Application of wireless technologies to smart grid environments

Seminar for the class of Wireless systems and networks

Marco Di Nicola
marco.dinicola@studio.unibo.it

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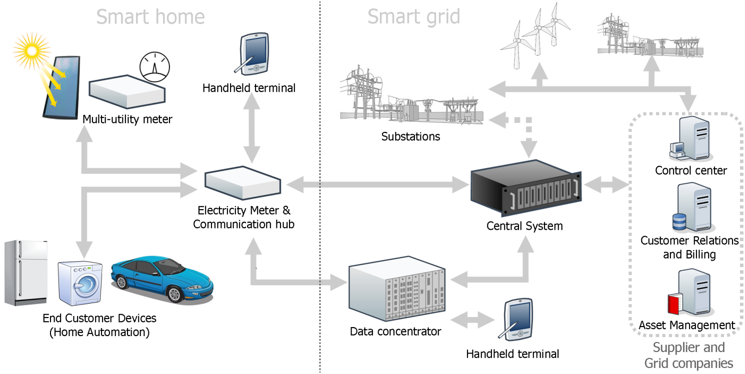
Smart grid

A modern electric power grid infrastructure for enhanced efficiency and reliability through automated control and information and communications technologies.[1]



A Smart grid view

[1] Vehbi C. Gungor, Dilan Sahin, Taskin Kocak, Salih Ergut, Concettina Buccella, Carlo Cecati, Gerhard P. Hancke. *Smart Grid Technologies: Communication Technologies and Standards*.

Smart meters

Electronic measurement devices used by utilities to communicate informations for billing customers and operating their electric systems.

- Electricity, natural gas or water consumption meters.
- Real-time or near real-time sensors, power outage notification, and power quality monitoring.
- Different means of communicating with the utility and the surrounding appliances: power lines, radio frequencies, etc.

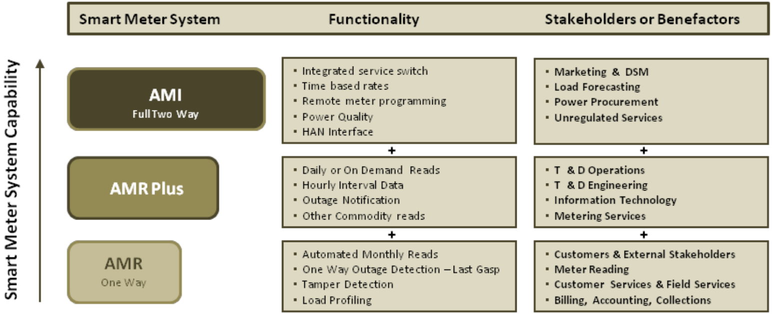
Advanced Metering Infrastructure

AMI: architecture for automated, two-way communication between smart meters and an utility company.

- Evolution of a simpler Automated Meter Reading (AMR) system.
- √ Allows for more advanced communication capabilities and dynamic reconfiguration of meters.
- Deployment of a rich set of applications in the smart grid.
  - Automated meter reading.
  - Real time pricing informations.
  - Outage management.
  - Electricity theft detection.
  - Support for distributed power generation.

Evolution of Smart meters systems

Evolution from AMRs to AMIs. [1]



Smart metering technology evolution

[1] Ellery E. Queen, Edison Electric Institute (EEI). 2011. *Smart Meters and Smart Meter Systems: A Metering Industry Perspective*.

Smart grid: Objectives

Increase reliability and reduce costs by:

- Sensing component problems before they fail (i.e. hot transformers, natural accidents, . . .).
- Sending repair crews to problem sites quicker and more accurately.
- Automatic (near real-time) billing.
- Having the informations to reduce peak demand or automatically control power consumption during peak and off-peak load times.

Reliable and real-time information is the key factor for reliable delivery of power from the generating units to the end-users.

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Limiting factors and requirements

Factors that should be taken into account in the smart metering deployment process:

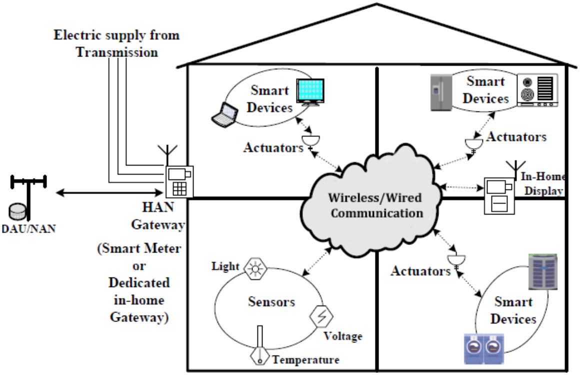
- Time of deployment.
- Operational costs.
- Availability of the technology.
- Rural/urban, indoor/outdoor environment. The path between a pair of transmitters and receivers can vary between plain line of sight to tall buildings, forest area and mountainous terrain.

Requirements:

- Security of information storage and transportation (for billing purposes and grid control).
- System Reliability, robustness and availability.
- Scalability.
- QoS mechanisms.

Communication Architectures: HAN

Home Area Network: smallest subsystem in the hierarchical chain of the smart grid.



- Smart meter.
- Smart devices with sensors and actuators.
- In-Home display for energy management system: EMS.

HAN: enabling Communications Technologies

The HAN handles energy efficiency management, and demand response by proactive involvement of power users and consumers (the so called Demand Side Management).

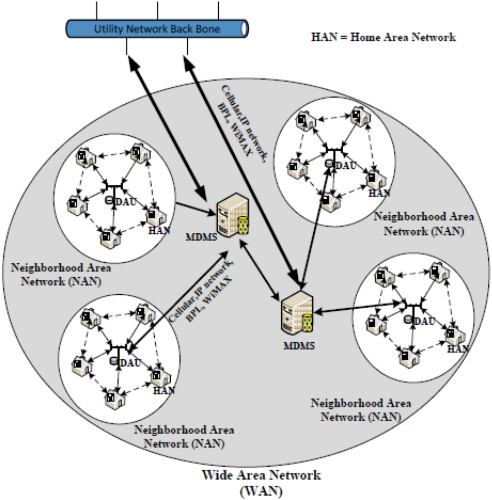
Short range wireless technologies:

- ZigBee, Z-Wave, WiFi, Bluetooth, etc.

Power Line Communication.

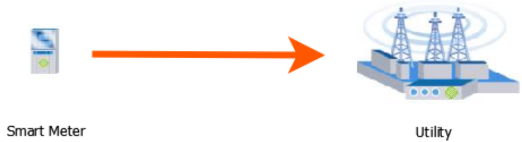
Communication Architectures: NAN

Neighborhood-Area Network: connects multiple HANs together.



NAN: enabling Communications Technologies

Data aggregator unit (DAU), the NAN Gateway, acts as a data sink to collect and relay the information from the consumer side to meter data management system (MDMS).



Wired Technologies:

- Power Line Communication.
- Digital Subscriber Line (telephone wires).
- Optical fiber.

Wireless Technologies:

- Cellular networks.

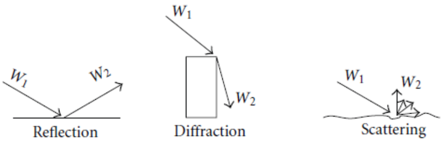
Power line communication

Using the existing power lines to transmit data signals from one device to the other, by adding a modulated carrier signal to the wiring system.

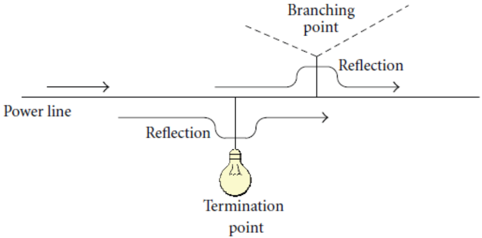
- **Narrowband** PLC: 3-500 KHz, lower data rates (up to a few hundreds kbps using OFDM) but longer range (up to several kilometers). Best suited for AMI: meter-to-data concentrator transmissions.
- Broadband PLC: higher frequencies (1.8-250 MHz), higher data rates (up to 100 Mbps) but shorter range. Last-mile solution for Internet (i.e. multimedia) distribution and home networking.

Typically smart meters are connected to an intermediate data concentrator through power lines and data is transferred to the data center via cellular network technologies (i.e. ENEL solution).

PLC vs Wireless



Propagation mechanisms in wireless communication.



Branching + impedance appearing at the termination points are the main source of impedance discontinuity in power line networks → reflections.

PLC vs Wireless (2)

	Wireless	**Powerline**
Path loss/attenuation	Highly dependent on the propagation environment	Dependent on the characteristics of used cables
Time dispersion/Freq. selectivity	Governed by reflection, diffraction, and scattering	Governed by reflections mainly due to impedance discontinuities along the propagation path
Time selectivity/Freq. dispersion	Mobility of transmitter/receiver pairs or motion of surrounding objects	Impedance variations over both long and short term
Noise	Mostly assumed AWGN, presence of impulsive noise in certain environments	More complicated noise structure: coloured background noise (computers, dimmers, hair dryers, . . .), narrow band noise and impulsive noise is very effective

Performance of PLC are degraded by various equipments connected to the power line, acting as noise sources.

PLC: pros and cons

- √ Can use existing infrastructure: virtually all line-powered devices can be controlled or monitored! Decreases installation costs of the communications platform.
- × Harsh and noisy transmission medium: affected by several types of noise!
- × Greatly affected by the wiring distance between devices, network topology and number of nodes.
- × Costly for wide area deployments.

ZigBee

Ideal LR-WLAN technology for smart lightning, energy monitoring, home automation, and automatic meter reading.

ZigBee Smart Energy 2 Applications Profile (SEP 2.0) [1] open standard for passing energy-related messages throughout the HAN, between many devices commonly found in residential and mid-sized commercial/institutional buildings (smart thermostats, refrigerators, . . .).

- Replaces the proprietary transport protocols of the 1.0 version with TCP/IP, adding support for a wider range of smart energy devices.
- Includes a set of commands designed specifically for EVs (electric vehicles) chargers.

[1] ZigBee Alliance. *Smart Energy Profile 2 (SEP 2) – IP based Energy Management for the Home*.

ZigBee: pros and cons

- √ Cheap, simple, easy to deploy (being based on the IEEE 802.15.4 standard), allows mobility, operates within an unlicensed spectrum (ISM band), requires low bandwidth.
- √ SEP 2.0 offers advantages for gas, water and electricity utilities, such as load control and reduction, demand response, real-time pricing programs, alerts about upcoming power cuts/surpluses, real-time system monitoring and advanced metering support.
- √ Allows deployment of mesh networks, thereby extending the range and making them self-healing.

- × Low processing capabilities and small memory size.
- × Low transmission data rate.
- × Subject to interference from IEEE 802.11 WLANs, Bluetooth and Microwave.

Z-Wave

Alternative solution to ZigBee: designed specifically for automation and energy management in the home and small commercial facilities.

- Easily embedded in consumer electronic appliances that require low-bandwidth data operations.
- Operates in the 868 for SRD (Europe) - 921(Australia) MHz frequency range.
  - √ Avoids interference with IEEE 802.11 and other systems operating in the (crowded) 2.4 GHz band.
  - √ Allows for a greater range than ZigBee.
  - × Competes with some cordless telephones and other consumer electronics devices.
- Uses Frequency-Shift Keying modulation on a narrowband, reaching a throughput of up to 100 kbps.
- Networks may include up to 232 nodes.
- Uses a far simpler protocol than ZigBee: allows faster development.

Wireless mesh

Smart devices, equipped with a radio module, route the metering data through nearby meters, which act as signal repeaters until the collected data reaches the electric network access point.

- √ Dynamic self-organization, self-healing and self-configuration capabilities: improved network performance and reliability.
- √ Extended coverage range (multi-hop routing, meters can act as signal repeaters).
- √ Capability of balancing the load on the network and implementing QoS policies.
- × Subject to fading and interference.
- × Inter-operability reduced by the use of proprietary mesh network technology (Silver Spring Networks, Itron, Elster, . . .).
- × A third party company is required to manage the network: need for encryption techniques, since metering informations pass through every access point.
- × Loop problems cause additional overheads in the communication channel.

Wireless mesh: Routing protocols

Routing in a smart utility network has to be compatible with a wide range of devices, from home appliances to metering devices to collectors.

- Perform device aware routing: must avoid battery constrained devices or devices under strain for frequent routing of packets.

Requirements considered: home automation routing (RFC5826), industrial routing (RFC5673), urban routing environments (RFC5548) and in-building routing requirements (RFC5867).

Examples:

- For home automation applications, the duty cycle of devices is less than 1% and the convergence time for the protocol is 500 milliseconds.
- For industrial automation applications the reliability ($\frac{\#successful\ transmissions}{\#attempts}$ in a given period of time) has to be as close to 100% as possible.

Wireless mesh: Routing protocols (2)

Two promising routing protocols:

- **Geographical routing**: distance vector routing protocol which uses a combination of weighted link metrics and geographical proximity to route data packets.
  - Nodes can be provided with the geographical coordinates during commissioning.
  - Based on computation of geographical distance between source, destination and nearest next hop.
- Routing Protocol for LLNs (Low power and Lossy Networks) or **RPL**: IPv6 distance vector routing protocol designed by the IETF-ROLL group.
  - Each node constructs multiple Destination Oriented Directed Acyclic Graphs (DODAGs) using an objective-function which operates on a combination of metrics and constraints to compute the best path for routing data packets to the destination.
  - Uses adaptive timer mechanism to maintain adjacency and keep routing tables updated.

Cellular networks

2G, 2.5G, 3G, WiMAX and LTE are the cellular communication technologies available to utilities for smart metering deployments.

- √ Cellular networks already exist, therefore a dedicated (and expensive) communication infrastructure is not needed.
- √ Long distance communication range.
- √ Well suited for AMI: an high data rate connection could be required for frequent bidirectional communications between the meter and the utility.
- × May **not** guarantee continuous availability of communications: cellular networks shared by the customer market may result in network congestion and decreased performance in emergency situations.

Other technologies

- IEEE 802.20 (Mobile Broadband Wireless Access): may be used for smart grid applications, such as broadband communication for plug-in electric vehicles and wireless backhaul for electric grid monitoring. Operates in the licensed frequency bands below 3.5 GHz.
  - √ Offers high speed data rate of 20Mbps and is optimized for full mobility up to vehicular speed of 250 km/h.
  - × Communication infrastructures for this technology are not readily available: may be a costly solution compared to cellular technology.
- Bluetooth: could be used for local online monitoring applications as a part of substation automation systems.
  - × Interferes with IEEE 802.11 WLANs.
  - × Offers weak security compared to other standards.

Overview of communication technologies

Technology	Spectrum	Data Rate	Coverage Range	Applications	Limitations
GSM	900-1800 MHz	Up to 14.4 Kbps	1-10 km	AMI, Demand Response, HAN	Low data rates
GPRS	900-1800 MHz	Up to 170 Kbps	1-10 km	AMI, Demand Response, HAN	Low data rates
3G	1.92-1.98 2.11-2.17 GHz (licensed)	Up to 2 Mbps	1-10 km	AMI, Demand Response, HAN	Costly spectrum fees
WiMAX	2.5 GHz, 3.5 GHz, 5.8 GHz	Up to 75 Mbps	10-50 km (LOS) 1-5 km (NLOS)	AMI, Demand Response	Not widespread
PLC	3-500 KHz (narrowband)	Up to 576 Kbps	100+ km	AMI, HAN, Fraud Detection	Low data rates, harsh, noisy channel environment
ZigBee	2.4 GHz, 868-915 MHz	250 Kbps	100+ m (outdoor)	AMI, HAN	Low data rates, short range
ZWave	868-921 MHz	Up to 100 kbps	100+ m (outdoor)	AMI, HAN	Low data rates, short range

Smart grid standards

On top of communication protocols is defined a set of standards for integration of advanced applications, smart meters, smart devices and renewable energy sources and inter-operability between them.

Some intended use cases and developed standards:

- Revenue metering information model: ANSI C12.19 (defines table structures for data transmissions between end devices and an utility), M-Bus (standard for remotely reading all kinds of meters, even wirelessly), etc.
- Powerline networking: Homeplug (create HANs between electric appliance and smart meters), HomePlug Green PHY, PRIME, G3-PLC, etc.

Smart grid standards (2)

- Home Area Network Device Communication Measurement and Control: Z-Wave, 6LowPAN, etc.
- Cyber Security: IEC 62351 (security suite for the other standards).
- (Pluggable) Electric Vehicles: SAE J2847 (communication messages between PEVs and the grid, for energy transfer and other applications), etc.

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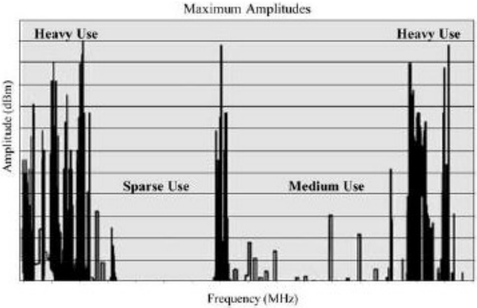
Spectrum utilization

Measurements in several locations across the United States show that:

- On average, only a fraction (0 % to 30 %) of the spectrum in the 30-2900 MHz bands is in use.
- Depending on the region, temporal and geographical variations in the utilization of the assigned spectrum range from 15 % to 85 %.



Spectrum utilization

Spectrum utilization: DSA

Need for a more efficient spectrum use paradigm: **Dynamic Spectrum Allocation** (DSA).

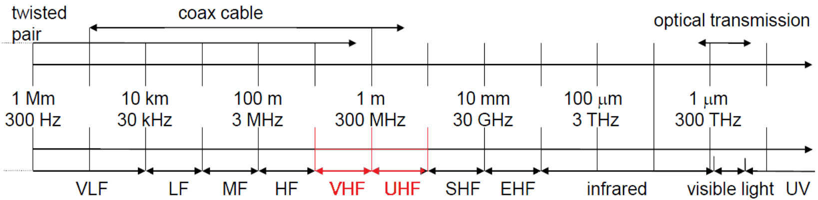
- Enable secondary users (or DSA users) to opportunistically use frequencies that are not occupied by primary (or incumbent) users.

Cognitive Radio (CR), able to perform spectrum sensing and change its transmitter parameters (i.e. transmission frequency) based on interaction with the environment in which it operates, is an important enabling technology for DSA.

White spaces

Unused portions of the VHF (30-300 MHz) and UHF (300-3000 MHz) spectrum.

- Allocated to a broadcasting service (i.e. Television) but not used locally: 698 to 806 MHz in the U.S. (UHF), VHF in the rest of the world.



VHF and UHF bands

Benefits from using these (relatively low) frequencies:

- √ Great signal propagation and penetration properties, allowing for a long transmission range.

White-space networking

Requirements:

- Detecting and avoiding interference to incumbents. This is done by building a dynamic database of "occupied" regions and frequencies.
  Two basic techniques to build it:
  1) Collecting and combining the sensing data from the secondary users (CRs).
  2) Use informations about registered primary transmitters and signal propagation models.
     - × Models can be inaccurate (not capturing shadowing/fading from buildings and trees).
     - × May be hard to build the database on a significative group of primary transmitter.
- Ability to operate in spectrum bands of varying widths.
- Handle temporal variations of transmissions, due to incumbents (i.e. wireless microphones) becoming active suddenly.

White-space networks

Architecture types:

- Distributed ad-hoc.
- Infrastructured, relies on base stations for communications: easily implemented and conformant to the FCC requirements (in the U.S.).

Two successfully implemented (infrastructured) standards:

- **IEEE 802.22** wireless regional area networks.
- **WhiteFi**.

802.22 WRANs

Wireless regional area networks that utilize UHF/VHF TV bands between 54 and 698 MHz.

Main target: providing access to the less populated (rural) areas.

- Wireless broadband access provided to areas of typically 17-30 km or more in radius (up to 100 km) from a base station and serving up to 255 fixed clients with antennas located at about 10 m above ground level.
- Minimum throughput delivered to clients: 1.5 Mbps in the downstream and 384 Kbps in the upstream.
- Supports incumbent detection by spectrum sensing and building a database using transmitter data.

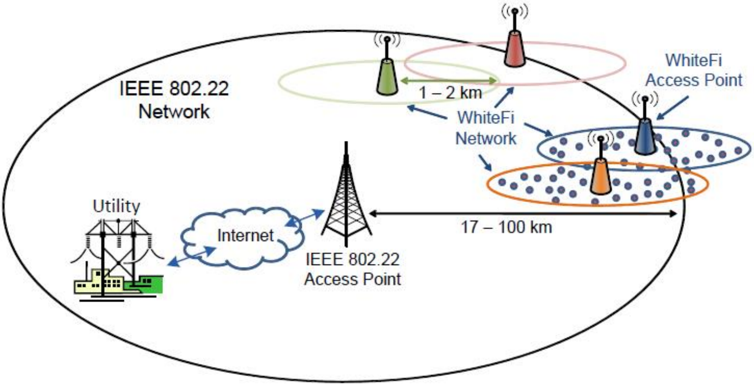
WhiteFi

Implementation of a WiFi like protocol on top of the UHF white spaces.

- Communication between the access point and clients done using stock WiFi cards along with software-implemented UHF translators.
  - √ Uses an inexpensive and easily available technology such as WiFi.
- Spectrum sensing performed using a separate UHF scanner: combination of a UHF antenna and a receive-only daughter board on a software-defined radio.
- Techniques for detecting incumbents, as well as methods for detecting WhiteFi access points and handling disconnections without causing interference to the incumbents.

AMI Communication over White Spaces

A proposed architecture [1], as an hierarchy of two types of wireless networks.



Architecture for AMI Communication over White Spaces

[1] Omid Fatemieh, Ranveer Chandra, Carl A. Gunter. 2010. *Low Cost and Secure Smart Meter Communications using the TV White Spaces*.

Architecture

Lower level: small-scale WhiteFi networks.

- Established and maintained by the utility companies.
- Its nodes are smart meters.
- Can easily expand in areas with radius of up to 2 km, due to the propagation characteristics of the TV spectrum.

Upper level: 802.22 networks, providing connectivity between WhiteFi access points and the utility company.

- Operated by independent broadband service providers that offer service to a utility by admitting the utility's access points in their network.

On distributed spectrum sensing

The large number and geographical separation of smart meters makes them a valuable resource for distributed spectrum sensing.

Aggregation of sensing data is also hierarchical:

1 - The WhiteFi base stations aggregate spectrum sensing data from the meters.

2 - The 802.22 service provider receives these data from the stations.

The 802.22 service provider may collect sensing data from other means: mobile units or sensors deployed specifically for this purpose (**crowd-sourcing**).

Benefits of the architecture

- √ Allows for higher data rates at an economical cost for communication between the meters and the utility.
- √ No need to form complex mesh networks: the penetration and long-range transmission properties in white spaces allow for direct communication between the meters and the WhiteFi access points.
- √ Smart meters provide a valuable base of spectrum sensors for the 802.22 service providers, which may lower their costs and improve their spectrum sensing: results in better protection for primary transmitters.
- √ Balance between independence and cost savings for the utility, while maintaining high data rate connections to the meters.
- √ Contributes to providing affordable broadband service to rural communities.
- √ Using standardized protocols, inter-operability between products from different vendors is allowed.

Limitations of the architecture

- × Requires a one-time cost of equipping smart meters with cognitive radios (partially covered by the spectrum sensing service they provide to the 802.22 provider).
- × There might be times or locations where no white space is available.
  Solutions:
  - Operate temporarily in the ISM bands: lower bit rates.
  - Purchase a narrow band at a small cost for emergency backup usage.
- × Energy consumption for battery powered smart meters, caused by the sensing overhead and data communications, makes them harder to maintain. A possible solution is to group meters into clusters and use a Master/Slaves model [1].
- × Security and reliability issues (subject to attacks such as primary emulation and others).

[1] Luca Bedogni, Angelo Trotta, Marco Di Felice, Luciano Bononi. September 10, 2013. *Machine-to-Machine Communication over TV White Spaces for Smart Metering Applications*.

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V2G: Overview

Consideration: most vehicles are parked an average of 95 percent of their time.

Idea: distributed electricity storage. Use EVs batteries to let electricity flow from the vehicles to the grid and back.

- Provide a back-up energy source at the time of electricity shortage or blackout.
- Participate in demand-side management programs.

EVs can be connected to the electric network (and therefore participate in the power market) in the residences of their holders, underground parking stations, airports, commercial centers, etc.

V2G: Ancillary services

- **Reserve power supply**: use a large-scale V2G system to maintain the balance between supply and demand in the grid by injecting power (thousands of EVs could provide the additional power required by a medium-sized factory at a certain time period, by simultaneously discharging their batteries).
- **Peak shaving**: a group of EVs can participate in peak shaving by coordinating charging (at off-peak hours) and discharging (at peak hours) of their batteries.
- **Renewable energy integration**: supply energy when renewable ones are unavailable (due to their stochastic and intermittent nature).

Communication architectures

1 - Direct line of communication between the EVs and a grid system control center.

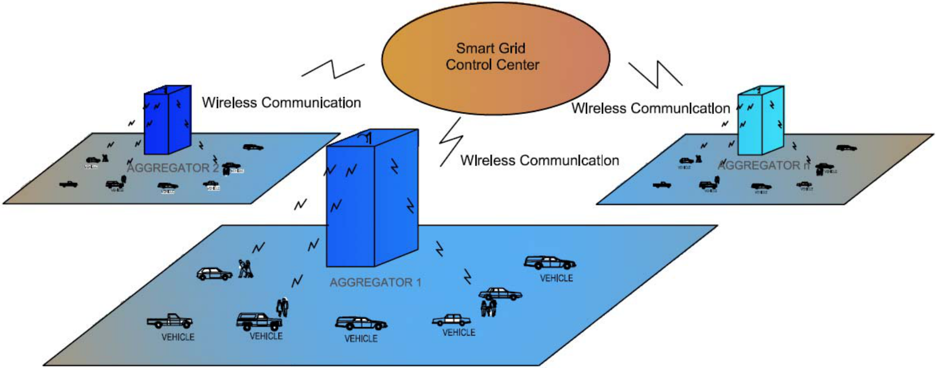
- × Significant overhead imposed on the control center: interact with millions of vehicles as they engage and disengage from the grid.

2 - Indirect communication by introducing **Aggregators**: single controllable power resources which aggregates the ancillary services provided by individual EVs.

Aggregators are intermediate entities between the vehicles and the grid:

- Receive ancillary services request by the control center.
- Issue charging/discharging commands to contracted vehicles (the ones available and willing to perform the service).

V2G: Indirect architecture



Indirect V2G system architecture

Communication requirements

- Bandwidth and latency: estimated by the United States Department of Energy to be up to 100 kpbs per EV and as low as 2 seconds.
  - More challenging as the number of EVs increase.
  - Supporting technologies: cognitive radio, MIMO communications and OFDMA.
- Reliability: achieved by using reliable transport layer protocols (TCP, SCTP).
- Security: assure the user's privacy (charging status and EV's location kept private), protect against charging/discharging requests from unauthorized intruders.

EVs-Aggregator

- PLC: commands sent by aggregators towards PLC receivers (i.e. Homeplug Green PHY based devices).
- ZigBee: SEP 2.0 includes messages for charging/discharging of EVs. Benefits, in regard of this context, are:
  - √ Transmission rates of 50-250 kbps are fast enough to transmit updated data.
  - √ Range can be as large as 400 m: adequate, for example, to reach every EV in a large parking lot with a small number of transceivers.
- Cellular networks: providers can serve as aggregators.
  - V2G systems could benefit from existing smartphone applications for EVs management (such as OnStar for iOS), in order to monitor state of charging, adjust charging/discharging schedules and other functions: these features can be coordinated by the aggregator via commands sent from the cellular towers.

802.11p for EVs-Aggregator communication

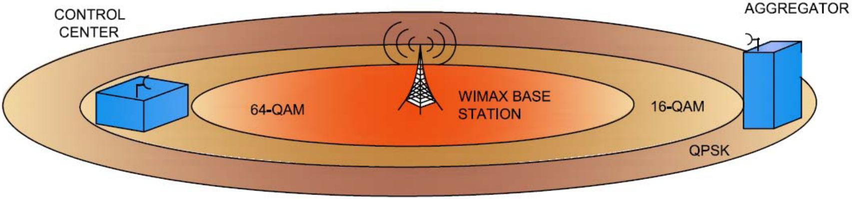
Extensions to IEEE 802.11 for Dedicated Short Range Communication between vehicles.

- Operates in the licensed ITS (Intelligent transportation system) 5.85-5.925 GHz band.
- Promising standard for improvement in safety of transportations, providing services like collision avoidance, route changing, etc.
- Includes data exchange between high-speed vehicles and between the vehicles and the roadside infrastructure.

Useful for notifying the Aggregator about an incoming charging period while moving, or cooperate with other vehicles to provide ancillary services to the grid.

Aggregator-Control Center

IEEE 802.16-2004 specification of the WiMAX standard, operating in the 2-11 GHz frequencies.



V2G WiMAX modulation schemes

The IEEE 802.16-2004 standard PHY specifications:

- A single carrier modulated air interface for LOS transmissions.
- OFDM/OFDMA-based systems, more suitable for non N-LOS transmissions.

Summary

We:

- Introduced some of the smart grid concepts and advantages.
- Compared different communication technologies for smart grid environments: PLC, ZigBee, ZWave, proprietary wireless mesh, cellular networks, 802.20, bluetooth.
  Considered their benefits and limitations.
- Examined a communication architecture which uses Dynamic Spectrum Allocation and wireless technologies (802.22 and WhiteFi) on the TV White Spaces in the VHF-UHF bands, for improved efficiency and reliability.
- Discussed the interactions in Vehicle-to-Grid contexts, for distributed power generation, and a few promising technologies.

Conclusions

- ZWave is a good protocol for deployment of smart HANs, capable of actively cooperating with the grid in Demand Response programs, since it overcomes some of ZigBee shortcomings.
- Cellular networks may also reveal to be a good choice for smart metering, as the infrastructures improve and become more reliable than they are today.
- Cognitive Radio is the most promising technology for smart metering, especially using the TV VHF spectrum and exploiting its great penetration properties for communications.
- 802.11p might be the best choice for Aggregator-to-EVs communication, in V2G context, because of its capabilities for better coordination between EVs participating in ancillary services for the grid.

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