IMPERIAL COLLEGE LONDON

Framework for Phantom Load Management

Feasibility Report

Members: Hsuan Te Phua, Salman Arif, Benjamin Hou, Jie Yu Jane Ng, Zhen Yi Ng, Suvichak Thongborisoot, Hao Ling Yap

Table of Contents

Abstract

In a time of electronics, the losses due to its inherent phantom load have grown in significance. Phantom load is defined as the power consumed by a device when it is not in active use but still plugged into the mains. While the power consumed from a single unit may be small, it has become typical for an average household to possess several devices that are idle for any given period of time. This results in unnecessary costs for both the household and the utility provider. Hundreds of pounds can be saved each year if the owner of the devices does one thing: turn the power off.

This may sound like a simple step but it is hardly taken by many homeowners. The number of devices in one's home make it extremely inconvenient to turn them all off when not in use. As such many solutions have appeared on the commercial market, ranging from remote controls that switch off outlets from a distance, to monitors that report the attached device's power usage. There have been several plausible solutions but few if any of these provide a holistic approach to tackling phantom load. Some devices provide short-range remote controls that allow the user to turn off the outlets, while others can be programmed to turn off outlets at a desired interval. However, these devices have failed to take off for a variety of reasons, ranging from high costs to complex setups.

Microwatt aims to integrate all the advantages of the current solutions while maintaining a cost-effective edge. The product will provide users a robust method to control and manage their electronic devices without costly setups. It will allow the homeowner to toggle the outlets through any internet enable devices, like a smartphone or from a laptop. When the device detects that it has gone into an idle state, it will send the user a notification and provide him with options to manage the said device. Microwatt also enables the owner to set macros that can be programmed to turn several devices on and off at the same time to allow optimum usability. All of this is achieved while less than a thousandth of the power consumed by an average device in the idle state.

The potential for Microwatt is immense, from the cost savings to the reduction in carbon emissions, and can extend beyond the household to offices and industries. Plans are underway with the Housing Development Board in Singapore to implement the devices into the nation's public housing, which constitute 80% of the population. Microwatt will give users a cost-saving medium that will benefit both the homeowners and utility providers.

This report aims to present the research that the team has procured on the feasibility of addressing phantom load. It also details the proposed device and the considerations taken in the design phase. Finally it provides an overview of the proposed solution versus the problem posed by phantom load.

1. Problem Outline

Phantom load is the power drawn by electrical appliances when they are in the idle state. It is due to peripheral characteristics such as a built-in clock, remote control or quick-start features. With the increasing pervasiveness of electrical appliances, Phantom Load can be accounted for up to 10% of monthly household power consumption. There are many commercial devices available to address the situation, yet this phenomena still persists. In this report the term Phantom Load will be used interchangeably with Standby Power.

2. Analyzing Phantom Load

In this analysis, the housing demographics will be investigated to determine the volume of electrical appliances in public housing. Based on these numbers, the cost of phantom load and its carbon emissions can be evaluated. Finally an examination of the current commercial solutions will be done to determine the basis for a new approach.

2.1. Housing Demographics

This section contains the demographics of people living in public housing and the percentage of households that possess electrical appliances. Singapore and Hong Kong were identified in our research as energy-dependent nations which can benefit from increased energy efficiency. As the data in Table 1 shows, a large proportion of the population live in public housing and possess at least one or more electrical appliances that consume significant standby power.

Country	Singapore	Hong Kong
Percentage of population living in public housing	82%	46.2%
Average domestic household size	-	3
Percentage of population that has at least one:		
Computer	84.0%	77.9%
Television	99.5%	-
Washing machine	94.7%	-
Air conditioner	74.7%	-

Table 1: Public Housing figures and household ownership of electronics and devices in Singapore and Hong Kong[12]

The data gives a foundation for the project to be based on, showing that there is a substantial number of households that possess electronic devices. The problem is apparent and provides a suitable market for the team to sell the device to. The initial markets would be densely populated countries such as Singapore and Hong Kong. As the product develops it can be implemented in other countries as well.

The reason behind the team's investigation into public housing statistics is to better collaborate with government bodies to implement the Microwatt device through policy-making. An initial correspondence with the Building Research Institute of the Housing Development Board, in charge of public housing in Singapore, has been established and the team is developing a timeline to prototype the device in test-bed housing. The exchange is detailed in Appendix B.

2.2. Power wastage

Phantom load adds to the electricity usage and therefore increases the household monthly utilities bill. This will lead to an increase in carbon emissions as more electricity is needed to supply the demand caused by phantom load. These consequences will be examined below.

Data was obtained from a study on standby power collected the standby power and standby time for common household appliances in an average household[3]. Below is a bar chart of the monthly standby power consumption for each appliance.

The average monthly and yearly standby power consumption in a household is then calculated. The total yearly standby power consumption calculated was about 340 kWh which adds about £33 to the yearly utilities bill. According to the Department of Energy Climate and Change, on average, the yearly UK household electricity bill is £453 in 2010[4]. This means that standby power accounts for about 7.3% of the average household utility bill.

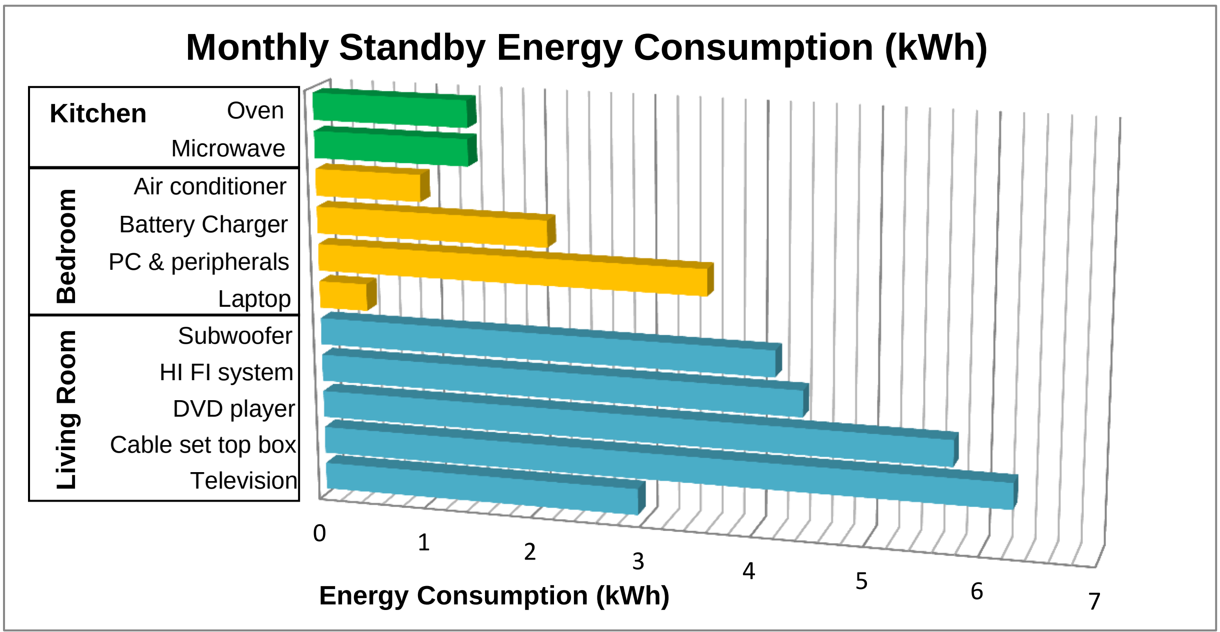


Figure 1: Bar Chart of the monthly standby energy consumption for each appliance

The data was obtained from the IEEE research paper and illustrated using a bar graph to better compare the phantom loads of various electronic devices. Three main sources of phantom load were identified in the household, where multiple devices can be grouped together and plugged into the wall adapter. This aims to reduce the number of devices the user will need to use in order to manage the phantom load. It can be observed that the living room produces the most phantom load from the television unit which can be turned completely off when not in use. The bedroom is the next source which is multiplied by the number of bedrooms in the household, which can be between 1 to 4 depending on the size of the family.

2.3. Carbon Emissions

According to the International Energy Agency, the amount of carbon dioxide emitted per kWh varies with countries[5]. It is multiplied with the yearly standby power consumption estimated in the previous section to obtain the total CO_2 emission due to standby power for each household. This value is then compared with the estimated carbon emissions in a household per year[67]. The percentage of CO_2 emissions due to standby power per household is as shown.

Country	Estimated yearly standby power consumption (kWh)	CO_2 released per kWh (kg/kWh)	Total CO_2 emission by standby power (kg)	Estimated CO_2 emissions in a house per year (kg)	Percentage of CO_2 emissions by standby power (%)
Singapore	340.308	0.523	177.98	3300.91	**5.39%**
Hong Kong		0.765	260.33	3491.46	**7.46%**

Table 2: Yearly Carbon Emissions by standby power per household

From these calculations, it is evident that standby power contributes a significant level of energy wastage and carbon dioxide emission. If we could find a way to effectively tackle this problem, we could both reduce the individual household's utility bill and help households be more environmental friendly. This also fits into the goals and promises of many countries to reduce their carbon emissions.

2.4. Current Solutions

There are various ways of solving phantom load. The cheapest and easiest way of reducing power wastage is to manually turn the main power off when appliances are not in use. However, switches are often out of reach and many people do not see the need to turn them off. Therefore, there are a variety of products on the market that aid users in toggling switches and monitoring their power usage. The following solutions are:

2.4.1 Smart Power Strips

Power strips have additional features that cut the power to selected devices, such as:

- Powering peripherals off automatically when the main device (e.g. a computer) is turned off.
- Heat detectors in the Isolé IDP-3050 turn the power off when a room is unoccupied for a specified length of time.
- Wireless remote controls which can be mounted on walls (such as for the Belkin Conserve Switch[8]).
- Timers which automatically turn the power off at the end of the day.

Limitations: Using a smart strip instead of the devices' own power switches might damage some devices which have a controlled shutdown sequence. It might also result in data loss, such as when computers shut down without the users intending them to.
Typical cost: Isolé IDP-3050 – £60

2.4.2 Energy Efficient Appliances

Another way to reduce phantom power loss is to change all old (about 10 to 15 years) appliances to energy efficient products, such as Energy Star products, which has a limit of 1 watt standby power requirement. This applies mainly to heavy duty appliances such as washing machines, refrigerators, boilers, etc.
Limitations: This requires a high capital cost, as users could be unwilling to spend a huge amount on replacing their appliances.
Typical cost: Dependent on appliance

2.4.3 Remote Controlled Sockets

These allow users to switch sockets off with a remote control, with a range of up to 20m. These sockets provide users with a convenient method to turn off their appliances thereby reducing standby power

Limitations: Although this is a cheap and straightforward solution, the user is still required to take continual active approach in reducing their power consumption.

Typical cost: Energenie Remote Control Sockets (Pack of 4) – £18

2.4.4 Energy Monitoring Devices[9]

Devices like these display the power consumption and cost per hour in real-time for individual appliances, so that consumers can keep track of their household usage habits. These devices typically consist of a adaptor which monitors and relays information to a wireless monitor for display.

Limitations: These devices only provide the user with information on their power consumption but it is not a direct approach to minimising standby power.

Typical cost: Belkin Corporation Conserve Insight Energy Saving Cost MO – £20

2.4.5 Intelligent Home Systems

Home systems such as the E.ON SmartPlus[10] and INSTEON Hub allow the user to monitor energy usage, change thermostat settings and schedule devices' on timings using a PC or a mobile application.

Limitations: The Intelligent Home Systems solution is either expensive or requires the user to subscribe to a long term service. This might upset the money saving aim. Although it gives a wider overview of the users' energy saving habit and aims to automate households, it is a higher end approach which does not target reducing phantom load.

Typical cost: INSTEON Hub – £100

3. The Solution

3.1. System Design Objectives

The aim of the design as a whole is to provide a framework for measuring the power consumption of electronic devices, and to transmit collected data wirelessly. Additionally, the product must allow power points to be switched off remotely. Note that the solution consists primarily of 2 modules: an "end-device" and a "router" that collates data and allows control commands to be executed.

1. **Measurement:** The end-device must be capable of measuring voltage and current values, as drawn by the connected peripheral.
2. **Calculation:** The device must be able to do calculation with the collected data to measure power.
3. **Duplex Communication:** A wireless module must be present on the device to establish a communication link with a router for data exchange to transmit data and receive commands.
4. **Power Efficiency:** As a whole, the system must consume less power than it did initially.
5. **Power Supply:** The power supply for the end-device must be capable of producing multiple distinct voltage levels as the operating conditions for major components within the device vary.
6. **Control:** The end-device must be able to act as a circuit breaker upon command from the router.

7. **Router:** The router will act as the processing unit. It must fulfil the following functions:
    a. *Data Consolidation:* The router must be capable of receiving statistical information collected from multiple devices and presenting them in a user friendly interface.
    b. *Connectivity:* The router must be accessible via Ethernet for remote control.
    c. *Management:* The router must allow the user to have precise control of each end-device terminal. This includes (but is not limited to) switching capabilities & scheduling.
8. **Intelligence:** The router may have an adaptive algorithm to automatically control the end-devices based on the consumer's usage habits for unattended optimization.

3.2. Modular Overview of Entire System

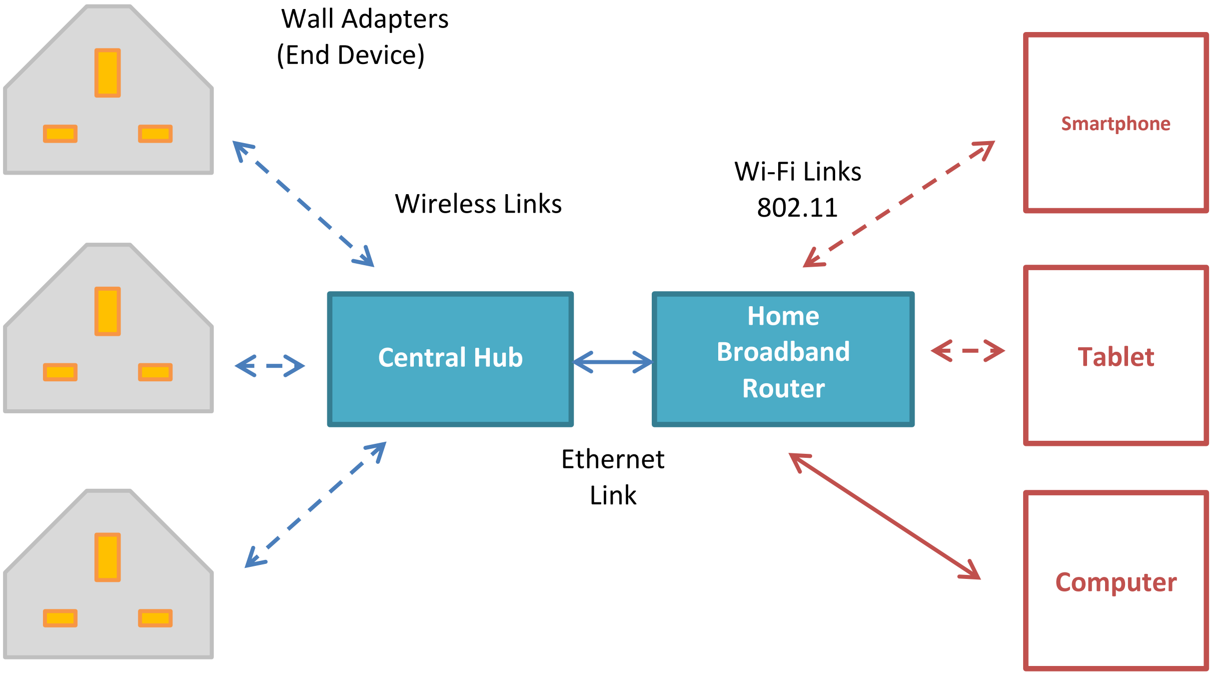


Figure 2: Macro-model of proposed solution

Based on these specifications detailed in the objectives section, the system comprises two main modules:

1. A central router to interface the wall adapters with the user's home network and control each adapter using different control profiles.
2. Separate wall adapters which are able to measure voltage, current and calculate the power consumption; and are able to transmit this data in real-time.

The communication between the wall adapters and the central hub will be using a wireless transceiver. The central hub will have an Ethernet link to connect it directly to the user's home network. The user will then be able to access and control the system via any of their peripherals. Note that the communication protocol on the user's network is independent of our system. Figure 1 Appendix A gives a detailed overview of the modular plan.

The microcontroller reads the values from the voltage and current sensor – these are both simplex data communication lines. Based on these reading and commands from the central hub, another simplex line can be used to send control instructions to the relay. Note that the microcontroller interfaces with the wireless module in a half-duplex mode – at any given instant, communication can only occur in one direction, even though it is a bidirectional communication link.

3.3. Design Configuration Options

Exploration of various methods to design the end-device was performed. As is the nature of product design and development of a product, we came across multiple options for each section of the design. This part of the feasibility study explores all options, comparing them objectively with our predefined requirements. Appendix A details each option mentioned below in detail (including circuit schematics).

Power Supply Configurations (see Objective Number 4)
As per the requirements listed before, we need to be able to power 3 main components. These are necessary for the design of an efficient working power meter, and are listed below:

1. A microcontroller – Requires 5V (normal configuration) or 3.3V (underclocked) V_{CC}
2. Wireless transceiver – Requires V_{CC}

Single / dual-rail operational amplifier – Can be configured to require both +ve or –ve supplies (dual-rail operation), or just one voltage supply level (single rail operation)

3.4. Wireless Standard Options

The table below compares the features of all these standards in order to assist with determining the most suitable choice for our purposes.

Feature	Zigbee	Wi-Fi	Bluetooth
Range	10-100 meters	50-100 meters	10 meters
Networking Topology	▪ Ad-hoc, peer-to-peer; Star, mesh	Client to access point	Ad-hoc, very small networks
Operating Frequency	▪ 868MHz (Europe) ▪ 900-928MHz (North America) 2.4GHz (Worldwide)	▪ 2.4GHz 5GHz	2.4GHz
Device Complexity	Low	High	High
Battery Life (days)	100-1000	0.5 – 5	1 -7

Table 3: Comparison of communication options

From the previous table, it is clear that Zigbee is the choice of wireless for the system. Zigbee typically consumes 75mA at 3.3V (1mW RF power) and 150mA at 3.3V (100mW RF power) for only when the radio is broadcasting and receiving, this translates to about 250mW to 500mW power consumption. When the Zigbee is asleep, the power consumption is reduced significantly as nothing runs except its internal clock.

Wi-Fi is not ideal because it has the most power consumption, and for a device trying to reduce power consumption, it is an adverse property. The selling point for Wi-Fi is its speed but for our system just sending a few bytes, the extra speed is unnecessary. Even though Bluetooth has low power consumption, it does not come close to the low power consumption of Zigbee. With a range of only 10metres, this range is not enough to span across a house. One advantageous aspect of using Zigbee is its unique mesh networking capability. It can greatly expand the range of the network by allowing devices to communicate in an ad-hoc manner.

The 2.4GHz band spans from 2400 MHz to 2483.5 MHz for all 3 protocols above. The frequency spectrum for the Zigbee protocol is largely separate from that of Wi-Fi, so the two protocols have channels which allow them to coexist without overlapping.

3.5. Higher Functions: Artificial Intelligence

Self-Calibration Algorithm

It is important for effective operation of the wall socket that it be able to detect a device entering standby mode. This will be done by checking if the power consumption has fallen below a certain threshold value. The wall socket will monitor the power usage continuously over a period of 24 hours, and the minimum value (greater than zero) will be saved to the socket as the standby power threshold. See Flowchart 1 Appendix A for details.

Software Functions A: Data Processing

In addition to control features, the router must also allow the user to perform the following tasks:

- View data collected graphically by means of a Graphical User Interface.
- Get a report of daily power consumption, with amount of standby power saved.
- See a virtual “map” presenting a per-socket overview of the entire network.
- Allow naming of sockets for easy identification for scheduling and management.

These features are higher level functions and will be programmed via JavaScript, PHP or HTML5.

Software Functions B: Intelligent Algorithms

To implement an automatic toggling feature, the router will allow the user to schedule on/off times. For example, the following schedule could be implemented:

Day	*Time / Description*	*Action*
Monday – Thursday	09.00 – Leave for work	Turn off all sockets
	17.45 – Arrive from work	Turn on all sockets
Friday – Sunday	00.00 – Sleep	Turn off all sockets
	10.00 – Wake up	Turn on all sockets

To ensure that the user is not inconvenienced, several countermeasures will be programmed into the router to prevent unnecessary toggling of switches. These include the following:

- A 5-minute “on interval” (see Flowchart 2 Appendix A) during which all (selected) switches will be turned on and the user may connect any of their devices. This will be activated by the press of a button (hardware or software).
- A 10-minute “tolerance period” during which the user is given some flexibility for their schedule management. This will activate whenever a “turn off” event is triggered.
- A 20-minute “time-out” after which all sockets will turn off if no devices have been plugged in. This will activate whenever a “turn on” event is triggered.

4. Summary

Each user is projected to use 3 wall adapters and 1 router device. The costs incurred by the user will be a one-off payment and will be recuperated in terms of savings from phantom load. Based on the research it will take the user 2 years to earn back his costs, thereafter which he will benefit from the device.

Item	**Cost**
Estimated Cost of Router	£5
Estimated Cost of Adapter x 3	£15 x 3 = £45
Technician Wage per Installation	£10
Miscellaneous	£10
Total Cost per Household	**£70**

Table 4: Breakdown of costs

Table 4 shows the team's estimations on the per-household expenditure for the system. The cost of each component was referenced from online electronics suppliers and factored with economies of scale to provide an en-mass price to the consumer. The miscellaneous item is included to provide buffer for any unforeseen costs. In total the user is expected to pay £70 from start to finish for the system.

Based on the power wastage study in the report, every year an average household loses £33 every year due to phantom load. The team estimates that the system will be able to capture at least 90% of the power losses, allowing the average user to save £30 per year.

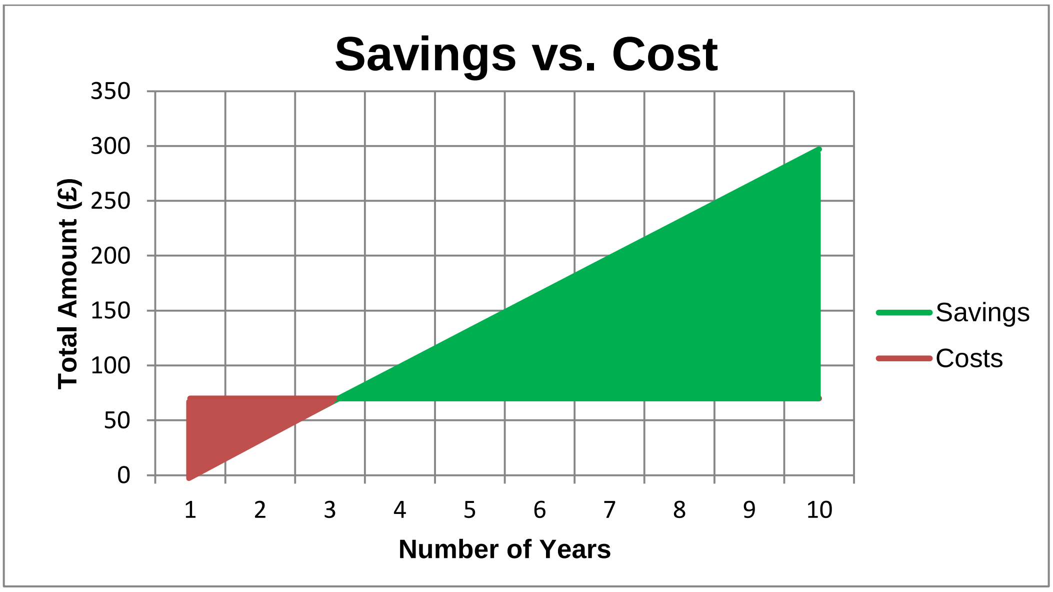


Figure 3: Savings vs. Cost of using Microwatt

Figure 3 shows that the savings from using the device outweigh the initial cost of installation over time. After 2 years a single household will proceed to benefit from the savings from phantom load. This is beneficial to the user in both terms of the monetary costs and the carbon footprint as well. The study is conclusive that targeting phantom load is a feasible project.

5. References

1. Information Services Department, Hong Kong Special Administrative Region Government, 2012. *Hong Kong: The Facts - Housing.*

2. Census and Statistics Department, Hong Kong Special Administrative Region, People's Republic of China, 2012. *Hong Kong as an Information Society (2012 Edition)*.

3. A. Prudenzi, A. Silvestri, R. Lamedica, M. C. Falvo, U. Grasselli, M. Regoli, 2011. *Standby Power End Users and Their Demand Management Impact on Household's Load Shape.* Digital Object Identifier (DOI): 10.1109/PES.2011.6039526.

4. Department of Energy and Climate Change, 2012. *Quarterly Energy Prices - March 2012.* ISSN: 1755-9103 (Online); 1475-6544 (Print).

5. International Energy Agency, 2012. *CO2 Emissions from Fuel Combustion - Highlights*.

6. H. Jensen, Troels Fjordbak. *AutoPowerOff plug banks - a Story with Energy Saving Perspectives.* ECEEE 2009 Summer Study, La Colle sur Loup, France, 1-6 June 2009.

7. L. Harrington, Hans-Paul Siderius, S. Novem, M. Ellis. *Standby Power: Building a Coherent International Policy Framework*. Proc. of ACEEE Summer Study 2008, California, 2008.

8. World Energy Council, n.d. *Hong Kong - Energy Efficiency/CO2 Indicators.* [Online] Available at: http://www.worldenergy.org/documents/hkg.pdf [Accessed 10 December 2012].

9. Ministry of the Environment and Water Resources, Singapore, n.d. *Singapore's National Climate Change Strategy - Mitigation of Greenhouse Gas Emissions.*

10. Belkin International,Inc, 2013. *Power - Belkin.* [Online] Available at: http://www.belkin.com/conservenow/ [Accessed 10 January 2013].

11. It Must Be Green, 2012. *Home Energy Monitoring & Energy Saving.* [Online] Available at: http://www.itmustbegreen.co.uk/acatalog/energy_meters.html [Accessed 10 December 2012].

12. Newton, T., 2012. *EON Smart Plus Monitor: Control your heating from your phone.* [Online] Available at: http://recombu.com/digital/news/eon-smart-plus-monitor-control-heating_M10638.html [Accessed 10 December 2012].

Appendix A: Product Design

The aim of the design as a whole is to provide a framework for measuring the power consumption of electronic devices (particularly in standby mode), and to transmit collected data wirelessly. Additionally, the product must allow power points to be switched off remotely. Note that the solution consists primarily of 2 modules: an “end-device” (which acts as a wall socket) and a “router” that collates data and allows control commands to be executed.

The following objectives outline the requirements for a proposed design for the complete system:

General Objectives

1. **Measurement:** The end-device must be capable of measuring voltage and current values, as drawn by the connected peripheral.
2. **Calculation:** In addition, the device may have the ability to perform calculations based on the aforementioned measurements. Specifically, it should be able to compute power consumed.
3. **Duplex Communication:** A wireless module must be present on the device to establish a communication link with a router for data exchange. This is necessary in order to enable the device to send gathered information and receive commands.
4. **Power Efficiency:** As a whole, the system must have power consumption lower than that due to phantom load. This is critical to the effectiveness of the solution.
5. **Power Supply:** The power supply for the end-device must be capable of producing multiple distinct voltage levels. This is necessary as the operating conditions for major components within the device vary.
6. **Control:** The end-device should be able to act as a circuit breaker. Upon receiving a relevant command from the router, it should be able to turn on/off the connected plug(s).
7. **Router:** As is essential to any monitoring & control system, the router will act as the processing unit. It must fulfil the following functions:
    a. *Data Consolidation:* The router must be capable of receiving statistical information collected from multiple devices. It may also have the capability to present this information in a user-friendly format.
    b. *Connectivity:* The router must be accessible via the user’s home network via Ethernet. This will allow the user to remotely control each end-device’s behaviour.
    c. *Management:* The router must allow the user to have precise control of each end-device terminal. This includes (but is not limited to) switching capabilities & scheduling.
8. **(Optional) Intelligence:** The router may have an adaptive algorithm to automatically control the end-devices based on the consumer’s usage habits. This will allow (to an extent) unattended optimisation of phantom load management.

Pertaining to the above criteria, the following details the technical requirements of the design:

Specific Objectives:

1. **Measurement:**
   This requires a microcontroller to be part of the device.
   a. *Current Sensing:* There are 4 possible techniques that can be used to ascertain the current. Each of these incorporates one of following components:
      - Current Transformer – Like an ordinary voltage transformer, except that the primary coil is connected in series with the live (mains) wire.
      - Current Transducer – A ferrite ring, through which the live wire is threaded. There is no (direct) physical contact with the wire.
      - Hall Probe / Integrated Circuit – Functions akin to the current transformer, except that is housed inside an IC package for simplified application.
      - Shunt Resistor – A small-value resistor connected in series with the live wire. The voltage drop across it is proportional to the current to be measured (which is obtained by application of Ohm's Law).

   b. *Voltage Measurement:* The voltage can be measured by using 2 different methods.
      a. Transformer – Using an ordinary transformer, the voltage can be stepped down to a safe level, and can then be fed into the microcontroller. Although this method is isolated (the microcontroller is not connected directly into mains), it may suffer from hysteresis (due to the core of the transformer).
      b. Passive Network – A simple voltage divider can be used step down the voltage, however it requires a direct connection between the microcontroller and the mains. Although this method eliminates any hysteresis, it may suffer from AC noise if it is not properly calibrated.

2. **Calculation:**
   Using the detected voltage and current, the power consumption can be computed using any one of 2 methods.
   a. *Microcontroller* – an algorithm can be written on the microcontroller to calculate the power before wireless transmission.
   b. *Energy IC chip* – an IC designed specifically to calculate power consumption in real time. The individual variables are stored on the chip's memory, and can then be accessed by a microcontroller. This is an algorithm in hardware.

3. **Duplex Communication:**
   There are 3 main wireless protocols to handle data communication between the end device and the router:
   a. *Wifi (802.11)* – common wireless protocol found in most laptop computers, generally in a point to hub topology, consumes a lot of power.
   b. *Bluetooth (802.15.1)* – common wireless protocol found in mobile devices and electronic peripherals, forms very small ad-hoc networks, low power consumption.

c. *Zigbee (802.15.4)* – less common protocol, can form a multitude of network topologies, very low power consumption.

4. **Power Efficiency**
The combined power consumption of all modules on the end device must not exceed 25% of the minimum possible standby power. In order to achieve this degree of efficiency, we may connect multiple wall sockets to one microcontroller and wireless module. Under the One Watt Initiative, we should aim to limit this to about 125mW. Having a shared wireless module is important as it would consume the most amount of power in our system (roughly 60mW).

5. **Power Supply**
A power supply must be designed to accommodate the various voltage requirements by different components in the end-device

Components	*Optimal Operating Condition*	*Other Operating Conditions*
Microcontroller	*+5V*	*+3.3V*
Wireless Module	*+3.3V ONLY*	---
Operational Amplifier	*+/-5V*	*0+V (single rail design)*

6. **Control**
A circuit breaker / relay module can be used to sever the connection of the live wire. This will permanently cut off any phantom current. It is important to have complete and total isolation from the mains supply; otherwise the system will be ineffective.

7. **Router**
The router itself will have a wireless module so it will be able to listen for incoming data on the home network. We will be using the default full mesh network topology. This allows enhanced communication of modules on the same Personal Area Network, by enabling transmissions to be re-routed via the modules themselves. By employing this feature, we can increase the coverage of the system's network.
To empower the user to control every aspect of the end-device, the router must not only be capable of relaying data, but also provide the user with a friendly interface. This interface should have controls to turn on or off the relays in each wall socket, as well as a feature to enable scheduled switching times. As a unique function, the router will also have artificial intelligence (see next objective).

8. **(Optional) Intelligence**

Modular Overview of an Individual Wall Adapter

In Figure 1, the wall adapters' internal design was not specified. Figure 2 below describes the functionality and layout of these end-devices.

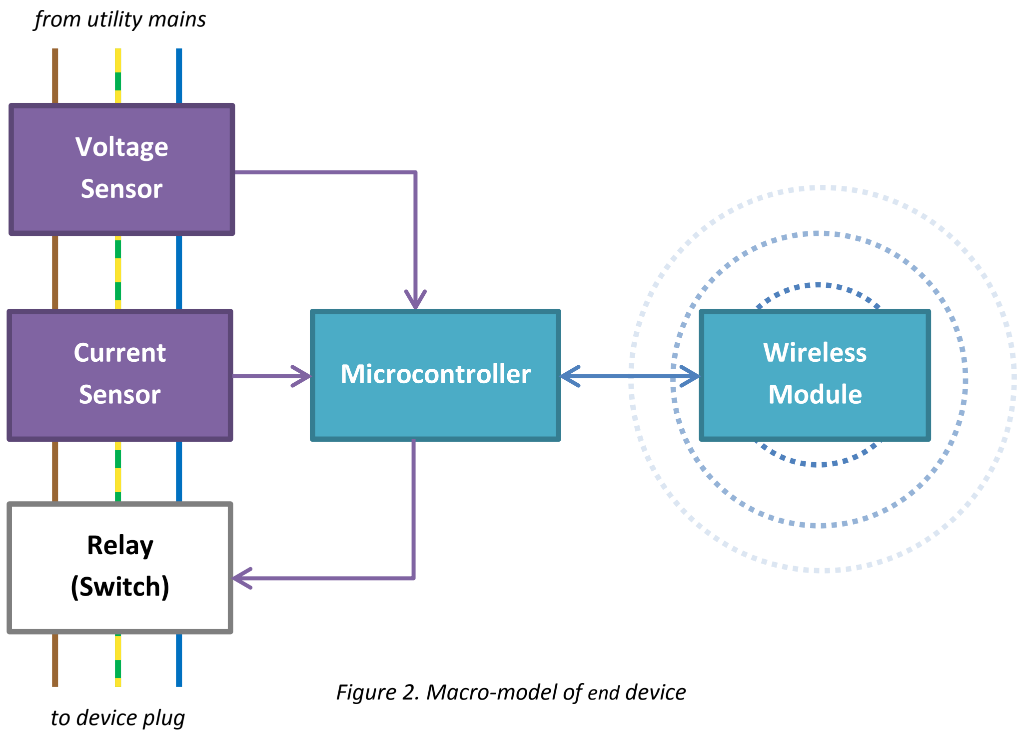


Figure 2. Macro-model of end device

The microcontroller reads the values from the voltage and current sensor – these are both simplex data communication lines. Based on these reading and commands from the central hub, another simplex line can be used to send control instructions to the relay. Note that the microcontroller interfaces with the wireless module in a half-duplex mode – at any given instant, communication can only occur in one direction, even though it is a bidirectional communication link.

Possible Modular Designs – Common

Exploration of various methods to design the end-device was performed. As is the nature of product design and development of a product, we came across multiple options for each section of the design. This part of the feasibility study explores all options, comparing them objectively with our predefined requirements. Based on this analytical study, we will be able to select modular designs to implement as part of the final proposed solution.

Power Supply Configurations *(see Objective Number 4)*

As per the requirements listed before, we need to be able to power 3 main components. These are necessary for the design of an efficient working power meter, and are listed below:

1. A microcontroller (detailed in upcoming sections)
2. Wireless transceiver
3. Single / dual-rail operational amplifier

Since the aforementioned parts require different voltage supply levels to operate, our power supply design must be capable of generating several distinct voltage levels. The schematics for each of these designs have been inserted below (see Figures 1 through 4).

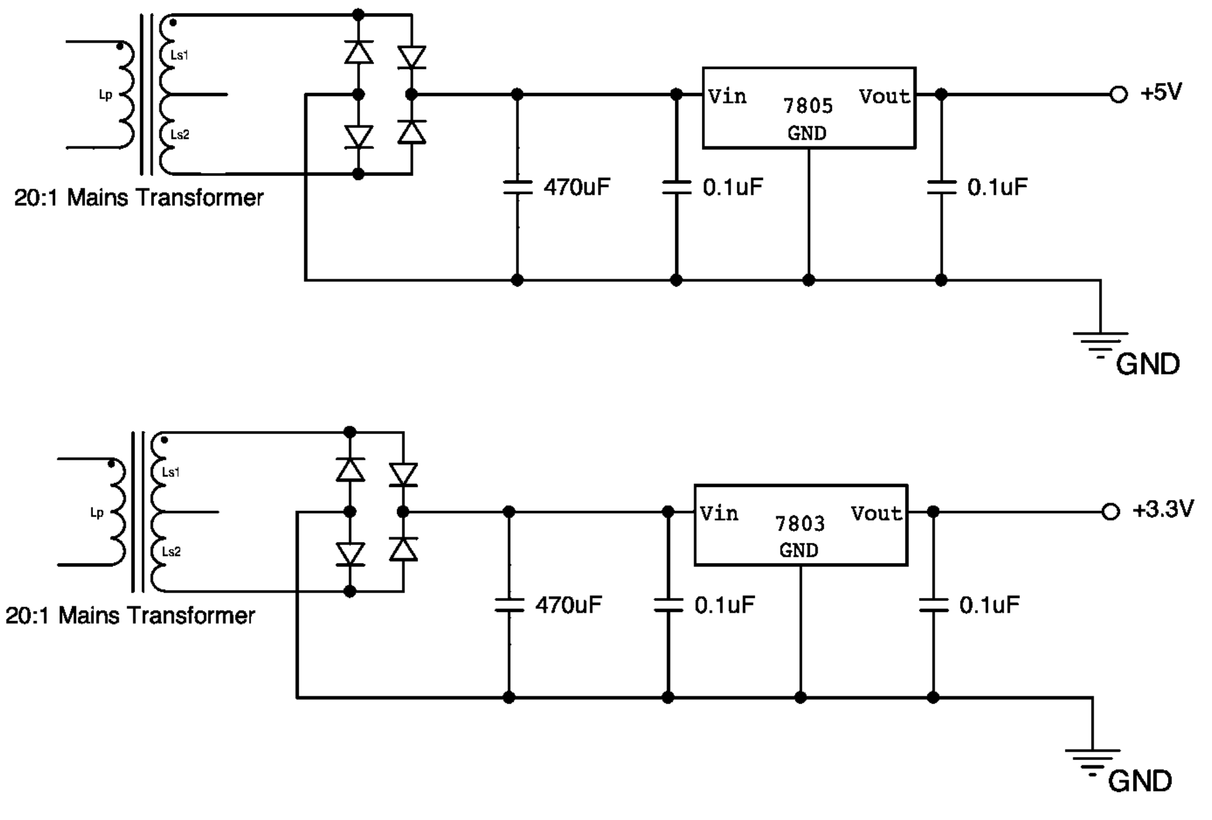


Figure 1 – Design A1 (Top) and Design A2 (bottom)

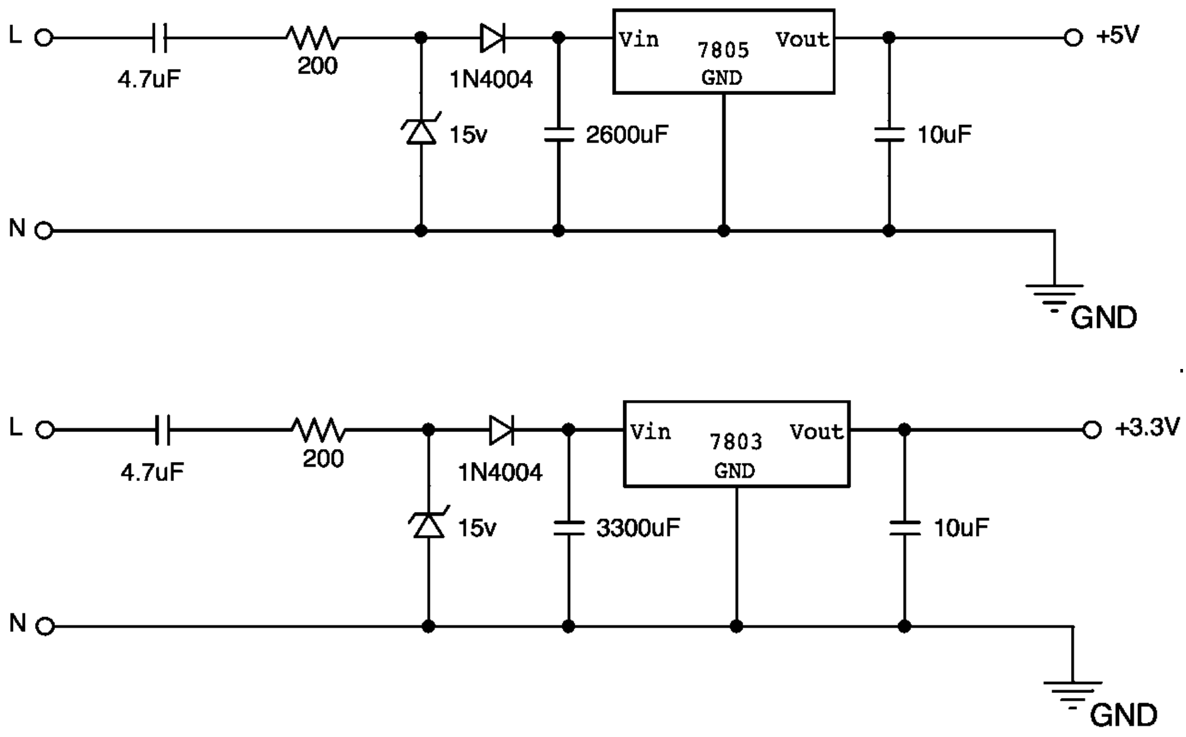


Figure 2 – Design B1 (Top) and Design B2 (Bottom)

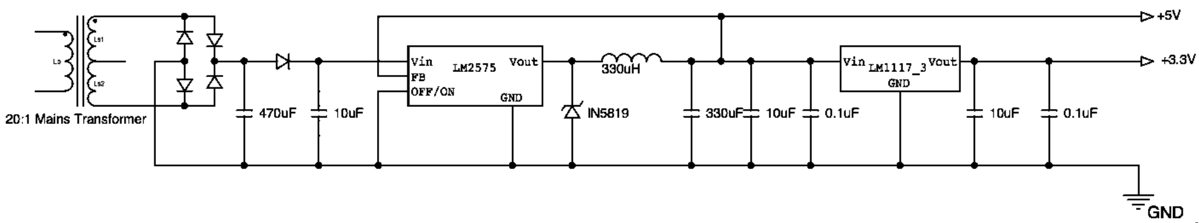


Figure 3 – Design C

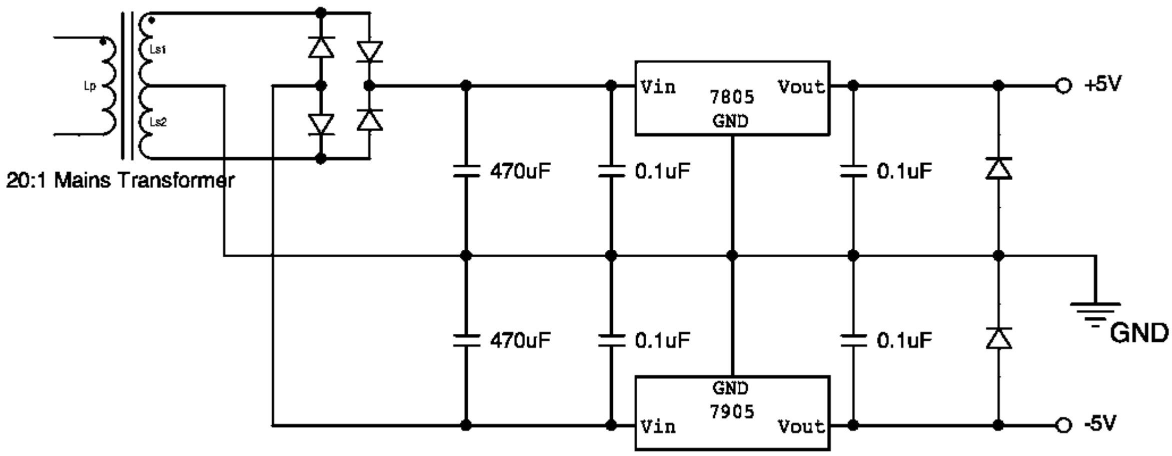


Figure 4 – Design D

Design A (Figure 1) and Design B (Figure 2) can have 2 configurations each – they can either be set up to generate a +3.3V supply rail or a +5V supply rail. For the sake of clarity, the following table lists out supply rail configuration options for each design:

Design Number	*Voltage Rail Output Levels*
A1, B1	+5V configuration
A2, B2	+3.3V configuration
C	Fixed +5V and +3.3V dual configuration
D	Fixed +5V and –5V configuration

The following table compares all designs based on efficiency, ease of implementation and component support to help determine the ideal configuration to use for the final solution:

Design Number	*Supported Components*				*Power Loss Factors*	*Step-down Method (in order of flow)*
	MCU	*Wireless*	*Op-Amp Rails Single*	*Op-Amp Rails Dual*		
A1	□		□		▪ Eddy and magnetising currents in transformer core ▪ Reactive losses in capacitors ▪ Hysteresis due to iron core transformer	Transformer; Full bridge rectifier; Switching regulator
A2	□	□	□			
B1	□		□		▪ Small resistive losses ▪ Small reactive losses ▪ AC interferences	Zener diode; Switching regulator
B2	□	□	□			
C	□	□	□		▪ Eddy and magnetising currents in transformer core ▪ Reactive losses in capacitors ▪ Hysteresis due to iron core transformer	Transformer; Full bridge rectifier; Switching regulator; Zener diode; Inductor; Linear regulator
D	□			□	▪ Eddy and magnetising currents in transformer core ▪ Reactive losses in capacitors ▪ Hysteresis due to iron core transformer	Transformer; Full bridge rectifier; Switching regulators

Since it has already been established that all 3 components must be supported, options A1, B1 and D can be eliminated. Option A2 uses a transformer to isolate the power supply from the mains – while this is a good precautionary measure, it will have unpredictable power losses due to the iron core as losses will vary from core to core. Option C also suffers from the same transformer issue.

Therefore, as option B2 supports all components and does not use a transformer, it is most suited to our requirements and is the one we will be incorporating into our final design. Unlike iron core losses, the AC interferences (due to a direct connection to mains) can be easily countered by means of a decoupling capacitor – this is because mains voltage is fixed and varies very little from house to house.

Wireless Standard Options

The IEEE 802 is a family of IEEE standard local and wide area networks, although 802 being the next available number in the nomenclature, it is also sometimes associated to the date of the standard being found (February 1980). The IEEE 802 family spans from 800.1 to 802.25, these include a variety of different networking protocols such as Ethernet, Fibre Optic, GSM, etc. For this project, we will only be considering the 3 most suitable options: 802.11 – Wi-Fi, 802.15.1 – Bluetooth and 802.15.4 – Zigbee.

Wi-Fi (802.11) – 2.4GHz and 5GHz

Wi-Fi is the most common wireless protocol used in computers and mobile phones in this day and age. It gives them the capability to connect to local area networks (LANs) without wires. With the price per module continuing to drop, using Wi-Fi can reduce the costs of network deployment and expansion, as is a more economical solution.

Wi-Fi comes in 4 different speeds, separated into a/b/g/n bands. A typical wireless router using 802.11b or 802.11g with a stock antenna typically has a range around 32m indoor and 95m outdoors. Due to reach requirements for wireless LAN applications, power consumption is fairly high compared to some other standards.

Bluetooth (802.15.1) – 2.4GHz

Bluetooth is another common wireless protocol found in electronic gadgets and peripherals on the consumer market. As it is based on low-cost and low-power transceiver microchips, it has a short range of 1m, 10m and 100m depending on the power-class of the module. It provides a quick and low power means to connect and exchange information between many devices such as mobile phones, telephones, laptops, personal computers, printers, GPS receivers, digital cameras, video game consoles, etc. Bluetooth makes it possible for these devices to communicate with each other when they are in range.

Zigbee (802.15.4) – 868MHz (EU), 900-928MHz (NA), 2.4GHz worldwide

Zigbee is a low cost and low power module, which is not commonly found on the consumer market. The protocol is intended for use in embedded applications, which requires low data rates and low power consumption. Hence, it is mostly found in industrial control and sensing networks.

Zigbee can go from sleep to active mode in 15milliseconds or less, therefore the latency can be very low and devices can be very responsive. Comparing to Bluetooth, Bluetooth has wakeup delays of around 3 seconds, resulting in very long latency times. Because Zigbee can sleep most of the time, the average power consumption can be very low, resulting in an extremely long battery life. Individual devices must have a battery life of at least two years to pass Zigbee certification.

The table overleaf compares the features of all these standards in order to assist with determining the most suitable choice for our purposes.

Feature	*Zigbee*	*Wi-Fi*	*Bluetooth*
Range	10-100 meters	50-100 meters	10 meters
Networking Topology	▪ Ad-hoc ▪ Peer to Peer ▪ Star ▪ Mesh	Client to access point	Ad-hoc, very small networks
Operating Frequency	▪ 868MHz (Europe) ▪ 900-928MHz (North America) ▪ 2.4GHz (Worldwide)	▪ 2.4GHz ▪ 5GHz	▪ 2.4GHz
Bandwidth - max (kbps)	250	300,000	720
Device Complexity	Low	High	High
Battery Life (days)	100-1000	0.5 – 5	1 -7
Security	128 AES plus application layer security	▪ WEP ▪ WPA ▪ WPA2	64 and 128 bit encryption
Typical Applications	▪ Industrial Control and monitoring ▪ Sensor networks ▪ Building automation ▪ Home control and automation ▪ Toys and Games	▪ Wireless LAN ▪ Broadband connectivity ▪ Internet	Wireless connectivity between devices such as phones, PDA, laptops, headsets

From the table above, it is clear that Zigbee is the choice of wireless for the system. Comparing with Bluetooth and Wi-Fi, it has several times the battery life. Zigbee typically consumes 75mA at 3.3V (1mW RF power) and 150mA at 3.3V (100mW RF power) for only when the radio is broadcasting and receiving, this translates to about 250mW to 500mW power consumption. When the Zigbee is asleep, the power consumption is reduced significantly as nothing runs except its internal clock

Wi-Fi is not ideal because it has the most power consumption, and for a device trying to reduce power consumption, it is an adverse property. The selling point for Wi-Fi is its speed but for our system just sending a few bytes, the extra speed is unnecessary. Even though Bluetooth has low power consumption, it does not come close to the low power consumption of Zigbee. With a range of only 10metres, this range is not enough to span across a house. One advantageous aspect of using Zigbee is its unique mesh networking capability. It can greatly expand the range of the network by allowing devices to communicate in an ad-hoc manner.

The 2.4GHz band spans from 2400 MHz to 2483.5 MHz for all 3 protocols above. The frequency spectrum for the Zigbee protocol is largely separate from that of Wi-Fi, so the two protocols have channels which allow them to coexist without overlapping.

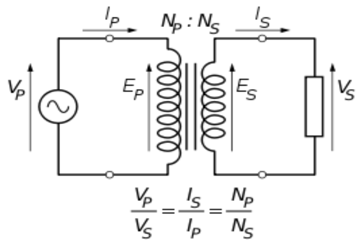
Possible Modular Designs – Wall Socket

The following methods and solutions are only specific for the wall socket end device. These are the modules that measure the current and voltage as well as the compute the current power consumption. Upon comparing all possible methods, we will the picking the most reliable and efficient method, as one of the goals is to use as the least amount of power as possible.

Current Sensing Methods

Current Transformer – circuit isolated from mains

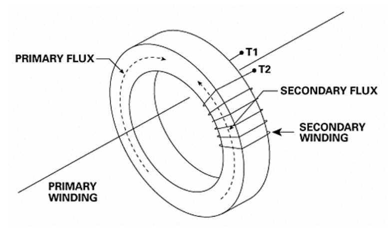
A current transformer is just like a regular transformer except the primary coil is connected in series with the live wire. The AC current flowing through the primary coil produces a magnet field in the core, which in turn induces a current in the secondary coil.



The primary objective in designing a current transformer is to ensure that the primary and secondary circuits are efficiently coupled, this will reduce any interferences so that the secondary current bears an accurate relationship to the primary current.

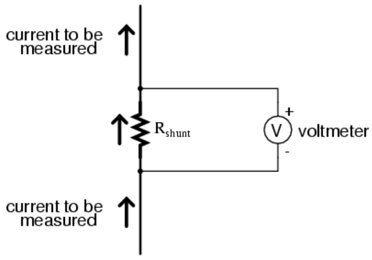
Current Transducer – circuit isolated from mains

A Current Transducer operates with the same principles as a Current Transformer. The live wire is fed through a ferrite hoop with secondary windings. Using Lenz’s Law of electromagnetic induction, the amount of current flowing through the live wire is proportional to the current flow (or potential) of the secondary windings.



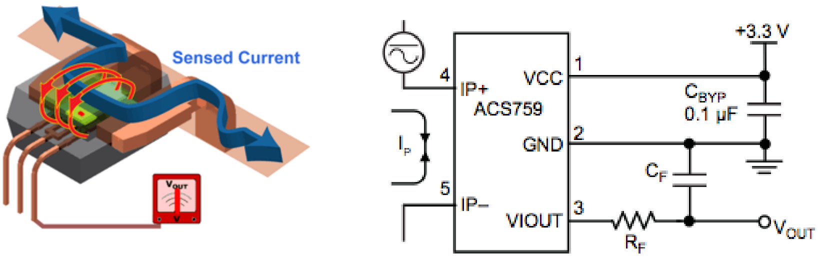
Shunt Resistor – circuit connected to mains

Using a shunt resistor is a quick and easy way to measure current without using induction, however this requires for a very low value resistor (in the range of micro ohms) to be connected directly to the mains. The potential drop across the 2 terminals is proportional to the amount of current flowing through the shunt resistor.



Hall-Probe / IC – circuit connected to mains

Using the theory behind the Hall Effect, companies such as Allegro MicroSystems have developed dedicated IC for measuring current very accurately. The amount of current flowing through across the input pins is reported accurately as a proportionality of the IC's max voltage (V_{CC}). This can be a very costly solution as the IC is fairly expensive, comparing with the cost of phantom load, using expensive component is not justified.



Current Sensor from *Allegro*® *MicroSystems, Inc.*

Voltage Sensing Methods

Unlike with current, voltage sensing is much straight forward and can be implemented using the following methods:

Transformer – circuit isolated from mains

The transformer steps down the voltage to safe level manageable that can then be sensed by a microcontroller. However there will be hysteresis in the iron core, which has to be accounted for when making precise voltage measurements.

Potential Divider – circuit connected to mains

This is the easiest method to step down voltages. Using a potential divider, the voltage can be divided between the 2 resistors. However this method does not have hysteresis, the tolerance of the components would have to be taken into account for.

Energy Measurement

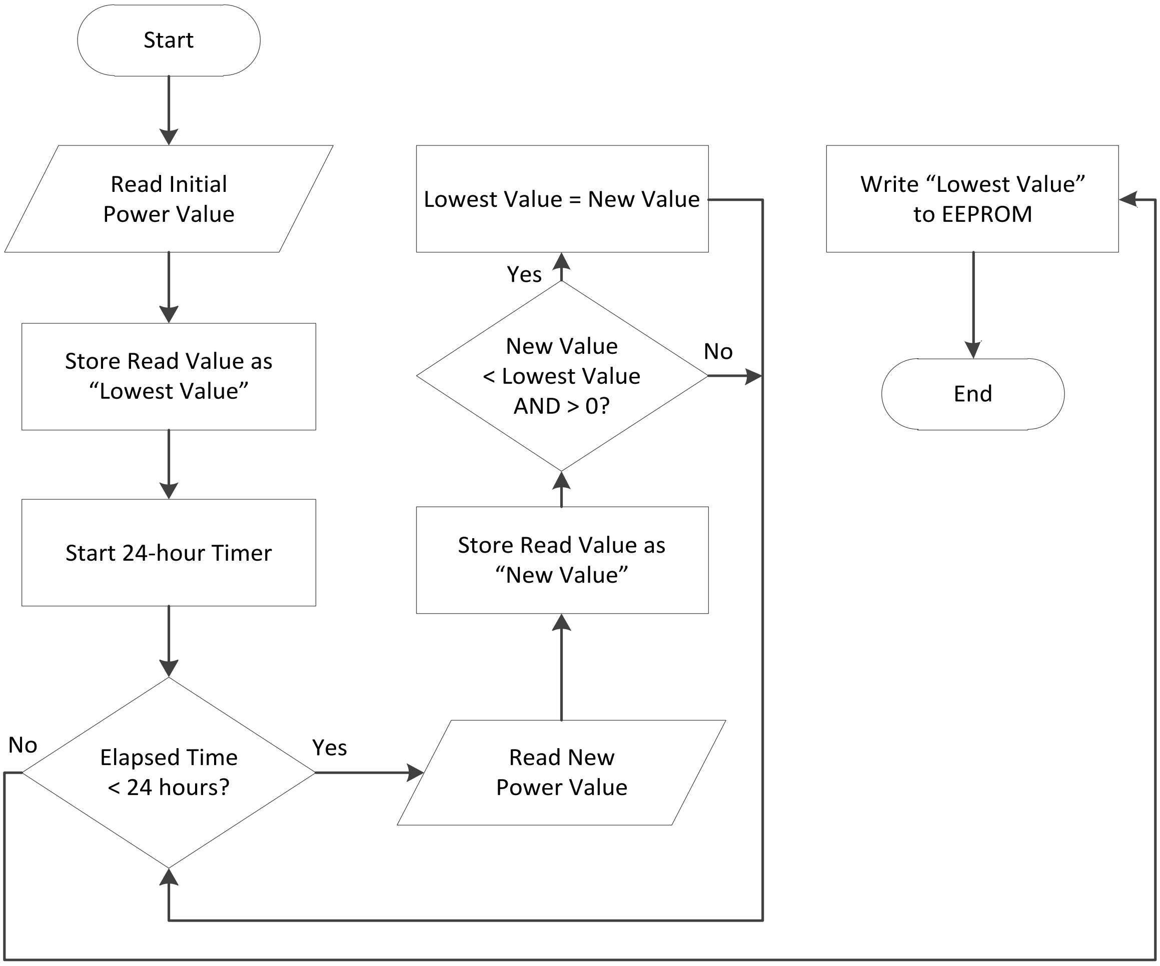
There are 3 major companies who manufacture Energy Measurement ICs to specifically perform accurate energy measurements; these companies are Cirrus Logic, Analog Devices and Microchip. The ICs have built in ADCs to measure the current and voltage of the live wire (after being safely stepped down) and are therefore able to compute the power consumed. Other quantities that the IC can measure are frequency, power factor, real and reactive power, harmonics, temperature, etc. Although these may not be required for our project, they may become useful in other applications. These ICs are essentially software in hardware form; the data gathered are stored within registers on the IC, which can then be accessed by a host microcontroller via SPI interface.

An alternative to using this IC is to code the algorithms ourselves on to the microcontroller, this save spending unnecessary budget on functionality we can implement ourselves. It's hard to prototype with these ICs as the chips are all SMD (solder directly onto PCB). The chips are sensitive to voltage spikes; therefore careful the circuit must be carefully designed with fail-safes to prevent the chip from shorting out (e.g. the cirrus logic differential voltage input is only 500mV).

Self-Calibration Algorithm

It is important for effective operation of the wall socket that it be able to detect a device entering standby mode. This will be done by checking if the power consumption has fallen below a certain threshold value. From the research phase, we determined that this threshold varies greatly from device to device. Hence, each wall socket must be capable of self-calibration to determine this minimum power value.

The following flowchart details the process of this self-calibration:



Possible Modular Designs – Router

A majority of this section deals with the software capabilities of the router, as a large part of the hardware design has already been explain in the previous “Possible Modular Designs – Common” section.

Microcontroller Selection

As per the layout in the modular overview of the system, we require the microcontroller in the router to have network capabilities in two areas:

1. Interface using a specified wireless protocol to communicate with the wall sockets;
2. Connect to a user’s home network to allow monitoring and control access from any third party device capable of web browsing.

Regardless of the particular wireless standard we choose to base our design on, the microcontroller must have serial transmit and receive pins. These will allow communication with a wireless module by making use of the Universal Asynchronous Receiver/Transmitter (UART) hardware capabilities.

To fulfil the second requirement, we must be able to interface with a home network. Ideally, we want this connection to be over Ethernet.

We have previously listed the Atmel ATMega88 (Figure 5a) microcontroller to use for performing power calculations in the wall sockets. The following objectively compares the said microcontroller unit with the much more powerful ARM Cortex M3 (see Figure 5b) processor in lieu with our requirements:

	Atmel ATMega88	*ARM Cortex M3*
UART Capability	☐	☐
Built-in Ethernet Connectivity	☐	☐
Central Processing Unit	8-bit AVR Processor	32-bit ARM Processor

As the M3 has both connectivity features, it is the clear choice for use in the router. In addition, the better communication rate is also beneficial - being a higher-level processor, the Cortex M3 will allow programs and calculations with a much greater degree of complexity to be used as part of our router’s software design. Such complexity is not necessary for the wall sockets on their own, as a result of which the 8-bit Atmel chip can be used for their simpler design.

The figures overleaf show the communication ports for each of the above microcontroller choices. The ports have been highlighted with a red outline for clarity.

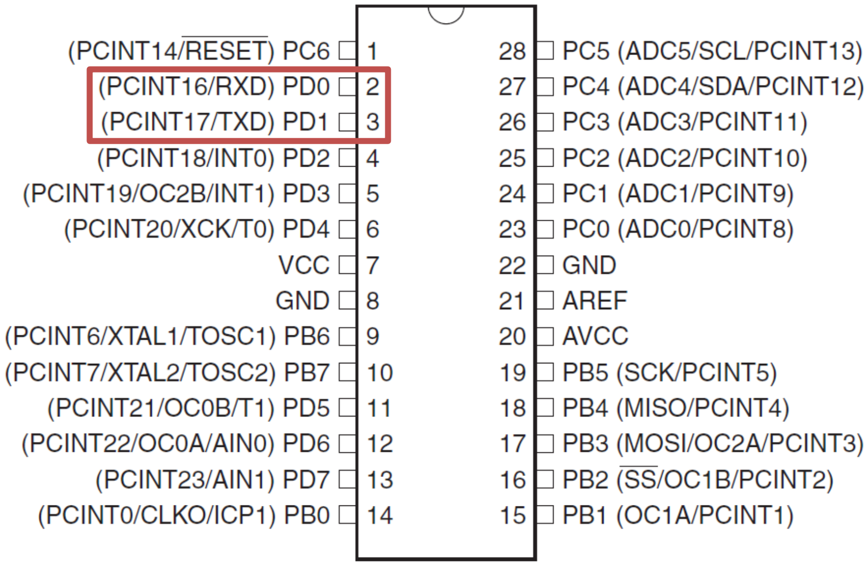


Figure 5a. Pin configuration of an ATMega88 MCU

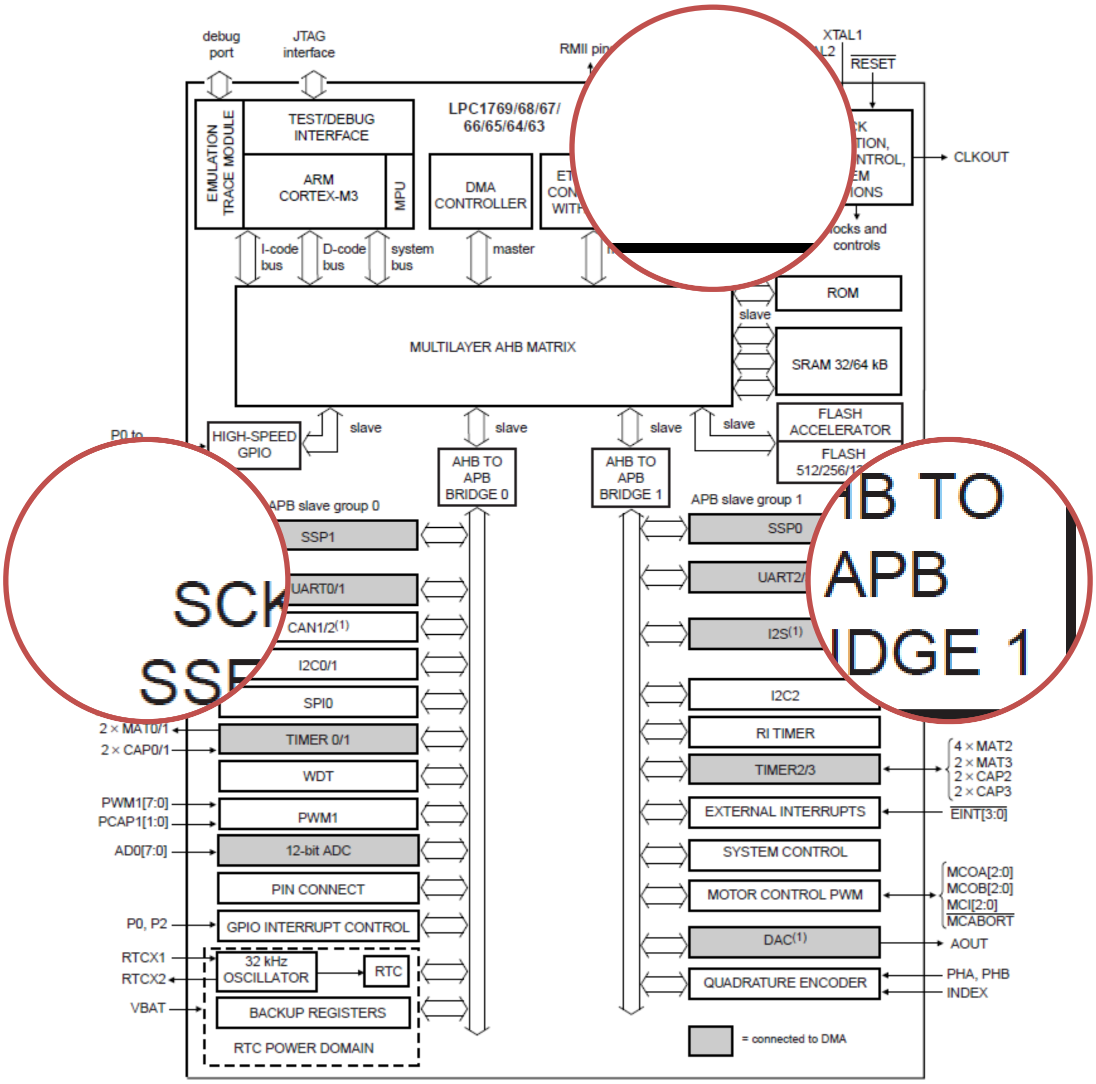


Figure 5b. Modular overview of an ARM Cortex M3 MCU

Software Functions A: Data Processing

In addition to control features, the router must also allow the user to perform the following taSsks:

- View data collected graphically by means of a Graphical User Interface.
- Get a report of daily power consumption, with amount of standby power saved.
- See a virtual “map” presenting a per-socket overview of the entire network.
- Allow naming of sockets for easy identification for scheduling and management.

These features are higher level functions and will be programmed via JavaScript, PHP or HTML5.

Software Functions B: Intelligent Algorithms

1. A 20-minute “time-out” after which all sockets will turn off if no devices have been plugged in. This will activate whenever a “turn on” event is triggered. *Figure 6. Flowchart for “5 minute on interval” Function*

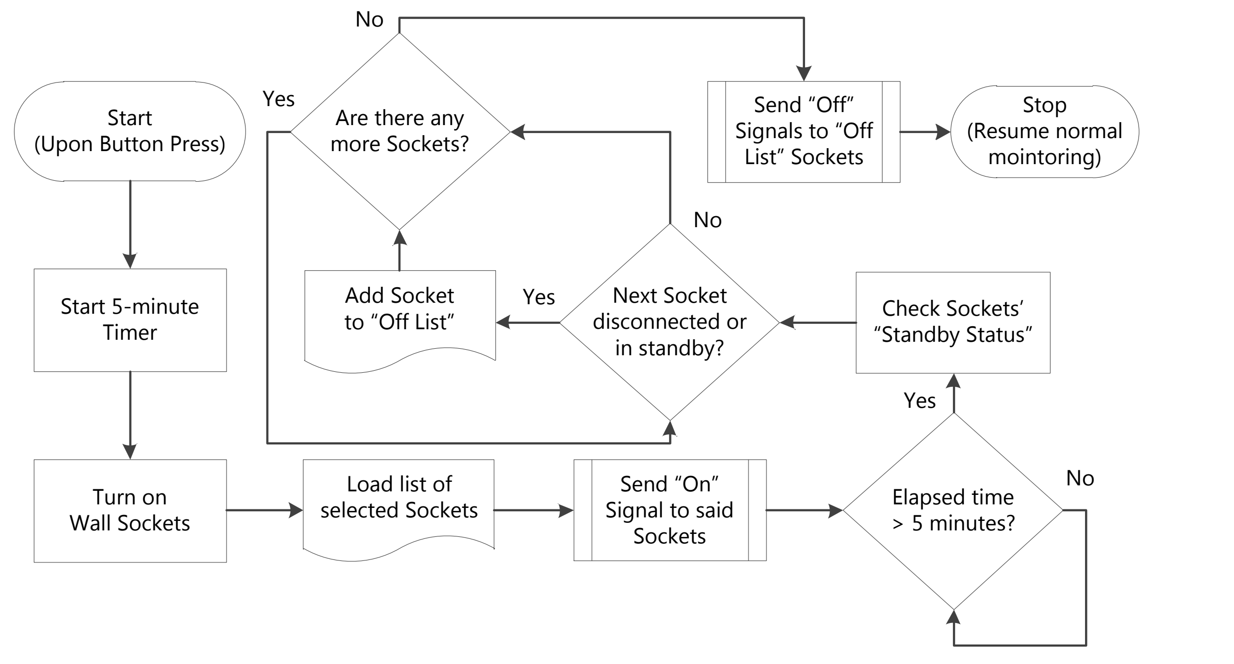


Figure 6. Flowchart for “5 minute on interval” Function

Figure 7 below details the process involved in intelligently toggling the wall sockets on / off based on the scheduled times. The algorithm has been designed to include the tolerances mentioned on the previous page. The times have been selected based on the practicality of living.

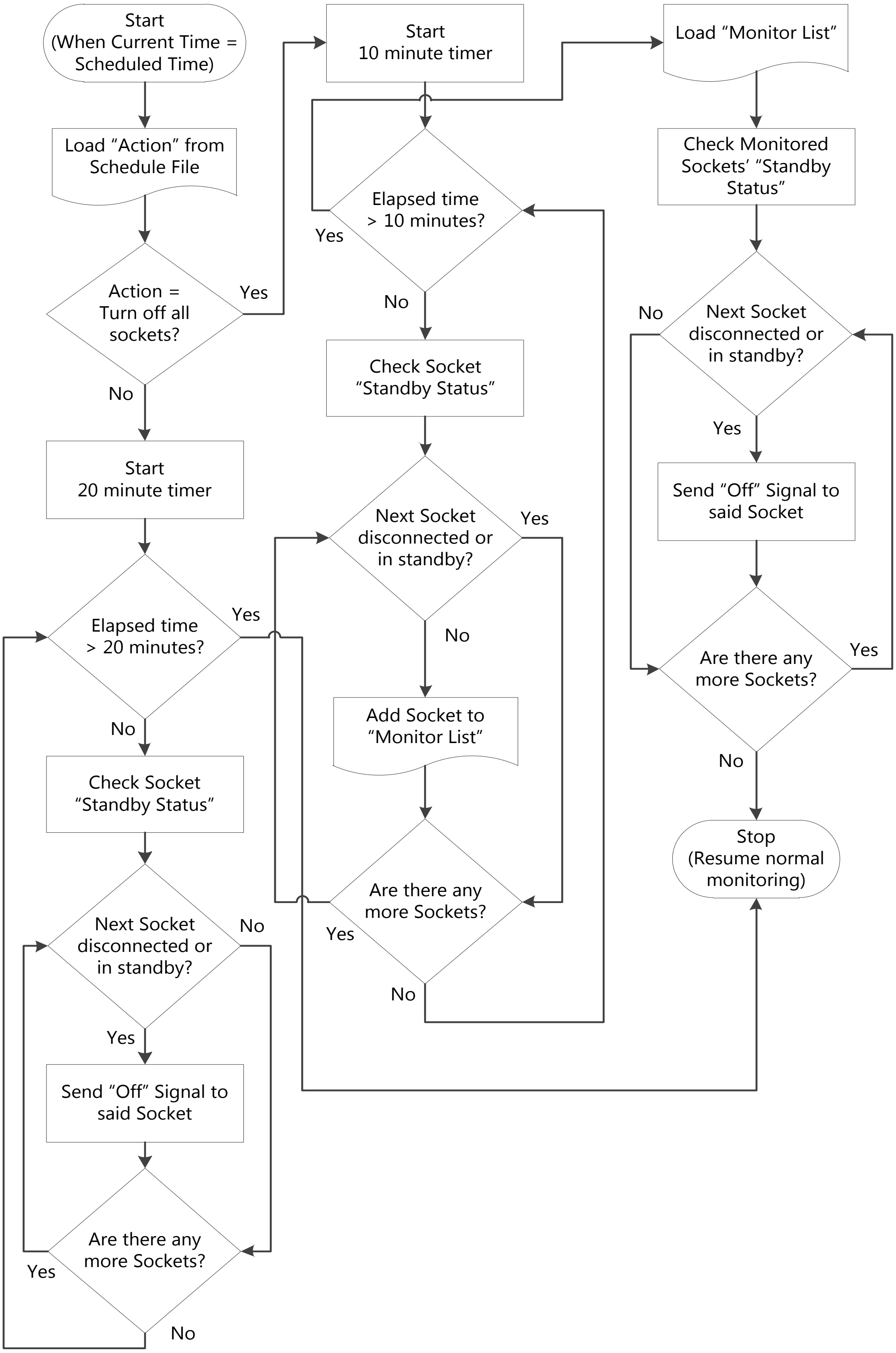


Figure 7. Schedule tolerance and timeout functions

Appendix B

From: Chek Sim TAN (HDB) [mailto:Tcs4@hdb.gov.sg]
Sent: 03 January 2013 09:00
To: Phua, Hsuan
Subject: RE: Autonomous House Systems

Hi Hsuan Te,

Thank you very much for the information. My apologies for not responding earlier as December is a month where most of us are away from office clearing our leaves. I've tasked my engineer to look into your proposal to explore any possibility of testing the system. It would be good if you can furnish us the report on Standby Power Consumption and the Product Design for us to review.

Warmest rgds & best wishes for the New Year,

Chek Sim

Tan Chek Sim . Dy Dir (Technology Research)
HDB Building Research Institute . Tel: 64902642
Housing & Development Board

From: Phua, Hsuan [mailto:hsuan.phua11@imperial.ac.uk]
Sent: Tuesday, 4 December, 2012 11:23 PM
To: Chek Sim TAN (HDB)
Subject: RE: Autonomous House Systems

Dear Mr. Tan,

Thank you for your reply. We wish to collaborate with HDB to provide a testbed to prototype the device and in the future implement this into public housing. It would be good if the team can determine the level of interest HDB has in managing home electrical systems to better gauge the feasibility of the project. I have attached an initial proposal in this email and have summarized the system below:

The aim of our project is to reduce Standby Power in homes. We want to develop a product that can be implemented seamlessly to current homes and can be easily controlled by the user. Our target audience will be pre-existing HDB flats although this technology can be implemented in all housing types. The system consists of 2 components, a wall adapter and a central hub.
The wall adapter works as an intelligent extension plug, allowing 3 other devices to be plugged into it. It will monitor the usage and determine when it has entered "idle" state and turn it if off autonomously.
The central hub works as a command and control centre, where the usage information from the wall adapters will be sent to and collated. It will store this information on a server online that the user can then login to view and manage. The level of autonomy can then be set through the website by the user to calibrate it. It can also be set to allow manual control i.e. the user will remotely command the wall adapters to turn the outlet off.

In the prototyping phase, the implementation will come in two stages**: 1) Consultation & Installation, 2) Servicing**.
In Stage 1, a technician will be despatched to the user's home to analyse the electrical appliances in the home and determine the optimum number of adapters to be installed. The installation will take place immediately and the central hub will be set-up. The entire process is estimated to take less than an hour.
In Stage 2, the system will be monitored for optimization.

We have a more extensive report on Standby Power Consumption and the Product Design. If you wish to review them I will be happy to send them to you.

Thank You
Hsuan Te

From: Chek Sim TAN (HDB) [mailto:Tcs4@hdb.gov.sg]
Sent: 04 December 2012 05:36
To: Phua, Hsuan
Subject: RE: Autonomous House Systems

Hi Hsuan Te,

Thank you for your email below. We would like to find out more on the proposal mentioned in your email and hope that you can share with us on the preliminary details. Hope to hear from you soon.

Warmest rgds,

Chek Sim

Tan Chek Sim . Dy Dir (Technology Research)
HDB Building Research Institute . Tel: 64902642
Housing & Development Board

From: Phua, Hsuan [mailto:hsuan.phua11@imperial.ac.uk]
Sent: Friday, 30 November, 2012 8:30 PM
To: Chek Sim TAN (HDB)
Subject: HDB: Autonomous House Systems

Dear Mr. Tan Chek Sim,

My name is Phua Hsuan Te, a Singaporean student currently studying Electrical Engineering in Imperial College London. I am writing to you to propose a technology that can potentially reduce household consumption by 10%.

I have formed a group of fellow electrical engineers and we are developing a system that is integrated into the household infrastructure which monitors and controls the electrical outlets in the house. It is capable of detecting when appliances have gone into the "idle" state such as televisions that are turned off remotely but still draw power from the mains, and thus turn the electrical outlet off.

This technology is targeted at Standby Power, power that is consumed by devices in the idle state and thus wasted, which can account for up to 10% of the power consumption in a house. We are also aware that the current technology on the market is capable of allowing the user to remotely turn the mains off directly, but yet it is not well implemented in houses.

We have identified this due to user inertia to purchase and use the products. We have collaborated with UCL who has done extensive research on the social aspect of this phenomena and have confirmed this. This is where our product stands out. Our technology will monitor and identify when appliances are not in use, and toggle the electrical outlets off accordingly. There will be fail-safes to allow the user to manually control the electrical outlets as well.

We are still in the stages of developing the technology, and would like to see what HDB's stand is on such a technology, as we are aware that the Building Research Institute is aiming to improve building efficiency and we are confident that our technology will be able to do so. Furthermore if HDB has any similar technologies in development perhaps we could work together in improving the energy efficiency of public housing.

Thank You
Phua Hsuan Te