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Characterizing Multi-radio Energy Consumption in Cellular/Wi-Fi Smartphones

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ABSTRACT

Cellular networks evolved to meet the ever increasing traffic demand by way of offloading mobile traffic to Wi-Fi network elements. Exploiting multi-radio interfaces on a smartphone has recently been examined with regards to heterogeneous bandwidth aggregation and radio switching. However, how a smartphone consumes its energy in driving cellular and Wi-Fi multi-radio interfaces, is not well understood. In this paper, we revealed the energy consumption behavior of 3G cellular and Wi-Fi multi-radio operations of a smartphone. We modified smartphone's firmware to enable multi-radios operations simultaneously and we performed extensive measurements of multi-radio energy consumption in a real commercial network. From the measured data set, we established a realistic multi-radio energy consumption model and it gave 98% stability from the derived coefficients.

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1. INTRODUCTION

There has been a dramatic increase in utilization of wireless communication technology such as LTE, 3G, and Wi-Fi. Smartphone devices have emerged with radio technologies which has resulted in the gigantic escalation in users of 3G and Wi-Fi data networks [1-2]. Smartphone devices work under many constraints of standardization bodies, they regularize the radio resources. The standardization body, 3GPP, is responsible to make standards for 3G wireless communication technology, it establishes different radio resource states (RRC) for 3G mobile network [3]. The radio states for 3G network operates on the configuration of inactivity timer, in the result of inactivity timer, data operation can save energy and reduce signaling overhead. The set of protocols for 3G network has been defined already to produce long-lasting battery life on different radio states. Despite of the defined protocols for 3G network, energy wastage during transition switching between low and high power consumption states per data operation, remain an issue [4-5]. In contrast to 3G technology, Wi-Fi is a well-accepted wireless communication technology for smart-devices [6].

Wi-Fi radio technology provides high data rate to end-users and helps network operators to offload mobile traffic with high accuracy [7]. IEEE 802.11 defined network states for Wi-Fi that can also be configured at some extent level. Wi-Fi also has inactivity timer that consumes more energy which cannot be ignored [8]. A keen interest has been shown by many researchers and industrial groups for optimization of energy utilization. In literature, several implications have been proposed to overcome this issue.

In literature, research work mainly focuses on energy consumption of individual hardware components or applications based performances [9]. In addition to this, some research has also been done to calculate the energy consumption of individual radio technologies. The bandwidth aggregation schemes were suggested in [10] to enhance live streaming of video using multiple channels. Furthermore, A software-based approach was used in [11] to activate multiple network interface activation on the smartphone.

On the other hand, so far, to the best of our knowledge no work has been investigated in the energy consumption issue for multi-radio in the smartphone. Therefore, we propose an energy consumption model which calculates energy consumption for multi-radios enabled smartphone that simultaneously triggers 3G and Wi-Fi radios. This model computes energy consumption in a real world cellular trace including form-factor investigation. We focus on the packet processing and inactivity timer for 3G RRC states and other different states of Wi-Fi radio during state transitions of both technologies in parallel. Our model gives fine-grained energy consumption of each radio modem along with power consumption of application processor (AP). Our work examines multi-radio energy consumption states for the smartphone. This imparts novelty to our research which has not been discussed yet by any other research group.

In this paper, we propose a workload-based multi-radio energy consumption model that incorporates both a smartphone AP's energy consumption and each modem part (3G and Wi-Fi)'s energy consumption. The proposed model is kind of a simple linear model and easy to apply in the real environment because it considers total workload in an observation period rather than individual packets' behavior (varying inter-packet time and non-uniform packet size). We experiment a comprehensive set of test cases in a real commercial network by changing workload, controlled by a variable packet transmission/reception (UL/DL) rate. Then, we set up a multi-radio energy consumption model that fits well with the measured results.

The remaining part of this paper is organized as follows: The background and related work of both radios are discussed in Section 2. A detailed measurement methodology for the multi-radio smartphone is provided in Section 3. Section 4 presents the multi-radio power model. In Section 5, the findings of proposed energy model are illustrated. Finally, the conclusion of this work is summarized in Section 6.

2. BACKGROUND AND RELATED WORK

2.1. Background (3G and Wi-Fi)

The 3GPP defined protocols for UMTS network and RRC liable to make skillful use of limited resources for the mobile device. The RRC allocates a protocol of state machine to each mobile phone which is connected to a network and contains three transitional states (DCH, FACH, and IDLE). Each state operates under the different configuration of inactivity timer consuming different radio resources and power. In the IDLE state, the mobile device consumes the least amount of energy and does not establish any connection to radio network controller (RNC). DCH state is well known for the dedicated channel; the most credible state for any user because it formulates RRC connection of the mobile device to a network and uses high transmission rate. During FACH state, the connection of smartphone is established with the network, but a user can only transfer low-speed data. FACH has the longest inactivity timer, and it consumes more energy even when the smartphone does not carry out any data operation. The device switches to a higher state when a promotion occurs, and to a low power consuming state in case of demotion.

For offloading data traffic, many operators prefer Wi-Fi over 3G [12-13] because Wi-Fi operates under two radio states, i.e. CONNECTED and IDLE. The Wi-Fi, in CONNECTED state, consumes more energy while performing a data operation. However, this consumption of energy is 10x less than the energy consumed by the 3G. In IDLE state, Wi-Fi consumes a very little amount of energy.

2.2. Related Work

Previous works which have already been done by different research groups described inactivity timer, which gave an overview of RRC state machine causing inefficient overhead due to state promotions. In [14], application resource optimizer (ARO) exposed the cross layer interaction of RRC state between layer 2 and layer 3 of network protocol stack. A deep look of RRC states response by network operators' specific parameters that affect power consumption of application performances as discussed in [8], [15]. By considering the results of previous research the authors in [5], an energy consumption model TailEnder interestingly focused on consumption of tail energy by comparing 3G and Wi-Fi, and introduced, protocol which presented the reduction of energy consumption during modern mobile applications. An experimentation study for per-frame energy consumption of Wi-Fi 802.11 components is conducted in [15], which describes a detailed study of protocol/implementation for both radio. The authors in [6] discovered light sleep mode of Wi-Fi with inter-arrival packet time and inactivity timer that affects UL and DL data operations. Furthermore, in [16] the construction of automated power model technique is introduced into the sensor of built-in battery of smartphone that explicitly controls the power management and activity states of individual components of smartphone. To extend the battery life the authors in [17] proposed a scheme to eliminate tail to discretionary level and it was concluded to save 17% of radio resources and reduced tail timer up-to 60%. A study was conducted in [9] and the author confirmed that 65% to 75% of energy is spent during third-party modules by background processes. Furthermore, a scheduling algorithm was presented in [18], substantiates for Android kernel to improve power efficiency. A very popular power model was testified in [1] to analyze power consumption for network and throughput based radio technologies including; 3G, LTE, and Wi-Fi and gave detailed study for all radios individually. The authors in [10], enabled the multi-radio approach in the operating system (OS) of smartphone, deals with the link aggregation approach that uses both LTE and Wi-Fi radios, resulting in high accuracy in packet streaming during a video. In extension to same approach PIMM [11], proposed a multi-radio power model based on inter-packet time and packet length. They separated an AP's power consumption from that of each radio (LTE or Wi-Fi). However, it is complex to trace each packet's interval and length individually, and also, the derived model coefficients are different for all possible ranges of packet length.

Aforementioned works considered energy consumption of smartphone devices by hardware components, application basis, network latency, interfaces of different radio components, switching based algorithms for various radio states, and individual radio energy utilization. The previous research resulted the power models which work on individual factors or producing very complex models that cannot be applied in the real world network. This motivates us to develop a new power model that can measure the energy consumption of radio components of a smartphone device when device is operating with multiple radios in parallel. Therefore, in this work, by enabling smartphone device to work on both radios (3G and Wi-Fi) in parallel, we present a new power model. This new power model performs fine-grained energy consumption of 3G and Wi-Fi radios for real-world network trace that can compute link capacity of 3G and Wi-Fi with zero packet loss.

3. MEASUREMENT METHODOLOGY

3.1. Measurement Setup

The experimental setup comprises of three components.

3.1.1. Multi-radio Smartphone

The changes are applied to a Samsung Galaxy Nexus smartphone's firmware for enabling 3G and Wi-Fi radio to work simultaneously. The smartphone used during the experimentation, has an Android OS. The default settings of an Android API *Connectivity Manager*, do not allow to activate both radios at the same time. We modified *Mobile Data State Tracker*, *Connectivity Manager and Conectivity Service* APIs and the *teardown* function to enable both radios. We also added routing table by using *iproute*. After these changes the kernel of smartphone OS can simultaneously process packets UL/DL both radio interfaces concurrently.

3.1.2. Power Monitoring Tool

The Monsoon power monitor is chosen, which is widely used and proved to be a highly efficient and accurate tool to measure the power consumption of device [1], [6], [16], [18-19]. In our setup, battery is isolated from the smartphone and directly connected to the computer in order to measure a drainage of power consumption accurately.

3.1.3. Experimental Server

The experimental server is a software-based component which mainly provides dual functions, it reads all the power matrices and provide the file that contains collected data from device. Compiled trace give complete results of power in which device components are included i.e., CPU, display of the screen, 3G, Wi-Fi radios, and other components. To measure accurate power consumption of 3G and Wi-Fi radios, we go through following.

a. The smartphone screen ON, background apps OFF, and sensors OFF.
b. Used back-to-back User Datagram Protocol (UDP) packets.
c. Ensure lowest UDP packet loss.
d. Repeat 25 runs for each test case to get average values.
e. Control workload by varying packet UL/DL rate.

3.2. Baseline Power Consumption of Multi-radio Smartphone

Our focus is on energy consumption of wireless radios, therefore in our experimental setup, we subtract all baseline energy values from the radio energy consumption part.

Table 1 shows the baseline results of different states of smartphone and energy expenditure, as discussed in section 3.1, we took experimentations and summarize results, each result is the average of 25 values which gives a clear glimpse of accurate values.

The display and other hardware components of the multi-radio smartphone consume much more energy but in our experimental setup, we only focus on energy consumption of 3G radio, Wi-Fi radio, and the energy consumed by the AP. By looking into it, we measured the energy consumption of individual components and summarized results in Table 1.

Table 1. Baseline Power Measurements

Smartphone States	Time (sec)	Power (mW)	Energy (mJ)
Screen OFF Radio Off	10	171	171
Screen ON Radio Off	10	734	734
Screen ON 3G ON	10	751	751
Screen ON Wi-Fi ON	10	762	762
Screen ON 3G On Wi-Fi ON	10	774	774
Screen ON App ON	10	827	827
Screen ON App On 3G ON	10	833	833
Screen ON App On Wi-Fi ON	10	831	831
Screen ON App On 3G ON Wi-Fi ON	10	847	847

We first determine the baseline power consumption when a smartphone is in a state with the screen on, radio off, and a measurement App on. The average baseline power obtained from measurement is 827mW. To obtain power and energy induced solely by packet UL/DL, we will extract this baseline power from raw measurement values using Monsoon monitor.

3.3. Using Packet Arrival Rate as a Control Parameter

Data packet contributes a lot to power consumption; TCP packet consumes much more energy during initial message exchange to establish a connection to any point, but UDP packet does not perform this check as it only sends or receive the packet without message exchange. We use UDP packet in our experimental setup. Although, we observe the packet loss as well because if packet loss occurs it causes loss of energy and it does not give power consumption efficiently. We sent back to back UDP packets and control packet generation rate from the server and performed our experimentation to get high throughput with zero loss of packet that makes our power model more robust for both radios during the data operation.

4. MODELING MULTI-RADIO ENERGY CONSUMPTION

We divided our model into two basic sub-models. The first model describes RRC states of 3G and Wi-Fi CONNECTED and IDLE state. The second model examines energy consumption of smartphone of four cases; $3G_{UL}$-$WiFi_{UL}$, $3G_{DL}$-$WiFi_{DL}$, $3G_{UL}$-$WiFi_{DL}$, and $3G_{DL}$-$WiFi_{UL}$.

Figure 1 shows our setup and pattern of separation of energy consumption between 3G and Wi-Fi radios along with energy consumption by the AP during processing of packets with different rates. Table 1 shows power consumption for each radio individually and separately when they do not perform packet processing and also when both radios are enabled without processing of packets, as shown in Figure 1.

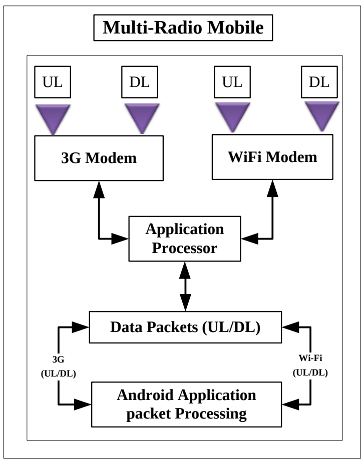

Figure 1. Experimental Setup of AP and Modem

Packets are generated from the developed Android application and the application is developed within 2.5K lines of code by which we can control packet generation, packet inter-arrival time, packet sending direction and calculation of multi-radio throughput. Android application send packets in both directions regarding four test case which will be discussed in Section 4.2. Energy consumption is sub-divided into modem and AP separately, for that (1) gives the mathematical expression.

4.1. Incorporating Radio State

Table 3 describes radio states of both radio technologies. 3G possesses different RRC states according to 3GPP standards and Wi-Fi having its different states according to IEEE.802.11 standards. We summarized all possible states, inactivity timers and expressions for measuring energy for both radios. By looking at the previous discussion we developed a mathematical power model for energy. The energy consumption during radio state transition has also been included as shown in Figure 2 to the total energy. The resulting model is obtained as in (1). We use the notations summarized in Table 2.

Table 2. Notations for Multi-radio Energy Consumption Model

Symbol	Description and Unit
E	Total energy during multi-radio operation (mJ)
E_{active}	Energy in active state during multi-radio operation
α_{ul}	Coefficient for the AP's processing UL data (mJ/Mbits)
α_{dl}	Coefficient for the AP's processing DL data (mJ/Mbits)
χ_{ul}	Coefficient for the 3G modem's processing UL data (mJ/Mbits)
χ_{dl}	Coefficient for the 3G modem's processing DL data (mJ/Mbits)
ω_{ul}	Coefficient for the Wi-Fi modem's processing UL data (mJ/Mbits)
ω_{dl}	Coefficient for the Wi-Fi modem's processing DL data (mJ/Mbits)
β	Coefficient for power consumption in active state (mW/s)
$r_{3g,ul}$	Data rate in 3G UL air (Mbps)
$r_{3g,dl}$	Data rate in 3G DL air (Mbps)
$r_{wifi,ul}$	Data rate in Wi-Fi UL air (Mbps)
$r_{wifi,dl}$	Data rate in Wi-Fi DL air (Mbps)
t	Time period in active state (sec)
$t_{3g,promo}$	Time period in 3G promotion state (sec)
$\rho_{3g,promo}$	Power consumption in 3G promotion state (mW)
$t_{3g,tail1}$	Time period in 3G tail1 state (sec)
$\rho_{3g,tail1}$	Power consumption in 3G promotion state (mW)
$t_{3g,tail2}$	Time period in 3G tail2 state (sec)
$\rho_{3g,tail2}$	Power consumption in 3G promotion state (mW)
$t_{wifi,promo}$	Time period in Wi-Fi promotion state (sec)
$\rho_{wifi,promo}$	Power consumption in Wi-Fi promotion state (mW)
$t_{wifi,tail}$	Time period in Wi-Fi tail state (sec)
$\rho_{wifi,tail}$	Power consumption in Wi-Fi tail state (mW)

Equation (1) is the mathematical expression for energy consumption of multi-radio power model that describes all possible network states and components that consume energy during data packet processing of 3G and Wi-Fi simultaneously. E is the total energy consumption for multi-radio during data operation and all other network states of 3G and Wi-Fi, next section describes four test cases using multi-radio smartphone.

A radio interface undergoes different radio states during a burst of UL/DL. For example, Figure 2a illustrates 3G radio's power trace in which promotion state, active UL/DL state, tail 1 and tail 2 states can be identified. Figure 2b Illustrates Wi-Fi radio's power trace in which promotion phase, active UL/DL state and a tail state can be observed. Therefore, we will separate these promotional and tail states from active UL/DL state and incorporate their components into total energy consumption.

$$E = \rho_{3g,promo}t_{3g,promo} + \rho_{wifi,promo}t_{wifi,promo} + E_{active} + \rho_{3g,tail1}t_{3g,tail1} + \rho_{3g,tail2}t_{3g,tail2} + \rho_{wifi,tail}t_{wifi.tail}. \quad (1)$$

The experimentation setup starts when the multi-radio smartphone is in IDLE mode in which it consumes a negligible amount of energy. To assign RRC state we first sent a UDP packet then device switches to the CONNECTED state, where it will overcome signaling overhead of remaining data operation.

To calculate promotional energy, we calculated promotional time, $t_{3g,promo}$, and average power consumed during 3G promotion, $\rho_{3g,promo}$. Additionally, to calculate energy consumed during tails after data operation we divided tail timers as, $t_{3g,tail1}$, and $t_{3g,tail2}$, the power consumed during both tails are, $\rho_{3g,tail1}$, and $\rho_{3g,tail2}$, parameters. Figure 2 (a) depicts transitional states of 3G.

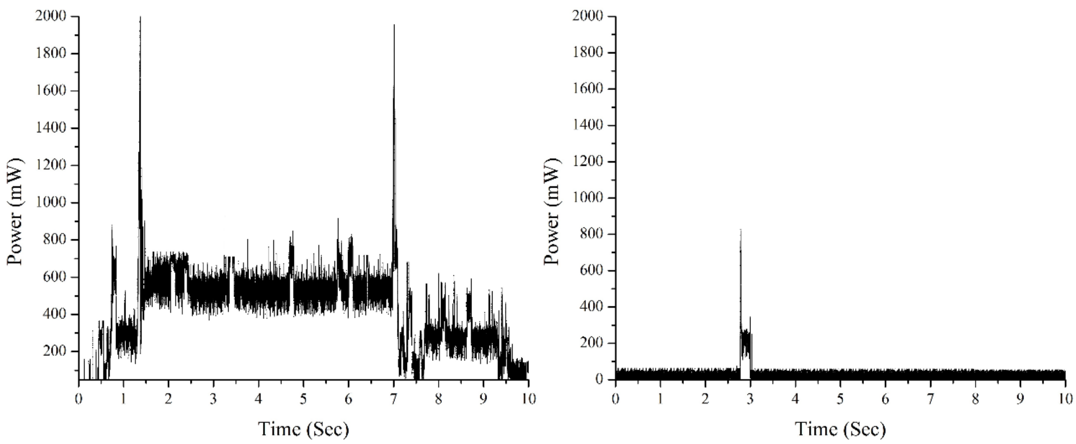

Figure 2. Radio State Transition of 3G radio (2a) and Wi-Fi Radio (2b)

In contrast to 3G, Figure 2 (b) shows transitional states of Wi-Fi. It contains only two states, CONNECTED and SLEEP. The inactivity timer is responsible for demoting radio state to low energy consumption state when no data operation occurs during the IDLE period and then goes to SLEEP mode. To calculate energy consumption during transitional states, in our power model, we set different parameters as summarized in Table 3 using (1).

Table 3. 3G and Wi-Fi Network States and Energy Consumption

Radio States	Time (sec)	Power (mW)	Energy (mJ)
3G promotion	1.4	403	564
3G tail 1	4.56	530	2416
3G tail 2	2.71	210	569
Wi-Fi promotion	0.02	360	7.2
Wi-Fi tail	0.254	690	175

4.2. Incorporating Packet Transmission/Reception Combinations

In a smartphone, UL of a packet is a two steps process. The first step is the AP's handling, includes the creation of a socket, TCP/IP stack processing, inter-processor communication with modem processors. The second step is a modem part, includes baseband processor, Radio Frequency Integrated Chipset (RFIC), RF chain such as power amplifier, and antenna and similarly for DL of a packet. We incorporate this consideration in our proposed multi-radio energy consumption model by separating the AP's energy consumption and each modem part's energy consumption.

4.2.1. 3G$_{UL}$ and Wi-Fi$_{UL}$

In this case, smartphone perform processing of data packets by using only UL from both radios. 3G and Wi-Fi start UL at the same time, node to node delay is being calculated to make sure that packet transmission is started at the same time from both radios. The reason is, Wi-Fi does not take long time for promotion as compare to 3G network, results are mentioned in Table 3. We used (2) to calculate the total energy consumption of 3G, Wi-Fi modems.

$$E_{active} = \alpha_{ul}(r_{3g,ul} + r_{wifi,ul})t + \chi_{ul} r_{3g,ul} t + \omega_{ul} r_{wifi,ul} t + \beta t. \tag{2}$$

The parameter for 3G and Wi-Fi are packet transmission are $r_{3g,ul}$ and $r_{wifi,ul}$ to control the rate of packets respectively, and α_{ul}, χ_{ul}, and ω_{ul} are co-efficient that are well-suited in to our power model.

4.2.2. 3GDL and Wi-FiDL

In this case, both radios perform DL data operation, as the node to node delay for both radios is already calculated. Therefore, packet reception is started at the same time from both radios simultaneously. To calculate total energy consumed during data processing and other network states, we used (3), given as

$$E_{active} = \alpha_{dl}(r_{3g,dl} + r_{wifi,dl})t + \chi_{dl} r_{3g,dl} t + \omega_{dl} r_{wifi,dl} t + \beta t \tag{3}$$

where α_{dl}, χ_{dl}, and ω_{dl} are the coefficients that are well suited to our model, $r_{3g,dl}$ and $r_{wifi,dl}$ are the parameters for controlling DL packet rate. From figures 3 and 4, it can be observed that the DL operation consume less energy as compared to UL. This difference in energy consumption occurs because of different hardware components.

4.2.3. 3GUL and Wi-FiDL

In this case, smartphone performs 3G UL and Wi-Fi DL packet processing. We used (4) to compute total energy consumption for both radios during active state of radios.

$$E_{active} = \alpha_{ul} r_{3g,ul} t + \alpha_{dl} r_{wifi,dl} t + \chi_{ul} r_{3g,ul} t + \omega_{dl} r_{wifi,dl} t + \beta t. \tag{4}$$

We use $r_{3g,ul}$ and $r_{wifi,dl}$ parameters to control the data packet flow for 3G UL and Wi-Fi DL respectively, the packets are generated and controlled from our developed program and calculate the energy consumption, α_{ul}, α_{dl}, χ_{ul}, and ω_{dl} are coefficients that best fit in this case.

4.2.4. 3GDL and Wi-FiUL

In this case, 3G performs DL and Wi-Fi performs UL data operation. We used (5) to calculate the energy consumption of active network states, during packet processing in AP, and both radios to send and receive data packets.

$$E_{active} = \alpha_{dl} r_{3g,dl} t + \alpha_{ul} r_{wifi,ul} t + \chi_{dl} r_{3g,dl} t + \omega_{ul} r_{wifi,ul} t + \beta t. \tag{5}$$

The rate controlling parameters for 3G DL and Wi-Fi UL are $r_{3g,dl}$ and $r_{wifi,ul}$ respectively. α_{ul} and α_{dl} are the coefficients for AP energy consumption, χ_{dl} and ω_{ul} are coefficients for energy consumption of 3G and Wi-Fi radios.

5. EVALUATION

5.1. Finding Model Coefficients

Multi-radio energy consumption model calculates the energy consumed in each component of the device, it involves data packet processing and network states. In the proposed model, we calculate energy consumption by varying packet rate as a controlling parameter and examine the behavior of network components along with energy consumption pattern. We found each coefficient represented in (1) by sub-dividing into four cases as discussed in preceding section.

Table 4. Determined Coefficients

Coefficients	α_{dl}	α_{dl}	χ_{ul}	χ_{dl}	ω_{ul}	ω_{dl}	β
Value	0.319	0.236	4.955	3.329	3.217	1.752	72.089

Table 4 shows the value of coefficients and Table 5 summarizes the model-driven coefficients for consumption of energy during all four test cases. The stability of model is proved from the value of R^2, it is the regression analysis coefficient and if the value is more than 80~90% the model shows the validity of derived coefficients that satisfy the driven model. The model-driven coefficients are showing high confidence level obtained by the linear regression that is more than 98% in each case (R^2 =1 means the approximation is perfectly fit). The unit for each coefficient is mJ/Mbps. Summary of standard error estimation in all test cases is shown in the Table 5 for redundant test cases.

Table 5. Validation of the Model in all Cases for Active State

Radio States	Standard error estimation		R^2 (%)
	3G (%)	Wi-Fi (%)	
$3G_{UL}$ and Wi-Fi_{UL}	3.2	1	98.9
$3G_{DL}$ and Wi-Fi_{DL}	5.2	1.2	95.7
$3G_{UL}$ and Wi-Fi_{DL}	11.8	0.7	98.1
$3G_{DL}$ and Wi-Fi_{UL}	5.2	1.2	98.8

Figure 3 shows the measured and calculated energy consumption of 3G UL and Wi-Fi UL modem by varying the rate of 3G and Wi-Fi packet UL. With the maximum packet rate of 3G, we have achieved throughput of 1.16 Mbps and 34.2 Mbps of throughput of Wi-Fi without any packet loss.

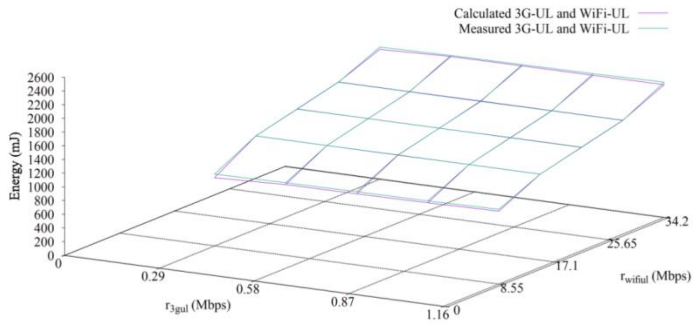

Figure 3. Comparison of Measured Versus Calculated Results for a Case of 3G and Wi-Fi Uplink

Figure 4 shows the calculated and measured energy consumption pattern of 3G and Wi-Fi by varying the rate of packet DL of both radios. With maximum packet rate, we have achieved throughput of 33 Mbps of Wi-Fi and 7.6 Mbps of 3G. The amount of energy consumption can be analyzed from the graph, as the packet rate increases the energy consumption also increases. As compared to UL case it consumed less energy because modem process DL operation.

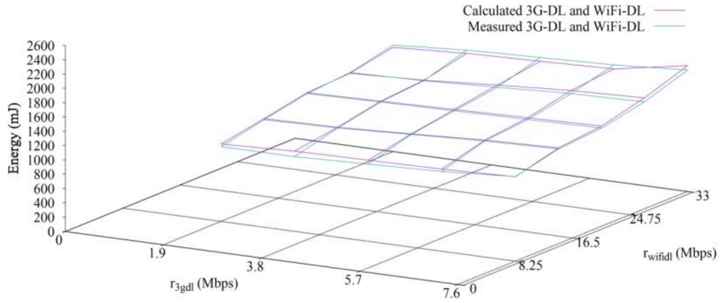

Figure 4. Comparison of Measured Versus Calculated Results for a Case of 3G and Wi-Fi Downlink

Figure 5 shows the measured and calculated energy consumption of 3G UL and Wi-Fi DL by varying the packet rate of 3G and Wi-Fi. With the maximum packet rate of 3G, we have achieved throughput of 1.16 Mbps and for Wi-Fi downlink 33 Mbps.

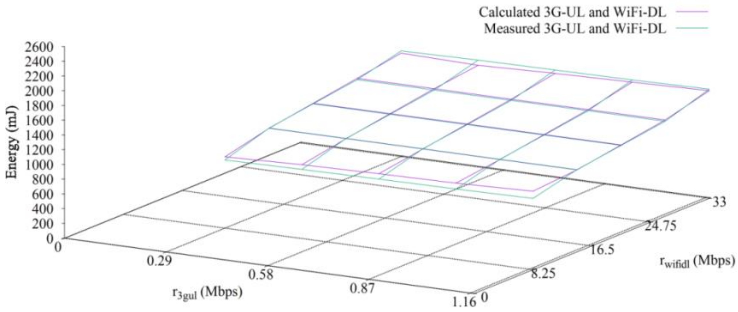

Figure 5. Comparison of Measured Versus Calculated Results for a case of 3G Uplink and Wi-Fi Downlink

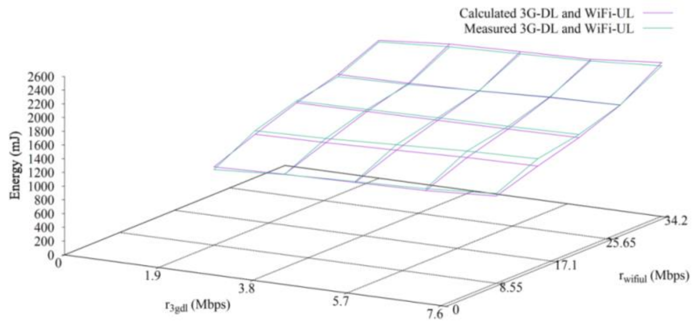

Figure 6. Comparison of Measured Versus Calculated Results for a Case of 3G Downlink and Wi-Fi Uplink

Figure 6 shows the calculated and measured energy consumption of 3G DL and Wi-Fi UL modem by sending burst of packet on both radios in both directions. The 3D graph explicitly shows that data rate consumed the maximum amount of energy as compared to other cases. This is because both radios are performing maximum rate of data processing and hence, a greater number of packets are involved.

Therefore, the highest amount of energy consumption is observed in this case. With the maximum packet rate, we have achieved throughput for Wi-Fi-UL is 34.2Mbps and 3G DL throughput of 7.6Mbps. In our methodology no packet loss is observed, it is therefore controlled to minimize the energy consumption of network components.

To analyze the results, all test cases are discussed, and the graphs are presented. The coefficient for 3G and Wi-Fi are derived from the system model equations. The increase in energy consumption is more linear as compared to energy measured by the power monitor, consumption of energy divided by energy consumed by AP and both radios. The system model provides the most fine-grained trace of the energy consumption.

6. CONCLUSION

A new workload-based energy consumption model for a 3G/Wi-Fi multi-radio smartphone is presented. It incorporates the energy consumption of both the AP and each part of the modem with high accuracy and zero packet loss. The demonstration of the proposed model fits well and gives 98% accuracy with measurement results in a real commercial network. The proposed model is derived from a particular multi-radio smartphone. The methodology and modeling approach presented in this paper for a smartphone can be applied to other multi-radio smart devices as well.

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