Communications for the Smart Grid

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Outline for Today's Talk

Smart Grid Communications Book

"Smart Grid: Communication-Enabled Intelligence for the Electric Power Grid." Bush, Stephen F. Wiley and Sons Publishers, (available in 2012)

Part I

Power Systems from a Communications Perspective

Outline

How do you see the smart grid?

The blind men and the elephant

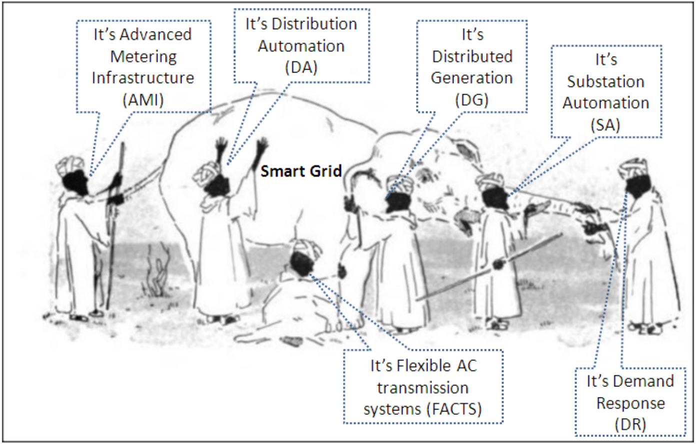


Figure: What is the smart grid?[1]

[1] http://en.wikipedia.org/wiki/File:Blind_men_and_elephant3.jpg

What is the power grid?

Traditional components

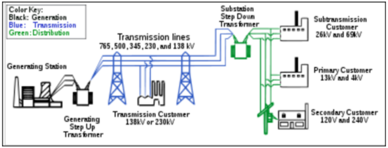


Figure: Traditional View.[2]

- Generation – creating the power
- Transmission – moving power over long distances to the consumer centers
- Distribution – dispersing the power among consumers
- Consumption – consumer/industrial use of power

Note the assumptions: generation is centralized and far from consumers, flow is in one direction

2 http://en.wikipedia.org/wiki/Electric_power_transmission

Characteristics

Old, slow evolution, complex

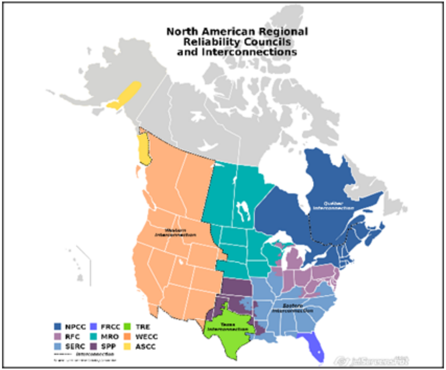


Figure: Largest machine in the world.[3]

- Most complex machine on earth
- First central power station in New York City in 1882
- Edison would still recognize it; Bell would not recognize communications

[3] http://en.wikipedia.org/wiki/Eastern_Interconnection

The **Traditional** Power Grid

Device components

- Substations
- Control centers
- Capacitor banks
- Transformers
- Customer meters
- Generally slow and/or had local, dedicated control mechanisms
- How do power systems and communication networking compare?

Power and Communications

An analogy

Characteristic	**Power Grid Network**	**Communication Network**
Content	Power	Information
Media	Power	Power
Form	Active Power	Modulation
Transmission models	Broadcast/multicast/p2p	Broadcast/multicast/p2p
Routing	Switched	Store and Foreword
Quality of Service	Power Quality	QoS
Format	Kilowatt-hours	Packets
Error correction	Capacitor banks	Channel coding
Compression	More pwr over same lines	Source coding
Buffering	Energy Storage (DR)	Memory or playback delay
Channel utilization	Reactive power	Bandwidth-delay product
Traffic shaping	Demand-Response	Leaky-bucket
Network management	State estimation	SNMP polling
...	...	...

Table: Power Grid and Communication Network Analogy

- In order to properly add communications, we need to have some understanding of the system – traditional power systems components, their relationship with communications (e.g. how dynamic they are), and how they are evolving

Transformers

The workhorse of power distribution

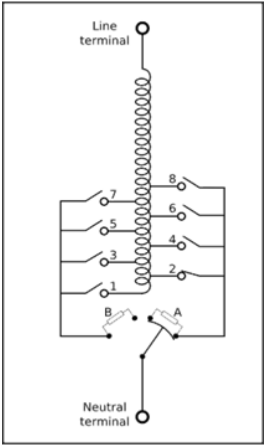


Figure: Line Tap Transformer.[4]

- Voltage regulation
- Not excessively dynamic in terms of control or monitoring
- Control tap changes
- Many different types... thermal problems, etc...

4 http://en.wikipedia.org/wiki/Tap_(transformer)

Substations

Contains switching, protection, and control equipment

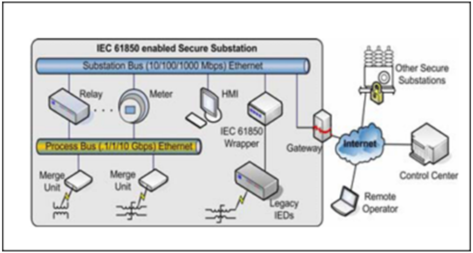


Figure: Substation. [5]

- Many types; role is to house equipment for switching, protection, control, and transformers
- Relatively dynamic, much activity can go on within a substation
- Critical control functions occur here and need to be monitored and controlled from the control center

5 Liang, Y., & Campbell, R. H. (2008). Understanding and Simulating the IEC 61850 Standard

Capacitor Banks

Tuning efficiency

- Role is to reduce power loss, increase capacity
- The amount of control needed depends upon load profile
- Communication required for automated control

Control Centers

Managing the system

- Control center allows operators to visualize and manage the grid
- All important information needs to be fed here
- They need to monitor and control the entire power grid

Customer Meters

Monitoring consumption

- Measure customer usage (kilowatt hours)
- Very dynamic
- Communication was useful for billing and perhaps load prediction

- Early AMR was only one way; AMI is two-way
- Communication has always been part of the power grid

Early Networking

Communication has been vital from the beginning

- Power line carrier around since at least 1918; power meters were read over telegraph lines
- More "modern" communications started within substations
- Serial I/O RS-232, RS-485 (multidrop)
- Moved to LAN (Ethernet)
- Longer distance communication tended to be ad hoc and specialized
- Now let's look at a simple overview of power system properties and analysis

Power Properties and Analysis

Fundamental concepts to be discussed

- Frequency
- Per unit system
- Symmetrical components
- Power flow analysis
- Fault analysis
- State estimation
- Phasors

- These illustrate the types of activities and information that may have to be communicated; here we provide a very basic introduction only

Frequency

Keeping the beat

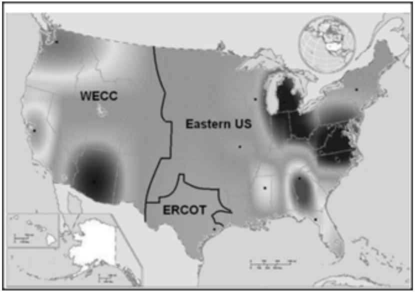


Figure: Frequency Map.[6]

- Referring to frequency at which AC current is transmitted (e.g. 60 Hz, but standards have ranged from 25 – 400 Hz)
- Changes with generation and load
- Significant changes indicate problems

[6] Zhong, Z., Xu, C., Billian, B. J., Zhang, L., Tsai, S. J. S., Conners, R. W., et al. (2005). Power System Frequency Monitoring Network (FNET) Implementation. IEEE Transactions on Power Systems, 20(4), 1914-1921

Per-unit System

pu

- Measure for power, voltage, current, impedance, and admittance
- Defined as a fraction of a base unit quantity
- Units are pu
- Easier to use than volts, ohms, or amperes
- Example: 138 kV transmission line as base; then 136 kV is $V_{pu} = \frac{V}{V_{base}} = \frac{136\,\text{kV}}{138\,\text{kV}} = 0.9855\,\text{pu}$

Symmetrical Components

Deriving balancing components

- Any set of N unbalanced phasors can be expressed as the sum of N symmetrical sets of balanced phasors
- Let three phase voltages could be written as $V_{abc} = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$
- Let three symmetrical components phasors be arranged into a vector as $V_{012} = \begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix}$
- Subscripts 0, 1, and 2 refer respectively to zero, positive, and negative sequence components
- A phase rotation operator α is defined to rotate a phasor vector forward by 120 degrees or $\dfrac{2\pi}{3}$ radians $\alpha = 1\angle 120°$

Symmetrical Components

Deriving balancing components

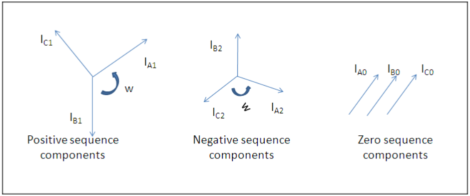


Figure: Symmetrical Components

- A transforms the phase vector into symmetrical components
$$A = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix}$$
- Phase voltages are generated by the sequence equation $V_{abc} = A \cdot V_{012}$
- Conversely, sequence components are generated from the analysis equations $V_{012} = A^{-1} \cdot V_{abc}$ where
$$A^{-1} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix}$$

Power Flow Analysis

Determining voltage and angle information throughout the system

- Determines voltage angle and magnitude for each bus
- Using Taylor Series: $\begin{bmatrix} \Delta\theta \\ \Delta|V| \end{bmatrix} = -J^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix}$
- ΔP (real) and ΔQ (reactive) are called mismatch equations
- $$\Delta P_i = -P_i + \sum_{k=1}^{N} |V_i||V_k|(G_{ik}\cos\theta_{ik} + B_{ik}\sin\theta_{ik})$$
  $$\Delta Q_i = -Q_i + \sum_{k=1}^{N} |V_i||V_k|(G_{ik}\sin\theta_{ik} - B_{ik}\cos\theta_{ik})$$
- J is a matrix of partial derivatives known as a Jacobian:
  $$J = \begin{bmatrix} \frac{\partial \Delta P}{\partial \theta} & \frac{\partial \Delta P}{\partial |V|} \\ \frac{\partial \Delta Q}{\partial \theta} & \frac{\partial \Delta Q}{\partial |V|} \end{bmatrix}$$
- Requires up-to-date information from the entire system

Fault Analysis

Keeping the grid healthy

- Any abnormal flow of electric current
- Need to determine momentary, persistent, symmetric (balanced), asymmetric (unbalanced) faults
- Need to collect this information from throughout the grid

State Estimation

Understanding the grid's condition

- Process to yield a mathematical model of the power system by deriving the best estimate of state variables (bus voltages and angles) of the power system based on the received noisy data
- Includes analog measurements e.g., real and reactive power flows through transmission lines, real and reactive power injections (generation or demand at buses), and bus voltage magnitudes; discrete values of the switches/breakers, and transformer LTC positions, etc; and computed values such as predicted bus loads and generation
- Secure communication is needed to gather all necessary in a timely manner

Phasors

Keeping your balance

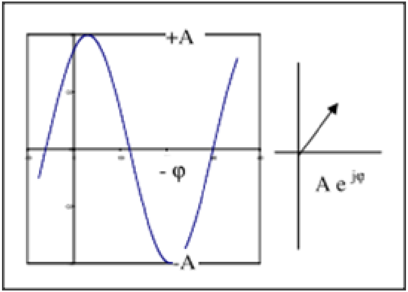


Figure: Phasor.[7]

- A representation of a sine wave whose amplitude (A), phase (θ), and frequency (ω) are time-invariant:
  $A \cdot \cos(\omega t + \theta) =$
  $\mathrm{Re}\left\{A \cdot e^{i(\omega t+\theta)}\right\} =$
  $\mathrm{Re}\left\{Ae^{i\theta} \cdot e^{i\omega t}\right\}$
- Makes working with AC significantly easier
- Comparing phasors in a meaningful way requires accurate timing

[7] Martin, K. E. (2010). Synchrophasors in the IEEE C37.118 and IEC 61850. 2010 5th International Conference on Critical Infrastructure (CRIS) (pp. 1-8)

Simulation

Combining power systems and network simulation

- Need for public domain power system/communication simulation packages
- Power grid is generally continuous; network simulation is discrete
- Need to combine the two (adevs and ns-2)

Standards

So many to choose from

- IEEE Standards Association
- NIST Smart Grid Interoperability Panel (SGIP)
- ITU-T Focus Group on Smart Grid (FG Smart)
- Microsoft Smart Energy Reference Architecture (SERA)
- International Electrotechnical Commission (IEC)
- CIGRE The International Council on Large Electric Systems
- EPRI Electric Power Research Institute
- DoE

Characteristics of Blackouts

Complexity view

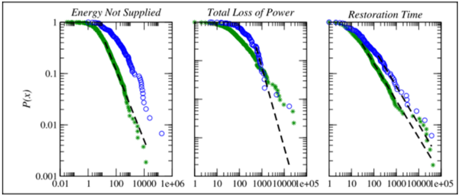


Figure: Power loss due to blackouts.[8]

- Complexity: living at the border of stability and chaos
- Self-organized criticality (SOC): a system that lives near an attractor
- Example: power flow entropy
- Smart grid will likely be even more complex leading to fewer, but more massive outages
- What does this mean for communications?

[8] Rosas-Casals, M. (2010). Power Grids as Complex Networks: Topology and Fragility. 2010 Complexity in Engineering, 21-26.

2003 Blackout

A specific example

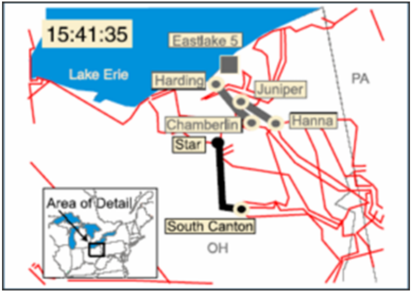


Figure: The 2003 blackout.[9]

- August 14th, 2003 NE blackout [6]
- Tree contact in OH cascaded into North East Interconnection failure (details on next slide)
- More data monitoring and control may predict and prevent blackouts
- Can it be compressed? What is the expected communication load? Does it's compression rate tell us anything about the information?

[9] Makarov, Y. V., Reshetov, V. I., Stroev, V. A., & Voropai, N. I. (2005). Blackouts in North America and Europe: Analysis and generalization. 2005 IEEE Russia Power Tech (pp. 1-7).

Blackout details

- US Eastern Interconnection was in a reliable operational state before 15:05 EDT
- Air temperature and electricity demand were high, though not unusually so
- Power flow was heavy from the south (Tennessee, Kentucky, Missouri, etc.) and west (Wisconsin, Minnesota, Illinois, etc.) to the north (Ohio, Michigan, and Ontario) and east (New York)
- These transfers were not beyond previous levels or in directions not seen before
- System frequency was variable, but within safe bounds
- Several generators were out of service that could provide real and reactive power to the Cleveland, Toledo, and Detroit areas
- Planning studies for August 14 determined that with these outages the system could still be operated safely
- Throughout the morning and midday voltages were depressed in northern Ohio
- Three significant forced outages occurred in the Ohio area prior to 15:05 EDT
- Phase 1:
- 13:31:34: Eastlake 5 tripped in Ohio – the system became unable to sustain some contingencies without overloads
- 14:02: Stuart-Atlanta 345-kV transmission line tripped in S. Ohio due to contact with a tree
- Phase 2: 14:14-15:59. Computer failure
- Phase 3:
- 15:05:41: Harding-Chamberlin 345-kV line tripped (tree contact); remaining lines into Cleveland, especially Hanna-Juniper, picked up more load
- 15:32:03: Hanna-Juniper 345-kV line tripped (tree contact); loading on the remaining 345-kV lines increased, with Star-Juniper taking the bulk. The Star-S. Canton load rose above normal but within emergency rating
- 15:41:33-41: Star-S. Canton 345-kV line contacted a tree 3 times and locked out at 15:41; flows increased on 138-kV lines to Cleveland and voltages began to degrade
- Phase 4: 138-kV system collapse in northern Ohio:
- 15:39-15:58:47: seven Pleasant Valley-Chamberlin-West Akron 138-kV lines tripped due to overloads
- 15:45:41 Canton Central-Tidd 345-kV line tripped and re-closed; this forced the Canton Central 345/138-kV transformers out, weakening the Canton-Akron 138-kV system
- 15:59 West Akron 138-kV bus tripped due to a breaker failure on transformer no. 1; caused the 5 remaining 138-kV lines connected to the West Akron substation to open
- 16:05:57 Sammis-Star tripped by protective relays reacting to high flow; loss of this line initiated a massive blackout

Drivers

What is driving the smart grid?

- The Green movement
- We think digitally
- Improving efficiency
- The impact of regulation
- Meeting future demand

Goals

Stated goals of the smart grid

- Provide power quality for the range of needs in a digital economy
- Accommodate all generation and storage options
- Enable new products, services, and markets
- Enable active participation by consumers
- Operate resiliently against physical and cyberattack and natural disasters
- Anticipate and respond to system disturbances in a self-healing manner
- Optimize asset utilization and operating efficiency

Power and Communications

Reducing communication energy

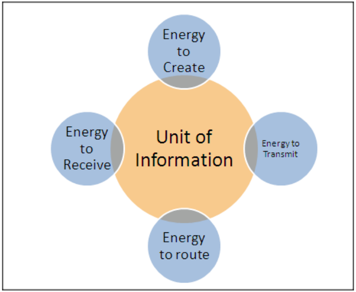


Figure: Minimizing Energy to Communicate.[11]

- As communication researchers, we've striven to reduce the power and energy needed for communications

10 Stephen F Bush, IEEE SmartGridComm 2010 Panel Session.

11 Stephen F Bush, IEEE SmartGridComm 2010 Panel Session.

Power and Communications

Communicating about energy

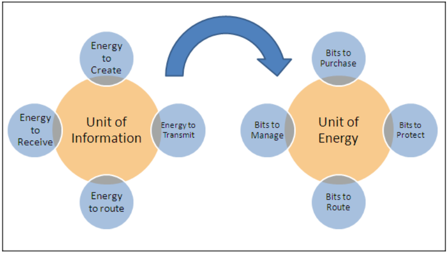


Figure: Communicating Information about Energy.[13]

- Now, we need to minimize the amount of information about energy and power

12 Stephen F Bush, IEEE SmartGridComm 2010 Panel Session.

13 Stephen F Bush, IEEE SmartGridComm 2010 Panel Session.

What did we learn?

Key points and next steps

- Communication and power systems have had a long past together
- Power systems are complex dynamic systems that need to be understood from an information theory and communications theory vantage
- Smart grid concepts are applying to all utilities
- Let's look at each component of the power system in a little more detail starting from generation, transmission, distribution, and finally the consumer

Smart Grid Communications Book

"Smart Grid: Communication-Enabled Intelligence for the Electric Power Grid." Bush, Stephen F. Wiley and Sons Publishers. (available in 2012)

Part II

Generation

Generation Outline

Power Generation

Before "smart grid"

- Generation has traditionally been centralized
- A relatively few very massive generators have been employed
- A few high capacity lines interconnect large areas ("Interconnections")
- One of the many aspects of the smart grid is distributed generation

Large Generators

Relatively few, but large prime movers

- Balance: need to maintain power output in sync with demand
- Rotational inertia may cause frequency swings

Control Centers

Keeping power under control

- Central nervous system; senses the pulse of the power system
- Adjusts its condition; coordinates its movement; provides defense against exogenous events
- ca. 1965 known as Energy Management Systems (EMS) first employed computing, communications were ad hoc
- In transition today to more distributed computing and standardized communication
- Manages: stability, load balancing, asset health
- Business/market impact is becoming a larger part of the control center

PS and Comm: Separated by a Common Langage

Simple examples

Security The ability of the system to withstand disturbances or contingencies, such as generator or transmission line outages – not cybersecurity

Active Network Communications and control technologies for distribution networks operating with distributed generation – not active (communication) networking

Active Networking Book

Bush, S. F., & Kulkarni, A. B. (2001). Active networks and active network management: a proactive management framework (p. 212). Springer US. Retrieved December 14, 2010, from http://www.amazon.com/Active-Networks-Network-Management-Proactive/dp/0306465604.

Microgeneration

Smaller generators

- Trend towards smaller power generation systems
- Closer to the consumer; less transmission loss
- More diversity and resiliency; less reliance on grid and potential faults
- Economy of scale makes large centralized generation cheaper

Distributed Generation

Many small generators working with the grid

- Microgeneration devices working with the grid
- Generally < 10 MW, interconnected at substation, distribution feeder, or customer level
- Includes photovoltaics, wind turbines, fuel cells, even down to 8oz microturbine packages, Sterling-engine based generators, and internal combustion engine-generators
- What are the problems related to the trend towards distributed generation? Pretty much everything e.g., synchronization, stability, protection, metering, etc... better communications will help

Distributed Generation
Challenges

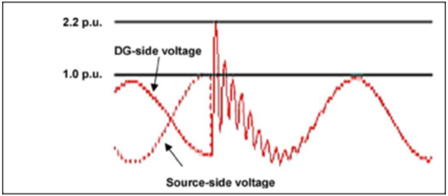


Figure: Reclosing out of step.[14]

- Distributed control
- Synchronization

14 Walling, R. A. R., Saint, R., Dugan, R. C., Burke, J., & Kojovic, L. A. (2008). Summary of Distributed Resources Impact on Power Delivery Systems. IEEE Transactions on Power Delivery, 23(3), 1636-1644.

Synchronization

Synchronization with the grid

- Does not currently rely on communications, typically relies on local estimates of grid voltage
- But where is communications needed? For monitoring and control, which will have higher entropy if synchronization becomes innaccurate or unreliable

Storing Energy

Smoothing out peak consumption

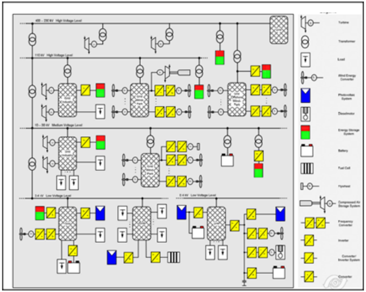


Figure: Energy storage.[15]

- Battery, super capacitor, fuel cell, flywheel, compressed air, pumped-hydro, ...
- Advantages of energy storage: peak load reduction, reduce price fluctuations
- Will it increase or decrease the overall requirements for communication?

[15] Mohd, A., Ortjohann, E., Schmelter, A., Hamsic, N., & Morton, D. (2008). Challenges in integrating distributed Energy storage systems into future smart grid. 2008 IEEE International Symposium on Industrial Electronics (pp. 1627-1632).

From Microgrids to Nanogrids

A change in scale

- Microgrids – thinking top down
- Nanogrids – thinking bottom up
- Small, self-contained "grids" capable of easily interconnecting
- E.g. USB-powered devices, power over Ethernet, electricity systems in cars (alternator), etc... [7]
- What does this mean for communications?

Think Smaller

Very small-scale power generation approaches

- 10 mm diameter generator rotor [8]
- Significant gains in power density when scale is decreased
- Many emerging approaches: Energy scavenging (long used for sensor power), graphene/water, thermoelectric, etc...

Electric power is everywhere present in unlimited quantities and can drive the world's machinery without the need of coal, oil, gas, or any other of the common fuels.

Nikola Tesla

Communication at the Nanoscale

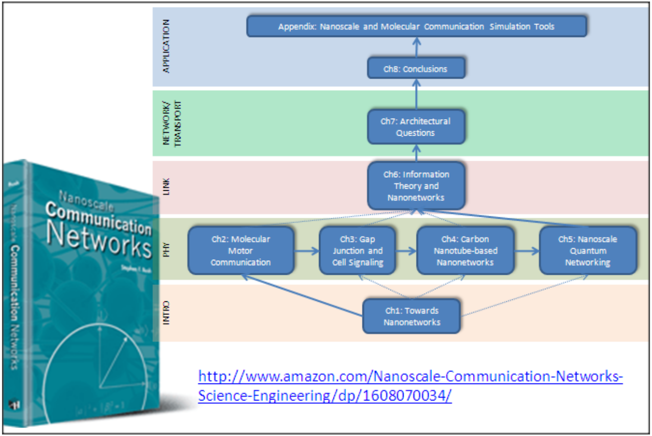


Figure: Nanoscale network protocol stack.[16]

16 Bush, S. F. (2010). Nanoscale Communication Networks (p. 308). Artech House Incorporated.

http://ge.geglobalresearch.com/blog/nanoscale-communication-networks/.

Change in Scale

Impact on communications

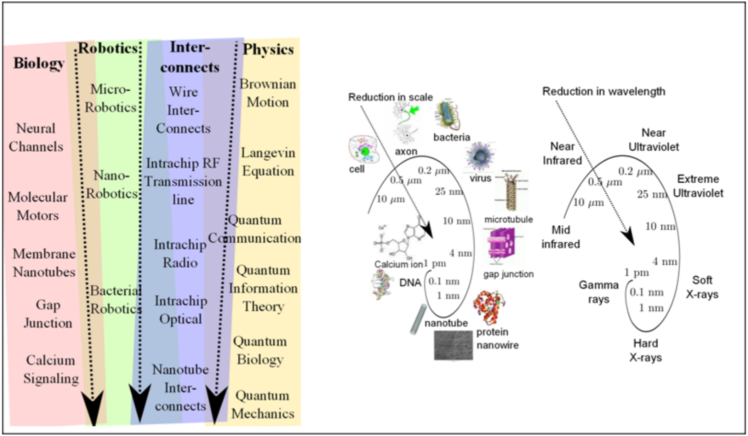
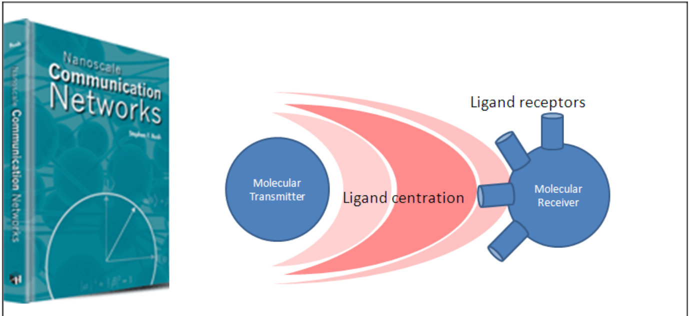


Figure: Nanoscale networks drivers and scale.[17]

17 Bush, S. F. (2011). Towards In vivo Nanoscale Communication Networks: Utilizing an Active Network Architecture. Frontiers of Computer Science (accepted for publication), 5(1), 1-9.

Nanoscale channels

Capacity



$$P(Y|X) = \begin{pmatrix} p_1 P_A & (1-p_2)(1-P_A) \\ (1-P_1)P_A & p_2(1-P_A) \end{pmatrix}$$

$$I(X;Y) = (H(p_1 P_A + (1-p_2)(1-P_A))) - (P_A H(p_1) + (1-P_A) H(p_2))))$$

Figure: Nanoscale networks channel capacity.[18] [19]

[18] Bush, S. F. (2010). Nanoscale Communication Networks (p. 308). Artech House Incorporated. Retrieved December 14, 2010, from http://ge.geglobalresearch.com/blog/nanoscale-communication-networks/

[19] Atakan, B., & Akan, O. B. (2009). Single and Multiple-Access Channel Capacity in Molecular Nanonetworks. Nano-Net, 14Ű23. Springer

Applications

"Real" nanogrid monitoring and control

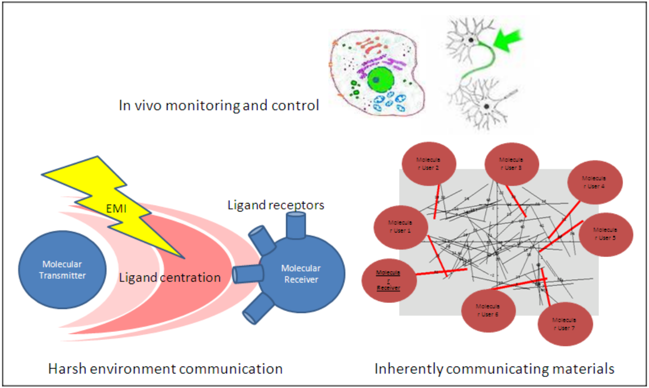


Figure: Nanoscale networks applications.[20]

[20] Bush, S. F., & Goel, S. (2006). Graph Spectra of Carbon Nanotube Networks. 2006 1st International Conference on Nano-Networks and Workshops (pp. 1-10)

Nanoscale Communications Working Group

IEEE Standard P1901.6

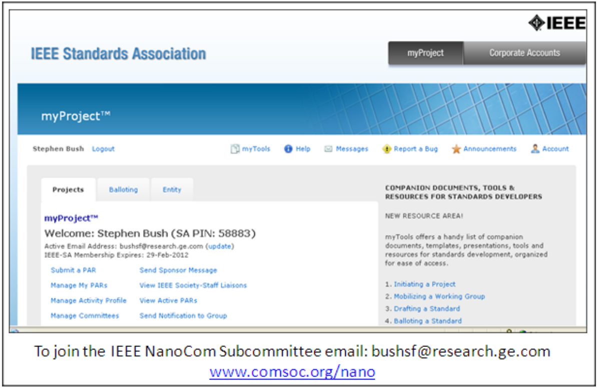


Figure: Nanoscale networks standardization.[21]

- Recommended Practice for Nanoscale Communications in P1901.6 Working Group
- Contact `bushsf@research.ge.com` to participate

21 `https://development.standards.ieee.org/my-site/home`

Energy and Information

Back to the physics of information

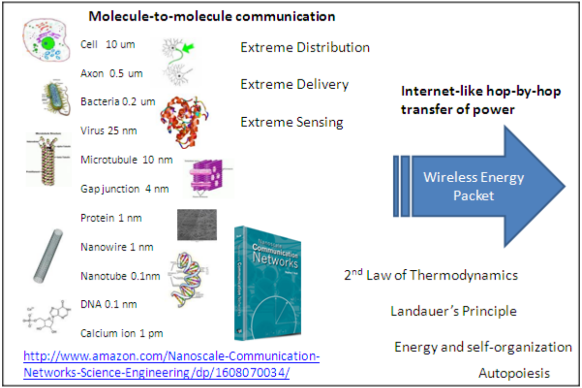


Figure: Energy and information.[22]

- More on this in a later section...

[22] Bush, Stephen F., IEEE SmartGridComm 2010

What did we learn?

Key points and next steps

- Moving from centralized to distributed generation
- From microgrids to distributed generation
- New ways of thinking about generation: nanogrids and nanoscale communication
- Next, let's look at transmission in more detail

Nanoscale Communications Book

Bush, S. F. (2010). Nanoscale Communication Networks (p. 308). Artech House Incorporated. Retrieved December 14, 2010, from `http://ge.geglobalresearch.com/blog/nanoscale-communication-networks/`.

Part III

Transmission

Transmission Outline

Overview

Moving power over long distances

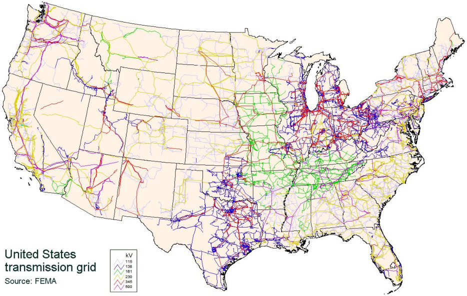


Figure: US Transmission Grid.[23]

- 300,000 km of transmission lines operated by 500 companies
- For a fair and transparent use of the transmission system information is available to the public via Open Access Same-time Information System (OASIS)
- How this flow is controlled impacts communication architecture

23 http://en.wikipedia.org/wiki/Electric_power_transmission

FACTS

Monitoring and control requirements

- Consider power flow across a line from point 1 to 2
- Phase difference is $\delta = \delta_1 - \delta_2$
- Real power flow: $P_{12} = \dfrac{V_1 V_2 \sin(\delta)}{X_L}$
- Reactive power flow: $Q_{12} = \dfrac{V_1^2 - V_1 V_2 \cos(\delta)}{X_L}$
- Changing either δ or X_L changes the flow across the line
- X_L changed via solid state power system devices (e.g., thyristor: 4-layer N/P device)
- This indicates what type of monitoring and control will be required and its impact on communication

Challenges

Meeting long distance power transport problems

- Minimizing line losses
- Control (FACTS): VAr, CVR, IVVC
- Geomagnetically induced currents
- If DG is successful, will transmission still be required?

VAr

It's not a typo :)

- $v = V_{max}\cos(\omega t)$
- $i = I_{max}\cos(\omega t - \theta)$
- $p = vi = V_{max}I_{max}\cos(\omega t)\cos(\omega t - \theta)$
- $p = \frac{V_{max}I_{max}}{2}\cos(\theta)(1 + \cos(2\omega t)) + \frac{V_{max}I_{max}}{\sin}(\theta)\sin(2\omega t)$
- Active power: $p = \frac{V_{max}I_{max}}{2}\cos(\theta)(1 + \cos(2\omega t))$ (oscillates around arbitrary value)
- Reactive power: $\frac{V_{max}I_{max}}{\sin}(\theta)\sin(2\omega t)$ (oscillates around zero)
- Average active power (over time): $P = VI\cos(\theta)$ (V and I are rms values)
- Average reactive power (over time): $Q = VI\sin(\theta)$
- Very different values with different properties; reactive power stays within the electrical network "pulsating" power

Conservation Voltage Reduction

Optimizing the grid: will it become more brittle?

- Conservation Voltage Reduction (CVR) is a reduction of energy consumption resulting from a reduction of feeder voltage
- Voltages usually higher than needed in order to insure supply reaches everyone
- The goal is to operate the grid closer to its limits

Integrated Volt/VAr Control

Improved control mechanisms

- Control objective: minimization of power demand (sum of power loss and consumption) while satisfying the voltage and loading constraints, power factor, or reactive power limits
- Feeder voltage and reactive power are closely related dependent variables
- Involves control of voltage transformers and/or voltage regulators and capacitor banks
- Provides flat voltage profile over the feeder while minimizing power loss
- Reduces unnecessary tripping
- Requires non-local information, i.e., timely and reliable communication

Geomagnetically induced currents

Impact of scale again

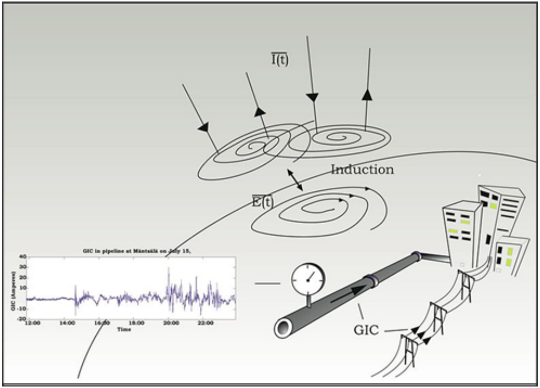


Figure: Geomagnetically induced currents.[24]

- Current in magnetosphere and ionosphere experiences large variations
- Currents induced in conductors on Earth's surface
- Higher voltages / lower line resistances reduce transmission losses over longer path lengths; encourages GIC
- Power transformers disrupted by the GIC offsets

24 http://en.wikipedia.org/wiki/File:GIC_generation.jpg

Power Quality

Quality issues

- General term for continuity of service, variation in voltage magnitude, transient voltages and currents, harmonic content in the waveforms, variations in frequency
- Harmonics introduced by switching and other sources

Large-scale Synchronization

Interconnecting interconnection networks

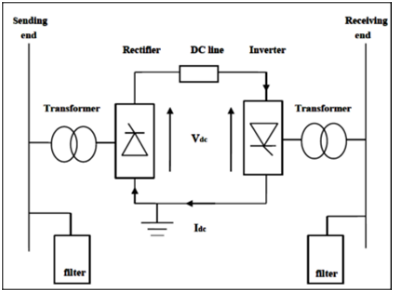


Figure: HVDC Interconnect.[25]

- Synchronization on a large scale

[25] Wang, H. (2010). The advantages and disadvantages of using HVDC to interconnect AC networks, 4-8.

HVDC Interconnects

Map

Figure: HVDC Interconnects.[26]

26 Bahrman, M. (2006). OVERVIEW OF HVDC TRANSMISSION. 2006 IEEE PES Power Systems Conference and Exposition (pp. 18-23).

Transmission Substations

More on substations as they relate to transmission and communications

- Connects two or more transmission lines
- Contains high-voltage switches that allow lines to be connected or isolated for fault clearance or maintenance
- May have transformers to convert between two transmission voltages, voltage control/power factor correction devices such as capacitors, reactors or static VAr compensators (FACTS)

Wireless Transmission

Transmitting power through space

- We do this all the time for communications :)
- Wireless AC power transmission has been looked at, particularly for hard to reach areas
- Millimeter wave transmission has also been considered

Summary

Key points and next steps

- FACTS
- Reactive Power
- Geomagnetically induced currents
- HVDC
- Wireless transmission
- Next, let's look at distribution in more detail

Part IV

Distribution

Distribution Outline

30. Overview of Distribution
31. Fault Detection, Isolation, and Restoration
32. Protection Techniques
33. Distribution Line Carrier
34. Summary

Distribution

The last mile for power

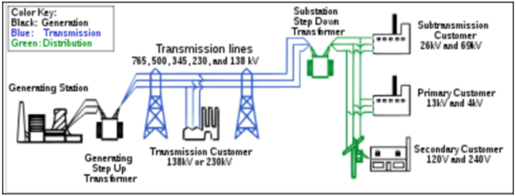


Figure: Distribution overview.[27]

- Delivers power from transmission to end customers
- Substation transformer takes the incoming transmission-level voltage (35 to 230 kV); steps it down; circuits fan out from the substation
- A distribution transformer steps voltage down to a low-voltage secondary, commonly 120/240 V

27 http://en.wikipedia.org/wiki/Electric_power_transmission

Distribution Topologies

Radial, loop, mesh

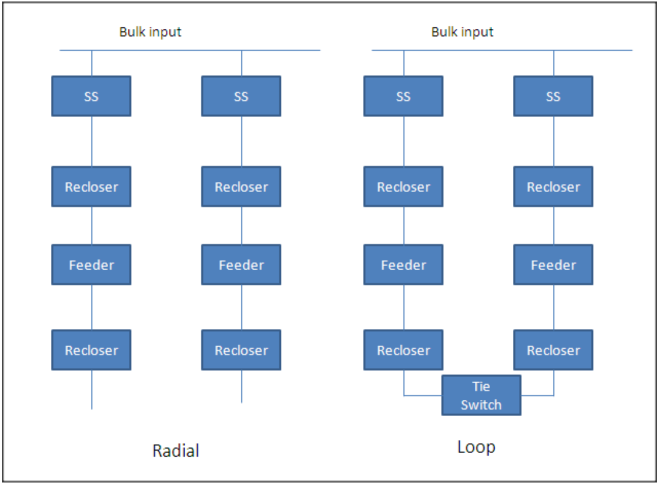


Figure: Distribution topologies.

Fault Detection, Isolation, and Restoration

Protecting customers

- Mitigate the impact of faults on customer power outages
- Protect customer lives and property
- Electrical protection techniques

Coordination

As athletes will say: it's all about coordination

- Blocking the right current at the right time
- Fuses, circuit breakers, reclosers
- They require/benefit from intercommunication
  - Reacts to overcurrent conditions
  - Inverse time current characteristic curve determines how to operate
  - Transient versus permanent faults

Protection Techniques

Detecting and isolating power faults

- Relays and reclosing
- Distance relays
- Pilot protection
- Protection and stability
- Special protection schemes

Relays and Reclosing

Balancing convenience with safety

- Simple and well-known: detect overcurrent, open and close, hope fault disappears
- Power grid is a network; can be analyzed as such

Distance Relays

Using knowledge of power line impedance

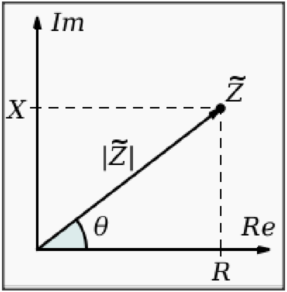


Figure: Complex impedance.[28]

- $Z = |Z|e^{j\theta}$ and
  $Z = R + jX$
- Determine the acceptable area

28 http://en.wikipedia.org/wiki/File:Complex_Impedance.svg

Pilot Protection

Requires communication

- Can use current or phase differential across a line to detect fault
- Kirchoff's Laws must apply
- Requires communication in order to do the comparison
- PLC often used

Protection and Stability

Oscillations

- Changing the topology of the power grid creates transient power imbalances
- Oscillations may occur among generators (magnetic vs. inertial forces)
- If oscillations are large or unstable, quick action (communication) is required
- Load shedding is one quick way to achieve balance

SPS/RAS

Special protection scheme/Remedial action schemes

- Abnormal conditions specific to the power system configuration can be computed a priori
- Specific actions to correct are initiated when detected
- Ad hoc approach to keeping the system stable

Distribution Line Carrier

A hostile communication environment

- The term DLC goes back to at least the early 1990s
- One of the first uses of PLC was for protection of power distribution systems (ca. 1920); continues to be one its core applications
- PLC rapidly expanded to general purpose data communication use (mid-1990s)
- Harsh channel: varying impedance and considerable noise not white in nature; frequency- and time-varying attenuation
- Reflections and multipath problems due to multiple paths and impedance differences
- Typical sources of noise: brush motors, fluorescent and halogen lamps, switching power supplies, and dimmer switches

Distribution Line Carrier

Overcoming the challenges

- FSK good for low data rates (power system protection applications), CDMA for medium rates, OFDM for high rates; extending the rate of FSK would require too much channel coding overhead
- CDMA spreads over a greater spectrum but requires a high processing gain, i.e. $P_G = \frac{\text{transmission bw}}{\text{data bw}}$, which does not exist over wide enough portions of the spectrum
- Does not provide large contiguous bands for data transmission
- Orthogonal frequency-division multiplexing (OFDM) allows N subcarriers, which can fit into usable PLC spectrum
- Subcarriers with high SNR can be made to carry more bits, known as Discrete-Multitone (DMT)

Distribution Line Carrier

A last mile proposal for communications

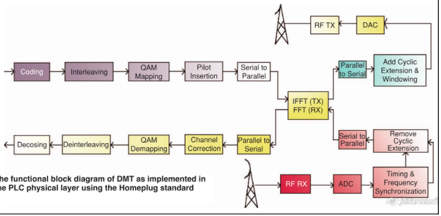


Fig. 6 The functional block diagram of DMT as implemented in the PLC physical layer using the Homeplug standard

Figure: Power line carrier coding.[29]

- Requires channel estimation, pilot signals, and bit loading algorithms
- Margin-adaptive algorithms– minimize the bit error rate while keeping the data transmission rate constant
- Rate-adaptive algorithms– data rate is maximized while maintaining a constant error rate
- In PLC standards, rate-adaptive algorithms have been adopted
- Reed-Solomon coding followed by interleaving and trellis coded modulation is often used for channel coding
- CSMA/CA used for channel contention

[29] Majumder, A., & Caffery, J. (2004). Power line communications: an overview. IEEE Potentials, 23(4), 4-13.

What did we learn?

Key points and next steps

- FDIR
- Protection techniques
- Protection devices
- Distribution line carrier
- Next, let's look at consumption in more detail

Part V

Overview of Communication Approaches

Communication Approaches Outline

35 Information Theory and Smart Grid

36 Complexity Theory

37 Supervisory Control and Data Acquisition

38 Wireless Communication

39 Sensor and Actuator Networks

40 Advanced Metering Infrastructure

41 Cybersecurity

42 Summary

Information and Energy

Communication and power systems

- Both communication and power transmission and distribution involve the spatial displacement of energy
- Landauer principle: logical state decrease, increase in physical entropy; bit erasure yields heat
- Power line carrier and wireless power transmission come close to blending energy and information through communication

Information Theory

Review

- Consider the power system from theoretical perspectives
- Source coding, channel coding, algorithmic complexity theory, algorithmic information theory, information-theoretic security, mutual information, channel capacity
- Defines what communication architectures will be necessary and sufficient
- Let's look at synchrophasors and compression...

Phasor Compression

Review Synchrophasor Communication

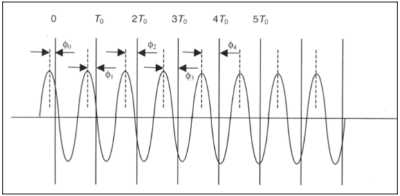


Figure: Phase sampling.[30]

- Observation interval T_0 is not an integer multiple of T
- Observed phasor has constant magnitude, but phase angles of the sequence of phasors $\{X_0, X_1, X_2, X_3, \ldots\}$ change
- $X = X_r + jX_i = \dfrac{X_m}{\sqrt{2}} e^{j\phi} = \dfrac{X_m}{\sqrt{2}}(\cos\theta + j\sin\theta)$

[30] Martin, K. E., Benmouyal, G., Adamiak, M. G., Begovic, M., Burnett, R. O., Carr, K. R., et al. (1998). IEEE Standard for Synchrophasors for Power Systems. IEEE Transactions on Power Delivery, 13(1), 73-77.

Synchrophasors

Putting measurements on the same absolute time base

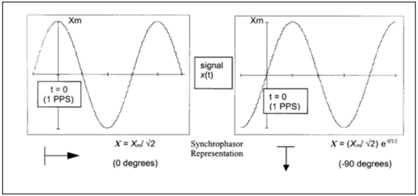


Figure: Synchrophasor representation.[32]

- Synchrophasors at 0 and 90 degrees
- 0 degrees when the maximum of $x(t)$ occurs at the UTC second rollover
- Assumes 1 pulse per second (PPS) time signal
- -90 degrees when the positive zero crossing occurs at the UTC second rollover

[31] Martin, K. E., Benmouyal, G., Adamiak, M. G., Begovic, M., Burnett, R. O., Carr, K. R., et al. (1998). IEEE Standard for Synchrophasors for Power Systems. IEEE Transactions on Power Delivery, 13(1), 73-77.

[32] Martin, K. E., Benmouyal, G., Adamiak, M. G., Begovic, M., Burnett, R. O., Carr, K. R., et al. (1998). IEEE Standard for Synchrophasors for Power Systems. IEEE Transactions on Power Delivery, 13(1), 73-77.

Phasors

Communicating synchrophasors

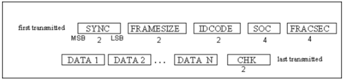


Figure: Frame transmission standard.[34]

- Frame sync word, bytes in frame, PMU ID number, time stamp (Second Of Century), fraction of second and time quality (clock accuracy), CRC (16-bit)

[33] Martin, K. E., Benmouyal, G., Adamiak, M. G., Begovic, M., Burnett, R. O., Carr, K. R., et al. (1998). IEEE Standard for Synchrophasors for Power Systems. IEEE Transactions on Power Delivery, 13(1), 73-77.

[34] Martin, K. E., Benmouyal, G., Adamiak, M. G., Begovic, M., Burnett, R. O., Carr, K. R., et al. (1998). IEEE Standard for Synchrophasors for Power Systems. IEEE Transactions on Power Delivery, 13(1), 73-77.

Synchrophasor Compression

Squeezing out the bits

- Source coding for PMUs; large amounts of phasor data to be transmitted or stored [4]
- Like compressed sensing, the techniques are taken from/used heavily in image compression
- Two steps: (1) use a priori knowledge to best represent synchrophasor data (2) use standard compression
- Temporal correlation i^{th} signal at time j: $M'_{i,j} = (M_{i,j} - M_{ref,j}) - (M_{i,j-1} - M_{ref,j-1})$
- Spatial correlation: nodes electrically close will have similar voltages, i.e. choose $M_{ref,j}$ wisely
- Then use your favorite compression algorithm

Information Theory in the Grid

Rough thoughts...

Information and graph theory concept	Smart grid application	How it applies
Channel capacity	Throughout the smart grid	Network capacity
Compressive sensing	AMI	Meter sampling
Compression	Synchrophasors	Phasor compression
Spectral graph theory	FDIR	Distribution graph
Inference	State estimation	Inferring state
Entropy and prediction	Demand-response	Predicting demand
Entropy and prediction	Distributed generation	Predicting power output
Entropy and prediction	Stability	Reducing variance
Network coding	AMI	Efficient transmission
Spectral graph theory	Grid-comm. networks	Network structures
Entropy	Security	Encryption strength
Quantum Info Theory	Security	QKD

Table: Information theory application to the smart grid.

Systems View

Complexity theory

- IT and complexity begin to provide us with a systems view
- This is crucial for implementing the best communication solution
- Communication efficiency depends upon the source model predictability of the information
- Predictability of the information depends upon having a predictable system
- Predictability of a system depends upon its complexity and how much is observable, monitored, and understood
- But the system is becoming even more complex because tied to the most complex system of all—markets and human behavior

Smart Grid and Complexity

Adding the market to the system

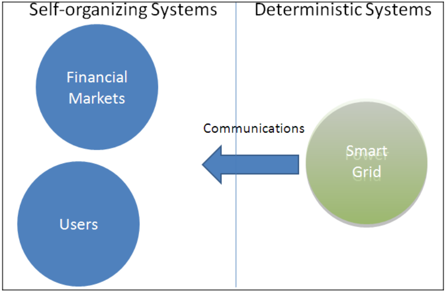


Figure: Smart Grid Moving Rapidly into Complex Systems Realm.

- The grid is becoming not just a conduit of power, but rather a bi-directional market mediator
- Consider the emerging field of network science and understanding the impact of network structure

Self-Organization

Complexity and self-organization apply to power systems

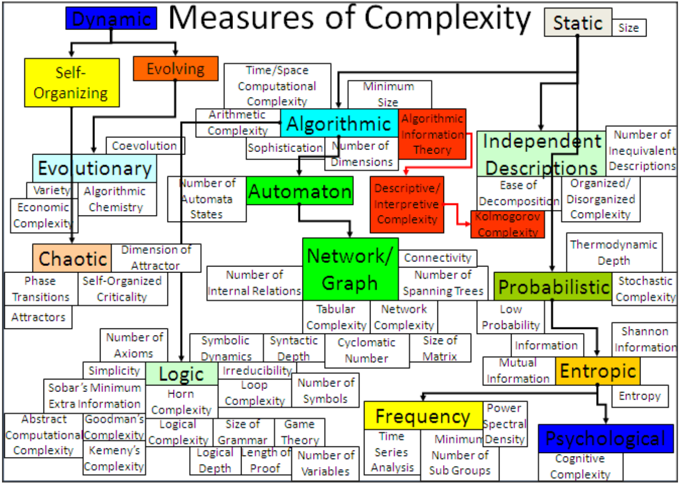


Figure: Complexity Map.

Network Topology

Graph spectra

- Graph theory and network science may take a more prominent role
- Decades of work have been done on power system network topology and communications
- Spectral graph theory and random matrix theory were developed in 1950's and 1960's
- Focuses on understanding network/graph eigenvalues (aka "graph energy" from quantum mechanics)
- Periodically applied to networks of all kinds, including the power grid
- Applied to nanoscale electrical networks[35]

[35] Bush, S. F., & Goel, S. (2006). Graph Spectra of Carbon Nanotube Networks. 2006 1st International Conference on Nano-Networks and Workshops (pp. 1-10). IEEE. doi: 10.1109/NANONET.2006.346234.

Compressed Sensing

Taking advantage of sparsity

- Many signals are sparse: many coefficients close to or equal to zero
- Takes a weighted linear combination of samples in a basis different from the basis in which the signal is known to be sparse
- Small number of such measurements contain nearly all useful information
- Converting the “image” back into the intended domain involves solving an underdetermined matrix equation
  - Because number of compressive measurements taken is smaller than the number of pixels in the full image
- Adding the constraint that the initial signal is sparse enables one to solve the underdetermined system of linear equations
- Least-squares solution is to minimize the L2 norm—that is, minimize the amount of energy in the system

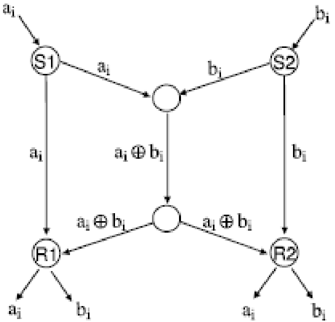
Compressed Sensing

Minimizing the L0 norm

- Leads to poor results for many practical applications, for which the unknown coefficients have nonzero energy
- To enforce the sparsity constraint when solving for the underdetermined system of linear equations, one can minimize the number of nonzero components of the solution
- L0 “norm” counts number of non-zero components of a vector
- Minimizing the number of nonzero components equivalent to maximizing the number of zero coefficients in the new basis (NP-hard)
- For many problems, it is probable that the L1 norm is equivalent to the L0 norm, allows one to solve the L1 problem, which is easier than the L0 problem
- Find the candidate with the smallest L1 norm expressed relatively easily as a linear program, for which efficient solution methods already exist

Network Coding: The Concept

Coding for maximum flow



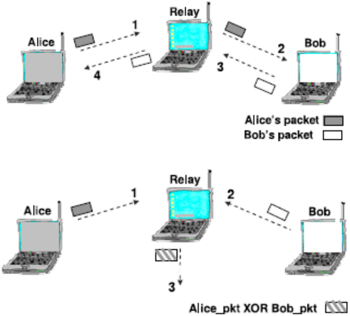
[36]

- Both messages are received by both receivers due to xor ($\oplus$) operation on center link
- Maximum flow through the network links is achieved
- The common link added in reception for both receivers

[36] Katti, S., Rahul, H., Wenjun Hu, Katabi, D., Medard, M. ; Crowcroft, J., "XORs in the Air: Practical Wireless Network Coding," IEEE/ACM Transactions on Networking, 2008

Network Coding: The Application

A simple example



[37]

- Consider a simple wireless routing scenario (with and without network coding)
- Four separate transmissions required without network coding
- Three separate transmissions utilizing coding (same xor operation as in previous slide)

[37] Katti, S., Rahul, H., Wenjun Hu, Katabi, D., Medard, M. ; Crowcroft, J., "XORs in the Air: Practical Wireless Network Coding," IEEE/ACM Transactions on Networking, 2008

Supervisory Control and Data Acquisition

Industrial monitoring and control

- Generally refers to industrial control systems: computer systems that monitor and control industrial, infrastructure, or facility-based processes
- Traditionally used combinations of radio and direct serial or modem connections to meet communication requirements
- Ethernet and IP over SONET/SDH is frequently used at large sites
- Legacy of the early low-bandwidth protocols remain
- Protocols designed to be very compact and polls RTUs
- Standard protocols are IEC 60870-5-101 or 104, IEC 61850 and DNP3
- Many of these protocols now contain extensions to operate over TCP/IP

Ethernet and IEC61850

Views of the protocol stack

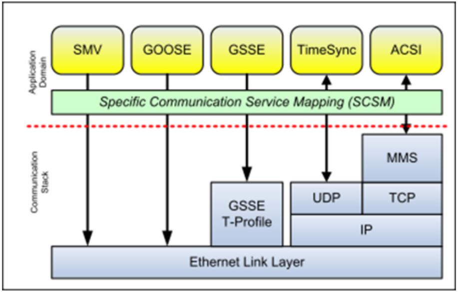


Figure: IEC61850 Stack.[38]

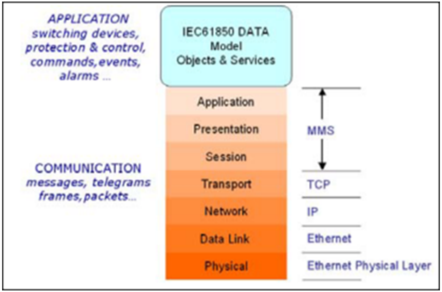


Figure: IEC61850 Stack.[39]

38 Liang, Y., & Campbell, R. H. (2008). Understanding and Simulating the IEC 61850 Standard. Retrieved December 9, 2010.

39 T.S. Sidhu, P. K. G. (2005). Control and automation of power system substation using IEC61850 communication. Proceedings of 2005 IEEE Conference on Control Applications, 2005. CCA 2005. (pp. 1331-1336).

IEC61850

Using "nodes" to create "functions"

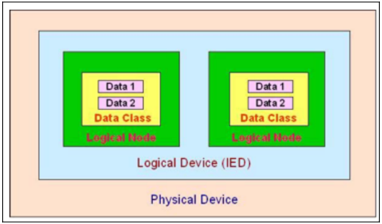


Figure: IEC61850 Node.[40]

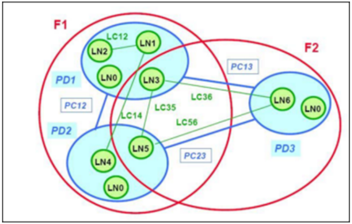


Figure: IEC61850 Function.[41]

40 T.S. Sidhu, P. K. G. (2005). Control and automation of power system substation using IEC61850 communication. Proceedings of 2005 IEEE Conference on Control Applications, 2005. CCA 2005. (pp. 1331-1336).

41 T.S. Sidhu, P. K. G. (2005). Control and automation of power system substation using IEC61850 communication. Proceedings of 2005 IEEE Conference on Control Applications, 2005. CCA 2005. (pp. 1331-1336).

- Give a very high-level overview of communication technologies
- Briefly review 802.11s, WiMAX (+mesh), LTE, 802.15.4/ROLL/6LoWPAN
- OR jump to summary depending on time...

WiMAX

Worldwide Interoperability for Microwave Access

- IEEE 802.16 standard family also known as WiMAX (Worldwide Interoperability for Microwave Access) [3]
- Designed to serve as the last mile connection for wireless broadband access
- Coverage is up to five miles with a bandwidth of up to 70 Mbps
- Support for mobility; a mesh support mode allowing users to route through one another to reach the base station
- IEEE 802.16d is the fixed location standard; IEEE 802.16e is the mobile WiMAX standard
- IEEE 802.16j standard defines a relay mode for IEEE 802.16e [1]

IEEE 802.11 and IEEE 802.16

A comparison

- IEEE 802.16 ranges in kilometers; IEEE 802.11 ranges in hundreds of meters
- IEEE 802.16 – time domain multiple access TDMA; IEEE 802.11 allows collisions, uses carrier sensing
- IEEE 802.11 potential for hidden and exposed terminals, addressed with RTS/CTS; IEEE 802.16 uses a three-way handshake
- IEEE 802.16 data and control channels are separate; control does not contend with data traffic
- IEEE 802.11 – best-effort type of communication; IEEE 802.16 – four QoS classes
- Interoperability between IEEE 802.11 and IEEE 802.16 has yet to be addressed [5]
- WiMAX connection-oriented; IEEE 802.11 is not
- WiMAX MAC connections identified by unique connection identifiers (CID), IP addresses mapped to CIDs
- Point-to-multipoint (PMP) mode: a base station (BS) and multiple subscriber stations (SS)
- PMP mode: communication only between subscriber stations and the base station, no communication allowed directly between SS

Mesh Mode

Multihop capability

- Allows multihop through subscriber stations (802.16d and 802.16e)
- IEEE 802.16j is a draft standard that supports multihop
- This draft has the network form a tree with the BS as the root; relay stations (RS) form the branches between the mobile stations (MS) and the BS
- In the “plain” 802.16 mesh mode, the communication from subscriber stations to the base station can take place through multiple subscriber stations
- Each SS becomes a router forwarding other traffic for other subscriber stations to the BS

WiMAX QoS

- Four service classes: unsolicited grant service (UGS), real-time polling service (rtPS), extended-real-time-polling service (ertPS), non-real-time polling service (nrtPS) and best effort (BE)
- UGS provides real-time constant bit rate (CBR) service
- rtPS is for real-time applications that generate variable size packets such as MPEG video
- ertPS allocates a dedicated bandwidth similar to UGS – allocation can be dynamically increased or decreased similar to rtPS
- nrtPS is similar to rtPS but with longer periods between slots – ideal for delay-tolerant applications
- BE service offers no minimum service requirements; slots used as they become available
- Stationary smart grid devices – a fixed network configuration among IED radios can be established; UGS service could provide constant bit rate service
- Another alternative is to use best effort service and construct smart grid specific reliability mechanisms

OFDM

Orthogonal frequency-division multiplexing

- A Frequency-division multiplexing (FDM) scheme
- Large number of closely-spaced orthogonal subcarriers
- Data is divided into several parallel data streams or channels (subcarriers)
- Each sub-carrier modulated with a conventional modulation scheme (e.g., QAM, PSK) at a low symbol rate
- Maintains total data rates similar to conventional single-carrier modulation schemes
- Primary advantage over singlecarrier schemes is ability to handle severe channel conditions (e.g., attenuation of high frequencies in long copper wire, narrowband interference and frequency-selective fading due to multipath) without complex equalization filters
- Channel equalization is simplified: OFDM may be viewed as using many slowly-modulated narrowband signals rather than a rapidly-modulated wideband signal
- Low symbol rate allows guard interval between symbols; handled time-spreading / eliminates ISI

Long Term Evolution

Brief overview

- Latest standard in the GSM/EDGE and UMTS/HSPA network family
- Commonly seen as a cell phone or common carrier development
- Also endorsed by public safety agencies in the US as the preferred technology for the new 700 MHz public-safety radio band
- Provides downlink peak rates of 100 Mbps uplink of 50 Mbps and round-trip times of less than 10 ms (between mobile and core network)
- Supports scalable carrier bandwidths from 1.4 MHz to 20 MHz and FDD and TDD
- Include System Architecture Evolution (SAE): a flat IP-based network architecture designed to replace the GPRS Core Network
- SAE ensures support for some legacy or non-3GPP systems (e.g. GPRS and WiMAX respectively)
- Claims high throughput, low latency, plug and play, FDD and TDD, simple architecture resulting in low operating costs

802.15.4/ROLL/6LoWPAN

802.15.4 Wireless personal area network (WPAN) which focuses on low-cost, low-speed ubiquitous communication between devices; includes real-time suitability by reservation of guaranteed time slots, collision avoidance through CSMA/CA and integrated support for secure communications

6LoWPAN IPv6 over Low power Wireless Personal Area Networks; encapsulation and header compression mechanisms that allow IPv6 packets to be sent to and received from over IEEE 802.15.4 based networks

ROLL/RPL Scalability requirements that a suitable routing protocol must satisfy: (1) routing state must not increase linearly with the number of nodes in neighborhood (2) local events must not lead to network-wide broadcast of routing messages (3) control cost (overhead) must be bounded by the rate of data packets; DAGs rooted at popular/default destinations a preferred mechanism to provide routing functionality; designed for large low-power and lossy networks, consisting of thousands of memory, power and CPU constrained nodes and unreliable links, presents unique challenges

802.11s

Multihop 802.11

- Draft IEEE 802.11 amendment for mesh networking
- Support multihop forwarding at the MAC layer: changes in MAC frame formats, an optional medium access
- Mesh network device is termed a Mesh Station (mesh STA)
- Mesh STAs form mesh links; mesh paths can be established using a routing protocol
- A default mandatory routing protocol (Hybrid Wireless Mesh Protocol, or HWMP)– allows vendors to operate using alternate protocols
- HWMP inspired by a combination of AODV (RFC 3561) and tree-based routing
- Mesh STAs can collocate with 802.11 Access Points (APs) and provide access to the mesh network to 802.11 stations (STAs)

Cognitive Radio

A smart radio for a smart grid

- Intelligent wireless communication system that aware of its surrounding environment (i.e., outside world)
- Learns from the environment and adapts internal states to incoming RF stimuli by making corresponding changes in certain operating parameters (e.g., transmit-power, carrier-frequency, and modulation strategy) in real-time
- Two primary objectives in mind: Highly reliable communications and efficient utilization of spectrum
- Must include prediction of interference that they would cause for present applications i.e., must not harm the grid
- Must be able to analyze the effects of their operations on the grid
- The goals of the smart grid (resiliency, self-healing, asset optimization) match those of cognitive radios

Cognitive Networks

- Taking the cognitive concept to the network level
- A network that perceives current network conditions, plans, decides, and acts on those conditions
- Learns from the consequences of its actions to achieve end-to-end goals

Active Networks

- "Active network" has different meanings in power systems and communications
- Extremely flexible networks capable of rapidly adjusting to demands

Sensor Networking

- Will likely use 802.15.4; many obvious sensor network uses
- Distribution network will likely be most challenging component to instrument: broadly distributed, near ground clutter and noise
- Power line robots (mobile sensors) a possibility
- Dynamic line rating system that uses floating couplers, RF communications, and ground based weather stations and CPU units
- Common approach: identify a 'critical span', and to monitor that location; given variability along line, this can be a flawed approach
- Line sag monitor that uses video camera to detect sag
- Example: clamp-on line sensor monitors cable temperature, wind velocity, rain/ice and a video picture of the line, and communicates via point-to-point wireless link with the substation
- An 802.11b clip-on line sensor in [2]

Advanced Metering Infrastructure

- Cell/pager networks, satellite, licensed radio, combination licensed and unlicensed radio, power line communication
- Fixed wireless, mesh network or a combination
- Wi-Fi and other internet related networks
- No single solution seems to be optimal
- Rural very different from urban or utilities located in difficult locations such as mountainous regions or areas ill-served by wireless and internet companies

Cybersecurity

- Currently focused on typical IT approaches
- Needs to be integrated with the grid better
- Needs more theoretical understanding e.g. information theoretic approaches

What did we learn?

Key points and final conclusion

- Smart grid hype comes from the analogy between the power grid now and the early Internet
- Will the explosion in innovation be the same?
- A complex problem, no single communications solution

Smart Grid Communications Book

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