Journal of Global Research in Electronics and Communication
Volume 2, No. 2, February 2025
Available Online at: https://jgrec.info/index.php/jgrec/index
ISSN: 2321-3175

REVIEW ARTICLE

Energy-Efficient Solutions for Extending Battery Life in Mobile Devices: Challenges and Innovations

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***Abstract*—Energy conservation in mobile devices has become increasingly critical due to rising power consumption and the growing complexity of modern applications. As mobile devices like smartphones become integral to daily life, battery life has emerged as a key concern. With power-hungry applications such as GPS, 5G, video streaming, and location-based services, energy efficiency is paramount. This paper explores factors influencing energy consumption, strategies to reduce power usage, and solutions to extend battery life, including hardware and software optimizations, energy-efficient technologies, and machine learning-based power management. Additionally, it discusses challenges such as background application activity, idle power consumption, and hardware limitations while investigating innovative approaches like AI-powered optimization, energy harvesting, and edge computing. Finally, it outlines future research trends, emphasizing advancements in battery technologies, AI and IoT integration, and energy management systems for improving mobile device energy efficiency.**

Keywords—Energy efficiency, battery life, energy consumption, AI, IoT, Mobile Devices.

I. INTRODUCTION

Modern digital circuit designers are becoming more and more concerned with energy conservation. With groundbreaking system performance and the advancement of digital technology into the twenty-first century, these circuits' power consumption is at all-time highs. In actuality, energy loss in the form of heat or power dissipation is approaching nuclear reactor levels. Chip reliability and life expectancy are sometimes compromised or impaired by the detrimental effects of power dissipation [1].

It has evolved into a vital piece of equipment in modern life. It is an electronic device that may be used for a variety of tasks, including running programs, connecting to wireless networks, and exchanging data in cloud computing and network environments. Its energy source is a battery. These batteries take 1 to 4 hours to charge, which is insufficient for a few hours of conversation time—up to 14 hours is the most. Social media, gaming, location-aware apps, streaming videos, and device connectivity are all done on mobile phones. The mobile device had to perform a great deal of processing to meet these criteria. When processing, a lot of electricity energy is used [2].

A battery-operated electronic gadget that weighs less than two pounds is considered portable. Although e-readers, headphones, and tables are all regarded as portable electronics, smartphones are by far the most widely used. Smartphone functionality has advanced to the point that it is now an essential part of their everyday lives. In actuality, personal computers are being replaced by cell phones. There were 1.54 billion cell phones sold globally between 2007 and 2017, and by 2020, that figure is expected to rise to 1.7 billion. 40% of people worldwide are expected to own a smartphone by 2021[3]. A detailed look at the features built into smartphones will reveal that they employ a range of sensors, ROMs that are in the gigabyte range, and RAMs that are equivalent to those found in computers. By the end of the first quarter of 2018, smartphone users may also pick from 3.8 million programs available in marketplaces such as the Apple App Store and Google Play [4].

Over the past few decades, the use of mobile devices has been steadily rising. Numerous complex jobs can already be completed by smartphones. Apple's iPad is leading the way in the breakthrough of tablet PCs at the same time. Additionally, a lot of gadgets are becoming more commonplace and blending in with their surroundings, and smart clothing is on the verge of becoming a reality. The demands they place on these various technologies rise along with their appearance and popularity [5].

Applications that use less energy are becoming more and more in demand every day. More innovative smartphone apps are now being created and utilized worldwide, utilizing power-hungry innovations like GPS, 5G, and Wi-Fi. Compared to common apps like email and texting, these ones demand higher processing power. FaceTime, YouTube, and other video streaming apps are widely used by millennials and rapidly deplete battery life. However, the user may prolong battery life by using a power-saving approach if they are aware of how their smartphone's battery is being utilized [3].

A. Structure of paper

This document has the following structure: Section II discusses factors influencing mobile device energy consumption; Section III explores strategies for reducing energy use; Section IV examines energy-efficient solutions and optimizations; Section V addresses challenges in extending battery life; Section VI investigates innovative approaches like AI and energy harvesting; and Conclusions and recommendations for further study are presented in Section VII.

II. Energy Consumption In Mobile Devices

Numerical errors occur in the mobile world and can occur in the operating system, apps, hardware, firmware, or external devices. These days, e-bugs, also known as energy bugs, are another new type of bug that has been discovered [6]. The primary energy source for mobile devices is energy. During e-bug, the mobiles use a surprising amount of energy. However, in response to the demands of mobile consumers, new methods and resources are being offered at a quick pace. The system that determines the power estimation is called an energy management system (EMS)[7], efficiency and performance of a certain system whose power consumption is available [8]. The maker of mobile phones claims that there are just two fundamental elements that determine energy consumption: operating systems and apps. Nevertheless, there are other energy-consuming elements that contribute to wireless optimization, sensors, and user interface [9], As illustrated by Figure 1.

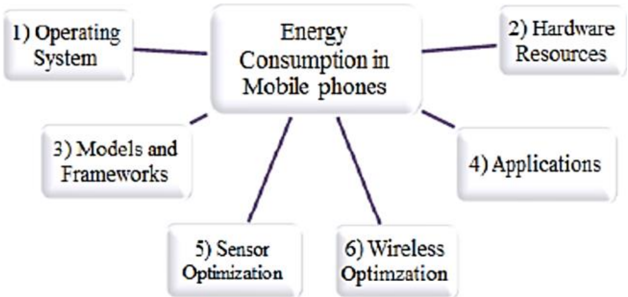

Fig. 1. Energy Consumption in Mobile Phones

The energy patterns of mobile workloads exist as a result of multiple factors involving hardware usage along with application requirements and network performance[10]. High performance activities such as gaming, together with video streaming and artificial intelligence driven computations, waste battery power because these applications overload CPU, GPU and memory resources. Passive energy utilization results from multiple background functions which involve push notifications along with location tracking as well as cloud synchronization[11].

Energy efficiency is influenced by display technologies, which mainly include high-refresh-rate screens. The power utilization of mobile devices depends on wireless signals through 5G and Wi-Fi as well as Bluetooth, which adjusts based on signal quality and data flow speed[12]. Mobile device battery performance depends heavily on efficient software and hardware design approaches that optimize fundamental operational factors[13].

The several tactics that may be used to lower mobile devices' energy usage include:

A. *Reduce power consumption by wireless interface:*

Any portable device's battery is a common issue, and its wireless interface is its most important component. It uses the mobile system's maximum power. For instance, there are several options that are crucial to power optimization:

- LTE can reduce the energy cost per transmitted bit.
- Bluetooth low energy.
- Low power Wi-Fi technique.

B. *User interaction and application:*

Gaining more insight into how users interact with their batteries and resources is crucial to extending battery life. The ability to determine when, where, and how the user depletes the battery, as well as when future charging changes will occur, is essential for any energy-aware system [14].

C. *Sensor optimization:*

In order to update locally relevant information and fulfill user requests, mobile applications frequently require location data. Various location sensor types with varying resolutions and energy requirements are found in contemporary smartphones: The average inaccuracy of GPS, Wi-Fi-based, and GSM location sensors is around 400, 40, and 10 meters, respectively [15]. Despite its greater energy requirements, GPS is frequently chosen over its alternatives, such as positioning systems based on GSM or WiFi, since it is known to be more accurate. These sensing devices can employ one of two sorts of solutions to reduce their power consumption:

- A system that minimizes inaccuracy and lowers energy usage by combining various sensors.
- Techniques that only employ probabilistic user location models to predict future locations in order to minimize the amount of sensor reads.

D. *Reducing the brightness of smartphones:*

One of the primary causes of cell phone battery drain is brightness. The phone has many brightness levels that you may adjust, including high, medium, low, and automatic[16]. This brightness may be reduced to save the battery life of the mobile device. Reducing or removing the brightness might help prolong battery life.

E. *Battery saving mode:*

The user may always monitor the battery level indication while thinking about the battery. It is preferable to check the battery level indication when the user has fewer opportunities to charge the smartphone. Turn on the battery-saving mode if the indication is less than 50% [17]. As a result, a number of additional functions that are significantly draining the battery would be turned off. The battery would be preserved by automatically terminating a number of services. For instance, because the program is not operating in the background, emails are not automatically received. However, the user has the option to utilize and manually work on emails[18].

III. Energy Efficient Solutions For Extending Battery Life In Mobile Devices

As mobile devices are used more and more for communication, entertainment, and work, battery life has emerged as a critical component affecting user experience.[19]. Energy efficient solutions are essential to prolong battery lifespan, reduce energy consumption, and enhance overall device performance[5]. This explores various techniques and technologies that help extend battery life in mobile devices.

A. *Hardware Optimization*

1) *Low-Power Processors*

Modern mobile devices incorporate energy-efficient processors designed to optimize power consumption. Chip manufacturers, such as Qualcomm and Apple, develop system-on-chip (SoC) architectures with lower nanometer fabrication processes[20], enabling reduced voltage requirements and lower energy usage.

2) Adaptive Display Technologies

Displays consume a significant portion of battery power. Technologies such as AMOLED and LTPO (Low-Temperature Polycrystalline Oxide) screens dynamically adjust refresh rates and brightness based on usage patterns, reducing unnecessary power drain[21].

3) Energy-Efficient Memory and Storage

Using low-power RAM and optimized storage solutions, such as UFS (Universal Flash Storage), contributes to reducing energy consumption while maintaining high performance[22].

B. Software Optimization

1) Power Management Algorithms

Operating systems like Android and iOS incorporate advanced power management algorithms to regulate background app activity[23], optimize CPU performance, and reduce energy consumption.

2) Adaptive Battery and App Optimization

Machine learning-based adaptive battery features analyze user behavior and restrict power-intensive applications from consuming excessive resources when not in use.

3) Dark Mode Implementation

Enabling dark mode on OLED and AMOLED screens significantly reduces power consumption by minimizing pixel illumination and extending battery life in compatible devices[24].

IV. Challenges In Extending Battery Life

Phone battery life faces several challenges because modern applications combined with hardware requirements continually extend performance demands. Key challenges include:

- **Background Application Activity:** The background status of many programs uses resources from the CPU to memory, GPS, Wi-Fi, and cellular data[25]. The constant operation of these applications creates massive energy consumption.
- **Idle Power Consumption:** Smartphones continuously drain power from batteries even when in standby condition because of their operating background activities alongside sending and receiving network signals. Power savings through ambient light energy harvesting techniques face implementation challenges despite attempts to counteract idle power consumption [26].
- **User Behavior and Application Usage:** The precise prediction of battery duration proves challenging because users interact differently and employ applications uniquely[27]. The development of models which forecast battery consumption based on real-time usage data poses a complex challenge that needs thorough data analysis [28].
- **Energy-Intensive Features:** The combination of high-resolution displays and constant network connectivity and location services reduces battery run time. Users face an ongoing challenge in managing energy consumption and selecting the right amount of use for high-consumption features[29].
- **Hardware Limitations:** The fast-growing power requirements of smartphones exceed the current advancements made in battery technology[30]. This disparity necessitates the development of more efficient energy management strategies and innovative hardware solutions [31].

V. Innovative Approaches And Technologies

The energy efficiency of mobile devices improves through innovative technologies and approaches that utilize AI power optimization systems, energy harvesting abilities, edge computing platforms and advanced charging developments. Together, these solutions utilize machine learning to optimize power management while extracting ambient energy and distributing computation tasks to minimize device energy consumption. Combined technologies enable mobile devices to extend battery duration and, operate faster and require less frequent battery recharges.

- **AI and Machine Learning for Energy Efficiency:** Machine learning (ML) and artificial intelligence (AI) have become potent instruments. Because of their size and weight, smartphones have a limited battery life. As a result, the smartphone's energy efficiency is essential to its functionality. They suggest adaptable power management modes to prioritize smartphone application access depending on users' demands to save battery life in order to address the rising concern of power utilization optimizations for smartphones[32]. Despite introducing common low-power modes and Doze settings, Android and Apple fail to take into account each user's unique smartphone use profile and dynamically adjust program management to suit their demands[3].
- **Energy Harvesting:** Energy harvesting technology involves the extraction of ambient renewable energy for powering devices while lengthening device battery duration and reducing recharging requirements. Researchers have examined this method for application in mobile technologies as well as wearable devices [33].
- **Edge Computing and Distributed Processing:** Mobile device power consumption decreases when computation moves closer to network infrastructure edges or fulfills those tasks in the cloud [34].
- **Battery Charging Innovations:** The advancement of battery charging through wireless charging fast charging methods and smart charging technology works to shorten charging times as well as extend battery durability [35].

VI. Future Directions And Research Trends

Mobile device energy efficiency gains from improved battery technology and energy management designs remain essential to the field. Scientific work investigates upcoming battery developments alongside methods for AI and IoT integration to enhance power management capabilities and analyses how regulatory criteria affect device design supervision.

A. Next Generation Battery Technologies:

- Current battery develops new technologies that use better storage capacities while giving increased security measures and stretching charging intervals [36].

- A describes the latest developments in metal-air, lithium-sulfur, and solid-state batteries, as well as how well-suited they are for use in the mobile device industry. This examines recent advances in metal-ion batteries that show potential as future lithium-ion battery replacements [37].

B. AI and IOT Integration for Energy Management:

- Artificial Intelligence (AI) dramatically improves energy efficiency to improve battery endurance in mobile devices. Cellular devices employ machine learning methods to assess battery states and enhance both power-saving techniques, battery life prediction capabilities, and energy distribution strategies. Bandwidth usage patterns enable AI systems to modify device settings automatically and this reduces electrical power consumption during inactive periods [38].
- In a similar vein, it is anticipated that integrating machine learning and artificial intelligence (AI) with battery management systems would be essential to maximizing charging and discharging cycles and so prolonging battery life.

C. Solid-State Li-Ion Micro-Batteries

The market for micro batteries may be lower than that for stationary power grid and electromobility applications, lithium-ion micro battery technology is important for a wide range of applications. Growth projections predict that by 2028, the company will have increased from a 2023 valuation of 0.5 billion USD to 1.3 billion USD[36].

VII. Literature Review

This section examines the research on ways to prolong a mobile device's battery life. Strategies to increase the battery life of mobile devices, and provide a summary in Table I:

In the study, Eppe et al. (2024) investigated secondary-battery-powered mobile computing and electronics, users often face premature battery drain due to incorrect discharge. Understanding battery electrochemical properties and synchronizing these with appliance load characteristics can prolong battery life. Strategies can enhance battery charge retention and reduce the number of charging and discharging cycles. They provide an algorithm and experimental investigation to support this, enhancing battery life and reducing usage[39].

In this study, Jiang et al. (2024) to optimize battery life and effectively utilize the device's computational capacity, a battery-aware workflow scheduling technique is suggested. Using deep neural networks to speed up budget optimization, a dynamic optimal budget strategy is first created to choose the most cost-effective processors to complete each job by the deadline. In order to reduce battery deterioration, the start time of each job is determined using an integer-programming greedy method that minimizes battery supply current variation. Lastly, the battery simulator, SLIDE, is used for Monte Carlo experiments and a long-term operation experiment. Results from experiments conducted over 1800 hours in real-world settings confirm that the suggested scheduling technique may successfully increase battery life by 7.31% to 8.23%[40].

In this study, Panimathi et al. (2024) proposed a precise technique for predicting from impedance the battery capacity at different temperatures and states of charge is proposed. The findings collected demonstrate the effectiveness of utilizing machine learning approaches to properly estimate battery health (SOC), as they incorporate relevant input parameters that have a significant impact on battery SOC. This technique can be especially beneficial in situations where knowing the remaining capacity of a battery is crucial, like in electric vehicles or portable electronic devices. This work therefore provides a basis for creating reliable battery health monitoring systems and improving battery use across a variety of applications[41].

This study, Flores-Martin, Laso and Herrera (2024)] tackled the problem of utilizing artificial intelligence methods, particularly deep learning, to forecast smartphone battery use in order to maximize energy efficiency. We created a prediction model based on user-specific behavior by gathering and evaluating data from mobile devices, including battery temperature, network type, screen time, application usage, and more. This model offers individualized energy-saving techniques and pinpoints the major factors influencing battery use. This method provides a way to enhance battery performance while adjusting to individual usage patterns and promoting more effective energy management in terms of both hardware and networking. Based on user-specific usage, the findings show that their method can considerably forecast the battery to anticipate power demands. Although there are still issues to be resolved, such as enhancing the model's generalizability across various devices, this strategy offers a scalable and flexible way to raise smartphone energy efficiency, enabling the suggestion of effective management solutions that will enhance battery and network management to enhance user experience and device longevity[38].

In this study, Shafiq et al. (2022) examined green energy harvesting techniques such as solar and radio frequency, contrasting power sources and electrical circuits. Egypt's mobile phones are becoming more efficient for everyday tasks, but they require regular battery charging for multimedia applications like video games. Innovations in energy-collecting technologies are being developed to increase battery longevity. This allows wireless or portable systems to be self-sufficient and battery-independent[42].

In this study, Barik, Singhal and Datta (2020) proposed UDAS as a dynamic adaptive multimedia streaming strategy for heterogeneous users that is utility-based. It enables low-battery users extend their battery life and makes optimal use of the wireless channel's bandwidth. Quality, power consumption, packet error ratio, and remaining battery are the four utility functions of the user devices that the adaptation algorithm takes into account at each scheduling interval in order to dynamically adjust the data rate. Maximizing a combined utility function of these four utilities is the optimization problem they pose. The finest adaptive multimedia material is chosen for end users to get at each scheduling interval thanks to the problem's solution. Videos are encoded using HEVC (high efficiency video coding) on-demand by the mobile edge computing (MEC) server located at the base station, which then chooses the most appropriate videos for various users. When compared to the most advanced non-adaptive multimedia streaming schemes and a well-liked scheme, simulation findings confirm that UDAS performs better in terms of battery energy savings and the number of low-battery customers that are not serviced. ESDOAS from literary sources[43].

In the following Table I, provide existing energy-efficient ways to extend mobile devices' battery life:

TABLE I. SUMMARIZING THE RELATED WORKS ON ENERGY-EFFICIENT WAYS TO EXTEND MOBILE DEVICES' BATTERY LIFE.

Ref	Focus Area	Key Contributions	Challenges/Obstacles	Limitations/Future Works
Eppe et al. (2024)	Battery Discharge Optimization	Developed an algorithm and conducted experiments to enhance battery life and reduce usage.	Incorrect discharge patterns leading to premature battery drain.	Further research is needed on optimizing electrochemical properties across different device types.
Jiang et al. (2024)	Battery-aware Workflow Scheduling	Proposed a scheduling algorithm using deep neural networks to maximize battery lifetime.	Minimizing battery degradation while ensuring computing efficiency.	Generalization across various computing environments and processor types needs improvement.
Panimathi et al., (2024)	Battery Health Prediction	Developed a machine learning-based approach for predicting battery capacity based on impedance.	Variability in temperature and state of charge affecting prediction accuracy.	Future studies should explore more input parameters and real-time applications in diverse conditions.
Flores-Martin, Laso and Herrera, (2024)	Smartphone Battery Consumption Prediction	Developed an AI-based model for predicting battery usage based on user behavior and system parameters.	Diverse smartphone models and usage patterns introduce variability.	Improving generalizability and adapting to different smartphone ecosystems is required.
Shafiq et al., (2022)	Energy Harvesting for Mobile Devices	Examined sustainable energy-gathering techniques such as solar and radio frequency.	Limited energy harvesting efficiency for high-power applications.	Further development is required for self-sustaining battery-independent mobile systems.
Barik, Singhal and Datta, (2020)	Adaptive Multimedia Streaming for Battery Efficiency	Developed UDAS, a dynamic streaming scheme to extend battery life and optimize bandwidth usage.	Balancing video quality and power efficiency across different user devices.	Further improvements are needed for real-world deployment and diverse network conditions.

VIII. CONCLUSION & FUTURE WORK

An increase in energy consumption, which in turn affects battery life, has resulted from the fast development and expanding functionality of mobile devices. Efficient power management is crucial for extending battery duration and enhancing user experience. Strategies such as hardware optimization, software management, and energy-efficient solutions are essential in addressing these challenges. Innovative approaches, including AI-driven power optimization, energy harvesting, and edge computing, offer promising solutions for improving energy efficiency in mobile devices. Ongoing research into next-generation battery technologies and AI integration will continue to drive progress in mobile energy management.

The creation of next-generation battery technologies, including solid-state and lithium-sulfur batteries, needs to be the primary emphasis of future research to meet the growing demands of mobile devices. Additionally, integrating AI and IoT for smarter energy management, improving charging technologies, and exploring energy harvesting techniques will be crucial in optimizing power usage. These advancements are expected to significantly extend battery life and improve overall mobile device performance.

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