The eCOMBAT: Energy Consumption Monitoring Tool for Battery Powered Communication Device

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***Abstract*—The ever rising demand for energy all over the world, following the dwindling of the fossil fuel resources and adverse effects on the climate change, has compelled the need to save energy and lower the cost of energy utilization in the wireless computing, communication and networking applications. One of the best ways to obtain energy-efficient communication and networking is to invest in the improved ways of energy generation, transmission and distribution through the renewable sources coupled with the development of smart energy consumption monitoring tools. As a result, this paper presents an energy monitoring software tool hereby referred to as the 'eCOMBAT' which is aimed at getting real-time information on the quantity of energy consumed by the communication and networking device. The knowledge of such data on time may enable the device user to reduce energy consumption, lower the CO_2 emissions into the environment and eventually save the cost of using energy in powering such device. This paper proposes an integrated battery's discharge and device's energy consumption model; the description of the developed tool and experimental results of the tool obtained through user friendly and well designed graphic user interfaces (GUIs).**

Keywords—communication device; eCOMBAT; energy consumption; rechargeable battery; State-of-charge.

I. INTRODUCTION

The growing awareness towards energy efficient wireless communication networks has paved way for new technologies in designing green networks. Saving power in base stations, mobile stations and wireless routers (or communication devices) is the primary focus in green wireless communication networks [1]-[3], [20]. One goal of green communication devices is to save energy and reduce power consumption while guaranteeing service quality and coverage for users. This can be achieved by minimizing the device's (base station's) energy consumption with energy efficient hardware design, power saving protocols for sleep modes, energy aware cooperative base station power management with self organizing cells, cell zooming, or by using renewable energy sources [1]. The use of renewable energy resource like sustainable bio-fuels, solar and wind energy are the upcoming energy sources to power the wireless communication devices in the areas where there is no public and stable power supply, inhospitable terrain, neglected infrastructure, remote areas, deserts, islands among other remote areas [1]. These wireless communication devices are considered to have rechargeable batteries which draw their charges from the renewable energy sources. As such innovation grows widely; the need to develop an energy consumption monitoring tool customized for green communication devices powered by rechargeable batteries must evolve. This paper proposes such a tool referred to in short as the eCOMBAT that provides timely information for combating the unnecessary energy consumption [3].

Just as a "fuel gauge" function for a fuel tank in a car, knowing the amount of energy left in a battery at all times gives the user of a battery powered device an indication of how much longer a device and battery will continue to perform before the battery needs to be recharged. This has a profound impact on the reliability of network devices and future green networking. As a result, this paper contributes in developing a new software tool based on a mathematical model and a user friendly graphical user interface (GUI) to allow flexible actions aimed at reducing the energy consumption, lowering energy costs and $C0_2$ emissions to the environment compared to the commercial-based main's electric energy consumption monitors [2].

The rest of this paper is organized as follows: Section II provides the prior art about the battery and communication device monitors; Section III outlines the related simulation models in existing network simulators (NS2 and NS3); Section IV provides the proposed energy consumption emulation model; Section V deals with the eCOMBAT description and functionality; Sections VI and VII furnishes the performance and conclusion of the eCOMBAT, respectively.

II. RELATED WORK

Batteries are the power providers for almost all portable green computing, communication and networking devices [3]. They can also be used to build energy storage systems for large-scale power applications. In order to design battery systems for energy-efficient architectures and applications like in green communications, system designers require computer aided design tools that can implement mathematical battery models, predict the battery behavior and thus help the designers search for the optimal schemes. The basic types of battery models are mainly, the experimental, electrochemical and electric circuit-based models [4]. However, experimental and electrochemical models are not accurately tuned to monitor and estimate the performance of the battery and other critical battery parameters like state of charge (SoC), state of health (SoH), time to run (TTR) among others [5]-[6]. The SoC is the percentage of the maximum possible charge that is present inside a rechargeable battery;

$$SoC\left[\%\right] = 100 \cdot \left(1 + \frac{\int_{t_s}^{t_f} idt}{Q}\right), \tag{1}$$

where Q is the rated maximum battery capacity (Ah or mAH) and the operational times of the battery are (Start time t_s) and (Stop time t_f). The SoH is a 'measure' that reflects the general condition of a battery and its ability to deliver the specified performance in comparison with a new battery. The TTR is the estimated time that the battery can supply the current to a portable device or load under valid discharge conditions before it will stop functioning;

$$T_r(i,t) = \frac{C_s - C_f}{i}, \tag{2}$$

where C_s is the battery capacity at the start of discharge and C_f is the battery capacity at the stop of discharge. It is calculated on the basis of:

$$C_f = \frac{SoC(EMF_B)}{100} Q_{\max}, \tag{3}$$

where SoC (EMF_B) [%] represents the SoC calculated on the basis of the estimated EMF at point B and Q_{max} represents the battery's maximum capacity [7].

On the other hand, the electric circuit-based models can be useful to represent electrical characteristics of batteries. For instance in [7], Shepherd developed an equation to describe the electrochemical behavior of a battery directly in terms of terminal voltage, open circuit voltage, internal resistance, discharge current and state-of- charge (SoC). Using this classical model, Tremblay et al. [5] utilizes the SoC as the only state variable to accurately reproduce the manufacturer's discharge curve, nominal and exponential zones, for any of the four major types of battery chemistries. These four types are: Lead-Acid, Lithium-Ion (Li-Ion), Nickel-Cadmium (Ni-Cd) and Nickel-Metal-Hydride (Ni-MH). The battery discharge model uses a simple controlled voltage source in series with a constant resistance. It assumes that the charge and discharge cycles have the same characteristics which exhibit a hysteresis phenomenon of voltages versus SoC, at the exponential zones. Thus, using the measured battery data, a mathematical model of the battery is developed which takes into account battery operating temperature and the rates of the battery charge/discharge currents. The model is validated against the manufacturers' discharge curves and finally applied to dynamic simulation of the hybrid electric vehicles (EV) [8]. The proposed eCOMBAT tool in this paper utilizes such concepts of the rechargeable battery discharge models to create a more sophisticated energy monitoring tool which can be implemented at the lower layers of the protocol stack [20].

Tremblay and Dessaint [9] explain that the central unit of an EV and other electronic systems including the communication devices is the battery. This is because the battery unit has the capacity to store a substantive amount of the energy to be released when necessary. The battery enables the regenerative braking in an EV and allows supplementing a slow dynamic energy source, such as the fuel cell. The authors [9] perform various experimental validations of the battery dynamic model for the EV applications. However, their work has not considered energy consumption in green communication devices. In [10], rechargeable batteries are exploited to power the village base stations (VBTS). This initiative provide four main benefits: a flexible off-the-grid deployment due to low power requirements that enable local generation via solar or wind; explicit support for local services within the village that can be autonomous relative to a national carrier; novel power and coverage trade-offs based on the intermittency that can provide bursts of wider coverage; and a portfolio of data and voice services. However, the work has not considered developing a monitoring tool for tracking the VBTS energy consumption for the off-the-grid VBTS.

In [11], a battery-operated Renewable Energy Monitor is developed for educational evaluation monitoring, with the measurement software for graphical display of performance characteristics on your PC. It offers a 2 line liquid crystal display (LCD) screen for viewing measurements that you cycle through at the push of a button. Numerous experiments and evaluation activities for hydrogen fuel cells, miniature wind turbine kits, and solar panels can be quantified in real time for voltage, current, power, joules, resistance, and even revolution per minute (RPM) speed. In [12], a SystemSens: an R&D tool is proposed for monitoring usage context in terms of energy consumption units. The study is motivated by the fact that, any application interested in location information also should also capture the CPU and screen activity energy consumption. This makes such application able to distinguish between users that are sedentary versus those that leave their smart-phones on the desk for long periods. The SystemSens tool collects and logs smart-phone usage parameters in the wild in an unobtrusive manner—it has no user interface to minimize impact on usage, and expandable way (a small footprint in terms of memory, CPU, and energy computational consumption). The tool consists of an Android logging client and a visualization web service. The tool helps identifies the primary energy cost and timely sends feedback information to the user for a possible energy saving action. However, the tool works at the application level not at the lower level of the network protocols where huge amount of energy is often wasted by the network interface cards [13]-[14]. The eCOMBAT tool brings benefits of the application and network levels in order to improve on monitoring and evaluation of the energy consumption [20].

Measurement based studies of power consumption statistics of wireless local area networks devices are reported in [13]-[14]. The goals are to understand where, when and how the power is consumed in the network. The results provide a detailed anatomy of power consumption in networks devices that can be exploited in designing schemes extending lifetime (between recharges). However, energy consumption monitors arising from such analysis are linked to the operation modes of the communication devices rather than various battery discharge models. As a research and development

(R&D) tool, the eCOMBAT integrates the rechargeable battery discharge models with the various device energy consumption models.

III. ENERGY CONSUMPTION BATTERY-DEVICE MODEL: NETWORK SIMULATION CASE

In order to develop a new energy consumption monitoring tool for the battery powered communication device (eCOMBAT), one takes a look at the existing and related network simulators (NS) [15]-[16]. Regarding the NS2 and NS3, the energy framework to estimate the energy consumption of the wireless devices and their subsystems (e.g. Wi-Fi/cellular radio interfaces, memory and CPUs) consists of separate major components. These are namely, the energy source and device energy consumption models as shown in Fig. 1. Concerning the energy source model, the energy supply to the device such as a battery is modelled. This model maintains the total and changes in energy in order to simulate the generic power consumption of different device subsystems such as the communication device interfaces, and other subsystems. On the other hand, the device model simulates the functionality of the network device. In this model, either the total power consumption of the device as a unit can be estimated or the power consumption of different device’s subsystems can be estimated. These network simulators provide different models for individual subsystems. Normally, the communication device’s power consumption at a network interface card is modelled based on the information provided by the physical layers [13]. This is because, the physical layer has full control over radio states, and provides interfaces to put radio into transmit, receive and sleep state, as well as waking it up. It also keeps track of radio energy consumption at all times. Whenever the radio state changes, it updates the energy source model to subtract the appropriate amount for the previous state, based on the time interval and current drain for the given state [13]-[14].

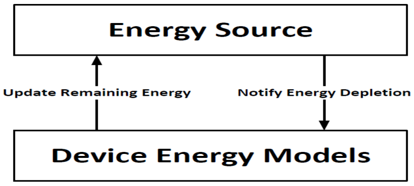


Fig.1. The energy consumption simulation model in NS3 [15].

In general, the model can be fitted to any type of Li-Ion [17], Ni-MH [18] or Lead Acid Battery [8], respectively, by simply changing the model parameters. However, the NS3 provides an example of the Panasonic CGR18650DA Li-Ion battery cell [17]. Each time energy is drained from the cell, the object oriented C++ class evaluates the discharge curve to get the actual cell's voltage, accordingly to the SoC and current's drain. If the actual voltage of the cell goes below the minimum threshold voltage, the cell is considered depleted and the energy drained event gets fired up. The NS3 simulation model implemented by [5], requires several parameters to approximate the discharge curves.

- InitialCellVoltage, maximum voltage of the fully charged cell
- NominalCellVoltage, nominal cell's voltage, is used to determine the end of the nominal zone.
- ExpCellVoltage, cell's voltage at the end of the exponential zone.
- RatedCapacity, rated capacity of the cell, in Ah.
- NomCapacity, cell's capacity at the end of the nominal zone, in Ah.
- ExpCapacity, cell's capacity at the end of the exponential zone, in Ah.
- InternalResistance, internal resistance of the cell, in Ohms.
- TypCurrent, typical discharge current value, used during the fitting process, in Ah.
- ThresholdVoltage, minimum threshold voltage below which the cell is considered depleted.

Such parameters are used to describe the base class for energy sources and the energy sources keep track of remaining energy. The device energy models function to update the remaining energy in the energy source as a way of knowing when to behave energy-efficient or greedy. The energy source itself does not update the remaining energy but keeps a list of device energy models installed on the same node so as to be aware of the network loads. When the remaining energy level reaches 0, the energy source will notify all device energy models stored in the list to switch-off.

IV. PROPOSED ENERGY EMULATION MODEL

Motivated by the NS3 energy models, the development of the energy consumption monitoring tool (eCOMBAT) starts by considering a basic battery discharge model coined from the Shepherd model [7]. This model is modified to represent the voltage dynamics when the current flowing through the communication device acting as the load, varies and takes into account the open circuit voltage (OCV) as a function of SoC. This is done by adding a term concerning polarization voltage and resistance to better represent the OCV behavior. The resulting battery discharge model becomes [5]:

$$V_{batt} = V_0 - \underbrace{K \times \frac{Q}{Q - i \times t}}_{Polarisation\ voltage} \times i \times t - R \times i + \underbrace{A \times \exp(-B \times i \times t)}_{Exponential\ voltage} - K \times \underbrace{\frac{Q}{Q - it}}_{Polarisation\ res.} \times i^* , \quad (4)$$

where V_{batt} is the battery voltage drop (V), V_0 is the battery constant voltage (V), K is the polarization constant (V/(Ah)) or polarization resistance (Ω), Q is the battery capacity (Ah), and it is the actual battery charge (Ah), A is the exponential zone amplitude (V), B is the exponential zone time constant inverse $(Ah)^{-1}$, R is the internal resistance (Ω), i is the battery current (A) and i^* is the filtered current (A) flowing through the polarization resistance [9].

The exponential zone of (4) is valid for the Li-Ion battery and an extension to models of other batteries require that the exponential term be represented by a non-linear dynamic system:

$$\dot{Exp}(t) = B|it| \times \left(-Exp(t) + Au(t)\right), \qquad (5)$$

where $Exp(t)$ is the exponential zone voltage (V), $i(t)$ is the battery current (A), and $u(t)=0$ if the battery is in discharge mode, otherwise unity if the battery is in charge mode. Combining (4) and (5) at the exponential zone, one obtains the generic battery discharge model as:

$$V_{batt} = V_0 - \underbrace{K \times \frac{Q}{Q - i \times t}}_{Polarisation\ voltage} i \times t - R \times i + \underbrace{B \times |it| \times A \times \exp(-B \times i \times t)}_{Exponential\ voltage} - K \underbrace{\frac{Q}{Q - i \times t}}_{Polar.res.} \times i^* . \qquad (6)$$

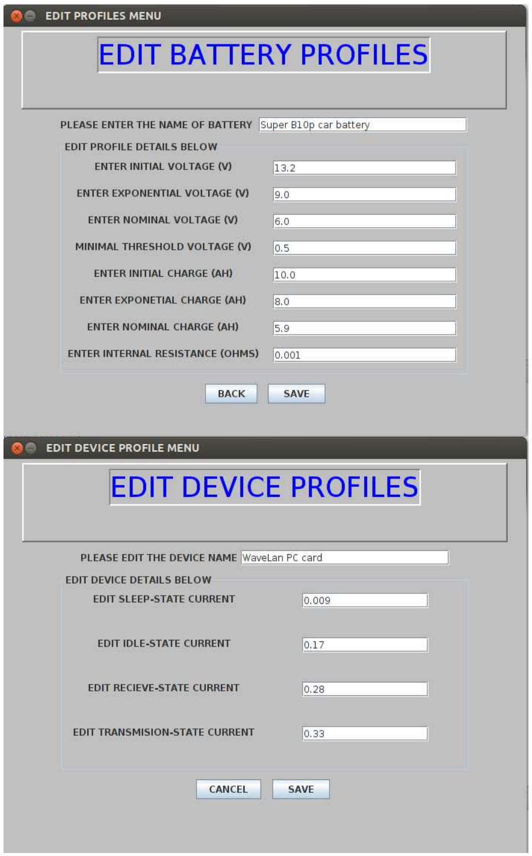
In order to integrate the generic battery discharge model in (6) to the energy consumption models of the communication device, the basic linear analytical model in [14],[20] is exploited. This model outlines that the energy consumed by the communication device when it sends, receives or discards or idle listens to a packet traversing the network, is represented by a linear function of the size of the packet at the communication device:

$$E = m \times Size + b . \qquad (7)$$

Integrating (6) and (7) and simplifying the result, one obtains an energy consumption emulation model in (8):

$$E_{batt\_device} = V_{batt} \times i \times t \times \frac{Size\ of pckt}{Pckt\ delivery\ ratio} + E_0 , \qquad (8)$$

where E_0 is the initial constant energy consumed at the beginning of the battery's discharge and device's operational modes. This study equates the initial constant energy E_0 to zero as energy gets consumed only after the commencement of the emulation experiment. The energy consumption emulation model was implemented in C++ programming language on a open source Linux platform [16]. By the help of a user friendly graphical user interface (GUI), the battery and device input profiles are edited as shown in Fig. 2. Information such as the battery type, the exponential and nominal voltages, the initial charge and internal resistances are logged into the database. The device type, the sleep, idle, receive and transmit threshold currents are also entered into the database. Once saved, the live or report-based simulation is executed in order to yield the printable outputs in Fig. 3 and Fig. 4.



PLEASE ENTER THE NAME OF BATTERY: Super B10p car battery

EDIT PROFILE DETAILS BELOW

ENTER INITIAL VOLTAGE (V): 13.2

ENTER EXPONENTIAL VOLTAGE (V): 9.0

ENTER NOMINAL VOLTAGE (V): 6.0

MINIMAL THRESHOLD VOLTAGE (V): 0.5

ENTER INITIAL CHARGE (AH): 10.0

ENTER EXPONETIAL CHARGE (AH): 8.0

ENTER NOMINAL CHARGE (AH): 5.9

ENTER INTERNAL RESISTANCE (OHMS): 0.001

PLEASE EDIT THE DEVICE NAME: WaveLan PC card

EDIT DEVICE DETAILS BELOW

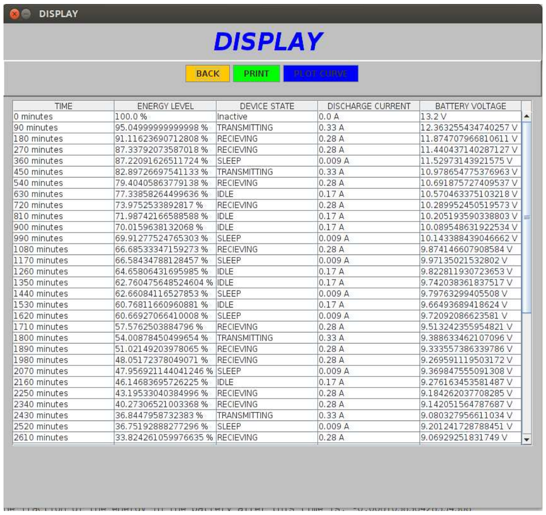
EDIT SLEEP-STATE CURRENT: 0.009

EDIT IDLE-STATE CURRENT: 0.17

EDIT RECIEVE-STATE CURRENT: 0.28

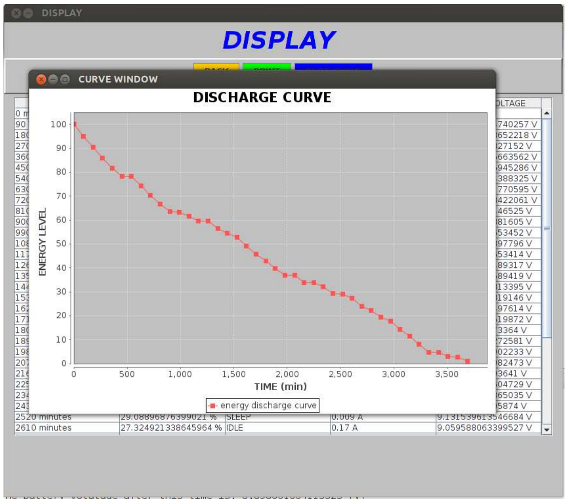
EDIT TRANSMISION-STATE CURRENT: 0.33

Fig. 2. The battery and device simulation input profiles.



TIME	ENERGY LEVEL	DEVICE STATE	DISCHARGE CURRENT	BATTERY VOLTAGE
0 minutes	100.0 %	Inactive	0.0 A	13.2 V
90 minutes	95.04999999999998 %	TRANSMITTING	0.33 A	12.363255434740257 V
180 minutes	91.11623690712808 %	RECIEVING	0.28 A	11.874707966810611 V
270 minutes	87.3379207358701‍8 %	RECIEVING	0.28 A	11.440437140287127 V
360 minutes	87.22091626511724 %	SLEEP	0.009 A	11.5297314392157‍5 V
450 minutes	82.89726697541133 %	TRANSMITTING	0.33 A	10.978654775376963 V
540 minutes	79.40405863779138 %	RECIEVING	0.28 A	10.691875727409537 V
630 minutes	77.33858264499636 %	IDLE	0.17 A	10.570463375103218 V
720 minutes	73.975253389281‍7 %	RECIEVING	0.28 A	10.289952450519573 V
810 minutes	71.98742166588588 %	IDLE	0.17 A	10.205193590338803 V
900 minutes	70.0159638132068 %	IDLE	0.17 A	10.089548631922534 V
990 minutes	69.91277524765303 %	SLEEP	0.009 A	10.143388439046662 V
1080 minutes	66.68533347159273 %	RECIEVING	0.28 A	9.874146607908584 V
1170 minutes	66.58434788128457 %	SLEEP	0.009 A	9.97135021532802 V
1260 minutes	64.65806431695985 %	IDLE	0.17 A	9.822811930723653 V
1350 minutes	62.760475648524604 %	IDLE	0.17 A	9.742038361837517 V
1440 minutes	62.66084116527853 %	SLEEP	0.009 A	9.79763299405508 V
1530 minutes	60.76811660960881 %	IDLE	0.17 A	9.66493689418624 V
1620 minutes	60.66927066410008 %	SLEEP	0.009 A	9.7209208662358‍1 V
1710 minutes	57.5762503884796 %	RECIEVING	0.28 A	9.513242355954821 V
1800 minutes	54.00878450499654 %	TRANSMITTING	0.33 A	9.388633462107096 V
1890 minutes	51.02149203978065 %	RECIEVING	0.28 A	9.333557386339786 V
1980 minutes	48.05172378049071 %	RECIEVING	0.28 A	9.269591119503172 V
2070 minutes	47.956921144041246 %	SLEEP	0.009 A	9.369847555091308 V
2160 minutes	46.1468369572622‍5 %	IDLE	0.17 A	9.276163453581487 V
2250 minutes	43.19533040384996 %	RECIEVING	0.28 A	9.184262037708285 V
2340 minutes	40.27306521003368 %	RECIEVING	0.28 A	9.142051564787687 V
2430 minutes	36.8447958732383 %	TRANSMITTING	0.33 A	9.080327956611034 V
2520 minutes	36.75192888277296 %	SLEEP	0.009 A	9.201241728788451 V
2610 minutes	33.824261059976635 %	RECIEVING	0.28 A	9.06929251831749 V

Fig. 3. The device energy consumption behavior, showing the simulated values of sleep, idle, receive and transmit currents (A) and the power (W).



2520 minutes	29.08896876399021 %	SLEEP	0.009 A	9.131539613546684 V
2610 minutes	27.324921338645964 %	IDLE	0.17 A	9.059588063399527 V

Fig. 4. The simulated battery-device energy discharge curve.

V. DESCRIPTION OF THE ECOMBAT TOOL

The eCOMBAT tool is an integrated software that implements the rechargeable battery discharge model and the communication device's energy consumption state model. The battery discharge model is derived from the generic formulation in [9], while the communication device's energy consumption state model is derived from [13]. The uniqueness of the technology is the design, development and integration of the two independent models into a R&D tool, which possesses the testing capability of both battery and device types. As shown in the Fig. 5, the hardware platform consists of the alternative energy source, the rechargeable batteries, and the multimeter across the device and the battery, the communication network device and the multimeter across the battery and the device to measure the voltages and currents. The alternative energy source supplies the battery with the charge, the battery stores the charge and power up the communication device and the communication device draws the power as it operates various states, sleep, packet send, packet receive and idle as shown in Fig. 2 [13][20].

The technology is described by the input (current drain, voltage drops and power data logged), process (monitoring), and output (display) system.

Input: As the communication device draws power from the rechargeable battery during its operations, the eCOMBAT software collects real-time information on the energy use, captured by a multimeter data logger. The logged measurement data reveals the energy consumption information about the batteries discharge current.

Process: The captured data from the data logger is conveyed to a file platform of the device and either stored as records for report-based energy consumption emulation or incorporated into the battery drain mathematical model as live emulation. In the eCOMBAT, the battery drain or discharge model as well as the device energy consumption model have been formulated as a function of time [9].

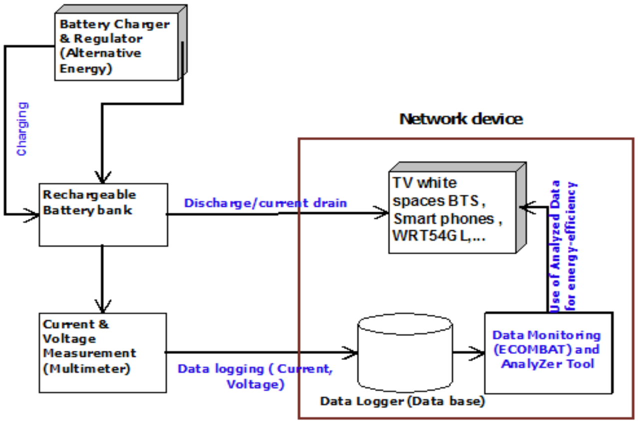


Fig. 5. Schematic diagram of the eCOMBAT technology

Output: The tool produces battery discharge indication and the device energy consumption state indication. Two alternate emulation outputs are exhibited, the live emulation and the report-based emulation. The live emulation produces the battery discharge visual indication, as the energy drains and state information are provided in real-time, while for report-based emulation the battery discharge curve as well as the devices state information is displayed for later analysis and management. For the usability of the eCOMBAT tool to be feasible, it is assumed that discharge and charge characteristics of the battery are the same, otherwise useful parameters like exponential and nominal voltages could be difficult to estimate [7].

VI. EMULATION MODEL PERFORMANCE

In order to accurately obtain the performance characteristics of the developed eCOMBAT tool, the battery electrodes were connected in series with the wireless communication device on which an application to ensure the typical energy consumption behaviors were run. With a multimeter connected across the fully charged battery and the device, various current values were logged onto a computer, which was for the purposes of data analysis only. The apparatus are set-up as shown in Fig. 6.

The battery and device types' profiles are created and loaded onto the system's database. In Figs. 7 and 8, either live or report-based emulation buttons are pressed on the GUI. The battery and device input parameters are captured by the system. In particular, the live emulation of the energy consumption is monitored and depicted graphically using battery symbols or charge indicators. The indicator in Fig. 7 shows that 100% of energy is available in the battery at the start of emulation, and the indicator in Fig. 8 shows that only 25% of the energy is remaining in the battery after a progressive period of time. These graphical indicators provide timely useful energy consumption information in order for the user to devise a timely combat mechanism of the unnecessary energy consumption.

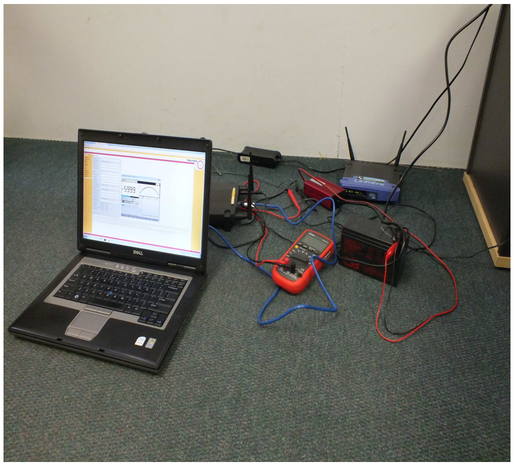
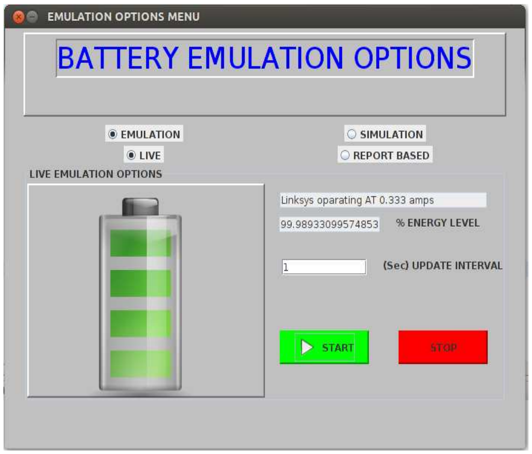


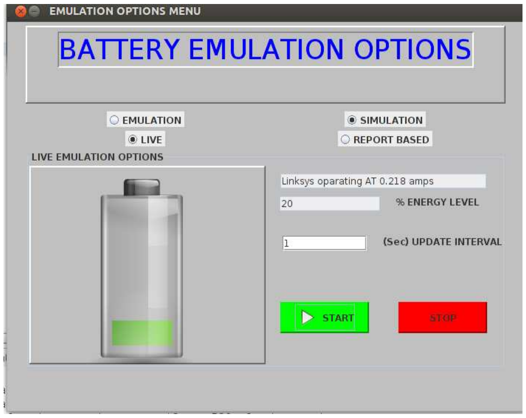
Fig. 8. The eCOMBAT performance set-up.



● EMULATION
● LIVE
○ SIMULATION
○ REPORT BASED

Linksys oparating AT 0.333 amps
99.98933099574853 % ENERGY LEVEL
1 (Sec) UPDATE INTERVAL

Fig. 7. Visual indicators of 100% of energy full.



○ EMULATION
● LIVE
● SIMULATION
○ REPORT BASED

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20 % ENERGY LEVEL
1 (Sec) UPDATE INTERVAL

Fig. 8. Visual indicators of 25% of energy full.

VII. CONCLUSION AND APPLICATIONS

This paper has presented a new energy consumption monitoring tool, the ‘eCOMBAT’. Through a user friendly graphical user interface (GUI), it has shown to monitor battery powered communication devices. The technical novelty of this tool lies on the integration of the classical battery discharge and device energy consumption models. The description and functionality of the tool indicate that the tool contributes significantly in energy monitoring and management in green networks. Timely knowledge of energy consumption prompts timely management. As a R&D tool, it be could be used by the learning and research institutions to study the energy consumption performances of networks. The commercial network infrastructure vendors might also find the tool handy as a benchmark tool for designing their proprietary solutions.

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