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Power Consumption Analysis, Measurement, Management, and Issues: A State-of-the-Art Review of Smartphone Battery and Energy Usage

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ABSTRACT The advancement and popularity of smartphones have made it an essential and all-purpose device. But lack of advancement in battery technology has held back its optimum potential. Therefore, considering its scarcity, optimal use and efficient management of energy are crucial in a smartphone. For that, a fair understanding of a smartphone's energy consumption factors is necessary for both users and device manufacturers, along with other stakeholders in the smartphone ecosystem. It is important to assess how much of the device's energy is consumed by which components and under what circumstances. This paper provides a generalized, but detailed analysis of the power consumption causes (internal and external) of a smartphone and also offers suggestive measures to minimize the consumption for each factor. The main contribution of this paper is four comprehensive literature reviews on: 1) smartphone's power consumption assessment and estimation (including power consumption analysis and modelling); 2) power consumption management for smartphones (including energy-saving methods and techniques); 3) state-of-the-art of the research and commercial developments of smartphone batteries (including alternative power sources); and 4) mitigating the hazardous issues of smartphones' batteries (with a details explanation of the issues). The research works are further subcategorized based on different research and solution approaches. A good number of recent empirical research works are considered for this comprehensive review, and each of them is succinctly analysed and discussed.

INDEX TERMS Battery availability prediction, battery capacity, battery charging, energy profiling, energy-saving techniques, hazards, issues, Lithium-ion batteries, power consumption estimation, power consumption modelling, power management.

I. INTRODUCTION

A. BACKDROP

The general purpose and mass computing revolution began with the emergence of the microcomputers and the PC, in the 1970s, which took out the big immobile centralized computer systems from the fixed dedicated rooms to ones' desktop [1]–[3]. With the advancement in miniaturized hardware, the size of computers gradually became smaller, ultimately bringing a new computing paradigm called mobile computing (also referred as nomadic computing) [4]–[6]. Over the years, the mobile computing scenario also has changed drastically, and with the emergence of smartphones, mobile devices have become our new computers in a true sense [7]. Significant advancement in smartphones such as intensification in the raw computing power,

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efficient OSs, or supporting feature-rich application-based functionalities, etc., can be attributed for the key enablers for this [8], [9]. In fact, today's smartphones are fairly compared to yesteryear's supercomputers [10]. A networked grid of these smartphones offers a suitable alternative to the large data centre based computing systems as well as supercomputers, providing a feasible and promising solution for economic and sustainable HPC [10], [11]. This has been made possible because modern smartphones are loaded with highly capable computing hardware such as [12]:

- Powerful SoCs.
- Multi-core CPUs, GPUs, and GPGPUs.
- Several specific-purpose processors such as DSP, ISP, etc.
- Large RAM, ROM, and flash memory.

Not only as a computing device, but also the accessibility, portability, and ubiquity of smartphones have instigated several innovative application areas. For example, smartphones have become a crucial enabler for smart homes and smart cities, supporting context-awareness [13] for the IoT [14], the primary component of a smart city [15]–[17] and its core elements like smart building [18], [19], smart traffic [20], [21], smart parking [22], [23], etc. Besides, smartphones have demonstrated promising potential in many other application areas, as mentioned in Table 1. In addition to computing capabilities, the following assets of modern smartphones are the motivation for the diverse usage of smartphones:

- Apt, efficient, and feature-rich OS.
- Capability of running web browser-based applications.
- High-resolution and large displays.
- Cutting-edge wireless communication.
- Multiple network interfaces that support operations of different wireless communications simultaneously.
- A number of internal and external sensors.

TABLE 1. Usage of smartphones and smartphone-based apps in various application areas.

Application area	References
Smart home and smart building	[24], [25], [26], [27], [28], [29], [30]
Smart city	[31], [32], [33], [34], [35], [36], [37]
Urban development and construction	[38], [39], [40], [41], [42], [43], [44]
Traffic, transport, and driving	[45], [46], [47], [48], [49], [50], [51]
Disaster management	[52], [53], [54], [55], [56], [57], [58]
Society	[59], [60], [61], [62], [63], [64], [65]
Environment	[66], [67], [68], [69], [70], [71], [72]
Agriculture and plants and trees	[73], [74], [75], [76], [77], [78], [79]
Business, e-commerce, and CRM	[80], [81], [82], [83], [84], [85], [86]
Consumer service	[87], [88], [89], [90], [91], [92], [93]
Travel and tourism	[94], [95], [96], [97], [98], [99], [100], [101]
Education and e-learning	[102], [103], [104], [105], [106], [107], [108]
Healthcare	[109], [110], [111], [112], [113], [114], [115]
Clinical care	[116], [117], [118], [119], [120], [121], [122]
Fitness and wellbeing	[123], [124], [125], [126], [127], [128], [129], [130]
Human activity recognition	[131], [132], [133], [134], [135], [136], [137]
Disability	[138], [139], [140], [141], [142], [143], [144], [145]
Elderly care	[146], [147], [148], [149], [150], [151]
Childcare	[152], [153], [154]. [155], [156], [157]
Animal care and management	[158], [159], [160], [161], [162], [163]
Science	[164], [165], [166], [167], [168], [169]
Chemical analysis	[170], [171], [172], [173], [174], [175], [176]
Military and forces	[177], [178], [179], [180], [181], [182], [183]
Affective computing	[184], [185], [186], [187], [188], [189], [190]

B. ISSUE

Commensurate with the hardware capabilities, application developers are encouraged to develop enriched and complex apps for smartphones which are supposed to make the life of the users easy, as exampled in Table 1. Depending on the functionality, most of these applications demand intense computation and high-speed data transmission [191]. Also, as per application requirements, many of the apps want rich contextual information which are acquired through different embedded sensors [192]. These functionalities in a modern smartphone demand much more power compared to the feature phones with only basic capabilities such as voice calls and SMS [191]. Along with the high usage, the combination of heavy hardware and software has increased the energy demand severely.

The smartphone receives the required energy, to run itself, from the battery within it. Typically, a rechargeable battery is used for this purpose, which may be implanted (fixed) within the device or may be detachable. The battery accumulates energy when it is being charged, stores the energy for a duration and that is discharged when the device is on or/and in operation. Due to this continuous discharging, and the fact that the batteries of mobile devices are limited in capacity, the battery needs to be recharged periodically and most often in quick succession (maybe several times in a day, depending on several parameters, as discussed in Section 4).

The energy capacity of a battery is determined and constrained by its chemical properties. But, the researchers have not been able to move forward in increasing the capacity by enhancing these parameters since the emergence of LiBs (more details in Section 3) which are commonly used in today's mobile devices [193]. In fact, for a long time, the research on batteries have been stagnant [12]. As a result, the battery capability (especially, in terms of capacity) is by far lacking compared to the other components of the mobile devices [12]. Consequently, smartphone batteries often fail to cater to the power demand, and this has made energy a scarce operational resource. And, in all probability, the gap between the smartphone and its battery, in terms of capability and advancements, is going to be further widened in the coming years [194]. And so, for the time being, the worthiest option to deal with energy inadequacy is to understand the energy consumption patterns in a smartphone and optimize and regulate its architecture and usage accordingly.

C. MOTIVATION

There are two key motivations in studying about energy management and energy-efficient operations and methods in smartphones:

a) Efficient energy management in the device may maximise its battery life to a great extent. But, for effective management of energy consumption, a clear and convincing understanding of the energy requirement of each entity of a smartphone and their energy usage policy and algorithms is required [195]. Understanding the reasons and patterns of energy consumption in smartphones is very crucial, though not trivial, due to the following reasons 191]:
   - **Crucial:** The hardware, platform, and application designing can be optimised based on that information. Especially, the Android application developers are mostly either individuals or a very small team and hence, they do not have dedicated quality assurance measures and procedures. They typically are focused on the functionalities and outlooks of the applications, ignoring the energy inefficiency aspect. An overall understanding of the energy issues and solutions is, therefore, crucial to the application developers to identify the energy holes and control the energy seepage. Also, if the users have a clear idea of the remaining operating time of their device, they can acclimate their application usage accordingly.
   - **Non-trivial:** A smartphone consists of various hardware and software components, working coherently. Also, designing and implementation of these components vary extensively as per the device makers. Hence, to engineer energy-efficient mobile devices, efficient power consumption modelling, prediction, and optimization are needed for each component as well as for the whole unit. This becomes even more challenging for smartphones with different architectures and platforms.

b) As listed in Table 1, smartphones are being used in every sphere of our life. As a result, they will consume a huge amount of electricity, which will increase the carbon footprint considerably, which in turn impact global warming significantly. Efficient power management and energy-efficient techniques and the adoption of green principles for smartphone batteries could be a great help in maintaining sustainability in smartphone usage [196].

Acknowledging these two factors, monitoring power consumption and attempting energy-efficiency have always been among the hot research topics related to mobile computing and communication [197]. In the earlier days of mobile computing, the research was focused on and around the core hardware (e.g., CPU, transistors, internal data transfers, etc.). But the popularity of internet-based mobile services and utility applications for smart mobile devices has shifted the research direction towards the other aspects such as signalling module (Wi-Fi, Bluetooth, etc.), software (applications), and user behaviours (usage pattern); although the research intensity on the cellular technologies (3G/4G/5G) more or less has remained even.

D. PURPOSE

The primary aim of this paper is to report the different recent research works, aiming to address the power consumption in smartphones by rendering a comprehensive literature review on different aspects of smartphone batteries and energy consumption. To attain energy efficiency, it is very crucial to have a good understanding of where and how energy is used. Hence, this paper also aims to cater this prerequisite by providing a detailed analysis of the power consumption of modern smartphones. This paper also aims to provide the readers with the state-of-the-art of the smartphone batteries by reporting the recent and future developments.

E. CONTRIBUTION

The major contributions of this paper are as follows:

- An outline of the smartphone batteries is presented for preliminary understanding.
- A detail analysis of the various entities and factors that are responsible for the majority amount of the total power consumption in a smartphone.
- Different issues associated with lithium-ion based smartphone batteries, which might cause severe hazardous mishaps, are explanatorily discussed.
- A comprehensive review of research papers, addressing different aspects of energy consumption in smartphones and its battery. For this, we have considered the latest empirical research works and classified them into four broad categories, as follows:
   a. Works that focused on the measurement of power consumption of different entities in a smartphone.
   b. Works that focused on the power consumption management (e.g. reducing energy requirement, optimizing energy usage, etc.) in smartphones, which includes different energy-efficient methods and techniques.
   c. Works that focused on various aspects of smartphone batteries, which includes increasing capacity, decreasing charging time, increasing battery life, alternate energy sources for charging, etc.
   d. Works that focused on mitigating the hazardous issues associated with LiBs.

F. ORGANIZATION

The highlights and the organization of the paper are depicted in Fig. 1. To make it easy for the readers, Table 2 lists the acronyms used in this article.

II. RELATED WORK

To the best of our effort, we could find only a few survey/review papers focusing on smartphone power

Introduction — Section 1
- This introductory section sets the backgroud and motivation of the paper by establishing the importance of studying power consumption of smartphones.

Related works — Section 2
- The similar survey and review papers are discussed, mentioning their limitaions and the forte of this study.

Basics of smartphone battery — Section 3
- The basics of smartphone battries (including one-cell and two-cell) are architecturally explained.

Smartphone power consumption analysis — Section 4
- Power consumption of the hardware components
- Power consumption of the signalling modules
- Power consumption of the software components
- Power consumption due to usage patterns
- Other factors leading to high power consumption

Review of smartphone power consumption measurement — Section 5
- Power consumption profiling and modelling
- Energy consumption analysis and estimation of smartphone hardware and related modules
- Energy consumption estimation and analysis of smartphone OS and applications
- Detecting energy hotspots, energy bugs, and energy leaks
- Estimating and predicting residual battery and depletion time
- Tools and applications for power consumption monitoring and analysis

Review of smartphone power consumption management — Section 6
- Power management methods in smartphones
- Reducing energy consumption for smartphone operations
- Device operation optimisation
- Optimizing device display and colour representation
- Optimizing application design for energy efficiency
- Power saving by task offloading

Review of research and commercial developments on smartphone batteries — Section 7
- Slow discharging and increasing operational duration
- Larger capacity
- Faster charging
- Increasing energy density
- Longer battery lifespan
- Alternate power sources for charging smartphone batteries

Hazardous issues associated with smartphone batteries — Section 8
- The major hazardous issues associated with smartphone batteries are discussed.

Review on mitigating hazards in smartphone batteries — Section 9
- Notable research works that have attempted to minimise the hazardous issues discussed in the previous section are reported.

Conclusions and prospects — Section 10
- The paper is concluded with a futuristic view on smartphone battery.

FIGURE 1. Highlights and organization of the paper.

consumption. Some of the worth mentioning among them are discussed below.

Ahmad *et al.* presented a survey in [198], on energy estimation and power modelling schemes for smartphone applications. They considered studying energy estimation and modelling schemes for smartphone apps only, but not the hardware. The hardware-based mobile application energy estimation suffers from a few drawbacks, such as

TABLE 2. List of acronyms.

Acronyms	Full forms
ACO	Ant Colony Optimization
AI	Artificial Intelligence
AMOLED	Active-Matrix Organic Light-Emitting Diode
API	Application Programming Interface
AR	Augmented Reality
AST	Abstract Syntax Tree
BLE	Bluetooth Low Energy
BMU	Battery Monitoring Unit
CPU	Central Processing Unit
CSA	Cuckoo Search Algorithm
D2D	Device-to-Device
DNN	Deep Neural Network
DRX	Discontinuous Reception
DSL	Deep Supervised Learning
DSP	Digital Signal Processor
DTM	Dynamic Tone Mapping
DuT	Device under Test
DVFS	Dynamic Voltage and Frequency Scaling
DVS	Dynamic Voltage Scaling
E_3	Energy Efficient Engine
eMMC	embedded Multi-Media Controller
FSM	Finite State Machine
FTP	File Transfer Protocol
GHz	Gigahertz
GPGPU	General-Purpose GPU
GPRS	General Packet Radio Service
GPS	Global Positioning System
GPU	Graphics Processing Unit
HMD	Head-Mounted Display
HMM	Hidden Markov Model
HPC	High-Performance Computing
HTTP	Hypertext Transfer Protocol
I/O	Input/Output
IaaS	Infrastructure as a Service
IEEE	Institute of Electrical and Electronics Engineers
IHV	Independent Hardware Vendor
ILP	Integer Linear Programming
IoT	Internet of Things
ISP	Image Signal Processor
ISV	Independent Software Vendor
JSON	JavaScript Object Notation
LAN	Local Area Network
LCD	Liquid Crystal Display
LED	Light Emitting Diode
Li^+	Lithium ions
LiAB	Lithium-air Battery
LiB	Lithium-ion Battery
LiBOB	Lithium bis(oxalato)borate
Li-Poly	Lithium Polymer
LiSB	Lithium-Sulphur battery
LMB	Lithium Metal Battery
LPDDR SDRAM	Low-Power Double Data Rate Synchronous Dynamic RAM
LTE	Long Term Evolution
MAE	Mean Absolute Error
mAH	Milliampere Hour
MEC	Mobile Edge Computing
MIT	Massachusetts Institute of Technology
ML	Machine Learning
MLP	Multi-Layer Perceptron
MoS_2	Molybdenum disulfide
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
mW	MegaWatt
NiB	Sodium-ion Battery
Ni-Cd	Nickel-Cadmium
Ni-MH	Nickel-Metal Hydride
OEM	Original Equipment Manufacturer
OLED	Organic Light-Emitting Diodes
OS	Operating Systems
OSPM	OS Power Management
PC	Personal Computer
PMIC	Power Management ICs
POEM	Portable open source energy monitor
PPI	Pixels Per Inch
PSO	Particle swarm optimization
PTC	Positive Temperature Coefficient
QoS	Quality of Service
RAM	Random Access Memory
RGB	Red, Green, and Blue
RMSE	Root Mean Square Error
RNL	Receptaculum nelumbinis-like
ROM	Read only memory
SaaS	Software as a Service
SD	Secure Digital
SD-UDN	Software-Defined Ultra-Dense Network
SEI	Solid Electrolytic Interface
SEMO	Smart energy monitoring system
SMB	Sodium Metal Battery
SoC	System-on-Chip
SSIM	Structural-Similarity-index
SVM	Support-Vector Machine
TCO	Task Caching and Offloading
TCP	Transmission Control Protocol
UDFS	User-Driven Frequency Scaling
UDP	User Datagram Protocol
UE2	User Equipment 2
USB	Universal Serial Bus
USB OTG	USB On-The-Go
VoIP	Voice over Internet Protocol
VoLTE	Voice over Long-Term Evolution
VR	Virtual Reality
WAN	Wide Area Network
Wh	Watt-hour
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Network
XML	eXtensible Markup Language
ZAB	Zinc-air Battery

time-consuming and resources expensive. On the contrary, code-based energy estimation provides a wide range of options to the developer. Energy estimation against a smartphone application provides an opportunity to the developer for remodelling the design with the objective of lowering the battery consumption. In a nutshell, the authors described existing smartphone energy estimation applications, qualitative and quantitative analysis of energy estimation schemes and some of the future research issues related to optimization of smartphone energy estimation to improve battery lifetime. In this context, a lightweight energy estimation framework design for mobile application is projected to be one of the future challenges to the research community.

A survey on smartphone power consumption and energy-saving techniques has been conducted by Zaman and Almusalli [199]. This paper discusses the importance of power-efficient software design to make the device more useable. It has highlighted the role of no sleep bugs whose presence causes unexpected energy drainage from the smartphone battery during the idle period. In the default condition, all the components should either remain in off status or in idle condition except intentional coding by the developer to keep the component on. Such leakage of energy may occur due to mishandling power control APIs. The availability of automatic detection of such no sleep bug and their ability to reduce the power consumption up to 32% have been described. The authors discussed the role of energy profiling by the developer to analyse power consumption.

A. Degu presented a systematic literature review in [200], where he categorizes the reviewed works by different aspects of the performance of Android-based smartphones. A total of thirty-one papers are studied and mapped into categories such as performance testing, resource leaks, memory utilization, and energy utilization. The presentation approaches of the studied papers are also identified, i.e., whether the paper presents a method, tool, evaluation, or a framework. Also, different research issues on these aspects are identified and discussed.

In a survey [201] on energy consumption in mobile phones, Javed *et al.* considered different factors which consume energy in a smartphone, such as OS, hardware, applications (e.g., browsers, social media, games, etc.) and user interaction with them, and wireless (e.g., Wi-Fi, Bluetooth, 3G, etc.) and sensor networks.

An energy-aware profiler collects data from the OS, hardware, applications, services and the usage pattern of a mobile device for analysing energy consumption. Jofri *et al.* [202] presented a survey on energy-aware profiler for energy management in mobile devices. The authors classified the elements of energy profilers and reviewed related papers for each category. The challenges related to energy profilers are also discussed very briefly.

Ahmad *et al.* [203] presented a survey on energy profiling of mobile applications. They discussed various software and hardware-based application energy profiling schemes and also compared these two types of profiling schemes. The paper also presents a taxonomy on the existing energy profiling schemes of mobile application as well as a discussion on the related research issues.

Another review on energy profilers for mobile devices is presented by Hoque *et al.* [204], in which, in addition to describing the terminologies and measurement methodologies of energy modelling and profiling, the authors have compared the existing power profilers, while stating their limitations and challenges in terms of accuracy and usability.

The survey presented by Rodriguez and Crowcroft in [205] covers a much wider range of energy management techniques for mobile phones than the papers mentioned till now. The authors classified the reviewed papers in six different categories, such as energy-aware OSs, energy measurements and power models, users' interaction, wireless networking, sensors optimisations, and computation off-loading.

None of the above-mentioned studies imparts an all-inclusive discussion, as expounded in this paper. Most of them have focussed only on a single aspect of energy consumption (e.g., either profiling, or modelling, or analysis, or estimation, or energy-efficiency techniques, and so on). Moreover, no studies cover the aspect of research on smartphone battery, like this paper.

III. BASICS OF SMARTPHONE BATTERIES

LiB is being used popularly as an energy source for smartphones. It possesses a better energy density compared to lead-acid, Ni-Cd or Ni-MH batteries. In addition, it has the least self-discharge of 5-10% per month, compared to Ni-cd or Ni-MH batteries whose self-discharge is in the range of 10-30% [206]. The typical voltage level of LiB is 3.7V, the lifecycle of approximately 1000 or more and specific energy of 150 Wh/Kg. In addition, they are available in wide shape and sizes, making them suitable for various gadgets other than smartphones. Fig. 2 highlights the advantages and disadvantages of LiBs compared to other rechargeable batteries such as Ni-MH and Ni-Cd. Many often, LiBs are confused with LMBs. However, they are quite different, as can be seen from Fig. 3.

As shown in Fig. 4, a LiB consists of an anode, a cathode, an electrolyte and a separator. The cathode is positively charged, and the anode is charged negatively. It uses Li intercalation compounds as positive and negative materials [207]. The separator is a micro-perforated plastic that keeps the anode and cathode away from each other. The Li^+, with the help of the electrolytes, can travel easily through the separator. During the charging phase of the LiB, as shown in Fig. 4(a), the Li^+ are pushed from the cathode through the separator. Anode, being negatively charged, attracts the ions. During this period, electrons travel from anode to cathode through the battery charger. The maximum possible accumulation of Li^+ in the anode is referred to as a full-charged condition of the battery. A discharging process, which is just the reverse of charging, is described by Fig. 4(b). During this phase, the Li^+ are gradually released from the anode and are attracted towards the cathode. This results in current flow through the smartphone, which is acting as a load to the battery. As the user continues to use the device, the energy stored in the battery gradually decreases and needs to be recharged.

As we have seen in Section 1, incalculable use of smartphones in various application areas demands a substantial amount of energy from the battery of the smartphone. For that, the batteries need to be capable of storing as much energy as possible and can supply power to the device for a longer period. To meet this challenge, the manufacturer primarily adopts the following two techniques:

a) Employ high energy density battery with large capacity.
b) Use of energy-efficient hardware and software.

Combining both techniques while designing a smartphone is the most popular approach. LiBs are being popularly used in the smartphone which offers good energy density as compared to its predecessor technology such as Ni-Cd or Ni-MH. Currently, most of the manufacturers is a smartphone with LiB or its other variant, Li-Poly battery having the capacity in the range of 3000-4000 mAH. The capacity can be extended

Lithium-ion Battery	
Advantages	**Disadvantages**
Light-weight	Involves risk of bursting
Have higher energy density than other rechargeable batteries	Costly, compared to other batteries
Rate of charge loss is less	Complete discharge damage the battery
Have a greater number of charge and discharge cycles	Extremely sensitive to high temperatures (degrades very quickly, if exposed to heat)
Need not be discharged completely (due to absence of memory effect)	Very short lifespan (2 to 3 years from the date of manufacturing, even if not in use)
Operates at higher voltage than other rechargeable batteries (approx. 3.7 volt)	Not available in standard cells sizes (AA, C, and D) like others

FIGURE 2. Advantages and disadvantages of Li-ion batteries compared to other rechargeable batteries [412].

Lithium-ion Battery	Lithium Metal Battery
• Lithium compounds are used • Other metals (generally, graphite) are used as anode • Rechargeable • Lower energy density • Short lifespan (about three years) • Lithium diposition of lesser amount • Less hazardous • Ideal for consumer electronic devices	• Lithium is used in its pure metallic form • Lithium metal is used as anode • Non-rechargeable • High energy density • Much longer lifespan • Heavy lithium disposition • Highly hazardous • Best suited for devices need to be powered for long without charging or replacing (e.g., pace-makers, smoke detectors, etc.)

FIGURE 3. Difference between lithium-ion and lithium metal batteries.

by using a battery with a larger dimension but again limited by the physical specification of the smartphone.

Some of the manufacturers adopt a two-cell approach to enhance the capacity. The LiB in iPhone X employs dual-cell battery to enhance the capacity [208] over its predecessor iPhone 8 plus which uses a rectangular shaped battery. The two cells in iPhone X are placed at a right angle to each other, forming the L-shape package, which maximizes the internal area occupancy, as shown in Fig. 5(a). But in iPhone XS, Apple again used single-cell L-shaped battery, as shown in Fig. 5(b), with minimal loss of mAH. Some other manufacturer like Innos 6000 uses two separate cells: one is internal and non-removable, and the other one is just below the back cover and removable. The phone works perfectly with the internal battery only. Two batteries get charged simultaneously with a single micro-USB port. Such an arrangement provides higher battery capacity up to 6000mAH. A similar approach is applied in the OPPO R17 Pro smartphone, which contains two batteries to provide a total capacity of 3700mAH.

Increasing demand for mobile devices put proportionate demand in rechargeable batteries. LiB technology is playing the role of flag-bearer in such a domain. The huge growth of such market is expected to put severe pressure on resources and supply chain [209]. Researchers in their quest to find substitute materials for Li have experimented with different alternatives [210]. Among them, the LiSB [211], the LiAB [212], [213], NiB [214], [215], and ZAB [216], [217] are most promising. But due to inherent and fundamental challenges, these batteries are yet to be in the mainstream production for mass uses. It might take a few years for these battery technologies to fully develop for achieving reliable and cost-effective performances as compared to LiBs. Nevertheless, it seems to have a promising

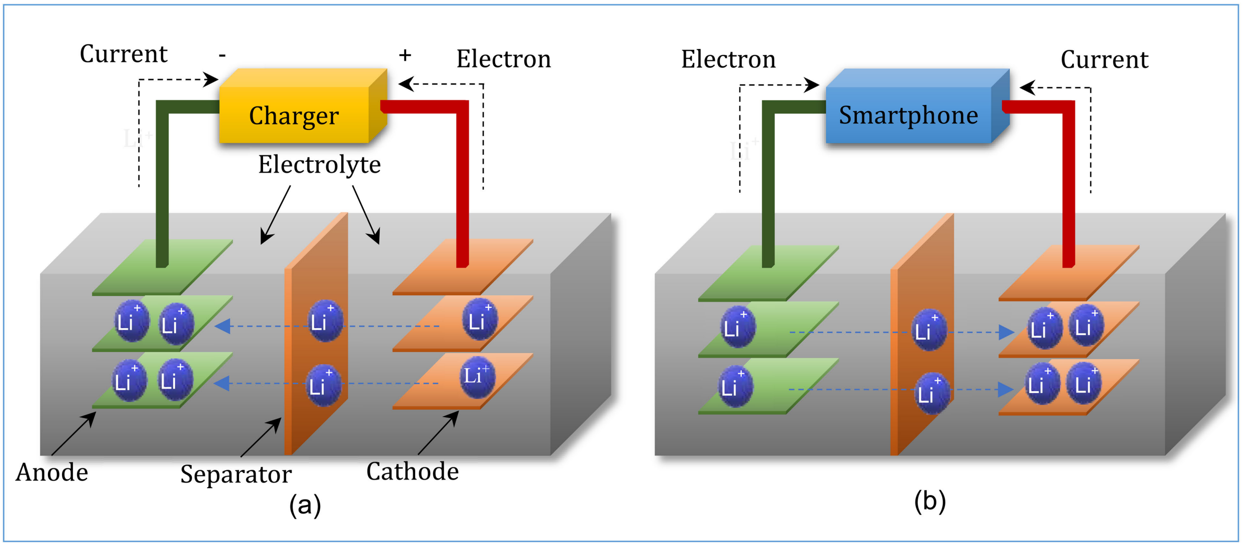

FIGURE 4. **(a) Charging and (b) discharging of Li-ion battery.**

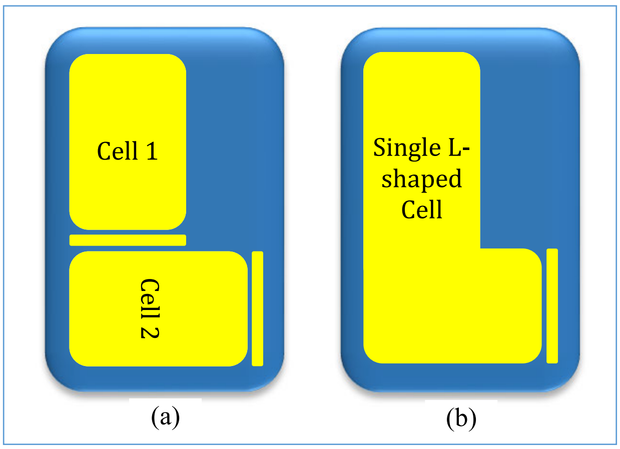

FIGURE 5. **Smartphone battery with (a) two cells and (b) single L-shaped cell.**

future for LiAB [218], [219], LiSB [220], NiB [209], and ZAB [221], which may well be the suitable alternatives to LiB, reducing the stress on the demand and supply gap.

IV. SMARTPHONE POWER CONSUMPTION ANALYSIS

For an effective and efficient management energy management in a smartphone, it is very important to understand the power consumption details of each entity within or associated with a smartphone. A smartphone is a complex system and is composed of various hardware components and software applications. Both the hardware and the software components are responsible for the power consumption of a smartphone. If the hardware is efficient and the software is not able to carry out that efficiency, then the power consumption will be higher, and the same holds true for inefficient hardware with optimised software. Therefore, it should be noted that both the hardware and the software components must be equally efficient in order to provide maximum performance with less power consumption in a smartphone. Therefore, to understand the power consumption in a smartphone, a holistic approach is needed; especially, knowledge of the followings is essential:

- A good understanding of each component of a smartphone
- The hardware and software relationship and coordination
- Where, how, how much, and in which condition the energy is used
  - Energy consumption of each individual hardware
  - Energy consumption of the OS and other system software
  - Energy consumption of the applications
  - Energy consumption due to usage
- The external factors responsible for power consumption

This section attempts to identify the all possible power consumption sources in a smartphone and provide a basis for the understanding of energy requirement and consumption in smartphones. Several research works, e.g., [222]–[224], have attempted to find out the key factors that are responsible for major energy consumption in mobile devices. But none of them covers the all-inclusive factors, like our effort in this paper. Furthermore, along with identifying the power ingesting sources and estimating the approximate amount of ingestion, the possible solutions to minimise the power expense of each component also have been suggested.

But, as already mentioned, a smartphone is a complex system; exact analysis and estimation of power consumption of different components individually are not straightforward. It is further complexed due to the fact that besides the users and the manufacturers, many other external entities are directly or indirectly involved with smartphone ecosystem and they play a crucial role in its overall power consumption,

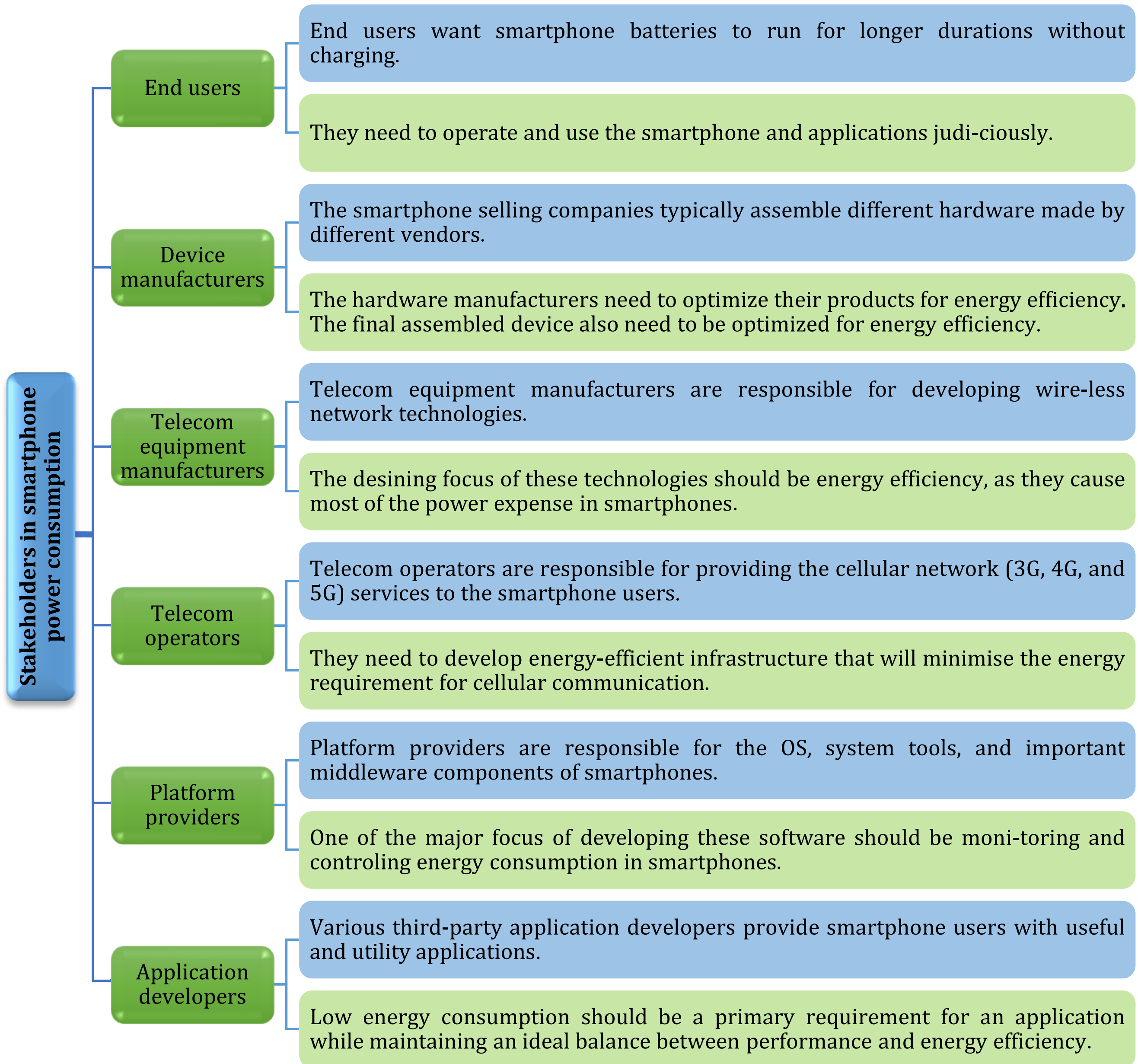

FIGURE 6. Stakeholders in smartphone power consumption and their roles [191].

as listed in Fig. 6. Therefore, in this section, we have adopted a generalised approach in discussing the causes of energy consumption in a smartphone and probable way-outs to minimise that. Table 3 summarises the probable sources and reasons for power consumption in a smartphone and probable ways to minimise.

A. POWER CONSUMPTION OF THE HARDWARE COMPONENTS

The power consumption of the hardware components depends on several parameters, as follows [198]:

- Power consumed by the component at idle state, i.e., the minimum power needed for the component to be at active state with the minimal workload.
- To what extent the component is used?
- How many modelled power states are defined for the component?
- The number of transitions within the power states.
- The power consumption rate for each transition.

Identifying and estimating the consumed power on account of each of the above-mentioned parameters, individually, is really complex. Hence, for a component, the energy consumption is considered as the accumulative sum of power expended by all the modules within for all the parameters for an activity time frame during operation. For example, to estimate the energy consumption of a networking module during a network communication, the collective power consumption for each of the different activities such as sending

TABLE 3. Summary of different sources and reasons for power consumption in a smartphone and probable ways to minimise the consumption.

Power consumption category	Source/reason	Probable ways to minimise
Hardware components	CPU	• Voltage regulation • Clock frequency optimization • Minimizing switching activities • Code optimization • Using GPU for computing • Hardware accelerators • Dedicated functions
	GPU	• Resolution scaling • Refresh rate scaling • Hardware accelerators • Dedicated functions
	Memory	• Avoid increasing RAM size unnecessarily • Usage management
	Storage	• Reduced read-write operations • Temperature control
	Display	• Efficient technology • Resolution scaling • Lowering pixel density • Decreasing the refresh rate • Reducing backlight
	Sensors	• Restricted application permission
Signalling modules	Cellular network	• Network mode selection • Increased signal strength • Controlled handoff • Operator selection
	Bluetooth	• Manual starting when needed • Using other modes of data sharing • Introducing BLE
	Hotspot	• Preferring USB tethering • Using Bluetooth instead of Wi-Fi • Using lower frequency band
	Wi-Fi	• Manual starting when needed • Using lower frequency band • Get closer to the Wi-Fi access point
	GPS	• Manual starting when needed • Use GPS where the satellite signal is decent • Using optimized GPS application
	FM radio	• Manual starting when needed • Antenna management • Display standby during FM radio usage
Software	Operating system	• Using smartphone-oriented kernel • Using kernel-level display server
	Applications	• Verified installations • Managing application permissions • Uninstalling unused applications • Disabling auto start-up applications
Usage patterns	Calling	• Use 2G network wherever applicable • Avoid calling with poor signal strength
	Internet usage	• Selection of best connection • Restrict network access of applications • Restrict application background data
	Gaming	• Selecting thermally conductive material • Effective internal cooling technology • Downclocked CPU • Lowering display brightness
	Music playback	• Standby display • Activated sleep mode • Controlled volume • Optimised audio bit-rate
	Video playback	• Avoid high-resolution videos, where applicable • Go for videos with low frames per second (FPS)
	Running heavy applications	• Code offloading • Computation offloading
Other miscellaneous factors	Inter-device communications	• Inter-device task distribution • Optimised processing across devices • Optimised scheduling • Optimised data transfer • Energy-efficient communication protocols
	Heating	• Device material selection • Not charging and discharging simultaneously
	Ageing and faulty battery	• Battery replacement • Using power-saving mode

data, receiving data, and closing the network socket trigger are considered [198].

In this section, some of the most important hardware components that may lead to higher power consumption in a smartphone are discussed. Further, the solutions to reduce power consumption are also discussed for all of the components.

1) CPU

Why, how, and how much: CPU is the most power-hungry component among all. The factors that are responsible for the CPU power consumption can be categorised as:

- **Dynamic power consumption:** A CPU is a collection of millions of switches (transistors) represented as logic gates that are constantly toggling to perform various operations. As a result, the capacitors present in the CPU rapidly charge and discharge; drawing a power which is approximately proportional to the CPU frequency, and to the square of the CPU voltage [225].
- **Short-circuit:** During every operation, the transistors present in the CPU changes its state, i.e. it either turns on or off. During this switching, some of the transistors may need more time than the others resulting in a short-circuit.
- **Leaking transistor:** Transistors are semiconductor devices that have differently doped portions for either allowing or resist the flow of current depending on the needs. But in fact, a very minimal amount of current is always leaked by the transistor. This leaking of the current may vary depending upon the transistor state, material, size, temperature and other physical properties.
- **Clock frequency:** For a given device, operating at a higher clock rate may require more power. The clock frequency of a CPU indirectly represents the total number of operations the CPU can perform at a particular time. CPU frequency and the number of operations is directly proportional, i.e., increasing the clock frequency will increase the capability of the processor to perform more operations. But as a consequence, the increased clock frequency comes with its own drawback as pointed out below:
  - It will consume more power from the source, generating more heat and hence there is a high chance of CPU throttling (CPU is downclocked automatically).
  - Since the current leakage is dependent on the amount of power, both dynamic power consumption and short-circuit are dependent on the clock frequency.
  - The energy consumption behaviour of microprocessors is found to be convex, meaning that there is an optimal point where the power consumption of a particular microprocessor is minimal at a certain clock frequency without affecting the processing capability to a large extent [226].

How to reduce: Newer technologies require the microprocessors to have a greater number of transistors, making the transistor density of a microprocessor higher with every newer version. In such scenarios, it is very important to design a microprocessor that is capable of doing more intense operations than its predecessor but keeping the energy consumption at the minimum level. It is very difficult to keep a balance and optimize these parameters; a study is made to point out some of the ways that are typically used to solve this problem:

- **Voltage:** Input voltage of a CPU determines many characteristics of the CPU. A CPU using more power needs higher input voltage, but this is not ideal due to the fact that higher voltage results in higher heat production. Hence, the most optimal input voltage can be considered as the minimum voltage that can be applied in the CPU without hampering its operation.
- **Clock frequency:** Researches suggest that lowering the input voltage to the CPU without changing the clock frequency can be considered as a good way to minimize energy consumption [227]. It can also be noted that decreasing the clock frequency helps reduce energy consumption at the cost of lesser operations per unit time. A power-efficient CPU should be able to run at a minimum clock speed with which it can perform all the operations it is intended to do. Also, sometimes, it is better to have a higher clock frequency than having more transistor density.
- **Reduced switching activities:** Techniques needs to be adopted in order to reduce the switching functions inside the CPU. Encoding techniques such as Gray code addressing [228], or value cache encoding such as *power protocol* [229] can be considered.
- **CPU cooling:** The heat produced by the CPU is one of the main reasons of the power dissipation of a CPU as the heat resists the current flow and hence more power is needed in higher temperature environment. CPU cooling needs to be done either by using some form of the heat sink or liquid cooling, using some coolant technologies.
- **Optimizing codes:** Compilers can be optimized in order to execute operations more efficiently, reducing the power consumption of a CPU significantly [230].
- **GPU computing:** Utilizing the mobile GPU for general purpose computing can achieve a 4.25x speedup in performance and 3.98x reduction in energy consumption, in comparison with a CPU-only implementation on the same platform [231].
- **Hardware accelerators:** Unlike general-purpose CPU, a smartphone has several processing components that are able to perform a specific task instead of performing multiple operations. OS identifies the most suitable processing component in order to provide maximum efficiency. Sometimes, the use of computer hardware specially made to perform some functions is more efficient than it is possible using certain software running on a general-purpose CPU.

- **Dedicated functions:** A CPU can be configured to utilize a certain portion of its overall performance for performing some specific functions. This makes sure that only one program is unable to take over the entire CPU utilization. Further, there is always some of the CPU performance left over for a new job.

2) GPU

Why, how, and how much: GPU is a special type of processor that is responsible for processing graphical tasks like rendering 3D objects and playing games etc. Power consumption model of a GPU can be obtained as:

- **3D rendering:** Basic effects on the home screen don't need GPU rendering, but modern transitions are more difficult to process by the CPU and hence are processed by the GPU. The GPU can handle transitions smoothly and efficiently, but the power consumption is typically higher due to the transitions. Also, 3D models are handled by the GPU and power is consumed [231].
- **Resolution:** Though the resolution is the property of a display, it is driven by the GPU and sometimes CPU. Resolution is directly proportional to power consumption.
- **Pixel density:** Pixel density is another property of a display, but it is driven by the GPU or the CPU. More the pixel density more is the power consumption as the processing unit needs more power to drive a greater number of pixels.
- **Refresh rate:** Refresh rate of a display is another property of the display, but it is driven by the GPU or the CPU. The more the refresh rate, the smoother the transition of the frames will be. Most of the mobile display works on the 60Hz refresh rate. The refresh rate is directly proportional to the power consumption of a GPU as the images are processed by the GPU then sent to the display.

How to reduce: The following measures can be adopted to reduce the GPU power consumption:

- **Resolution scaling:** Modern high-resolution displays can down-scale items to a certain degree to fit more items and details on the same size as the display. Increased resolution provides increased room for more items that sometimes may exceed human vision capabilities. The resolution of a device can be downscaled in order to achieve a higher power efficiency, still keeping a good quality of the image [232], [233].
- **Refresh rate scaling:** Refresh rate of a device can also be reduced at runtime by the GPU in order to achieve better power efficiency [232].
- **Hardware accelerators:** Similar to CPU, the GPU is also not efficient for performing certain tasks. A GPU comprises hundreds of cores, running at a lower frequency. This enables a GPU to perform parallel operations efficiently. In contrast, CPUs have a lower core count, but with much higher clock frequency, enabling it to perform serial operations efficiently. Hence, it is always recommended to use hardware accelerators and use of proper processing unit for specific jobs.
- **Dedicated functions:** Just like a CPU, a GPU can also be configured to reserve a certain portion of its overall performance for performing some specific and special functions. This makes sure that there is always some of the GPU left over for a new job.

3) MEMORY

Why, how, and how much: With the increasing usage of smartphones, the memory size is also being increased, which consume more energy. However, modern smartphones incorporate LPDDR SDRAM which is a type memory that is much more power-efficient than their ancestors due to improved technology; making them ideal for use in small devices like mobile, tablet, laptop, etc. The major reasons for power consumed by RAM are:

- **Steady-state power consumption:** Unlike microprocessor transistors, which can be completely or partially turned off when not in use, the RAM semiconductors behave similar to capacitors, but to store data instead of a charge. This implies that RAM always draws power to keep the data alive in its cell.
- **RAM capacity:** The RAM memory is made of MOSFET, which consumes energy constantly. Furthermore, increasing the size of the memory in RAM requires more numbers of MOSFETs to be installed in the RAM, making the power consumption more. So, the power consumption of a RAM can be considered directly proportional to its memory capacity.
- **Read-write power consumption:** Apart from the constant power draw by the MOSFETs, each and every read-write operation consumes a certain amount of power. This power draw is dependent on the type of the MOSFETs and the technology used to architect the RAM.

How to reduce: The power consumption of RAM can be checked by the following measures:

- **Memory capacity:** As mentioned earlier, the power consumption of a RAM is directly proportional to the size of the memory; it can be a good option to choose the RAM size wisely.
- **User intervention on RAM:** The read and write operations performed on a RAM are mostly done by the OS. The OS decides which data needs to be written to the RAM and when it needs to be retrieved or discarded. But the OS also provides a feature to the user to take control of this operation manually. So, the user can include or remove programs in the RAM, making the power usage more. The solution to this problem can be either to remove this feature completely, or the users should refrain from making any changes unknowingly.

4) STORAGE

Why, how, and how much: The secondary storage of mobile devices includes solid-state eMMC and external expansion

SD cards. Considering the technologies used, these storage media can consume power with the following aspects:

- **Read-write power consumption:** Just like RAM, secondary storage devices need the power to perform the read and write operations. The more read-write operation performed relates to higher power consumption.
- **Temperature:** The temperature plays a very vital role in power consumption model of any storage device. More temperate indicates a higher probability of power consumption due to several factors, such as:
  - Due to higher temperature, the clock frequency of the storage controller needs to be downclocked in order to function correctly without hampering the physical hardware.
  - Memory cell damage may occur if the storage hardware is exposed to a higher temperature continuously.

How to reduce: The following measures can be helpful in minimising the power consumption accounting to storage in smartphones:

- **Read-write operation:** Reducing read-write operations can significantly decrease power consumption and increase the life of the storage unit. Restricting unnecessary use of heavy write or read operations like video recording, photo shooting, installing un-necessary application, deleting big files, reinstalling OS frequently may help in reduced power usage.
- **Temperature:** All electronic components are sensitive to heat and temperature. Increased temperature adversely affects the performance of storage media. Therefore, implementation of a better cooling mechanism and keeping the device idle during high temperature may help in less energy consumption.

5) DISPLAY

Why, how, and how much: There are several factors that affect power consumption when considering the display of a mobile device. All of the below-mentioned factors are collectively responsible for the power dissipation:

- **Display technology:** There are a variety of display technologies available in the smartphone world; but broadly, it can be divided into two categories:
  - **LCD:** LCD displays don't have backlit, and hence they need a backlit source to provide the light. LCD displays need power to move the liquid crystals; hence, every time a movement is needed in the display, power is consumed.
  - **LED:** LED displays consume less power compared to LCDs. Each and every pixel consist of LED and are self-lit, i.e. they that do not need any other backlit source.
- **Resolution:** Resolution is a property of the display that defines how many items can be seen clearly at once in a display. More the resolution, more the number of items can be seen at once. Increasing a device resolution does not affect the power consumption directly, but the power needed to process and drive a higher resolution display is obtained mostly by the GPU and sometimes CPU. So, the resolution is also directly proportional to the power consumption in this case.
- **Pixel density:** The pixel density is the number of pixels present in a display in a unit area. More the pixel density better is the display in terms of image quality; the main objective here is to have a pixel density, such that individual pixels are not visible to the human eye. More the pixel density more is the power consumption as the processing unit needs more power to drive a greater number of pixels.
- **Refresh rate:** Refresh rate of a display is the frequency at which the display is operated. The more the refresh rate, the smoother will be the transition of the frames in the display. Most of the mobile display works on the 60Hz refresh rate. The refresh rate is directly proportional to the power consumption of a display.
- **Backlight:** LCD displays don't have their own light source, so the LCD displays use LED light source as a backlit to the display. The power rating and the colour temperature are two of the most important aspects of the backlit. The power consumption of the LED-backlit is dependent on the number of LEDs used and their overall power rating. At the maximum brightness of the display, this rating of the power can be seen. Hence, the brightness intensity of the display is directly proportional to the consumed energy [234].

How to reduce: Power dissipation due to above-mentioned factors can be lessened by adopting the following measures:

- **Display technology:** LED displays are preferred architecture when power is a factor. LED displays don't need separate backlit and the LED displays power up the pixels that have some items, the rest of the pixels are completely turned off, making it ideal for low power consumption environment.
- **Resolution:** Keeping the resolution low will help in reducing the power consumption as there are a smaller number of display items that need to be addressed by the processor.
- **Pixel density:** 338 PPI in a display can be considered a good display. Below, this level of PPI, individual pixels are visible, also, increased PPI consumes more power. An energy-efficient display can consider 338 PPI for the optimal display quality and power consumption.
- **Refresh rate:** Downclocking the refresh frequency may improve battery life significantly. Recent devices have higher refresh rates, and they have an option to decrease the refresh rate as well, which improves power consumption.
- **Backlight:** The battery of a device with low brightness lasts almost twice longer than the battery of a device with high brightness [235]. Also, newer technologies like LEDs can be developed that will consume less power with brighter illumination.

FIGURE 7. Different sensors embedded in smartphones.

6) SENSORS

Why, how, and how much Today's smartphones are loaded with various internal and external sensors [236]. Internal sensors are used to monitor the status of the internal components of a smartphone, such as its battery, CPU, and wireless networks. External sensors, as shown in Fig. 7, perform a variety of sensing jobs such as assessing the location, physical proximity, compass direction, temperature, atmospheric pressure, humidity, user gestures, etc. [191]. The external sensors are also responsible for monitoring and estimating the orientation and acceleration of the smartphone. Most of these sensors are employed in continuous operation, hence, consuming a huge amount of power.

How to reduce: The following actions can be taken to cut the power consumption accounting to smartphone sensors:

- **Power management:** An important criterion to decrease power dissipation from sensors is to cut off their power when not in use. This is usually done by the OS, but some settings can be manually handled by the user in order to turn off the unused sensor.
- **Restricted application access:** Some applications may request access to a sensor present in a device out of context of its functionality. This kind of applications tends to use the sensor unnecessarily consuming huge amount of the power form the device. The solution, in this case, would be to install a verified application and also to manually provide or restrict access to sensors according to the need.

B. POWER CONSUMPTION OF THE SIGNALLING MODULES

The signalling and networking modules together consume the most power than any other categories, as can be seen in Fig. 8, which presents a suggestive power consumption share of different components in a smartphone. This section discusses various signalling modules that cause considerable power loss, along with suggestive ways to curb the power expense.

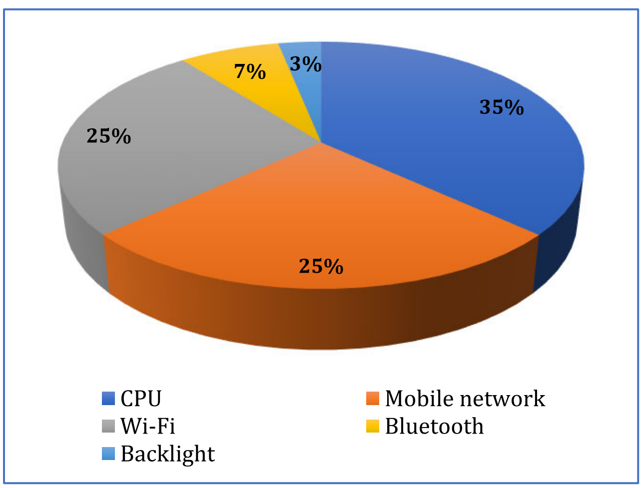

FIGURE 8. Power consumption percentage share of different components in a smartphone as per [198].

1) CELLULAR NETWORK

Why, how, and how much: A mobile device is architected in a way that it is constantly connected to a cellular network. Therefore, the power dissipation in a smartphone is highly dependent on the quality of the signal being received by the device at a particular location. Weak signal strength leads to an increase in power consumption of the Tx/Rx module, causing high energy drainage [237]. For most of the time, a smartphone handles the switching of the cellular frequencies automatically with no further need for user interaction. But some manual controls are also provided to the advanced users for network type selection. This automatic network type selection feature tries to provide maximum network performance, but it may consume more power. In addition to the regular power consumption, signal fluctuation causes huge battery loss. Due to the location change of a device, the connection is frequently passed over to a better network for uninterrupted voice and/or data connectivity known as *handoff*. The handoff needs high power during the process to make it seamless. Hence, frequent network handovers result in severe battery depletion.

How to reduce: The following factors might be considered for reducing power consumption due to cellular network:

- **Cellular frequency:** To consume less power during sessions when no data connectivity is needed, the operator may switch to a GSM 2G network (if available) from either 3G or LTE.
- **Signal strength:** If the device is near a place where the signal strength is decent, then the radio signal amplifier needs less power to amplify the signal in order to make it clear. In addition, adding a cellular network repeater may help reduce the power consumption in this context.
- **Controlled handoff:** Handoff is very important due to the fact that the network at a given time must be stable and uninterrupted, but a concept to minimize the power consumption of a handoff may be to use a lower cellular frequency. This will improve the network coverage of a single cell but will adversely affect the speed of the data transmission.
- **Network operator:** Though minimising energy consumption due to a cellular network is not network operators' primary concern, but a tactful and optimised configuration of wireless access networks and deployment of the base stations can minimise the energy consumption of a cellular phone while using the cellular network.

2) BLUETOOTH

Why, how, and how much: A Bluetooth is a wireless technology standard for exchanging data between devices over short distances using short-wavelength radio waves ranging from 2.400 to 2.485 GHz. It is primarily developed as a replacement for a wired medium of data transfer and keeping power efficiency in mind. With each development cycle, Bluetooth has been made more efficient in terms of data transfer and power consumption. Newer Bluetooth versions have a significant increment in the data transfer speed, as can be seen in Table 4.

TABLE 4. Power consumption of different Bluetooth device classes.

Bluetooth Class	Power Consumption (mW)
1	100
1.5	10
2	2.5
3	1
4	0.5

Considering smartphones have a large set of hardware for performing different task, even a single mW of power consumption counts. Bluetooth being efficient device consumes very less power, but most of the power-consuming operations related to Bluetooth are pointed below:

- **Constant connectivity:** Some devices (like smartwatches, Bluetooth speakers/headphones, etc.) need to be constantly connected to the smartphone to perform its desired operation; hence, the Bluetooth of the smartphone is always turned on, draining its power.
- **Auto-searching devices:** Even if the Bluetooth device is not connected to any nearby device; it still searches for the devices present nearby and tries to connect to an already paired device. This is another reason that Bluetooth drains constant power, even if it is disconnected.
- **Networking:** Bluetooth is easy to connect and power-efficient; but considering the amount of data transfer needed and the Bluetooth technology used, it may not be ideal in many situations due to lack of proper connectivity and/or huge data size.

How to reduce: The following measures can be followed to minimise Bluetooth's power consumption:

- **Turn off:** Turning the Bluetooth device completely off during the period when there is no need for it is a better choice when power saving is the main objective.
- **Prefer alternatives:** Using different technologies like Wi-Fi when more amount of data needs to be transferred, and infrared where applicable may save some power in the smartphone.
- **Use the latest version of Bluetooth:** A device with the latest version of the Bluetooth technology must be preferred due to its better connection reliability, efficient data transfer speeds and less power dissipation.
- **Utilise BLE:** Using BLE standards, wherever possible, will make sure reduced power consumption without compromising the communication range.

3) HOTSPOTS

Why, how, and how much: The hotspot is the technology of sharing the internet connection of a device, mostly using some form of wireless media like Bluetooth and Wi-Fi. Depending on which medium the hotspot is operating, different aspects such as data transmission speed and distance, and hence, the power consumption is varied. A WLAN is created in order to connect to the nearby devices and share the internet. Power consumption in this regard can be classified into the following categories:

- Typically, the hotspot is used to share the internet connection of the smartphone, so that nearby device can use the same connection. In order to do that, either Bluetooth or Wi-Fi is needed, which consumes power.
- There is a need of constant connectivity with the cellular network during the hotspot operation, hence cellular network uses power with respect to the type of the cellular network it is in as already discussed in Section 4.2.1.
- In order to connect multiple devices and create a WLAN, the smartphone acts as a router, which consumes constant power during this operation due to constant network traffic routing.
- Sharing a higher frequency of Wi-Fi hotspot may be beneficial when data transmission speed is the priority, but it is definitely more power-hungry.

How to reduce: The following suggestive measures might be helpful in lessening the power consumption for using hotspots:

- **Wired sharing:** A USB-based tethering option can be used wherever applicable to share the smartphones internet connection instead of using the wireless medium. This will share the internet over the USB cable, making it more reliable and transfer speeds will be uncompromised. Furthermore, the device will constantly charge during the entire operation.
- **Efficient alternatives:** Using Bluetooth instead of Wi-Fi will be a better option when the network range is within ten meters, and data transmission speed is not that much important.
- **Radiofrequency:** Selectin of a lower bandwidth frequency for Wi-Fi hotspot (i.e., selecting a 2.5GHz instead of 5GHz where available) is preferable during power efficiency dominant situations.

4) WI-FI

Why, how, and how much: Wi-Fi is a wireless technology of transferring data between connected devices, mostly by creating a WLAN. This is one of the most familiar and highly used wireless mobile networking technologies currently used. Devices ranging from smartphones, tablets, TVs, and almost any other device capable of networking uses this technology. Wi-Fi power dissipation characters are pointed below:

- **Wakeup power consumption:** Whenever a Wi-Fi device is started, it needs to perform a very lengthy process of searching nearby access points and select the most trusted access point and connect to that. This makes the wakeup process of Wi-Fi devices to consume high power.
- **Connection maintenance power consumption:** Once the Wi-Fi device is enabled, it needs constant power in order to actively maintain the connection. Therefore, this is another factor that higher power consumption.

How to reduce: As mentioned below, intelligent use of Wi-Fi may reduce the power consumption considerably:

- **Turn off:** Wi-Fi modules, when not in use, goes to sleep mode, which consumes less power. But it is more preferred to turn the Wi-Fi module completely off to reduce the power dissipation.
- **Opt for low-frequency bandwidth:** Selectin of a lower bandwidth frequency for Wi-Fi (i.e., selecting a 2.5GHz instead of 5GHz where available) is preferable during power efficiency dominant situations.
- **Get close to the access point:** After Wi-Fi is enabled, if it is connected to an access point, then it is preferable to keep it as close as possible. This makes sure no data packet is dropped and reduces the probability of power consumption of the energy required to transfer per bit.

5) GPS

Why, how, and how much: GPS is a hardware device that is responsible for tracking the location of a smartphone using Satellite data. GPS is widely used by many applications and OS services for providing personalized location-based recommendations. Location service is important but is one of the most power-hungry services of a smartphone. The power consumption details of GPS are pointed below:

- **GPS receiver:** GPS receiver consists of a microchip and an antenna located inside the smartphone. When operating, it continually maintains a network between your device and the satellites.
- **Dependency:** GPS receiver alone is not capable of providing a map as it is a service provided by internet map services like google maps. The GPS receiver is able to identify the geographic location in terms of coordinates. Further, the GPS receiver uses data from cellular towers and Wi-Fi networks in order to approximate the location of a device. This makes GPS be accurate but consumes very high power due to the use of multiple services.
- **Sleep mode:** With GPS turned on, the receiver is constantly receiving coordinate details of the device form the satellites making the device not to go to sleep mode hence consuming constant power.
- **Signal quality:** In a poor signal area there is a higher chance of the location service to consume more power from the device due to either amplification of a weak signal or searching in case of no signal.
- **Device position:** GPS signals can get weak if the device is near a wall or is covered by metal roofs. In those conditions, the receiver amplifier needs more power in order to capture the signal.
- **Application:** GPS service is not standalone, and hence, the location service is used by different applications to use GPS to its full potential. Sometimes a poorly optimized application or constantly running the application using the location services may consume a large amount of power from the smartphone.

How to reduce: GPS consumes relatively higher power than other signalling modules. So, other options such as Wi-Fi access points, IP Address, or Bluetooth beacons can be exercised for location-tracking instead of GPS. But this so-called *smart GPS* systems are still far from fully developed and being adopted. Therefore, for the time being, the following measures can be considered to minimise the GPS power consumption:

- **GPS receiver:** The easiest way of stopping the power dissipation from a GPS receiver is to turn off the location services totally, when not in use.
- **Signal quality:** Using GPS in a location with good satellite signals will ensure no extra power consumption.
- **Device position:** Turning the location service off when a device is near a wall or is covered by metal roofs will also ensure proper power consumption.
- **Application:** Applications that use location services must be properly optimized and verified. Also, closing the applications after they are used is a good way of keeping power usage at bay.

6) FM RADIO RECEIVER

Why, how, and how much: Although FM radio does not belong to the 'elite' group of signalling modules, as discussed above, in terms of usage it still might be favourite to a considerable number of users. And like every other radio, FM also consumes power to operate. The primary considerations for FM radio in smartphones are:

- **FM radio receiver chip:** The receiver chip consumes less power, which may not be that much of a deal until the received signal quality becomes too poor. In that case, the chip consumes more power in order to maintain proper amplification of the signal just like the GPS receiver.
- **Antenna:** The smartphone may not be sufficient for a large antenna that is required for the radio to function properly. Hence, a headphone connection is always needed. The connected headphones act as antennas and help to receive the radio signals. This is not very stable due to the movement of the earphone cables and also the materials used in the cable, invoking more power consumption.

How to reduce: The following measures can be considered to mitigate the FM radio power consumption:

- **Turn off:** Turning the FM radio receiver off when not in use and closing any application that may use the radio service will ensure no power consumption in this regard.
- **Put display off:** During use of the FM receiver, which is mainly for consuming audio, the display of the device may be turned off to avoid unnecessary power wastage.
- **Manage earphone cable:** Keeping the earphone cable in a fixed position where signal quality is good is preferred.

C. POWER CONSUMPTION OF THE SOFTWARE COMPONENTS

Though it is the hardware of a device that eats up the energy, the software is equally responsible for that. The software may not directly consume power, but they dictate the hardware power consumption as per the complexity of the software in terms of the number of hardware components required and the number of intermediate processes involved.

1) OPERATING SYSTEM POWER CONSUMPTION

Why, how, and how much: Mobile OSs are mostly based on some existing older OS architectures, typically developed for desktop-grade and more power-hungry computers. As an example, the most widely used smartphone OS, Android is based on the Linux kernel, the iOS on the UNIX kernel, and Windows Phone on the Windows NT kernel. The smartphone OS inherits many well-known features from their desktop counterparts; however, they must meet the requirements such as communication, location, power management for smaller batteries, and efficient computing [238]. The OS is responsible for managing all the hardware and software components on the smartphone, and it is responsible for system-level power management. Hence, it plays a critical role in the power consumption model of a smartphone. Also, due to the presence of a variety of services, OSs can be considered most power-consuming system software among all other software.

How to reduce: For today's ever-increasing feature-rich OSs reducing power consumption is not trivial. However, a couple of suggestions are mentioned in the following that might help in curbing the power demand of the smartphone's OS.

- **Smartphone oriented kernel:** Development of a kernel, keeping the smartphone parameters in mind will be a more critical, but sure way to increase the overall efficiency of the smartphones.
- **Kernel-level display server:** Using a kernel-level display server to draw graphics in the display may reduce the power consumption of a smartphone [239].

2) APPLICATION POWER CONSUMPTION

Why, how, and how much: Besides the usual apps such as social networks, games, utility apps, etc. many people use their smartphones for different specific purposes. Apps for fitness, mobile health [240], m-learning [104], context-aware applications and services [241], [242], etc. are very common nowadays. As already discussed in Section 4.1.3, the RAM consumes power during the read-write operations, so keeping multiple application alive in the memory may also perform a greater number of read-write operations, draining the battery more quickly. Also, some applications may not be fully optimized and can perform simple operations with very high power usage. Applications are sometimes made to use more permissions and resources than they actually need; hence, it becomes an unnecessary source of power consumption in a smartphone.

How to reduce: Like OS, it is difficult to minimise the power consumption of today's complex and feature-rich mobile applications. However, the following tips might help in reducing the power consumption of applications:

- **Install reliable applications:** Installing verified and popular applications developed by well-known

Background apps	•Apps like memory booster, file cleaning, Facebook, email, etc., run in the background continually, causing faster battery drainage. Also, continuous auto refreshing of the apps for social media, email, news, etc. discharge battery.
Regular updating of software	•Updating software involves connecting to the internet and downloading significant amount of data. This contributes to battery usage. Therefore, unnecessary updation should be avoided.
Music and video streaming	•Continuous streaming of music and videos is one of the major sources of power consumption.
Automatic data backup and apps synching	•The automatic backup of the data (e.g., photos, videos, or documents) and automatic synchronization of apps cause battery loss significantly.
Receiving notifications frequently	•Lighting, ringing, and vibration due to frequent notifications causes significant battery loss. •Notifications make the transceiver antenna busy, which also consumes battery.
Using lots of widgets	•Using a huge number of widgets, especially the health trackers (step counters, calorie burn calculators, etc.) definitely juice more battery power.
Bright & live wallpapers	•Live wallpapers or bright wallpapers with sharp contrast and vivid coloured on AMOLED display are quite notorious as battery burners.

FIGURE 9. Miscellaneous reasons for smartphone battery drain [12].

developers will ensure proper optimization and efficient power handling of the application.

- **Remove power-hungry applications:** Removing any application that seems to be consuming more power is also a good option to reduce power usage.
- **Remove unwanted applications:** Some applications are not at all required by the user and hence can be uninstalled. Further, an accidentally installed adware must be removed in order to save the device from using excessive power due to usage of the unwanted resource.
- **Manage permissions:** Giving proper attention after starting an application in order to provide only the required permissions to the application is preferred. The permission should be restricted to only the required services to perform its operation and not anything else.
- **Stop auto start-up:** Some applications tend to use the automatic start-up option; to reduce energy consumption, only system specified applications should be allowed to auto-start, and the rest of the apps need not have that permission.

D. POWER CONSUMPTION DUE TO USAGE PATTERNS

The usage behaviour of a user heavily determines battery life. Chen *et al.* recognized the user as one of the key factors responsible for power drain in smartphones [243]. This section attempts to identify the causes which are directly related to the user's smartphone usage pattern and accounts for major power consumption. In addition to the reasons discussed in this section, there are other miscellaneous reasons (user's smartphone usage habits), as listed in Fig. 9, which also account for the significant power loss of smartphone batteries. Fig. 10 and Fig. 11 lists a few suggestions on how users can extend everyday battery life and its lifespan, respectively.

1) CALLING

Why, how, and how much: One of the most basic functionalities of a smartphone is calling, and during a phone call, the smartphone needs constant and uninterrupted communication with the cell tower. Also, there are many technologies that support calling such as using the GSM mobile technology, VoLTE, VoIP, etc., and these technologies are different in terms of the quality of the calling and the power dissipation. GSM 2G technology provides a decent voice calling and less power but without the feature of video calling. GSM 3G technology is an upgrade over the 2G technology due to improved data connectivity and has the feature to make video calls. The power consumption models in regular calling using a 3G network mode is less power efficient than calling using 2G network mode. VoLTE provides voice and video calling over the LTE 4G network. The quality of the calling is far better than the previous generations of the network technology, and it doesn't need internet connectivity for calling. But regarding power consumption model regarding basic calling, 2G is the most efficient. In VoIP, a network service provides calling, and the quality and power consumption is dependent on multiple factors such as internet connection medium, speed, and server location.

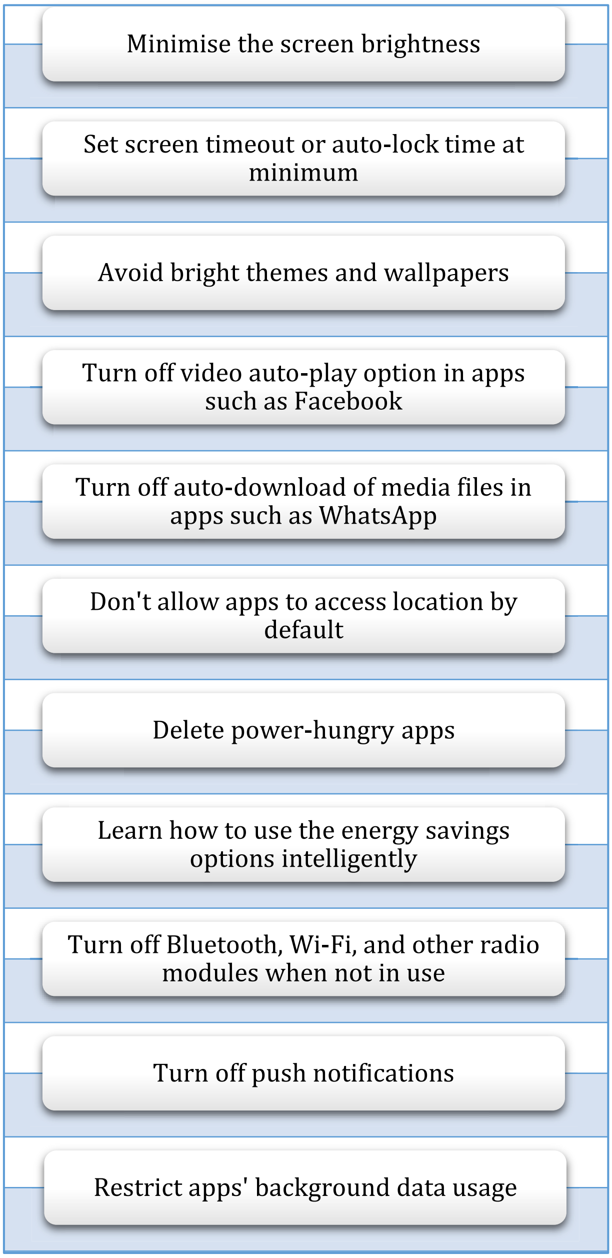

FIGURE 10. Smartphone usage tips to maximize everyday battery life.

How to reduce: Calling is one of the most important and used features of a smartphone that needs constant connectivity to the cellular network. Some points that may be used in order to decrease the power consumption of a smartphone during a call are:

- **Network mode:** Choosing 2G network mode (if available) during a basic audio call is most efficient in terms of power consumption.
- **Device location:** Calling from a location with proper signal strength will consume less power and also will not consume power accounting for signal loss. Avoiding places where mobile cellular networks are not very powerful can be a good solution to reduce power consumption.

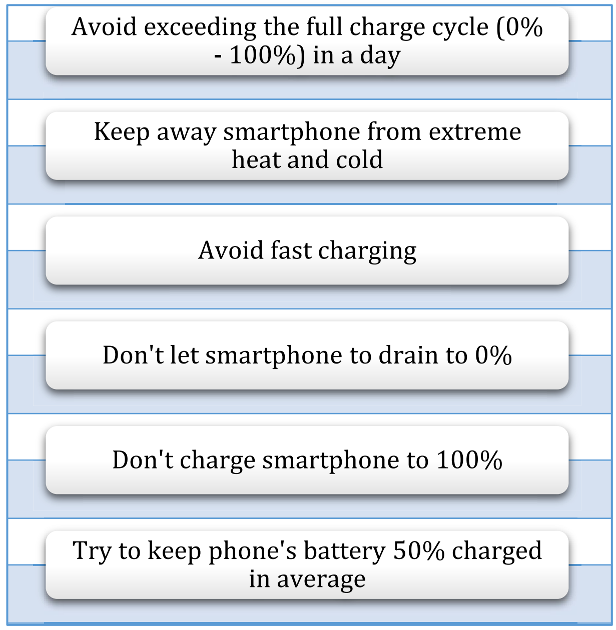

FIGURE 11. Smartphone usage tips to extend its lifespan.

2) INTERNET ACCESSING/WEB BROWSING

Why, how, and how much: Multiprogramming-supported OS allows the smartphone to maintain multiple internet connections simultaneously for different running applications with their corresponding servers. The apps are continuously remotely synchronised, and the application data are backed up to the server or the cloud. Also, an always-on connection allows servers to push asynchronous updates of the respective apps [191]. Smartphone provides decent access to the web not restricted to a location; making the internet browsing a basic functionality of the smartphone. Smartphone users perform networking interactions on a regular basis [244], and hence it can be considered as a reason for consuming some percentage of the power to the overall power consumption of the device. Internet connectivity always depends on either a local access point like a Wi-Fi, a Bluetooth device or a cellular network, each of which has their own power consumption criteria as already discussed in Section 4.2.4, 4.2.2, and 4.2.1 respectively. Web-browsing experience and power consumption model also depends on the browser and the optimization of the applications intended to use internet services.

How to reduce: Similar to calling, continuous internet browsing and watching online content requires constant connectivity of the mobile to the network either via cellular network or wireless mediums which consumes power rapidly. Some power consumption measures that may be adopted in the context as discussed below:

- **Connection selection:** If a smartphone has multiple ways to connect to an internet service provider (ISP), then selection of the best network should either be made by the user or the device should be self-capable of

connecting to the best network based on the speed and connection signal strength.
- **Restricted network access:** Manually restricting internet access to the applications that are not intended to connect to the internet can be helpful to reduce power consumption and will result in saving the internet data quota (if applicable).
- **Restricted background networking:** Many applications execute as a service or run in the background and keep using the data connection either for push notifications or for updating itself. Therefore, restricting background data usage will ensure that the application will be able to access the internet only if the application is focused and executed in the foreground. This results in a huge power saving option of the smartphone.

3) GAMING

Why, how, and how much: Smartphone has already become a very popular platform for playing games. Be it classic games or graphic-intensive games; smartphone GPUs have evolved a lot in this regard. Games can be considered as an interactive application with prominent visual effects and vivid textures. Games are very demanding in terms of hardware requirements of a smartphone. Some games may even outrun the capability of many of the mid-range mobiles during execution. Games mainly focus on the processor, GPU, and RAM of a device and try to utilize most of them in order to provide the best possible experience to the user. This, in turn, consumes a decent amount of power from the device. Continuous gaming may result in higher heat generation from the hardware components, which may consume more power and/or reduce performance. Since gaming involves multiple hardware, the power consumption model, in this case, can be considered as the cumulative power consumption of all the hardware components separately. All the other factors, apart from the factors mentioned in Section 4.3.2 for application power consumption, can be considered in gaming as well.

How to reduce: Gaming can be described as constant usage of CPU, GPU, RAM, Display and other hardware components present in a device, making gaming one of the most power-hungry usage of a smartphone. Following is a list describing the ways to reduce power during playing games on a smartphone:
- **Device material selection:** During gaming, some factors are most dominant in the power dissipation, like the material used in the smartphone. Aluminium body conducts heat easily than plastic or glass, meaning more efficient cooling is observed for aluminium devices.
- **Optimised cooling:** Devices meant for heavy gaming must include proper cooling technology to keep the internal temperature controlled.
- **Downclocked CPU:** Sometime during gaming, keeping the CPU downclocked to a certain percentage may have a great effect on the overall play quality. This confirms no overheating and hence no frame drops in the game.
- **Lowered display brightness:** During gameplay, the display needs to be continuously turned on. Therefore, the brightness of the display, if kept at a lower percentage, may be considered an effective solution in keeping the power dissipation low.

4) PLAYING MUSIC

Why, how, and how much: Smartphones are widely used to consume media in the form of audio or video. Audio playback is a very frequent task that most of the users perform regularly. The power consumption model for playing an audio file can be understood if the whole process is seen separately. First, the processor needs to perform a specific read operation on the secondary storage where the audio file is located and then load it in the RAM. After that, the audio processor processes the file and provides an output that passes through either the headphone amplifier or the loudspeaker amplifier whichever is applicable. All these stages consume power; such as a read operation on the RAM, audio processor, amplifier, and finally, the output hardware be it speaker or headphones. Higher bit-rate audio and multi-channel file provides better experience but needs more power by the audio processor during playback.

How to reduce: Some points to act on to save some power during audio playback are as follows:
- **Display standby:** Turning off the display during the audio playback session can provide more power for longer playback.
- **Sleep mode:** The smartphone requires a very less amount of processing power in order to play music, and hence the device may go to sleep mode during the music playback session, saving a good amount of power in this process.
- **Volume management:** Keeping the volume low will make sure not to overpower the speakers, reducing heat generation and hence may help lower power consumption.
- **Decreased bitrate:** The bit rate of an audio file can be downgraded using better compression techniques to improve power consumption without hampering the listening experience.

5) WATCHING VIDEOS

Why, how, and how much: Just like an audio file playback, the video playback follows the almost same procedure. Although the video files have more parameters that affect the power consumption models. The video files have parameters like resolution, frames-per-second, audio channels, audio bitrate, etc. Apart from all the power consumption criteria for the audio, video playback consumes higher power and CPU/GPU utilization for higher resolution video, and higher frame rate video. Depending on the quality and type of the video file, OS chooses either the CPU or GPU to playback the video smoothly.

How to reduce: The following measures can save some power during video playback:

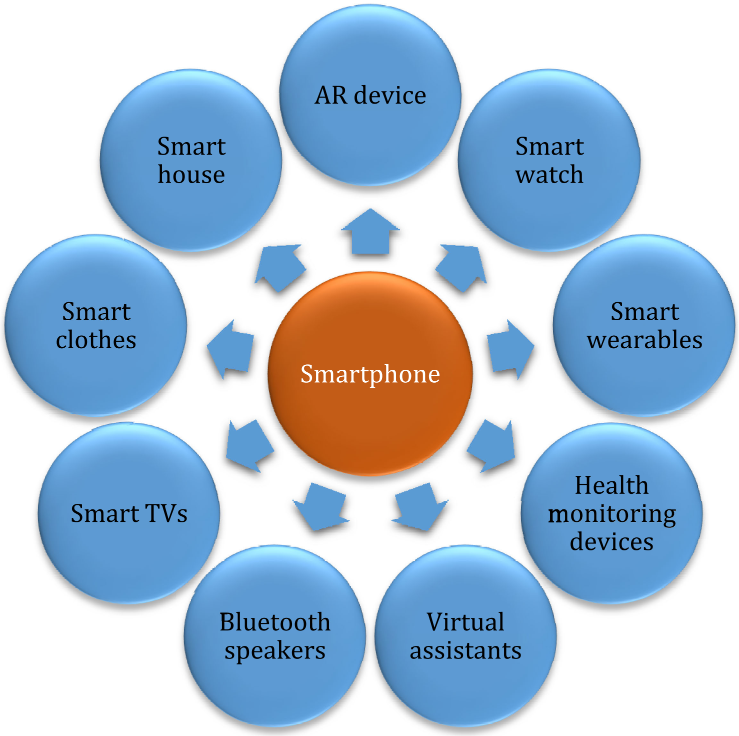

FIGURE 12. External entities in an inter-device communication with smartphones.

- **Resolution scaling:** During power saving mode, it is recommended to playback a lower resolution video file which will be less resource-intensive and hence consumes less power.
- **Lowered framerate:** Videos with higher framerate needs more processing and hence consumes more power when compared to a lower framerate video. Human eyes are not capable of identifying individual frames, if a video is played with 25 FPS or more. Therefore, playing videos having around 30 frames per second can be descent and efficient choice when power saving is important.

6) RUNNING HEAVY APPLICATIONS

Why, how, and how much: Smartphones drain battery power more quickly than basic feature phones not only because of their hardware components like brighter screens but also because of the power-hungry applications that are constantly running on the phone. Running computing-intensive applications such as real-time data analysis, image analysis and classification, etc. requires significant energy. Most of the smartphone applications use ML and AI techniques to solve complex operations in the mobile itself. ML and AI are widely used in largescale AR [245], VR [246], [247], and many more.

How to reduce: Computations performed on a smartphone require power, but for running heavy applications, the same power consumption concept extends due to the capability of a processor and time to complete heavy computations. Hence, the following approaches can be followed to reduce power consumption:

- **Mobile cloud computing:** Cloud services may be considered for executing large and complex jobs [248]. A user wanting to run a heavy application on his/her smartphone may get the service from a cloud service provider. In this scheme, transmitting and receiving data packets will cause power expense, but it will marginally less compare to the power requirement in processing those applications on the device.
- **Code and computation offloading:** Some power-hungry part of the computation or the code are offloaded to a nearby system [249]. It may be another smartphone in a crowd computing environment [250], a neighbouring smartphone in a mobile ad-hoc cloud [251], an fog/edge. device [252], or a traditional centralised cloud [253], [254]. This saves a lot of power and time during the process, depending on the volume of the computation.

E. OTHER FACTORS LEADING TO HIGH POWER CONSUMPTION

1) INTER-DEVICE COMMUNICATION

Why, how, and how much: A smartphone may interact with other wireless devices, as shown in Fig. 12 [191]. Nowadays, several wearable and health sensors are used for dynamic and real-time monitoring of health status [255], [256]. These devices provide a huge benefit in terms of usability of a smartphone, but at the same time, they are also responsible for power draining of the smartphone. Most of these devices require constant connectivity to the smartphone during their operation, and some require a connection even when not operating. Hence, even if these devices have other sources of power and is not consuming power directly from the smartphone, it still counts when considering more precision in terms of power consumption.

How to reduce: In an inter-device communications scenario, the following measures can be taken for energy preservation:

- **Inter-device task distribution:** Task distribution needs to be performed across multiple connected devices at the inter-device level. This makes sure that the smartphone single-handed will not be responsible for the task distribution. Each device will be self-capable of distribution of their task, hence reducing the power consumption overhead from the smartphone.
- **Optimised processing:** Implementing optimised processing across devices will mean the devices will know the features and specification of other devices, letting them decide when or whether to perform specific actions.
- **Optimised scheduling:**Scheduling is an important function of a multi-processing environment. When devices are interconnected, the devices need to have proper attention within a specific interval of time. This can only be archived with proper scheduling. Implementing proper scheduling will make sure that the connected devices are getting proper attention and hence, will make the process more energy-efficient.
- **Optimised data transfer:** There exist a variety of data transfer protocols for interconnected devices based on the type, size, and volume of the data. Selecting the data transfer method that is well optimised and requiring fewer data transportations is always preferred. Although, the compressed data will need less bandwidth, but will consume more processing power during compression and decompression procedure. Therefore, a very good optimization of compression must be maintained in order to optimize the data transfer and hence making device energy efficient.
- **Adopting energy-efficient communication protocols:** Communication protocols have a huge impact on the power consumption model of the interconnected devices. Connection-less and connection-oriented protocols are the two types of protocols. These protocols are used according to the necessity of the connection and considering security factors. These protocols control the flow of the data from one device to another device within the same network or across different networks, hence having a more device-oriented protocol may be an option to make the process more energy-efficient.

2) HEATING

Why, how, and how much: A small device consuming more than three watts of power may suffer failures due to excessive heat and/or performance degradation can be observed. The material used as the body of a smartphone is also responsible for the heating of a device. The heat should be dissipated from the processor and other components to the surrounding. Using better conductive materials such as aluminium will ease this process, whereas using a glass or plastic material as the body may not be ideal in heat dissipation. Excessive heat in the device will result in more resistance and hence increased power consumption. Processor reduces performance to keep the temperature low in order to save the components from failing due to excessive heating. Further, during charging, the device may get hot due to major energy transformations needed for fast charging technologies.

How to reduce: Heating of the smartphones can be controlled to a certain degree using the following methods:

- **Device material selection:** Aluminium is preferred body material of a smartphone as it conducts heat easily than plastic or glass, meaning more efficient cooling is observed in aluminium devices.
- **Don't use while charging:** Not using the device during charging may be a good option as it will not cause any harm to the charging components. In addition, the device needs to bypass the power from the charger to the smartphone as charging and discharging cannot occur simultaneously. Further, this kind of usage may generate heat and can cause harm to the device.

3) AGEING AND FAULTY BATTERY

Why, how, and how much: Any hardware device goes through the three stages of its lifecycle known as the early life, useful life and wear-out. A battery of a smartphone also follows the same phases. During the wear-out phase, the battery capacity gets low, charging time gets high, temperature increases more drastically during charging or discharging, and power wastage during charging also get high. As a conclusion, during the wear-out phase of a battery, its efficiency is highly reduced both in terms of charging and discharging.

How to reduce: Excessive power consumption in a smartphone due to ageing and the faulty battery can be controlled using the following points:

- **Don't use ageing battery:** Battery replacement is necessary when the battery is ageing or have some faults; this not only saves power but also reduces the risk of explosion.
- **Make use of power-saving mode:** If battery replacement is not an option due to some factor, the smartphone must be used in a power-saving mode in order to use the most important functions such as messaging and calling while switch the other functions off until a replacement battery is installed.

4) FAULTY HARDWARE

Why, how and how much: Smartphone hardware broadly includes different ICs (like charging, power management, etc.), microprocessor, motherboard connectors, signalling antennas, camera modules, components (like resistors, capacitors, inductors, diodes, etc.). All of the above-mentioned components are prone to failure at some point of time during the lifetime of a smartphone. Malfunctioning hardware may either result in a bricked device or some non-functioning portions of the device. Most of the smartphones suffer power loss due to failed components, which may result in heat generation; making other components fail in a series. This kind of failures is considered as chance failures, as no prediction can be made about when the hardware may fail. Sometimes, it can happen that a component failed, but still, the device works normally without showing any sign until some major components fail. This can be serious and may result in explosion or damage to the smartphone. Further, minor component failures may result in degradation of battery life.

How to reduce: Identifying and fixing faulty hardware may get complicated sometimes as already discussed, but some solution to increase the chance of detecting a fault and reduce the power expense is provided below:

- **Charging time:** Charging time can be a very easy but sure way of knowing whether the device's charging modules and the battery is in good condition. Knowing the approximate charging behaviour of a smartphone, one can identify if the charging time is changed to a large extent in an ideal condition.
- **Backup time:** This is an important criterion to judge whether a device has some internal faults or battery failures. As already discussed, the smartphone tends to draw more power if components have failed. In this situation, the solution would be to first check the battery and replace if needed. If the problem still exists, it is recommended to check the components by experts and take the necessary actions.
- **Hardware monitoring applications:** Some applications (e.g., CPU-z)[1] provide details of many of the hardware components present in a smartphone. By analysing the details, it may be possible to detect the malfunctioning component and replace or repair the component as soon as possible to reduce the risk of bricking the device.
- **Temperature:** If the device gets unusually hot during standby, then it may also be a sign of faulty hardware and may need a fix.

5) INCOMPATIBLE CHARGER AND FAULTY CHARGING SLOT

Why, how, and how much: Charging a smartphone also dissipates power in some ways. There may be a faulty charging cable which may result in a short circuit and consume power. This is more dangerous in a USB OTG enabled device, as it may short internal components. Sorting internal components may result in heat production, high resistance or both. If the charger is not compatible with the battery, the charging process gets disturbed, causing the device to be heated, which in turn, increase the energy depletion rate of the battery.

How to reduce: The power dissipation related to hardware faults in battery and charging components can be minimised by opting the following ways:

- **Usage patterns:** Restrict battery usage while charging the device. It will improve the charging efficiency and reduce power usage.
- **Compatibility:** It is always recommended to use a compatible battery and charger for better reliability and power efficiency. Not following the compatibility criteria may be unreliable and less power efficient.
- **Hardware maintenance:** Replacement of faulty hardware like charging slot, charging cable, charger or battery is mandatory for a smartphone to work efficiently. Failing to replace faulty hardware may not be good for the health of the smartphone and has more chances of unwanted power dissipation.

V. SMARTPHONE POWER CONSUMPTION MEASUREMENT

Different components of the smartphone and their use in a different situation may cause power dissipation in smartphones. CPU load, GSM, LCD, backlight, in-built sensors, GPS, Wi-Fi, Bluetooth, different background services, graphics, etc. all have a role in consuming considerable energy in some particular usage behaviours [235], [257], [258]. Monitoring of power consumption in smartphones is very much essential for getting energy-efficient system. Depending on the data monitored, different systems can be developed to control power consumption in smartphones. This section reports the research works that focus on analysing, assessing, and estimating power consumption and time need for next recharging.

A. POWER CONSUMPTION PROFILING AND MODELLING

Energy profiling schemes help in estimating the power consumption of a mobile device. It provides valuable insights about power consumption patterns of various hardware components in the device and helps to identify the cause of the energy drain. An ideal energy profiler correctly detects the abnormal energy consumption and energy bottlenecks in a smartphone. Consulting the energy profiler, application developers are able to identify the events, activities and segments of code that are responsible for heavy energy burning up, and adjust their application design accordingly for energy-efficiency.

Jofri *et al.* [202] classified the key elements of energy profilers into five categories, as shown in Fig. 13. An energy profiler typically works in three phases [259], as mentioned below and shown in Fig. 14.

i. **Data collecting:** This phase collects the energy consumption details of the hardware components and applications.

[1] https://www.cpuid.com/softwares/cpu-z.html

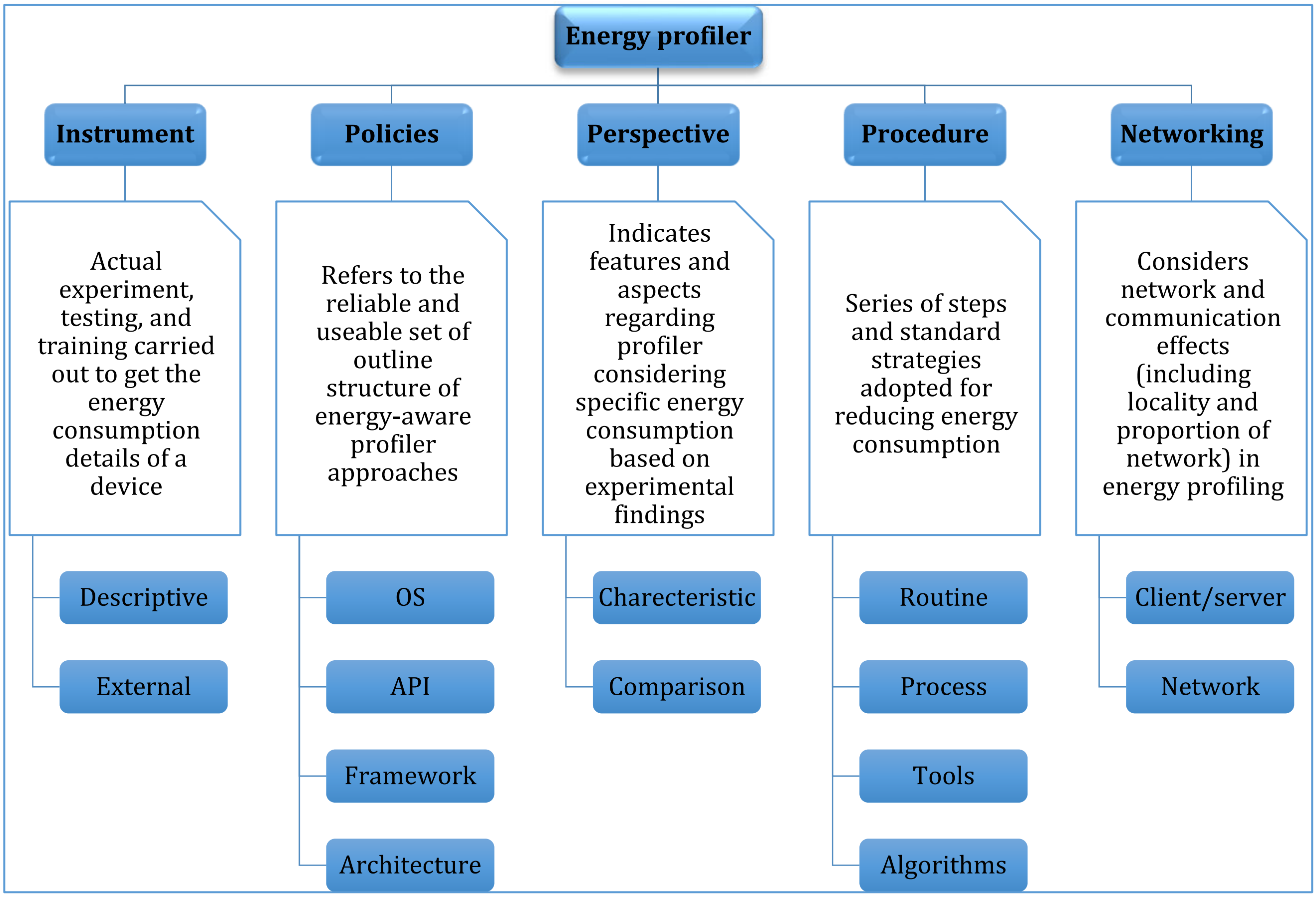

FIGURE 13. Key elements of an energy profiler.

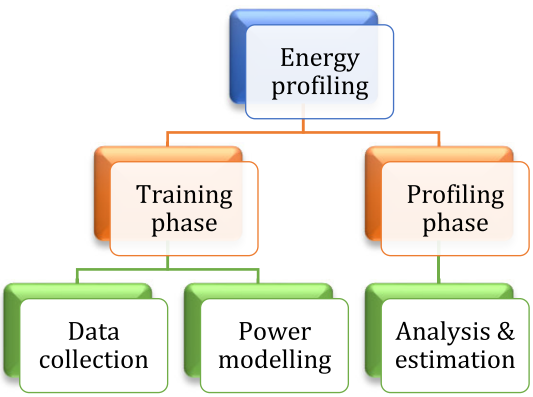

FIGURE 14. Energy profiling phases.

ii. **Power modelling:** The power consumption of a smartphone is represented by a power model as a function of its components' specific parameters [204]. Mathematical equations and models are applied to the collected power consumption information for finding the correlation between a power-consuming component and the power consumed by it. The mathematical models quantify the impact of several factors (e.g., usage level, component state, usage time, etc.) on the overall power consumption of each component [203]. The power modelling is also used to determine the inter-component dependency on the power consumption the components [260]. The power model may be the existing one (previously built), or the profiler might build their own to characterise the power consumption exclusively for each hardware component and application. Depending on the kind of input variables the model uses, modelling power consumption of a smartphone is divided into three categories, as shown in Fig. 15 [204], [261].

iii. **Analysing and estimating:** By applying the model power consumption of a hardware component or an application is analysed and estimated. The analysis and estimation might be for a specific operation and execution or overall power consumption.

This section discusses some of the worth mentioning research works addressing power consumption profiling and modelling in smartphones.

1) THE EARLY WORK

Way back in 2010, Carroll and Heiser [223] attempted to profile energy consumption of different hardware components (e.g., CPU, RAM, display, graphics hardware, flash storage,

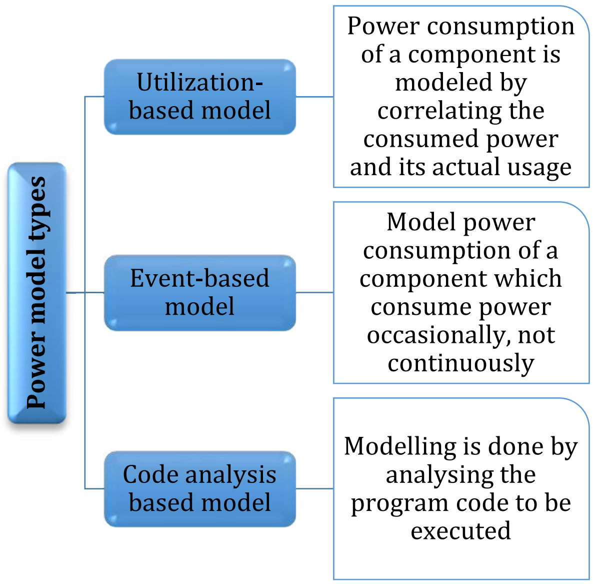

FIGURE 15. Types of power models [204].

Wi-Fi, GSM & GPRS, and GPS) of a mobile device. They used Openmoko Neo Freerunner (revision A6) mobile phone as the primary DuT, along with HTC Dream (G1) and Google Nexus One (N1), for further validation. They measured the supply voltage and current for each component to calculate its power consumption. They also considered the different usage scenarios (e.g., audio and video playback, messaging, calling, emailing, and web browsing) to assess the overall power consumption of the device. Besides the active state, the other two states of the device were considered: a) suspended (application processor is idle, but the communications system is awake to receive probable incoming communications) and b) idle (fully awake but no applications are running). It was observed that the GSM and display modules consumed the majority of the power while the RAM, audio, and storage subsystems consumed lowest. Although this work is really outdated in today's context, we get a fair idea about a smartphone's power consumption analysis.

2) LTE SMARTPHONE POWER MODEL FOR SYSTEM-LEVEL SIMULATIONS

The gap between smartphone battery capacity and the energy requirement keeps on widening due to the use of complex telecommunication protocols. Lauridsen *et al.* [262] modelled and optimised the LTE modem since the LTE modem consumes a lot of power and cannot be discarded during power modelling. A dummy battery is used to conduct the test of the model on a network emulator. The power model is upgraded from [263] to include cell bandwidth and DRX. The modem power consumption is defined as:

$$P_{modem} = m_{idle}.P_{idle} + m_{DRX}.P_{DRX} + m_{act}.P_{act}$$

where m is a Boolean value used for activation of different modes. To validate the model, measurements are carried on three different LTE smartphones, of which UE2 was selected as the base model. It is seen that the battery consumption using DRX in deep sleep mode is 1/35th of active mode consumption.

3) MODELLING ENERGY CONSUMPTION OF DATA TRANSMISSION OVER WI-FI

Wi-Fi usage takes up a lot of power from the battery, and the power consumption is dependent on the type of the network and the performance of the network. Xiao *et al.* [264] proposed a model that is deterministic in nature and uses traffic characteristics of the network to estimate the energy sent in Wi-Fi data transmission. This model is expected to work in both TCP and UDP transmission protocols. The Wi-Fi network interface (WNI) is in the active mode when either it is receiving or transmitting. The average power consumption is calculated on the duration of uplink and downlink bursts. The model is evaluated on four smartphones in the TCP transmission model. The results are then compared with PowerTutor [261] application results, and the results of PowerTutor seemed to deviate from the actual measured values because it only takes into account packet rate and upstream channel rate and is quite naive.

4) MODELLING USING SYSTEM-CALL

Energy estimation is necessary to understand and debug different smartphone applications. Most of the power models use the actual utilization of the hardware with the power models and cannot come up with accurate results. Pathak *et al.* [265] has gone through the present state-of-art utilization based power modelling schemes and proposed a system-call based power model that stands out from the limitations of the utilization based approach. This model captures both utilization and non-utilization based power usage. The model is implemented in both Android 2.2 and on Windows Mobile 6.5, and the model is found to perform better in terms of the error in fine-grained energy estimation than linear regression model [261], [266]. The fine-grained based energy estimation is also demonstrated manually by using the system-call based power modelling and is called Eprof, which can be used for optimizing the energy of different smartphone applications.

5) MODELLING OF POWER CONSUMPTIONS OF UPLOAD PATTERNS OF SMARTPHONES AND IOT DEVICES

The energy consumed by smartphones needs to be separated from each hardware component to generate power-efficient hardware. Donatiello and Marfia [267] focused on a modelling effort that takes into account the most popular categories of the application that upload the data collected into the cloud. The advent of the IoT has revolutionised the health care industry [255]. The trend of collection of data is likely to increase to a much higher level [268]. The modelling technique thus proposed is then analysed based on the data which was collected from nearly 1.4 million devices that run on the android platform. An algorithm is provided, which is used to compute the probability distribution function as the number and time of occurrence of each upload by each application, which is unknown to us.

6) PREDICTING ENERGY CONSUMPTION FOR ANDROID APPS

Hu *et al.* [269] proposed a statistical model-based technique to predict the energy consumption for Android apps. The energy consumption analysis is done at method-level and API-level. The method-level analysis gives details of energy consumption of the third-party apps, whereas API-level analysis gives the energy consumption information of Android APIs. Applying the model on a number of Android apps, the authors' conclusion on the power consumption shares of different software components is shown in Fig. 16.

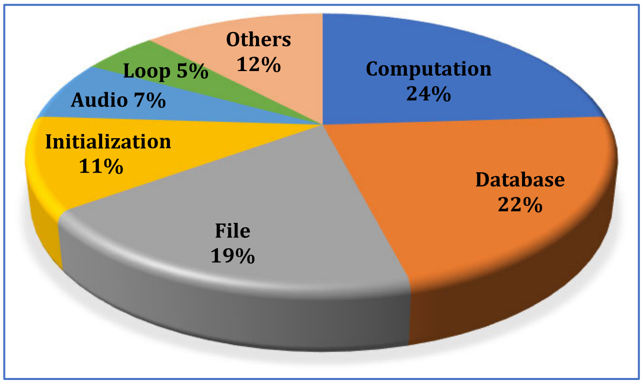

FIGURE 16. Energy consumption percentage of different software components as per [269].

7) MOBILE SOFTWARE'S POWER CONSUMPTION MODELLING USING MDE

For analysing the probable power consumption of mobile software architecture, Thompson *et al.* described a Model-driven Engineering (MDE) based tool, named System Power Optimization Tool (SPOT) [270]. Using SPOT, developers can create high-level models of a target software by utilizing System Power Optimization Modelling Language (SPOML), which allows capturing of the key software components related to power consumption. Executable emulation code, generated by SPOT out of these models, collect power consumption data which can be used by the application developer to understand the application's power consumption pattern. Since the power consumption estimation is done in the designing phase (i.e., early in the application development lifecycle) the actual power consumption (when it is installed) may be different dependent on varied operational environment.

8) ENERGY PROFILING BASED ON DIFFERENT USAGE SCENARIOS AND CONTEXT-AWARE FUNCTIONALITIES

Ardito *et al.* [271] researched for profiling the power consumption behaviour of a Samsung Galaxy I7500 and a Samsung Nexus S through external measurement hardware. Energy profiling is done by identifying different usage scenarios and secondly of a known source code providing context-aware functionalities. From the analysis of the experimental results, the research work concluded that the most recent smartphone, with their new OS and hardware components, shows prominently lower power consumptions than the least recent one, except for the CPU-intensive and active display units. This finding also shows that software with energy-awareness can improve the energy efficiency of mobile devices, maintaining the same functionalities.

9) A TOOL TO DEBUG APPLICATIONS TO ANALYSE POWER DRAINAGE

Metri et al. [272] explained the power profiling techniques to determine the energy efficiency of applications on Android devices. Software Power Monitor (SoftPowerMon) tool was introduced by which developers can debug applications from an energy perspective to detect the reasons for specific power consumption.

10) ON-DEMAND ONLINE PROFILER TO ACHIEVE ENERGY EFFICIENCY

An on-demand-online profiler, called pProf was reported by Shukla *et al.* [273]. The profiler pProf can learn from offline-precomputed model parameters and act efficiently, reducing the online profiling cost. This technique was tested in a customized setup of Android smartphones with embedded communicable sensors. The experimental results show that pProf achieves better energy efficiency in comparison to existing popular profilers like Amobisense and PowerTutor.

11) A MODEL-BASED APPROACH TO ANALYSE POWER CONSUMPTION

Nakajima [274] proposed a new model-based approach power consumption automaton (PCA) to analysis the asynchronous power consumption of Android applications. All the applications consuming power are represented as a library by this PCA; for example, Wi-Fi PCA is such an example. This paper focuses on the analysis of unexpected power consumption by checking whether the whole system stays at a particular power state for a long period unexpectedly.

12) DATA-DRIVEN MODEL TO PREDICT POWER CONSUMPTION OF APPLICATIONS

To predict battery consumption of smartphone applications, a data-driven model was proposed by Eastham *et al.* [275]. The researchers trained a regression model using data collected from logs and confirmed that the learning approach is correct under minor assumptions. The work demonstrated that the learned model consistently outperforms a model trained on microbenchmark experiments across different tasks.

13) UNSUPERVISED POWER PROFILING FOR MOBILE DEVICES

Kjærgaard and Blunck [276] proposed PowerProf, which is an unsupervised way of modelling smartphone power

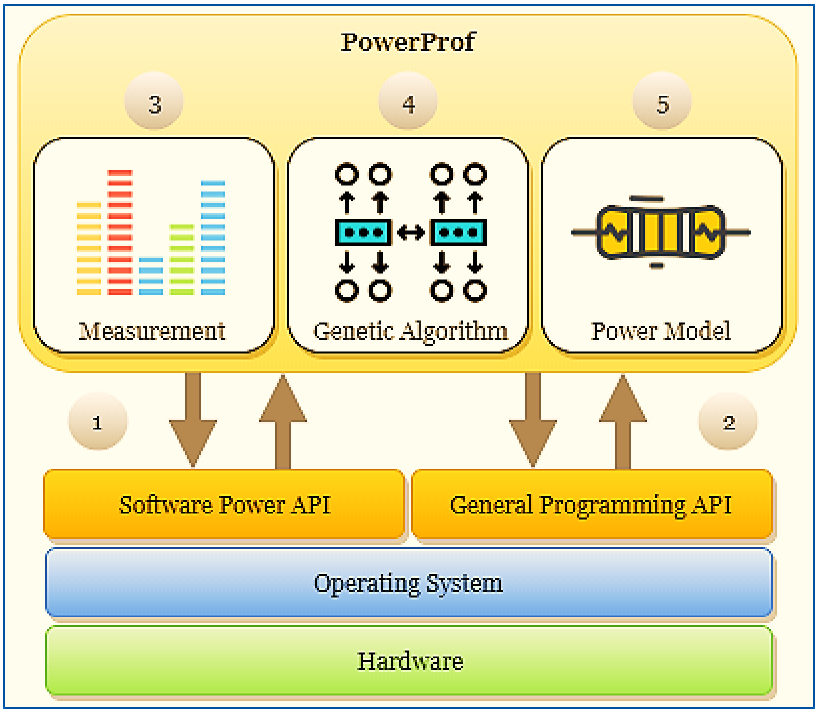

FIGURE 17. Steps of the PowerProf system from measuring to generating power models.

consumption using basic algorithms. PowerProf used the newly available smart battery interfaces that include software API's that provide access to the battery measurements. The conditional function for each smartphone feature models the feature's power consumption and depends on the input parameter t, which gives the timespan since the feature was last called using an API call. PowerProf is tested in three different types of smartphones and showed a median error of 0.012 watts and 0.145 watts in the 95th quantile. PowerProf is able to capture the general fluctuation in energy consumption, but the random spike is not captured in quite an accurate manner. The steps of the PowerProf system from measuring to generating power models is shown in Fig. 17.

B. ENERGY CONSUMPTION ANALYSIS AND ESTIMATION OF SMARTPHONE HARDWARE AND RELATED MODULES

To tackle the energy deficiency issue in smartphones, it is the prerequisite to understand the energy requirements of its different components. Proper analysis and estimation of energy consumption will allow device designers and manufacturers to optimise the hardware and platform. It will also allow the users to use their device sensibly, saving the energy and thus, extending the battery life. In our review process, we found most of the research works fall in this category, i.e., analysing and estimating the power consumption have been the topmost priority among smartphone energy research. Among them, the notable research works are mentioned below.

1) RUNTIME POWER ESTIMATION OF MOBILE AMOLED DISPLAYS

To estimate the energy behaviour of recent smartphones, the most important component is the display as it consumes most of the battery. Kim *et al.* [277] proposes an energy estimation and modelling for AMOLED displays of modern smartphones. They present a runtime power estimation of AMOLED displays while any random application is running. The model also takes into consideration of the RGB values of each sub-pixel. The data of every on-screen change is collected and used in this model. The RGB pixel data are collected dynamically, and the cost depends on the number of pixels on the screen. This model was experimentally tested on Samsung Galaxy S3,[2] with a 4.8-inch Super AMOLED display. An application called AppScope [278] is used to collect the energy information for each process. The proposed model is seen to show an error rate of 2.2%. Although the model gives a satisfactory result in the test, it might fail to detect the change of continuous video images.

2) CONSTRUCTING ENERGY MODELS FROM CROWDSOURCED MEASUREMENTS

Peltonen *et al.* [279] proposed a cost-effective approach to construct battery models using crowdsourced measurements to establish the relationship between battery drainage with different combined scenarios like high CPU load and automatic adjustment of screen brightness, medium CPU activity and manual adjustment of screen brightness, or strong Wi-Fi

[2]http://www.gsmarena.com/samsung-i9300-galaxy- s-iii-4238.php

signal with direct exposure of sunlight with the device. Consideration of combinations or different factors make this work separate from the others in the sense that the other modelling schemes consider only specific factors such as a specific sensor, system setting, or an application, our approach can. Whereas, this approach helps to identify the effects of multiple factors by capturing their relationship and hence provides a holistic view of the energy state of the mobile device.

3) POWER MONITORING THROUGH INBUILT BATTERY VOLTAGE SENSORS

An automated power model built-up technique named PowerBooter was presented by Zhang *et al.* [261]. Without using any external measurement equipment like a power meter, this system can monitor power consumption using built-in battery voltage sensors and the knowledge accumulated from the battery discharge behaviour.

4) POWER MONITORING THROUGH POWER SOCKETS

The wireless smart power sockets, developed by Yun *et al.* [280], can measure and transmit the power consumption data of electrical devices to a host server. Additionally, this system can control power consumption by turning on and off relays embedded into smart sockets through the Android application, which passes the command to the smart sockets. This system can draw graphs related to the power consumption of smartphones.

5) POWER MONITORING USING MULTI-METER

The work presented by Li *et al.* [281] directly measures the voltage and the current of the smartphone by multi-meter and study the power consumption of different modules at different situations of a CPU like single or multithreading, Wi-Fi and GPS. Considering power consumption P=UI, where U and I are the voltage and current on the tested module, respectively, the power consumption of a specific module is found by recording its current I1, keeping the smartphone to a predefined test condition with all irrelevant applications closed and 50% screen brightness. Then, the desired application is opened and record its current I2, so the current increment of the tested module is I2 - I1, resulting in power consumption as U (I2 - I1), where U = 4.2V is assuming an external DC power source with a fixed voltage of 4.02V.

6) CHARACTERIZING ENERGY CONSUMPTION THROUGH CROWDSOURCING

Peltonen *et al.* [282] constructed battery models by considering various information (e.g., CPU load, memory information, screen brightness, battery information, network information, etc.) collected from over 725,000 smartphones. It is observed that the higher ambient temperature, defective battery or a battery bug, moving the state of a person carrying the smartphone in direct sunlight can also have an influence in battery drain in addition to the internal hardware and software-related factors of a smartphone.

7) ESTIMATION OF POWER REQUIREMENT BY UTILIZATION-BASED AND FSM-BASED MODEL

An Android application based hybrid model is presented by Chen *et al.* [243] which combines both the utilization-based model and the FSM-based model to analyse and estimate the impacts of CPU, GPU, cellular, Wi-Fi and different apps running on the mobile phones on power consumption with the heterogeneous Android environment with different numbers of backend application and screen on-off scenarios.

8) BATTERY DISCHARGE RATE PREDICTION BASED ON MLP AND SVM MODELS

Chantrapornchai and Chantana [283] presented an ML-based model to predict battery discharge rate in three different usage scenarios: a) when the mobile is in the standby state, b) video playing, and c) web browsing situations. The battery prediction model is made using different regression functions based on the collected data on the HTC OneX platform enabling and disabling Bluetooth, Wi-Fi, GPS, etc. and also setting different brightness of the display unit. The effectiveness of two ML models based on MLP and SVM for predicting mobile phone battery usage considering linear and polynomial (3^{rd} order) regression were compared using the RMSE and MAE for all of the cases. The model with smaller value would be considered as a better model for prediction.

9) POWER CONSUMPTION ANALYSIS OF SAMSUNG GALAXY PHONES

Xiang *et al.* [257] investigated power consumption of a set of Samsung Galaxy series smartphones and identified that the hardware components like GPU, camera, cellular network module have greater influence in power consumption than Wi-Fi and multimedia codec in modern smartphones, the used therefore optimization in use of these techniques can save energy.

10) POWER CONSUMPTION MONITORING USING SOFTWARE TOOLS

Two applications, namely the PowerTutor and the AmobiSense were used by Tawalbeh *et al.* [284] to measure the power consumed of major components like CPU, OLED, Wi-Fi, and GPS units of the phone in addition to the total power consumed. The authors considered Galaxy Note3 and Sony Xperia Z2 smartphones for their experiment, which was conducted for both normal and airplane modes. The experimental results show that Wi-Fi, 3G unit and the OLED are the major power-consuming units in both devices.

11) ANALYSING ENERGY EFFICIENCY BY EXTERNAL AND INTERNAL SOFTWARE METHODS

Damaševičius *et al.* [258] presented a tool to measure and analyse the energy efficiency of an entire mobile computing system by using internal and external software techniques. An algorithm is developed using internal software for measuring the energy consumption taking care of the performance features of the mobile device. External software like Java API based method, sensor API-based method, and GSM modem-based methods are used as energy measurement methodologies.

12) POWER TRADE-OFF IN VIDEO TRANSMISSION

Spachos *et al.* [285] studied the power trade-offs in case of video transmission through mobile phones over four smartphones with different display size, resolution and also with varying video quality and communication mechanisms. The study asserts that the display size plays the most vital role, even more than display resolution, affecting the average power consumption during a video streaming. The study also identifies situations where power consumption is less affected by display resolution than communication technology. According to the results revealed in experiments, Wi-Fi showed more energy efficiency for video communication than LTE. This research work suggests preferred usage patterns and guidelines for users and developers.

C. ENERGY CONSUMPTION ESTIMATION AND ANALYSIS OF SMARTPHONE OPERATING SYSTEMS AND APPLICATIONS

As mentioned in Section 4.3, although the majority of the power in a smartphone is consumed by its hardware and networking modules, the continuous increase in adoption of complex and feature-rich operating systems and applications have instigated the power consumption further. This section discusses the few research works which aim to address the aspect of power consumption by the software components of smartphones.

1) BATTERY DRAINAGE DUE TO OS

In [286], not only hardware components but different OS-related factors are also identified for battery drainage. Different power consumption data are analysed and compared by the research, and it identifies that the power-save models are not very much efficient for saving power. In sleep, putting the smartphones in flight mode can help saving most of its energy, and thus extend its battery consumption. LTE, the new network, performs well in sleep mode.

2) ANDROID-BASED SOFTWARE TO MONITOR RATE OF POWER CONSUMPTION OF MOBILE APP

A smart energy monitoring system named SEMO, using Android OS is developed by Ding *et al.* [287] to monitor the rate of energy consumption by applications in a smartphone. SEMO checks the power drainage status and the temperature of the battery. After collecting the energy consumption data and data of battery power remained, the software can analyse the energy consumption of the applications, installed on the mobile devices, according to the data it collects.

3) SYSTEM-CALL BASED ENERGY PROFILING

Chowdhury *et al.* [288] proposed multiple system-call based energy models using multiple versions of five Android applications: Firefox, Calculator, Bomber, Blockinger, and FeedEx. System calls are used to predict the energy consumption of each application installed in mobile with the aid of machine learning technique. The model group together different system-calls that could be used to generalize measurement. By the dynamic tracing of system-calls and estimating the idle application energy usage, a developer can estimate the energy consumption of one application without a hardware power meter accurately.

4) MONITORING SOFTWARE DEPENDENCY ON POWER CONSUMPTION

Kurihara *et al.* [289] tried to monitor software dependencies on energy consumption of smartphones. The method can estimate GPS and wake-lock time more accurately than that of the standard system of the Android OS. By monitoring the start and end of the applications like GPS and wake lock, this system estimates the power consumption pattern of the applications installed.

5) CODE-LEVEL ENERGY CONSUMPTION ESTIMATION

Hao *et al.* [290] presented an approach named eLens which can estimate code-level energy consumption by tracking one application's path and analyse its energy information at runtime and thus estimating the energy consumption of each Application Programming Interface calls for the hardware parts of the system like CPU, memory, network-related components etc.

D. DETECTING ENERGY HOTSPOTS, ENERGY BUGS, AND ENERGY LEAKS

Due to various reasons, often smartphones loose power that is not counted to usual activities. This unwarranted energy outflow happens generally due to a flaw in smartphone hardware or software. The unjustified energy expense can be categorised into three types, as shown in Fig. 18 and discussed below.

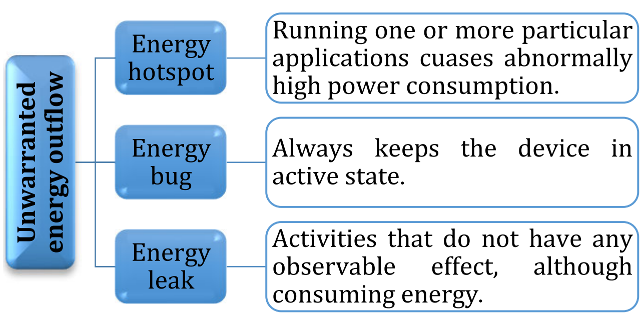

FIGURE 18. Classification of unwarranted energy outflow in smartphones.

- **Energy hotspot:** Energy hotspot refers to a condition where the smartphone experiences abnormally high energy outflow when certain applications are executed or certain activities are performed, even though the hardware utilization is low [291]. Common reasons and

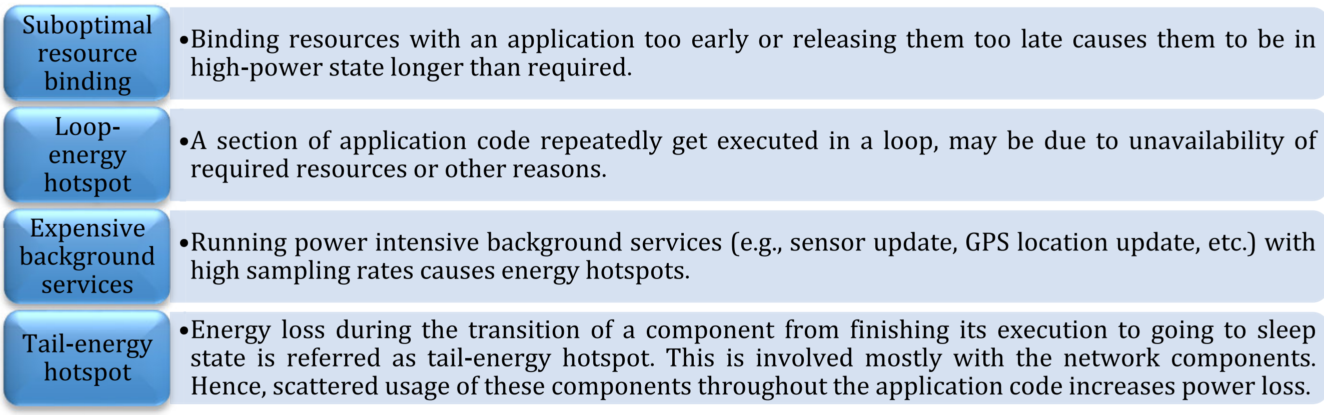

FIGURE 19. Sources of energy hotspots in smartphones [291].

sources of energy hotspots in smartphones are shown in Fig. 19.

- **Energy bug:** Many often, smartphones lose energy unwarrantedly due to a flaw in the hardware or software. This is known as energy bug. Energy bugs prevent a smartphone from going to sleep state, thus keeping the device or a particular always active. This is one of the reasons for faster charge loss of smartphone batteries. The presence of energy bugs not only leads to concerning battery drainage but also reduce the battery life immensely [292]. Energy bugs [237], [291] might be found in different components of a smartphone such as its hardware, OS, applications, networking modules, etc. Pathak *et al.* [237] presented a taxonomy of smartphone energy bugs, based on user feedback, as shown in Fig. 20. Jiang *et al.* [293] classified smartphone energy bugs in two broad categories as follows:
  - **Resource leak:** If an application does not release an acquired resource even if it is not required any more, it will prevent the system from going to the sleep mode. This will result in a continuous energy consumption situation, which is known as resource leak. Some examples of resource leaks are shown [293] in Fig 21.
  - **Layout defect:** Bad application design makes its layout structure complex and inefficient. If there are too many widgets or the layout is too deep in the hierarchy, it will require resources such as CPU, memory, etc. accordingly. This increases battery consumption. Also, for measuring and drawing of a complex and multi-level layout consume energy. Different types of layout defects are shown in Fig. 22.
- **Energy leak:** A direct effect of energy bugs is the energy leak, in which smartphone hardware dissipate power even when they are not actively used. Since the hardware is operated by the software, it can also be said that an energy leak refers to the energy consumption due to the smartphone operations or activities that do not have any direct or indirect effect on the user-observable output of the smartphone. In other words, if killing a task does not have any effect on the smartphone operation, then the killed task is said to be a source of energy leak. Zhang *et al.* [294] considered the following as the key sources of energy leaks:
  - **Unambiguous programming errors:** If there is an obvious bug in the source code or in the design, it is obviously reflected in the application behaviour. For example, an application is frequently acquiring a component but not using it. This causes unnecessary energy wastage.
  - **Reliance on predictions for prefetching:** To increase the response time and throughput often OSs prefetch the predicted next-executable tasks. Prefetching is also extensively done to improve the web browsing experience. But if the prediction goes often wrong, it causes energy wastage.

Though it seems that the hardware is the immediate source of power dissipation, it is the software which operates and directs hardware to consume power [295]. Therefore, it is the responsibility of the software and application developers to minimise the bugs in smartphone OS and applications. Applications are supposed to be efficient during the interaction with the hardware components. But it gets very difficult to keep optimised codes that are power efficient for applications due to the presence of a large number of component vendors, different drivers and operating system versions. The solution to this problem can be managed during the development stage only since it gets difficult with every iteration of software update to keep track of the faults that may cause a power leak.

This section discusses some of the research works addressing the issue of energy bug and energy leak in smartphones.

1) DETECTING ENERGY LEAKS IN ANDROID APP WITH POEM

Ferrari *et al.* [296] presented portable open-source energy monitor (POEM) to help developers automatically test and measure the energy consumption of single application component by using offline code analysis tool and code

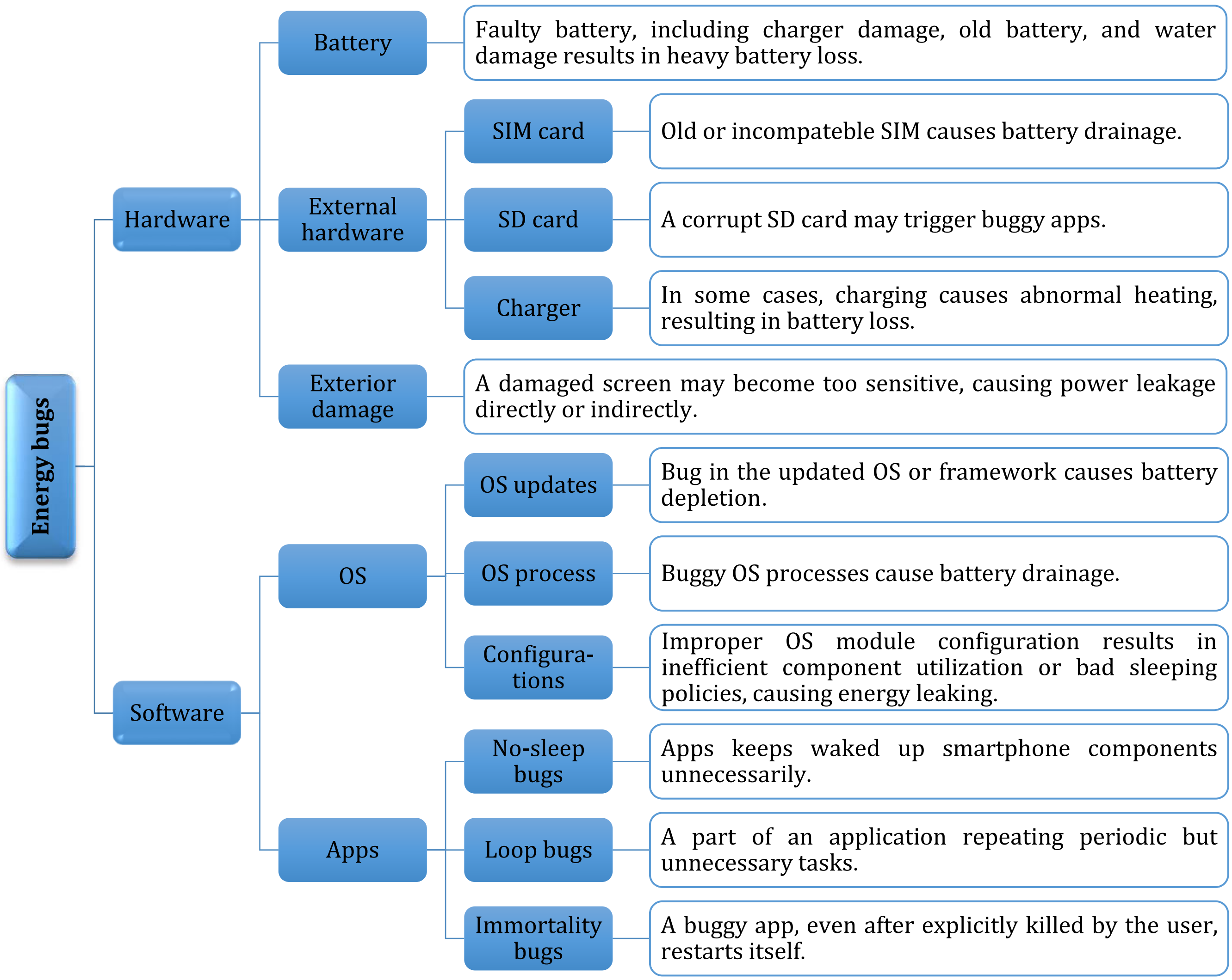

FIGURE 20. Taxonomy of energy bugs in smartphones [237].

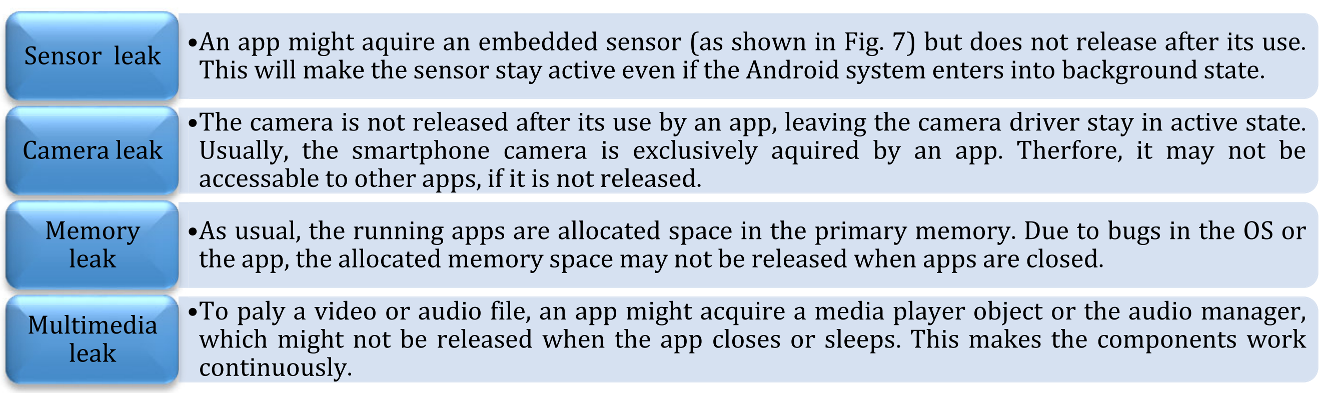

FIGURE 21. Examples of resource leaks in smartphones [293].

injection techniques to get measurements with numerous levels of granularity, extending to the call graph, basic blocks, API calls. POEM converts the code into control flow graphs of the application and tries to figure out the power leakage portions on the go. The basic block analysis is used to determine the branch and loops of every single method to find the

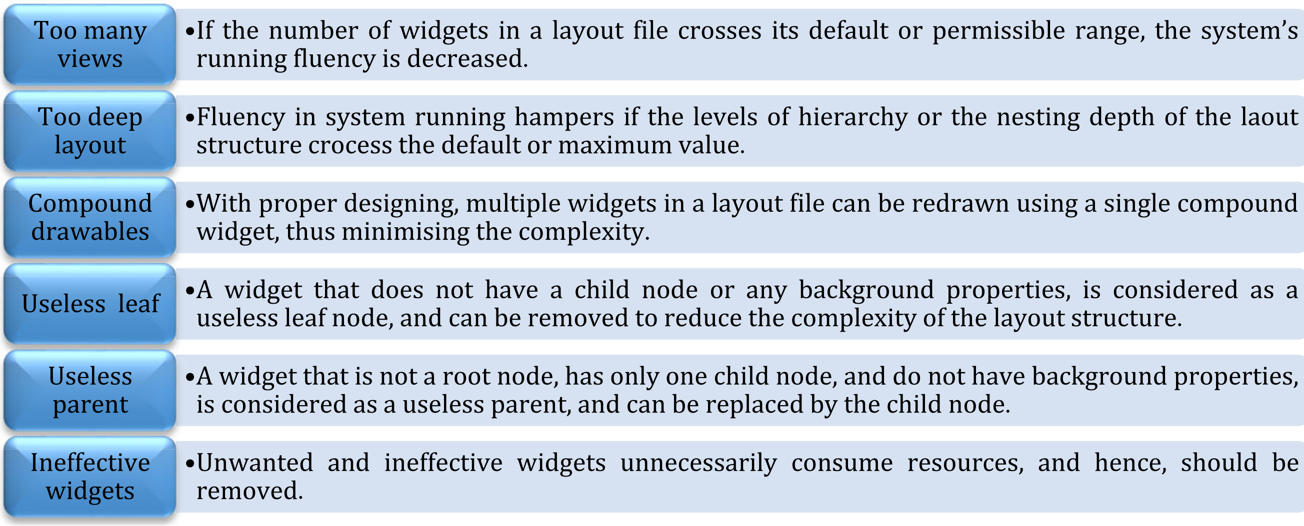

FIGURE 22. Different types of layout defects in smartphone applications [293].

tasks with intensive computation and differentiate them from other activities (i.e., the I/O tasks). This system can also help developers to understand which portion of the application is responsible for power leakage as well as identify the most efficient code during the development.

2) ANALYSING POWER LEAKAGE OF SMARTPHONE COMPONENTS

Choi and Kim [235] proposed a queuing model for analysing power leakage of different components in a smartphone. This analysis was used to assess the battery lifetime considering different usage scenario.

3) ENERGY PROFILING TOOL TO CHECK COLLATERAL ENERGY BUGS

A framework E-Android was proposed by Xing Gao *et al.* [297], extending the Android framework to improve accuracy in energy profiling by taking into account all collateral energy consumptions and bugs. E-Android can monitor all interactions between apps and maintains a collateral energy map for fine-grained energy accounting. The framework provides a revised battery interface to give information to users about energy consumption and how battery drainage is occurring.

4) DETECTING AND ISOLATING ENERGY LEAKING SOURCES

Zhang *et al.* [294] developed a tool named ADEL (Automatic Detector of Energy Leaks) to detect and isolate energy leaks in Android-based smartphones due to unnecessary network communication. ADEL traces the use of inbound data, received directly or indirectly, to determine their usefulness and effectivity using *dynamic taint-tracking analysis* [298]. The authors considered 15 real-world applications, including open and closed source, using ADEL. Out of them, six applications were found to have energy leaks, of which approximately 57% accounted for communication. The study identified the following four common causes of energy leaks, which might be useful for application and platform developers:

- Misinterpretation of callback API semantics
- Poorly designed downloading schemes
- Repetitive downloads
- Aggressive prefetching

5) AN ENERGY DEBUGGING FRAMEWORK

To diagnose energy bugs on smartphones, Pathak *et al.* [237] proposed a systematic framework, named EDB (Energy Debugging Framework), which comprises of the following three functionalities/ components:

a. Narrowing down the energy bug symptom to one entity: To isolate the energy bug source, EDB performs hardware tests that include battery and other hardware components (as shown in Fig. 20) tests, and history-based software diagnosis.
b. Pinpointing the software module responsible for the energy bug: If the bug is in the software component, it needs to be spotted with the specific software module.
c. Bug detection and patching: The root causes of energy bugs are to be zeroed through automatic detection tools.

6) ENERGY LEAKS CAUSED BY SENSORS

Several sensors, as discussed in Section 4.1.6, are a major source of energy consumption. Hence, improper use of these sensors and the sensor data by smartphone applications may lead to huge energy leak. Liu *et al.* [299] identified the following two common types of energy leaks caused by the inefficient use of sensors:

a. Sensor listener misuse: Before using a sensor, a smartphone application needs to register the corresponding sensor listener with the Android system. When the sensor is no longer in use, the listener should be unregistered; otherwise, the sensor will remain active and continue consuming power unnecessarily.

b. Sensory data underutilization: Acquiring sensory data demands a significant amount of energy consumption. Therefore, underutilising these acquired might have a negative ratio between the energy cost and their actual uses. Proper application design and implementation can help in regard.

For a systematic diagnosis of the energy holes, the authors adopted a code analysis to simulate the runtime behaviour of an application, which checks the utilization of the sensory data at each explored application state, along with monitoring the registration and unregistration of the sensor listener.

7) MITIGATING MEMORY LEAKS

To minimise the load time, OSs try to keep the frequently used or to be used in near future applications in the memory. This not only improves the user experience but also saves energy. But possible memory leaks may reduce this advantage because it might constrain the memory space as the number of running applications increases. Xia *et al.* [300] identified the common sources of memory leak as:

- Auto screen rotation
- Specific function calling
- Complex code pattern
- Launching and exiting applications

They attempted to minimise the leaking effects and energy wastage due to this by proposing a modified memory swapping policy which contains the following two modules:

a. Lightweight leak detector: Identifies the application responsible for leaking memory.

b. Priority adjustment module: Prioritizes the leaking apps to be killed.

8) TRACKING ENERGY HOTSPOTS AND ENERGY BUGS IN I/O-BOUND OPERATIONS

An automated test generation framework was proposed by Banerjee *et al.* [291] to detect energy hotspots/bugs in Android-based smartphone applications. To find out the possible energy hotspots and energy bugs in an application, a graph-based search algorithm [301] was used with the guidance heuristics. The proposed framework generates test inputs, each of them which captures a sequence of user interactions (e.g. touches or taps on the smartphone screen) that leads to an energy hotspot and energy bug. The energy hotspot and bug detection method proposed in this paper considers only the GUI-based events or the I/O operations only. CPU-bound operations also may involve unintended energy loss, which cannot be tracked using this framework. Moreover, the computed event flow graph may not be all-encompassing, i.e., some of the energy hotspots and bugs may not be exposed.

9) DETECTING ENERGY BUGS IN ANDROID APPS USING STATIC ANALYSIS

Jiang *et al.* [293] presented an energy bug detection scheme based on a static analysis technique, named SAAD (Static Application Analysis Detector), which can detect resource leak and layout defect in an Android application. To detect resource leak, SAAD uses context-sensitive analysis that includes component call analysis and inter- and intra-procedural analysis. It analyses the effective paths through which resource acquisition and release are made. The proposed framework that implements SAAD takes an APK file as input and gives the report of resource leak and layout defect as output. For detecting resource leak, SAAF [302], an open-source static Android analysis framework, is used while Lint,[3] another static analysis tool for Android project source code, is used to detect layout defects.

E. ESTIMATING AND PREDICTING RESIDUAL BATTERY AND DEPLETION TIME

If the precise information regarding the remaining battery (both in terms of power and time) of the user's smartphone can be provided, he/she can adjust his/her smartphone usage and also schedule his/her activities accordingly. Also, based on this information, an intelligent OS can moderate the energy consumption of various hardware components and applications. But estimating and predicting the remaining battery and the depletion time is very difficult because it involves considering several different factors and situations. Researchers have come up with different approaches, as discussed below, to get on with this.

1) PREDICTING BATTERY LIFE USING REAL-TIME USAGE DATA

Li *et al.* [303] proposed to use real-time smartphone usage traces to predict battery life. ML models for battery life prediction. Recognising the absence of runtime data as a big issue, the authors collected user data (e.g., system status, sensor indicators, system events, and application status) and applied ML algorithms on these Big data. It is claimed that the remaining battery life of a smartphone could be predicted accurately, using this model.

2) PREDICTION THROUGH CORRELATION ANALYSIS

Longo *et al.* [304] proposed a model that utilizes information of past owner's activity (charging state, screen state and brightness level, application execution, activated radios, etc.) to predict remaining battery life. To note any mobile user's activity with his/her device, a correlation analysis is performed using the Pearson correlation coefficient.

3) PREDICTION THROUGH DNN

In the research work [305], ML algorithms, especially DNN is used for the prediction of the battery depletion time by

[3]http://tools.android.com/tips/lint

drawing a personalized battery-usage pattern from time and location information provided by the mobile device and also taking into account the individual users' discharging patterns and personal behaviour information.

4) PREDICTION OF BATTERY LIFE BASED ON USAGE PATTERN

Kang *et al.* [306] proposed an approach to predict a mobile device's available battery lifetime based on the different usage pattern of voice calls, data communication, and video call usage. The paper calculated the average battery consumption rate for each state affecting power consumption and determined the usage pattern based on the time-series data.

5) SOFTWARE TO GUIDE USER TO REDUCE POWER CONSUMPTION THROUGH SMARTER USE

Bramble and Swift [307] proposed a software-based solution named SApp that will guide the user to reduce the battery consumption through smarter use and priority decisions. The researchers tested the impact of the specific device components and then measuring the performance of the applications they combine heuristics with the measurements to predict future application impacts which can guide users to make decisions.

6) PREDICTION USING EET

A study was conducted by Oliver and Keshav [308] to measure the energy consumption characteristics of 20,100 BlackBerry smartphone users to make the Energy Emulation Toolkit (EET) that helps developers to analyse the energy consumption requirements of their applications against real users' energy traces. This research paper also says that energy level can be predicted within 72% accuracy a full day in advance by classifying smartphone users on the basis of their charging characteristics.

Though several ways and approaches are proposed, as mentioned above, they are limited by particular hardware and software setup. Hence, these methods may not work for other devices with different specifications and properties. Also, these methods are very complex and heavy to run on smartphones which takes a toll on the CPU and RAM, which not only affects the smooth running of other heavy applications but also causes battery loss. Besides, the methods become ineffective as new smartphones with different hardware capabilities are getting launched regularly. Furthermore, with the new mobile applications that are being surfaced every other day, it is not a realistic approach to estimate the battery requirement of every application. Similarly, mobile OS's versions keep changing frequently. For that, a general method is required that can be used to estimate and predict the battery depletion rate and time, as well as the remaining battery time with precise accuracy.

F. TOOLS AND APPLICATIONS FOR POWER CONSUMPTION MONITORING AND ANALYSIS

Several applications and software-based methods are designed and proposed which aim to monitor, estimate, and analyse smartphone power consumption.

1) STUDYING SOFTWARE ENERGY CONSUMPTION BY HARDWARE MINING SOFTWARE REPOSITORIES

The system named GreenMiner presented in [309] estimates energy requirements of the installed application by using SVM and linear regression on the data collected of energy requirements of different applications. To evaluate the model, it uses three experiments which include: a) training and testing on same application b) training and testing on the same set of applications and c) training on different applications and predicting on a new application. Due to its parallel properties, the test is carried out quickly, and hence abusage of power is detectable.

2) RELATING ENERGY CONSUMPTION OF SMARTPHONES WITH ITS OPERATIONAL STATUS

Corral *et al.* [310] demonstrates a software-based measurement technique named CharM, which is an Android application to measure the influence of all related working components which have effect on energy consumption of a smartphone in different version of OS and in different situations and modes such as when the phone is connected and disconnected to a mobile network, when the screen is currently on or not, if yes with its different brightness intensity, with and without the Wi-Fi, Bluetooth, and GPS service. The main drawback is that it does not allow real-time analysis. This work analyses the power consumption by taking data in different modes of the smartphone, like normal mode, flight mode, with CPU stress, with OLED and video playback stress, with Wi-Fi and GPS stress. The application CharM identified and provided data that confirm that components like CPU, OLED display, and the Wi-Fi interface contributed the most to the system's energy toll, as shown in Fig 23.

3) MONITORING OF ANOMALOUS ENERGY CONSUMPTION

A methodology is proposed in [311], that monitors and helps in detection of anomalous energy consumption by a smartphone framework for the Android ecosystem by introducing an algorithm/application for the dynamic calibration of such model, thus allowing the automatic calibration of the model through an API for any Android device.

4) ESTIMATING POWER CONSUMPTION BY INSTRUMENTING THE SOURCE CODE OF AN ANDROID APPLICATION

Couto *et al.* [312] presented a tool named GreenDroid[4] that can estimate the power consumption of Android-based

[4]https://github.com/greensoftwarelab/GreenDroid

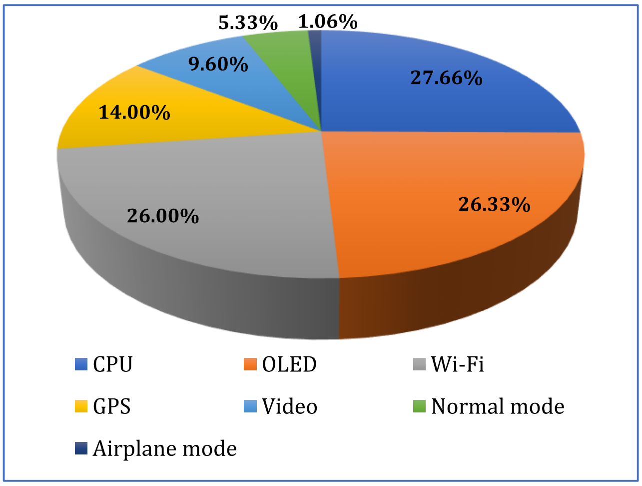

FIGURE 23. Energy consumption of different smartphone components as per [310].

mobile devices. It also has the capability to identify abnormal power consumption in an application's source code by parsing of Android/Java programs and constructs an AST. The result obtained by the generalized tree traversal in the AST is put in the Android testing framework to collect and analyse power consumption data at run time.

5) ONLINE MEASUREMENT METHOD OF SMARTPHONE ENERGY CONSUMPTION

Online energy modelling and power measurement have recently gained a lot of attraction, and more and more research works are being focused on this. Ma *et al.* [313] computes the different methods of power modelling like the offline Power Monitor[5] and the online BMU based scheme and compares them to deduce accuracy of each of them. The energy consumption of the CPU, display, Wi-Fi module is measured using each of the types of scheme. BMU-AVG is being used to represent the BMU which submits the average current, and BMU-INS is being used to represent the BMU which uses the instantaneous current. The models are eventually evaluated with the frequency of collecting data 2Hz, which is collecting the data after every 0.5 seconds. It is seen that the energy consumption accuracy rate of BMU-INS is less than the BMU-AVG. The higher accuracy rate of BMU-INS is directly proportional to the sampling rate.

6) DEVSCOPE - AN ONLINE POWER ANALYSIS TOOL

The need for understanding smartphone power requirements is immense to build energy-efficient applications and hardware. Jung *et al.* [314] proposed an online power analysis tool that uses a built-in BMU. The current value provides a much higher accuracy over-voltage curve method and hence is used to measure the current of each smartphone component. This tool has the advantage of generating a dynamic model. DevScope derives power model at runtime and is conducted in an automatic manner without the requirement of any external devices. DevScope dynamically plans the conditions under which the test will be performed. DevScope is tested on two different smartphones, and the online results seem to be accurate enough to the models generated by the offline ones which use the previously generated model.

[5]https://www.msoon.com/powermonitor-support

VI. SMARTPHONE POWER CONSUMPTION MANAGEMENT

Intelligent management of power consumption can make smartphones more energy-efficient. Several early works [315]–[317] acknowledged the importance of proper power management in smartphones in order to save energy. Since then, several solutions and approaches have been proposed in this direction. In this section, the notable ones among them are discussed.

A. POWER MANAGEMENT METHODS IN SMARTPHONES

Efficient power management plays a crucial role in controlling power consumption of smartphone due to Wi-Fi, 3G/4G/5G connections, screen brightness, CPU frequency, GPS, background applications, etc. to extend the battery life. Different power management techniques and tools are as follows:

1) REDUCING POWER CONSUMPTION USING APM

Advanced power management (APM) [318], introduced by Intel and Microsoft is one layered interface in which applications, OS, device drivers, and the APM BIOS work together to reduce power consumption.

2) CONTROLLING THE POWER NEEDS THROUGH ACPI

Advanced configuration and power interface (ACPI) was introduced in 1997 by Intel, Microsoft, and Toshiba, with the contributions from IHV's, ISV's, and OEM's [319]. It allows both the OS and user's choice to manipulate the hardware and applications to control the power needs and backup.

3) POWER MANAGEMENT THROUGH PMIC

The introduction of PMICs [320] in smartphones is quite helpful in power management in recent times. PMICs are integrated circuits consisting of multiple power rails and power management functions like voltage conversion and regulations, battery chargers, battery fuel gauges, LED drivers, real-time clocks, power sequencers, and power control.

4) POWER MANAGEMENT THROUGH OSPM

Pervasive power management can be done by OSPM, introduced by Intel. The power management can be done through hardware, software, especially by the OS and firmware by managing I/O and logic voltages and clock gating.

5) ANDROID POWER MANAGEMENT

It is the application framework implemented by Android [321] on the uppermost layer of the kernel to regulate the power state of the device. It includes the following battery life enhancements:

- Application Restrictions: User can restrict some power-hungry apps by getting a suggestion.
- Application Standby: The idle applications can be kept in standby mode.
- Doze: If users are inactive for a certain period of time, the system will be transferred to a deep sleep state.
- Exemptions: Preloaded system apps and cloud messaging services are typically exempted from Application Standby and Doze by default.

B. REDUCING ENERGY CONSUMPTION FOR SMARTPHONE OPERATIONS

This section investigates the research initiatives that propose different ways to reduce energy consumption in a smartphone.

1) REDUCING ENERGY CONSUMPTION BY ALARM-INDUCED WAKEUPS

Devices frequently wake up when not required and waste a lot of energy. Park *et al.* [322] analysed the energy consumptions caused by different mobile applications, and it was found that the energy consumed from wakeups of the fifteen installed apps were 35.9% greater than when the apps were not there. They introduced a scheme called AlarmScope to save energy. AlarmScope detects not required wakeups and delays the alarm to reduce energy waste. The energy reduction came from the increase in the number of the grouping of wake-up alarms. The scheme was tested on Nexus 4 smartphones, and it was found that nonrequired alarms were reduced by 50% and the total wakeup time was reduced by around 25%. AlarmScope may sometimes ignore functions called by time-critical functions.

2) REDUCING ENERGY CONSUMPTION OF DATA EXCHANGE

The increase in the number of smartphone apps has led to the use of different data interchanges type. These different data interchange types have varying performances and have varying energy consumption. The efficiency in terms of synchronization of the different formats of file XML, JSON and Protocol Buffers are analysed by Gill and Trezentos [323]. It also analyses the impact of data compression on power management. JSON format with synchronization turned out to be the best performer in time synchronization, parsing on server-side and battery performance. The impact of data compression also turned out to be quite good in text formats. For slower networks like 3G, the results were most impressive with a decrease in power consumption across all three types of data formats.

3) REDUCING ENERGY CONSUMPTION OF WI-FI SENSING

The researchers have proposed a system for smartphone called WiFisense [324], which uses the user's mobility information and adaptively determines the frequency of Wi-Fi sensing. WiFisense includes algorithms that proactively sense Wi-Fi access points and uses Wi-Fi in an energy-efficient way. The experiment of the model was carried out in both outdoor and indoor scenarios, an Android based smartphone. The model was seen to have energy consumption less by 79% due to Wi-Fi sensing. Although the model is seen to perform well in locations, it already aware of, it might not perform as well when tested in some new place.

4) REDUCING ENERGY CONSUMPTION OF SCREEN

The Energy Efficient Engine (E_3), proposed by Han *et al.* [325], automatically tracks the scrolling speed of the screen of a smartphone and dynamically adjusts its frame rate. The model initially starts with keeping track of the scrolling speed and adjusting the frame rate. Then it evolves according to the preference of the user. The schematic diagram of E_3 is shown in Fig. 24 The test was conducted on the proposed model on a variety of smartphones and tablets and was found that the E_3 model significantly improved the power consumptions for bigger screens and as an effect, the power saving was more. The major drawback of the E_3 is when using applications with high frame rates, the model significantly decreases the user experience.

5) REDUCING ENERGY CONSUMPTION OF VIDEO APPLICATIONS

Video applications drain a lot of energy and has emerged as one of the biggest problems with video streaming on smartphones. Hemalatha *et al.* [326] first analyses the relationship between the wireless and mobile data energy consumption and proposes a model that comprises of four parts. The first module is responsible for encoding and compressing, followed by the second part that deals with cloud storage. The streaming engine helps to select appropriate bitrate from the available bandwidth. The final module consists of a system that monitors the power consumption of the phone. The model has been tested with many multimedia file formats and showed an average of 4% power savings across all the different file formats.

6) REDUCING ENERGY CONSUMPTION OF WI-FI USAGE

Wi-Fi uses up a considerable amount of battery. Zang *et al.* [327] proposed a model called HoWiES that enables energy saving in Wi-Fi communication. energy saving in Wi-Fi communication. The HoWiES, as described, uses the WiFiZigBee [328] message delivery scheme which has been described by Texas Instrument New Center [329]. The HoWiES optimizes in three states of Wi-Fi operation, namely the scanning state, the standby state and the energy waste due to wake up contention. The Wi-Fi ZigBee message format is also extensively described. The proposed model is tested on mobile as well as a laptop platform. The model is seen to save power by 88% in Wi-Fi scanning mode and 88% in standby mode. Though the model saves a lot of power, the system is not fully reliable.

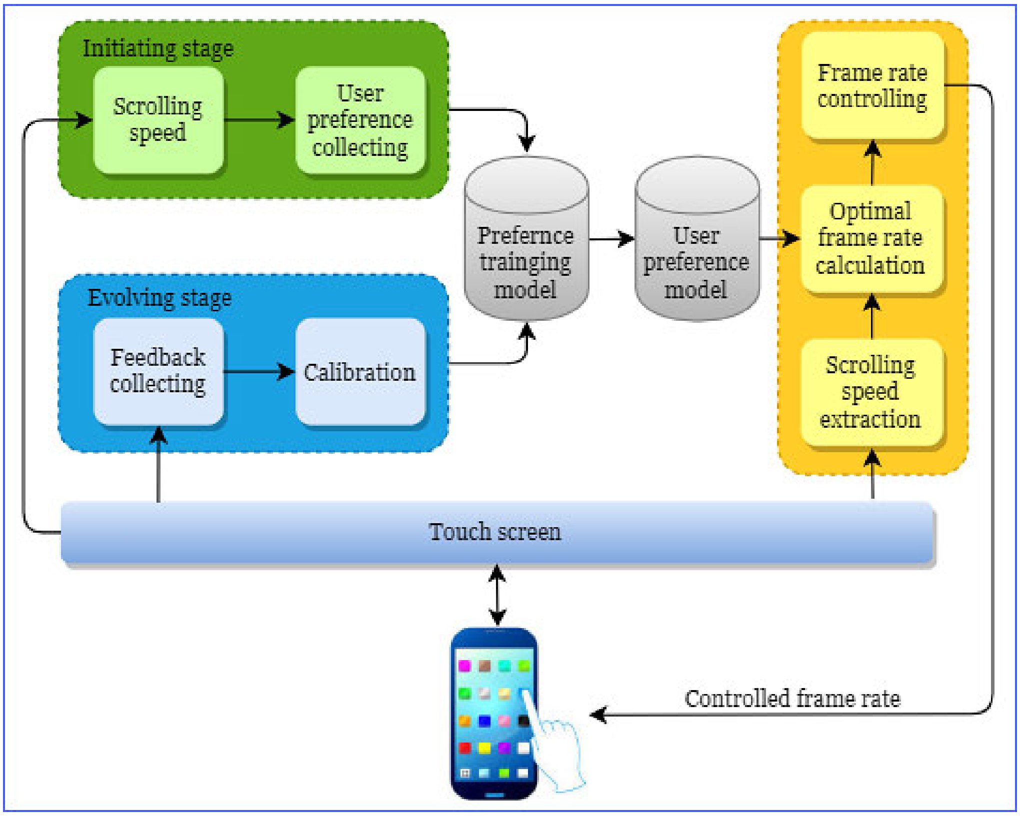

FIGURE 24. Schematic diagram of E3 proposed in [325].

7) REDUCING ENERGY CONSUMPTION OF LOCATION SENSING

Zhuang *et al.* [330] suggested a method for improving the energy efficiency of location sensing in smartphones. The proposed method has four different energy-saving parts, as shown in Fig. 25, and the integrated operation could reduce energy consumption. The dynamic location sensing mechanism keeps track of the location the user visits. The mobility state of the user is tracked using low powered sensors and suppresses the high-power location-sensing sensors when not required. When multiple location sensing applications are used at the same time, the model proposes to use the location used by another application within a certain time without making a new location-sensing request.

C. DEVICE OPERATION OPTIMISATION

Overall power consumption can substantially be checked by optimising the device functioning and operation. Therefore, this particular has garnered significant attention from the research community. This section discusses the research works that attempt to reduce power consumption by device optimization.

1) PARALLELISM AND SCHEDULING OVER MULTIPLE CORES

Use of multi-core processors is now very much common in mobile devices, resulting in the need for effective power management [195]. Different research shows that efficient parallelism can lessen the power expenditure.

a: PARALLELISM ENSURES ENERGY EFFICIENCY

In the research work [331], two energy optimization problems, namely, single delay-tolerant assignment (SDA) that does not allow parallelism and multiple delay-tolerant assignment (MDA) that permits parallelism, are discussed. The MDA algorithm can reduce more energy consumption than SDA using a 4G network with rigorous smartphone usage.

b: DYNAMIC ADJUSTMENT IN RESOURCE ALLOTMENT

Mukherjee and Chantem [332] proposed an integrated system-level resource management framework to minimize the total energy consumption of a smartphone. The work considers applications' offline profiles and dynamic access of resources as well as the dynamic setting of voltage, CPU frequency and memory bandwidth as per need while maintaining QoS. The proposed solution was being experimented on a Nexus 6 smartphone, and it was observed that on average, 23% (up to 31%) reduction in energy consumption, in comparison to other similar approaches, is achieved. While compared to the performance of the default Android governor, the average energy reduction is 19% (up to 27%). Furthermore, for applications that do not have prior resource usage data, the energy savings is claimed to be up to 22%, in comparison

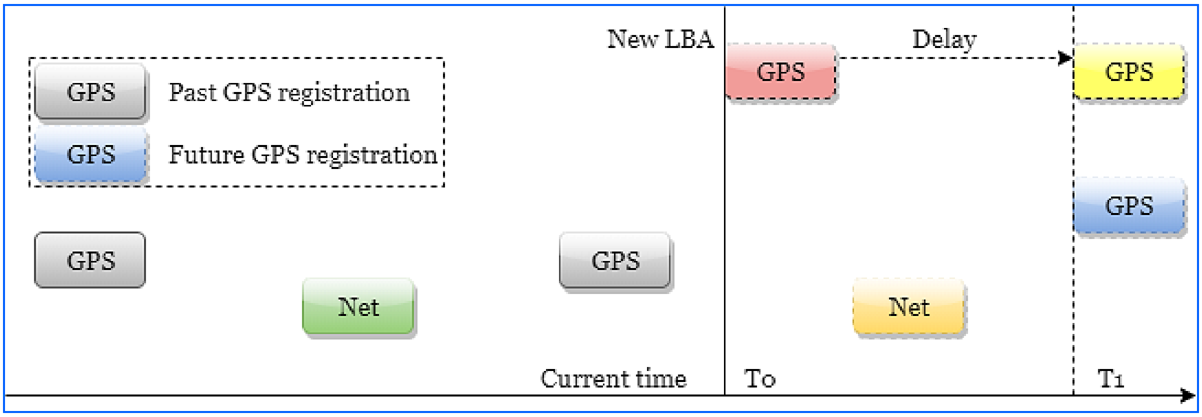

FIGURE 25. Schematic diagram of sensing piggybacking proposed in [330].

to existing works and 18%, in comparison to the default Android governor.

c: TASK PARALLELISM WITH DVFS

The common CPU power consumption reduction technique DVFS is enhanced to dynamic parallelism in the research work [333]. The dynamically reconfigurable isolation cells (DRICs) that decrease the synchronization overheads are offered, and energy-aware task parallelism was integrated with DVFS intelligence to select optimal parallelism, voltage, and frequency trio dynamically based on the resource allocation graphs and a profile-based parallelism and voltage and frequency selection (PPVFS) algorithm. The autonomous parallelism, voltage, and frequency selection algorithm guarantees high power efficiency. In this technique, CPU power consumption can be reduced via the adjustment of the operating frequency and voltage of the devices. Here users' satisfaction is ignored and also it is observed that most of the time, some extra frequency level is used for each application.

d: POWER OPTIMIZATION IN A MULTICORE ENVIRONMENT

Li and Mishra [334] measured the power consumption of different parts of a multicore smartphone using hardware and software-based techniques. They considered the effect of running applications like Facebook, Pandora, Candy Crush, Google Maps, YouTube, and MPEG convertor with Wi-Fi on stage. They also proposed a middleware layer in multi-core smartphones to dynamically schedule an optimal number of cores online with dynamically adjustable frequencies of each of the online cores based on the current CPU load, performance, user experience, the impact of remaining battery life, and expected time interval to charge the phone again.

2) INTRA-DEVICE OPTIMIZATION

As already mentioned, a smartphone is a complex system consisting of several components. These components often work cooperatively. Energy wastage can be minimised if this cooperative communication and operation can be optimised. Few such works in this direction are reported below.

a: DECISION TREE-BASED RECOMMENDATION FOR SETTING HARDWARE-SOFTWARE COMBINATION FOR BETTER ENERGY EFFICIENCY

Peltonen *et al.* proposed for a decision-tree based recommender system Constella [335] that can reduce battery drain by recommending different system settings. The decision tree is created with different factors like Wi-Fi status as a node, presenting a huge complex combination of system settings. The analysis is done in cloud by mobile data offloading, and recommendation is directed to the users suggesting which system setting can give better energy efficiency.

b: SELF-ENERGY MODELLING

By leveraging the smart battery interface of mobile systems, a self-energy modelling of mobile systems named Sesame is presented in [336], where a mobile system makes an energy model of itself without any external assistance. The Linux-based prototype of Sesame achieved 95% accuracy for laptop (T61) and 86% for smartphone (N900) at a rate of 1 Hz, which was similar to current system energy models constructed in the lab with the help of a second computer. Furthermore, Sesame achieves 88% and 82% accuracy for T61 and N900, respectively, at 100 Hz, which was at least five times faster than present system energy models.

c: DYNAMIC CHANGE OF CPU FREQUENCY

In smartphones, power is vastly used by the CPU. The power consumption is proportional to the CPU frequency and the square of the voltage. The research work [337] introduced a system of CPU power consumption reduction enabled with DVFS and UDFS at the same time. In this paper, an optimum frequency is calculated and considering user feedback; optimum frequency is updated depending on user pessimism. This technique is implemented in the Samsung Galaxy S2, and it reduces 25% power consumption compared to default DVFS and 3% than existing UDFS technique.

d: NATURE-INSPIRED POWER OPTIMIZATION

A client/server-based power optimization technique called nature-inspired power optimization (NIPO) is presented in [338], where some algorithms found in nature like PSO, ACO, and CSA with Levy Flights are used. This research work met the user-defined time-to-last requirement of battery lifetime by developing a mathematical model of power consumption for OLED displays in smartphones and applied on a smartphone running Android OS for client-side and a Windows Server for the server-side.

D. OPTIMIZING DEVICE DISPLAY AND COLOUR REPRESENTATION

As mentioned in Section 4.1.5, the display is one of the major power consumers in a smartphone. Hence, using energy-efficient display technology and optimising display and colour settings can save a substantial amount of energy.

1) ENERGY-EFFICIENCY FOR OLED DISPLAY

OLED has become the utmost effective emergent display technology with improved image quality than traditional displays such as LCD. Power consumption for OLED screen rests on linearly on pixel colours displayed on the screen. The OLED displays have an electro-luminescent layer of organic semiconductor compounds, with each pixel lights up independently according to their respective RGB diodes. Energy consumption by OLED display frame can be stated as the sum of power consumed by individual pixel components for the entire screen area. Several power optimization techniques have been proposed based on OLED's colour-dependent power consumption. A couple of them are discussed below.

a: DYNAMIC VOLTAGE SCALING AND DIMMING OF OLED PANEL

The research work [339] accomplished local dimming by put on down-scaling to pixel colours of peripheral screen areas, and the paper [340] is based on DVS of the OLED panel with appropriate image compensation.

b: POWER REDUCTION IN MULTI-WINDOW OPERATION

The multitasking, multithreading, along with concurrent visualization of several applications on mobile display screen are liable to battery drainage in smartphones in recent days. The power consumption muchly depends on the colours displayed. Ginny *et al.* presented MultiDroid [341], a display power reduction technique can reduce approximately 10% to 25% power consumption during multi-window operations for the OLED screens without degrading performance. By the implementation of dynamic local dimming powered by alpha blending technique, it can alter the opacity and translucency of the pixels of the screen of the non-critical application window through context switching. An activity window stack is maintained for concurrently displayed applications.

2) COLOUR AND BRIGHTNESS ADAPTION

The optimised setting of colour and brightness can save battery power. A couple of examples, in support of that, are mentioned below.

a: COLOUR ADAPTATION IN THE WEB BROWSER

Chameleon, a colour adaptive web browser, is presented by Zhong and Dong in [342], with power-optimized colour schemes. Within the user-provided constraints, the Chameleon puts on only display, darkening to front images which act well with incrementally rendered large photos to reserve reliability. Cloud is appropriately used by Chameleon to do the rigorous computation-oriented task like mapping optimization offline, performing only the categorically essential tasks in real-time. By this, for web browsing, 41% average system power consumption is reduced, and display power consumption is reduced by 64% without introducing any noticeable delay.

b: BRIGHTNESS SCALING ON PRINCIPLE OF DARK ADAPTATION OF THE HUMAN EYE

The human eye has the ability to adapt in the dark environment, i.e., eye sensitivity is increasingly augmented as one occupies more time in the dark. Yan *et al.* [343] presented a brightness scaling system named Strix, which utilizes this eye adaptation principle within the HMD to optimize the display power consumption in smartphone VR. This work can assure the brightness perception and realizes 25% on average energy reduction without degrading user view sensing.

3) ENERGY-EFFICIENCY FOR VIDEOS

Playing videos eat up a lot of power. A few research initiatives to minimize energy expense for running or streaming videos are mentioned below.

a: VOLTAGE SCALING IN VIDEO STREAMING

A DVS technique is presented in [344] to maximize the energy-saving in video streaming applications through structural-similarity-index (SSIM) monitoring which helps to retain the display quality and optimal voltage control scheme under input constraints. This technique can reduce OLED power consumption on average, simultaneously maintaining a high display quality. The energy-saving efficiency varies at different display resolutions, refresh rates, and display contents.

b: POWER REDUCTION BY DYNAMIC TONE MAPPING

A video classification based DTM scheme, DaTuM is proposed by Chen *et al.* [345] using the HMM classifier. By this technique, remapping of the colour range is possible. DaTuM scheme decreases OLED screen power by 17.8% on average with least display quality degradation.

c: POWER EFFICIENCY BY AUTO ADJUSTMENT OF COLOUR AND LIGHT IN OLED

Mobile OLED-friendly recording and playback system (MORPh), working on-camera recording and video stream playback phase, is proposed by Chen *et al.* in the research paper [346], by which OLED power optimization and simultaneously video quality enrichment can be achieved. Autofocus guided local dimming algorithm, auto exposure guided with colour range mapping algorithm and auto white balancing enhancement with colour tone mapping algorithm are proposed here as optimization techniques. MORPh is realized as a practical Android application on the Samsung Galaxy S5, and several performance evaluation experiments result show that MORPh can reduce the power consumption of 20.3% on average with better video quality.

E. OPTIMIZING APPLICATION DESIGN FOR ENERGY EFFICIENCY

Energy efficiency is now one biggest challenge for application developers because inefficient software can drain a device's battery much quicker than required. Below, a few examples of energy-saving approaches by optimising applications are mentioned.

1) OPTIMIZATION THROUGH APPLICATION USAGE PATTERN

According to Zhao *et al.* [347], the battery energy consumption optimization can be done by predicting application usage in a smartphone. With the knowledge of the next application probably to be used, the battery energy consumption can be planned and optimized in advance to conserve the battery life of smartphones.

2) OPTIMIZATION IN CODING TECHNIQUE

Android Energy Profiler (AEP) is developed by Chen and Zong [348] to measure the detailed power consumption of various Android apps for analysing the effect of different languages (C/C++/Java) and different coding techniques like recursion versus iteration, serial versus parallel processing on power consumption and efficiency. This work also shows that compiler optimization and appropriate use of native codes and style of programming can also reduce power consumption.

3) POWER SAVING BY TASK OFFLOADING

The transfer of workloads with rigorous computation and resource intensiveness to from one system to other systems termed as computing offloading. These offloaded systems might be the cloud or edge devices or any other nearby capable mobile or static device. Generally, emerging smartphone applications with artificial intelligence, wearable cognitive assistants, and augmented reality need huge memory capacity, processing speed, computational resources. The mobile devices, with insufficient physical resources, wanting to run those applications adopt the offloading approach by passing on the heavy tasks to an offloaded system which might be cloud, an edge device, or any other nearby mobile device. This offloading can also be utilised to save power in smartphones. The power-hungry computing tasks are offloaded from a device which has less battery capacity or is running low on battery to an offloaded system which does not have apparent energy limitation. Below a few such research approaches are discussed.

a: ENERGY CONSUMPTION MEASUREMENT FOR COMPUTATIONAL OFFLOADING

The use of Android smart battery interface for energy consumption monitoring is investigated by Nguyen *et al.* [349]. A portable and cheap microcontroller-based power monitoring device is designed, and the accuracy of this device and the smart battery interface are examined by comparing the results with the measurement data from an oscilloscope. On the basis of experimental results, the correlation between energy dissipation of local computation and network communication is also examined by this work. The energy cost for data transfer over two popular wireless technologies, namely Wi-Fi and 3G are compared, by which the advantages of Wi-Fi technology are highlighted.

b: LIGHT-WEIGHT OFFLOADING ALGORITHMS

SaaS and IaaS, the two main components of cloud computing are employed by Shiraz *et al.* [350] in the computation offloading framework named Energy Efficient Computational Offloading Framework (EECOF). The framework uses a lightweight procedure to minimize the application migration at runtime while leveraging application processing services to the cloud. Gao *et al.* in [351] presented a lightweight and decentralized algorithm for computation offloading based on the alternating direction method of multipliers (ADMM) algorithm. In this work, they distributed the workload among nearby cloudlets to reduce the huge power consumption by the centralized cloud data centre.

c: ML-BASED MOBILE OFFLOADING

In the research works [352] and [353], mobile offloading frameworks based on ML are proposed where offloading decisions are taken based on the findings of prior offloading decisions and their correctness. Both the offloading schedulers mentioned in these papers are coarse-grained and based on the LAN and WAN.

d: DSL-BASED DYNAMIC AND COST-EFFECTIVE OFFLOADING

In [354], a DSL based dynamic offloading framework for mobile users has been proposed. The fine-grained computation offloading framework aims to minimize the cost for computation offloading for MEC [355], considering both the local execution overhead and fluctuating network conditions.

e: COMPUTATIONAL OFFLOADING BY DNN

Eshratifar and Pedram [356] framed an optimal computation offloading framework for forwarding propagation in DNN by solving an ILP setup, adapting battery usage constraints on the mobile side and limited available resources on the cloud. The simulation result shows that it is achieving speedier execution time and also gains energy efficiency in the mobile devices

f: COMPUTATION OFFLOADING ALONG WITH RESOURCE ALLOCATION

The task offloading for MEC in an SD-UDN is offered by Chen and Hao [357], which can resolve the location of processing, i.e., whether it is within the mobile device or in the edge cloud depending upon the residual battery capacity of the mobile device. Also, this system decides which edge will be assigned for the task, depending on the availability and the load of edges available and also decides the number of computing resources of the edge to be assigned for each task. Experimental results show that this scheme can lessen task duration by 20% and energy cost by 30%.

g: ONLINE SERVICE CACHING AND OFFLOADING

Hao *et al.* [358] proposed an algorithm named TCO for joint optimization of task caching and offloading on edge cloud with the computing and storage resource constraint based on an alternating iterative algorithm. An online algorithm, called Online seRvice caching for mobile Edge cOmputing (OREO) proposed by Xu *et al.* [359], based on Lyapunov optimization, performs online stochastic dynamic service caching and task offloading to address the main problems of MEC, including service heterogeneity, unknown system dynamics, spatial demand coupling and decentralized coordination and can effectively lessen computation latency for end users with low energy consumption.

h: TASK OFFLOADING IN TWO-TIER CLOUD

Mazouzi *et al.* [360] proposed a offloading policy for task offloading of mobile devices to a two-tier cloud (1st - cloudlet and 2nd - remote cloud), based on the consideration of the tasks that should be offloaded and the offloading location (i.e., to the cloudlet or the cloud), along with the allocation of required bandwidth. The proposed solution follows a distributed linear relaxation heuristic, based on the Lagrangian decomposition approach. The proposal was tested, as an offloading middleware, on a real testbed comprising client terminals and the offloading servers (local and remote). The experiment was evaluated for three Android devices, each of which has different traffic patterns and resource demands.

i: ENERGY EFFICIENCY IN DECISION MAKING FOR OFFLOADING

The research work presented by Balakrishnan *et al.* [361] uses CPU frequency scaling to get energy efficiency and also emphasises on the mechanism which can reduce energy consumption in decision making in offloading process. A lightweight decision-making system is presented here enabled with context sensing approach.

j: OUTSOURCING DATA TRAFFIC TO SAVE ENERGY

Ta *et al.* [362] presented a cooperative system in which smartphone users with high battery level can help to carry the data traffic of users with the low battery level. This approach helps to reduce the probability of the battery running out before the target usage time. As per the authors, the system can be realized as a proximity service utilizing D2D communication architecture over LTE technology. In this approach, a user with low battery needs to request its neighbours. One of the agreed neighbours will act as a relay device and lends its battery for that transaction. The system is expected to perform better with an increase in the number of users in a neighbourhood. Functional verification of the technique through MATLAB has been carried out, and simulation results with the cooperative system and non-cooperative system are also described.

k: IMPLEMENTATION OF OFFLOADING WITH A MATHEMATICAL DECISION OF DOING IT

Majid Altamimi implemented an offloading framework for mobile devices in a cloud computing environment in his PhD thesis [363]. The experimental result reveals that the offloading of heavy applications from mobile to the cloud can reduce energy consumption at least 30%. But it is also true that in some system offloading is not at all effective to reduce power consumption. To take the right decision of offloading, mathematical model of energy estimation is incorporated in this research work in the offloading framework to calculate the cost of data transfer in every phase of networking. The concept of multimedia cloud computing was introduced to provide Energy-as-a-Service (EaaS) by the same researcher in the paper [364] to compare the energy costs in multimedia related task offloading and not offloading situations. The experiments were done by using HTTP and FTP Internet protocols with 3G and Wi-Fi network interfaces on an Android-based HTC Nexus One smartphone. The results show that MCC can save smartphone energy from 30% to 70%.

VII. RESEARCH AND COMMERCIAL DEVELOPMENTS ON SMARTPHONE BATTERY

It is a bitter fact that there has been no breakthrough advancement in the field of battery for mobile and handheld devices for decades since LiBs came in the market. This has prevented the utilization of smartphones as per their potential, despite substantial progress in other aspects of smartphones. Nevertheless, on an optimistic note, we might experience power revolutions for mobile devices very soon. Extensive research is going, both in academia and commercial arena, on various aspects of batteries. People are coming up with innovative solutions; be it extending the operating time of the batteries, increasing the lifespan of the batteries, minimising the charging time, or unconventional ways to charge the batteries [12]. In this section, we shall review some of the most promising research and commercial developments on smartphone batteries.

A. SLOW DISCHARGING AND INCREASING OPERATIONAL DURATION

A lot of research works are devoted to increasing the battery operation time without charging, in other words, to lessen the requirement of charging the battery frequently. This can be achieved if the rate of charge loss is minimised. The notable efforts towards this direction are discussed below.

1) LOW SELF-DISCHARGE CARBON ANODE

Porous carbon materials can improve the performance of carbon-based LiBs. Wu *et al.* [365] used fermented flour to prepare biomass porous and double-doped carbon materials to be used as an anode in LiB. The experimental result confirms of low voltage discharge rate and better cycling performance of LiBs.

2) REDUCING DISCHARGE RATE USING RNL MOS_2@GF AS ELECTRODES

Combining 3D graphene foam [366], [367] with MoS_2 can be a potential solution to increase the electrode performance in LiBs [368], [369]. Zhang *et al.* [370] suggested the use of RNL structure in combination with a strongly coupled MoS2-3D graphene hybrid (MoS2@GF) as electrodes for LIBs. These hybrid (RNL MoS2@GF) based electrodes are claimed to exhibit a slow discharging rate (charging/discharging ratio is 60s/3000s) of LiBs. Furthermore, these electrodes also allow ultrafast charging and excellent cycle stability.

3) SUPPRESSING THE VOLTAGE FADE

After several charging and discharging, the energy holding and emitting capacity of a LiB decrease due to voltage fade [371]. Usually, the metal oxide coated cathode material is the root of voltage fading [372]. Zou *et al.* [373] probed the advantages of using Li-rich layered cathode materials $xLi_2MnO_3 \cdot (1-x)LiMO_2$ (M $\Rightarrow$ Mn, Ni, Co, etc.) (LNCM) [374], [375] in reducing the voltage fade of LiBs.

B. LARGER CAPACITY

Another way to extend the battery operating period is to increase the capacity of the battery so that it can store more energy, eliminating the need for frequent charging. For instance, The K10000[6] smartphone from Oukitel is probably the largest battery capacity smartphone in the world, boasting a mammoth 10000mAh battery which supports up to 10-15 days of normal use, and even capable of going up to 21 days on a single charge with moderate usage. Companies are loading their products with batteries, having huge capacities, with successful marketing strategies. Several attempts have been taken to increase the capacity of a LiB by manipulating or adding different electrodes [376], [377]. Below, a couple of such initiatives are discussed.

[6] http://www.oukitel.com/products/k/k10000-42.html

1) INCREASING CAPACITY USING NANOSTRUCTURED ANODE MATERIAL

The LiBs that are conventionally used in smartphone operations has reached perhaps its limits. The researchers at the University of Vienna [378] have developed a nanostructured anode material developed from a mixture of metal oxides and graphene, which enhance the performance of the LiBs. This new material has shown a huge promise in increasing the capacity of batteries much higher than the ones currently used.

2) INCREASING CAPACITY USING CARBON NANOTUBES

The ever increasing demand for power from batteries has led the researchers at MIT to develop an electrode material [379] that is developed by dipping the base material in a solution of carbon nanotubes that are alternatively charged for each layer which also serves as a positive electrode rather than being just the negative electrode as is the case in conventional LiB. The output energy per given weight is seen to be five times greater, and the power delivery rate increased by around ten times as compared to general LiBs.

C. FASTER CHARGING

With increased battery capacity, the charging time also increases. But users certainly do not like to put their smartphone attached to the charging slot for longer. Hence, a great deal of research attention has been given to find ways to charge batteries in quick times. Thankfully, companies are already releasing their latest smartphones with the fast charging technologies such as Quick Charge, Super VOOC Flash Charge, StoreDot, etc., which have enabled charging smartphone batteries very fast. Table 5 lists the popular commercial fast-charging technologies available in the market. Below, the major research works in this direction are discussed.

1) USING BIODEGRADABLE SEMICONDUCTORS

The researchers at Tel Aviv University have developed a charger called the StoreDot charger, which uses biodegradable semiconductors that are made from organic compounds [380]. The SoreDot charger is compatible with current smartphones and can recharge a smartphone in a very short period of 60 seconds. The battery has high safety precautions that prevent it from the problems of overheating and over-voltage.

2) INCREASING PERFORMANCE USING ADDITIVE SUBSTANCES

Zheng *et al.* [381] proposed the addition of a small quantity of an additive substance would increase the performance of LiBs. The small quantity of additive can greatly alter the interfacial reactions between the metal Li and dual-salt electrolyte containing lithium bis(trifluoromethanesulfonyl)imide (LiTFSI) and lithium bis(oxalato)borate (LiBOB) in the carbonate solvents. The performance of LiBs through manipulating the salt by adding

TABLE 5. Commercial fast-charging technologies.

Product	Company	Quick charging capability
Super VOOC Flash Charge[7]	OPPO	Can achieve a 0% to 100% charge in less than 40 minutes.
Super Charge 2.0	Huawei	Can charge to a full battery in little more than an hour.
Warp Charge[8]	OnePlus	Can charge to 50% in a matter of minutes. Warp charge also takes care of the heat, unlike other fast charging protocols.
18W Fast Charging[9]	Google	Can charge up to 50% in around 40 minutes of time.
Dash Charge[10]	OnePlus	Can charge to the extent of 60% in a matter of just 30 minutes.
Quick Charge 4.0[11]	Qualcomm	Charges at a rate of 20% faster than normal chargers with higher efficiency.
Lumopack[12]	Lyte Systems	Can charge the full battery in 30 minutes.
StoreDot charger[13]	StoreDot	Can charge a smartphone battery in 5 minutes.

the additive compound by changing the chemistry of the electrolytes.

3) USING OTHER METALS

Researchers have been trying to find an alternate architecture for metal batteries, as discussed in Section 3. Metallic batteries use high capacity sulphur (S), selenium (Se), or ceramic cathode, opposing a metal Li or sodium (Na) anode and have a potential to increase the energy up to 2-3 times of the general LiB. Sulphur (S) is quite abundantly available and is thought to be the cathode for the next generation metal batteries. Sulphur and selenium-based LMBs and SMBs, proposed in [382], serve as a fast charge cathode for both SMBs and LMBs while still using the existing standard carbonate electrolyte.

4) FAST CHARGING BASED ON LOCAL VOLUME EXPANSION CRITERIA

There has always been a lack of a simple method to derive the maximum current a cell can accept while charging. Spingler *et al.* [383] used the relation between the local expansion of the battery to the Li plating of the anode. 24 cells were used for the experiment and were tested over 16 fundamental experiments. The fast charging helps to charge the battery at a rate of 11% higher than the normal rate, and it leads to a 16% reduction in the capacity of the battery in each and every cycle.

D. INCREASING ENERGY DENSITY

Batteries with a high energy density are able to store more energy without increasing the size. Batteries with a high energy density, but low power density can have a relatively longer operation period of time [384], which is exactly needed in smartphones. Therefore, researchers are trying to find out ways to thrust maximum energy within a size-restrained battery. Some of the prominent research efforts towards increasing the energy density in batteries are discussed below. But shoving too much energy in a battery involves high risk of combustion as discussed in Section 8.3.

1) INCREASING STABILITY OF SOLID-ELECTROLYTE INTERPHASE

The demand for LiB has increased by an unprecedented percentage in the last decade. The solid electrolyte interface stability has been hindering the advancement of these daily used LiBs. The researchers of Penn State have developed a new SEI [385] using a polymer comprising of polymeric Li salt, Li fluoride nanoparticles, and graphene oxide sheets. This might help to increase the energy density of the battery to a great extent and increase the safety of these types of batteries [386].

2) USING NON-FLAMMABLE ELECTROLYTE

With the increasing need for power in daily life, companies have been starting to make high energy density batteries, but some recent accidents have led companies and researchers alike to adopt safer means. ADA Technologies[14] have developed a safe electrolyte with nano-engineered cathode-based LiB that is proven to be better than the general LiBs in terms of safety, as well as from the energy perspective [387].

3) USING IRON-BASED CATHODE

The researchers at University Maryland have developed an iron-based cathode that truly realises the potential of the commercial graphite anode [388]. This iron-based cathode can increase the energy density of the general LiB by nearly three times [389]. The increase in energy density can facilitate the developments of smartphone batteries that have augmented battery life [390].

E. LONGER BATTERY LIFESPAN

Due to frequent charging and discharging, LiBs tend to wear out fast. Practically, people often tend to charge their device to its fullest but as the charge state goes up (e.g. to 90%, 95%, or 100%), the faster the electrolyte degrades, hence, minimising the lifespan of the battery. Ideally, the battery

[7] http://www.oppo.com/en/technology/vooc
[8] https://www.oneplus.in/product/oneplus-warp-charge-30-car-charger
[9] https://store.google.com/product/pixel_3
[10] https://www.oneplus.in/3t/dashcharge
[11] https://www.qualcomm.com/solutions/mobile-computing/features/quick-charge
[12] lytesystems.com
[13] https://www.store-dot.com/
[14] http://www.adatech.com/

charge state cycle should be within 45% to 55%. Considering this, increasing the lifespan of these batteries has attracted the attention of the researchers. Below, a few such research efforts are discussed.

1) GOLD NANOWIRE BATTERIES

Nanowires [391] are thin wires which have high conductivity that would increase the lifespan of batteries. The researchers of the University of California, Irvine have used these nanowires to build a battery that has not shown any signs of degradation even after repeated charging and discharging [380]. The only thing that stands between the way of the regular use of these batteries is the commercial large-scale production of nanowires [392].

2) SAND-BASED BATTERIES

The use of silicon in place of LiB has been the point of research for a long time now. Pure silicon was being used to build these types of batteries but failed due to the nonviability of production. Researchers have developed a battery that outperforms the LiB by using sand in place of pure silicon. The product has already started taking the commercial market through a company named Silanano.[15]

3) INCREASING THE LIFECYCLE OF ZABS

Despite the potential, the growth of ZABs has been short-lived due to the high corrosion rate of zinc so to overpower this drawback, Minar *et al.* [393] have used zinc electrodes coated with an ionomer and an electrolyte modified by addition of certain additive to reduce the solubility of zinc. The combined effect of both these two solutions have decreased the corrosion of zinc in the solution and led to an increase in the lifecycle of ZABs by about 50%.

F. ALTERNATE POWER SOURCES FOR CHARGING SMARTPHONE BATTERY

This section highlights some of the research and commercial initiatives, exploring the alternate sources of energy to charge smartphone batteries.

1) SOLAR-CHARGED BATTERIES

The use of solar energy has much been the driving force of the new age renewable sources of energy. Alcatel has developed a smartphone that captures solar energy using a thin transparent solar panel that is placed just above the screen of the mobile [394]. Like the standard solar panels, the phone is supposed to work with direct sunlight as well as other ambient lights [380].

2) BATTERIES CHARGED BY HUMAN BODY HEAT

Leonov and Vullers [395] proposed a method to generate a small amount of energy from the body heat radiated by using a thermoelectric generator. According to the laws of thermodynamics, a very small percentage of the actual generated body heat can be converted into electricity. But this electricity might be even useful to charge the battery of smartphones to a certain extent.

3) URINE-POWERED BATTERIES

Bristol Robotic Laboratory has developed a microbial fuel cell-based battery that can generate electricity from urine. The batteries have shown to be competent enough to power smartphones. In the microbial fuel cell, the microorganisms break down the urine to produce electricity from it [380].

VIII. HAZARDOUS ISSUES ASSOCIATED WITH SMARTPHONE BATTERY

Smartphone batteries are predominantly Li-based. But the LiBs have some serious inherent problems. The major issue with LiBs is that they are susceptible to generate a lot of heat in unfavourable conditions, which makes them extremely volatile and risky as they typically use flammable liquids as the electrolyte. However, the scale and degree of the problems associated with LiBs used in mobile devices are less, because of their small size. This section highlights some of the major issues faced with LiBs for smartphones.

A. TEARDOWN OF ELECTRODE SEPARATORS

One of the solutions to have extra power is to increase the size of the battery. But increasing the battery size will increase the device size also. Therefore, companies are trying to accommodate the large batteries into a comparatively smaller space than what is required. This results in lack of enough physical room for accommodating any flaw in battery operation. The following two problems may occur due to squeeze a large battery into a small space [396]:

- In a LiB, separators keep the positive and negative electrodes separate to avoid their touching and sparking. In an attempt to minimise the battery size, companies tend to make the separators too thin, as in the case of Samsung Galaxy Note 7. As a result, there is a risk of a teardown of the separator.
- When batteries are charged, they tend to expand a little, and the electrodes are bent. This causes a short circuit. To avoid this, normally, approximately ten percent extra space is left. If enough space is not provided for accommodating the swelling, there is a high risk of exploding the battery.

B. LITHIUM PLATING

Faster charging means trying to drive too much current into the battery in quick time. This can lead to a problem known as *lithium plating* or *lithium deposition* [397]. With normal charging, the Li^+ are easily intercalated (diffused into the graphite anode). If the transport rate of Li^+ exceeds the rate at which these ions are intercalated, the ions get deposited outside, as metallic Li, as shown in Fig. 26(c). Once this deposition starts, the current is divided into two flows - one is the usual intercalation current, and the other new one is

[15]https://silanano.com/

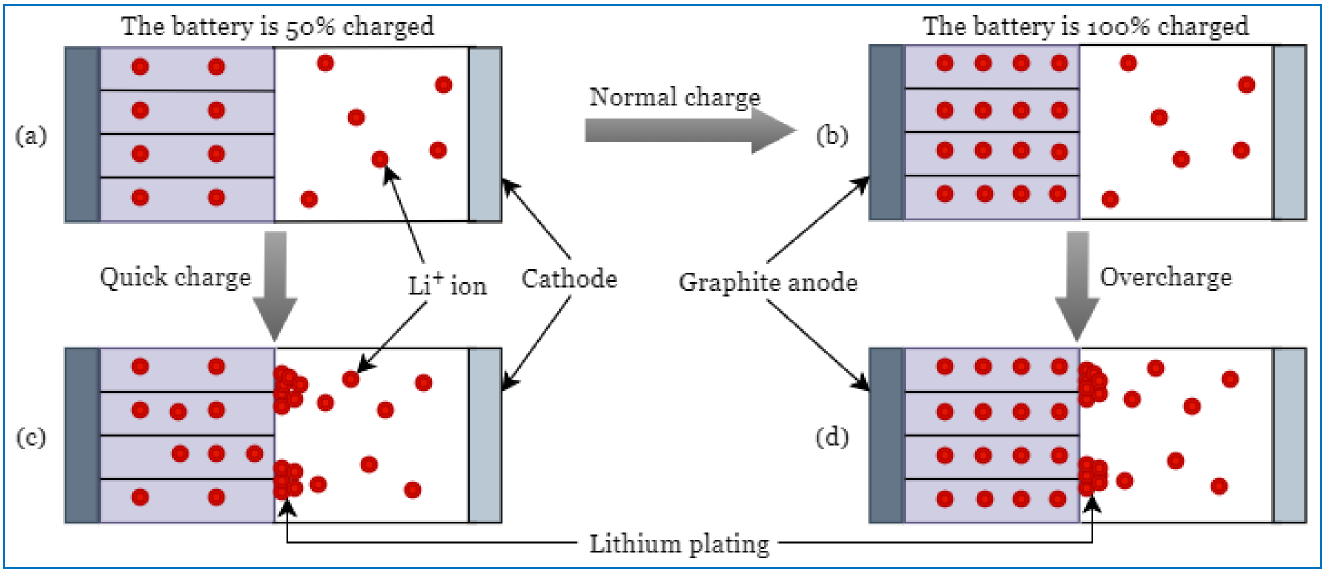

FIGURE 26. Quick charging and overcharging batteries, causing lithium plating (adapted from [398]).

the Li plating current. With continuous charging, gradually, the intercalation current decreases due to reduced space and the limited solid-state diffusion in the graphite anode, whereas the Li plating current increases because the transport rate of Li^+ exceeds the Li^+ intercalation rate [398]. Therefore, the successive charges will cause more Li^+ deposition, forming needle-like structures, known as *dendrites* [399]. This leads to an internal short circuit, producing significant heat which causes fire or explosion of the battery [400]. That's why Li plating is considered as the gravest safety concern for LiBs. It also degrades the battery's lifespan and durability.

C. OVERCHARGING

To have more energy capacity, companies pushing the existing technology to its extreme limit. We have already managed to achieve the 90% of the operating period a LiB for mobile devices can provide, theoretically [399]. So, the only option left to increase the battery life is to shove more power into the cell. Therefore, battery manufacturers often attempt to store more power in the cell by increasing the voltage, considering the assumption that more power will allow the battery to run longer, and higher the voltage, higher the power [399]. Increasing the input voltage beyond normal values is known as overcharging. Overcharging implies charging the battery continuously at a specific charge rate that is beyond the safe voltage limits [401]. But increasing the voltage will result in travelling of Li^+ with more force, which prohibits the ions from being intercalated by the anode smoothly. As a result, the ions will be deposited outside, as shown in Fig. 26(d), making the battery an explosive one. Overcharged cells exhibit much lower thermal stability and can cause thermal runaway at a temperature as low as 40°C [402].

D. THERMAL RUNAWAY

Most smartphones have a single cell battery, but some of the smartphones like iPhone X have two cells. The LiBs with multiple cells suffer from the *thermal runaway* effect. In this case, if one cell gets overheated, the heat is propagated through the other cells in a cascading manner. A cell can get heated due to an internal short circuit or other reasons. If it generates very high temperature, the surrounding area of the cell (known as a local hot spot) is also get heated. The local hot spot triggers the propagation of negative electrode, which initiates further chemical and combustion reactions [401]. As a result, the battery turns into a highly explosive substance, causing massive burst and fire. Sometimes, the anode propagation itself leads to another thermal runaway, causing cathode propagation. This is more devastating. The local hot spot may be formed if the temperature (due to a short circuit) rises to as low as 60°C, but it becomes extremely critical if the temperature reaches close to 100°C [403]. The whole thermal runaway process is depicted through a flowchart in Fig. 27.

IX. MITIGATING HAZARDS IN SMARTPHONE BATTERIES

Considering the hazardous incidents and risks of LiBs, efforts have been made to minimise the vulnerability of smartphone batteries. Some of the research works in this direction are discussed in the following. A snapshot of these works is presented in Table 6.

A. SEPARATOR WITH VOLTAGE SENSING FUNCTION

In addition to electronically insulating the cathode and anode, bifunctional separator with polymer-metal-polymer trilayer configuration can sense voltage [404]. The sudden drop in voltage, usually due to piercing through the separator, if detected, can be helpful to prevent a short circuit situation between the two electrodes. The growth of hazardous

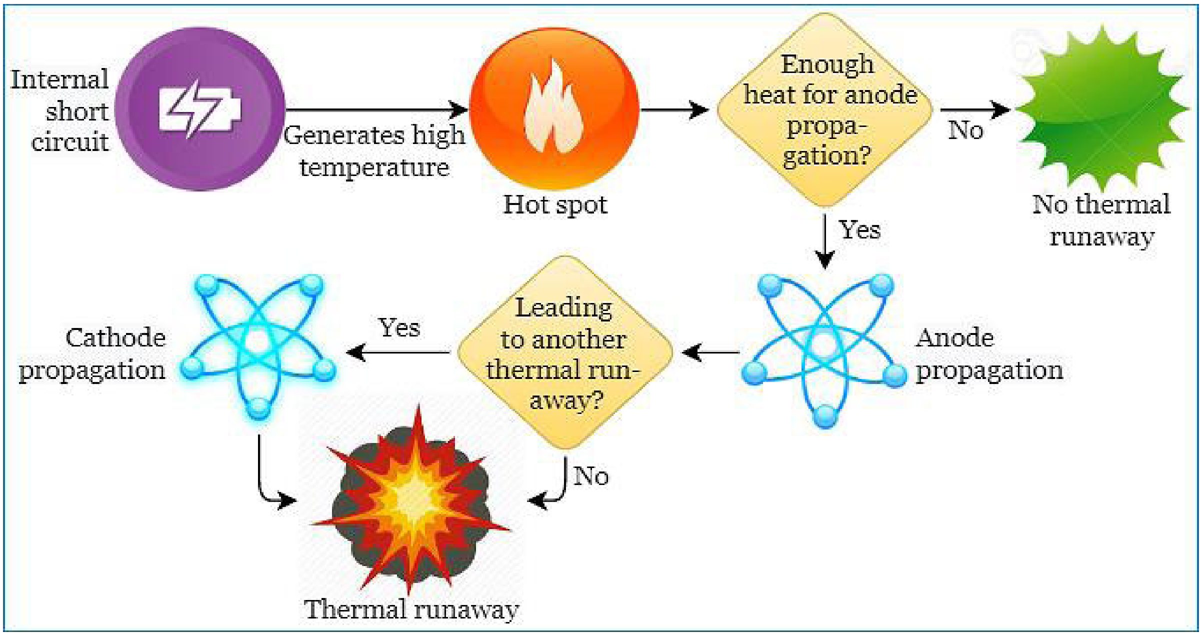

FIGURE 27. Flowchart of the thermal runaway process [401].

dendrites can be consumed by the trilayer separator resulting in slowing down the growth of such dendrites further. This leads to improved safety as well as the life of the LiB.

B. SEPARATOR WITH COATING

The thickness of a separator in a LiB is of the order of 12-25μm. When a very small conductive particle enters inside the separator, it can easily cause a short circuit between anode and cathode [405]. Battery failure due to a short circuit is a common issue in LiBs. To get rid of such situation, ceramic coating as thick as 2μm is applied on one or both sides of the separator. Such coating helps to reduce the separator shrinkage, which occurs at shutdown temperature.

C. BATTERIES WITH A BUILT-IN FIRE EXTINGUISHER

LiBs use flammable liquid organic electrolytes. Due to internal or external short circuit, exothermic reactions may take place, causing the battery temperature to rise and may result in thermal runaway and may ignite the battery. Researchers at Stanford University have come up with LiBs with built-in fire extinguishers to overcome such undesirable situation [406]. A flame-retardant component, namely triphenyl phosphate (TPP) is added to the plastic fibre separator of the battery. When a large amount of heat is generated inside the LiB due to abnormal conditions, the polymer sheath melts, and the flame retardant is released which prevents the burning of electrolyte. This work demonstrates its capability to stop fire in battery within a fraction of second [407].

D. DETECTION AND CONTROL OF LI PLATING

Researchers in [398] have done a survey to identify different possible ways to detect the Li plating problem in LiBs, especially of anode Li plating. The authors identified physical characterization methods such as solid-state nuclear magnetic resonance [401](NMR) spectroscopy and neutron diffraction help to understand the Li plating process. In addition, electrochemical methods such as Coulombic efficiency and discharge voltage profiles are also found to be useful. According to the survey, optimization of electrolyte composition and modification of graphite surface structure using coating and doping are the techniques to overcome the Li plating issue. In addition, maintaining the appropriate temperature and adoption of the proper charging protocol can reduce the Li plating of the anode terminal.

E. MITIGATION OF ABRUPT DEGRADATION OF USABLE CAPACITY

A group of researchers in [408] has thoroughly investigated the issue of sudden degradation of usable capacity of LiB. The investigation identified the heterogeneous ageing of graphite electrode as the key factor behind the degradation. Homogenous pressure distribution in the cell while the design and the use of negative active material that is resistant to active discharge potential have been suggested as a remedy to improve the LiB usability.

F. BATTERIES THAT ARE SAFE FROM EXPLOSIONS

In LiB, a volatile liquid electrolyte is used between the anode and the cathode electrodes. One research endeavour at Tufts University demonstrated the development of a battery which uses plastic film as an electrolyte and can avoid the risk of catching fire. The battery claims to provide double the capacity of LiB and can withstand being pierced and shredded and doesn't catch fire even when exposed to heat [409]. As per

TABLE 6. Snapshot of researches carried out to mitigate hazards in smartphone batteries.

Works described in	Challenges addressed by contributors				
	Separator degradation	Teardown of electrodes	Lithium plating	Overcharging	Thermal runaway
[404]	Separator with a voltage sensing function			Additives to protect overcharging	Non-flammable electrolyte
[405]	Separator with ceramic coating	Improvement in the interface between electrolyte and anode. Use of improved cathode material			
[406], [407]	Flame resistant separator				Batteries with a built-in fire extinguisher
[398]			Optimization of electrolyte composition and modification of graphite surface structure using coating and doping		
[408]			Mitigation of abrupt degradation in battery capacity due to heterogeneous ageing of graphite electrode		
[409], [410]					Use of plastic film as electrolyte
[411]				Charging within the safe operating zone	
[412]				Overcharging and short circuit protection	Improved thermal stability
[413]					PTC devices restrict the flow of current
[414], [415]					Flame retardant material in the electrolyte
[416], [417], [410]					Solid electrolyte improving capacity and reducing fire hazard
[418]	Printable and flexible non-porous separator				High-temperature resistant electrolyte

the researchers, the technology requires further investigations and analysis before it is made available in the market. An attempt to use plastic in place of the electrolyte in the regular LiB [410] is made by a company named Ionic Materials.[16] The plastic being used by the company is both inflammable and a good conductor. The challenges posed next is to develop a polymer that will be used in manufacturing the batteries commercially.

G. CHARGING WITHIN THE SAFE OPERATING ZONE

To mitigate the problem of overcharging and electrical abuse, IEEE suggested a safe operating window for LiBs used in mobile devices [411]. As per this specification, the operating temperature should be within 10°C to 45°C with a charging cut-off voltage of 4.25 V and a maximum specified charge rate. Charging at too high current can lead to a condition similar to overcharge or can heating at internal or external connections and may lead to undesirable effects. Fig. 28 shows the schematic of safe operating voltage and temperature window for charging Li^+ cell/battery packs. The transfer rates of the electrolyte and electrode vary according to temperature. Therefore, at lower temperatures (<10°C), to eliminate the possibility of Li deposition, the charge rate and the cut-off voltage are required to be decreased. Whereas, the normal charge rate can be employed at higher temperatures (>40°C) [401].

[16] https://ionicmaterials.com/

H. OVERCHARGE AND SHORT CIRCUIT PROTECTION

The overcharged condition and short circuit situation may be prevented in LiBs if the cathode is made up of phosphate as it can withstand higher temperature [412]. Under abusive condition also, such batteries are not easily subjected to thermal runaway, thereby offering more safety to the user. Carefully controlled charging and monitoring algorithms are used in an external circuit to prevent overcharging condition. Both internal and external control mechanisms provide a safer battery option to smartphone manufacturers.

I. USE OF PTC DEVICE

Thermal runaway of LiBs primarily occur due to accumulation of heat generated over a longer period of time. PTC devices are composed of a thin conductive polymer

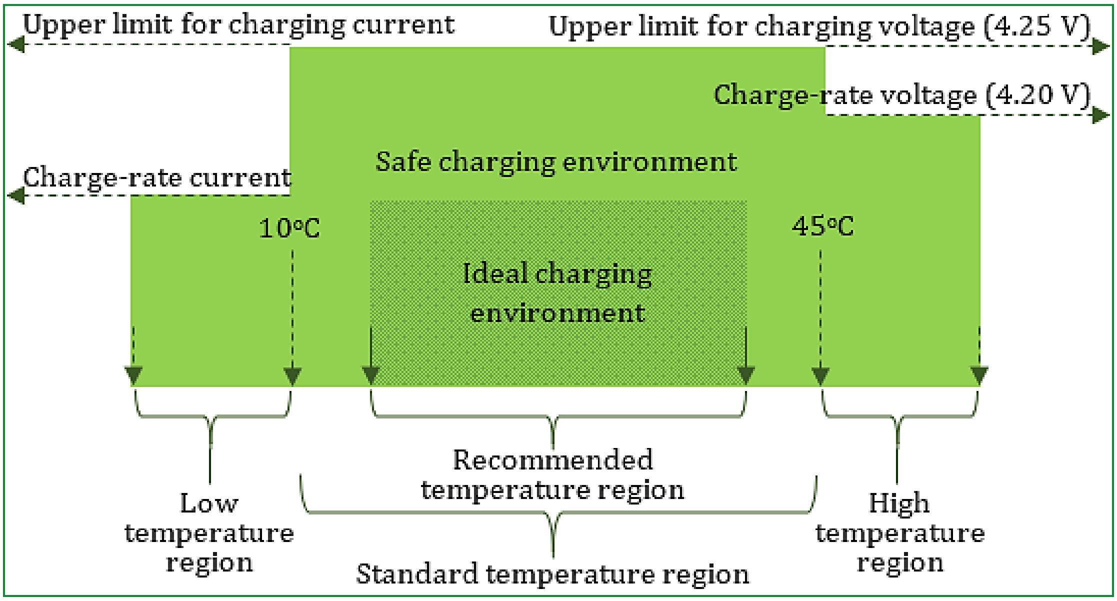

FIGURE 28. Safety ranges for current and voltage for charging Li cells as per IEEE 1625 standards (adapted from [401]).

layer, exhibits a positive temperature coefficient of resistance. To prevent thermal runaway, LiBs are being equipped with PTC devices whose resistance increases with the accumulation of heat, thereby limiting the current flow in the battery. Restriction in current flow causes the battery and the PTC device to cool down, leading to avoiding of thermal runaway [413].

J. USE OF FLAME-RETARDANT MATERIAL IN ELECTROLYTE

This approach suggests the addition of flame-retardant material with a very high flash point to the electrolyte without degrading the performance of the battery [414]. Xu *et al.* [415] synthesized tris-(2,2,2-trifluoroethyl) phosphate (TFP), bis(2,2,2-trifluoroethyl)-methylphosphate (BMP), and (2,2,2-trifluoroethyl) diethyl phosphate (TDP) which show flame retarding capability vis-a-vis good electrolyte conductivity.

K. NEW GENERATION SOLID ELECTROLYTE TO IMPROVE CAPACITY AND THERMAL STABILITY

The increase in demand for more power from the batteries is ever-increasing and with this is increasing the longing for a safer form of batteries. The researchers at the University of Michigan [416] has proposed the use of a solid electrolyte as it will help to achieve a better electrochemical and chemical stability in comparison to the general LiBs [417]. This kind of battery will provide a high current density and also lead to a stable cycle of the battery. The battery is like the improved form of both solid-state batteries and LiBs. Solid-state electrolyte enables the use of metallic Li anodes that offers high energy density [364]. The combination of solid-state electrolyte and metallic Li anode is claimed to be market leaders of the next generation of LiBs.

L. IMPROVED LIQUID ELECTROLYTE

Kohlmeyer *et al.* have reported the development of improved separator and a liquid electrolyte which can work satisfactorily at high temperature without thermal runaway [418]. The researchers demonstrated the use of printable and highly flexible Al_2O_3-poly (vinylidene fluoride) nanoporous separator membrane and carefully designed high boiling point LiBOB-based liquid electrolyte that are capable of stretching the working temperature up to 120°C.

X. CONCLUSIONS AND PROSPECTS

Smartphones are increasingly useful for a wide spectrum of applications. Many innovative and new applications of smartphones are being developed, such as location detector, monitoring of environmental conditions, sensing of traffic on the road, monitoring health conditions of people, gaming, and so on. All these applications work on real-time and consume a substantial amount of energy. The battery within the smartphone supplies the required power to it. But there is a limitation of the battery capacity, which is determined by its chemical properties and cannot be increased beyond a certain limit. This has been a roadblock in unleashing the true power of smartphones. To bear with the energy limitations, it is suggested to use energy cautiously and miserly. Efficient energy management in a smartphone is all about maximising its battery life. For that, a rigorous understanding of the energy requirement and consumption of each component of a smartphone is required. In this paper, we have understood the different internal and external factors are responsible for energy depletion in a smartphone battery. It is observed that the components like CPU, memory, and wireless network modules (e.g., Wi-Fi, Bluetooth, GPS, network radios, etc.) consume most of the energy. Nevertheless, all the stakeholders in the smartphone energy ecosystem should be responsible for realizing their roles in minimising energy consumption and have a methodological approach and planning to attain that.

Researchers have come up with various approaches to manage the limited energy issue in smartphones. A lot of work has been devoted to measuring the energy consumption, which includes analysis of energy requirement and modelling power consumption pattern of different components. Some have tried to estimate the remaining battery time and thus, predicting how long the device will run before it needs to be recharged. Though the accurate prediction of remaining operating time of a battery before it needs to be plugged in is extremely challenging. Many researchers have given special attention to overcome the energy scarcity, to some extent, by proper management of the energy usage and optimised designing and operation of smartphone hardware and software. Some have proposed to handover the energy-demanding tasks to other devices, having a higher battery level. In order to maximise the battery life, attempts have been made following different approaches such as reducing the charging frequency by extending the battery operating life, making batteries with larger capacity, minimise the time duration required for charging, increasing the energy density, etc. Though these approaches have succeeded somewhat to lessen the pain of quick battery drainage experience, over-stretching of these methods involves some serious hazards such as Li plating, thermal runaway, etc., which might cause heating and explosion of the batteries.

Though research on battery for mobile devices has not yielded much development for a few decades, we hope that we are on the verge of witnessing a major breakthrough in this regard. Especially, the emergence of wireless charging with its potential to offer charging ubiquitously and exploration of other alternative power sources used for charging smartphone's battery, it is expected, very soon users will be free from the worry of battery discharging menace and the full potential of smartphone's capabilities will be realised.

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