Sensors are Power Hungry: An Investigation of Smartphone Sensors Impact on Battery Power from Lifelogging Perspective

Inayat Khan, Shah Khusro, Shaukat Ali, and Jamil Ahmad

***Abstract* – Smartphones are ubiquitous devices with millions of units are sold around the globe every year. To meet the growing performance needs of innovative applications, smartphones industry has shown tremendous developments in computing, storage capacity, communication, and battery power technologies. The integration of sensors has turned smartphones into powerful sensing methods with unlimited opportunities for devising novel applications for solving real-world problems. This has given rise to a new area of research called smartphone sensing which have potential applications in different domains including lifelogging. However, continuous and inefficient usage of sensors in lifelogging can consume significant amount of battery power and can drain out fully charged battery within a few hours. In this paper, we have presented the importance of smartphone sensors in monitoring users' daily life activities and their usage effects on smartphone battery lifetime. For this purpose, an Android app Energy Monitoring System for Smartphones Sensors (EM3S) is developed. EM3S is experimented in several real world scenarios for estimating smartphones sensors battery power consumptions information. It is found that smartphone sensors consume varying amount of battery power during different daily life activities. However, collectively, they can affect smartphone performance and is a major hurdle for smartphone sensors-based applications. This study is aimed to help researchers, manufacturers and developers in exploring optimal sensors battery power consumption methods while developing pragmatic smartphone sensors-based applications.**

***Index Terms* – Context-Awareness, Lifelogging, Power Consumption, Sensors, Smartphone.**

I. INTRODUCTION

The advancements in science and technology have empowered semiconductor technology to manufacture low-cost, high-power, and multi-functional mechanical devices called chips.

In general, following Moore's law, the number of transistors in a unit area doubles after each eighteen months and smartphones goes one step forward by fabricating more and more functionalities in a single chip to compensate budget [1]. Recent developments in the sensors' issues such as size, processing requirements, and cost effective production have enabled sensors integrations in products and appliances [2].

Smartphones are modern high-end mobile phones combining the features of pocket sized communication devices with PC like capabilities [3]. Smartphones are powered with powerful hardware and sophisticated operating systems that enable them to execute sophisticated even scientific applications covering a wide variety of domains and store as well as process a large volume of data [4]. It was formalized that extending sensory technology to smartphones could substantially increase their capabilities and functionalities. Smartphones sensing capability includes a rich set of specialized sensors (i.e., GPS, accelerometer, proximity, gyroscope, magnetometer, microphone, Wi-Fi, and ambient light etc.). [5]. Incorporation of sensors in smartphones has changed their role from traditional communication devices into life-centric sensors [6]. Sensing capabilities enables smartphones to unobtrusively monitor and accumulate a broad range of dynamic information about people's physical activities [5, 7], contexts-awareness and environmental conditions [8, 9] etc., in real time.

Increasing incorporation of sensors in smartphones fosters the proliferation of various sensors-based applications. The smartphones ambient sensing power can be used as a primary tool for providing context information to a new class of smartphones cooperative services [1]. Sensors-based applications can sense a user's environment and provides effective context-aware services [9] such as Google Maps can use Global Positioning System (GPS) sensor to provide location-aware services to navigate hikers in a rural area, and accelerometer sensor can aid functionalities to games and photography etc. Lifelogging is a special bread of context-aware applications that emphasizes on the creation of surrogate memory (digital archive) of a person's lifetime experiences by continuously and unobtrusively capturing and storing of contextual information about his daily life activities. Lifelogging systems urge on the use of sensory technology for ambient sensing of contextual and environmental information about users, and using of the captured information as cues to augment their episodic memories. Ambient sensing of contextual information for lifelogging can bring applications' capabilities to new level of sophistication such as providing memory aids to the peoples suffering with cognitive memory impairments (e.g., Alzheimer, and Amnesia etc.) etc. The sensory capabilities make smartphone as a suitable lifelogging device. However, accurate context identification needs accurate measurement of context features including motion, background condition, and location etc., which are resources intensive tasks.

The increase in smartphones sensing capabilities has raised power need issue to a level which could not be met by the current smartphones limited power source. In smartphones, battery size and capacity is severely restricted due to size and weight constraints of the devices [3]. A smartphone featuring with a conventional cellular radio antenna, collection of sensors and services, touch screen, and many others requires greater power source because each one is taking toll on the limited battery resource [10]. Empirically

Inayat Khan, Shah Khusro and Shaukat Ali are with Department of Computer Science, University of Peshawar, KP, Pakistan and Jamil Ahmad is with the Department of Computer Science, Research Center for Modeling and Simulation (RCMS), National University of Sciences and Technology, Pakistan.

Email:inayat_khan@upesh.edu.pk,khusro@upesh.edu.pk,shoonikhan@upesh.edu.pk, dr.ahmad.jamil@gmail.com.

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applications using sensor can be the root cause of power wastage by failing in determining the effective use of sensors and their data [11]. Therefore, sensors are needed to be used cost-effectively otherwise would result in complete battery drain quickly [11]. Smartphone limited battery power can foster big hurdles and restrictions for smartphone-based lifelogging applications which require huge power due to using sensors. Researchers have investigated power consumption optimization at different levels (i.e., hardware and software etc.) and defined power management strategies either by immediately shutting down of unnecessary sensors or by carefully alignment of sensors duty cycles [1]. However, suggesting an effective strategy requires prior insight knowledge of different smartphone sensors power consumption rates. Such precise knowledge would also enable lifelogging applications developers to employ sensors on where and how philosophy in order to save power while producing qualitative lifelogging applications without jeopardizing the underlying platforms.

In this paper, we have presented the importance of smartphone sensors in monitoring users' daily lives activities and their usage effects on smartphone battery lifetime. To help in our investigation, an Android app namely Energy Monitoring System for Smartphones Sensors (EM3S) is developed to effectively monitor, record, and analyze the power consumption rates of the various smartphone sensors. For estimating energy consumption rates of each sensor explicitly and in conjunction with other sensors, an extensive test criteria has been defined which consists of different real world scenarios. All of the tests in each of the scenarios are carried out using EM3S on QMobile A12 smartphone. Results obtained have revealed that smartphone sensors can consume excessive amount of battery power during tasks completion; therefore, can be the major source effecting smartphone battery lifetime. In addition, sensors have variable power consumption rates where some sensors consume less and the others consume very much battery power.

II. ANDROID POWER MANAGEMENT SYSTEM

Android implements a mechanism to prolong battery life. When an Android device is left idle, it will first dim, then turn off the screen, and, finally turn off the CPU. Android provides a dedicated power management API in the Applications Framework layer which can be accessed by the running applications and services using Wake Locks Power Manager system service to control the power state of the host device. Android provides four Wake Locks types where each Wake Lock type determines CPU, screen lightness, and keyboard lightness as shown in Table I. PARTIAL_WAKE_LOCK is used by the Android services which run in the background and have no user interface for users' interactions. CPU will be shut down if no Wake Lock is active. An active Wake Lock, depending on its type, thwarts device from suffering full system suspend state (.i.e., WAKE_LOCK_SUSPEND) or low-power state (.i.e., WAKE_LOCK_IDLE) [12].

When an application is launched, it initiates a new Wake Lock by requesting CPU for Power Manager API in the Application Framework which creates a Wake Lock and transfers the lock request to the Power Management service contained in the Linux kernel. The Power Manager also response back to the application about Wake Lock creation and signifies resources consumption depending on the Wake Lock type created. Fig. 1 depicts the Linux modified internal power management framework for Android devices with limited battery power.

III. SMARTPHONES AND SENSORS BACKGROUND

The growing adoptability of smartphones by people and recent technological developments has paved the way of a new sensing paradigm by embedding a number of specialized sensors in smartphones. Today's smartphones have several high valued embedded sensors that are having rich sensing capabilities. In addition, smartphone can also communicate with external sensors using wireless networking protocols (e.g., Bluetooth etc.). To exploit the rich sensing and technological capabilities of smartphone, research community and industry have envisioned several high valued applications for solving real world problems in different domains such as health monitoring [14-16], physical activities recognition and fall detection [5, 7, 17, 18], pollution monitoring [19], traffic monitoring and automatic accident detection [8, 20], social networking [21] etc. Using smartphone as sensor has several practical advantages over traditional wireless sensor networks [19, 22].

Table I. Android Wake_Lock Options [13].

Wake Lock	CPU State	Screen Lightening	Keyboard Lightening
FULL_WAKE_LOCK	Running	Full Bright	Backlight Illuminated
SCREEN_BRIGHT_WAKE_LOCK	Running	Full Bright	Backlight Off
SCREEN_DIM_WAKE_LOCK	Running	Dim Light	Backlight Off
PARTIAL_WAKE_LOCK	Running	Off	Backlight Off

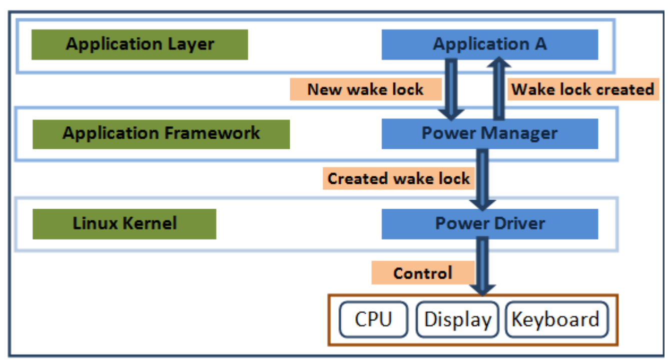

Fig. 1 Android power management architecture.

- Smartphones are always accompanied by users; therefore, solves the problems of power management, and network formation and maintenance.

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- Nodes in a wireless sensor network have relatively high prices that increases the overall cost of a network implementation. Using smartphone as sensors can have high economy of scale as manufactured in large quantities, and already owned by the users. All together, could help in surpassing the overall cost in millions.
- Smartphone can provide coverage to geographical areas where static sensors are hard to deploy.
- Smartphone can provide coverage where it is needed the most and provide a close intact to the measuring phenomenon to get accurate observations.
- Human users assistance to smartphone can be used to improve applications' functionalities such as camera can be pointed appropriately by a human user to a target object to be sensed.

A. Smartphones Sensors Classification

Sensors in smartphone can be categorized into physical sensors and virtual sensors [23]. Physical sensors are hardware-based sensors that are fabricated directly into smartphone and derive their data directly by measuring a particular environmental/contextual feature. For example, accelerometer, gyroscope, and proximity etc. falls into the category of physical sensors. Virtual sensors (also called synthetic sensors or logical sensors) are software-based sensors that are deriving their data by employing one or more hardware-based sensors. For example, in Android platform linear acceleration and gravity sensors are virtual sensors. The number and types of sensors in smartphones varies depending on the underlying smartphone platform and usability. Understanding the potentialities of sensors and increasing miniaturizations in technologies will enable the integration of more advanced sensors in the future smartphones [23]. Smartphone physical sensors can be divided into two categories: general purpose sensors and network interface sensors.

1) General Purpose Sensors

General purpose sensors either measures physical properties related to the internal conditions or obtain information about outside environmental/contextual features. Each of the general purpose sensors captures information about a particular topic which could be read and analyzed by applications for effective decision making. Some of the general purpose sensors available in modern smartphones includes [23]: (1) proximity sensor detects any nearby object in the electromagnetic field without any physical contact, (2) accelerometer sensor can measure the acceleration of a smartphone in 3-axis: X, Y, and Z to detect orientation of the phone, (3) ambient light sensor can measure light of the surrounds to optimize screen visibility accordingly, (4) digital compass sensor recognizes the North for identifying users directions, (5) gyroscope can measure the position and orientation of a phone in 3-axis: yaw, pitch, and roll, (6) Global Positioning System (GPS) sensor receives geo-spatial information from GPS satellites and calculate a user's location, (7) CMOS camera sensor uses MOS (Metal Oxide Semiconductor) transistors to convert an optical image into electrical signals, (8) microphone sensor detects air pressure as vibration and creates an electrical signal proportional to the vibration, and (9) temperature sensor gives information about the ambient temperature using solid state principles.

2) Network Interface Sensors

Network interface sensors are embedded sensors which locate an external signal in the radio range, establish a connection, and receive transmitted signals. The information received by network interface sensors can be read by applications for further usage. Each of the communication sensors uses wireless networking technologies and protocols for connecting with the remote objects (i.e., communication devices or sensors etc.) using a particular frequency range of electromagnetic spectrum at a specific data rate. Some of the network interface sensors available in smartphone includes: (1) Bluetooth sensor (IEEE 802.15.1) is a short range lower-power broadcast communication sensor for connecting personal consumer gadgets, peripherals, and sensors etc. available in a proximity with a data rate less than 1Mbps, (2) Wi-Fi sensor (IEEE 802.11) enables connectivity between smartphone and a nearby (i.e., typically within 50 to 150 meters) Wi-Fi hot spot to provide high performance and bandwidth of Wireless Local Area Network (WLAN) such as Ethernet etc., and (3) Global System for Mobile Communication (GSM) sensor enables connectivity and maintenance with nearby BTS which in turn will be connected to MSC.

B. Role of Smartphones Sensors in Daily Life Activities

The marvelous expansion of sensory technology in smartphone has enabled to track dynamic information about environmental impacts (e.g., noise level, air pollution level, humidity, and temperature etc.), and objects movements patterns (e.g., people's activities, and traffic and road conditions etc.) etc., and model them in fruitful ways (e.g., rendering of tracking information on a map and sharing users' contextual information with online social communities etc.). In addition to using smartphone sensing capability to solve daily life problems, sensory applications could also ease quick data gathering in an urgent situation such as during disaster-relief operation (i.e., earthquake, flood, or outbreak of a disease etc.) personnel (e.g., sociologist, engineers, doctors, biologists, aid-worker etc.) can use their smartphones to sense, monitor, and visualize real world phenomena for realizing public-health threats, and environmental hazards etc. This growing interest in smartphone sensing is due to the technological advancements [24]. First, the availability of cheap embedded sensors in smartphone has made possible the creation of disruptive sensing applications. Second, smartphones are open and programmable which eliminates the barriers of entry for third-party programmers. Third, vendors have app stores allowing application developers to deliver their applications to large number of user across the globe. Fourth, developers can use the high valued resources and services on back-end servers of cloud computing for computation of large scale sensory data and other advanced processing.

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A number of real world scenarios can be outlined utilizing smartphone sensing capabilities. An excerpt of possible applications of smartphone general purpose sensors in users' daily life activities are summarized in Table II.

- A context aware smartphone can recognize the context of a user using sensors and can either change its behavior accordingly or initiate a service automatically. For example, a smartphone might either not accept any call or switch off entirely in situations when a user is in bathroom or in meeting etc.
- Smartphone can automatically obtain weather information (e.g., temperature, humidity, and wind force etc.) either using embedded sensors or nearby connected external sensors and throw an automatic text message to formers using an automatic notifications application to inform them about potential dangers to their seeds or crops in advance.
- Smartphone can use sensing capabilities for accurate capturing of information about traffic and road conditions and share them with other people in an area using some wireless networking technology (e.g., Bluetooth, GSM network, Wi-Fi etc.) to help them in finding alternative and time saving paths to their destinations.
- Smartphone can use embedded sensors or external sensors attached to different body parts of a person to get health information (e.g., measuring blood pressure, heart beat, temperature level, and obesity etc.) in real-time and either prompt messages to the users or inform emergency responders to take appropriate actions. For example, a smartphone sensing system might observe a person's food intake, calculate the amount of calories taken, and suggest him the amount of exercises he is needed to burn extra calories.
- Having real-time knowledge of altitude value and turning GPS on and off accordingly can be preemptive to a bad situation for hikers in a mountainous region. An application using altimeter sensor can trigger an alarm reminding the altitude level upon reaching a threshold elevation value and might turn on the GPS upon reaching a threshold elevation value, saving battery power considerably while recording tracks relatively accurately.

C. *Smartphones Sensors and Battery Power*

The limited battery capacity of smartphone can hinder and restrict the effectiveness of sensors-based applications and services irrespective of their usefulness. Among the others, noticeably the embedded sensors in smartphone are the major sources of battery power consumption. For example, Nokia 95 smartphone can support telephone conversation for more than ten hours if battery is fully charged, but a turned-on GPS receiver can completely drain out the same battery within six hours whether getting GPS readings or not [1]. However, sensors vary in battery power consumption rates where some are very greedy as compared to others. For example, a switched on GPS receiver can completely drain a Nokia N95 8GB battery in 7.1 hours and 11.6 hours respectively in indoor and outdoor, whereas, accelerometer can took 45.9 hours to completely drain out the same battery [25]. Typically, the energy consumption rate of a sensor depends on its sampling rate for reading contextual data: the higher the sampling rate the higher the energy consumption and vice versa. For example, accelerometer, gyroscope, barometer, and magnetometer sensors reads contextual data on uniformed sampling rate, whereas, proximity, and ambient light sensors reads contextual data on non-uniformed sampling rate.

In addition to sensors, the integration of diverse functionalities such as voice communication, web browsing, audio and video playback, SMS/EMS and email communication, and gaming etc., can also produce sever pressures on battery lifetime. The application developers are providing sophisticated solutions and engaging usage experiences through applications by exploiting the desktop-like features of smartphone such as powerful processor, RAM, sensors, and bright colorful display. But, being power hungry, the continuous usage of these hardware components can shorten the battery life significantly. An investigation has shown that majority of Android applications have been reported suffering with energy inefficiency problems by the users. Most of the problems are caused by sensor for two reasons. First, the Android framework gives full sensor management control to developers, which could result into excessive power wastage if mismanaged. Second, most of the Android applications are developed by small teams tending to provide functionalities without dedicated quality assurance and majorly overlook power inefficiency problems.

Under these circumstances, an effective power management is needed intensively. An effective and efficient power management is subjected to clear understanding of where and how power usage formula. It should be defined that which part of a system should use how much of the system's power and under what circumstances [3]. In smartphone sensing applications, power saving can be achieved by shutting down unnecessary sensors as well as carefully selecting sensors duty cycles (i.e., sensors will adopt periodic sensing and sleeping instead of being sampled continuously) [1]. Sensors sampling rate should be adjusted according to users' contexts. For example, GPS receiver should be turned on while operating outdoor and should be turned off while operating indoor. Furthermore, time intervals should be introduced between consecutive samples.

IV. RELATED WORK

Several researchers have attempted to find out how power is consumed in smartphone. Many researchers have concluded power consumption as the primary problem in smartphone management and devised their own ways to save power. In the recent years, researchers have contributed fair amount of work investigating smartphone applications and services utilizing sensors data. Applications ineffectively using smartphone sensors are explicitly found wasting most of the energy. Most of the researchers have used a single sensor in a big list of available smartphone sensors for energy

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consumption estimations. However, some of the researchers have concluded energy consumption estimations using all of the available smartphone sensors but they are suffering with certain limitations as well.

Fehmi Ben Abdesslem, et al. [25] have presented SenseLess system which leveraged the different energy characteristics of sensors for maximizing battery life for smartphone sensing applications usage. Each sensors (i.e., GPS both indoor and outdoor, microphone, Bluetooth, and accelerometer) is used explicitly and continuously on a Nokia N95 8GB smartphone until the battery is completely depleted. It is found that GPS is more power hungry and accelerometer is less power hungry among the all. The approximate battery life for GPS (outdoor), GPS (indoor), microphone, Bluetooth, and accelerometer is found 7.1, 11.6, 13.6, 21.0, 45.9 hours respectively. The approximate battery life when all of the sensors are turned off is 170.6 hours. However, SenseLess suffers from certain limitations. First, it did not experiment other available sensors in smartphones such as proximity sensor, light sensor, magnetic field sensor, and orientation sensor etc. Second, it only tested power consumption of GPS in indoor and outdoor, whereas, other sensors power consumptions in indoor and outdoor activities are completely ignored.

Fangwei Ding, et al. [26] have developed Android based smart energy monitoring system SEMO for profiling smartphone applications with battery consumption. SEMO system works by checking the battery's status, collecting energy consumption data of applications in accordance to data collection, and ranking the applications using energy consumption rates. However, SEMO focus on recording and understanding applications' energy consumption information from developers' perspectives and does not record energy consumption information of energy hungry smartphone components such as screen light, network interfaces (e.g., Wi-Fi etc.), and sensors (e.g., GPS etc.).

Mian Dong, et al. [27] have described a self-modeling paradigm namely Sesame which leverages smart battery interface for self-power measurement without any external assistance and gains accuracy and rate much higher than smart battery interface using a suite of novel techniques. The experimental result showed that Sesame generated system energy model has 95% accuracy. They highlighted the dependency of energy model on hardware configuration, usage, and smartphone. After experiments, they proposed that increase in the memory size and CPU cycles will have effect on battery consumption. Furthermore, media player application has been found more energy consuming application as compared to others.

V. MATERIALS AND METHODOLOGY

To calculate and analyze the power consumption rates of the smartphone sensors, we have implemented an Android app namely Energy Monitoring System for Smartphone Sensors (EM3S). EM3S can find the energy consumption of each available smartphone sensor explicitly and in collection with other sensors at the same time in different real world scenarios. The considered scenarios are four in numbers where each scenario is composed of user states (i.e., motion or stationary), smartphone states (i.e., motion or stationary), sensors states (i.e., on or off), environment states (i.e., building/indoor or open ground/outdoor), and user activities (i.e., walking, upstairs, down stairs, standing, or sitting). Table III depicts the four scenarios along with their compositions.

These compositions are inspired of the real world situations which are experienced by the users in their daily

Table II. An Excerpt of Smartphone Sensors Applications in Daily Life Activities

No	General Purpose Sensors	Applications
1	Proximity Sensor	Detecting nearby objects in different systems such as in blind people guidance systems to help them during walking etc.
2	Accelerometer Sensor	Measuring movements, angles, inclination, and acceleration information of users while conducting a multitude of physical activities in different systems such as old people health care systems, automatic traffic accident detection systems, and games etc.
3	Gyroscope Sensor	
4	CMOS Camera Sensors	Taking pictures of users and surrounding environment which could be used in a number of systems such as recognizing user surrounding environment and location systems, and recognizing users' inclination systems etc.
5	Ambient Light Sensor	Measuring light intensity data of surrounding environment to be used in environmental pollution monitoring systems, picture capturing systems, and weather forecasting systems etc.
6	GPS sensor	Measuring users' locations and direction data for using in several systems such as tourists helping systems in a new city, and soldiers helping systems in battle field or combat etc.
8	Microphone sensor	Measuring voice levels either produced by different object in smartphone's external environment or by the user for using in systems such as voice identification system, environmental pollution monitoring system, automatic traffic accident detection system, and spying helping systems etc.

Table III Scenarios and Their Compositions.

Scenario	User	Smartphone	Sensor	Environment	Activities				
					Walking	Up Stairs	Down Stairs	Standing	Sitting
Indoor motion	Motion	Motion	ON	Building	✓	✓	✓	✓	×
Indoor Stationary	Stationary	Stationary	ON	Building	×	×	×	✓	✓
Outdoor Motion	Motion	Motion	ON	Open Ground	✓	✓	✓	✓	×
Outdoor Stationary	Stationary	Stationary	ON	Open Ground	×	×	×	✓	✓

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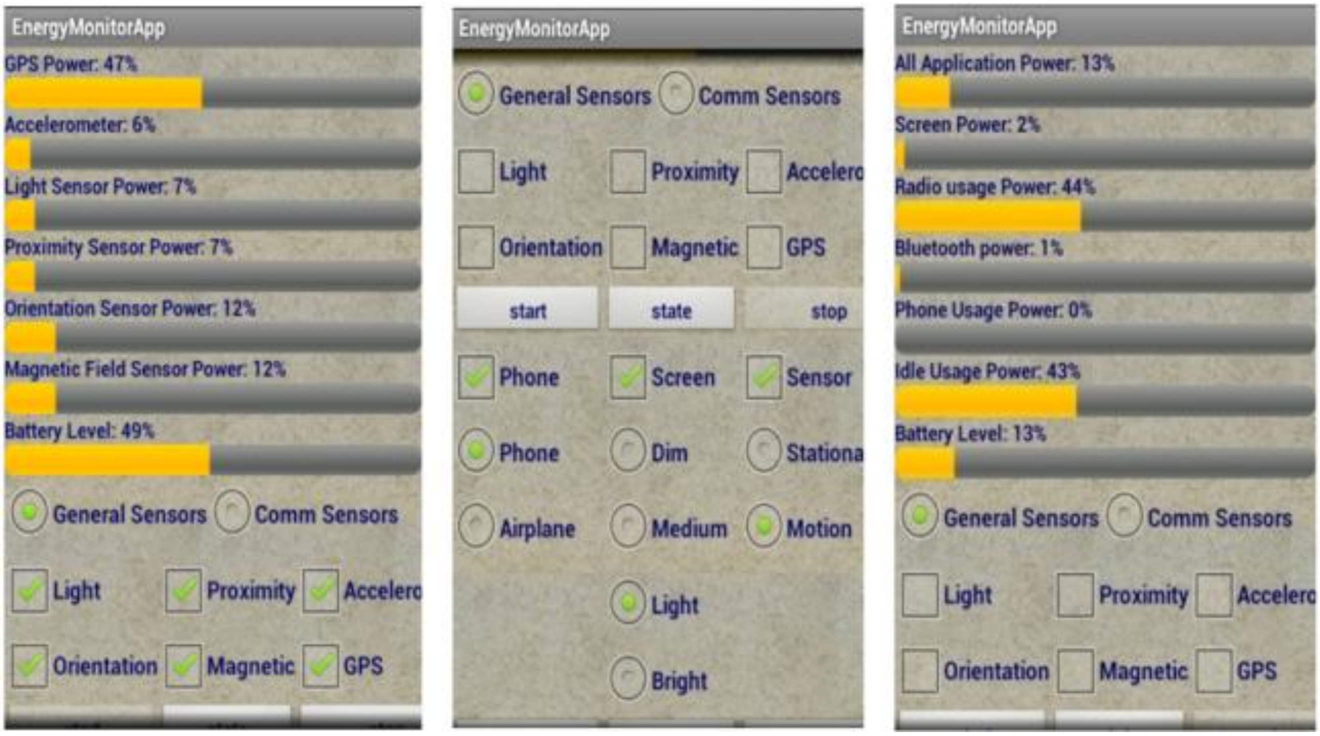

Fig. 2 Screen shots of EM3S main user interface.

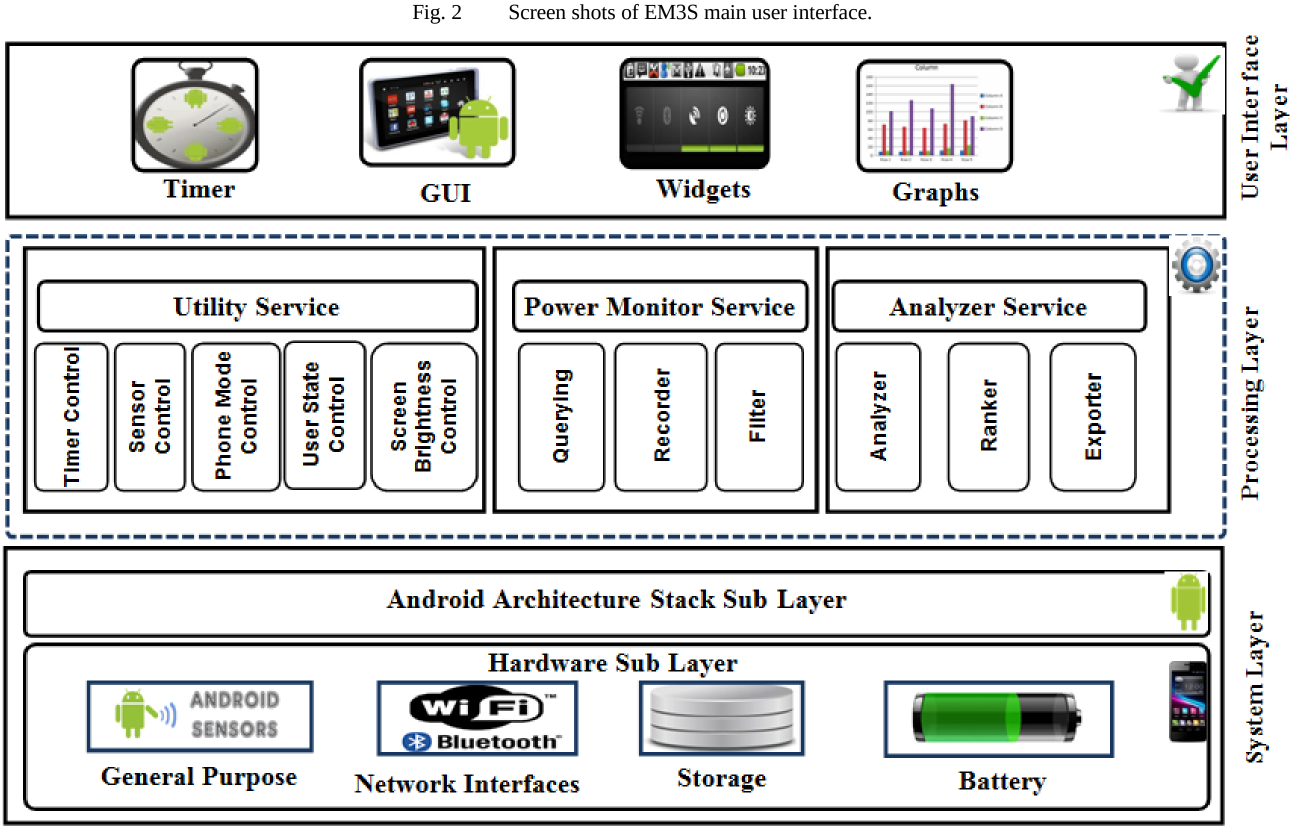

Fig. 3 EM3S three layer architecture.

life activities. In daily life, a user accompanied with smartphone could be in movement or stationary, indoor or outdoor, and involved in an activity or sitting idle. To accurately determine sensors power consumption rates, EM3S relies heavily on the Android's built-in modules (i.e., Battery States, and Sensor classes etc.). At first, EM3S check the battery's status (i.e., temperature level, and remaining power) to initialize other components of the system. During operation, EM3S queries continuously Android services for pitching information. The collected bunch of data includes the remaining battery's power at the very time, names of the running applications (i.e., including sensors) at the time, and

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the applications' total running time so far. EM3S data analysis and the corresponding algorithms filter the retrieved data for finding sensor's energy consumption information and transform it into percentage for user display. EM3S main user interface snapshots are shown in Fig. 2.

A three-layer architecture has been proposed for EM3S consisting of user interface layer, processing layer, and system layer as shown in Fig. 3. Each layer is composed of several sub-components and exploits the capabilities of the layers below. The flow of interactions and communications between the different layers' components is depicted in Fig. 4.

A. *User Interface Layer*

User interface is the space where interaction between users and EM3S takes place. EM3S user interface is easy to use, easy to understand while having lower learning curves, having professional aesthetics, and requiring minimum steps to obtain the desired results. User Interface layer is composed of parent activity, providing features to invoke other activities such as graphs etc. The parent activity layout is composed of numerous controls (e.g., radio buttons, checkboxes, buttons, and progress bars etc.) for providing rich set of features and displaying information in percentage such as sensors turning ON/OFF, smartphone modes changing, energy consumption rates of all active applications, active sensors, screen light, active network interfaces, and battery remaining power etc. Buttons on the parent activity enables users for controlling lower layers components such as turning ON/OFF SensorApp etc., displaying graph activity depicting sensors power consumption in bar chart graph, and invoking Android's built-in battery information service. Parent activity works as an inspector, continuously pooling lower layers components for required power consumption statistics and current battery status. When the battery power reaches a critical condition (i.e., less than 10% etc.), parent activity can also warn users for appropriate actions.

B. *Processing Layer*

Processing layer is an interface between user interface layer and system layer where all of the technical operations would take place. Processing layer is composed of three sub-components namely utility service, power monitor service, and analyzer service. Utility service is a general purpose service which provides methods to configure the app environment. It receives configuration commands such as turning sensors, ON/OFF, and changing modes etc. from the user interface layer and invoke Android's built-in modules in the system layer to fulfill the required tasks. Power monitor service acts as a query, filter, and recorder. Power monitor service starts automatically with EM3S start and periodically queries Android's services in the system layer to retrieve composite information including battery related information, active sensors and modes, energy consumption information, and other miscellaneous information. Power monitor service filters and splits the bunch of information received from system layer into individual information. The service, after processing information, records information in database in the system layer for future necessary actions. Analyzer service could also be started by the interface layer components and consists of three sub-components namely analyzer, ranker, and exporter. Analyzer component analyzes the information recorded by the power monitor service in the database. Ranker component uses the information produced by the analyzer component to rank sensors by their energy consumption rates in the different modes. Exporter component provide methods to pull the database object (file) into PC for performing advance powerful analysis using statistical tools. Both ranker and exporter will make it easy to determine which sensor consumes more power and in which mode.

C. *System Layer*

The lower system layer encompasses the Android's built-in services and libraries which are used by the EM3S. The important built-in services and libraries at this layer includes BatteryStates, SensorManager, and SQLLITE. BatteryStates service provides methods to retrieve different types of information including battery status, remaining power in percentage, health, and temperature etc. SensorManager service provides methods to turn required sensors ON/OFF. Phone modes are changed by invoking the built-in system settings services by passing appropriate predefined constant values and other numerical values to adjust accordingly. SQLLITE is used for creating database to store retrieved power consumption information that are to be used for analysis purposes. From SQLLITE, the database file can be exported to PC, where applications such as NavicateLite, and MS Excel etc., can be used for conducting more powerful analysis.

VI. RESULTS AND DISCUSSION

The current version of EM3S is developed in Java and aimed for Android based smartphones running with Ice cream Sandwich 4.0.3 or higher. The application is mainly tested on QMobile A12 smartphone. In order to demonstrate the viability of EM3S, the system is tested closely in a real world domain. A program of user tests is developed to define activities in all of the four scenarios (as shown in Table III). To accomplish the objectives of our study, we considered six different activities: walking, ascending stairs, descending stairs, running, sitting, and standing. However, the number and intensity of the activities varies depending on scenarios and tests. All of the activities are performed uniformly and randomly for a period of two hours during a scenario test. To carry out tests, three participants are given QMobile A12 smartphones and they are trained how to use EM3S application. The participants are instructed to test a scenario for two hours a day continuously for a week. The data collected after performing each test is analyzed and results are compiled. All of the tests are accomplished inside the premises of the University of Peshawar, Pakistan.

A. *General Purpose Sensors*

EM3S calculates power consumption information about general purpose sensors in real world scenarios that are

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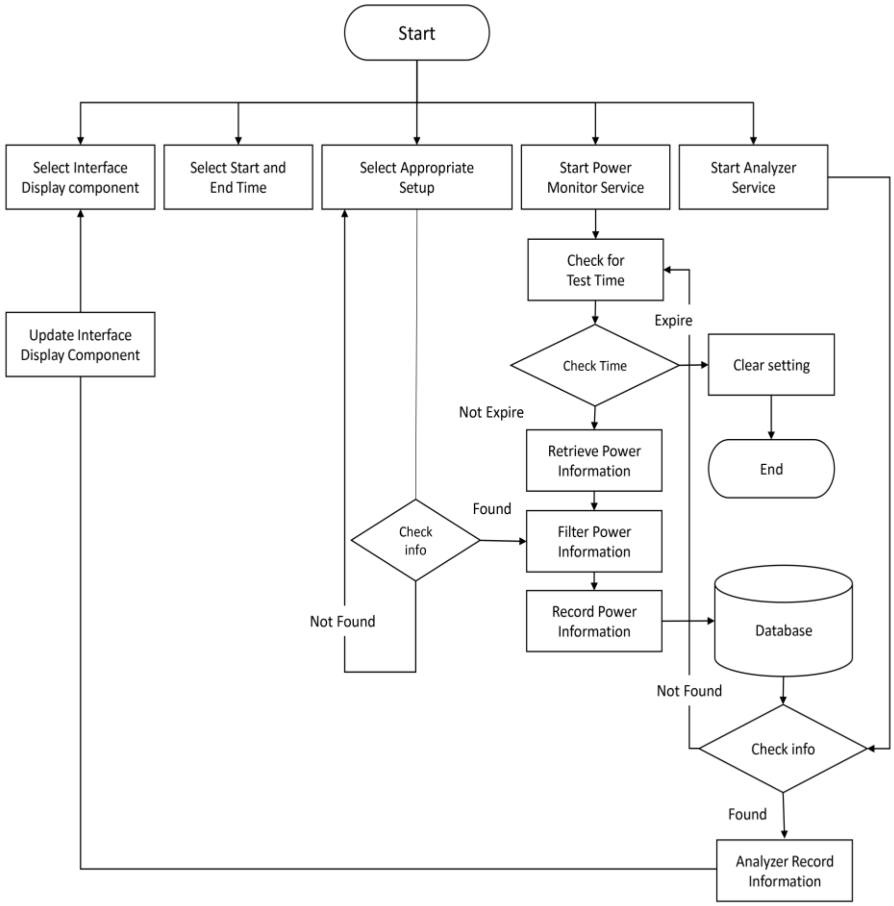

Fig. 4 EM3S flow chart.

Table IV General Purpose Sensors Energy Consumption in Percentage.

Sensors	Indoor Motion	Indoor Stationary	Outdoor Motion	Outdoor Stationary
Accelerometer	6.35%	5.95%	8%	6.6%
Proximity	6.7%	5.9%	5.9%	6.9%
Orientation	13.23%	9.7%	5.9%	6.9%
Light	6.9%	6%	6%	6%
Magnetic Field	13%	11.4%	12.5%	12.9%
GPS	46%	45.22%	53%	51%

described earlier. The algorithm used by EM3S for general purpose sensors power consumption rates estimations can be mathematically described in the following equations:

$$P_{sensor} = P_{power} * T_{timeunit} \quad (1)$$

$$P_{sensor}(j) = \sum_{t=1}^{n} P_{sensor}(t) \quad (2)$$

Equation (1) represents the power consumed by a sensor P_{sensor} using the power consumption information specified by the sensor manufacturer for a unit of time. In equation (1), P_{sensor} is equivalent to the nominal power P_{power}, and the time unit $T_{timeunit}$. Equation (2) represents the total power consumed by a sensor in a scenario while the sensor is active. In equation (2), $P_{sensor}(j)$ represents the total power consumed by a sensor P_{sensor} in a scenario j, that is equivalent to the summation of power consumed by the sensor P_{sensor} in scenario time from *1* to *n*.

After performing all of the tests, the power consumptions information (i.e., obtained through (1) and (2)) for each of the general purpose sensors are analyzed and presented in Fig. 5.1, Fig. 5.2, Fig. 5.3 and Fig. 5.4 respectively for indoor stationary, indoor motion, outdoor stationary and outdoor motion scenarios. The overall power consumption information of the general purpose sensors in the considered scenarios is shown in Table IV and Fig. 5. Comparatively, it is found that GPS sensor is more power hungry and accelerometer is least power hungry in all of the scenarios. GPS consume more energy because of its frequent communication with satellites to find geo-location of smartphone. Using the information presented in Fig. 5, the following facts are found:

- Accelerometer sensor takes readings continuously with a predefined interval time (i.e., interval time can be changed but in this study the default interval time is used). Accelerometer consumed less power in indoor stationary and more power in outdoor motion. Furthermore, accelerometer consumed slightly more energy in outdoor as compared to indoor. It was expected that accelerometer will consume the same power amount in all of the cases but slight difference was observed. However, the difference is very small and negligible.

- Magnetic field sensor takes readings continuously with a predefined interval time (i.e., interval time can be changed but in this study the default interval time is used). Magnetic field consumed less power in indoor stationary and more power in indoor moving. Like accelerometer, magnetic field was expected to have the same power consumption amount in all of the case but slight difference was observed. However, the difference is very minute and negligible.
- Proximity sensor is event based sensor and takes readings upon event occurrences. Proximity consumed almost the same power in all of the cases. The difference is not because of the proximity but can be attributed to users' mistakes in frequency and timing of event occurrences, and users' quickness in actions.
- Light sensor, like proximity sensor, is event based sensor. Light sensor consumed same power in indoor stationary, outdoor stationary, and outdoor motion. This is because of the fact that the light conditions remained the same in these cases. In indoor motion, the power consumption is slightly greater due to varying light conditions inside a building etc.
- Orientation sensor takes readings continuously with a predefined interval time (i.e., interval time can be changed but in this study the default interval time is used). Orientation consumed less power in outdoor stationary and more power in indoor motion. Furthermore, like accelerometer, orientation consumed somewhat how more power in outdoor as compared to indoor. It was expected that orientation will consume the same power amount in all of the cases but slight difference was observed. However, the difference is very small and negligible.
- GPS sensor is event based sensor that continuously sense but records readings upon event occurrences (i.e., changing location etc.). According to expectations, GPS consumed more power in indoor as compared to outdoor. It is already proved that GPS consumes more battery power in indoor as compared to outdoor [25]. However, the difference observed is not as much as claimed by [25].

B. Network Interface Sensors

Network interface sensors are commonly used for data communications either between smartphones and LAN, smartphones and cellular network, or between smartphones. Network interface sensors have turned smartphones into data centric devices. Like general purpose sensors, the ineffective use of network interface sensors can also be a major source of smartphone battery power loss. Using EM3S, the energy consumption rates of network interface sensors is estimated in real world scenarios that are described in Table III. The algorithm used by EM3S for general purpose sensors power consumption rates estimations can be mathematically described as:

$$P_{data} = (D_{sent} * T_{timeunit}) + (D_{received} * T_{timeunit}) \qquad (3)$$

$$P_{control} = (C_{sent} * T_{timeunit}) + (C_{received} * T_{timeunit}) \qquad (4)$$

$$P_{sensor}(j) = \sum_{t=1}^{n} (P_{data}(t) + P_{control}(t)) \qquad (5)$$

Equation (3) represents the power consumed by a network interface sensor for original data transmission P_{data} that is equivalent to the amount of data sent D_{sent} and amount of data received $D_{received}$ in a unit of time $T_{timeunit}$. Equation (4) represents the power consumed by a network interface sensor for control data transmission $P_{control}$ that is equivalent to the amount of control data sent C_{sent} and amount of control data received $C_{received}$ in a unit of time $T_{timeunit}$. Equation (5) represents the amount of power consumed by a network interface sensor P_{sensor} in a scenario j is equivalent to the summation of power consumed by original data P_{data} and control data $P_{control}$ communicated for the duration of the scenario time from *1* to *n*.

Like general purpose sensors, network interface sensors (i.e., Wi-Fi, GSM, and Bluetooth) are also tested using the same methodology. However, for more insight results, two different test cases are defined for carrying out tests in the scenarios that are network interface sensors active without data transmission, and network interface sensors active with data transmission. In the first test case, the sensors are active only (i.e., in connection with nearby access facility) while having no data transmission. In the second test case, the sensors are active as well as having data transmission. The power consumption rates of the network interface sensors for the scenarios in both test cases are shown in Table V and Table VI respectively. Furthermore, their average power consumption rates of the sensors in both of the test cases are also depicted in Fig. 6.1, and Fig. 6.2 respectively.

- Wi-Fi consumed more power as compared to other network interface sensors in both of the test cases. Wi-Fi consumed less power in indoor stationary and more power in outdoor motion. More power consumption in outdoor motion could be due to overcoming the obstacles, high motion, and distance from nearby access point. Wi-Fi power consumption rate in the second test case is also greater in all scenarios than the first test case. Obviously, it is because of the data transmission in addition to connection. However, averagely Wi-Fi power consumption rate is very high and could drain out smartphone battery exponentially. Therefore, needs improvements.
- GSM consumed less power than Wi-Fi in both of the test cases. However, GSM power consumption rate is less than Bluetooth rate in the first test but more in the second test. In both of the test cases, GSM consumed less power in outdoor stationary and more power in indoor motion. More power in indoor motion could be due to overcoming the obstacles, movement, signal strength, and distance from nearby BTS. Like Wi-Fi, GSM power consumption in the second test is greater in all scenarios than the first test case. Obviously, it is

because of the data transmission in addition to connection. However, averagely, like Wi-Fi, GSM power consumption rate is very high and could drain out smartphone battery exponentially. Therefore, it also needs improvements.

- Bluetooth showed uniform power consumption in all of the scenarios in each of the test cases. Like Wi-Fi and GSM, Bluetooth power consumption in the second test case is greater in all of the scenarios than the first test case. Obviously, it is because of the data transmission in addition to connection. However, averagely, like Wi-Fi and GSM, Bluetooth energy consumption rate is very high and could drain out smartphone battery exponentially. Therefore, it also needs improvements.

Table V. Energy Consumption With No Data Transmission In Percentage.

Scenarios	Wi-Fi	GSM	Bluetooth
Stationary Indoor	22%	24%	25%
Stationary Outdoor	29%	18%	25%
Moving Indoor	25%	26%	25%
Moving Outdoor	32%	20%	25%

Table VI. Energy consumption with data transmission in percentage.

Scenarios	Wi-Fi	GSM	Bluetooth
Stationary Indoor	24%	30%	28%
Stationary Outdoor	32%	25%	28%
Moving Indoor	27%	33%	28%
Moving Outdoor	37%	28%	28%

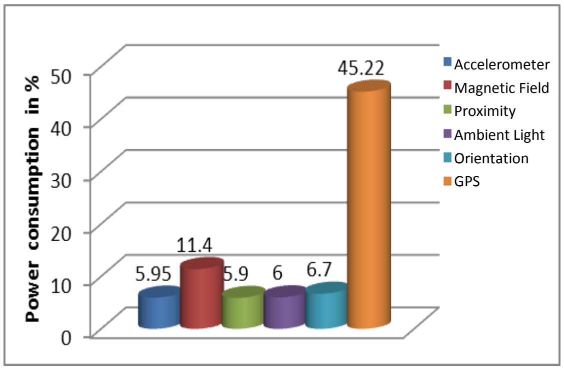

Fig. 5.1 Energy Consumption indoor stationary

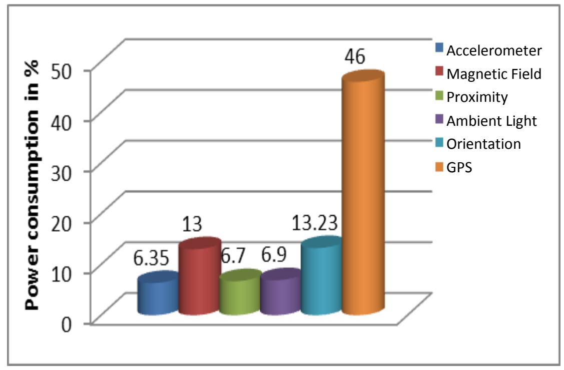

Fig. 5.2 Energy Consumption indoor motion

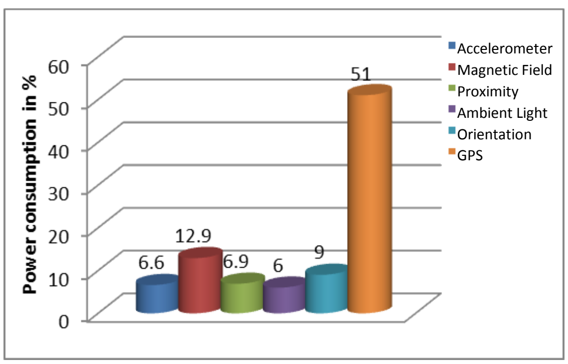

Fig. 5.3 Energy Consumption in outdoor stationary

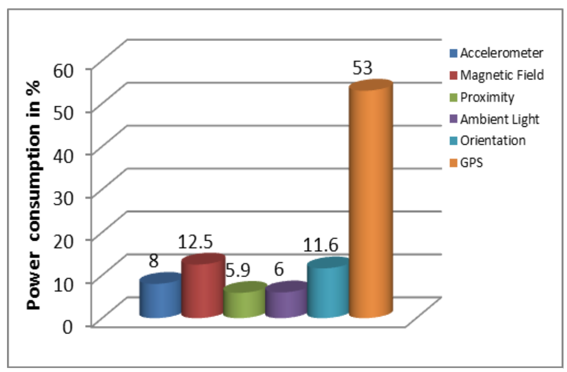

Fig. 5.4 Energy Consumption in outdoor motion

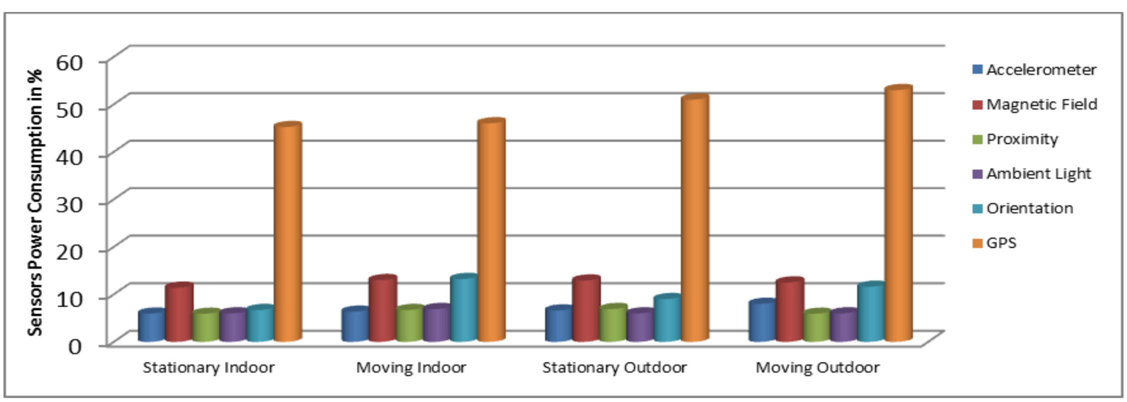

Fig. 5.5 Overall energy consumption in different scenarios

Fig. 5 General purpose sensors energy consumption rates

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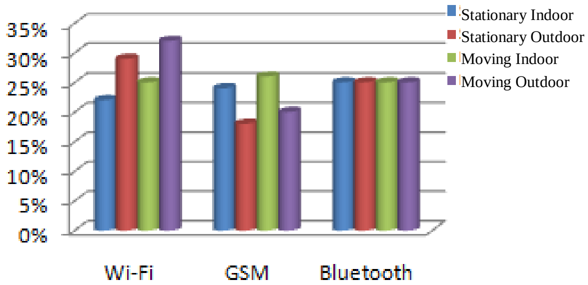

Fig. 6.1 Energy consumptions without data transmission

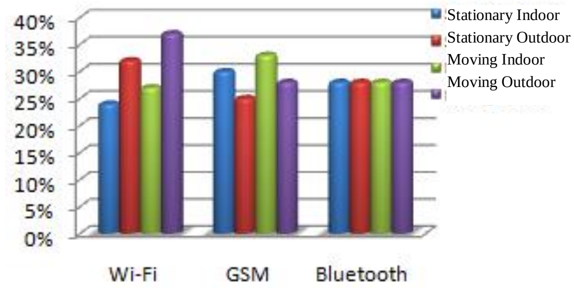

Fig. 6.2 Energy consumptions with data transmission

Fig. 6. Network interface sensors energy consumption rates

VII. CONCLUSION

Smartphone capabilities and functionalities are increased exponentially with the integration of sensors. Today's smartphone come with a number of high valued embedded sensors that are having rich sensing capabilities. Increasing incorporation of sensors in smartphone fosters the proliferation of various sensors-based applications especially lifelogging. Smartphone-based lifelogging applications can leverage the smartphones sensing capabilities for capturing variety of content and contextual data about users' daily life activities. However, the limited battery power capacity of smartphones restricts the scope and applications of smartphone-based lifelogging applications due to their heavy reliance on sensors utilization. Smartphone embedded sensors are noticeably found as the major source of battery power consumption. Therefore, sensors are needed to be used cost-effectively in lifelogging applications otherwise can drain out battery quickly. Generally, effective and efficient power management requires detail understanding of sensors power consumption rates to determine where and how power usage strategy (i.e., which sensor should use how much of the power and under what circumstances).

This paper investigates the effects of sensors usage on a smartphone battery lifetime. It is found that smartphone sensors are found highly power hungry and their continuous usage for a short period of time can result in complete depletion of battery. EM3S app is developed for helping in sensors power consumptions estimations in daily life activities. EM3S is an Android based application and implemented on Android powered QMobile A12 smartphone for performing sensors power consumption tests in a number of real world scenarios. The open nature of Android helped us in conducting thorough analysis which are not possible with other commercial smartphone operating systems otherwise. The obtained results are analyzed statistically and found that sensors not only consumes significant portion of smartphone battery power but they also showed significant variations in their power consumption rates as well which are not expected ideally. Comparatively, GPS in general purpose sensors and Wi-Fi in network interface sensors are found most power hungry sensors. Furthermore, it is observed that sensors power consumption rates are not fixed and depending on the usage environment. Sensors showed variations in their power consumption rates in indoor and outdoor as well as stationary and motions situations. It is also deduced that sensors which are expected to have the same power consumption rates in all of the possible situations due to their operating procedures resulted into different power consumption rates. Collectively, smartphone sensors are found more power consuming components which could sabotage smartphone normal functionalities. With this work, we have delivered an automatic system with a systematic approach for finding sensors power consumption rates which could be helpful for laying down novel sensors power management methods in research laboratories around the globe.

VIII. FUTURE WORK

For future work, we are interested in finding methods for determining the power consumption rates of sensors in proportion to the amount of information that they captured. We are planning to uncover the amount and quality of sensory information captured in variable sampling rates. We are intended to investigate that how to reduce power consumption rates of sensors by designing ambient intelligent algorithm(s) that will dynamically determine optimal sensors sampling rates. However, the information captured by an optimal sampling rate should be rich enough to define users' contexts accurately with minimum latency. Furthermore, we are intending to commence our future experiments by designing real world smartphone-based lifelogging applications that would be using multitude of sensors for deriving more accurate and widely acceptable results.

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