

MELOS : A Low-Cost and Low-Energy Generic Sensing Attachment for Mobile Phones

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ABSTRACT

Ubiquitous availability of cellular network and cheap mobile phones have made them promising sensing platforms for various application domains including healthcare, environment, and astronomy among others. However, existing mobile phone platforms, including even smartphones, provide limited in-built sensing capabilities and lack standard interfaces to connect external sensors. In this paper, we propose MELOS (Mobile Extension for LOW-energy Sensing) a low-cost mobile phone extension that works virtually with all the mobile phones, including low-cost phones since it interfaces with the phone over standard audio port and Bluetooth.

The proposed platform augments mobile phones with additional sensing capabilities with minimal overhead in terms of energy consumption. MELOS provides capability to switch on-board modules off as per application requirements while keeping low power interface (audio) “always-on” (to keep the connection) thus resulting in significantly small active mode power consumption. Local storage capability on board ensures that the data is transferred over high bandwidth, high-power consuming Bluetooth interface in burst mode resulting in low energy consumption per byte of data transfer. Interface with a mobile phone ensures that the capabilities of the MELOS platform can be exploited remotely using the cellular connectivity. Using MELOS, we prototype a sample application to monitor energy consumption of several electrical appliances and also demonstrate appliance control using a relay based circuit.

Categories and Subject Descriptors:

B.4.2 [HARDWARE]: Input/Output and Data Communications - *Input/Output Devices*;

C.3 [COMPUTER SYSTEMS ORGANIZATION]: Special-purpose and Application-based Systems.

General Terms: Design, Experimentation, Measurement.

Keywords: Mobile phones, Sensing attachment, Low-cost, Low-energy, Audio communication, Cellular communication, Energy monitoring

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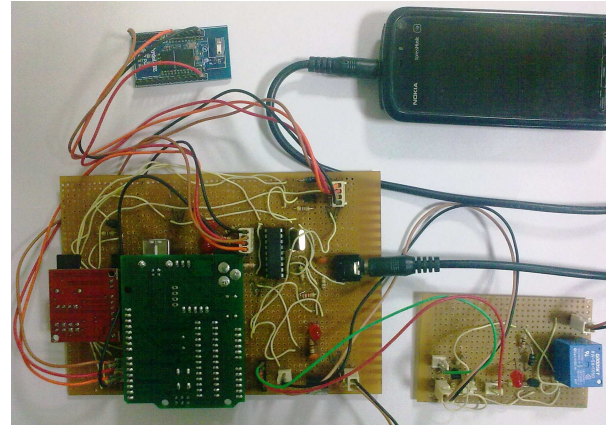


Figure 1: Prototype of MELOS platform

1. INTRODUCTION

In modern day scenario mobile phones have evolved from being just communication devices to being smart devices with several embedded sensors (such as light, location, proximity, microphone, camera, and accelerometer among others) together with high computing capabilities. The operating system of these smartphones provide a good programming environment that can easily exploit the on-board sensors for several applications across multiple domains including healthcare, environment, astronomy, and transportation among others. A survey discussing the mobile phone sensing applications, scale and paradigms, challenges and issues, is presented in [7]. Systems such as VTrack [13], Mobile Millennium [1], CenceMe [9], PEIR [10], UbiFit [4] are built by utilizing the various sensors present on smartphones. However, phones used in all of these systems are expensive and hence have limited penetration amongst the common public in developing regions. Low-cost mobile phones with standard features such as audio interface, SD card and Bluetooth dominate the market in these regions.

Phones at the lower end of the price spectrum do not possess similar capabilities as smartphones. The number and variety of embedded sensors is vastly reduced and they also lack a robust programming environment to develop applications that utilize in-built sensing capabilities. Moreover, interfacing any external sensors, as per application requirements, to mobile phones is also difficult[11] as most phones do not use standard communication interfaces such as UART, I2C, and SPI. Some phones use proprietary protocols by their respective vendors thus making it challenging to design a standard platform that can interface across broad

category of low cost mobile phones. Such constraints necessitates a low-cost sensing extension for the mobile phone that can help bridge this gap and provide even low-cost phones with sensing capabilities that can enable their use in broad range of applications. The extension should be programmable, contains standard interface for sensors, and a communication channel to connect to majority of phones especially low-cost phones. Moreover, it is essential that the system consumes low power to enable longer deployment periods for sensing. As an example, [12] presents a system that offloads the continuous sampling and processing operations to a low-power sensing attachment to reduce energy consumption.

In this paper, we present a low-energy and low-cost generic sensing attachment called MELOS that attaches to a mobile phone through its audio port and is capable of attaching any external sensor, local storage, and controlled high bandwidth communication for data transfer. Fig. 1 displays a photograph of the prototype of MELOS platform. The ubiquity of the audio port in mobile phones makes MELOS compatible with a large range of mobile phones. MELOS can connect up to 6 external sensors as per application requirements. MELOS also allows fine-grained switching control of on-board communication and storage devices thus reducing the total energy consumption. The total cost of MELOS platform for a single node from off-the-shelf components is approximately 65 USD. Simply with scale and using the necessary ICs in place of off-the-shelf breakout boards, the cost can reduce by a significant factor.

MELOS takes control information in the form of DTMF (Dual Tone Multiple Frequency) tones from locally connected mobile phone. The control information can be provided remotely using audio call over cellular network (allowing use of non-programmable local phone), and, optionally, using SMS if the local phone is programmable. At the heart of MELOS node is an AVR microcontroller. The microcontroller takes input in the form of DTMF tones to process the commands mapped to the corresponding tones. We demonstrate commands for switching on-board modules (Bluetooth communication and memory interface) for low power operation, switching external appliances using on-board relay, and switching the on-board ADC to start sensing the necessary parameters. We prototype a sample application to monitor energy consumption of external electrical appliances and also demonstrate appliance control using a relay based circuit incorporated in MELOS.

In summary, the key contribution of our work is a generic mobile phone extension platform that connects to any mobile phone over standard audio and Bluetooth interface. We minimize power consumption of the platform by providing fine-grained switching of various system components. We further extended the capabilities of the platform to switch external appliances and allow for remote command input over both SMS and voice call over cellular network.

The rest of the paper is organized as follows. Section 2 presents a review of the similar hardware systems. In Section 3, we present an architecture of MELOS platform, followed by discussing its various components and different modes of operation together with illustration of energy consumption in each node. A case study of MELOS for energy monitoring system is explained in Section 4 followed by conclusions in Section 5.

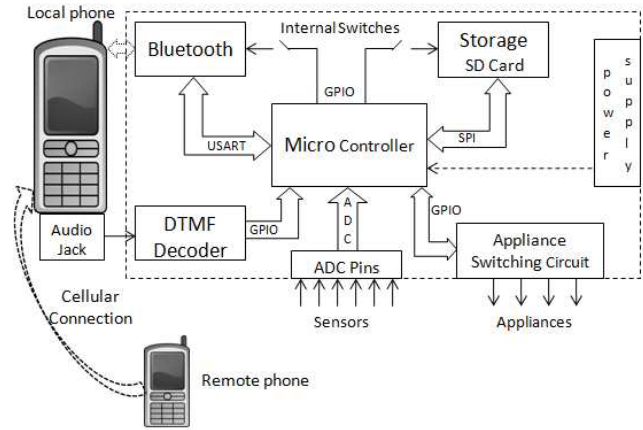


Figure 2: Architectural diagram of MELOS node

2. RELATED WORK

Low power consumption for long lifetime has been a key requirement in many sensing applications. Several approaches have been used in the past to reduce the overall system power consumption including switching the modules off as per application requirements. As an example, LEAP [8] allows low energy operation while supporting for high computing operations using a two tier approach for both computing and communication. A low energy computing (and communication) module is used in “always-on” state. A high-energy module is turned on when required to reduce the overall energy consumption per computation (or per byte transferred). We use a low power microcontroller in our MELOS platform. For communication, we use the low-energy audio interface in “always-on” state while turning high-bandwidth, high-energy Bluetooth interface as per requirements. We also control switching on-board memory module as per requirements to further reduce the overall system power consumption.

Several platforms have also been proposed in the past [11, 5, 2, 3, 6] extending capabilities of mobile phones for sensing applications. However, most of them are designed for higher end mobile phones. [11] realizes a phone-centric body sensor network which requires a mobile phone’s SD/MMC card slot for external interface. However, there is no focus on reducing the overall power consumption of the platform. Similarly, a mobile extension for air pollution monitoring, proposed in [5] also relies on high end GPS enabled mobile phones for operation.

Similar phone extensions that extend the sensing capabilities of mobile phones include FoneAstra [3] and HiJack [6]. FoneAstra extends the functionality of non-programmable low cost phones by using their serial interface for communication. Since FoneAstra implements a subset of Nokia’s proprietary serial protocol called FBUS, its use is limited to only a small range of supportable lower-end phones. Moreover, the data port on these mobile phones, called as pop port, is not used in recent low end mobile phones, even from Nokia. Since MELOS interfaces with a mobile phone over standard audio port and Bluetooth interface, it is generic enough to work with a wide variety of mobile phones.

HiJack uses the audio interface to provide power and setup a bidirectional data communication link with external sensing attachment. However, it is designed specifically based on the iPhone’s audio interface characteristics and it is not

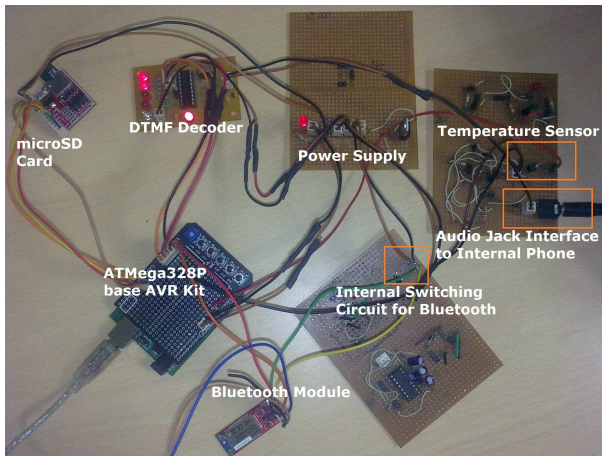


Figure 3: Different modules of MELOS node

clear if it can be easily extended to be generally applicable on all phones, including low cost phones. Further, although the the data communication has lower power requirements than our MELOS node, it requires encoding and decoding of audio signals, it necessitates a special software running on mobile phone thus limiting its use to smaller range of higher-end programmable phones.

MELOS provides a generic low-power system for sensing that can be attached to a mobile phone over standard audio interface. We provide fine-grained control of on-board modules and selection of different power modes to facilitate low-power sensing. The uniqueness of our proposed system lies in merging the ubiquity of mobile phones with low-power consumption thus enabling a large number of potential applications (energy monitoring, healthcare, among others) over a long deployment period.

3. SYSTEM DESIGN AND EVALUATION

Hardware design typically entails a trade-off between overall system cost (and other parameters such as power consumption) and time to develop a prototype platform. For our MELOS prototype platform, we are currently using off-the-shelf hardware attachments for several modules involved in the design (such as Bluetooth communication and external memory interface) that helped us reduce the time to develop a working platform. However, using external hardware attachments also results in increased power consumption for the overall system due to additional ICs incorporated on each of these attachments. Even with such an approach of using multiple off-the-shelf hardware attachments, the overall system cost as well as system power consumption of MELOS node is small. We believe that a customized hardware design with required components laid out on a single board will further reduce the overall cost as well as the power consumption by a significant factor from the current values. Next, we explain the architecture of MELOS in detail followed by different modes of operation and evaluation of the system for overall power consumption.

3.1 Architecture

Fig. 2 displays the architectural diagram of MELOS node. We chose to interface locally to a mobile phone rather a standard GSM/GPRS module (although a standard GSM module would have enhanced the interface options) since a cheap, second-hand mobile phone can be used to interface directly

with MELOS without requiring the user to purchase a new, specific GSM module. The platform interfaces with a local mobile phone over the audio interface using a standard 3.5 mm audio jack. Communication with a local mobile phone over the audio port works as a one way communication from the phone to the platform wherein different commands can be send from the phone to the node using DTMF tones. The advantage of using the audio port for interface are three folds - 1. It is a standard interface across phones from all manufacturers and across all price range; 2. Even a non-programmable phone (with auto-answer capability) can be used as an interfacing device to receive the commands from a remote mobile phone over the cellular network; 3. Audio interface consume insignificant power when in standby mode thus ensuring low power “always on” interface between the phone and the MELOS node.

A connection can be setup between remote and local mobile phone using audio call (obviating the need for a programmable local phone) to pass on multiple commands over ubiquitous cellular network. With inexpensive call rates available in developing regions, such a connection ensures low cost command passing interface remotely to a MELOS node. DTMF tones which are received on local mobile phone are directly passed over audio cable to MELOS node. Optionally, SMS-based connection can also be used, if the local phone is programmable (limited for Java enabled mobile phones as of now). In this case, a push registry based J2ME application will be invoked automatically on the local mobile phone whenever a new SMS arrives. The application will parse the SMS and plays the corresponding DTMF tone which will be passed over audio cable to MELOS node. A DTMF decoder is used on the MELOS node to decode the commands. We use Zarlink Semiconductor’s MT8870D¹ IC for decoding DTMF tones because of its low-power consumption and TTL output corresponding to binary value of each key press. The IC also provides an option of a power down pin that can be used to further reduce the power consumption of the node by inhibiting the operation of the DTMF decoder chip, if desired.

At the heart of MELOS is Atmel’s ATmega328P² microcontroller, that can be used for any customized programming requirements. There are multiple advantages of using ATmega328P microcontroller: 1. It provides several low power modes of operation with low standby power of less than 1 μ A and active power consumption of 0.2 mA; 2. It is readily and cheaply available; 3. It supports self programming mode and can be easily programmed using C; 4. Six on-chip Analog to Digital Converters (ADCs) that can be used for sensing multiple parameters; 5. In-built USART for serial communication with on board peripherals (Bluetooth module and external memory interface); 6. Enough on-chip memory (1KB EEPROM, 32KB Flash) for storing program and sensed values; and 7. Sufficient speed(16MHz) for all processing. All the aforesaid features made ATmega328P as the most suited choice for MELOS compared to other mid-range controllers such as PIC, MSP430. The microcontroller takes input from DTMF decoder to process the commands mapped to the corresponding DTMF tones. These commands include switching on-board modules (Bluetooth communication, memory interface) for low power operation, switching external ap-

¹www.zarlink.com/zarlink/hs/82_MT8870D.htm

²www.atmel.com/dyn/products/product_card.asp?part_id=4198

Mode (Power)	Controller Kit (100mW)	Bluetooth (230mW)	SD card (300mW)	DTMF Decoder (15mW)	Miscellaneous power (mW)	Total Rated power(mW)	Measured power(mW)
Standby	On	Off	Off	On	100	115	235
Data Logging	On	Off	On	On	165	415	500
Data Transfer	On	On	On	On	165	645	400-700

Table 1: Total rated power and measured power for different modes of operation of MELOS. Power consumption of passive components and sensors are listed as miscellaneous power.

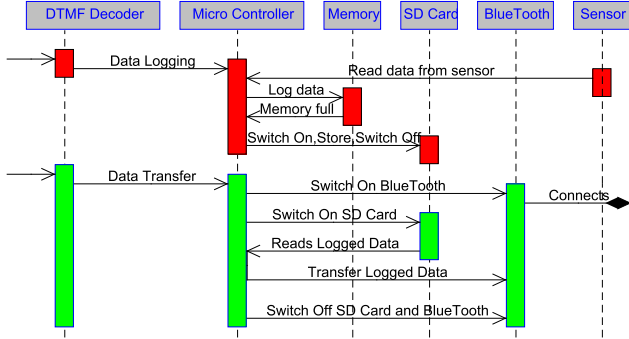


Figure 4: Transition diagram for Data Logging and Data Transfer modes of operation of MELOS.

pliances using on-board relay, and switching the on-board ADC to start sensing the necessary parameters.

The microcontroller supports six 10-bit on-chip ADC channels. DTMF tones are used to start sensing on these ADC channels. The sensed data is stored in the on-chip memory and periodically transferred to the external memory. The frequency of transfer is decided based on frequency and volume of sensed data to reduce the overall system power consumption. Since external memory consumes significant amount of power, it will be switched on only when data transfer is required and will be switched off remaining time. For example, if a temperature sensor is attached to MELOS and the data logging frequency is 1Hz, by taking the mean value of higher frequency sensing, then approximately once in every 85 minutes external memory will be switched on and readings will be transferred from internal data memory to external memory. We use a breakout board³ to interface a microSD card to our device. The card is connected to the microcontroller over SPI (Serial Peripheral Interface). With low cost high capacity microSD cards easily available, the total memory capacity of the system can be enhanced as per the application requirements. Data stored in the microSD card can be retrieved by physically detaching the SD card as well as over Bluetooth interface.

To collect the sensed data remotely, a Bluetooth module is used to communicate sensor data from the microcontroller to the local phone. Data from the local mobile phone can then be sent to a remote location over cellular network (SMS/GPRS). Bluetooth connection provides the return connectivity from the MELOS node back to the local mobile phone. We use off-the-shelf BlueLINK Bluetooth⁴ module that supports a large variety of baud rates ranging from 9600 to 115200 and has a multiple low power modes with variable sniffing time that can be easily configured us-

ing AT commands. Communication between microcontroller and Bluetooth module takes place over a serial link (UART). Since Bluetooth consumes significant power (approximately 70mA) during data transfer, we chose to store the data in the local memory instead. The stored data can then be transferred between the microcontroller and external device, as and when required, by turning on the Bluetooth module using “always-on” DTMF interface. Burst transmission over Bluetooth (at 9.6Kbits/s) results in achieving small energy consumption of approximately $208\mu\text{W}$ per byte transferred. However, a user can also chose to directly transfer the sensed data over Bluetooth without storing it intermediately in a local memory.

MELOS also supports on board relay modules to control switching of external electrical appliances. The relay switch is connected to GPIO pin of the microcontroller. A command to switch the external appliances can be issued by a remote user that is passed on over cellular network to the local mobile phone and then on to the microcontroller using the DTMF tones. For the energy monitoring application, as illustrated in Section 4, on-board relays provide capability to switch the electrical appliances as per requirements in addition to current sensing.

MELOS can be powered by an external battery or by an adapter (between 6-18V DC). A low-power (8mA) voltage regulator, LM7805⁵, is used to generate 5V from the external power supply. All peripherals and the microcontroller operate on 5V supply voltage. The break-out boards used for SD card and Bluetooth module are 5V compliant thus obviating the need of level converters. Fig. 3 displays a picture depicting different modules of MELOS node wired together. The picture is only for illustration purpose; for the prototype node, we have connected these modules on a single board as illustrated in Fig. 1. Next, we discuss different modes of operation possible with MELOS board that can be used to optimize the overall energy consumption for a given sensing application.

3.2 Modes of Operation

We divide operations of MELOS into three primitive modes - Standby, Data Logging, and Data Transfer. The Standby mode is disjoint with other two modes. The last two modes are not disjoint. In other words, MELOS could be in a mode, which is a combination of Data Logging and Data Transfer. Fig. 4 displays the state transition diagram and shows the state and operations of data logging and data transfer mode of MELOS with respect to commands from the user. Active components and corresponding total power consumption of each mode is specified in Table 1.

To evaluate the power consumption for each mode we connected a 10 Ohms resistor in series to the power supply of MELOS. Then we measured the voltage across this resistor using oscilloscope from which we calculated the current con-

³www.embeddedmarket.com/products/Micro-SD-card-Interface-Breakout-Module-for-3-3V-and-5V-Logic-Level

⁴www.rhydolabz.com/index.php?main_page=product_info&products_id=454

⁵<http://www.fairchildsemi.com/pf/LM/LM7805.html>

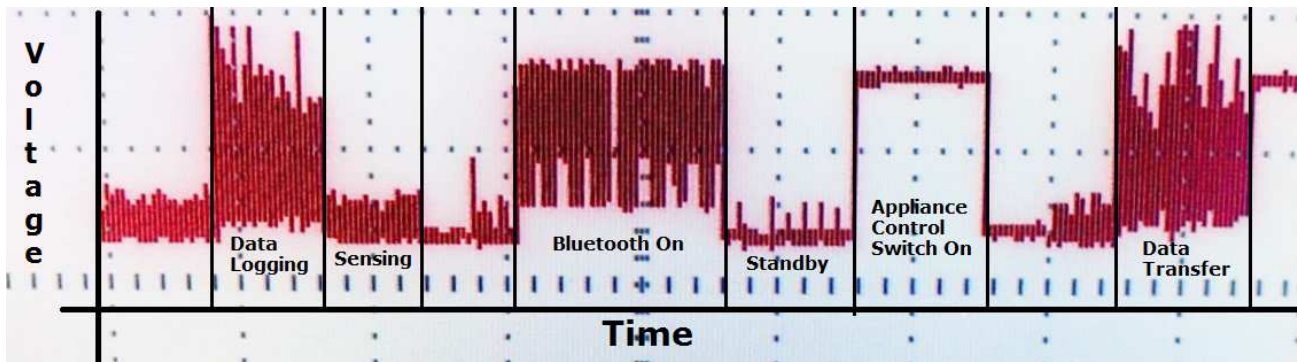


Figure 5: Voltage readings from oscilloscope for different modes of operation of MELOS.

sumption. Fig. 5 shows the plot of voltage change for each mode of MELOS. The measured power in Table 1 includes the power consumption of a few passive components we used on the board. Also, the microcontroller kit consumes 100mW because it has inbuilt FTDI chip (for USB communication) and few more passive components. All these passive components power can be reduced if we design MELOS on single board. An overview of all the three modes is discussed next.

3.2.1 Standby Mode

This is the initial and the default mode of MELOS. After powering up or resetting the node, the microcontroller initializes all sub modules connected to MELOS and goes into the Standby mode. In Standby mode, no operation is performed and the microcontroller keeps on waiting to receive control information. All modules are powered down except the DTMF decoder, from which, the control information is received. Depending upon the control information received from the DTMF decoder, MELOS goes to either Data Logging or Data Transfer mode. The total rated power consumption in standby mode is power consumption of microcontroller kit and DTMF decoder on the board, which is about 115mW. The measured power in the standby mode was 235mW that includes the power consumption of passive components.

3.2.2 Data Logging Mode

When the user sends control information to activate a particular sensor, MELOS goes into the Data Logging mode. Unique control information is used to activate or deactivate each of the ADC channels inside the microcontroller. Once a particular sensor is activated, data logging begins at a predefined frequency. By default, all sensor readings are stored temporarily in on-chip memory. Once all available on-chip memory is full, SD card module will be switched on and all data from local memory will be transferred into SD card. As a result, SD card module need not be active all the time reducing the overall energy consumption in this mode.

In the Data Logging mode, the total rated power consumption is the consumed power for microcontroller kit, DTMF decoder and SD card. Thus, the total power consumption is 115mW, when data is logged into internal memory and 415mW when writing data to SD card whereas the measured power is 500mW. The miscellaneous power includes the power consumption of passive components and active sensor. Depending upon the next control information received from user, MELOS either goes to Standby or Data Transfer mode.

3.2.3 Data Transfer Mode

MELOS goes into Data Transfer mode when user wants to transfer the logged data from the SD card to another device, which could be a mobile phone or laptop with Bluetooth support. Once it receives the unique control information for data transfer, Bluetooth module is switched on. The Bluetooth module will be in listening mode to accept connection from other Bluetooth enabled devices to which data is to be transferred. After establishing the connection, microcontroller switches on the SD card module, if it is not already switched on. Then, the microcontroller starts sending the logged data via Bluetooth as a data stream. Maximum power is consumed in this mode as all the modules of MELOS are switched on. The total rated power consumption of this mode is about 645mW and measured power consumption is between 400 to 700mW that depends on the duration of Bluetooth connection establishment.

4. CASE STUDY: ENERGY MONITORING

This section presents one of the applications of MELOS for energy monitoring, although it can be used for many other applications such as healthcare, environment sensing. Energy consumption in residential and commercial buildings account for a significant percentage of total national consumption across the world. Even a small percentage reduction at building level can have significant additive impact in reducing the overall consumption. A system that allows fine-grained monitoring of energy consumption of appliances can give a great insight into the consumption during different time-intervals in the day. This information can then make the user aware of an optimum usage pattern or perform this pattern automatically by intermittently switching off the appliances.

MELOS platform can both remotely control appliances as well as monitor the energy consumed by each appliance using ubiquitous cellular network. We interface a current sensor ACS714⁶ that can measure bidirectional current in the range -5A to +5A. The appliance to control and monitor is connected in series with the current sensor and the switching relay (driven by one of the GPIO pin of the microcontroller). Using DTMF tones passed on as a command from a remote phone (over SMS/audio call), the control information is passed to the microcontroller to turn on the appliance and start sensing the current.

Fig. 6 shows the plot of energy consumption of three appliances: An incandescent bulb, wall-mounted fan, and a com-

⁶http://www.rhydolabz.com/index.php?main_page=product_info&products_id=506

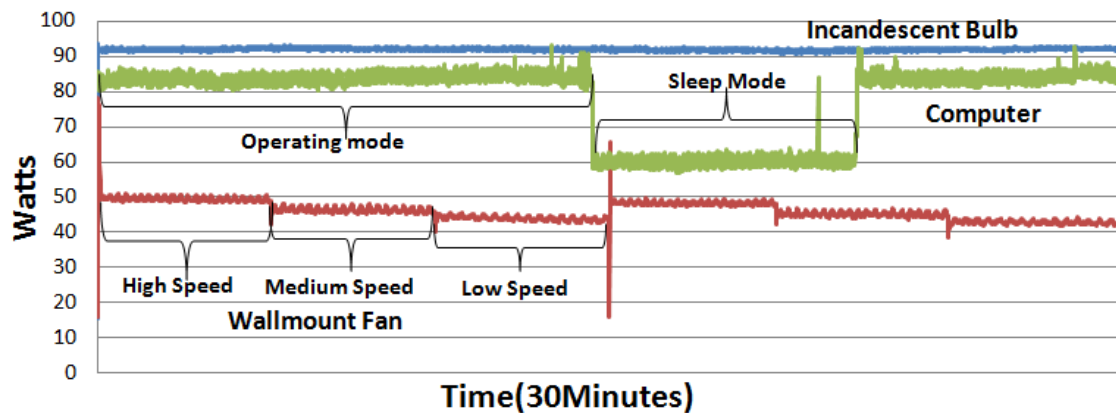


Figure 6: Energy consumption of different appliances as monitored by MELOS

puter as monitored by the MELOS node. Current sensing observations were collected in the local memory and passed on to the computer over Bluetooth. A negative spike in the plot for the computer happened when the monitor went to sleep mode. For wall-mounted fan, we manually adjusted the speed to measure the power consumption in each state. Together with current sensing, we can also have a diode-based full wave AC to DC rectifier circuit, followed by a step down converter to measure the voltage consumed by the load using the ADC ports available on MELOS. Furthermore, we can also use zero-crossing detectors to measure the power factor thus giving a more accurate idea of power consumption of each load. Using on-board relays, switching of external appliances can also be performed easily using MELOS node. This switching can be either manually controlled (through commands passed using remote mobile phone) or can also be automated based on sensor observation as performed by the MELOS node. The setup can be easily extended to monitor home and office premises by attaching sensors like motion, light, vibration, and gas among others.

5. CONCLUSIONS

Low cost and low energy sensing attachments for low end mobile phones can significantly enhance their capabilities for use in critical sensing applications such as energy monitoring and healthcare. In this paper, we proposed a mobile extension called MELOS, that interfaces with a mobile phone over generic audio and Bluetooth interface. The generic audio port is used as low-energy, “always-on” unidirectional interface for passing the control information from the locally attached mobile phone to the MELOS node. This control information can be used for multiple purposes: 1. Switching the on-board memory and communication interface as per application requirements; 2. Switching of external appliances using on-board relays; 3. Initiate sensing of necessary parameters. We discuss the architecture and various modes of operation illustrating reduced energy consumption of the MELOS node. We also present a case study for energy monitoring and appliance control system using MELOS node.

6. ACKNOWLEDGMENT

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