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Green Internet of Things (GIoT): Applications, Practices, Awareness, and Challenges

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ABSTRACT Internet of things (IoT) is one of key pillars in fifth generation (5G) and beyond 5G (B5G) networks. It is estimated to have 42 billion IoT devices by the year 2025. Currently, carbon emissions and electronic waste (e-waste) are significant challenges in the information & communication technologies (ICT) sector. The aim of this article is to provide insights on green IoT (GIoT) applications, practices, awareness, and challenges to a generalist of wireless communications. We garner various efficient enablers, architectures, environmental impacts, technologies, energy models, and strategies, so that a reader can find a wider range of GIoT knowledge. In this article, various energy efficient hardware design principles, data-centers, and software based data traffic management techniques are discussed as enablers of GIoTs. Energy models of IoT devices are presented in terms of data communication, actuation process, static power dissipation and generated power by harvesting techniques for optimal power budgeting. In addition, this article presents various effective behavioral change models and strategies to create awareness about energy conservation among users and service providers of IoTs. Fog/Edge computing offers a platform that extends cloud services at the edge of network and hence reduces latency, alleviates power consumption, offers improved mobility, bandwidth, data privacy, and security. Therefore, we present the energy consumption model of a fog-based service under various scenarios. Problems related to ever increasing data in IoT networks can be solved by integrating artificial intelligence (AI) along with machine learning (ML) models in IoT networks. Therefore, this article provides insights on role of the ML in the GIoT. We also present how legislative policies support adoption of recycling process by various stakeholders. In addition, this article is presenting future research goals towards energy efficient hardware design principles and a need of coordination between policy makers, IoT devices manufacturers along with service providers.

INDEX TERMS Fifth generation, Internet of Things, green Internet of Things, fog, machine learning.

I. INTRODUCTION

The fifth generation (5G) mobile network is backed up by advanced communication technologies that is going to play a significant role in wide spread of internet of things (IoT) based services in future generation [1], [2]. 5G network is conceived to support multiple Giga bits per seconds (Gbps) data speed at lower latency, network slicing to offer a distinct part of the network for an intended service. In addition to existing macro cell towers, 5G also proposes to use a huge number of smaller micro cells that effectively create a blanket of high speed network. 5G radio access network (RAN) is designed to support new MIMO antennas installed at base stations (BS) and devices. Fourth generation (4G) long term evolution (LTE) systems were intended to offer high speed mobile broadband services as compared to previous generation networks. However, 5G creates a platform to not only offer superior broadband services than its ancestors but also supports real time critical services and fulfill the IoTs dream of connecting everyone, everything and everywhere. A mix of lower-band (under 1 GHz), mid-band (1 GHz to 6 GHz) and higher-band spectrum (millimeter wave (mmWave)) is used for the 5G network deployment to support high data speed, lower latency, and better spectrum utilization [3].

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TABLE 1. Performance benefits of 5G [4].

Performance parameters	Quantified benefits
Data Latency	10x reduction
Average number of connections	10x increase
Spectrum utilization	3x increase
Data rate	10x increase
Traffic capacity	100x increase
Network efficiency	100x increase

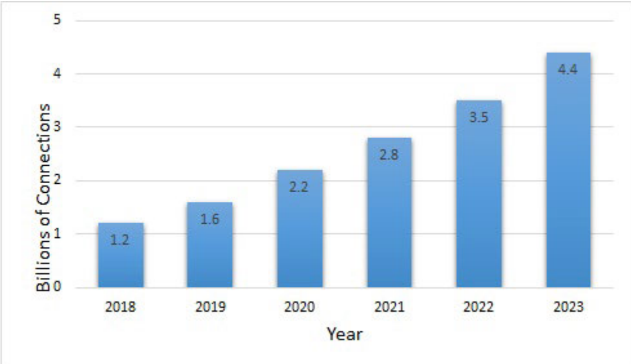

FIGURE 1. Predicted mobile IoT growth [4].

As shown in Table 1, the latency rate takes a leapfrog from 10 - 50 ms delay in 4G to five to ten times lower rate conceived in 5G networks. Such reduced latency rate is able to provide a real time user experience to consumers and applications such as in self drive vehicles or remote medical services. Leveraging on much wider spectrum and advanced antenna capabilities, 5G is expected to offer 10 fold higher connection density, better spectrum efficiency, and uniform multi Gbps throughput. IoT was first conceptualized by Kevin Ashton in the year 1999 [5] who proposed interfacing of radio frequency identification device (RFID) with internet. IoTs are prime contributor in the transformation of dumb and passive devices into smarter ones by making them able to transmit large amount of relevant data over the internet. These sensors communicate with each other as well as humans and hence a sense of context awareness can be created. Interoperability is one of a unique and useful feature of IoT that impacts different sections of life. Processing and analysis of data within the IoT ecosystem makes the devices work all alone without or very little intervention by the humans. Cisco predicts more than 500 billion devices connected to internet by 2030 [2]. Figure 1 shows an estimated number of connected devices to the IP networks by the year 2023 will reach 3 times more than that of global population. In current era, IoT impacts and applications are significantly noticed in environment sensing, healthcare monitoring system, supply chain management of logistics, real estate construction, energy management, drones based application, manufacturing industry and many more. IoT network needs to interconnect & establish communication link between massive ubiquitous things, which results in a large and heterogeneous amount of data. Limited computing capacity and battery, like energy sources of IoT devices, limit data processing by the devices themselves. Hence, it is a good idea to leverage on cloud computing paradigm for the processing of data generated from IoT network devices [6]. Cloud computing offers centrally located efficient data processing and storage for IoT based services like personal services involving minimal data collection and storage to "big data" based services [7], [8]. However, growing demand of real time applications, latency sensitive services and limited network bandwidth play a bottleneck in cloud computing. Fog & Edge computing complements cloud computing, offers situational awareness and cater to bandwidth and latency requirements. Fog computing, proposed by Cisco in 2012, extends cloud based services to the network edge to offer computing, communication and storage services near to sensors and IoT devices resulting in lower latency and higher bandwidth [9]. Edge computing also avoids the need of transmitting data to the cloud center, and data computations are carried at the edge of network, thus improving response speed and latency [10].

Another perspective to look into is the price that environment pays in short and long term for the technical advancement taken place worldwide in last few decades. Billions of IoT devices require a large amount of energy as huge data are generated and travel through networks. Billions of batteries supporting the operation are also discarded and needed throughout the life-cycle of these IoT devices. Combined global electronic waste (e-waste) generated in year 2016 was 44.7 million metric tonnes (Mt) which averages to 6.1 kilogram per inhabitant (kg/inh) as compared to 5.8 kg/inh in 2014. E-waste generation is projected to reach 52.2 Mt or 6.8 kg/inh by 2021. However, only 20% i.e. 8.9 Mt of total global e-waste is documented and recycled globally [11]. A report by Guardian Environment Network estimates that in next 10 years 3.5% of the global carbon emissions i.e. 1.9 GigaTonnes will be coming from IoT devices and data centers [12]. In United States (US), data centers will be gulping over 100 TWh of electricity and 416.2 TWh globally. The carbon dioxide (CO_2) that cellular networks emits stands at 345 million tons in the year 2020 [13]. Considering environmental challenges, the design, manufacturing, deployment, in service and withdrawal of electronic devices should meet stringent environment guidelines laid out and use innovative approaches. Energy harvesting, low-power chip-sets are core focused areas towards the development of IoTs today. Green internet of things (GIoTs) is here to realize greener world where humans will be aware about the impact of current technologies on environment and human health. GIoT goal is to offer efficient technical services without stressing on natural resources, energy efficient solutions, reducing the wastes and emissions during manufacturing to field application.

Large amount of data generated from IoT devices needs efficient techniques to extract useful information. Big data schemes and models based on machine learning (ML), data mining and various others are used to reveal hidden data patterns, detect faults, perform predictive modeling and

TABLE 2. List of acronyms & abbreviations.

Acronyms	Full Form
IoT	Internet of Things
MIMO	Multiple Input Multiple Output
m-MIMO	Massive Multiple Input Multiple Output
CoMP	Coordinated Multipoint Processing
CRAN	Centralized Radio Access Network
RRH	Remote Radio Heads
GICT	Green information & communication technologies
AI	Artificial Intelligence
ML	Machine learning
WSN	Wireless Sensor Networks
SD-WSN	Software Defined Wireless Sensor Networks
NFV	Network Function Virtualization
CR	Cognitive Radio
RAN	Radio Access Network
LTE	Long Term Evolution
mmWave	Millimeter Wave
RFID	Radio Frequency Identification Device
DC	Data Centers
NFC	Near Field Communication
SANY	Sensors ANYware
IPAWS	Integrated public alert and warning system
WirelessHART	Wireless Highway Addressable Remote Transducer Protocol
TSP	Trust, Security and Privacy
SDN	Software Defined Network
QoS	Quality of Service
SoA	Service Oriented Architecture
M2M	Machine to Machine
LoRa	Long Range
LR-WPAN	Low Rate Wireless Personal Area Network
CTCA	Cooperative Topology Control with Adaptation
LPL	Low Power Listening
DCLA	Duty cycle learning algorithm
MO	Multi-Objective
ABC	Artificial Bee Colony
RANO	Reservation Aloha for No Overhearing
WISP	Wireless Identification and Sensing Platform
ATPC	Adaptive Transmission Power Control
B-MAC	Berkeley Medium Access Control
MS	MultiSlotted
MSS	Multislotted with Selective Sleep
MAS	Multislotted with Assigned Slots
ESR	Equivalent Series Resistance
MCS	Multiple Classifiers
HMAX	multi-classifier multicore processor with Hierarchical model
SIFT	Scale Invariant Feature Transform
SIMD	Single Instruction Multiple Data
WBSN	Wireless body sensor networks
SBM	Single Board Microcontrollers
e-CAB	Energy efficient Context-aware Broker
OA	Orchestration Agent
C-MOSDEN	context-aware mobile sensor data engine
MILP	Mixed Integer Linear Programming
VM	Virtual Machines
OLA	Opportunistic Large Array
SNR	Signal to Noise Ratio
BEMS	Building Energy Management System
DCRDL	Device Control Rule Description Language
RPL	Routing Protocol for Low-Power and Lossy networks
IoMT	Internet of Multimedia Things
VoIP	Voice over Internet Protocol
EEU	Energy-Efficient Unicast
RU	Reliable Unicast
AODV	Ad-hoc On-demand Distance Vector
TBDT	Topic-based Data Transmission
MPSFC	Mobile Publish/Subscribe Fog Computing
EMS	Energy Management Scheme

undertake appropriate decisions. Artificial intelligence (AI) based algorithms employ techniques to analyze huge volumes of data generated in IoT networks to deliver value added public services [14]. GIoT design principles are adopted in similar computing devices, communications protocols, and networking architectures as of IoT, keeping ecology, energy efficiency and carbon emissions as decisive factors. Following design components have to be taken into consideration to obtain an efficient GIoT realization [15]:

- Usage of eco-friendly & bio-products.
- Reducing energy consumption of facilities.
- Utilization of renewable green sources of energy.
- Decentralized processing and storage at network edge to overcome bandwidth and latency limitations.
- Predictive data delivery using Edge/Fog/Cloud architectures to reduce network data.
- Adopting energy-efficient routing techniques.
- Reducing wireless data path using methods like cooperative relaying etc.
- Deploying security & data privacy mechanisms.

A. RELEVANT PRIOR ART

The GIoT has become tech buzzword as an enabler of smart and sustainable world to reduce carbon emissions and power consumption. A plethora of research papers as presented in Table 3 is published in recent times to tackle several topics related to GIoT [13], [15]–[33]. A number of techniques targeted to reduce energy consumption of IoT network is proposed but most of these solutions are standalone in nature. Alsharif *et al.* presented detailed review of strategies like green wireless sensor networks - Long Range (LoRa), Bluetooth, low rate wireless personal area network (LR-WPAN), WiMax and WiFi where data rate, transmission range, cost, energy consumption are considered. Hardware like processors dedicated for sensing, processing, transmission of data, active and sleep modes to maximize power efficiency are also presented [23]. In [15], authors highlighted significance of the GIoT as a felicitator of sustainable world and humans well-being. Various sectors in society are key beneficiaries of GIoTs through environmental protections, customers satisfaction and increased profit margins. Dong *et al.* has proposed Reservation Aloha for No Overhearing (RANO) protocol intended to avoid overhearing problem during RFID communication. Here, a tag reserves its communication time in advance through broadcast frame and then enters into low power sleep mode. A comparison of average power consumption of tags against different protocols including RANO is carried out to prove energy savings upto 60 times is achievable. However, timer-based self-wakeup hardware used in said proposal is not accounted as an overhead neither how much energy is consumed [34]. In [16], [19], technologies that can reduce IoT's energy consumption and helpful in realizing green RFID, green wireless sensor network, green cloud computing, green machine-to-machine (M2M) and green data-centers are reviewed and discussed. Reduced RFID size results in reducing non-biodegradable material consumption, dynamically adjusting transmission power at nodes are promising methods. Using low power sleep modes during inactivity, radio optimization, energy efficient routing techniques and data minimization techniques are contributor to a green wireless sensor network. Activity scheduling and energy harvesting are helpful in green M2M implementation and green energy powered data centers were mentioned in the article. However, these techniques are not analytically proven or supported with data that can validate mentioned designed principles. Abedin *et al.* proposed IoT system model based on energy efficient scheduling algorithm with three main stages, i.e. on-duty, pre-off duty and off duty. Reported energy consumption during these three stages is not bench-marked or compared in absence of proposed algorithm [21]. Taxonomy of energy saving techniques is discussed in [18]. Strategies adopted in reducing the energy consumption of IoT networks, such as green data-centers, transmission of data from sensor in an energy efficient way, policies promoting green energy approaches, are discussed and evaluated. Five proposals for reduction in energy consumption are made, i.e. reducing network size, reducing data by selective sensing, incorporating mix of active and passive sensors, stressing need of policies for various stake holders and applying trade-offs where possible to reduce energy consumption. However, we strongly believe there is lack of details in the article regarding how to go about awareness creation among stakeholders, any effective model in place or proposal about awareness programs, global or regional policies or governments action etc. Authentication and confidentiality of IoT data using Hybrid Logical Security Framework (HLSF) is proposed in [25]. Efficient network functionality & security in energy efficient IoT networks is achievable using HLFS which was implemented using three distinct stages i.e. registration, authentication and security. Proposed HLSF framework is benchmarked with constrained application protocol (CoAP) and object security architecture (OSCAR). Authors claim HLFS is 18% energy efficient compared to CoAP and consumes 55% less energy than in OSCAR architecture. Reported energy consumption data is accounted only for the active or passive motes whereas additional hardware in the sensor circuit is not accounted.

B. CONTRIBUTION AND OUTLINE

In this article, we present a comprehensive survey of sectors that are benefited from the proliferation IoT devices and ever expanding IoT networks. Twelve significant application domains of IoT in urban, rural, industrial and health sectors are presented and how the arrival of 5G communication network is further going to boost data rate and network density. Although [18] has extensively discussed techniques for realizing a GIoT, approaches like habitual, awareness, policy related and recycling related global or national laws and governance involvement for the cause is left out. To the best of our knowledge, this is the first survey to explore every possible technique that can be an enabler of GIoT. The analytical energy models based on network characteristics is presented in Section II-C and III provides an estimated energy consumption within a IoT network and fog based computing services. IoT reference model is discussed in Section II.B presents an abstract framework that provides optimal sets of unifying concepts, postulates and interdependence of network entities and also presents ideas and definitions for building IoT architectures. The model comprises of multiple sub-models that defines the scope of IoT design space and addresses architectural perspectives.

The aim of this article is to provide insights on hardware and software approaches to minimize energy consumption of IoT based services. Green machine-to-machine (M2M) technology for data exchanges, wireless sensor network (WSN) employing efficient data aggregation techniques, active and passive RFID tags and microcontroller units (MCU) implemented on advanced very-large-scale-integrated-circuits (VLSI) design principles were discussed extensively. Context based computing as a green software design approach is discussed as a enabler for reduced data volume. We have presented various behavioral change models to bring changes to energy saving habits that will contribute in an efficient energy utilization. Policy related recommendations that will encourage various stakeholders to adopt GIoT strategies is presented. We also presented growing environmental concerns with increasing e-waste pile up and how recycling and reuse policy will be able to mitigate environmental risk. Centralized cloud computing often fails to provide real time services due to large number of IoT devices leading to network congestion and increased latency. Fog computing is an extension of cloud computing enabling decentralization of data centers. Fog & Edge computing have emerged as potential solution in minimizing data latency and offer better computational performance of IoT based services. Computational Intelligence provides new paradigm with an integration of optimization theory, statistics, cognitive science etc. Machine learning (ML) is an offshoot of AI where computational devices learn from its experience, analogies and examples. ML based techniques helps to sense increase in rate of energy consumption from given temperature conditions and power status of IoT systems, predicting natural or artificial calamities etc. We present energy consumption model of fog computing in Section III. Also, green software design techniques like scheduling is presented for a distributed environment. A diverse number of techniques/strategies like green RFIDs, green data centers, green sensors network, green distributed computing should be in place to meet greening of IoT requirements. Therefore, various models & strategies are grouped in 6 main classes on the basis of technologies adopted.

The key contributions can be summarized as:

- This article discusses every aspect of strategies needed to be adopted for the overall greening of IoT based applications. We present energy consumption model in a fog-based services including routers and switches. Although the work in [18], [27] are closer to ticking all the columns in Table 3, they clearly lack a distinction between cloud & edge computing and further integration with AI. In addition, a discussion about latency issues with regard to cloud-based computing which

TABLE 3. Prior relevant articles.

Ref.	Major contributions	RFID	WSN	M2M	Energy harvesting	Cloud / Fog / Edge	AI & ML	DC	GICT	Recycling / Policy / Pollution
[13]	Role of IoT & future research goals, challenges etc.	✓	✓	✓	✓	✗	✗	✗	✓	✗
[15]	Significance & impact of the GIoT for a sustainable world.	✓	✓	✓	✓	✓	✓	✗	✗	✗
[16]	Technologies & issues related to GIoT contributing to reduction in energy consumption.	✓	✗	✓	✓	✓	✓	✓	✓	✗
[18]	Strategies for the minimization of energy consumption in IoT's.	✓	✗	✓	✓	✓	✓	✓	✓	✓
[19]	Enabling technologies in internet, smart objects & sensors for GIoT.	✓	✓	✓	✗	✓	✗	✗	✗	✗
[20]	Energy harvesting techniques and solutions for powering IoT devices.	✗	✗	✗	✓	✗	✗	✗	✗	✗
[22]	Energy efficiency, energy harvesting & pollution related solutions for IoT's.	✗	✗	✗	✓	✗	✗	✗	✓	✓
[23]	Study of energy saving practices & hardware for greening IoT.	✓	✓	✓	✓	✗	✗	✗	✓	✗
[24]	Performance evaluation of slotted ALOHA in LoRaWAN & energy, delay bench-marking of devices against variable payload.	✗	✓	✗	✗	✗	✗	✗	✗	✗
[25]	Comparison of HLFS versus CoAP, OSCAR protocols employed in authentication & data confidentiality.	✗	✓	✗	✗	✗	✗	✗	✗	✗
[27]	Survey of current research work & technologies contributing in greening of IoT.	✓	✓	✓	✓	✓	✗	✓	✓	✓
[29]	Review of LPWAN, security & control related issues in 5G IoT.	✗	✓	✗	✗	✗	✗	✗	✗	✗
[30]	Framework for the implementation of circular economy with IoT's in a cooperative arrangement.	✗	✗	✗	✗	✓	✗	✗	✗	✓
[32]	Review of IoT systems application & analysis of devices efficiency & solutions to problems identified.	✓	✓	✗	✗	✓	✗	✓	✓	✗
[35]	Proposed hierarchical network designing, an energy efficient IoT model, energy efficient optimal transmission algorithm.	✗	✓	✗	✗	✗	✗	✗	✓	✗
[36]	An optimized model based on hierarchical framework for GIoT's, and an energy consumption algorithm of the proposed model.	✗	✗	✗	✗	✗	✗	✗	✓	✗
[37]	Customized generic algorithm for scheduling-implementation using heuristic approach in order to minimize latency against IoT requests.	✗	✗	✗	✗	✓	✗	✗	✓	✗
Our Work	Discussion on various energy efficient hardware, distributed computing, data centers & software based data traffic management using schedulers etc., and techniques in greening of IoT's.	✓	✓	✓	✓	✓	✓	✓	✓	✓

necessitates introduction of fog-based computing is not discussed in [18], [27].
- This article presents the integration of AI with IoT networks, such as edge computing, which can offer advantages like filtering out relevant data from undesired ones.
- We present the IoT reference model proposed by [38] which can serve as a reference to build application specific IoT architectures.
- To meet goals of green IoT, e-waste management is a small contributor but a significant one at larger perspective. E-waste management and reuse is a policy-based issue which is required to be addressed and all parties involved should be made aware about. We present an overview of various awareness strategies and policy-based recommendations.
- Challenges & future research goals such as complexity issues in real time mode and heterogeneity issues are identified and discussed.

The most used acronyms with respective abbreviations are presented in Table 2.

II. INTERNET OF THINGS (IoT): AN OVERVIEW

IoT has emerged as promising technology in last decade that is capable of improving the quality of human's life. It creates a platform equipped with new generation communications technology, wide a range of sensor networks and interconnected embedded devices that can perform jobs with much higher accuracy by talking and sharing information over the network [39]. Over the past few years, IoT has been able to touch upon human life's. Figure 2 shows broad category of IoT application areas such as our homes, cities, educational institutions, industries, factories, warehouses, offices, transports, agricultural activities, hospitals and healthcare facilities and services [40]–[44].

A. APPLICATION AREAS

The motivation for development of IoT applications irrespective of their functionality is to support users in making intelligent decisions, choose the best opportunity in any case or to offer smart services and hence, increase the quality of human life [46]–[48]. Libelium listed 50 sensor applications for the smarter world and placed under 12 major application domains of IoT as shown in Fig. 2, also services classification under each domain is briefly discussed in Table 4. A smart city is defined as one that implements primary and critical services like administration, education, healthcare, public safety, real estate, transportation and utilities using advanced information and communication technologies [49]. Monitoring real time parking space, structural health of buildings, bridges and monuments, electromagnetic radiation, optimal traffic management, adaptable lighting system, waste management, etc. are significant applications in smart cities. There are six distinct characteristics of any smart city: smart economy, smart habitats, smart governance, smart mobility, smart environment, and smart living standards [50].

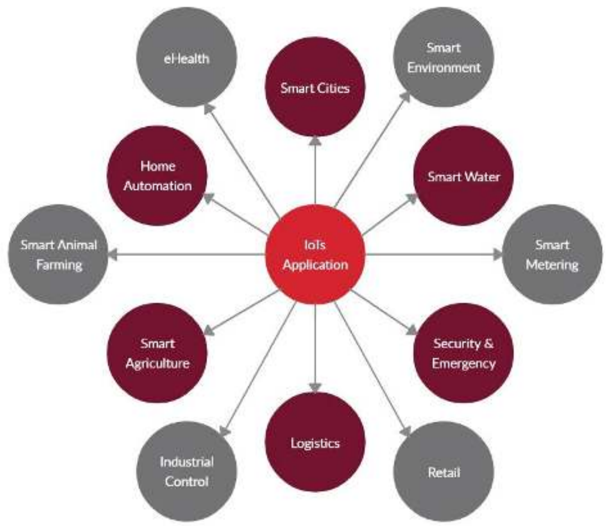

FIGURE 2. IoT Applications [45].

TABLE 4. Applications of IoT [45].

Application	Domains
Smart city	Smart parking, structural health, noise urban maps, smartphone detection, electromagnetic field levels, traffic congestion, smart lighting, water management, and smart roads
Smart environment	forest fire detection, air pollution, snow level monitoring, landslide and avalanche prevention, and earthquake early detection
Smart water	Portable water monitoring, chemical leakage detection, swimming pool remote measurement, pollution levels in sea, water leakages, and floods
Smart metering	Smart grid, tank level, photo-voltaic installations, water flow, and silos stock calculation
Security and emergencies	Perimeter access control, liquid presence, radiation levels, explosive and hazardous gases
Retail	supply chain control, NFC payment, intelligent shopping application, and smart product management
Logistics	quality of shipment conditions, item location, storage incompatibility detection, and fleet tracking
Industrial control	M2M application, indoor air quality, temperature monitoring, Ozone presence, indoor location, and vehicle auto-diagnosis
Smart agriculture	Wine quality enhancing, green houses, golf courses, meteorological station network, compost, and hydroponics
Smart animal farming	Offspring care, animal tracking, and toxic gas levels
Domotic and home Automation	Energy and water use, remote control appliances, intrusion detection systems, art and goods preservation
eHealth	fall detection, Medical fridges, sportsmen care, patients surveillance, ultraviolet radiation

A smart environment can be one which leverages upon IoT services, and supports resource management (i.e., water\energy) and applications for the efficient and effective use of the environmental resources [51], [52]. A smart water is the real-time management process of monitoring quantity and quality of water [53]. Applications of IoT services during planning, distribution, spillage or leakage detection and metering are utilized in industrial, commercial and domestic water services. The water supply regulator (Ofwat) in U.K. reports a 20% potable water loss due to difficulty in leakage identification [54]. Water leakage also adds up to energy cost during water pumping and transportation [55]. Smart meters collect usage information on electricity, gas or water and reports back to utilities in real time mode. An insight information regarding consumption is provided to service provider as well as a consumer to understand usage habits and maintenance of respective supply networks. Service providers are capable of gathering time based data, manage distribution and service interruptions, handle peak demand and billing [56].

Prepaid metering system helps consumers in regulating their supply consumption and avoiding cutoffs due to insufficient or zero credits [57], [58].

Natural calamities like fire accidents, earthquake disasters, flash floods and humans created emergencies like terrorist attacks, state of civil war etc., require in advance situational awareness for an effective response. An accurate idea about the intensity of disaster helps in reducing the extent of human life loss and damages to the property. IoT based crises response system is able to support better decision making and real time response [59]. Initiatives like open standard sensor networks i.e., Sensors ANYware (SANY) [60], integrated public alert and warning system (IPAWS-Open) [61] are in place as an alert system based on cloud IoT [62].

With the arrival of IoTs in retail industry, both retailers and buyers are going to benefit in terms of accessibility, time spent, cost, etc. Few examples of IoT enabled retailing are proposed such as the RFID tagging of inventories, smart carts, virtual mirrors, etc., [63]. Real time data tracking helps in tracking products and maintaining stocks across the entire supply chain and also customers can track their order status [64]. Keeping real time information of goods offers advantages such as a reduction in storage cost and reducing loss in perishable goods or theft. Implementation of IoT in supply chain management helps in effective demand management, goods replenishment and customization [65]. IoT based logistics systems manage transport of goods type and quantity, operation and location of transport vehicles as well as outsourcing of logistics to meet market demands [66].

Industrial control processes, such as factory automation, process control, and monitoring control loops, are supported using IoT network. Industrial standard networks like IEEE 802.15.4e and WirelessHART are in place for better stability of control processes [67]–[69]. Remotely located industrial plants are able to receive diagnosis and maintenance services using wireless technology. Manual configurations of individual processes and interacting devices are avoided due to every device communicating with each other on the network and hence, reduces engineering cost. Real time data provides an opportunity for better quality control, secure and predictive service features [70].

Smart agriculture plays a significant role to equip farmers with high end automation processes and helps in decision making. IoT sensor network provides data like rainfall pattern and amount, soil nutrients and moisture, solar exposure, insects and pest attacks, leaf wetness, humidity, temperature, wild animal attacks and theft like incidents [71]. A smart farming integrated system is able to use optimal resources and better productive at several stages of cultivation, harvesting and storage of farm products [72]. Milk and Meat are the two prime products of animal farming and a smart monitoring system of livestock barn can minimize losses due to natural damages and disease [73].

Smart Home is built using diverse sensing devices, controller and a communication network to provide an intelligent, comfortable, and secured home environment [74]. Remote meter reading and billing of essential commodities like water, cooking gas, electric power and telecommunication services are possible using these smart homes networks. Access to doors, windows, room ventilation, air conditioning, and lightening etc. can be monitored and controlled through IoT network access. Smart home automation system reduces significant amount of energy wastages and contributes towards energy conservation [75], [76].

eHealth system is in place with IoT enabled infrastructure to offer services like keeping health records, enabling accurate diagnosis results, monitoring of health parameters that is processed and analyzed in real time domain and supporting in rehabilitation after the medication being carried out [77]. Advances in electronic design automation have helped to develop devices like biochips, wearable biosensors that is used in clinical diagnosis to physicians analysis. IoT enabled devices support paramedics in remotely assessing critical health parameters of patients and plan a data based treatment schedule [78]. eHealth services are meant to provide health services between the patients, doctors, sports-persons and coaches with well-established accuracy irrespective for their geographical locations [79].

B. IoT ARCHITECTURE

Bauer *et al.* presented IoT reference model shown in Fig. 3, which provides the ideas and definitions for building IoT architectures. The proposed reference model consisted of multiple sub-models that defines the scope of IoT design space and addressed architectural perspectives. The technology independent ''IoT Domain Model'' is the primary model that defines all other models as well as IoT reference architecture. The important concepts of IoT like devices, services and virtual entities (VE), and relationship among them are defined by IoT domain model. Based on the application type, models like IoT communication model, IoT trust, security and privacy model shown in the reference model are optional but IoT domain model is mandatory. How one model is built using concepts and aspects of other models is depicted by arrows in Fig. 3. ''IoT information model'' built on the basis of IoT domain model defines IoT related relations and attributes at a higher abstraction in IoT system. The information related to

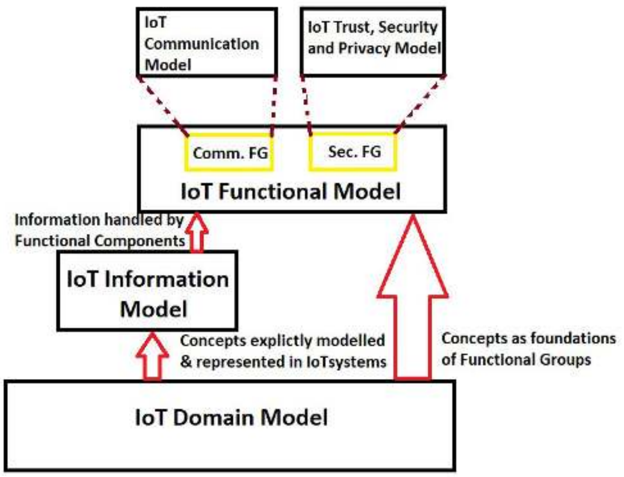

FIGURE 3. IoT Reference Model [80].

attributes in IoT information model is modelled and information about devices, services, and VE is stored in IoT system. "IoT functional model" defines functionality groups (FG's) needed for concepts declared in IoT domain model. These FG's utilizes "IoT information model" and provides functionalities for information exchanges needed for VE or IoT services. Communication link between various heterogenous components in a distributed IoT environment is handled and managed at IoT communication model. Appropriate FG's, inter-dependencies and data exchanges are introduced in Trust, Security and Privacy (TSP) model based on a typical IoT services [38]. IoT network architecture is a system of physical and virtual things like sensors, actuators, communication layers, cloud network services, IoT specific communication protocols, technology developers, users, enterprise layers, etc. There is no universally accepted definition of IoT architecture where different researchers proposed different architectures based on their application [81], [82]. Fundamental requirements for the development of IoT network architectures are modularity, scalability, flexibility, interoperability, etc. Some of the well defined IoT network architectures are: three Level architecture, SDN-based architecture, QoS-based architecture, SoA-based architecture, mobility-First architecture, cloudThings architecture, IoT-A architecture, S-IoT architecture [83].

1) THREE LAYER ARCHITECTURE

Figure 4(a) illustrates three-layer IoT network architecture with three distinct layers (perception layer), network layer, and application layer. Perception layer, also known as sensor or physical layer, consists of variety of devices like sensors, readers, RFID tags, video cameras, smart phones, etc., that collects data from surroundings. These large amount of data is needed to be aggregated and analyzed at network layer which bridges perception and application layer [84]. Network layer, also known as transmission layer, is responsible for establishing connection between devices. Wired and wireless communication technologies like WiFi, LTE, 4G, 5G, etc. lay a datapath using internet gateways, switches and routers. The application layer acts as an interface between the user and network. Data accumulation, assimilation and presentation in a user friendly format takes place in this layer. Optimal requirements at application layer are low-latency, accuracy and energy efficiency [85].

2) SOFTWARE DEFINED NETWORK (SDN)

Last decade has witnessed a drastic increase in traffic load on mobile networks due to arrival of IoTs and hand held devices with innovative services and applications. Complexity in operation and management of ever increasing network usage poses operational challenges to traditional networks [86]. Software defined networking (SDN) is a promising solution to by decoupling control plan and the data plan. The management and control of a huge number of connected objects in IoTs by SDN is met without need for changing underlying architectures [87]. As shown in Fig. 4(b), SDN implements a software-based controller, also known as application programming interfaces (APIs), to route traffic on the network and interface with underlying hardware. SDN comprises of three layers i.e. infrastructure layer that includes network devices like routers, control layer and application layer [88].

3) SERVICE-ORIENTED ARCHITECTURE (SoA)

Service-oriented architecture (SoA) based IoT system treats each physical object as a service consumer as well as service provider using compatible APIs [89], [90]. Figure 4(c) illustrates the SoA based network architecture intended to connect and communicate between heterogeneous objects. Middleware technology is used as a software layer between application layer and technological layer. Interface between devices or objects is performed using APIs. Middleware layer performs context aware syntactic and semantic interoperation to verify the information format and meaning associated with the data being exchanged [91]. Application layer on top of the SoA architect exploits middleware layer features and interface with the user through web service protocols. Service composition is a sandwiched layer between application and middleware layer. This layer is independent of devices and consists of application services being offered by networked objects. Service management layer defines functions like service configuration, status monitoring, and object dynamic discovery for each object. This layer is capable of providing remote deployment of new application specific services during run-time. As the name suggest, object abstraction is meant for harmonizing the access request from large number of heterogeneous devices. Trust, privacy, and security management are vertical layer that provides a surveillance mechanism to safeguard user data breach [92].

C. ENERGY MODELS

IoT devices may be deployed into remote areas where power supply from the grid is not available. Therefore, it is a general practice to adopt stringent power budgeting and follow best

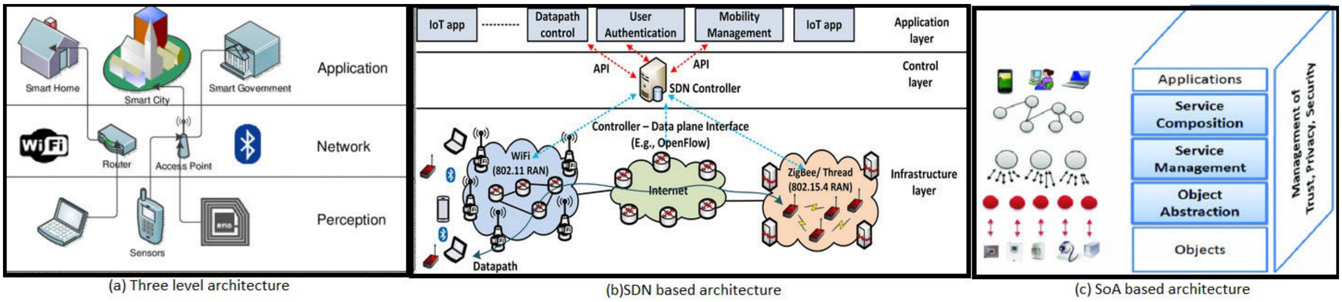

FIGURE 4. IoT architecture.

possible design practices to reduce the power consumption and hence improve the battery lifetime. Power consumption in IoT devices can be categorized into three components [93]:

1) Power utilization by the processor like microcontrollers
2) For the functioning of peripherals like sensors, actuators etc.
3) For establishing and maintaining communication link on IoT network

Hence, a total power consumption in IoT device is expressed as:

$$P_{consumed} = P_{data\_sent} + P_{data\_received} + P_{data\_sensed} + P_{actuator} + P_{ambient\_loss} - -P_{generated} \quad (1)$$

where P_{data_sent} and $P_{data\_received}$ represent power consumption during transmission and receiving modes of IoT devices, respectively. The IoT may need to upload sensed data to network connected databases, exchange messages with other IoT devices, update the status etc. during transmit mode. In receive mode, firmware updating of IoT devices may take place, receive command signal or simply forward the received data. P_{data_sensed} is the energy consumption during reading of environmental data by the respective sensors. $P_{actuator}$ is the power utilized by a component to control other mechanism or system like a motor controlling a door latch. $P_{ambient\_loss}$ is the static power consumption of IoT devices and $P_{generated}$ is power gain that may be from methods like energy harvesting.

Management of power consumption in IoT is crucial as sensors deployed are battery powered and thus have limited operational life cycle. Accurate power models of IoT network is needed for the sufficient and effective power management. Data routing protocols and routing between source and destination are significant factors in power consumption. Power estimation approaches can be grouped in two categories [94]:

- Power measurement
- Power modeling

Power measurement approach is followed by usage of external measuring tool like monsoon power monitor. Power monitor tools give an overall estimate of power being used in the network but individual components consumption is not accounted. Modeling based method may use simulation tools like network simulator ns-2, PowerToSSIM etc. to account for power consumption [95], [96].

Mehmet Erkan Yüksel performed power measurement class of analysis for WiFi enabled ESP32 SoC IoT on micropython-programmable FiPy development board that can be configured in standalone or in slave mode. Network prototype created using WiFi IoT devices connected to internet and communication between them was established through router. Authors conclude that factors that impacts power consumption are hardware characteristics, application type, data-rate, data length, security protocol etc. Current drawn in different modes like active transmission, active listening, and idle mode were $180mA$, $97mA$, $60mA$, respectively. These power estimations have been taken at power supply of $3.3V$ and ambient temperature of 25°C [97].

D. ENVIRONMENTAL HAZARDS

The IP data flow management like processing, storing, or communication is carried out at data centers. Exponential growth in demand and internet users is pushing the data centers services to its limits. Figure 5 shows an estimated growth in internet data traffic, power consumption & workload of data centers between 2015 to 2021. Internet traffic in 2015 stood at 100 exabyte per month (Eb/M) and it is projected to be reach 519 Eb/M at compound annual growth rate of 31.58% [98]. Increasing growth of internet traffic, computational requirement, data storage and communication networks have fueled emissions in the environment. Cisco reported that global internet traffic tripled between 2015 to 2019 and projected to reach 4.2 zettabytes by the year 2022 from 100 Exabytes in year 2015 [100]. Energy information administration projected energy related CO_2 emissions from 35.6 billion metric tons in the year 2020 to 43.2 billion metric tons in 2040 [101]. Silicon and rare metals used in the manufacturing process of mobile phone is estimated to triple the carbon footprint by the year 2020. Also the most rapid contributor of emissions is data-centers. Carbon footprint has grown upto 5 folds in between the year 2002 to 2020 as every section in our modern IT enabled society is adding servers [102].

Large amount of data processing at ever expanding IoT network is the reason for ever increasing power consumption and consequently resulting in large quantity of diverse technological wastage's which results in negative impact on human's health and global environment. According to

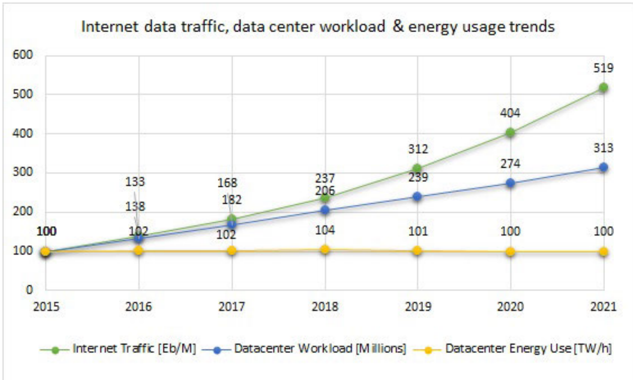

FIGURE 5. Global computing trends [99].

Cisco 2020 report on global networking trends, environmental sustainability poses a major challenge to the organizations as the world is continuously getting interconnected. Greenhouse gas emission, preservation of natural resources & biodiversity, reducing manufacturing waste as well as using recycled e-waste are going to be new benchmarks for the organizations [103]. Concept of green IoT (GIoT) is adopted to reduce carbon emission and power consumption to support development and sustainability of smarter world [15], [104].

III. GREEN INTERNET OF THINGS (GIoTs)

Primary objectives of GIoTs are to drastically reduce (CO_2) emissions, other toxic pollutants, environment conservation activities and reduction of power consumption in IoT devices [35], [36], [105]. Adoption of techniques to reduce power consumption in IoT devices will lead to healthier and greener environment [18]. Faisal Karim *et al.* defines GIoT as the "energy efficient procedures (hardware or software) adopted by IoT either to facilitate reducing the greenhouse effect of existing applications and services or to reduce the impact of greenhouse effect of IoT itself [19]. In the earlier case, the use of IoT will help reduce the greenhouse effect, whereas in the later case further optimization of IoT greenhouse footprint will be taken care. The entire life cycle of green IoT should focus on green design, green production, green utilization, and green disposal\recycling to have no or very small impact on the environment" [19]. Significant characteristics of the GIoT can be summarized as [16], [106]:

1) Power efficient hardware and software design techniques to reduce energy requirement in IoT based applications.
2) Adoption of improved encryption and decryption techniques with minimal data path.
3) Refraining from continuous data transmission avoiding data redundancy.
4) Eco-friendly techniques in manufacturing process of IoT devices.
5) IoT network powered by renewable energy sources as an alternative to conventional energy sources like fossil fuels.

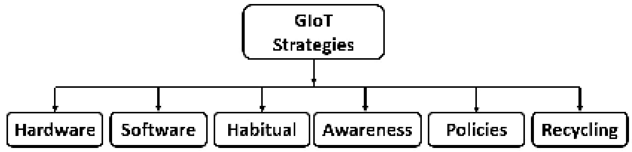

FIGURE 6. GIoT implementation strategies.

Implementation of GIoTs can be achieved using green RFIDs, green data-centers [18], [107], green sensor networks [108], green cloud computing [109], [110], etc.

GIoT implementation is achievable by adopting various strategies that can be widely grouped under classes as shown in Fig. 6. A detailed taxonomy of GIoT techniques is presented in [18].

1) EFFICIENT HARWARE IMPLEMENTATION

Hardware based GIoT enabling techniques can be classified into four groups [23], namely:

- Machine-to-Machine (M2M) technology establishes communication link between wired and wireless connected IoT devices and also plays an importance role in autonomous devices without human intervention [111]. Power efficient routing protocols during data transmission, cooperative techniques in the network, dynamic transmission power adjustment, inactive nodes pushed to sleep mode, interference minimization, energy harvesting are the few techniques employed to realize a green IoT.
- Wireless sensor network (WSN) is a network of sensor nodes that sinks into the BSs. A low power WSN performs tasks like scheduling, interference reduction, resources allocation, routing, and acts as gateway to local area network [112], [113].
  Two categories are defined for wireless networks, i.e. wireless local area networks (WLANs) and wireless personal area networks (WPANs). Higher data rates over a comparatively longer ranges are supported by WLANs whereas WPANs is preferred in lower data rate and short-range applications. LR-WPANs i.e. IEEE 802.14.4 is designed to support low cost wireless networking offering device level connectivity at lower data rate and power consumption. LR-WPANs are based on IEEE lower data rate standard, "Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low Rate Wireless Personal Area Networks (LR-WPANs)" [114]. Mammoth increase in IoT devices, applications and generated data is pushing for a new distributed computing models where network admins are expected to devise scalable and efficient automatic identification, classification, adequate application and monitoring of policies in addition to conventional connectivity and security services [103].
- RFID is an electronic tag that acknowledges identification request from the reader. There are two types of RFID tags depending on whether the battery is powered

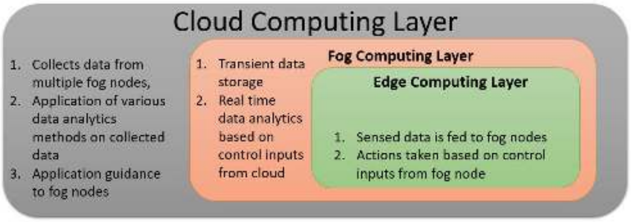

FIGURE 7. Illustrating cloud, fog, edge computing.

or not. An active RFID tag is battery powered and identified from or passive type RFID tags.

- Microcontroller unit and integrated circuit (MCU) is a standalone low cost processing unit.

Machine-to-Machine (M2M) technology

Cloud computing offers services like data computation, storage, and network management functions at centrally located data-centers. Geographically distributed billions of IoT devices present serious bottlenecks to cloud based data centers [115]. Cloud computing often fails to provide services to real time based applications, resulting in network congestion and increased latency in data delivery [116]. To meet such demands, Cisco came out with a concept of "Fog Computing" in Sept. 2011. Fog computing is an extension of the cloud based services layered between the cloud based data centers and the end devices leading to decentralization of data centers. Hence benefits of fog computing are support to real-time applications, lower latency, location awareness, supporting mobility, geographical distribution of services, low-power consumption, reduced network congestion, cost effective, reliable etc [117]–[119]. As shown in Fig. 7, edge computing refers to technology that enables data computation at network edge on downstream data as a cloud service whereas IoT services on upstream data [120].

Edge computing processes data at the source node itself instead of transmitting it to central server. It is advantageous in situations where connectivity is not possible due to remote locations, poor internet connectivity. Also, latency introduced due to long distance communication is negated in edge computing. Fog computing is a term coined first by Cisco in 2014 that brings cloud computing capabilities closer to the network. Fog computing is a decentralized model of distributing data, communication, storage and application in between end nodes and the cloud. Cloud computing is a computational technique where collection and processing of data is highly centralized. Sensor data is transmitted over internet to network of remotely located servers for storage or processing purposes. Hence cloud computing offers flexibility to access information remotely, analyze and take appropriate decisions. However, security concerns raise need for highly secure internet communication protocols which is typically cost intensive as compared to edge and fog computing. Energy consumption during a fog based service in response to a request N from an object is split in three parts [9], i.e.: (i) during request transmission on transport network, $E^{fog}_{Acs,N}$ (ii) during the processing and storage of request N, $E^{fog}_{prc-str,N}$ and (iii) fog communicates with cloud for service if needed, $E^{fog}_{fwd,N}$. Hence total power consumption is modelled using eqn. 2. Here $E^{fog}_{Acs2,N}$ is energy consumption in fog while responding back to object. β is the ratio of number of requests from nodes sent to cloud to total request to the fog i.e. $\beta = \frac{N_{sent}}{N_{total}}$.

TABLE 5. Symbols & corresponding description.

Symbol	Description
i	identifier used for cloud or fog.
K	request size in bytes, N.
R	response size in bytes.
$E^i_{network}$	E^{fog}_{edge} or E^{Cld}_{core}.
E^{fog}_{edge}	energy in joules during a byte of data transmission within the edge network.
E^{Cld}_{core}	energy in joules during a byte of data transmission between node & cloud.
U	utilization factor.
C^i_{idle}	average idle capacity of network in bytes/sec.
C^i_{max}	average maximum capacity of network element in bytes/sec.
P^i_{idle}	idle power of network element in kw.
P^i_{max}	maximum power of network element in kw.

$$E_{fog} = E^{fog}_{Acs,N} + E^{fog}_{prc-str,N} + \beta * E^{fog}_{fwd,N} + E^{fog}_{Acs2,N} \quad (2)$$

Energy consumption model of a cloud based service is presented in eqn. 3, comprising of two components. Here, $E^{cld}_{Acs,N}$ is the energy consumption in transport network between the requesting node and cloud data center, energy consumption in the cloud is $E^{cld}_{prc-str,N}$, whereas cloud communicates with the requesting node consumes energy as $E^{cld}_{Acs2,N}$.

$$E_{cld} = E^{cld}_{Acs,N} + E^{cld}_{prc-str,N} + E^{cld}_{Acs2,N} \quad (3)$$

Energy consumption by the routers & switches connecting nodes and fog called as access energy is shown in eqn. 4. Notations used in this expression is shown in Table 5:

$$E^i_{Acs,N} = k * E^i_{network} + k * h_i * (\frac{P^i_{idle}}{C_{idle}} + \frac{P^i_{max}}{U * C^i_{max}}) \quad (4)$$

Assuming $E^i_{pr-str,N}$ & E^i_{store} represents average energy consumption during processing and storage of a byte of data, then total energy during data processing and storage in fog is given by eqn. 5.

$$E^i_{pr-str,N} = k * E^i_{process} + K * E^i_{store} \quad (5)$$

where,

$$E^i_{process} = P^i_{idle} * \frac{T_N}{T_{tot}} + P^i_{max} * \frac{T_{act,N}}{T_{tot}} \quad (6)$$

Energy consumption due to transmission from fog to cloud is modelled using eqn. 7.

$$E^{fog}_{fwd,N} = k * E^{fog}_{core} \quad (7)$$

Power optimization: Transmission energy can be minimized by optimization of data compression techniques [121],

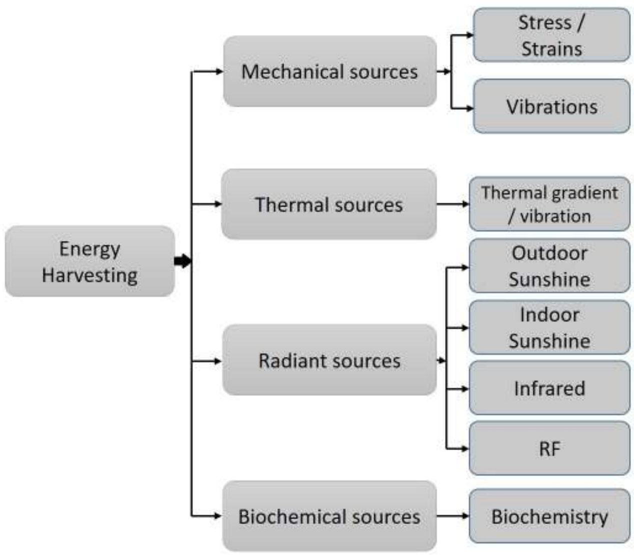

FIGURE 8. Energy harvesting sources [128].

spatial correlation between the IoT sensors is exploited to suppress redundant data and reduces channel access contention [122], the dependence of correlation characteristics of sensors on other sources of a network play significant role in BS scheduler for resource allocation [123]. Battery powered IoT devices may not be a feasible due to their shorter lifetime, higher maintenance cost and serious environmental concerns as it turns out to be major contributor to e-waste. Fig. 8 lists multiple energy sources that exists in nature like radiation, light, mechanical displacements, thermal gradients etc., used to harvest sustainable energy [124], [125]. Energy harvesting from RF signals is preferred choice in recent times as it can act as continuous source of energy as well as data carrier. Other energy harvesting resources like wind, solar, vibrations, thermoelectric effect etc., used in power up of IoT devices are less preferred compared to RF signals due to their energy variations related issues [126]. RF sources not only can be one of the energy sources for energy harvesting, but also stimulate the development of RF-MEMS based energy harvester was developed by Sudou *et al.*, utilizing RF induced power supply suitable for IoT sensor nodes. They demonstrated RF-electromagnetic wave of a mobile phone used in generating DC voltage through a rectifier circuit within an antenna [127]. In addition to energy harvesters there is a need to develop efficient energy converters as most of the IoT based energy harvesters are standalone micro power devices generating only few millivolts of power.

Communication protocols: Razvan *et al.* mentioned that the location of the nodes in a network is not fixed in advance, and optimally placed in the network to minimize various resources such as power [129]. Combined optimization of optimal rate allocation and transmission structure will lead to reduced transmission power in the WSN [130]. Chang *et al.* presented measure of information loss distortion occurred during reconstruction of non-transmitted sensing node due to data correlation [131].

Power saving mechanisms: Cognitive radio (CR) functions are capable of achieving power optimization [132]. Scheduling techniques like selectively switching the inactive sensor nodes to low power modes. Temporal and spatial redundancy utilization and cooperative security mechanism results in power saving [133]. Medium access control (MAC) layer protocol for adaptive energy-harvesting technique was developed by [134] achieving higher throughput and lower transmission delay.

Scheduling: Device management technique at gateway level is presented to remove heterogeneity among sensing nodes, and dynamic auto configuration with third party IoT platforms [135]. Access control algorithms for sensor devices with BS through grouping and coordinator selection means are adopted to improve upon energy efficiency [136].

Wireless sensor network (WSN)

Radio optimization: Chu *et al.* introduces cooperative topology control with adaptation (CTCA) in a wireless multi-hop network scenario that enables power adjustment at every node [137]. Power consumption in a MIMO system can be more as compared to single input single output (SISO) systems due to large transceiver circuitry and physical size limitations at sensor nodes. Hence, in short range applications with fixed data rate and modulation scheme, it was observed that SISO offers better performance as compared to MIMO based system [138]. In an un-coded wireless network, optimization of transmission time and modulation parameters can result up to 80% power savings in comparison to non- optimal system [139].

Sensor nodes activity: Reducing the number of active sensor within the area of interest will mitigate problem of data redundancy as well as improving network coverage. Misra *et al.* proposes network coverage algorithm by selectively activating subset of sensor nodes with minimal overlap area and hence minimizing energy consumption [140], [141]. Synchronous and asynchronous duty cycling (fraction of time when nodes are active) technique at sensor nodes like preamble sampling also known as low power listening (LPL), receiver initiated transmission, on demand wakeup, random duty cycling, schedule based methods promises energy saving and consequently increase devices lifetime [142]. Duty cycle learning algorithm (DCLA) can dynamically alter duty cycle during run time results better power efficiency without compromising on data integrity [143].

Powering of sensory nodes: Energy harvesting using unconventional energy resources like solar, thermal, wind, etc. and efficient energy management techniques at protocol level are emerging means of handling power needs at sensor nodes [144], [145]. Wireless energy transfer mechanism using electromagnetic (EM) waves virtually offer active sensing nodes throughout their operational life [146]–[148].

Routing protocols: Kumar *et al.* presented cluster-based routing protocol offering advantages like scalability and efficient communication. In a hierarchical network, processing is being carried out at higher energy nodes and data sensing at lower energy nodes [149]. A uniformly distributed sensor nodes in a multi-hop clustering network model, clusters head near sink (e.g. BS) will experience high data traffic and hence creates "energy hole" problem. Li et.al. proposed an unequal clustering technique to minimize the energy requirement at individual sensor nodes [150], [151]. Localized multipath routing protocols were proposed for WSN that is intended to balance load by distributing data traffic over multiple paths [152]. Efficient deployment of relay nodes in WSN with constrained node locations is considered as multi-objective (MO) optimization problem and addressed using Artificial Bee Colony (ABC) algorithm [153]–[155].

Data aggregation algorithms minimize redundant data transmission to BS using fusion of data collected from multiple nodes. Hence, this reduces number of data transmission needed for data collection and subsequently improves energy saving [156], [157].

RFID

Mitigating overhearing problems: A reader initiates an interrogation of RFID tags by sending a wakeup signal to its surrounding which results in multiple surrounding tags comes out of their sleep mode. All unintended tags continue to remain in active mode until they receive a sleep command from the reader and hence, contributes in energy consumption known as overhearing problem. To mitigate such energy wastages, a tag should be aware of time and duration of its effective communication in advance. Reservation Aloha for No Overhearing (RANO) protocol is proposed to avoid such energy consumption [158].

Anti-collision protocols like Aloha and tree mitigates simultaneous tag responses in order to avoid collisions leading to wastage of bandwidth, energy, and identification delays [159].

A Wireless identification and sensing platform (WISP) based passive RFID sensor node was developed for the implementation of radio wake-up technique. Simulations under different operating conditions were carried out to establish stability of wake-up radio in open environment [160].

Adaptive transmission power control (ATPC) based power control algorithm is developed that establishes correlation between transmitted power and link quality. Such feedback-based power transmission control algorithm is capable of dynamically maintaining link quality over time [161]. Transmission power control with Berkeley MAC (B-MAC) protocol under various operating conditions like variable distance between nodes, simultaneous transmission reports energy saving up to 57% [162].

*RFID reader*s encounters situations where multiple tags simultaneously transmit their respective IDs in response to its interrogation signal. Anti-collision protocols like Aloha or binary tree search [159] doesn't guarantee on reading time due to their probabilistic nature or results in higher energy consumption due to multiple queries and responses. Three novel anti-collision protocols namely Multislotted (MS) scheme, Multislotted with Selective Sleep (MSS) scheme and Multislotted with Assigned Slots (MASs) scheme [163] offer better energy saving at both reader and active tags compared to query tree protocols.

Successive film deposition of lithium cobaltate $LiCoO_2$, lithium phosphorus oxynitride (LiPON) and tin dioxide SnO_2 is used in fabrication of batteries. Thinfilm solid-state batteries offer benefits like extended life cycle and non-toxic in nature. These batteries support the integration with thermoelectric scavenging from human-body without compromising on comfort, and maximizing the thermoelectric conversion [164].

antennas with battery-supported RFID tag with a thin and flexible film battery is designed. Battery influence with antenna is avoided by placing the battery on some part of the antenna [165]. Solar powered WSN architecture is proposed with a hybrid energy storage scheme. Here the WSN comprises of three main modules i.e. energy harvesting, energy storage, and control voltage processing unit. Power management module of developed hybrid storage system comprised of battery and Low-Equivalent Series Resistance (ESR) ultra-capacitor [166].

Microcontrollers

Spotting a unique object from image and efficiently extracting features information is an important requirement for surveillance based applications. Object recognition processors in place generally use single classifier instead of multiple classifiers (MCSs). However, multi-classifier systems (MCSs) deliver more accurate pattern recognition along with higher robustness in decision making in extreme conditions like noisy scenario. Park *et al.* developed multi-classifier multi-core processor with hierarchical model and X (HMAX) and scale invariant feature transform (SIFT) descriptors on a single integrated chip. This approach offers better results in complicated or camouflaged targets, accurately identify blurred or very small size objects and use context aware feature. This processor is implemented on 0.13μm 8-metal CMOS technology with die area of $25mm^2$ and gate density of 1.8M with 200KB on chip SRAM. Integration of 21 IP cores collectively consumes 260 mW power at an average clock speed of 200 Mhz [167].

Single instruction multiple data (SIMD) permutation engines integrated with power-constrained processors or system on chips (SoC's), needed to perform at nominal as well as ultra-low supply voltages. Hsu *et al.* proposed a re-configurable SIMD vector permutation engine, implemented on 22nm tri-gate bulk CMOS device. Throughput improvement of 25% to 42% and power saving of 40% to 53% reported [168].

Wireless body sensor networks (WBSNs) are the enabling communication technology in the realization of IoT base smart health monitoring system. Multiple light weight sensors are attached to human body and each sensor node is capable of processing a definite low rate physiological signal. Comparative analysis of implementing a health monitoring system on single-core and a multi-core processor architecture was carried out. Power vs. performance analysis for a multi-lead electrocardiogram signal shows that the multi-core processor architecture consumes 66% less power for high computational needs(50.1 MOps/s) and 10.4% more power in low computation needs (681 kOps/s) [169].

Single-board computer (SBC) is a full-fledged computer system built on a single circuit board, with microcontrollers / microprocessors, RAM/ROM memory, input/output (I/Os) and features like operating system. Sensors in an IoT network need significant processing/computations on sensed data but limited locomotion. Single-board Microcontroller (SBMs) are suitable for this task operating generally in slave mode. The SBMs are utilized in commercial and industrial applications due to various types of interfacing capabilities like serial bus interface, Ethernet, USB, etc. Arduino is one of the widely used SBM with different flavors like Arduino Uno, Arduino Mega, and Arduino Mega 2560 to match the suitability with specific applications. the most popular SBCs in present time are Raspberry Pi and Banana Pi. Raspberry Pi 3 B, powered by ARM Cortex-A53 1.2GHz CPU is superseded by Raspberry Pi 3 B+ running on ARM Cortex-A53 1.4GHz CPU. Wi-Fi capability stands at 5 Ghz data transfer support and Ethernet support up to 300 Mbps [170]. Typical power consumption in a Raspberry Pi 3 model is 700 mW and arduino uno R3 consumes upto 175 mW.

The IoT contributes significantly in big data explosion and future computer systems design. Data movement is identified as one of the major contributors to energy dissipation among all classes of microprocessors. Recent three dimensional (3D) die-stacking reduces chip-to-chip communication but poses limitations with larger workloads distributed across multiple chips. Hardware accelerators have been proven to be energy efficient and supports high computational speed over general purpose processors [171].

Among various embedded system design platforms, field programmable gate arrays (FPGAs) based platforms borrow best from application-specific integrated circuits (ASICs) and microcontrollers (MCUs) world. FPGAs offer highly parallel processing capabilities leading to higher performance like ASICs as compared to MCUs, and run-time reconfigurebility using partial or dynamic reconfiguration methods, providing better flexibility when compared with ASICs. In recent times, FPGA integrated embedded (hard or soft) processors cores into their existing architecture known as Field-Programmable Systems-on-Chips (FPSoCs). FPSoC are suitable implementation alternative to low-end IoT sensor nodes, as they offer advantages like scalability, flexibility, versatility, higher performance, low power solutions and secure infrastructure [172].

Reduced power consumption and better computational performance are main design goals of IoT applications. Kiat *et al.* presents a reconfigurable reduced instruction set computing (RISC) processor to meet design goals of IoT applications. The FPGA based processor can be reconfigured into either multi-cycle execution mode or pipeline execution mode depending on dynamic workload requirement of IoT applications [173].

2) GREEN SOFTWARE DESIGN

If the consumption and impact on environmental resources due to the deployment of a software is accounted and optimized then such software's called green software [174]. Green software aims to reduce energy consumption by adopting green design principles in software intensive systems. Orchestration Agent (OA) is installed on individual devices at client site to optimally select servers based on their energy consumption profiles [175]. A significant amount of energy can be saved during idle status of sensors by switching them into ON, pre-OFF and OFF power modes through implementation of energy efficient scheduling algorithms [21]. Scheduler allocates tasks to capable resources at a specific time. Most common scheduling problems have four basic issues i.e. (i) Resources – refers physical or logical devices (ii) Tasks – operations that resources execute (iii) Constraints – refers to conditions that are considered before assigning task to resources (iv) Objectives – are the evaluation criterion for the schedulers [37]. In a distributed environment, scheduling is categorized into three major groups i.e. resource, workflow and task scheduling [176]. There are two class of methods used to solve scheduling problems: exact methods and heuristic method. An optimal solution to a scheduling problem is found in exact method whereas heuristic method does not guarantee for an optimal solution but takes less time. Energy optimization in cloud & fog computing networks is achieved mainly due to scheduling algorithms. Energy consumption of a data center can be reduced by increasing the number of idle hosts by pushing them into sleep / low power mode. Hence a scheduling algorithm is required to achieve a maximum number of idle hosts & prioritize already in use hosts over those in sleep mode. A scheduler in a fog network will require additional constraints in order to keep processing at fog layer instead of cloud to reduce latency [177].

Data centers have an important role to play in realization of energy efficient IoT network [178]. Energy efficient context-aware broker (e-CAB) algorithm developed by [175] utilizes an orchestration agent (OA) in a client-server model and responsible for context evaluation at server levels. As an overhead, the OA is required to be installed at each client device and servers to meet reliability targets but results in elevated energy consumption. Charith *et al.* proposed a context-aware, specific, location aware and activity aware mobile sensing platform called context-aware mobile sensor data engine (C-MOSDEN) that used selective data sensing to offer better energy efficiency [179].

An energy efficient algorithm with sole purpose of scheduling duty cycle of sensor nodes is presented by [180]. The proposed scheduling algorithm has three different operational stages i.e. on-duty, pre off-duty and off-duty. In an on-duty mode, sensor device will perform regular operation like sensing, receiving and data transmission. Hence, devices will function as relay or sink node and data processing is moved to virtual environment on cloud. Pre off-duty state follows on-duty state where devices move to idle state for

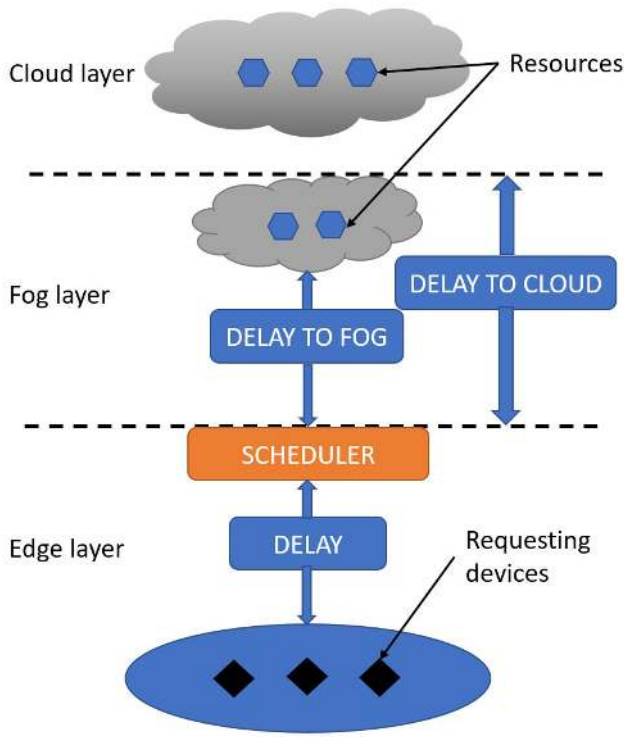

FIGURE 9. Scheduler in a fog & cloud computing [37].

finite time. The device can switch state to either on-duty or off-duty state from pre off-duty state. Here, a device can receive or transmit only certain commands from the sink node to change the state to on-duty or off-duty states. Off-duty state presents three further states - hibernate, sleep, and power off as an energy saving mechanism under different circumstances. An overhead of this proposal is requirement of embedded server with redundancy to meet server failure conditions.

Data centers in WSN offers flexibility in integration of renewable energy resources due to their flexibility in workload. Hence, renewable energy generators powered data centers can drastically reduce energy cost as well as carbon footprint. A framework for workload distribution among data centers with renewable energy generators is proposed by [181]. The design was meant to continually monitor the number of service request waiting at data centers queues.

An energy efficient mixed integer linear programming (MILP) model is proposed to design cloud computing platform for IoT networks. It consisted of four layers in which lowest layer comprised of IoT sensor devices. The networking elements like relays, coordinators and gateways form remaining three layers. The task of data aggregation and data traffic management is performed by networking elements whereas data processing is managed by virtual machines (VM) present at networking elements. Number of mini clouds hosting VMs, their location in the network is optimized for power consumption up to 36% [182].

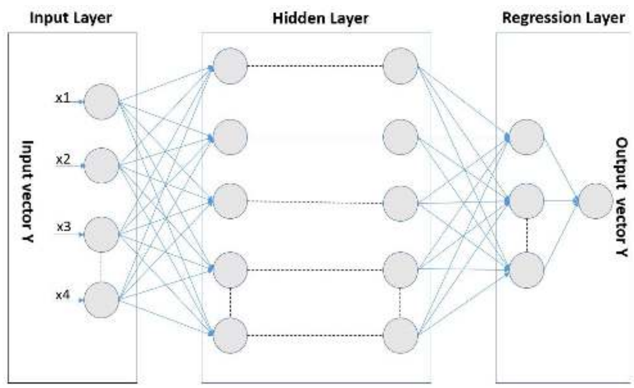

FIGURE 10. Neural layer network at fog layer [188].

Liu *et al.* presented Gemini, a green deployment scheme for IoT with characteristics like hierarchical approach for system framework in IoT deployment, optimized green model of proposed system framework and optimal energy consumption model. Analytical results proved that dynamic routing mechanisms in WSNs are not feasible in outdoor application due to electromagnetic interference, air humidity, elevated operating temperature. Therefore, IoTs should be configured using static routing mechanisms in a hierarchical structure [183].

Cooperative communication between wireless sensor nodes is established using opportunistic large array (OLA). OLA is a cluster of nodes in a network that follows active scattering mechanism in response to source node. In cooperative transmission, nodes with signal to noise ratio (SNR) above a threshold is selected by OLA. The benefit of proposed algorithm claimed by [184] is that the information about sink node is not needed and high transmission energy at source nodes is not required. The approach suits to health care applications needing continuous monitoring and energy saving upto 57%. Google AI introduced another version of machine learning known such as federated learning (FL) in 2017. It exploits federation between fog and cloud offering enhanced data collection, processing and storage without using centralized training data. Here ML model generation is carried out at nodes generating data under the orchestration of a central coordinating server (e.g., a cloud server). The original data never leave the edge devices in FL mitigating privacy issues as well as cost involved in traditional, centralized machine learning.

3) ARTIFICIAL INTELLIGENCE (AI) ENABLED COMPUTING

Artificial Intelligence (AI), have emerged as potential driver in optimizing energy resources and machine learning (ML) is fueling growth of IoT services [185]. AI have capability to mimic like human mindset and ML models can identify patterns from randomly acquired data [186]. Hence, localized AI in edge computing will filter data and only relevant data gets transmitted to cloud. This results in substantial savings in terms of bandwidth and cost of data transmission. In summary, edge AI computing offers benefits like (i) reduced latency (ii) localized filtering of unwanted data (iii) higher uptime as data processing can take place without network connectivity and (iv) predictive approach in troubleshooting [187]. Adoption of edge computing can be attributed to AI where machine learning (ML) algorithms trained at cloud are employed to deliver local compute, storage and processing capabilities to IoT networks. The arrival of new, purpose-built hardware accelerators running ML models at higher speed and lower power level assist the CPU of edge devices. Examples of Edge AI-enabled devices include video games, smart speakers (e.g., Alexa, Siri), drones, surveillance cameras, and wearable health monitoring devices etc. Fog computing processes requests from user nodes and distribution network (DN) providers, and thereby helps to reduce work load of cloud computing and improved latency. AI modules deployed at the fog layers can be very effective in pattern recognition and machine learning with increasing amount of data. As shown in Fig. 10, regression analysis is performed using learning & training on sampled data in neural network layer. In this way regression analysis helps to understand data pattern and behavior of end users. Service providers utilizes such regression results to predict and manage load in an optimal way [189].

Machine learning (ML) is used for the implementation of AI using data parsing algorithms. Deep learning (DL) technology is used for the realization of ML whereas reinforcement learning (RL), is an evaluation learning technique in ML [190]. Security related issues in IoT devices is addressed using ML within an IoT gateway [191]. Canedo *et al.* proposed artificial neural network (ANN) based ML gateways monitoring subsystem components in an IoT network whereas state of entire system was monitored using ANN at application layer [192]. There are three commercially leading AI accelerators/platforms available for edge computing tasks: NVIDIA Jetson, Intel Movidius & Myriad Chips and Google Edge TPU. NVIDIA have Jetson family of GPUs specifically designed to suit requirement of the edge. They are 100% compatible with their respective enterprise data center partners. These GPUs have fewer cores and hence power consumption is minimal as compared to traditional GPUs that powers desktops and servers. Movidius a niche chipmaker of computer vision processors was acquired by Intel. The flagship product of Movidius was Myriad, a chip used for image processing & video streaming in surveillance products. Similarly, Google have Tensor Processing Units (TPUs) integrated to its cloud platform to accelerate machine learning workloads.

Integration of AI with IoT promises multiple benefits that can result in IoT data efficiency, but there is also challenges that needs to be answered for the successful convergence of IoT with AI like (i) complexity due to coordination issues related with IoT constraints like processing power, memory, and delay in real time applications (ii) heterogeneity (iii) security & privacy concerns in an wireless environment (iv) standardization related concerns like interoperability of IoT with AI integration (v) accuracy & latency issues in real time application. Conventional IoT network was based on centralized client-server model. However, such model limits expansion of IoT system and hence decentralization is the preferred choice to meet future expansion needs. Blockchain have emerged as a suitable decentralization platform with distributed database and available to participating parties in a network. IoT integration with AI & blockchain will able to handle billions of data transaction between devices resulting in significant cost reduction of maintaining larger centralized data centers.

Kim *et al.* proposed energy-efficient dynamically accessing of data packets from medical cloud to medical IoT devices via wireless access points. Energy efficient dynamic buffering algorithm estimates power allocation to the access points on the basis of buffered backlog and channel state. The proposed algorithm self-calibrates parameters that is used for adaptive energy management of the network [193].

Peng *et al.* proposed energy policy description language, called EPDL and guiding parameters in defining power control policy for smart buildings. A collaborative effort between humans and smart building systems proves to be vital in energy efficient system. Open web services are used in access and control of devices on the network. EPDL is claimed to be user friendly in defining energy management policies for building energy management system (BEMS) with limited information about smart building's and programming in limited time. The EPDL includes simpler programming constructs based on device control rule description language (DCRDL) [194].

Alvi *et al.* mentions data management of multimedia data is overlooked in IoT system networks also known as "multimedia things". Increasing development of multimedia based applications like online video conferencing, games, etc. have been limited due to scalar sensor based IoT network systems. Therefore, an improved routing protocol for low-power and lossy networks (RPL) is proposed for internet of multimedia things (IoMT). The proposed RPL protocol is expected to reduce carbon footprint and energy consumption. The voice over internet protocol (VoIP) typically experiences a delay of 120 ms whereas delay in video transmission varies due to metrics like video resolution, data rate, variable packet size. Proposed routing algorithm considers quality of intermediate nodes in between the source and sink in terms of already consumed energy and their potential to support further traffic [195]. IoT sensor nodes feeds enormous amount of sensed data to the network, however, conventional means of individually connecting sensors to applications are not feasible. A context aware computing as a middleware understands sensed data and used to determine which information and services is provided to the user. Dey defines context aware system as "A system is context-aware if it uses context to provide relevant information and/or services to the user, where relevancy depends on the user's task" [197]. A six-layer sensor network based on device capabilities is proposed by Perera *et al.* as shown in Fig. 11. Capability is the data processing, data communication, memory, energy, etc. at each layer and it increases from low-end sensor node to cloud.

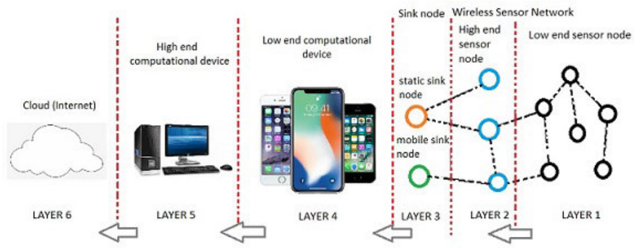

FIGURE 11. Layered structure of a sensor network [196].

Context processing cycle have essentially four phases: acquiring data from possible sources, data modelling based on underlying context, processing modelled data at higher context level and distributing collected data to intended users [196].

A real time power management and resources allocation technique of cloud based data centers with minimal data latency is proposed by Mehmood *et al.* Algorithm to estimate power demand of data center and the cooling systems is proposed. Energy cost of a community and cloud based data center powered using green energy results in 15.09% cost saving. Proposed cloud based model establishes communication link with power consumers on a 4G and 5G network [198].

Sakai *et al.* proposed energy-efficient unicast (EEU) and reliable unicast (RU) efficient routing protocols between communicating nodes as well as energy model of energy consumption at individual nodes. Energy consumption at nodes depends on software processes involved in transmission and reception of messages and number of attempts undertaken during transmission. Ad-hoc on-demand distance vector (AODV) protocol is used as shortest path between the communicating nodes and probability of successful delivery of messages on a path is determined using RU protocol. The EEU protocol finds a route with minimal energy consumption at nodes in between source and destination. The delivery probability and energy consumption for finite number of nodes is reported as shown in Table 6. Minimal energy consumption using EEU protocol and higher delivery probability using RU protocol is achieved [199].

Topic-based data transmission (TBDT) protocol is evaluated on mobile PS (publish\subscribe) Fog computing model (MPSFC) by Saito *et al.* Data traffic on IoT network and servers can be reduced using an event driven context aware distribution system. Simulation results established reduced data traffic in TBDT protocol with smaller delivery ratio [200].

Said *et al.* proposed an energy management scheme (EMS) for IoTs with heterogeneous energy-constrained nodes. Among three strategies adopted here, first strategy is to reduce volume of transmitted data in IoT network, second is work scheduling at IoT nodes and finally provision of fault tolerant IoT nodes. Sensors node data is one of the major factors in energy consumption due to processes like data gathering, data processing, data transmission etc. Data minimization process at each node is unique as each class of nodes have associated functions like data prioritization, data compression, and data fitting. Here data fitting processes refers to data gathering and transmission, data compression means data processing and transmission, and data prioritization is responsible for data gathering, processing and transmission. Queuing theory is used in the EMS to handle the IoT network congestion scenario. Data scheduling reduces energy consumption by delaying the node processes using issues like present energy level, energy source, alternate nodes, heterogeneous energy level nodes, significance of node, period of a particular task or location of node. Fault tolerant strategy replaces a node with an alternate one in case of energy failure of nodes. The IoT sensor nodes were classified into different levels based on their importance and fault tolerance strategy is adopted based on node levels. Average energy consumption rate, number of nodes failing, data throughput and network lifetime were used as a performance metrics to benchmark proposed EMS [201].

TABLE 6. Simulation with varying # of nodes [199].

Path	Energy Consumed			Delivery Probability		
Nodes	RU	AODV	EEU	RU	AODV	EEU
11	2.4J	2.4J	1.75J	0.9	0.8	0.86
13	2.6J	2.5J	1.95J	0.89	0.79	0.85
15	2.8J	2.6J	2.1J	0.88	0.77	0.84
17	3.15J	2.75J	2.2J	0.87	0.74	0.83
19	3.45J	2.9J	2.4J	0.86	0.72	0.82

4) HABITUAL PRACTICES

Some basic habitual changes can help to achieve energy efficiency and consequently reduce carbon footprint. This is a small-scale measure in achieving greening of IoT but adding up at global scale makes a significant difference [178]. Like every technology, IoT technology too have certain drawbacks as it has potential to change our life styles and habitual practices. IoT technologies have increased the utilization of certain raw materials considered either scarce or precious. Cost of electronic devices as a part IoT nodes has become affordable to users leading to increased production volumes and utilization of resources [202]. Household energy demand in developed countries is projected to grow multi-fold in coming years due to improved living standards among citizens and their increased dependence on electricity powered appliances [203]. Monitoring energy consumption in households is important for factoring out consumer's behavior. Technology based applications based on consumer behavior can be deployed to improve energy efficiency [204]–[206]. A series of actions undertaken due to individual habits can be called as habitual behavior. A habitual behavior cycle through three distinct stages called as "habit loop" such as the cue, routine, reward, and back to cue [207]. A cue is a trigger that causes brain to move in autopilot mode. Routine is a physical, mental, and emotional action taken by an individual which results in reward. A reward is a satisfaction due to routine completion and potential chances of repeating the habit cycle [208]. Table 7 lists some of the behavior models reviewed by [209] while proposing a framework for exploiting micro

TABLE 7. Common habitual behavior change models.

Model	Description
Transtheoretical model [210]	Motivational psychology literature is synthesized to develop a motivational framework. Motivational goal(s) at each stage is defined and recommendation(s) were made to achieve these set goals using technology.
Dynamical perspective for habit prevention [211]	Dynamical perspectives drawn on processes that can play a role at a particular stage in the development of a habit.
Model-based reinforcement learning [212]	Study suggests a model-based valuation system leveraging on goal directed behaviors like changes in action-outcome contingency and sensitivity to changes in the value of the outcome itself.
Motivational interviewing (MI) [213]	The MI defines a way within underlying challenges by an arrangement of conversation so that people can talk themselves to change.
Reasoned action approach [214]	Humans social behavior is predictable and understood using finite set of constructs limited to particular domain.
Delivering behavior change based on habits [215]	Triggers a behavior change to modify a habit which is based on the classification of habit and extent of deviation from the habit.

moments and mobile recommendations that aimed to advance evidence based, technology-enabled energy efficiency recommender systems.

5) AWARENESS

A real-time energy consumption awareness to homeowners through a dedicated channel like display, website and messaging, have proved effective in reducing consumption by 6-10% [216]–[219]. However, researchers were critical about the reported reduction in energy consumption and argued that smart grid technologies now able to sample larger data size and conclude upon large-scale conservation through a real-time feedback stands at 3–5% [220]. Type and mode of feedback means adopted defines its effectiveness on energy saving mission. A direct feedback mechanism can be web portal update, direct meter reading, dedicated or real-time displays whereas indirect means may be accurate, frequent and detailed bill delivered to consumers. European framework initiative for energy and environmental efficiency in the ICT sector recommends action plans for creating awareness among various stakeholders of the society is tabulated in Table 6 [221].

Proper planning and synchronous set of activities in energy awareness campaigns are effective means of creating awareness among users and encourage energy saving practices. Energy awareness campaigns at schools using aids (i.e., placards, videos, displays, posters, and awareness themed games) create awareness among students. Awareness activities in office environment involve advising employees to practice energy saving, encourage employees to identify energy saving areas, energy awareness posters in office building, etc. Real time data from IoT sensors supports reliable statistics that can support the campaign and collect participant's feedback for betterment of future campaigns [222].

TABLE 8. Recommendations for raising awareness.

Targeted Community	Recommendation Examples
Technical professionals	Training professionals in green ICT skills (such as the hardware, software, and network level) and practices across different consumer's sector on making ICT more sustainable. Creating awareness on implementation & benefits of green ICT, cooperative approach among experts from cross-sectors.
Academicians & Scholars	restructuring curriculum and including courses on green ICT at university level programs or courses.
Public administration	Capacity building and encouraging frontrunners in designing and implementation of green ICT procurement practices, adopting green ICT policies.
Citizens	Promotion programs about green ICT lifestyle and how behavioral changes can bring financial benefits.
Future generation	Educating younger generation about importance of adopting sustainable lifestyle like green ICT. Importance of circular economy and how to reduce energy consumption. By educating and creating awareness in younger generation from their childhood will result higher-value in future and appreciating it as life learning process.

As IoT is gradually becoming ubiquitous in society, need for more disciplined and engineering oriented approach on generation, delivery and usage of IoT based services is needed. As services covers range of diverse activities like healthcare, logistics, utilities, financial & public services, education etc., the challenges associated to these sectors need more than just efficient solutions. Service science, also known as service science, Management, and Engineering (SSME), has emerged as a discipline conceived to support service industry. The social science flavor induces understanding of cost and benefit and encourages users to suspend or defer the services at the times of peak demand whereas a management approach may introduce dynamic pricing for the services being used.

6) POLICIES

Real time data generated on the IoT network helps in developing policies and strategies on saving energy at larger scale. Energy efficient system is built by proposing policies for various stages of IoT implementation like monitoring, sensed data management, user feedback and automation system. Behavioral differences of habitats in a building cause variation their respective energy consumption. Such data can give insights in development of policies & strategies for different parts of the same building [18]. With a mission to identify underlying drivers of energy consumption in buildings, International Organization for Standardization (ISO) have their own in-house technical expertise groups to recommend necessary actions in building energy efficient automation and control systems. A predictive model of energy consumption on the basis of usage data, climate data and building architecture helps in design of various energy saving approaches.

However, a robust characterization of energy usage is felt for buildings due to rapid growth in real-state sector in last few decades. Buildings have distinct energy usage profile based on purpose for which it is used for and activities carried out. In residential buildings energy consumption is due to indoor activities whereas factory buildings have energy consumption attributed due to machinery and processes in place. European committee for standardization (CEN) EN15251 standard proposes policies for energy management in buildings due to indoor environment parameters like (temperature, ventilation and lighting) and building (including systems) design and operation [223].

7) RECYCLING

The process of extracting a component material and processing to recover the same raw material or degraded material is known as recycling [224]. Natural resources available on earth like copper, silicon, plastics, few other non-biodegradable elements are used in manufacturing of mobile phones. Most of the IoT devices are built using harmful chemicals & elements like lead, mercury, cadmium, beryllium and brominated flame retardants. Next generation electric cars poses threat to the environment due to large size lithium ion batteries in place [225]. The UN reports global e-waste generated in the year 2016 was 44.7 million metric tons and estimated to grow up to 52.2 million metric tons (Mt) by the year 2021. A significant amount of tiny devices like trackers and wearable devices gets discarded once their battery drains out. Devices manufactured using precious and toxic materials should be designed with keeping the recyclability and sustainability in mind to keep check on e-waste generation [226].

Recycling process of electronic waste involves five distinct stages: e-waste collection, toxic removal, preprocessing, end-processing and discarding. Implementation and management of these stages vary globally like e-waste collection may be carried out by ''waste-pickers'', voluntarily or compulsorily ''take-back'' programs by the manufacturers. Harmful parts, such as batteries, are removed during toxic removal stage followed by dismantling and sorting of homogeneous group of materials. In next stage, homogeneous group of materials (i.e. gold, copper, plastic etc.) undergoe chemical treatment or metallurgical process. Components that cannot be sold or reused is discarded using incineration or landfill [227].

From Table 9, we conclude that highest quantity of waste in 2016 was generated from Asia, at 18.2 Mt, or 4.2 kg per inhabitant (inh). However, 2.7 Mt of e-waste went through recycling process too. Oceania stands highest per inhabitant average at 17.3 Kg/inh and recycles 6% of e-waste, i.e., 43 kilotons. Steep annual growth in the quantity of e-waste being generated globally resulted in establishment of time-bound issue management group (IMG) by UN environment management group (EMG) in the year 2016. The IMG aims to strengthen the cooperation and coordination between member states of the UN in promoting eco-design policies [229]. Globally, a totally of 67 countries have policies by legislation to effectively manage e-waste collection and recycling. Several conventions exist at regional and international levels, i.e., Basel convention, to regulate export of e-waste to developing countries [228].

European framework initiative for Energy & Environmental efficiency submitted policy related suggestions for IoT sector. Examples of recommendation are:

- Tax benefits: Anyone who adopts manufacturing to adoption of GIoT products or services should receive lower taxes. On the contrary higher taxes should be levied on non-sustainable products.
- Circular economy: Recycling and reuse targets through legislation on ''design to be repaired'' rather than dumping & buying new.
- Specific priorities: Priorities should be well defined and specified for each IoT dimension. Unique targets and specifications should be hardware, software, network, or data centers.
- Awareness campaign: Promotional activities & mass campaigns on consumer habits based on sustainability level rather cheaper prices.
- Carbon reporting: mandatory reporting on carbon footprint by manufacturers especially by small & medium enterprises (SMEs) for accurate and close control of carbon consumption.

IV. OPEN RESEARCH ISSUES AND CONCLUSION

A. OPEN RESEARCH

The heterogeneous nature of IoT technology, clouds, and network protocols are designed and developed by multiple vendors paint a challenging environment that threatens interoperability and portability in a IoT cloud [230], [231]. Cloud based IoT services is implemented using virtualization of machines & abstracted from common physical server. Hence a possibility of data breach exists through a virtual machine (VM's) to its neighboring VM leading to security issues. Cloud data is prone to security threats and vulnerabilities such as man-in-the-middle attack, SQL injection, malware injection, and flooding attack [232]. Despite of generic security solutions existing in the literature, a detailed security related reference model is needed which can meet IoT specific cloud issues. Moreover, in recent times, blockchain technology has emerged as a mean to connect billons of devices on IoT networks. Blockchain technology provides an autonomous data communication between a pair of devices without transaction certification from third party. This technology is further used for the analysis of big data originating from IoT devices [233]. Blockchain technology provides a secure mesh network with reliable intercommunication between the IoT devices & thus avoids threats to centralized server models. As the network size expands with increasing number of devices, the conventional computing strategy directly influences overall energy consumption. Each computer in a distributed database of blockchain network is identified as a node and capable of accessing transaction copies from

TABLE 9. Continent-wise generation & collection of E-waste [228].

Indicator	Africa	Americas	Asia	Europe	Oceania
No. of countries	53	35	49	40	13
Population (Millions)	1174	977	4364	738	39
WG (kg/inh)	1.9	11.6	4.2	16.6	17.3
Indication WG (Mt)	2.2	11.3	18.2	12.3	0.7
Recycled (Mt)	0.004	1.9	2.7	4.3	0.04
Collection Rate	0%	17%	15%	35%	6%

the network [234]. However, this creates privacy and trust issues in addition to other anticipated challenges like scalability, latency and energy consumption, and flexibility. In an absence of recognized standards, development of an integrated IoT platform exploiting blockchain technology still remains an open issue. Standardization can support deployment of a GIoT ecosystem by reducing energy consumption, resource costs, and material utilization while meeting expected performance goals.

Spatial and temporal correlation of WSN traffic data is exploited in dual prediction (DP) and data compression (DC) techniques leading to reduced energy consumption & bandwidth. The DP scheme can predict data at edge nodes/cloud and hence transmissions for the data points can be suppressed. Numerous prediction algorithms can be implemented over the DP scheme. Data blocks at sensor nodes can be compressed into smaller sizes leading to lesser number of transmissions. The DC scheme usually impacts accuracy and delay of the data collection process. Hardware related challenges like failure of sensor nodes may lead to gaps in the generated data points and hence leads to synchronization errors. Therefore, adequate techniques must be developed to avoid such errors.

B. CONCLUSION

The IoTs have brought physical and digital world together along with intelligent decision making capabilities without human intervention. Huge amount of real time data being collected and processed is improving the efficiency, productivity, reliability, and quality of service in every sector of business. A reference model of the IoT architecture is discussed in this article. IoT gateways connect the sensed data to the cloud and play a significant role in extending battery life, reducing latency & transmission sizes. Type of IoT connectivity depends whether data has to be transmitted in short or long range. Examples of short-range low power IoT networks are Bluetooth, WiFi where as low-power wide-area networks are 5G, 4G LTE, Sigfox networks. SDN networks are promising as the nature of IoT networks should be diverse, flexible, scalable, agile and adaptable. In addition, this article has discussed a tool based power model where the model shows significant reduction in power consumption is achievable using power harvesting techniques. Cloud computing offers efficient way of data processing due to superior computation and storage capabilities. However, cloud computing is client-server model, computations and data transactions are carried out at cloud only. Hence, network bandwidth and ultimately data latency become a limiting factor. Fog computing integrates network edge devices and cloud-based data-centers where various heterogeneous devices situated at network edges are ubiquitously connected and offers collaborative computation, communication and storage services. Therefore, data transfer time and the bandwidth requirements are significantly reduced. In this article, a discussion on fog computing that offers real-time or latency-sensitive services is provided. We presented an energy consumption model in a fog-cloud computing environment. Powering up of IoT devices using energy harvesting technique is discussed and certainly RF signals have an edge over other sources like wind, vibration, solar and thermoelectric effect as RF not only produce energy but also carry and process information simultaneously. Collected data of a IoT network is of little or no use unless there is a method in place to analyze and understand such large data. Analytical capabilities in AI can be effective in IoT data analysis and further classify and understand patterns that make decision making processes more informed and logical. However, we identified certain challenges in the integration of AI with IoT like coordination, heterogeneity and security/privacy concerns. At planning stage of IoT application based systems, the choice of hardware electronics such as various sensor devices, software based communication protocols, data processing & storage and computational requirements must be optimally selected and designed to meet stringent power budget goals. To meet GIoT goals, this article presents strategies at various levels of IoT based services can lead to overall reduction in power consumption and sustainable environment for the future. In this survey article, we have analyzed and evaluated various strategies at hardware and software levels in IoT network design to keep the power consumption at optimal levels. We have presented policies at global and regional levels being adopted to cause habitual changes among the citizen to fulfill GIoT ambitions. Finally, how governments can promote culture of recycling to reduce the menace of e-waste. FPGAs can offer flexible, specific application based solution, real-time data processing, optimal hardware usage and connectivity with the security features. Further research is needed to be carried out to validate claims from the FPGA vendors.

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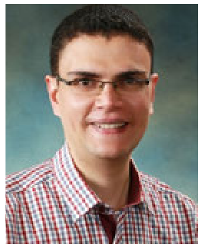

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