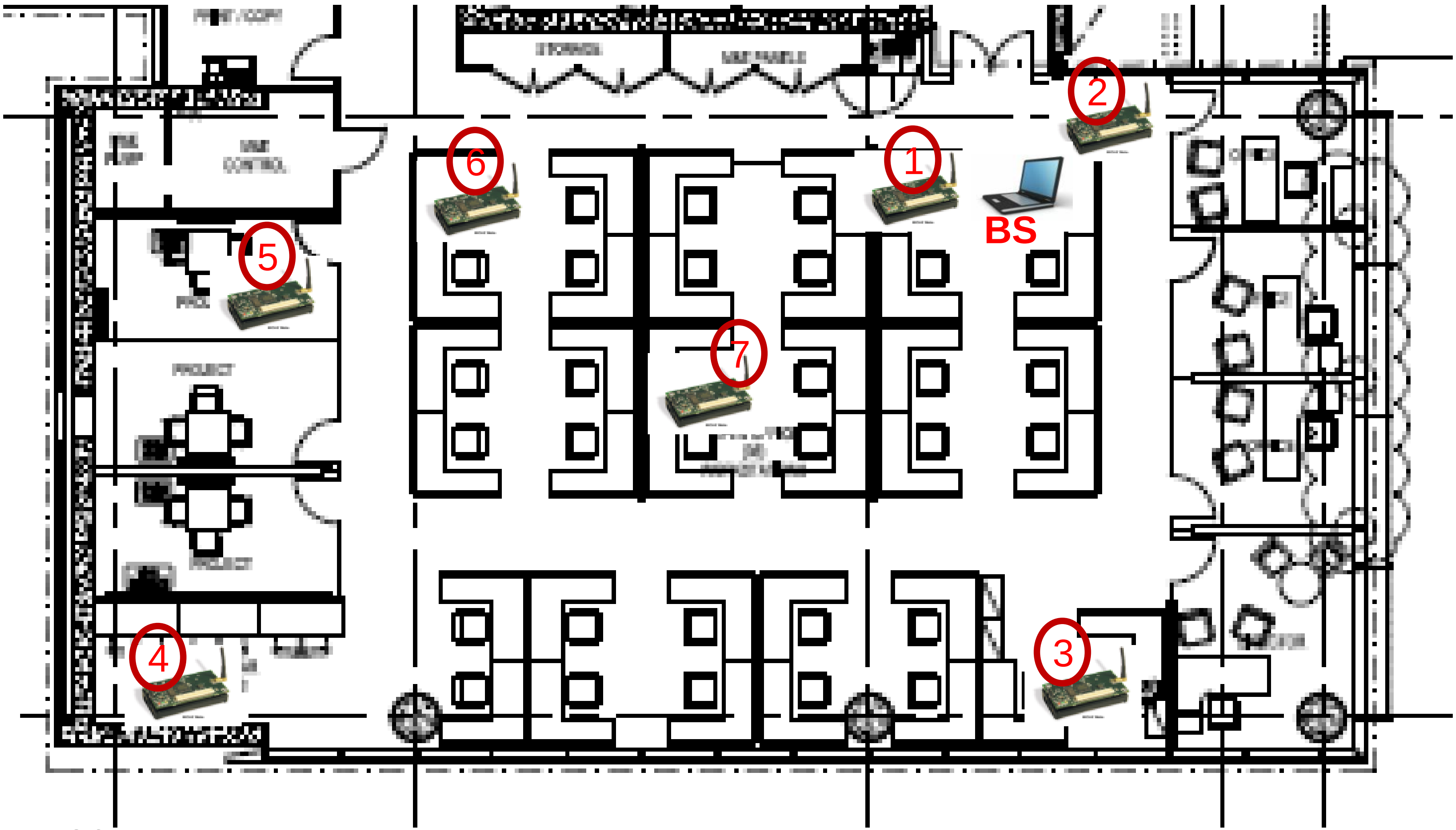
- Components of Smart Grid relevant to BMS:
  - Distributed Energy Resources (DERs): small scale energy generation, e.g. solar panels, fuel-cells, and storage, e.g. batteries, flywheels, chilled water
  - Advanced Metering Infrastructure (AMI): monitoring of energy usage at fine resolution within building and interfacing with Smart Grid
  - Demand Response (DR)/ Demand Side Management (DSM): balancing power supply and demand
- Femtogrid, a single-building version of Microgrid, is an autonomous, self-contained network of power generation, transmission, distribution and storage.
- Femtogrid brings about new possibility of energy saving. Together with BMS, it allows a holistic approach in reducing energy bill from the Grid.

Communications Technologies

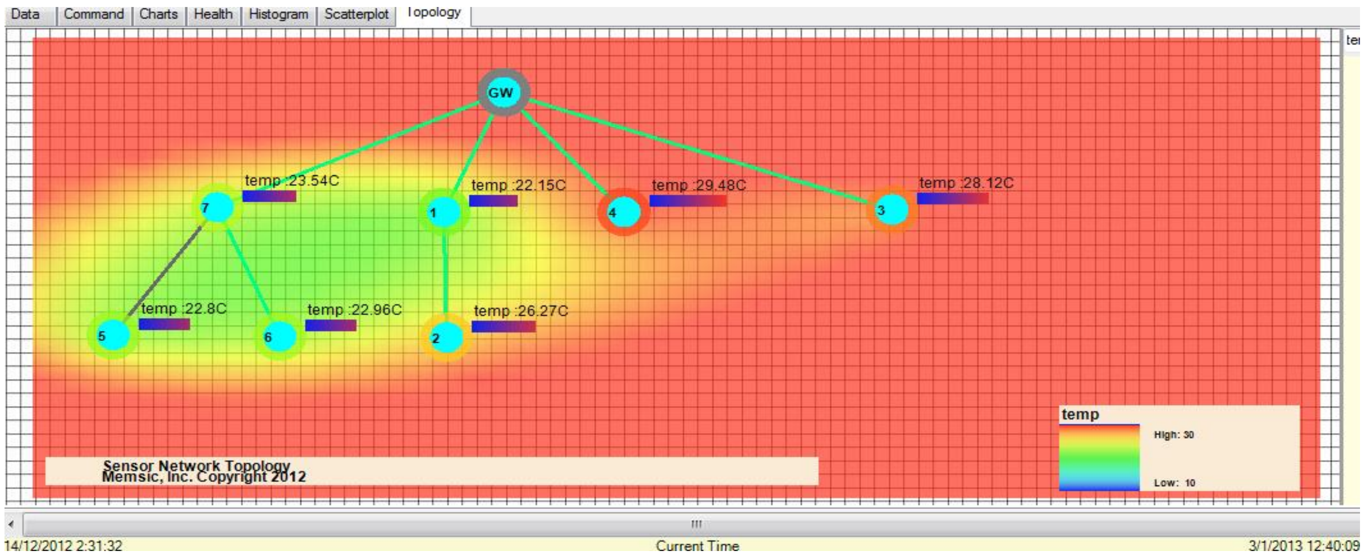
- Key communication technologies could consist of:
  - Wireless: ZigBee, 6LoWPAN/802.15.4g, White Spaces, LED lighting based
  - Wired: Power Line Communication
- Cognitive radio techniques to combat harsh wireless environment.

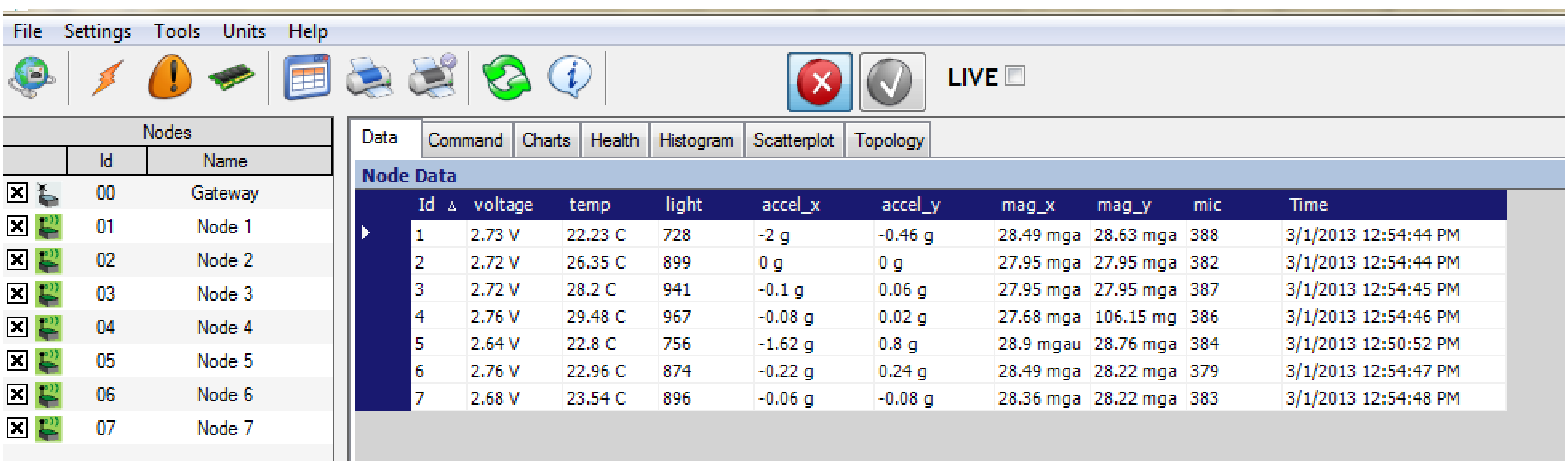


WSN Setup in CREATE



User Interface for WSN Data Gathering

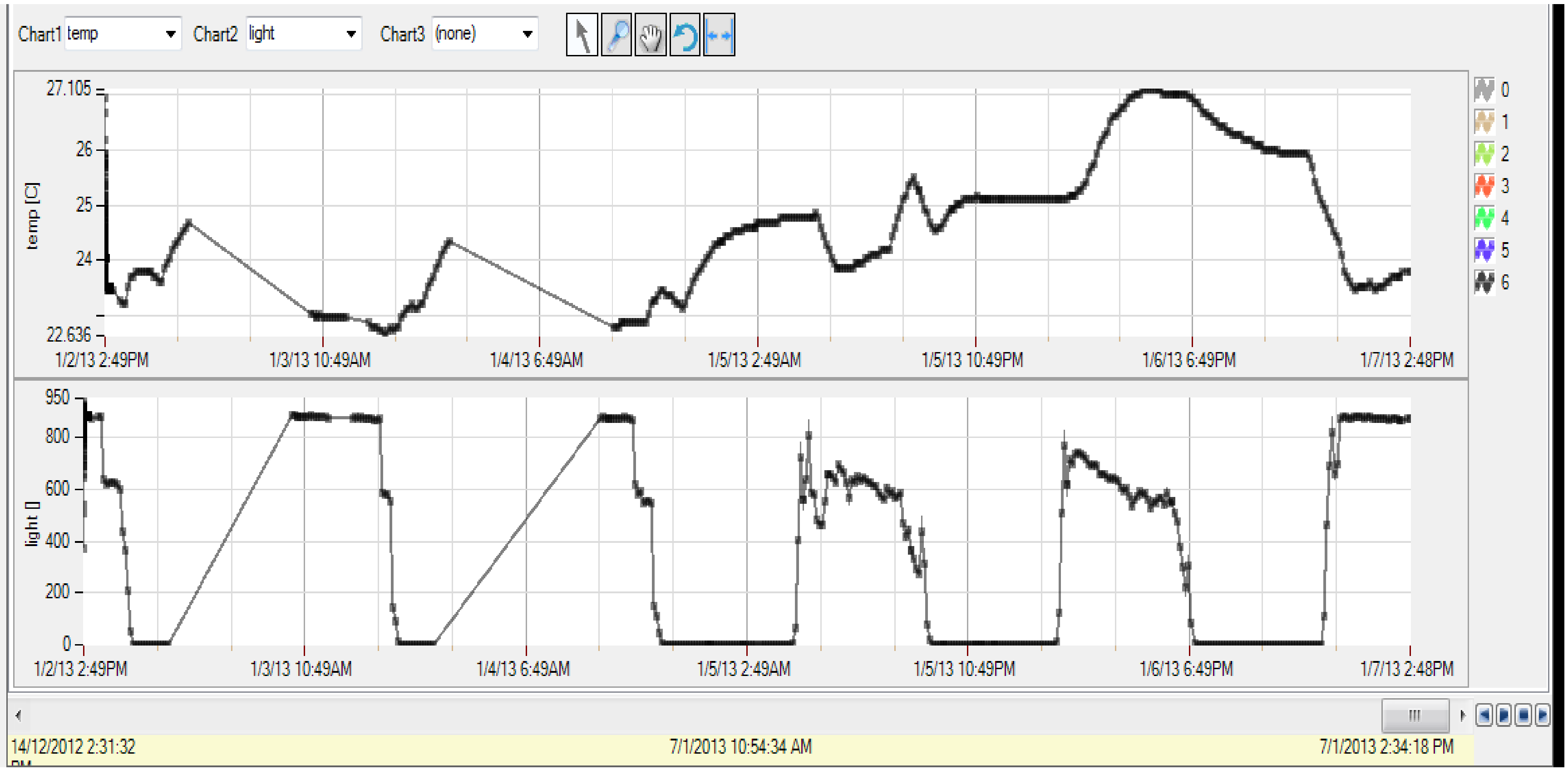




Id	Name
00	Gateway
01	Node 1
02	Node 2
03	Node 3
04	Node 4
05	Node 5
06	Node 6
07	Node 7

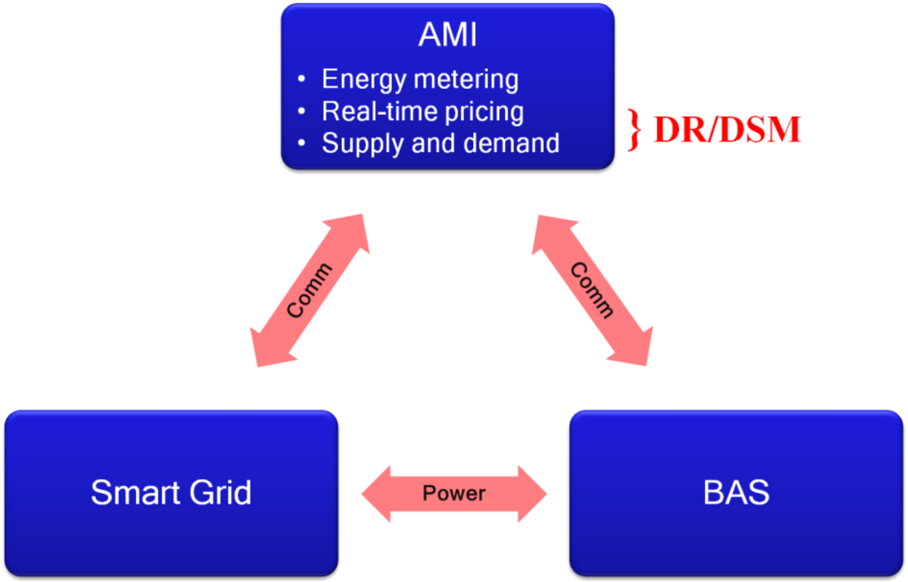
Id	voltage	temp	light	accel_x	accel_y	mag_x	mag_y	mic	Time
1	2.73 V	22.23 C	728	-2 g	-0.46 g	28.49 mga	28.63 mga	388	3/1/2013 12:54:44 PM
2	2.72 V	26.35 C	899	0 g	0 g	27.95 mga	27.95 mga	382	3/1/2013 12:54:44 PM
3	2.72 V	28.2 C	941	-0.1 g	0.06 g	27.95 mga	27.95 mga	387	3/1/2013 12:54:45 PM
4	2.76 V	29.48 C	967	-0.08 g	0.02 g	27.68 mga	106.15 mg	386	3/1/2013 12:54:46 PM
5	2.64 V	22.8 C	756	-1.62 g	0.8 g	28.9 mgau	28.76 mga	384	3/1/2013 12:50:52 PM
6	2.76 V	22.96 C	874	-0.22 g	0.24 g	28.49 mga	28.22 mga	379	3/1/2013 12:54:47 PM
7	2.68 V	23.54 C	896	-0.06 g	-0.08 g	28.36 mga	28.22 mga	383	3/1/2013 12:54:48 PM

WSN Data Gathering



Energy Demand Response Management

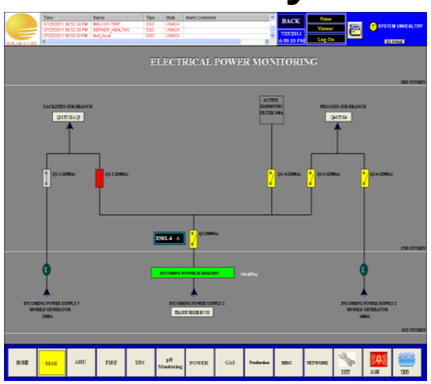
- AMI
  - main communication interface between BMS and Smart Grid
  - facilitates DR/DSM, allowing temporary load reduction and load management
- Optimization of energy usage with Smart Grid – power scheduling in response to:
  - Generation capacity due to local weather pattern
  - Real-time pricing of energy
  - Load profile of building



Interactive User Information

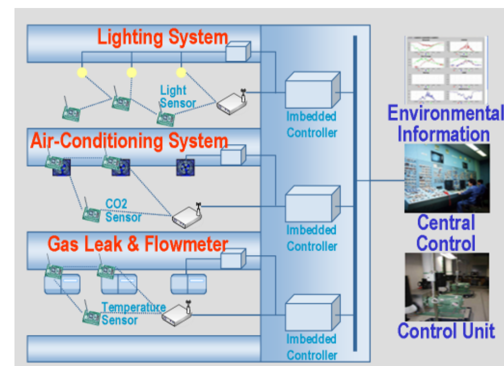
Objectives: By utilizing pervasive sensing of embedded devices with sensors and communication technologies. Through ICT to provide information on user's real time preferences according to the price, metrics, outside environment etc**.**

Grid/Electricity Monitoring



Residential Urban Building

Building infrastructure network BMS (lighting, MAVC gas, water),



SMART GRID