ENERGY INFORMATION SYSTEM DASHBOARD INTEGRATING WIRELESS SENSING DEVICES WITH WIRED METERING AND CONTROLS – A CASE STUDY

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ABSTRACT

According to the most recent Annual Energy Review published by the United States Energy Information Administration, residential and commercial buildings are responsible for 40% of the energy consumed in the United States, 66% of the electricity use, and 39% of the carbon-related emissions (EIA - U.S. Department Of Energy 2009). The current emphasis is to design and construct energy efficient buildings that use 70 percent less energy (than today's average building) by 2030, and to achieve zero net energy by supplying the remaining energy from clean and renewable resources (U.S. Department of Energy 2007). An Energy Information System (EIS) is an essential informational link towards realizing this goal.

This case study exams a facility where several (wired and wireless) data acquisition systems gather energy and thermal comfort data in an institutional office building occupied predominantly by research scientists and support staff, and these systems are integrated into a single EIS. The EIS includes graphical reporting features to convey building information to operators, managers, owners, occupants and facilities personnel who have the capability to act upon the information to impact energy efficiency and comfort in the building.

As EISs are still a new field, it is important to identify what needs to be done in the future to ensure their usefulness as a tool to improve energy efficiency and occupant comfort in buildings. They are an essential step on the road to achieving buildings that use zero net energy.

Keywords: Energy Information System (EIS), Wireless Sensing Network, HVAC, Energy Use

1. INTRODUCTION

A considerable amount of research has been conducted on design, construction and operational technologies, and practices which would lead to buildings that use zero net energy (U.S. Department of Energy 2007). One critical step to increase energy efficiency is to understand how energy is currently used and identify where improvements can be made.

An Energy Information System (EIS) - broadly defined as performance monitoring software, data acquisition hardware, and communication systems used to store, analyze, and display building energy data - is an available technology that can provide the information necessary to improve the efficiency and comfort within a building (Granderson, Piette, Ghatikar, & Price 2009A). Energy savings may be realized via an EIS in a number of ways:

- Benchmarking and Base-lining
- Anomaly detection
- Energy rate analysis
- Off-hours energy use
- Load shape optimization
- Retrofits and retro-commissioning

An EIS provides the analysis tools to convert energy data into actionable information and often includes graphical analysis and reporting features to convey the information to operators, facilities, managers, owners and occupants (Granderson, Piette, Ghatikar, & Price 2009B). Information gathered from EIS research can be used to guide the design of new buildings and will assist in creating systems which can be implemented into new and existing buildings to make real-time improvements to operational technologies and practices.

2. BACKGROUND

Most commercial buildings have some existing sensing capabilities for control of Heating Ventilating and Air Conditioning (HVAC) systems. Often, a building's main gas and electrical systems are metered but seldom is this real-time data remotely available. A building's HVAC system may be interconnected to a variety of temperature, occupancy, and air quality sensors to operate the system. To gain a more thorough understanding of a building's energy usage (by system, location, or load type) more sub-metering is needed. During the design stage of a building this sub-metering can be easily accomplished using a wired network to connect all metered points. In an existing building, however, the metering becomes more challenging to incorporate, and the electrical systems have often had numerous revisions over the years, necessitating more meters to capture the desired data. In those cases where the addition of a wired metering system to an existing building would be cost prohibitive, especially while it remains operational, a wireless sensing network becomes very appealing.

3. DESCRIPTION

The subject building of this study is a 90,000 ft^2 (8,360 m^2) institutional office building (Building 90) at Lawrence Berkeley National Laboratory (LBNL) occupied predominantly by research scientists and support staff. The building has four floors plus an occupied basement. It was built in 1960 and has had many changes to its electrical systems in the last 50 years. The building has a history of problems with thermal comfort, ventilation, energy use and maintenance. It scored very poorly on an occupant survey with the most common complaints pertaining to thermal comfort and indoor air quality (Stein, 2008). In 2003 air conditioning was added to the building to address these concerns, yet due to system control limitations, areas of the building were overcooled while other sections remained too hot. Using the limited number of temperature sensors originally installed in the building it was difficult to understand how the system was performing. This problem was compounded by the lack of a written sequence of operations (SOO) documenting how the system was designed to work. This combination of an inadequate amount of sensors and lack of a SOO lead to inefficiencies, such as operating the cooling and heating systems concurrently. To determine how the HVAC system was performing more temperature sensors were needed.

For an existing building, installing a battery powered wireless sensing network is a desirable option due to the lower installation cost and reduced disruption to occupants. Wireless systems can operate on a variety of different protocols, each with their own advantages. The features offered by the different protocols will affect wireless range, battery life, network size, data rate, and latency; which is the elapsed time from when a measurement is taken until the signal is received by the gateway (LaJoie, 2010). These priorities will vary by application and certain wireless systems will be better suited to those particular needs. In addition to the operational protocol, the sensor hardware will determine how well suited a sensor network is for a given application; it can determine how easily the network can be implemented and will also affect the wireless range, battery life, and data rate.

The intended application will determine the necessary reporting rate. Some measured data will cycle at high frequencies or change fast enough to require higher sampling rates. For applications where the data is more static, lower reporting rates can be used to prolong battery life. Wireless systems that allow custom tailoring of network parameters, such as the reporting rate, make it possible to optimize the network for each application.

There are many wireless networks that operate using a mesh communication configuration in which nodes act as routers or repeaters to relay information from other nodes back to the gateway; a simplified example of this for Building 90 is shown in Figure 1. The motes represented in this figure refer to sensor nodes that perform processing, data gathering, and communication with other connected nodes in the network. This configuration allows a wireless node to have several pathways to deliver data; if one link is lost the node can still transmit on another pathway, improving network reliability. A wireless mesh system is also useful to allow nodes to communicate around obstacles commonly found in a commercial building environment that would otherwise block the signal.

An EIS will often separate electrical loads by the system type or category such as HVAC, lighting, or miscellaneous electrical loads (MELs) as shown in Figure 2. HVAC and lighting energy usage are commonly understood; there is less information available for the electrical use and patterns for the plug-in devices that fall into the MEL category. However, the devices in this category can account for 10% to 50% of the energy used in commercial buildings (Brown, Meier, & Lanzisera, 2010) and, as lighting and HVAC systems get more efficient, that ratio will only increase.

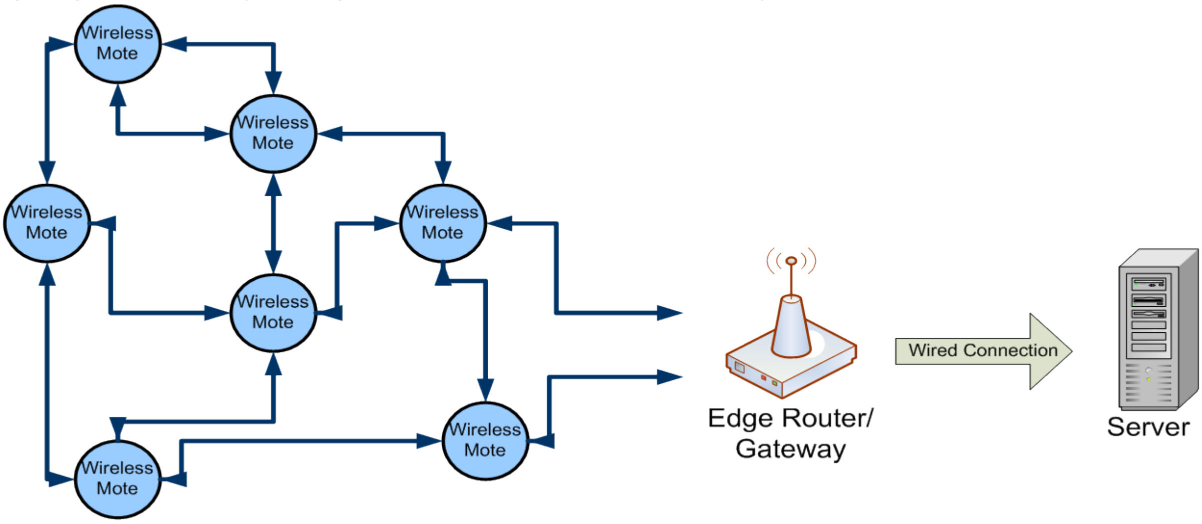

Figure 1: Wireless mesh network communication configuration

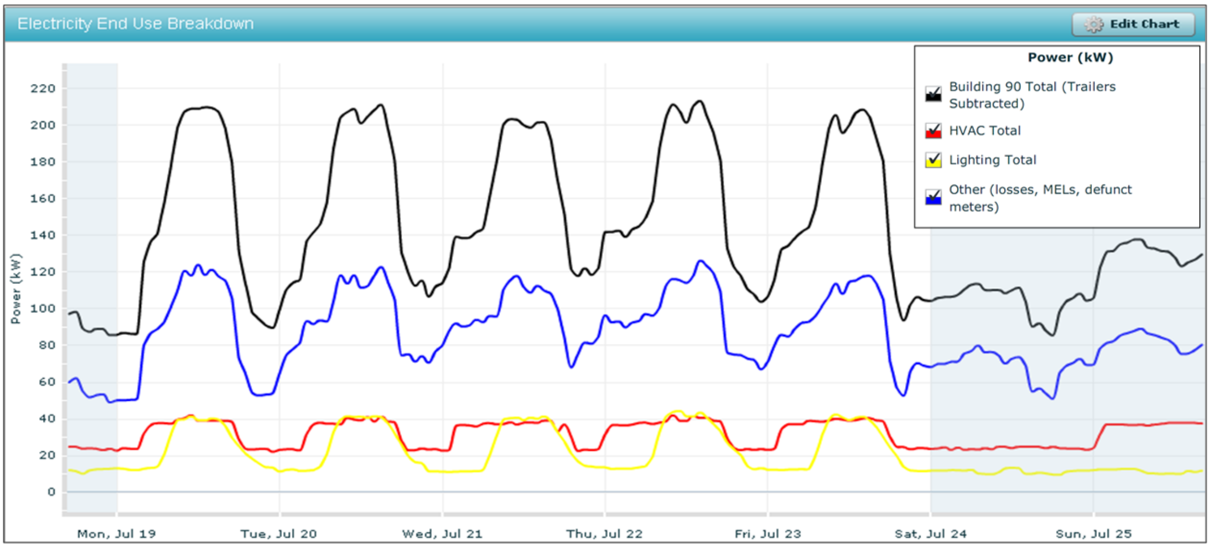

Figure 2 - Graphical comparison of HVAC, Lighting, and MELs in Building 90

Despite previous studies on plug-in MELs, it can be difficult to implement successful energy saving strategies due to their unique nature. It is believed that since many MELs are portable and can be plugged into various outlets, conventional metering techniques are of limited value. The usage patterns can vary widely and be specific to an individual user, making universal energy reduction strategies difficult to devise. Since plug-in devices evolve much more rapidly than HVAC or lighting systems, any energy saving measures must be adaptable and work effectively despite constant changes. Furthermore, the variety of the devices in this category and their various functions require many different strategies to address the unique characteristics of each device (Brown, Meier, & Lanzisera, 2010).

It is common practice in commercial building design to group similar electrical loads onto the same panel which is fed by a single circuit from another panel. This reduces the sub-metering in the building; a single meter can be used to measure the panel main and capture all of the loads. For example, the lighting for an entire floor can be measured at a panel's main circuit breaker if no other load is fed from the same panel. Research (Brown, Meier, & Lanzisera, 2010) has shown, however, that to effectively monitor and study MELs, however, each device must usually be metered individually at the plug. This level of sub-metering necessitates a much more intensive program than that required to meter HVAC and lighting systems. Building 90 had approximately 4,000 plug loads compared with less than 100 points that would need to be monitored to fully sub-meter all of the HVAC and lighting by floor. The data from each plug load meter must be stored, categorized, and analyzed to effectively use the information. Managing the quantity of data is itself a challenge in any plug load study; however, to fully analyze device patterns data should be obtained over an entire year to identify trends and seasonal patterns. Additionally, when multiple loads are connected to a single circuit there is often an averaging effect which tends to stabilize the load fluctuations. When measuring a single device this effect is non-existent; therefore, the meter's sample rate must be increased to capture rapid fluctuations, increasing the amount of data that needs to be managed.

Energy Information Systems should collect data from all of the building's meters to ensure that the data is properly analyzed to produce actionable information. This data can then be stored, grouped, and presented in charts, reports or graphs. An easy to navigate graphical display (shown in Figure 3), commonly referred to as a building dashboard system, can present critical data and relationships and effectively communicate trends, inefficiencies, and anomalies. The dashboard may be tailored to a particular audience such as facilities managers or the public. Ideally, the EIS could provide dashboards uniquely configured to suit the varying interests of multiple user groups. Communicating the information gained from the EIS is a critical link to achieving energy improvements.

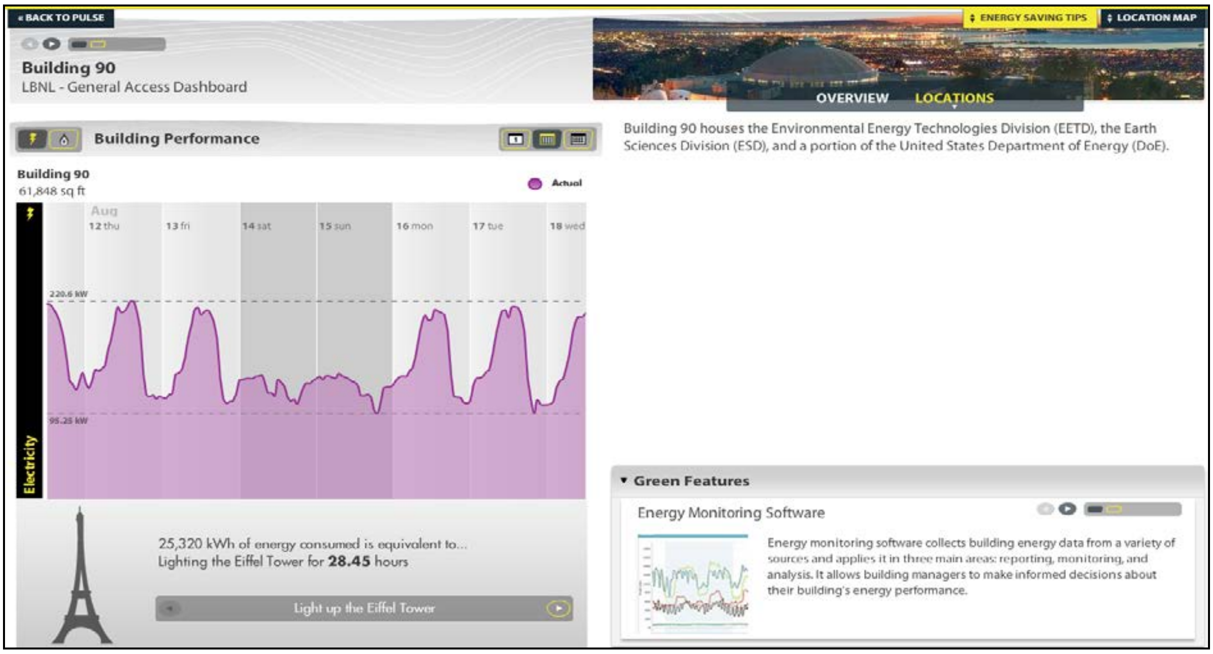

Figure 3 - EIS Dashboard in Building 90

4. MATERIALS AND METHODS

4.1 Wireless Sensing Networks

Each wireless system in Building 90 functioned as an independent network and each system was required to reliably sense and deliver data to the EIS, as shown in Figure 4. Since each system operated with different protocol and network architectures there were a variety of challenges to integrate all systems. Each network used proprietary software designed to work with their system and present useful network information and visual tools to analyze the data. Path signal strength, data reliability, number of times the node has joined the network and information on the upstream and downstream devices at each node can be used to troubleshoot network connectivity and stability issues. Visual tools such as network maps, floorplans, and charts can highlight network problems, and trends or gaps in the data.

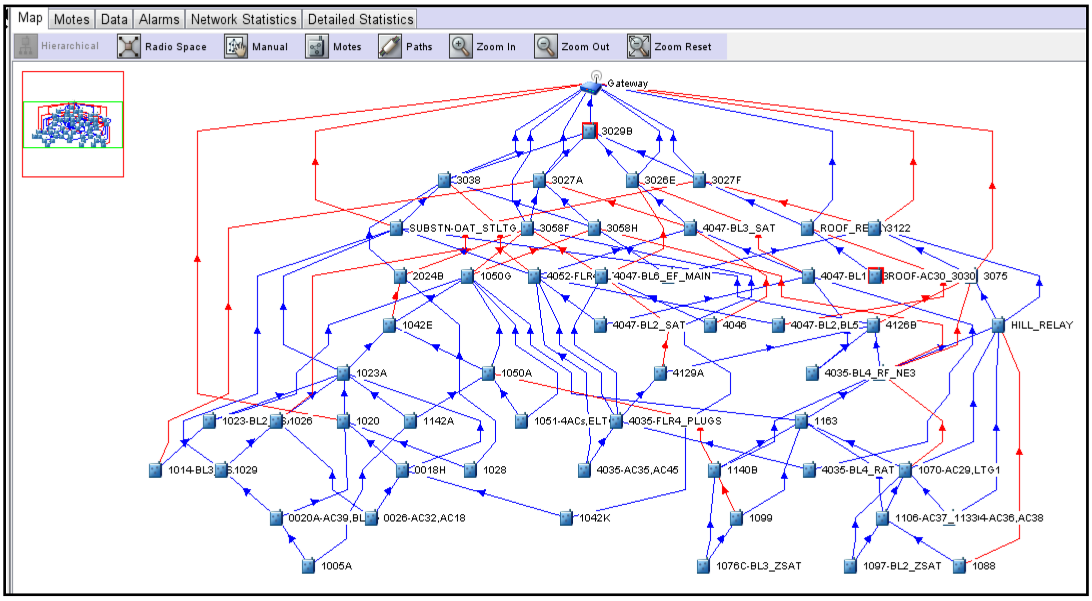

Figure 4 – Mesh instrumentation configuration for wireless sensing network

An integral part of any system in the EIS is web-based integration, which introduces another area for problems to arise. Even if the network is reliably delivering data to the gateway it cannot be used by the EIS unless the path from the gateway to the EIS dashboard is complete. This requires knowledgeable IT personnel to configure the necessary IP connections and firewall settings.

4.2 Wireless Plug-In Device Metering

With over 4,000 plug-in devices, a comprehensive study would be cost prohibitive and offer limited benefits as compared to a study which monitored a smaller, representative cross section of devices. To identify all of the plug loads in the building a device inventory was conducted to record the location and type of every plug-in device. From this list of devices, a random sample was chosen for monitoring.

The meters sent data wirelessly using a mesh configuration. The data was stored in a local database and analyzed using custom analysis tools. All of the analysis was done using custom code written for the project. When data and network issues arose they were addressed on a case-by-case basis using tools similar to the other wireless networks as well as physical trips to the meters to identify problems.

4.3 Commissioning the EIS

Developing an understanding of the current inefficiencies in a building depends heavily on the quality of the real-time data. To use the data gathered by the EIS, the system first needed to be commissioned, and the first step in the commissioning process was to confirm which devices each meter was measuring. Due to the age of the building and the number of changes that had been made, documentation was either inaccurate or non-existent. The building panel schedules and single line diagrams needed to be confirmed, in some cases by physically inspecting the panel. Next, the extent of power usage by type and floor needed to be determined to achieve the desired level of detail. This was done by using the panel schedules once they were determined to be accurate. The electrical meters were then checked to ensure that they were properly connected and metering the desired circuit. The final step involved comparing the displayed data with the actual measured data. Because data was arriving at the EIS from multiple pathways and sources, there were numerous opportunities for errors to be introduced. To confirm that the data displayed by the EIS was accurate, electrical output from the circuits were measured and checked against the information displayed by the EIS. Once each data point was validated in the EIS, it served as a tool to provide building energy use information to occupants, facilities managers, building owners, and the public. As shown in Figure 5, the EIS was composed of multiple subnetworks, which monitored a variety of parameters:

4.3.1 FMCS data, which monitored zone temperatures, HVAC temperatures, blower speeds, pump status, and control valve and damper commands, was sent to a remote server to be used by facilities personnel for building controls. The EIS retrieved trended data from the server for use in Building 90 EIS.

4.3.2 Three different power meters monitored primary circuits. Data was sent by Modbus to a data logger, and by IP connection to the EIS.

4.3.3 Boiler and main gas were monitored and data was sent to the data logger and by IP connection to the EIS.

4.3.4 A node-configured wireless system monitored zone temperatures and power to certain devices. The data was collected and sent to a wireless sensing network server, then retrieved for use in Building 90 EIS.

4.3.5 Another node-configured wireless system monitored zone air temperatures and. The data was collected on a virtual server, and then transmitted to the EIS.

4.3.6 Proprietary plug load meters monitored individual plug-in device power use and sent data wirelessly through the gateway to a local server. The EIS retrieved the data from this server.

4.3.7 Plug strips monitored individual plug-in device power use, occupancy, light levels and temperature. Data was sent via USB, Ethernet or wirelessly to a local server.

5. RESULTS

5.1 Wireless Power Sensing Network

The wireless power sensing network was responsible for delivering both power and temperature data to the EIS. Aside from intermittent data gaps in individual nodes the system performed reasonably well from the time it was commissioned until early June 2010 when the entire system collapsed and did not automatically recover. At this time, the system was not being monitored on a daily basis and the problem went unnoticed until the end of the month when the data was needed for this research project. Protective measures such as connecting the server and gateway to an uninterruptable power supply (UPS) can protect the system from power outages, spikes, and data gaps. However, for ease of maintenance, the network should be designed to automatically restart in the event of a system-wide failure. This event also highlighted the need for alerts, configurable by all subsystems as well as by the EIS that can relay information about critical network events to personnel who can provide the necessary response. Alerts can act as another line of defense in the event the system does not automatically restart.

When the system was operating near the threshold of stability anything that could cause a single node to lose connection, such as a dead battery, would trigger a chain reaction and cause the system to become unstable:

- Nodes that relied on other nodes with dead batteries to relay information would no longer be able to communicate with the network and would also fall offline. The mesh network topology attempted to solve this by offering each node multiple pathways on which to transmit data to the gateway, but it required a dense network configuration so that every node could connect with more than one other node closer to the gateway.
- If the mesh network worked properly, other nodes would relay data that was previously transmitted through the dead node. However, these pathways would not be as ideal since the nodes choose the best available pathway for data transmission. The effect on battery life for the remaining nodes varied for different networks and configurations.

The nodes were configured to search for a network within a preset period of time and if no connection was found they would revert to a power-saving mode. After another preset period of time the nodes resumed their search to establish network communication. This feature greatly reduced the drain on batteries caused by constant searching; the highest power drawn experienced by the wireless sensors.

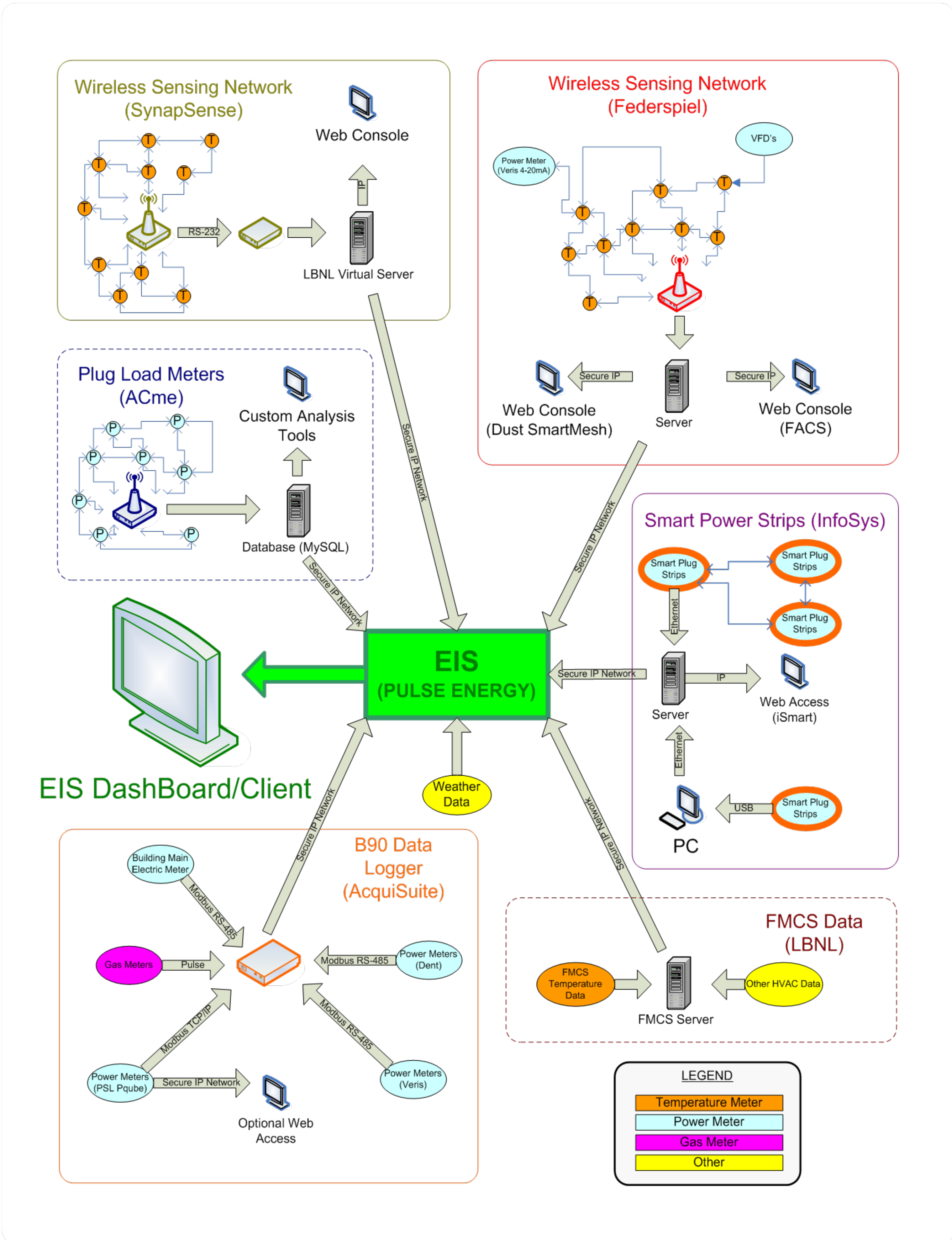

Figure 5 - Building sensing networks and data communications architecture

5.2 Wireless Temperature Sensor Network

The wireless temperature sensors had a slightly different background; this network was used as a semi-permanent installation as a part of a thermal comfort study designed to provide a more thorough understanding of the current performance of the HVAC system. This data also would be used for retro-commissioning projects and to improve building EIS.

Two primary differences were found between the two battery powered wireless networks that is important for commercial building applications; the system operating frequency and device sleep schedule. The temperature sensor network operated at 900MHz while the power sensing network operated at 2.4GHz. The 2.4GHz transmission frequency was found to have almost no signal strength between floors, while the 900MHz network had a limited ability to transmit between floors. Since each frequency has its benefits it is important to perform an analysis of the radio space of the building where the network is to be installed to determine the ideal configuration.

The temperature motes were configured to sleep after a period of unsuccessful attempts to connect with a network, preserving batteries. The motes, however, were designed for use in a data center network where the network is very dense and the sensor data highly critical. Because of this, if the motes were off the network, they were designed to go into full power search mode until they reconnected and could send data again. No sleep schedule was implemented in the version used in Building 90 since they were never expected to be unable to communicate with the network where they were typically deployed.

This network had been deployed once before for testing, and then packed into a box for several months until they were needed again for this project. At the beginning of this project every mote in the box had dead batteries. It was found that they had been left active when they were stored and all of the motes went into search mode and drained the batteries. According to the device manufacturer, the life of the lithium batteries used in the motes should be no less than seven years under normal operation. However, if the motes were left in the full power search mode the batteries would be drained in under a month, nearly 100 times sooner. This is a good example of both the need for an appropriate sleep schedule as well as the dramatic difference that battery saving features can have.

5.3 Plug Load Meters

The plug load meters had the advantage of continuous utility power; therefore, they could forgo battery saving techniques such as sleep schedules, to increase performance. The network operated at 2.4GHz and also had no signal between floors, requiring at least one gateway per floor. The higher density of the 500 meters in Building 90 was partially offset by the non-ideal locations typical of the plug strips and outlets where the meters were installed. The mesh topology allowed motes that were buried under desks and behind cabinets to still connect with the network and deliver data.

Metered devices were chosen using a multi-stage stratified random sample; each floor being a stage and strata included 6-8 categories such as computers and imaging.

5.4 EIS Commissioning

EIS commissioning included a two-stage verification of the data presented at the dashboard. The first stage required verifying that the theory behind the metering and calculations was valid. This involved a validation of the electrical one line diagrams and panel schedules in conjunction with physical visits when the documentation was incorrect or insufficient. A comprehensive schematic of the electrical system showing the end use (by category) and, where possible, the floor or location was developed from an earlier version. An abbreviated block diagram of the system is shown in Figure 6.

In general, the Misc loads in Building 90 were obtained by subtraction; for example, the Misc. – 3rd Floor load on Panel 216A required that Lighting (3075) be subtracted from the main meter on Bank 216. This approach also required compensation for the power consumption of the bank. This was not always the case, however. For example: on Panel 90A6A there were 3rd floor lighting loads and one circuit from Panel 90A6A30A that fed Misc. loads in 3111. By metering the Misc. circuit and subtracting it from the meter on Panel 90A6A main the 3rd floor lighting load could be measured indirectly by subtraction, using one meter instead of two.

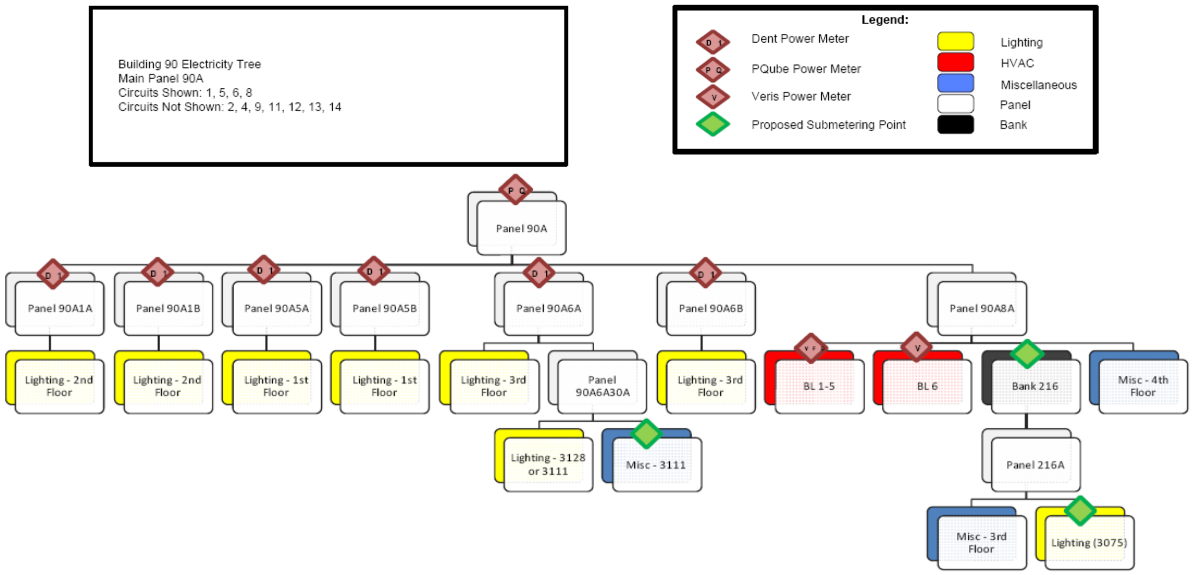

Figure 6 - Part of the electricity tree for Building 90, showing end uses and metered points

Many errors were identified during the development of the electrical schematic, including incorrect labeling, incomplete disaggregation of the end uses, and areas where meters were not measuring the intended parameter. This document served a critical role and provided a necessary visual quick reference; it should be considered essential for any EIS metering project.

The second stage of commissioning was to confirm that the meters were physically connected to and measuring the loads shown in the single line diagram and panel schedules. This step was performed in conjunction with facility electricians to confirm that no meters had been connected to the wrong circuits; all wiring was found to be correct.

A final stage was verifying that the meters were reporting accurate data to the dashboard. Each metered point was measured directly with a calibrated electrical analyzer and compared to the value presented by that meter at the dashboard. At this stage points were either classified as accurate, plausible, or inaccurate; this would be of aid in future investigation and troubleshooting. A point could be deemed inaccurate for many reasons:

- faulty meter
- no network connection
- problems encountered during data delivery from the network to the dashboard
- inaccurate calculation extracting the true power value from a raw sensor value

6. CONCLUSION

Though they have benefits such as lower installation costs and reduced disruption to occupants, wireless sensing networks are not without their challenges. Installation and maintenance often requires knowledgeable IT personnel who can establish the network connections and troubleshoot when necessary. The wireless technology also creates a need for regular maintenance as connections may become unstable. Any battery powered mote will necessitate battery changes periodically, however, if the system is operating as designed this should be on the order of years rather than months. Occurrences such as power outages which affect the gateway or server added another source of network problems if they could not automatically recover.

Regardless of the ability to communicate between floors it was determined that the best configuration would be to have multiple gateways for each wireless network in the building. This increased the signal strength of the network, which improved reliability, stability and battery life. Because of the mesh topology a single gateway could be used by adding nodes in stairwells or outdoors to act as relays between floors but this method created a reliance on particular nodes which could result in a collapse if critical relay nodes fall offline. This method could also create longer pathways which require more transmissions to reach the edge router, reducing reliability and battery life.

The EIS needs to be a reliable and accurate tool. As more connections are added along the path from sensing to dashboard more sources for error are introduced. Each component and connection must be highly reliable and accurate. In Building 90 errors were incurred at many points along the chain, requiring skilled troubleshooting and often IT assistance. To confirm the accuracy of the EIS an end-to-end verification must be performed to identify inconsistencies.

To improve the installation and integration process there should be a level of interoperability with standard EIS components. Currently, however, each system has proprietary network and software components which require case-specific integration with other systems. Interoperability would move EISs closer to an ideal, plug-and-play type integration, where they can gain widespread use in commercial and residential buildings.

7. ACKNOWLEDGMENTS

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8. DISCLAIMER

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