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SURVEY

A Review of Energy Hole Mitigating Techniques in Multi-Hop Many to One Communication and Its Significance in IoT Oriented Smart City Infrastructure

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ABSTRACT A huge increase in the percentage of the world's urban population poses resource management, especially energy management challenges in smart cities. In this paper, the growing challenges of energy management in smart cities have been explored and the significance of elimination of energy holes in converge cast communication has been discussed. The impact of mitigation of energy holes on the network lifetime and energy efficiency has been thoroughly covered. The particular focus of this work has been on energy-efficient practices in two major key enablers of smart cities namely, the Internet of Things (IoT) and Wireless Sensor Networks (WSNs). In addition, this paper presents a robust survey of state-of-the-art energy-efficient routing and clustering methods in WSNs. A niche energy efficiency issue in WSNs routing has been identified as energy holes and a detailed survey and evaluation of various techniques that mitigate the formation of energy holes and achieve balanced energy-efficient routing has been covered.

INDEX TERMS Balanced load routing, energy holes, energy management, Internet of Things (IoT), many to one communication, multi-hop communication, smart cities (SC), wireless sensor network (WSN).

I. INTRODUCTION

In the previous few decades, there has been a significant rise in the world's urban population. The percentage of the world's urban population has varied from 30% in the 1950s to 54% in 2014 and is expected to reach 66% by 2050 [1]. In addition, services offered by the modern cities include more information-oriented and collaborative city-systems cantered on digital information sharing between several services.

Due to the huge increase in urbanization, condense big cities with huge populations introduce novel challenges for the authorities governing these cities. These challenges include resource management, environmental issues, citizen well-being and safety. The city infrastructures are expected to deliver prosperous economies, enhanced lifestyle, friendly business opportunities, optimum resource utilization and least environmental damage in order to be viable at not only local or national scale, but internationally [2]. This requires new technologies and novel approaches such as wireless sensors, smart devices, and systems, etc. to work in an inter-connected and autonomous manner. Internet of Things (IoT) provides a foundation for such modern smart cities with inter-connected services and infrastructure. Such a smart city infrastructure can optimize not only energy, traffic and other city resources but can offer improvements in the health sector,

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academia, and public safety. This optimization of resources can improve the quality of life at a huge scale in the smart cities [3].

The IoT uses modern technologies such as devices equipped with advanced sensors for data collection from real environments, micro-controllers, transceivers with digital communication capabilities, and suitable protocol stacks [4] for autonomous and improved service delivery in an urban context i.e., smart city.

Due to the increasing applications of IoT in modern interconnected smart cities, the number of IoT devices are increasing day by day. According to Ericson's forecasts, this number will reach 5.5B by 2027 [5] whereas, the study conducted by Farhan et. al suggest that IoT devices worldwide will reach 24.1B by 2030 [6]. With a growing number of devices, there are challenges of increased energy consumption in the transmission and storage of this huge data. International Data Corporation (IDC) forecasts that IoT connected devices are anticipated to contribute 79.4 ZB towards overall data in 2025 [7]. With the growing number of devices and increasing demand for energy, the challenge of energy consumption in smart cities and its enabling technologies such as IoT and WSNs, needs to be investigated thoroughly.

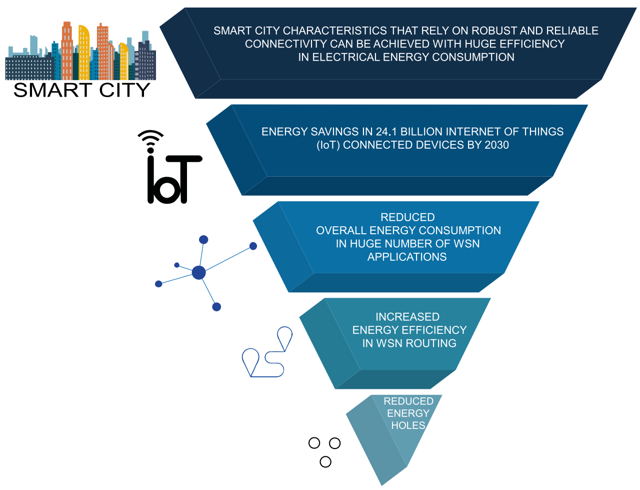

FIGURE 1. Significance of energy hole mitigation on overall lifetime increase of WSN assisted IoT in smart city.

Furthermore, multi-hop communication and hierarchical routing are considered as energy efficient data gathering approaches used by such devices. However, due to varying amount of data and transmission distances of devices an imbalance in energy consumption has been identified as a significant challenge. As a result of this imbalance, the nodes closer to the gateway are prone to early depletion of available energy and form energy holes [8]. Due to this imbalance, 90% of the total initial energy is still unused when the network lifetime is over [8]. Network stability is determined by the duration between the death of first node and last node. For better stability, this duration should be minimum [80]. Therefore, in this paper the significance of mitigation of energy holes in the overall energy efficiency of Smart City infrastructure has been explored.

Figure 1 explains the significance of mitigation of energy holes in hierarchical routing on the overall energy efficiency of smart city infrastructure. This can be achieved by maintaining balanced energy consumption of devices deployed at various levels and various locations within the networks. As discussed, earlier removal of energy holes with balanced energy consumption increases network lifetime and energy efficiency of the hierarchical routing in WSN. The gain in energy savings is multifold as multiple WSNs are expected to operate collaboratively through IoT infrastructure to deliver the underlying characteristics of smart city. Figure 1 demonstrates how the removal of energy holes spreads the overall gain in energy savings throughout the huge infrastructure as smart city.

In this review paper fundamental characteristics and applications of smart cities are explored to identify the significance of the area. It is considered that Internet of Things (IoT) and Wireless Sensor Networks are fundamental enabling technologies for smart cities. For this reason, the challenge of energy consumption is thoroughly studied among these fundamental enablers of smart city infrastructure. Finally, it is uncovered that balanced energy consumption among battery constrained wireless sensing devices is critical. Limitations in the existing energy hole mitigation methods and open challenges for future research have been identified.

A. MOTIVATION

This paper discusses energy-efficient approaches in WSN assisted IoT that allow to achieve smart city characteristics and applications. Smart city is a huge infrastructure that encourages inclusion of modern technologies to offer an improved quality of life for the citizens. With the continuous addition of innovative technologies and increasing applications under the umbrella of smart cities, resource management particularly energy management is one of the major challenges. One of the most important drivers of such applications is sensing technologies. Often sensing devices are deployed wirelessly to obtain information about their surrounding environment and to support collaborative services. Internet of Things (IoT) and Wireless Sensor Networks (WSNs) due to flexible communication infrastructure and effective data gathering capabilities are considered as fundamental enablers for such interconnected service delivery. This study starts with surveying the significance of energy management within smart city infrastructure including its characteristics and applications. A focus on energy efficiency in two major enabling technologies for smart cities i.e., IoT and WSN has been maintained. It is identified that not only energy efficiency but balanced energy consumption among WSN assisted IoT devices is important to extend the network lifetime and performance. Finally existing energy hole mitigation techniques have been thoroughly explored and evaluated in terms of limitations and open challenges. The main goal is to ensure that the reader understands the impact

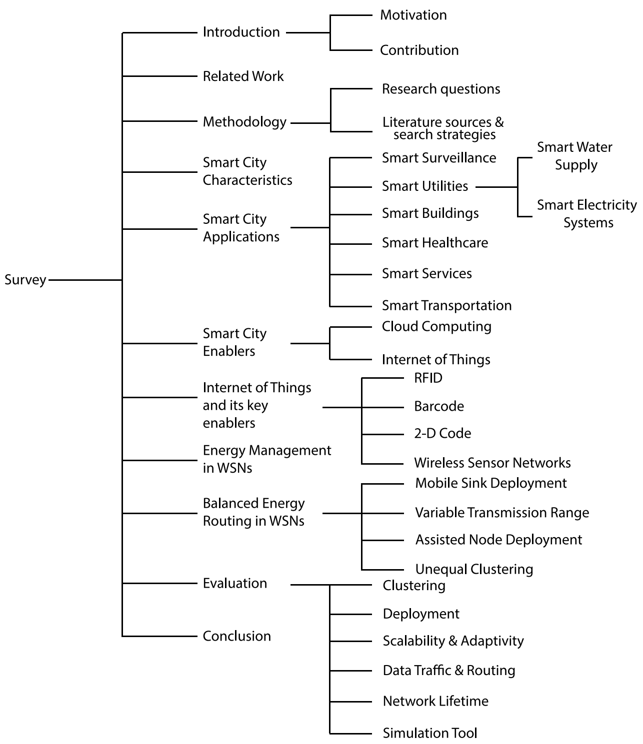

FIGURE 2. **Organization of the paper.**

of removal of energy holes on the overall energy savings of the smart city infrastructure.

B. CONTRIBUTION OF THIS SURVEY

In contrast to the surveys included in Table 1, this study summarizes significant research on smart city infrastructure including characteristics, applications and enabling technologies. Energy efficient approaches in two major enabling technologies of smart cities i.e., Internet of Things (IoT) and Wireless Sensor Networks (WSN) have been thoroughly reviewed. Finally, energy hole mitigation techniques in hierarchical routing have been evaluated. Scalability and adaptivity of existing techniques in varying contexts have been considered as the main evaluation criteria.

The following contribution are claimed in this survey:

1. The main contribution of this study is to provide a holistic view on significance of balanced energy operation of heterogeneous devices with varying capabilities within a smart city infrastructure. It is identified in this research that balanced energy consumption in addition to energy efficiency increases network lifetime that in turn enhances the reliability of services offered by smart city. Interoperability and relationship of enabling technologies i.e., IoT and WSN has been thoroughly surveyed.
2. This survey presents a thorough review of significant literature in smart city and energy efficient hierarchical routing techniques within WSN assisted IoT to achieve smart city characteristics. The review also covers the relationship between smart city and its fundamental enabling technologies.
3. This study presents an in-depth evaluation of existing hierarchical routing techniques with balanced energy consumption. Scalability and adaptivity of these techniques are judged in terms of their suitability in applications with varying network characteristics. Review demonstrates a comparison of existing techniques in terms of their suitability of operation in networks with different dimensionality i.e., 2D or 3D and geometric shapes such as square, circle etc., with different types of distribution of devices i.e., homogeneous and heterogeneous, with stationary and mobile devices, and with single and multiple base stations.
4. The review provides compact classifications of energy management in WSNs and presents taxonomy of energy hole mitigation techniques. A thorough discussion about advantages and limitations of each technique has been added.

C. ORGANIZATION OF PAPER

The organization of the survey paper, as shown in Figure 2, is as follows: The related work has been included in section II. The survey methodology is explained in section III. Smart city attributes followed by smart city applications are explained in sections IV and V. Section VI discusses major enablers of smart city and in section VII Internet of Things and its key enablers have been explored. Section VIII elaborates energy management challenges in Wireless Sensor Networks. Section IX introduces classifications of existing balanced energy routing methods in WSNs. Evaluation of energy hole mitigation techniques has been presented in section X. Finally, a conclusion has been added in section XI.

II. RELATED WORK

To the best of our knowledge, no other review covers the significance of energy hole mitigation in relation to energy efficiency in smart city and its major enablers i.e., Internet of Things (IoT) and Wireless Sensor Networks (WSNs). However, there are surveys that are connected to different areas of this work. Table 1 summarizes the aspects covered by existing reviews in relation to this paper.

Hanke et al. [9] presented an overview of the state-of-the-art with regards to sensing applications in smart cities. Although this paper covered an analysis of the sensing applications in smart cities and IoT, it did not include the significance of mitigation of energy hole on the increase in network lifetime. This survey was conducted in 2013 thus the references included are outdated and do not cover the recent research in the area.

Mohanty et al. [10] gave a literature summary to familiarize researchers with the emerging concept of smart cities. This review included discussion on smart city infrastructure, applications and enabling technologies. It included discussion about the impact of growth in urban population on resources required to achieve the attributes of smart city.

TABLE 1. Summary of the topical coverage in related surveys.

Survey Title	Authors	Year	Journal	Research Questions	Hierarchical Routing	Smart Cities	Internet of Things	Energy Holes	Energy Efficiency	Similarities	Differences
The Role of Advanced Sensing in Smart Cities [9]	Gerhard P. Hancke, Bruno de Carvalho e Silva and Gerhard P. Hancke Jr.	2013	MDPI Sensors Journal	Overview of the state of the art with regards to sensing in smart cities.	✘	✓	✓	✘	✓	Application of sensing in smart cities	No discussion about energy holes.
Everything you wanted to know about smart cities: The Internet of things is the backbone [10]	Saraju P. Mohanty, Uma Choppali, Elias Kougianos	2016	IEEE Consumer Electronics Magazine	Discussion on smart city infrastructure, applications and enabling technologies.	✘	✓	✓	✘	✓	Growth in urban population, and its impact on Smart City. A brief coverage on survey of IoT.	No discussion about the role of sensing technologies in SC. Energy efficiency and balanced energy consumption have not been covered. No survey of energy hole mitigation techniques.
A Survey of Clustering Techniques in WSNs and Consideration of the Challenges of Applying Such to 5G IoT Scenarios [11]	Lina Xu, Rem Collier, and Gregory M. P. O'Hare	2017	IEEE INTERNET OF THINGS JOURNAL	Clustering techniques in WSN assisted IoT considering energy efficiency and other QoS requirements.	✓	✘	✓	✘	✓	Survey of QoS requirements for WSN assisted IoT. Discussion on energy efficient clustering methods.	No focus on network lifetime. Balanced energy network operation not considered. Geometric shape specific classification not provided.
A Survey of Network Lifetime Maximization Techniques in Wireless Sensor Networks [12]	Halil Yetgin, Kent Tsz Kan Cheung, Mohammed El-Hajjar, and Lajos Hanzo	2017	IEEE COMMUNICATIONS SURVEYS & TUTORIALS	Review of developments in WSNs, including their applications, design constraints, and lifetime estimation models.	✘	✘	✘	✓	✓	Covers a survey of WSN network lifetime maximization techniques.	No focus on network lifetime. Balanced energy consumption not considered. Limited attention given to heterogeneous and 3D networks.
A survey and taxonomy on energy management schemes in wireless sensor networks [13]	Jaspreet Singh, Ranjit Kaur, Damanpreet Singh	2020	ELSEVIER: Journal of Systems Architecture	A systematic taxonomy of energy management schemes in WSNs that examine various energy provisioning-based techniques.	✓	✘	✓	✘	✓	Focus on the energy management schemes. Considers energy efficiency and energy holes.	Impact of network lifetime maximization on Smart Cities not covered. Focus is not on efficient energy utilization. Limited attention given to heterogeneous networks.

TABLE 1. *(Continued.)* **Summary of the topical coverage in related surveys.**

Comparative Study of Energy Efficient Routing Techniques in Wireless Sensor Networks [14]	Rachid Zagrouba and Amine Kardi	2021	MDPI Information	Energy efficient routing protocols have been reviewed.	✓	✗	✗	✗	✓	A thorough review of WSN protocols and energy efficiency is primary characteristic and a limited attention given to balanced energy consumption and hierarchical routing	Does not cover relationship between Smart Cities, IoT and WSN. Limited discussion on network lifetime. A survey of balanced energy techniques in various protocols is not present.
A Decade Review on Smart Cities: Paradigms, Challenges and Opportunities [15]	Tarana Singh, Arun Solanki, Sanjay Kumar Sharma, Anand Nayyar, and Anand Paul	2022	IEEE Access	Review of research on smart city initiatives between 2011 and 2021. Emergence of this concept and discussion on the typical architecture.	✗	✓	✓	✗	✗	Contains a review of majority of concepts in smart cities and performs a thorough analysis of characteristics and architecture of smart cities. An overview of applications and enabling technologies for smart cities.	The focus of this survey is on the security and data analytics but not on energy efficiency in smart cities. No deeper analysis of communication and network aspects. A limited attention has been given to WSN.
Holistic survey on energy aware routing techniques for IoT applications [16]	Poornima M.R., Vimala H.S., Shreyas J.	2023	ELSEVIER: Journal of Network and Computer Applications	Energy-aware routing protocols and algorithms that require less energy consumption during data transmission	✓	✓	✓	✗	✓	Covers the context of homogeneous and heterogeneous sensors in IoT. Focus on routing and does not consider clustering in detail. Only the protocol that are used in IoT.	Impact of network lifetime maximization on Smart Cities not covered. Geometric shape specific classification of the methods is important due to segmentation methods used but this survey does not classify methods with respect to shape.

Mohanty et al. also did not cover the role of sensing technologies and IoT to acquire the desired characteristics of smart city. This research also did not include the impact of energy hole mitigation and the advantage of balanced energy consumption on overall energy savings in smart city infrastructure.

Xu et al. [11] reviewed clustering techniques in WSN assisted IoT while keeping in view energy efficiency and other quality of service (QoS) requirements. Though energy efficient clustering is an important aspect to extend network lifetime, the overall significance of network lifetime maximization on smart city and IoT was not considered. While evaluating a clustering technique in terms of scalability, it is important to consider its operation in networks with different geometric shapes. Xu et al. did not consider these parameters to evaluate the performance of energy efficient clustering techniques.

An in-depth review of developments in WSNs including their applications, design constraints and lifetime estimation models has been provided by Yetgin et al. [12]. This survey covered energy efficient hierarchical routing and included a limited discussion on energy hole problem. However, research included only covers homogeneous devices deployed within 2D networks whereas this work provides a thorough review of methods with varying network parameters. Furthermore, Yetgin et al. did not demonstrate the significance of network lifetime maximization on IoT enabled smart city. The focus of this review was on energy efficient clustering while a brief importance was given to balanced energy routing by mitigation of energy holes.

Sing et al. [13] categorized the energy management schemes in WSNs but these schemes were limited to energy provisioning-based techniques. On the contrary, in this work techniques with efficient utilization of existing energy on network devices has been considered. Sing et al. also did not describe the relationship of energy savings through balanced network operation on smart city.

Rachid Zagrouba and Amine Kardi conducted a survey on energy efficient routing protocols for WSN assisted IoT [14]. The routing methods were classified based on latency, energy efficiency, next hop selection method, network architecture considered, initiator of communication, network topology, protocol operation, delivery mode, path establishment and application type. This review paid limited attention to discussing the role of routing and clustering for enhanced network lifetime. The importance of energy efficient sensing in relation to smart city has also been ignored.

Sing et al. [15] presented a literature summary of the emergence of smart city concept by exploring research between 2011 and 2021. This survey covered research in smart city with respect to architecture. The discussion on enabling technologies such as WSN assisted IoT is not as robust. The focus was on the importance of security and data analytics at each level of architecture as opposed to energy efficiency. An in-depth analysis of communication methods and the implications of imbalance in energy consumption was not included.

The energy efficient operation of homogeneous and heterogeneous sensor networks has been surveyed by authors in [16]. This survey exhibited the performance evaluation of existing hierarchical routing protocols in WSN assisted IoT while the concept of energy hole and balanced energy consumption was ignored. The review included a very limited discussion about the significance of increase in network lifetime on overall energy savings of the smart city infrastructure.

III. SURVEY METHODOLOGY

The survey covers energy challenges in trending research topics i.e., smart city and WSN assisted IoT. A significant literature has been explored and significance of the literature has been measured according to the citations as well as relevance of the existing literature. The process used in conducting the survey is described in the following subsections.

A. RESEARCH QUESTIONS

The aim of this comprehensive survey is to provide an overview of the energy management challenges with the increasing applications of sensing technologies in smart city and its fundamental enablers. The following research questions outline the overarching objective:

RQ1. Why is energy management in sensing applications significant?

RQ2. What are characteristics and applications of smart cities that require the use of sensing technologies?

RQ3. Which journals and forums have published significant research on the role of sensing technologies to achieve smart city attributes?

RQ4. How is smart city supported by Internet of Things and Wireless Sensor Networks?

RQ5. Which Journals and forums have published research on the role of WSNs and IoT to enable smart city to achieve required attributes?

RQ6. How can the existing research on energy management in WSNs be classified?

RQ7. Identify and evaluate the major techniques that introduce balanced energy consumption among the network devices?

RQ8. How can the existing energy hole mitigation techniques be classified?

RQ9. Which Journals and forums have published research on the balanced energy consumption techniques?

RQ10. What are the main network parameters that introduce challenges of scalability, adaptivity and suitability of different energy hole mitigation techniques in huge infrastructure such as smart city.

B. LITERATURE SOURCES AND SEARCH STRATEGIES

This survey considers literature survey from books, reports by reputed agencies, transactions, journals, research magazines and conferences proceedings. Based on the proposed research topic keywords related to research questions have been used in the first step to identify the relevant literature. These keywords included "smart city", "sensing technologies/WSNs", "IoT", "energy holes/hierarchical routing", and "network lifetime/energy efficient routing".

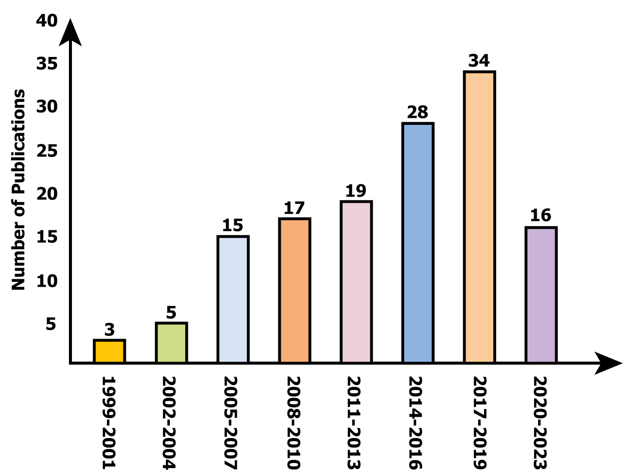

FIGURE 3. The number of papers between the years 1999 to 2023.

Furthermore, citations from papers identified through keyword search were included while finding answers to the research questions. Around 130 references were shortlisted based on their citations and relevance to the research questions for the final review. The number of publications included over every three years period between 1999 to 2023 has been shown in Figure 3.

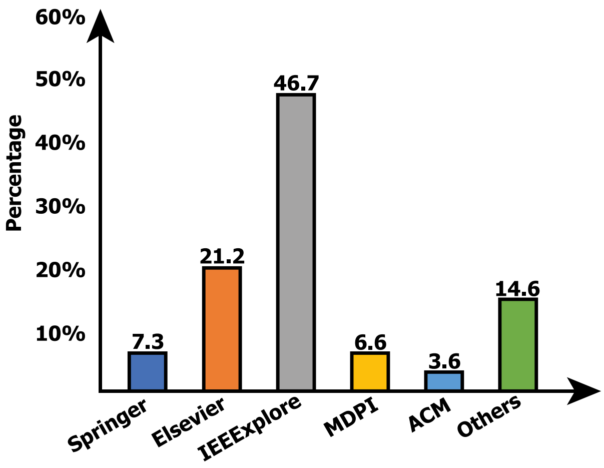

FIGURE 4. The percentage of resources from different databases.

Figure 4 shows the percentage distribution of resources considered from major databases. Researchers interested in this area can clearly focus databases such as IEEE Xplore, and Elsevier. Category "others" includes books and reports in addition to a few databases with low coverage of the topic area.

A breakdown of the number of publications containing each keyword used in this search has been demonstrated in Figure 5. It can be seen that significant literature has been covered across each keyword. Most papers considered have coverage of multiple keywords.

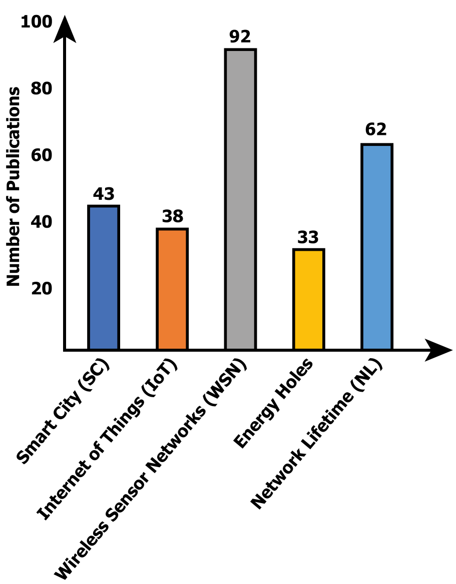

FIGURE 5. The number of resources containing each keyword.

Figure 6 shows the overall frequency of each type of resource consulted. The frequency has been calculated in terms of the resource type after scrutinizing papers in the duration from 1999 to 2023. It can be seen in Figure 6 that most resources considered were journal and conference papers. To develop a clear and concise relationship between the topics considered, books, thesis documents and reports were used.

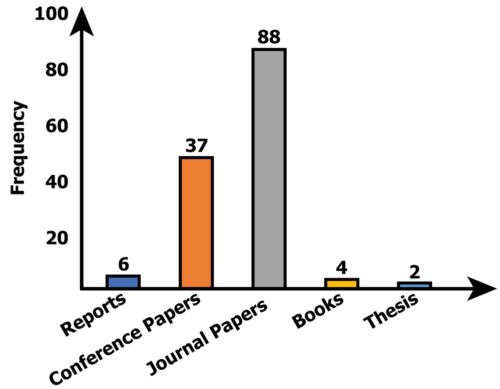

FIGURE 6. Frequency of each type of resource consulted.

IV. SMART CITY CHARACTERISTICS

In a smart city, to offer enhanced quality of life, the city's infrastructure must be structured on smart objectives of smart governance, smart economy, smart mobility, smart environment, smart people, and smart living, etc. [17], [18]. Figure 7 shows fundamental characteristics of a smart city infrastructure.

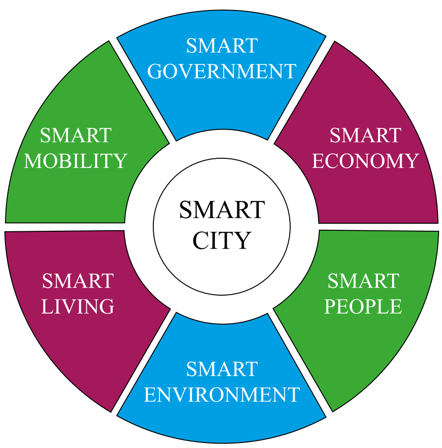

FIGURE 7. Smart city characteristics [18].

In relation to the characteristics of Figure 7, the European Parliament's Directorate General of International Policies in its study of 2014 on "mapping the smart cities in Europe" presents the working definition of smart city as: "city seeking to address public issues via Information and Communication Technology (ICT)-based solutions on the basis of a multi-stakeholder, municipally based partnership" [18].

In order to achieve the above-mentioned characteristics of the smart city in an energy efficient manner the associated enabling technologies, applications and research challenges must be explored in detail. The next section contains an overview of energy efficiency in enabling technologies and applications to demonstrate the significance of the area.

V. SMART CITY APPLICATIONS

Smart city applications can be classified into seven broad areas as shown in Figure 8.

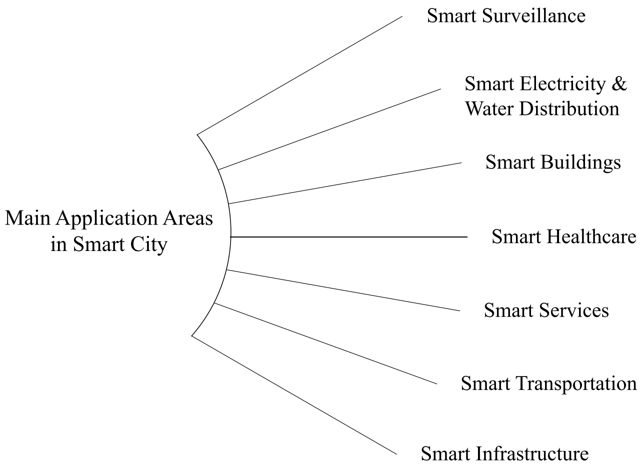

FIGURE 8. Main application areas in smart city [9].

A. SMART SURVEILLANCE

Although conventional CCTV systems provide some level of infrastructure for smart surveillance there has been valuable research in advanced sensing capabilities, artificial intelligence, and collaborative methods to improve surveillance and prompt responses to the events of public safety. Conventional surveillance systems do not have built-in intelligence and are human operated however, modern sensing capabilities allow to monitor people's actions, issue triggering alerts for events and quicker responses to the events.

Examples of such works include the use of infra-red videos [19] and infra-red cameras for tracking and detecting pedestrians at night. A framework in [20] to perceive items held by people, a crowd behavior monitoring algorithm in [21] and semantic video surveillance of [22] are some additional examples.

There have been numerous other works in advanced sensing systems, connectivity, intelligence, and algorithms to improve smart surveillance systems for public safety in smart cities. There are challenges of complex infrastructures, heterogeneous technology environments and resource management that put limitations on the integration of all these advancements in smart city infrastructure.

B. SMART CITY AND UTILITY

Distribution of capital resources by the governments can be broadly classified into electricity and water distribution infrastructures. Both distribution networks have numerous applications to achieve smart attributes of a modern interconnected city:

1) WATER SUPPLY SYSTEM

Amongst the resources that make life possible not only in the city but also in villages, an important resource is water. Conventional water distribution systems consist of water collection, water storage and distribution. These systems generally consist of a network of pipes, storage tanks, control valves and several operating points. The limitations of such systems are that they do not incorporate modern sensing capabilities to detect fault locations, quality of water, prior distribution zones and available resources. In addition, they also lack intelligence and connectivity infrastructures to communicate the analysis of required sensing needs and available resources between several ends.

Smart Water distribution requires advanced sensing and communication capabilities to improve the quality of service. Advanced sensors are deployed for continuous monitoring in the pipeline [23] for prompted and exact fault analysis. Sensors to detect vibration, pressure sound, and water flow are used for this purpose [24]. A Wireless Sensor Network has been deployed in [25] to monitor hydraulic, flow, acoustic data, and water quality. In addition to advanced sensing technologies, [26] presents a survey of connectivity advancements and IoT infrastructure for improved quality of service in water distribution systems.

Although these recent advancements in the area provide improved water distribution architectures for the smart cities, they pose challenges of expensive architecture and increased energy consumption.

2) ELECTRICITY DISTRIBUTION SYSTEMS

Electricity distribution systems are as important as water distribution systems and so is electricity an important resource. Traditional distribution systems that distribute electricity are recognized as least intelligent as they dictate unidirectional flows from generating stations to consumers. However, Smart Grid (SG) works as an automated distributed advanced energy supply network by using bidirectional information and electricity flow [27]. Smart Grid (SG) is a modern electric system that uses two-way information to deliver the tasks of electricity generation, transmission, and distribution to the consumption level with the help of modern cyber-secure methods, and advanced computational intelligence. This allows the electric system to be deliverable to the population in a cleaner, safer, secure, reliable, resilient, and sustainable fashion [27]. Such grids cover the service delivery in its entirety from the generation of electricity to consumers and different levels of substations [28].

Smart grid is a complete framework for electricity generation and distribution in an optimized and intelligent manner. Various surveys on the smart grid have been completed in [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41], and [42], that discuss comprehensively different aspects and challenges in smart grid to meet the requirements of the modern smart city model. These surveys and a lot of others reflect the recent activity and vast applications and developments in smart grids to meet the requirements of energy efficiency, data security, prompted demand responses and coherent fault removal, etc. However, the challenges of energy efficiency are still under debate and need revisiting consistently with the new advancements in technology.

C. SMART BUILDINGS

Traditionally buildings were built based on the drawing, structural, materials and other feasibility plans which were limited to the initial planning. There was a lack of provision for continuous developments in such plans as they were made only at the start. In addition, the operational management of buildings was carried out in a fashion where there was lack of communication and connectivity between different operations of the building.

A smart building not only integrates modern technologies and connectivity features but also revisits several services in a manner that structural health, optimum resource utilization and comfortable living or service is provided to the people. More precisely smart buildings term refers to buildings equipped with advanced and integrated technology systems to support building services. Such integrated building technology systems include automation systems, safety systems, telecommunication systems, and different facility management systems [43].

In this regard, many areas have been explored to introduce and improve smart building systems within smart cities. In [44] an architecture for green and sustainable smart buildings and associated challenges have been explored. In [45] researchers present a recent survey on next generation smart sensing technologies for improved structural health monitoring of smart buildings. Opportunities and challenges of Heating Ventilation and Air Conditioning (HVAC) systems in large scale buildings have been discussed in [46] to improve smart behaviors in terms of resource utilization in smart buildings. Most importantly, [47] discusses smart technologies for efficient and sustainable energy and other resources utilization in smart buildings.

In the current context, only an overview of a few prominent applications of smart buildings has been mentioned. These horizons of smart city applications identify the importance of resource utilization in the implementation of these services.

D. SMART HEALTHCARE

Due to the tremendous growth in population and the reason that primary healthcare in the cities is not only projected for citizens but also for the referred patients from the villages and nearby cities, traditional healthcare services are unable to accommodate everyone. Also, during extraordinary circumstances like recently due to globally declared pandemic, present conventional and static health service capabilities are insufficient. A dynamic, flexible, and stretchable health service infrastructure is a need of time. Although advanced infrastructures and state of the art medical technologies are available today, expensive, and limited facilities make them unapproachable for everyone [48]. To deal with such circumstances one of the main objectives for smart healthcare is to make people self-health aware by educating them about medical status and terminologies. COVID-19 self-testing kits are a good example of such services. However, there is still a huge need to transform the current health facility to a large-scale flexible and stretchable manner so that such health service crisis can be dealt with promptly. Such a Smart healthcare provides users with an ability to self-tackle some emergency situations [10]. In addition, Smart healthcare allows optimum resource utilization by remote monitoring of patients and reduces cost. Remote health monitoring is achievable through emerging Wireless Body Area Networks and IoT devices [49]. IoT is fundamentally based on advanced sensor technologies while a sensor is used to recognize events with its built-in analytical ability combined with a biological element [50].

Smart healthcare is not only an advanced version of healthcare but a requirement for people's awareness and control of disease growth rates. With the increasing number of chronic diseases, especially in developing countries, it is necessary to use ICT for early discovery and stoppage. This also reduces the overall expenditures on healthcare [51], [52], [53].

Research published in [54] discusses a comprehensive survey of enabling technologies for smart healthcare and considers IoT as the backbone for smart healthcare. These enabling technologies and sensor infrastructures raise the challenges of complexity, energy efficiency, privacy, and heterogeneous network structures, etc.

E. SMART SERVICES

Conventional law enforcement models are impractical and inefficient in modern smart cities [9]. IBM in their smarter planet initiative have proposed solutions to such law enforcement issues. These solutions integrate investigations, geographic information systems (GIS) and intelligence analysis [55]. Such solutions enable information sharing between different agencies that results in an efficient, coherent, and synchronized implementation of the law.

Fire-fighting is one more service that could result in efficient facility with coordinated and connected services infrastructure as in an IoT enabled smart city. Traditional fire-fighting could be enhanced as discussed in [56]. TelosB based wireless sensor networks are placed on fire-fighters bodies. Each TelosB mote is equipped with sensors to measure temperature, carbon dioxide, hydrogen, and hydrocarbon concentration. This enables fire-fighter to know their locations relative to other fire-fighters within the network using Received Signal Strength Indicator (RSSI) based localization. This also allows fire-fighters to compute escape paths.

There is huge potential in introducing more public services using IoT and Smart city infrastructures. There are still challenges for standardization and legislation in this regard. A complete architecture can allow increased efficiency of such services with improved service satisfaction.

F. SMART TRANSPORTATION

Due to the massive rise in the number of vehicles on roadways in recent years, there is a growing need for effective traffic management for optimum traffic flow with reduced traffic jams, especially at peak times. Conventionally, this was managed with the help of traffic lights that either was controlled on fixed time interval switching or human controlled. Start and stop function in modern vehicles is a traffic adaptive management system and can result in reduced fuel consumption. Intersections are the critical points where such methods would increase efficiency if appropriately managed. In this situation, a method to estimate the number of cars approaching an intersection could generate information for dynamic switching intervals of traffic lights depending on traffic conditions at different times. However, such a method must be based on accurate data from real-time sensors in order to make an intelligent estimation. Advanced sensing, IoT and wireless technologies are key enablers for such systems. Methods, where traffic lights and stop signs are completely removed, have also been presented in [57]. In such methods vehicles communicate with each other while approaching an intersection to avoid collisions. In [57] coordinated time-slot allocations have been used to avoid collisions at intersections. Another method to manage this in a coordinated manner is through the use of Radio Frequency IDentification (RFID) wireless communication between the vehicles and traffic signs [58]. Reference [59] presents a comprehensive survey on applications and technologies used for smart traffic systems in a smart city context. Advanced sensing technologies are the backbone for smart traffic systems. The limited energy resource and inefficient utilization of available energy resources are very disadvantageous in smart cities.

This increase in application areas and technological advancements in Information and Communication Technologies (ICTs) and their integration in modern smart city infrastructures pose challenges on available resources. One of the major challenges is energy consumption in these ICTs and smart devices in order to achieve the smart characteristics of a smart city. According to analysis in [60] if remarkable improvements were not made in the electricity efficiency of wireless access networks and fixed access networks only Communication Technology (CT) could use as much as 51% of global electricity by 2030. According to research, 75% of the world's capitals and energy is used by cities [10]. According to [61] if the urban expansion continues to grow at present rate urban energy consumption which was observed 240 EJ in 2005 will reach 730 EJ by 2050 which is threefold. This limitation results in an imbalance of demand and available resources, and then must be elaborated. Here we will discuss fundamental enablers of a smart city so that this energy consumption challenge can be broken down into different areas.

VI. SMART CITY FUNDAMENTAL ENABLERS

Different architectures for smart cities have been proposed based on foundational concepts of instrumented, interconnected, and intelligent services [62]. To understand the challenges of energy it is better to understand different divisions of smart cities. In their report on China's smart city pilots' authors in [63] conclude that most of China's smart cities are adopting four-layer architecture that consists of sensing layer, processing layer and application layer. Internet of Things (IoT) and cloud computing are key fundamental technologies that allow interconnected and coordinated decisions between several services of such a smart city infrastructure.

A. CLOUD COMPUTING

Cloud computing gives rise to virtual data centers with processing and storage of data in a cost-efficient and timely manner [64]. Such computing can allow quick data storage and fetching for services to produce collaborative results efficiently. Cloud computing offers huge peta-bytes of data storage and processing capabilities with their unlimited expansions. Cloud computing provides energy efficiency due to reduced data transmission distances as in centralized computing methods.

B. INTERNET OF THINGS

Figure 9 below shows that the smart characteristics of a smart city rely on a robust and reliable network which not only demands high speed, continuous connectivity and vast coverage but also features such as mobility, the autonomy of operation, collaborative decisions, etc. [17], [18]. Internet of Things (IoT) is a revolutionary paradigm for such heterogeneous interconnection of ubiquitous computing devices.

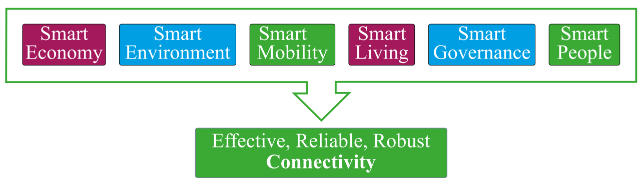

FIGURE 9. Reliance of smart city characteristics on connectivity.

Internet of Things (IoT) is a huge infrastructure that works as a backbone to achieve core objectives of a smart city. It is very important to further elaborate energy consumption in IoT and its enabling technologies to achieve the objective of energy efficiency.

VII. INTERNET OF THINGS AND ITS KEY ENABLERS

Internet of Things is a radical evolution of the present internet into a network of interconnected things that not only harvests information from environment (sensing) but interacts with the physical world [65], [66]. The Internet of Things is a state-of-the-art technology that proffers to connect an excess of digital devices equipped with several sensing, actuation, and computing capabilities with the Internet [67]. This allows an autonomous and improved service delivery in the context of a smart city.

Various forecasts have been made about the growing number of IoT devices. As mentioned above [5] this number is predicted to be 4.1 B in 2024. In addition, it is forecasted by International Data Corporation (IDC) that the data generated by these devices will reach 79.4 ZB in 2025 [7].

This huge increase in the number of devices and associated data transmission introduces constraints in the energy consumption of information and communication technology (ICT) used for IoT proliferation in smart cities.

To consider the challenges in energy consumption of these devices and data transmissions it is important to break down IoT in its enabling technologies. Reference [68] provides a very good survey of the enabling technologies for IoT. In this survey, the authors divide the IoT infrastructure into four layers and classify enabling technologies with respect to the layer they function in. The four different layers as shown in Figure 10 have been named as perception layer, network layer, service layer and application layer. Enabling technologies only work in the first three layers. The enabling technologies and corresponding layers they perform in are described below.

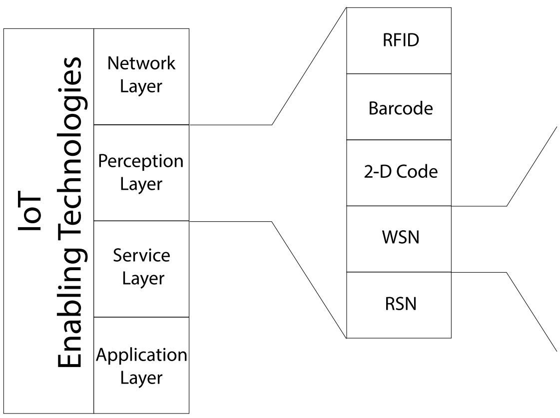

FIGURE 10. **IoT enabling technologies explored.**

The perception layer consists of sensing capabilities [4] and its primary function is to recognize and track objects [68]. The network layer is known as the transmission layer [69] and is used to govern routing and provides support for data transmission functions [68]. The third layer which is located between the network layer and application layer is the service layer. The service layer provides services that can support the application layer [4]. Finally, the application layer performs a bridging function and receives data transmitted by the network layer. This layer then uses this data to support the required services or operations. For example, application layer can provide the storage facility to maintain the backup of received data or can provide analysis facility to perform evaluation operations on the data acquired. Due to the enormous transmission data as big as 79.4 ZB as a result of the increased number of devices as mentioned in the previous section, a significant energy resource is spent on data gathering, transmission and storage. Efficient management of this infrastructure and its key enablers at the perception layer is very important. The main enabling technologies are Wireless Sensor Networks (WSNs), Radio Frequency IDentification (RFID), Barcode, 2-D Code, RFID sensor networks (RSNs) in the perception layer as shown in Figure 10.

A. RADIO FREQUENCY IDENTIFICATION (RFID)

Radio Frequency IDentification (RFID) is a widely used technology in IoT that uses radio signals over a short distance [60] to identify and track objects. RFID system infrastructure uses RFID tag on the object to be tracked, RFID reader and antenna [70]. An RFID tag is a unique code that is put on the object. RFID uses radio signals to read the code and the signals are transmitted between the tag and reader using an antenna.

B. BARCODE

Barcode, also called 1-D code consists of different width of black lines separated by different widths of white spacing. These lines are arranged with special coding [71]. A machine is used to scan the bar-code and read the information in it with the help of an infrared beam [72]. There are limited chances of managing energy at this level.

C. 2-D CODE

2-D code saves information in the form of black and white color pixels laid on a plane. Black color pixels represent a binary "1" value and white color pixel represents a binary "0" value [73]. In comparison to bar-code, 2-D code is highly reliable, has better robustness and gives high information content etc. [74].

D. WIRELESS SENSOR NETWORKS (WSNs)

Wireless sensor networks are used for monitoring various real-time variables in different IoT devices [73], [74], [75]. WSNs serve as a bridging function between the physical world and cyber world [76]. Using WSN gives the advantages of scalability, reliability, small size, and low cost as compared to other technologies. But deploying small battery nodes poses challenges of energy requirements and long-life requirements. This will be discussed in detail later.

VIII. ENERGY MANAGEMENT IN WSNs

The wireless sensor network is a foundational technology for IoT [77]. Increased energy consumption in IoT can be dealt with using lightweight routing and data aggregation protocol stack or limiting energy consumption in wireless sensor networks itself [77].

A sensing node consumes power in sensing, processing, storing and communication [78], where the most common source of power for a sensor node is an electrical battery [79]. In a large-scale network of nodes like WSN-Assisted IoT with dissimilar conditions such as surrounding environment, area of the network, etc. battery-powered sensor nodes cannot be suitably replaced or recharged [80].

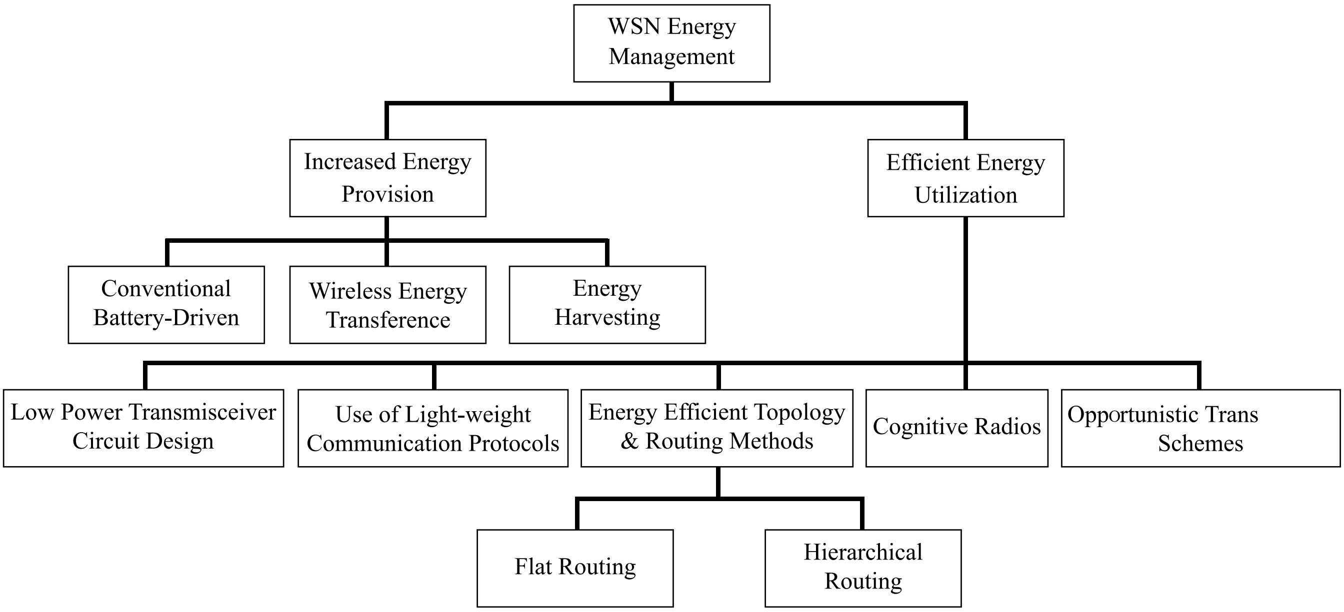

FIGURE 11. Taxonomy of energy management approaches in WSN.

Energy consumption in WSN is important to decide the overall network lifetime. Network lifetime can be improved by either increasing the electrical battery of individual sensor nodes or by finding methods of efficiently using the available electrical energy as shown in Figure 11. Besides conventional methods of increasing electrical battery life, methods of capturing ambient energy [81], [82], [83], [84] and wireless energy transference approaches have been developed in [85] and [86] to increase energy provision at the sensor node. However, ambient energy is not a reliable source [87] and energy transference approaches introduce environmental noise.

In this survey, we focus on efficient energy utilization methods in wireless sensor networks for IoT. Among the four energy consuming operations i.e., sensing, processing, storing, transmission, and reception operations the most dominant consumer of energy is the network node's radio operations [88], [89], [90].

Recent techniques to reduce energy consumption in radio operations of a network node, in the context of IoT can be broken into the following areas: transceiver circuit design, transmission power control, use of lightweight protocols, opportunistic transmission schemes, cognitive radios, and energy-efficient routing [91] as shown in Figure 11. A detailed survey about all these techniques is beyond the scope of this survey paper. However, a focus has been maintained on lifetime maximization routing schemes for WSN assisted IoT that support smart cities.

Typically, wireless sensor networks contain hundreds or thousands of sensor nodes in an IoT context. Besides sensing, routing sensed data to a gateway is also a primary purpose of these nodes. Energy efficiency in routing this data is very important to increase the overall network lifetime of WSN assisted IoT. Taxonomy in Figure 11 shows two major classifications of WSN routing protocols: flat routing and hierarchical routing protocols. In flat routing, each node plays the same role as shown in Figure 12(a), but due to such a large-scale deployment of nodes, routing is not energy efficient [92].

A hierarchical routing protocol as shown in Figure 12(b), defines structural hierarchies where lower layer nodes perform sensing tasks and higher layer nodes relay the aggregated data from lower layer nodes. Such a hierarchical deployment of nodes divides the network into clusters where each cluster has a cluster head (CH) at a higher layer. Hierarchical routing gives advantages of scalability, longer lifetime, low latency, and energy efficiency [92].

Due to multi-hop communication of clustered WSNs, nodes closer to the sink suffer from increased load, resulting in unbalanced energy consumption across the network. Higher layer nodes consume more energy as compared to lower layer nodes and result in the early death of a node. This, in addition to increased energy consumption, also introduces the problem of energy holes. According to [8], 90% of the total initial energy is still unused when the network lifetime is over. A network is said to be stable if the time duration between the death of the first node and last node is minimum [80].

IX. BALANCED ENERGY ROUTING IN WSNs

Hierarchical routing has proven to be energy efficient as compared to flat routing methods due to the separate roles of different sensor nodes.

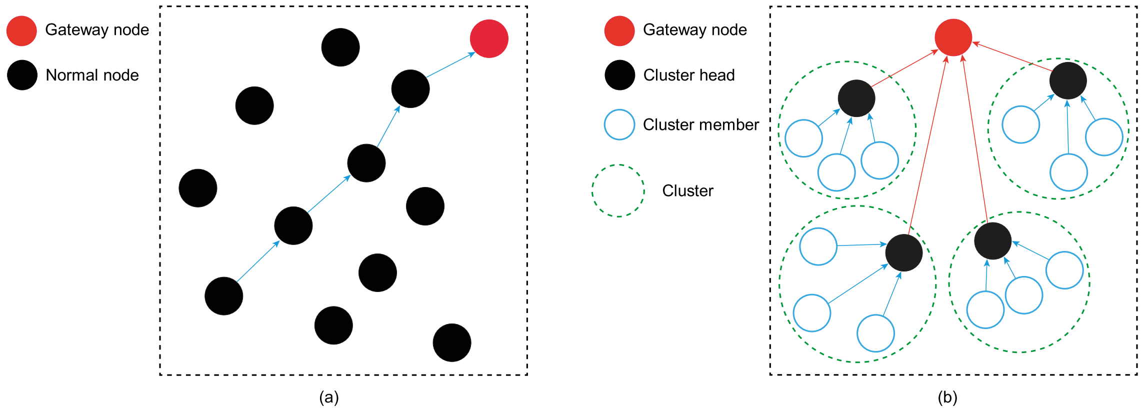

FIGURE 12. Two popular routing topologies: (a) Flat routing topology and (b) Hierarchical routing topology [92].

One of the first and most significant hierarchical routing protocols is Low Energy Adaptive Clustering Protocol (LEACH) [93]. The operation of LEACH is broken into rounds where each round of operation constitutes a set-up phase and a steady-state phase. In the set-up phase clusters are organized and the steady-state phase contains data transfer operations towards the base station. For each new selection of a set of (CH) nodes, a new round starts. LEACH gives advantages of energy efficiency in routing due to clustered nature of nodes and balanced load distribution between the nodes by rotation of (CH) role among nodes. However, since (CH) selection is randomized, the probabilistic balanced operation of nodes is not completely achieved. In LEACH base station (BS) is fixed and nodes are homogeneous in terms of initial energy which limits it to certain scenarios. It does not include inter-cluster multi-hop communication that can enhance the network lifetime.

To further reduce the energy consumption by computation of (CH) selection LEACH Centralized (LEACH-C) an extension of LEACH was proposed by [94]. In this protocol the centralized cluster formation by a (BS) is implemented. This reduces energy consumption by energy-constrained sensor nodes due to complex computations for cluster formation and (CH) selection. In each round of operation, the number of (CH)s in LEACH-C equals a pre-determined optimal value. The advantage of LEACH-C is that the (BS) makes sure that a node with less energy does not become a (CH). Its disadvantage is that the (BS) decides on the global information from the network and nodes farther from the (BS) are unable to send their energy and location status to the (BS) in large-scale networks.

Hybrid Energy-Efficient Distributed clustering (HEED) [95] is a multi-hop clustering algorithm that limits the cluster formation time to certain iterations and brings the distributed decision opposite to LEACH-C. (CH)s are selected based on local information about residual energy and intra cluster communication costs. The advantage of HEED is that it is not limited to homogeneous energy nodes and uses multi-hop communication between (CH)s and (BS), but HEED gives the disadvantage that it produces a larger number of (CH)s and only considers a two-level hierarchy.

Cluster-Chain Mobile Agent Routing (CCMAR) [96] focuses on data aggregation methods to improve the energy consumption of WSNs. CCMAR seemingly improves energy efficiency by embedding advantages of cluster-based and chain-based strategies of LEACH [93] and Power efficient Energy Gathering Sensor Information Systems PEGASIS [97] respectively. Where CCMAR reduces the disadvantages of overhead and latency in LEACH and PEGASIS respectively, its mobile agent deployment for data aggregation from (CH)s also introduces the challenges of fault tolerance, security, and increased length of topology formation cycle.

Wireless Sensor Network Energy Hole Alleviating (WSNEHA) algorithm [98] uses adaptive range adjustment strategy to enhance network lifetime. It balances the energy consumption of first radius nodes to the sink but does not address the energy consumption of other regions. Energy consumption is unbalanced in other regions of WSNs and can cause energy holes in other regions. To extend the WSNEHA algorithm, authors in [99] proposed a Balanced Energy Consuming and Hole Alleviating (BECHA) algorithm which levels the load distribution of the entire network. A further improvement of BECHA is Energy Aware BECHA (EA-BECHA) which was proposed later in [100], to reduce the packet drop and further increase energy efficiency. These efforts do not address end to end delay and are not adaptable to a few scenarios with different kind of network such as Under Water Sensor Networks with mobility and strip-based networks with linearly extending network architecture.

Hierarchical routing has proven to be energy efficient as compared to flat routing methods due to the separate roles of different sensor nodes.

In strip-based WSNs, [101] presented an accurate-distances-based transmission scheme to achieve balanced load distribution but again the scheme is not adaptive for other kinds of WSNs. Balanced Energy Adaptive Routing (BEAR) [102] is another similar attempt that only focuses on a typical kind of network and not others. Energy hole

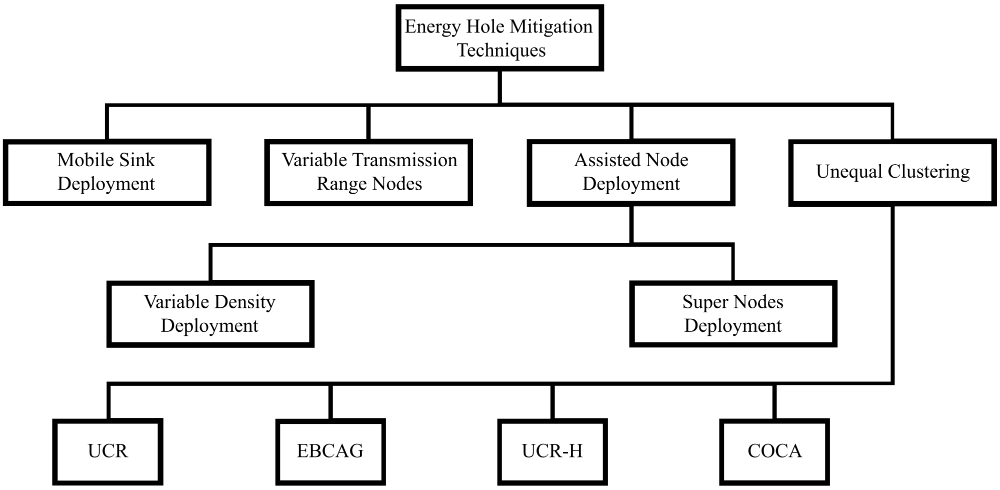

FIGURE 13. Taxonomy of energy hole mitigation techniques.

mitigation techniques for hierarchical routing in WSNs can be classified into the following primary areas as shown in Figure 13.

- Mobile Sink Deployment
- Variable Transmission Range Nodes
- Assisted Node Deployment
- Unequal Clustering

Details and techniques belonging to each class have been explored further in the discussion below.

A. MOBILE SINK DEPLOYMENT

In a many-to-one communication architecture, the load for relaying the data increases at nodes nearer to the sink. For this reason, such communication produces imbalanced energy consumption amongst the nodes. By using a mobile sink this load can be diverted onto other areas with rich energy nodes for a certain period. In such a network, where the sink is constantly changing its position, routing with minimum information loss becomes challenging. A mobile sink, with a virtual grid infrastructure for this purpose, has been proposed in [103]. Continuously tracking the location information of the sink node introduces overheads and makes the overall system inefficient in terms of energy consumption.

Deployment of mobile relay nodes considered in [104] is a potential solution to such a problem in mobile sink deployment. Although the routing protocol is less complex and needs low processing, it introduces latency in the overall network operation.

The primary disadvantage of mobile sink deployment is latency and increased power consumption in moving the mobile relay or sink nodes throughout the network.

B. VARIABLE TRANSMISSION RANGE

Energy consumption in the transceiver of network nodes depends on transmission distance, number and sizes of the data packets to be transmitted. Transmission power increases with distance and vice versa, the Balanced Load Distribution (BLOAD) [105] scheme prolongs the stability period and lifetime by dividing the data of each node into three fractions: small, medium, and large. For even distribution of these fractions of data, the transmission range of each sensor node is calculated in a logical manner on the basis of transmission distance and amount of data aggregated by the corresponding node. One of the major disadvantages of this scheme is that each node sends a fraction of data directly to the sink, which might not be possible in a large-scale Internet of Things infrastructure, where nodes are distributed very far away from the sink node in many applications. Additionally, BLOAD only addresses the problem of a specific type of network i.e., Under Water Sensor Networks (UWSNs) and does not address the feature of terrestrial and body area types of WSNs.

The super links-based data drainage scheme [106], uses nodes with extraordinary transmission link capabilities at logically worked locations. This scheme brings the concept of hybrid transmissions between direct and multi-hop transmission.

C. ASSISTED NODE DEPLOYMENT

Recently the challenge of energy hole in many to one (converge cast) communication of WSNs has been tackled by assisted node deployment methods in a variety of ways [107], [108], [109], [110], [111]. Assisted node deployment gives an advantage in increasing the overall network lifetime by balanced energy consumption. There are two main ways through which assisted node deployment can balance the energy consumption of the network as listed in Figure 13.

Firstly, by dividing the network area into suitable regions and then deploying extra energy nodes (super nodes) in areas where energy holes occur i.e., areas near to the sink. One such attempt was made by authors in [108], where the overall network area is divided into different coronas and super nodes are deployed by mathematical calculations for a balanced operation of the network. This technique was more suitable for circular sensor areas and networks with identical coronas. Also, extra energy nodes are deployed which is not an efficient utilization strategy.

Secondly, assisted node deployment can achieve a balanced consumption if the density of homogeneous energy nodes is increased in the area near the sink. Energy balanced Node Deployment with Balanced Energy (END-BE) [110] determines a function that calculates a number of nodes in each successive corona by fixing initially the number of nodes in the outer corona for the balanced operation of the network. Further, it also proposes END-MLT for Maximum Lifetime. This is done by rearranging appropriate sensor nodes in the outer corona, to achieve energy balance. This denser node deployment produces redundant data near the sink [107]. Similarly, [109] uses Archimedes spiral for distribution of nodes in the coronas and increase of energy efficiency. These methods give a balanced energy consumption but sometimes control over deployment strategy is not achievable in holistic environments.

In addition to the above assisted node deployment methods, additional relay nodes can be deployed to assist cluster heads (CH)s in their data relaying operations. One such work is presented in [111] where relay nodes have been deployed to reduce the load on (CH)s. The method balances energy consumption but at the cost of high energy, and expensive new nodes deployed.

D. UNEQUAL CLUSTERING

Unequal clustering algorithms are different from traditional uniform clustering algorithms such as (LEACH) [93] in such a way that cluster sizes are different. By reducing the aggregation load, for (CH)s nearest to a sink node, allows the clusters to save more energy for relaying the data. In this manner, unequal clustering methods are attractive for balancing the load in the overall network.

First, the Unequal Clustered based Routing (UCR) protocol was proposed in [112]. It consists of two parts: Energy Efficient Unequal Clustering (EEUC) algorithm to manage topology and greedy geographic and energy-aware routing protocol for inter-cluster communication. EEUC selects (CH)s using local information in such a way that clusters closer to the sink have smaller sizes. UCR enhances the network lifetime by balancing the load, but it is not feasible for heterogeneous sensor nodes with a multiple parameter sensing environment. The cluster size is only dependent on the distance between the (CH) and sink but a more detailed analysis considering other factors like transmission power could give better results. In Energy Balancing Unequal Clustering Approach for Gradient-based routing (EBCAG) [113], (CH) compresses data received from each member node by a fixed aggregation coefficient. In EBCAG each node keeps a gradient value that is worked in a manner that defines the minimum hop count to the sink. Cluster sizes are computed based on gradient value of the chosen (CH) and a ring-based network model is constructed. Although cluster sizes account for minimum total energy consumption and balanced load distribution in the rings but the computation of the number of rings is not thoroughly addressed. Including more parameters like transmission power could better this computation, also the determination of the optimal number of rings is very important which is ignored. Constructing Optimal Clustering Architecture (COCA) of [114] divides the sensor field into equal-sized square units. Units closer to the sink should have more clusters than the ones away. Based on minimum energy consumption and balanced load distribution, an optimal number of units is worked out. COCA performs better than UCR, but it is very complex and the division of the sensor field into square units is not tractable.

For energy efficiency, it is convenient to use a single sink for several types of sensor nodes deployed in the same area, monitoring various kinds of parameters. Such a network is an example of a heterogeneous sensor network and efficient energy utilization of sensor nodes in such a network is even more important as compared to homogeneous sensor networks. This factor of heterogeneity has been considered in the Stable Election Protocol (SEP) [115] but it limits the heterogeneity to only two types of nodes. The decision on whether to be a (CH) or not is made by each kind of node based on its election probability weighted by its initial energy relative to other kinds of nodes. SEP only provides a two-level heterogeneity and is also not suitable when heterogeneity is caused by several types of data gatherings of different nodes. SEP does not use unequal clustering as shown in Table 2 which can provide further advantages for balanced load distribution. Distributed Energy Efficient Clustering (DEEC) [116] considers multi-level heterogeneous nodes and (CH)s are selected by the probability based on the ratio between the remaining energy of each node and the average energy of the network. DEEC achieves a longer lifetime than SEP and has several levels of heterogeneity but once determined the node with high residual energy continues to penalize it, which results in the early death of such a node as shown in Table 2. DEEC also does not account for unequal clustering which can minimize the overall advantage that could have been achieved. Developed DEEC (DDEEC) in [117] is considered that after a few rounds, advanced nodes may contain the same residual energy as the normal nodes, hence the election probability as (CH) is calculated in a similar fashion if that is true. This reduces the consistent penalty on the nodes with high residual energy, but DDEEC only considers two levels of heterogeneity as shown in Table 2, thus ignoring multilevel heterogeneity. Enhanced DDEEC (EDDEEC) [118] enhances DDEEC to three levels of heterogeneity but does not use multi-hop communication between (CH)s. On the other hand, in [119] and [120], two new protocols, LEACH-Energy Association (LEACH-EA) and LEACH-Load Balancing (LEACH-EC), are proposed to improve the energy consumption and thus extend the network lifetime. These two protocols are then evaluated in homogeneous and heterogeneous environments and compared to other protocols, namely LEACH, Threshold sensitive Energy Efficient Sensor Network protocol (TEEN) and SEP. The results obtained showed that these two approaches are significantly better than these protocols in terms of energy consumption and stability. To reduce sensor node energy consumption, several researchers have focused on using K-Means, particularly in large-scale networks. But this research has not given much attention on the impact of K-Means on network performance and quality of service (QoS) metrics such as throughput, energy, latency, etc. [121] applied the K-Means algorithm in the LEACH routing protocol before the CH election to minimize energy consumption. This approach applied K-Means before CH selection and studied the impacts of K-Means on several QoS criteria. Applying K-Means prior to CH election divides the network into K clusters where all nodes in each cluster are very close to the centroid location, making the nodes closer to the CH. As a result, LEACH-K reduced energy consumption and latency, increased network stability time, network lifetime, and throughput. Moreover, [122] proposed the LEACH-G-K protocol to improve the QoS of hierarchical routing protocols. Specifically, LEACH-G-K is based on the LEACH-K protocol. LEACH-G-K divides the area into equal-sized clusters using the grid function. Subsequently, for each cluster, the K-means algorithm is implemented to gather the nodes near the centroid, where the cluster head is located. The simulation results obtained show that LEACH-G-K can improve the energy consumption and QoS criteria compared to LEACH, TEEN, LEACH-K and MDC-maximum residual energy protocols.

Then, [123] proposed a new hybrid protocol MDC-LEACH-K, which is a combination of Low Energy Adaptive Clustering Hierarchy-K-Means LEACH-K (approach) and mobile data collector (MDC), to enhance the LEACH protocol. The goal of this protocol is to extend the lifetime of the network and improve its QoS criteria. This protocol uses the K-Means clustering algorithm to reduce the energy consumption during the CH election phase and to improve the CH election. In addition, it uses an MDC as an intermediary between the cluster leader and the BS to further improve the QoS criteria of the WSN, minimize the delay during the data collection, and improve the transmission phase of the LEACH protocol. This protocol provides a significant energy gain of 296% of the residual energy compared to the LEACH protocol, 237% compared to TEEN and 257% compared to LEACH-K, and more than 100% compared to LEACH, TEEN, LEACH-K and MDC Maximum residual energy LEACH in terms of latency. Therefore, for a dynamic WSN, it is most important to sustain a smart MDC to continue the propagation of data even with the inevitable changes in the WSN topology. Given all the above challenges, [66], [124] propose a novel intelligent MDC based on the Traveling Salesman Problem (TSP) to determine the optimal path traversed by the MDC in terms of energy efficiency and latency. More specifically, the Mobile Data Collectors-Traveling Salesman Problem-Low Energy Adaptive Clustering Hierarchy-K-Means (MDC-TSP-LEACH-K) protocol uses the K-Means and Grid clustering algorithm to reduce energy consumption during the CH election phase. Furthermore, the MDC is used as an intermediary between the CH and the BS to improve WSN QoS, reduce delays during data collection and improve the transmission phase of the LEACH, LEACH-K, LEACH-G-K, MDC-K, MDC-LEACH-K protocols.

Unequal clustering presents a methodological solution to the problem of unbalanced load distribution in hierarchical routing contrary to assisted node deployment. Assisted node deployment is based on the provision of additional energy in the network that is why it is not attractive. Similarly, mobile sink deployment offers balanced load distribution at the cost of increased latency and increased energy. Unequal clustering is also advantageous over variable transmission power nodes due to the provision for multi-hop communication which saves further energy. Hence taxonomy expands major unequal clustering methods.

X. EVALUATION OF EXISTING TECHNIQUES

Table 2 evaluates the existing energy hole mitigation techniques in terms of the level of heterogeneity, unequal clustering deployment, consistent penalty on nodes with high residual energy, inter-cluster communication, network lifetime, stability, and data routing. The table highlights the research gaps in existing balanced load distribution routing methods for many to one communication in WSNs.

It can be seen that some network parameters remain similar throughout all the methods. Such as deployment of nodes is random in majority of methods other than MMS [125] and SEHR [126]. As discussed earlier it should be noted that deployment plays an important role in terms of network lifetime and energy balance. Another evaluation criteria that is consistent across all the methods is the number of cluster heads. Although the number of cluster heads is different, but every method fixes this number once the data transmission phase initiates. Moreover, all the methods considered use simulation as opposed to real world deployment. It is believed that this is due to the ease of operation and cost associated with real world deployment.

As explained earlier some methods produce energy efficiency at the cost of a constant penalty to the high energy nodes, e.g., COCA [114] and SEP [115] whereas the others do not account for multi-hop inter-cluster communication, e.g., EBCAG, DEEC, DDEEC and EDDEEC. Unequal Clustering can be an advantage for balanced load distribution among the network nodes. However, only UCR, EBCAG, COCA, WEMER and UCR-H take advantage of unequal clustering to have balanced load distribution and efficient energy utilization. UCR-H embeds unequal clustering and uses multi-hop inter-cluster communication for multi-levels in many to one communication which is advantageous in order to achieve maximum lifetime. However, it does not account for energy-efficient and balanced load distribution routing in WSN with any other area than rectangular.

A detailed discussion in terms of evaluation criteria used in Table 2 has been presented below:

A. CLUSTERING

There are many parameters that are important in the design of a hierarchical routing method. As discussed above the number of clusters and cluster heads is a very important parameter while comparing different techniques. All the methods considered in this review have a fixed number of cluster heads. However, due to the continuously updated residual energies of devices a dynamic selection of number of cluster heads can result in increased network lifetime. Another important parameter in clustered networks is the size of each cluster. The majority of the clustering methods use equal size clusters but due to multi-hop inter cluster communication relaying load is accumulated on cluster heads closer to base station. To avoid this imbalance in load that results in generation of energy holes, unequal size clusters have been proposed in [112]. This parameter plays a significant role in reducing energy holes and increasing network lifetime. In this review existing energy hole mitigation methods have been evaluated and classified in terms of equal or unequal sized clusters. It can be seen that [93], [94], [95], [96], [97], [98], [99], [100], [105], [115], [116], [117], [118], [125], [126], [127], [128], [129], [130], and [131] use equal clustering and [66], [112], [113], [114], [121], [122], [123], [124], [132], [133], [134] use unequal clustering whereas [119] proposes two techniques LEACH-EA that uses unequal clustering and LEACH-EC that uses equal clustering.

Furthermore, both direct and multi-hop communication methods are used for inter-cluster communication. Where direct communication between cluster heads and base station may be suitable for balanced energy operation, multi-hop inter-cluster communication is energy efficient and increases the overall network lifetime. Table 2 shows that, [66], [93], [94], [96], [97], [113], [114], [115], [116], [117], [118], [119], [121], [122], [123], [124], [127], [131], and [134] use direct communication between cluster heads and base station while [95], [98], [99], [100], [105], [112], [125], [126], [128], [129], [130], [132], and [133] use multi-hop inter cluster communication. This classification allows to determine trade-off between balanced energy operation and energy efficient operation of the network.

B. DEPLOYMENT OF NODES

Deployment of devices or nodes in a network can have a direct impact on the network performance in terms of energy. Firstly, the deployment could be evaluated in terms of initial energies of the nodes deployed. Based on the initial energies network can be characterized into two classes i.e., homogeneous, and heterogeneous network. LEACH [93], LEACH-C [94], HEED [95], CMMAR [4], PEGASIS [97], WSNEHA [98], BECHA [99], EA-BECHA [100], BLOAD [105], UCR [112], EBCAG [113], COCA [114], WEMER [134], MMS [125], MDC [127], SEHR [126], ERNS-EEC [129], UDCH [135], ECUC [132], LEACH-EA [119], LEACH-EC [119], LEACH-K [121], LEACH-G-K [122], MDC-LEACH-K [123], MDC-K [66], MDC-TSP-LEACH-K [66], [124] are among the methods that use homogeneous energy network deployment. On the contrary a heterogeneous energy network can further be classified based on number of different levels considered for the initial energies of nodes. SEP [115], DDEEC [117], and GWO [128] use two levels of initial energies for nodes whereas DEEC [116], EDDEEC [118], UCR-H [133], ETASA and TEAR [136] use multi-levels of heterogeneous energies for the network nodes.

Due to various levels of energy, it is also important to distinguish methods that consistently penalize high energy nodes by selecting them excessively for relaying operations. Table 2 confirms that SEP [115], and DEEC [116] exploit heterogeneity and use nodes with high initial energy as cluster heads for longer times which result in the early death of such nodes and reduces network lifetime. On the contrary, DDEEC [117], EDDEEC [118] are among the methods that constantly examine the residual energy distribution among network nodes to assign cluster head roles.

Another important factor related to deployment that influences network performance in terms of energy is the type of the sink node. As discussed above mobile sink deployment has been used to prioritize the data aggregation from specific regions of the network as well as to balance the relaying load on cluster heads. The majority of the methods considered in this review use stationary sink node except CMMAR [96], MMS [125], and MDC [127] that use mobile sink node to extend network lifetime. However, these methods increase end to end delay.

Lastly, the number of sink nodes deployed can also play a significant role in energy savings of the network. Although, most of the methods consider a single sink node but HEED [95] and MMS [125] are two techniques that use multiple sink nodes. This divides the network into smaller regions and allows energy efficient data gathering operations. However, centralized data collections are timelier and more suitable for collaborative operations in smart city.

C. SCALABILITY AND ADAPTIVITY

Energy hole mitigation techniques can also be evaluated based on scalability and adaptivity. As discussed previously, distance between network nodes and overall size of the node play an important role in network performance. A technique may balance the energy consumption of network in small scale and not be suitable for large scale deployment. In this review energy hole mitigation techniques have also been evaluated in terms of consideration to scalability. Table 2 summarizes that LEACH [93], LEACH-C [94], PEGASIS [97], SEP [115], ERNS-EEC [129], UDCH [135], ECUC [132], LEACH-EA [119], LEACH-EC [119], LEACH-K [121], LEACH-G-K [122], MDC-LEACH-K [123], MDC-K [66], and MDC-TSP-LEACH-K [66], [124] demonstrate scalability of the operation in different size networks whereas the rest of the techniques are limited to specific network sizes considered.

In addition to scalability, adaptivity of the routing method to varying geometric shapes and multi-dimensional network is also important due to varying requirements of IoT enabled smart cities. A technique suitable for circular shape network may not perform well if the shape of the network is slightly changed. For this reason, the techniques have been categorized with reference to the geometric shape and area of the network considered. Techniques that perform well in square shape networks consist of LEACH [93], LEACH-C [94], HEED [95], CMMAR [96], SEP [115], DEEC [116], DDEEC [117], EDDEEC [118], MMS [125], GWO [128], SEHR [126], ERNS-EEC [129], UDCH [135], ETASA & TEAR [136], LEACH-EA [119], LEACH-EC [119], LEACH-K [121], LEACH-G-K [122], MDC-LEACH-K [123], MDC-K [66], (MDC-TSP-LEACH-K [66], [124] whereas PEGASIS [97], UCR [112], COCA [114], UCR-H [133], and MDC [127] perform well in rectangular shape networks. Similarly, WSNEHA [98], BECHA [99], EA-BECHA [100], BLOAD [105], EBCAG [113], WEMER [134], ECUC [132] are the techniques that perform well in circular shape networks.

Moreover, it is important to explore the performance of these techniques in 3-dimensional deployment of nodes as majority of applications of IoT enabled smart city are in 3 dimensions.

D. DATA TRAFFIC AND ROUTING

Although table 2 consists of hierarchical routing techniques only a few of these include further details of the routing. This has also been summarized in table 2 e.g., LEACH [93], LEACH-C [94] use hierarchical routing with probability-based selection of cluster heads. CMMAR [4], MDC [127], MMS [125] and MDC-LEACH-K [123] use hierarchical routing supported by mobile data collector. WSNEHA [98] uses a routing table based on the data send table. In ERNS-EEC [129], and MMS [125] relay nodes are used in addition to cluster heads of hierarchical routing. COCA [114] and TEAR [136] use energy aware hierarchical routing to enhance network lifetime. GWO [128] uses improved shuffled frog leaping algorithm to balance load on the cluster heads. This algorithm works for both equal and unequal loads on sensor nodes. EBCAG [113] is a Gradient-based Routing and sets up a gradient value for each sensor according to the minimum hop count towards sink. Finally, WEMER [134] uses a chain-based routing similar to PEGASIS [97] in a sectoring-based network division to increase network lifetime.

In terms of evaluation matrix, it is seen that first order radio model is used with power control between free space and multi path power levels. Additionally, transmission power levels are considered for each technique majority of techniques considered have adjustable transmission power levels to communicate data in a hierarchical routing manner to the base station.

Finally, the techniques have been evaluated on basis of their throughput or packet delivery ratio as shown in Table 2. Table 2 summarizes that in 500 rounds of operation EA-BECHA [8] has a packet drop ratio of 35% less than that of WSNEHA [98], SEHR [126] delivers between 16×10^4 to 18×10^4 packets during complete operation, UDCH [135] receives 610,000 packets during 2000 rounds, LEACH-K [28] delivers 30017 packets when K=10, LEACH-G-K [122] delivers 15292 packets, MDC-LEACH-K [123] delivers 27865 packets, MDC-K [66] delivers 18300 packets per round and MDC-TSP-LEACH-K [66], [124] delivers 18910 packets per round.

E. NETWORK LIFETIME AND STABILITY

Network lifetime and stability are the primary criteria used for evaluation of existing energy hole mitigation approaches in this review. Table 2 draws a comparison between existing techniques in terms of network lifetime based on several criteria. Various criteria have been used to demonstrate network lifetime and stability such as round of operation in which first node dies (FND), and last node dies (LND) are two widely used criteria for determining the network lifetime. The less the difference between FND and LND the better the stability. To remove energy holes stability is important but it should not be achieved at the cost of decrease in overall network lifetime. Similarly, another criterion used to determine network lifetime is the amount of data transmitted at the time when first node dies, or last node dies as opposite to the round of operation as different methods use different number of bits for each transmission. Also, some techniques demonstrate performance evaluation with respect to the time duration from the start of the network till the first or last node dies instead of the number of rounds of operation.

It can be seen in table 2 that the operation time of LEACH [1] till the first and last nodes dies is 8 and 3 times longer respectively as compared to minimum-transmission-energy routing protocol. When initial energy of homogeneous nodes is chosen to be 0.5J, the network lifetime of LEACH on FND and LND scales is 932 and 1312 rounds, respectively. However, if the initial energy is set as 1J, LEACH gives FND=1848 rounds and LND=2608 rounds.

In LEACH-C [94] authors measure the amount of data packets delivered against number of alive nodes to illustrate the network lifetime. On this scale LEACH-C delivers 10 times more data even though operation time is less than MTE. Homogeneous initial energy of network nodes is considered as 2J. LEACH-C delivers about 40% more data per unit energy than LEACH. End to end delay time is calculated based on total number of nodes, average number of hops to the sink and time to traverse a single hop. It can be concluded that more data in LEACH-C can be traversed in each amount of time as compared to LEACH and MTE.

HEED [95] is hybrid between hierarchical and chain-based routing methods and is suitable for large scale networks.

AQ:5 **TABLE 2.** **Comparison of existing methods in literature for balanced energy routing.**

Clustering Method / Technique	*Unequal Clustering*	*Multi-Hop Inter Cluster Comm.*	*Level of Heterogeneity*	*Penalty to Advance nodes*	*Deployment of nodes*	*Scalability*	*Sink Node (Stationary / Mobile)*	*Simulation Tool Used*	*No. of Sink Nodes*	*No. of CHs*	*Real World /simulation based*	*Network Lifetime*	*Packet Delivery Ratio*	*Energy Consumption*	*End to End Delay*	*Routing protocols*	*Transmission Range*	*Sensor Field*
LEACH [93]	×	×	0	N/A	Random	✓	Stationary	MATLAB	1	Fixed	Sim	Initial energy=0.5J FND=932 LND=1312 Initial energy=1J FND=1848 LND=2608	-	4 to 8 times reduction as compared with MTE routing	-	Hierarchical (probability based) routing.	All nodes are assumed to be in communication range.	Square
LEACH-C [94]	×	×	0	N/A	Random	✓	Stationary	Network Simulator NS	1	Fixed	Sim	LEACH-C can deliver ten times more amount of data during network lifetime.	-	Initial energy=2J. LEACH-C delivers about 40% more data per unit energy than LEACH	More data in LEACH-C during a period as compared to LEACH and MTE	Hierarchical (probability based)	All nodes are assumed to be in communication range.	Square (100 × 100)
HEED [95]	×	✓	0	N/A	Non-Uniform	×	Stationary	MATLAB	Multiple	Fixed	Sim	-	-	-	-	Hybrid	Two nodes communicate using the same transmission power.	Square (2,000 × 2,000)
CMMAR [96]	×	×	0	N/A	Rand	×	Mobile	NS-2	1	Fixed	Sim	FND = 400^{th} round	-	12.5% less than PEGASIS and 60% less than LEACH	4% less than LEACH and 70% less than PEGASIS.	Cluster Chain Mobile Agent Routing	Variable i.e., $30m$ for $100m \times 100m$ and $50m$ for $500m \times 500m$	Square ($100m \times 100m$)
WSNEHA [98]	×	✓	0	N/A	Rand	×	Stationary	MATLAB	1	Fixed	Sim	lifetime increased up to 361.92% when r=60	-	Energy consumption decreased up to 78.35%	-	Routing Table based on the data send table	Variable (10m, 20m, 30m, 60m, 90m, 120m)	Circular ($500m$)
BECHA & EA-BECHA [99], [100]	×	✓	0	N/A	Rand	×	Stationary	MATLAB	1	NA	Sim	BECHA: 13% and 100% more than WSNEHA and ECMSE. FND=2*10^2 rounds EA-BECHA: 58% and 166% more than WSNEHA and ECMSE	r = 10, 9×10^4 bits of data are transmitted with energy dissipation 6 mJ. When r= 100, 0.1×10^4 bits of data are transmitted with energy consumption 1mJ. EA-BECHA: In 500 rounds the packet drop ratio is 35% less than WSNEHA	EA-BECHA: 25% less than WSNHEA and 51% less than ECMSE	More latency as compared to WSNEHA.	Energy aware routing	Variable Transmission range	Circular ($250m$)
PEGASIS [97]	×	×	0	N/A	Rand	✓	Stationary	MATLAB	1	NA	Sim	In minimum total energy algorithm FND is15% to 30% more than closest neighbour algorithm.	-	Initial energy = 0.5 to 1J. Minimum total energy algorithm has consumption that is only 10% of closest neighbour algorithm. For multiple chains minimum total energy algorithm energy consumption is 40% of closest neighbour algorithm.	-	Two chain-based routing protocols have been proposed	-	Chain (*Rectangular*)

TABLE 2. ***(Continued.)*** **Comparison of existing methods in literature for balanced energy routing.**

BLOAD [105]	×	✓	0	N/A	Random	×	Stationary	MATLAB	1	Fixed	Sim	FNDT=20s as compared 5s and 10s in NRF and Homo-BR respectively ANDT of Homo-Bload=100s in comparison to 90s in Homo-BR and NRF. Hetero-BR has 5% better stability than Homo-BLOAD	10 Packets/s considered. Packet load distribution is done by the packet distribution table as a result of the weight mechanism.	Initial Energy = 1J Homogeneous scenario. Energy consumption of BLOAD in heterogeneous scenario is more than Hetero-BR.	-	-	Adjustable transmission i.e., Three transmission ranges i.e., r, 2r and dtx	Circular ($1000m$)
UCR [112]	✓	✓	0	N/A	Random	×	Stationary	MATLAB	1	Fixed	Sim	Residual energy of each node is balanced by unequal transmission load on cluster heads.	-	Higher overall energy consumption	-	Unequal clustered routing	Each sensor has adjustable power control capabilities.	Rectangular
EBCAG [113]	✓	×	0	N/A	Random	×	Stationary	MATLAB	1	Fixed	Sim	Until 5% of the nodes die. For a network of 400 nodes stability is 35 rounds and for a network of 800 nodes it is 24 rounds.	-	Overall energy consumption not given	-	Gradient-based Routing	-	Circular
COCA [114]	✓	×	0	N/A	Random	×	Stationary	NS-2	1	Fixed	Sim	Network lifetime improved between 166 to 229 percent as compared to UCR for different network sizes.	-	Initial energy of each node = 2J	-	Energy aware routing	Maximum transmission range	Rectangular
SEP [115]	×	×	2 Level	✓	Random	✓	Stationary	MATLAB	1	Fixed	Sim	Stable region of SEP is extended compared to LEACH by 8% to 26% depending upon the percentage of advanced nodes.	More than LEACH and FAIR.	-	-	Advanced Nodes are used.	-	N/A
DEEC [116]	×	×	Multi-Level	✓	Random	×	Stationary	MATLAB	1	Fixed	Sim	DEEC obtains 20% more number of round than LECH-E. FND=969 rounds LND=5536 rounds	More than LECH-E and SEP	-	-	Advance, and super nodes are used	-	Square ($100m \times 100m$)
DDEEC [117]	×	×	2 Level	No	Random	×	Stationary	MATLAB	1	Fixed	Sim	30% more lifetime than SEP and 15% more than DEEC in terms of FND. FND=1355 rounds LND=5673 rounds	-	-	-	Advance nodes are used for relaying most of data	-	Square ($100m \times 100m$)
EDDEEC [118]	×	×	Multi-Level	No	Random	×	Stationary	MATLAB	1	Fixed	Sim	FND=1717 rounds LND=8638 rounds	More than EDEEC and DDEEC and DEEC	20 Normal nodes having E0, 32 advanced nodes having 2Eo and 48 super nodes containing 3.5Eo	-	-	-	Square ($100m \times 100m$)
UCR-H [133]	✓	✓	Multi-Level	NA	Random	×	Stationary	MATLAB	1	Fixed	Sim	Roughly around 1500 rounds FND based on node density.	-	Balanced energy consumption among clusters in different units.	-	-	According to distance it is adjustable	Rectangular

TABLE 2. ***(Continued.)*** **Comparison of existing methods in literature for balanced energy routing.**

WEMER [136]	✓	×	0	NA	Random	×	Stationary	MATLAB	1	Fixed	Sim	FND=582 rounds. HND=1128 rounds LND=1478 rounds	-	Initial Energy 0.5J. Average energy cost=0.042847J	High	Chain constructio n.	Threshold distance in a sector dth.	Circular
MMS [125]	×	✓	0	NA	Variable	×	Mobile	MATLAB	Multiple	Fixed	Sim	FND=409 rounds HND=482 rounds Total remaining energy in 200th round is 14.387J which is more than LEACH (10.605J), MOFCA (11.228J) and OPT-LEACH (13.945J)	-	Initial energy is 0.25J. Proposed method optimizes energy consumption 19% in terms of FND and HND scales.	-	Hierarchica l routing supported by relay nodes and cluster heads	Each sensor can adjust strength of its transmission signal	Square ($200m \times 200m$)
MDC [127]	×	×	0	NA	Uniform	×	Mobile	MATLAB	1	Fixed	Sim	Number of rounds when first node dies is between 6000-7000 and when last node dies are between 8000-9000	-	Initial energy=5J. Due to transmission range and adjustable speed of MDC the network achieves less average energy consumption of a node.	-	Mobile Data Collector	Adjustable	3D Rectangular
GWO [128]	×	✓	2 Level	NA	Random	×	Stationary	MATLAB	1	Fixed	Sim	FND between 800-900 and HND between 900-1100 rounds depending upon the number of sensor nodes.	-	Less than 250J for equal load and less than 230J for unequal load with 100 sensor nodes.	-	Improved Shuffled Frog Leaping Algorithm (ISLFA)	-	Square ($50m \times 50m$)
SEHR [126]	×	✓	0	NA	Variable	×	Stationary	MATLAB	1	Fixed	-	FND=597 rounds LND=251 rounds better than that of DR.	Between 16×10^4 to 16×10^4 packets	-	-	3-tier architecture is used for hierarchical routing.	-	Square ($100m \times 100m$)
ERNS-EEC [129]	×	✓	0	NA	Random	✓	Stationary	MATLAB	1	Fixed	Sim	31 nodes are still alive after 5000 rounds. It does not perform well on FND scale. Only 120 nodes are dead after 1000 rounds	-	Initial Energy=0.5J Due to minimum energy consumption lifetime is between 5000-6000 rounds.	Average time per round is 0.04 seconds	Relay nodes-based routing	-	Square ($200m \times 200m/300m \times 300m$)
UDCH [135]	×	✓	0	NA	Random	✓	Stationary	MATLAB	1	Fixed	Sim	FND=1220 rounds LND=1870 rounds	610,000 packets received during 2000 rounds	Initial energy is 0.3J. Overall residual energy starts to drop below the half of initial energy from 700th rounds.	-	-	-	Square ($200m \times 200m$)
ETASA & TEAR [136]	×	×	Multi-Level	NA	Random	×	Stationary	MATLAB	1	Fixed	Sim	FND is between 1000-1030 rounds. HND is between 2400-2500 rounds. LND is between 3990-4030 rounds.	ETASA delivered slightly more number of packets as compared to TEAR	Initial lower bound energy 0.5J. Average residual energy of ETASA is more than 0.3J during 1500th round while that of TEAR was close to 0.2J.	-	Traffic and Energy Aware Routing (TEAR)	-	Square ($100m \times 100m$)
ECUC [132]	✓	✓	0	NA	Uniform	✓	Stationary	OMNET++	1	Fixed	Sim	22% longer network lifetime than OCCN and 32% longer network lifetime than DBS in small scale network (R=50m) Whereas 16% and 25% longer lifetime than DBS and OCCN in large scale network (R=200m)	-	30% reduction in energy consumption as compared to OCCN and 28% reduction as compared to DBS.	-	Energy-efficient and coverage-guaranteed unequal-sized clustering	Transmission ranges are considered to be adjustable.	Circular

TABLE 2. ***(Continued.)*** **Comparison of existing methods in literature for balanced energy routing.**

LEACH-EA [119]	✓	×	0	N/A	Random	✓	Stationary	MATLAB	1	Fixed	Sim	4200 rounds when number of clusters = 3 and 5000 when nc=5	-	LEACH-EA shows 50% improvement as compared to SEP and 74%		Both equal and unequal clustered routing is tried.	-	Square
LEACH-EC [119]	×											and 5000 for nc=7000.		with respect to LEACH				
LEACH-EC-EA [121]	✓	×	0	N/A	Random	✓	Stationary	MATLAB	1	Fixed	Sim	1600 rounds as compared to 700 rounds for LEACH Lifetime gain LEACH 300% TEEN 20% SEP 82%	-	LEACH 105% SEP 43% TEEN 7%	-	-	-	Square ($100m \times 100m$)
LEACH-K [121]	✓	×	0	N/A	Random	✓	Stationary	MATLAB	1	Fixed	Sim	Stability = 1399 rounds when K=10	30017 packets When K=10	41.497J when K=10	96.1602 when K=10	-	-	Square ($100m \times 100m$)
LEACH-G-K [122]	✓	×	0	N/A	Random	✓	Stationary	MATLAB	1	Fixed	Sim	Stability=352 rounds. Lifetime = 4528 rounds	15292 packets	Initial Energy=0.5J/node Half of the energy (24.95J) is consumed in 745 rounds which was 595 rounds in LEACH and 645 rounds in TEEN.	0.089 ms	Two scenarios first with LEACH and second with TEEN	-	Square ($100m \times 100m$)
MDC-LEACH-K [123]	✓	×	0	N/A	Random	✓	Stationary	MATLAB	1	Fixed	Sim	Stability= 2967 rounds	27865 packets	Residual energy =0.027J when rest LEACH, TEEN, LEACH-K has 0 energy.	0.047 ms	mobile data collector	-	Square ($100m \times 100m$)
MDC-K [66]	✓	×	0	N/A	Random	✓	Stationary	MATLAB	1	Fixed	Sim	Stability=1992 rounds Lifetime=5505 rounds	18300 packets/round	High than LEACH, TEEN, and LEACH-K	50,001 ms	Mobile Data Collector with LEACH	-	Square multiple simulations ($100m \times 100m$) to ($1000m \times 1000m$)
MDC-TSP-LEACH-K [66], [124]	✓	×	0	N/A	Random	✓	Stationary	MATLAB	1	Fixed	Sim	Stability = 2000 rounds Lifetime=7321 rounds	18910 packet/round	-	35,16 ms	MDC with TSP	-	Square multiple simulations ($100m \times 100m$) to ($1000m \times 1000m$)

With initial energy of 4.0J, for each node when performance is evaluated in 2000m × 2000m network, HEED demonstrates a network lifetime between 300 − 450 rounds on FND scale.

Network lifetime of CMMAR [96] on FND scale is 400 rounds. It consumes 12.5% less energy as compared to PEGASIS and 60% less energy than LEACH. CMMAR delivers similar number of packets to LEACH and PEGASIS in 4% and 70% shorter time respectively.

In PEGASIS [97] authors have performed a range of experiments by randomly selecting initial energy of the nodes between 0.5J to 1J and average results are used for evaluation. There are two chain-based data transmission routing algorithms used namely, closest neighbor and minimum total energy algorithm. Minimum total energy algorithm achieves 15% to 30% more lifetime on FND scale as compared to closest neighbor algorithm. For a network of 50 nodes the energy consumption of minimum total energy algorithm with linear chains is 10% of that of closest neighbor algorithm. Whereas, for multiple chains the energy consumption of minimum energy algorithm is 40% of the closest neighbor algorithm. Due to the chain routing type, there is huge end-to-end-delay in its operation.

WSNEHA [98] applies a routing table to balance load on the network nodes out of the first radius in the network. When the first radius is set to 60m, energy consumption with WSNEHA applied is 78% less and lifetime is 361.9% more in comparison to without WSNEHA applied.

Authors in [8] and [99] proposed BECHA and EA-BECHA that extend WSNEHA to reduce the formation of energy holes out of the first. In BECHA an optimal radius has been calculated for WSNEHA to balance the energy consumption of nodes and EA-BECHA enhances BECHA by adding energy aware routing in addition to optimal radius. When $r = 10m$, 0.9×10^4 bits of data are transmitted with an energy consumption of 6mJ, and when $r = 100m$, 0.1×10^4 bits are transmitted with an energy consumption of 1mJ. EA-BECHA consumes 25% less energy than WSNEHA. Moreover, EA-BECHA maintains a packet drop ratio 35% less than WSNEHA.

BLOAD [105] accounts for time interval instead of number of rounds to exhibit the network lifetime. First Node Death Time (FNDT) is 20s as compared to 5s and 10s in Nominal Range Forwarding (NRF) and Homogeneous Balanced Routing (Homo-BR) respectively, when initial energy is set to 1J. Similarly, All Node Death Time ANDT = 100s for BLOAD in comparison to 90s in Homo-BR and NFR. However, when initial energy of nodes is set heterogeneous, Hetero-BR has 5% better stability than Homo-BLOAD.

UCR [112] uses unequal clustering to balance energy consumption among network nodes at the cost of increased overall energy consumption. EBCAG [113] enhances the network lifetime and stability further. Evaluation criteria for network lifetime has been used as the death of 5% nodes. With this criterion in a network of 400 nodes the stability is 35 rounds and becomes 24 rounds if the number of nodes increase to 800. Overall energy consumption has not been used as evaluation parameter in these methods, but stability is the main aim.

COCA [114] is another unequal clustered routing method and improves the network lifetime between 166% to 229% as compared to UCR depending upon the size of the network when initial energy of nodes is set to 2J.

SEP [115] exploits heterogeneity to increase stability of the network and demonstrates 8% to 26% better stability than LEACH depending upon the percentage of advanced nodes used. Similarly, DEEC [116] increases the number of heterogeneity levels and demonstrates 20% rise in network lifetime as compared to LEACH. In DEEC first node dies in 969th round and last node dies in 5536th round of operation.

DDEEC [117] enhances the network lifetime further to 30% more than SEP and 15% more than DEEC so that FND = 1355 rounds and LND = 5673 rounds. EDDEEC [118] is another enhancement of DEEC that achieves FND = 1717 rounds and LND = 8638 rounds when 20 normal nodes with initial energy Eo, 32 advanced nodes with initial energy 2Eo and 48 super nodes containing initial energy of 3.5Eo each are deployed.

In UCR-H [133], FND = 1500 rounds based on the node density in network. This method is more useful for balancing energy consumption in rectangular shape networks. WEMER [134] uses homogeneous energy nodes and achieves FND = 572 rounds, HND = 1128 rounds and LND = 1478 rounds. WEMER uses initial energies = 0.5J for all network nodes and demonstrates an average energy cost of 0.042847J.

MMS [125] with initial energy of 0.25J per node optimizes energy consumption 19% in terms of FND and HND scales making FND = 409 rounds and HND = 482 rounds. Performance evaluation also shows that after 200 rounds residual energy of the complete network is 14.387J for MMS which is more in comparison to that of LEACH (10.65J0), MOFCA (11.2J) and OPT-LEACH (13.945J).

MDC [127] shows variations in network lifetime between 6000-7000 rounds when the first node dies and between 8000-9000 rounds when the last node dies when initial energy of each node is set at 5J.

GWO [128] achieves FND = 800-900 rounds and HND = 900-1100 rounds depending upon the number of sensor nodes in the network. Overall energy consumption is 250J less for equal load and less than 230J for unequal load with 100 nodes network.

When initial energies of 100 homogeneous nodes are set to 0.5J each, SEHR [126] demonstrates FND = 597 in comparison to 403 in Dynamic Routing (DR), which is an improvement of 94 rounds. Similarly, SEHR achieves an improvement of 251 rounds as compared to DR on LND scale.

Network lifetime in ERNS-EEC [129] is measured in terms of number of nodes alive after 5000 rounds. Although the performance of this technique is not good on FND scale, but energy consumption is very low. Only 120 out of 1000 nodes are dead after 1000 rounds and 31 nodes remain alive even after 5000 rounds. On LND scale the network lifetime achieved by this technique is between 5000-6000 rounds.

Energy consumption in UDCH [135] is very low. As shown in Table 2 when the initial energies of homogeneous nodes are set to 0.3J each, after 700th round when the overall residual energy of network drops below half of the initial energy the network is still free from holes. It produces results of network lifetime on FND scale as good as 1220 rounds and LND as 1870 rounds.

ETASA & TEAR proposed in [136] set 0.5J as initial energy of each node for performance evaluation. The performance evaluation exhibits that after 1500th round the average residual energy of ETASA is more than 0.3J and that of TEAR was close to 0.2J. The network lifetime on FND, HND and LND scales is between 1000-1030 rounds, 2400-2500 rounds and 3990-4030 rounds, respectively.

ECUC [132] is a scalable technique that illustrates consistent gain in network lifetime over small scale (R = 50m) as well as large scale (R = 200m) networks. Network lifetime is 22% longer than OCCN and 32% longer than DBS when network is spread over radius of 50m and 16% longer than OCCN and 25% longer than DBS when network size is 200m. In terms of energy consumption ECUC achieves 30% reduction in energy consumption as compared to OCCN and 28% reduction as compared to DBS.

In [119] two variations of LEACH i.e., equal clustering LEACH-EC, and unequal clustering LEACH-EA have been proposed. There is no improvement in stability of network operation using LEACH-EC whereas, LEACH-EA expresses 50% and 74% improvement in overall energy consumption as compared to SEP and LEACH, respectively. Moreover, LEACH-EA confirms that overall network lifetime is 4200, 5000, and 5000 rounds when number of clusters is 3,5, and 7.

In [121] authors have proposed two variations of LEACH i.e., LEACH-K that uses K-Means clustering in LEACH and LEACH-EC-EA. LEACH-K shows an overall energy consumption of 41.497J when K is set to 10 and achieves a stability equal to 1399 rounds which is very high. LEACH-EC-EA enhances this work and gives a 300%, 20% and 82% gain in network lifetime as compared to LEACH, TEEN, and SEP, respectively. LEACH-EC-EA shows a network lifetime of 1600 rounds as compared to LEACH.

For a network of 100 nodes with initial energy = 0.5J/node LEACH-G-K [122] shows that even after 745 rounds 50% of the energy is remaining in comparison to LEACH and TEEN that consume 50% energy in 595th and 645th round respectively. LEACH-G-K completes 4528 rounds of operation over complete lifetime with stability measured as 352 rounds.

MDC-LEACH-K [123] uses a mobile data collector but its stability period is as high as 2967 rounds. Performance in terms of energy consumption is better as it maintains an overall residual energy of 0.027J when LEACH, TEEN and LEACH-K has 0J remaining.

MDC-K [66] shows a lifetime of 5505 rounds when 100 nodes with initial energy = 0.5J/node are deployed in a 100m by 100m network. Stability period of MDC-K is 1992 rounds and energy dissipation is higher than that of LEACH, TEEN, and LEACH-K.

MDC-TSP-LEACH-K [66], [124] uses a mobile data collector by using travelling salesman routing algorithm and provides stability period of 2000 rounds and network lifetime of 7321 rounds. Its energy dissipation is better than LEACH, LEACH-K, TEEN, LEACH-G-K and MDC-K.

F. SIMULATION TOOLS

Various simulation tools are used to evaluate the performance of a wireless network. It is advantageous for a researcher to have a knowledge of simulation tool that was originally used to determine the performance of a specific technique. For this reason, table 2 adds information about simulation tools which were used during the original evaluation of each technique. MATLAB has been seen as prominent tool that is used for evaluation of majority of methods in comparison to network simulator (NS-1 / NS-2 / NS-3) and OMNET++ that are rarely used. MATLAB is used due to its easiness and availability of pre-programmed functions [124]. Furthermore, the mathematics of radio model is easy to be evaluated in MATLAB.

XI. CONCLUSION

Due to increased urbanization trends and integration of modern ICTs in Smart Cities, supported by IoT and WSNs there are huge challenges of increased energy consumption. The challenge of energy consumption has been thoroughly surveyed in Smart City and its enabling technologies, particularly in WSNs and IoT. It is determined that energy efficient routing and clustering can play a significant part in efficient energy utilization of such integrated infrastructures. An outstanding challenge of energy holes that can be a major contributor in this area has been the primary focus of this work. The significance of removal of energy holes on the overall scenario has been highlighted.

A summary of limitations in existing energy hole mitigation techniques has been presented that concludes recent attempts to extend network lifetime and remove energy holes for effective and longer operation of WSN-Assisted IoT devices. Energy holes can be avoided by efficient deployment of nodes, appropriate choice of number and size of (CH)s, optimizing transmission power in relation to the distance of the network nodes and by mobility management of nodes. Due to the wide variety of applications of WSN-Assisted IoT in Smart Cities, application specific methods are not suitable for determining and defining a particular architecture for IoT.

Techniques that have been proposed to avoid energy holes so far, have limitations in terms of scalability and adaptivity. These techniques are designed for area or volume specific applications, whereas Smart City is a huge infrastructure and requires adaptability and scalability in terms of size and geometric shape of the network. Moreover, most of these methods only consider 2D networks and do not perform effectively in 3D. However, most real-life applications are 3D.

A fixed proportion of (CH)s throughout the lifetime of network nodes is another drawback. Modern cities are equipped with a variety of flexible and emerging services. These services perform by making collaborative decisions and generate an intense amount of data. Transmission of this data requires a standard yet flexible, adaptive, and successive routing and clustering technique that can account for homogeneous as well as heterogeneous operations. The standard energy efficient routing is also expected to overcome the challenges of stationery as well as mobile nodes.

For the standardization of future network protocols flexible and modular approaches are required that may perform as pieces of a jigsaw. In order to produce an effective framework for IoT it is important to overcome energy management challenge in a suitable fashion.

REFERENCES

[1] C. Yin, Z. Xiong, H. Chen, J. Wang, D. Cooper, and B. David, "A literature survey on smart cities," *Sci. China Inf. Sci.*, vol. 58, no. 10, pp. 1–18, Oct. 2015, doi: 10.1007/s11432-015-5397-4.

[2] A. Vaquero-García, J. Álvarez-García, and M. Peris-Ortiz, "Urban models of sustainable development from the economic perspective: Smart cities," in *Sustainable Smart Cities* (Innovation, Technology, and Knowledge Management), M. Peris-Ortiz, D. R. Bennett, and D. P.-B. Yábar, Eds. Cham, Switzerland: Springer, 2017, pp. 15–29, doi: 10.1007/978-3-319-40895-8_2.

[3] P. Wlodarczak, "Smart cities—Enabling technologies for future living," in *City Networks*, A. Karakitsiou, A. Migdalas, S. T. Rassia, and P. M. Pardalos, Eds. Cham, Switzerland: Springer, 2017, pp. 1–16, doi: 10.1007/978-3-319-65338-9_1.

[4] L. Atzori, A. Iera, and G. Morabito, "The Internet of Things: A survey," *Comput. Netw.*, vol. 54, no. 15, pp. 2787–2805, Oct. 2010, doi: 10.1016/j.comnet.2010.05.010.

[5] *Ericsson Mobility Report June 2022*. Stockholm, Sweden: Ericsson 2022. [Online]. Available: https://www.ericsson.com/49d3a0/assets/local/reports-papers/mobility-report/documents/2022/ericsson-mobility-report-june-2022.pdf

[6] L. Farhan, S. T. Shukur, A. E. Alissa, M. Alrweg, U. Raza, and R. Kharel, "A survey on the challenges and opportunities of the Internet of Things (IoT)," in *Proc. 11th Int. Conf. Sens. Technol. (ICST)*, Dec. 2017, pp. 1–5, doi: 10.1109/ICSensT.2017.8304465.

[7] E. Estopace. (Jun. 22, 2019). *IDC Forecasts Connected IoT Devices to Generate 79.4ZB of Data in 2025*. FutureIoT. Accessed: Jun. 17, 2023. [Online]. Available: https://futureiot.tech/idc-forecasts-connected-iot-devices-to-generate-79-4zb-of-data-in-2025/
[8] C. Song, M. Liu, J. Cao, Y. Zheng, H. Gong, and G. Chen, "Maximizing network lifetime based on transmission range adjustment in wireless sensor networks," *Comput. Commun.*, vol. 32, no. 11, pp. 1316–1325, Jul. 2009.
[9] G. Hancke, B. Silva, and G. Hancke Jr., "The role of advanced sensing in smart cities," *Sensors*, vol. 13, no. 1, pp. 393–425, Dec. 2012, doi: 10.3390/s130100393.
[10] S. P. Mohanty, U. Choppali, and E. Kougianos, "Everything you wanted to know about smart cities: The Internet of Things is the backbone," *IEEE Consum. Electron. Mag.*, vol. 5, no. 3, pp. 60–70, Jul. 2016, doi: 10.1109/MCE.2016.2556879.
[11] L. Xu, R. Collier, and G. M. P. O'Hare, "A survey of clustering techniques in WSNs and consideration of the challenges of applying such to 5G IoT scenarios," *IEEE Internet Things J.*, vol. 4, no. 5, pp. 1229–1249, Oct. 2017, doi: 10.1109/JIOT.2017.2726014.
[12] H. Yetgin, K. T. K. Cheung, M. El-Hajjar, and L. H. Hanzo, "A survey of network lifetime maximization techniques in wireless sensor networks," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 2, pp. 828–854, 2nd Quart., 2017, doi: 10.1109/COMST.2017.2650979.
[13] J. Singh, R. Kaur, and D. Singh, "A survey and taxonomy on energy management schemes in wireless sensor networks," *J. Syst. Archit.*, vol. 111, Dec. 2020, Art. no. 101782, doi: 10.1016/j.sysarc.2020.101782.
[14] R. Zagrouba and A. Kardi, "Comparative study of energy efficient routing techniques in wireless sensor networks," *Information*, vol. 12, no. 1, p. 42, Jan. 2021, doi: 10.3390/info12010042.
[15] T. Singh, A. Solanki, S. K. Sharma, A. Nayyar, and A. Paul, "A decade review on smart cities: Paradigms, challenges and opportunities," *IEEE Access*, vol. 10, pp. 68319–68364, 2022, doi: 10.1109/ACCESS.2022.3184710.
[16] M. R. Poornima, H. S. Vimala, and J. Shreyas, "Holistic survey on energy aware routing techniques for IoT applications," *J. Netw. Comput. Appl.*, vol. 213, Apr. 2023, Art. no. 103584, doi: 10.1016/j.jnca.2023.103584.
[17] L. G. Anthopoulos, "Understanding the smart city domain: A literature review," in *Transforming City Governments for Successful Smart Cities*, M. P. Rodríguez-Bolívar, Ed. Cham, Switzerland: Springer, 2015, pp. 9–21, doi: 10.1007/978-3-319-03167-5_2.
[18] RAND E. Catriona MANVILLE (RAND Europe). (Jan. 2014). *Mapping Smart Cities in the EU*. Accessed: Jun. 17, 2023. [Online]. Available: https://policycommons.net/artifacts/1339578/mapping-smart-cities-in-the-eu/1949353/
[19] J.-T. Wang, D.-B. Chen, H.-Y. Chen, and J.-Y. Yang, "On pedestrian detection and tracking in infrared videos," *Pattern Recognit. Lett.*, vol. 33, no. 6, pp. 775–785, Apr. 2012.
[20] D. Damen and D. Hogg, "Detecting carried objects from sequences of walking pedestrians," *IEEE Trans. Pattern Anal. Mach. Intell.*, vol. 34, no. 6, pp. 1056–1067, Jun. 2012.
[21] B. Wang, M. Ye, X. Li, F. Zhao, and J. Ding, "Abnormal crowd behavior detection using high-frequency and spatio-temporal features," *Mach. Vis. Appl.*, vol. 23, no. 3, pp. 501–511, May 2012.
[22] L. Calavia, C. Baladrón, J. M. Aguiar, B. Carro, and A. Sánchez-Esguevillas, "A semantic autonomous video surveillance system for dense camera networks in smart cities," *Sensors*, vol. 12, no. 8, pp. 10407–10429, Aug. 2012.
[23] N. Metje, D. N. Chapman, D. Cheneler, M. Ward, and A. M. Thomas, "Smart pipes—Instrumented water pipes, can this be made a reality?" *Sensors*, vol. 11, no. 8, pp. 7455–7475, Jul. 2011.
[24] M. Lin, Y. Wu, and I. Wassell, "Wireless sensor network: Water distribution monitoring system," in *Proc. IEEE Radio Wireless Symp.*, Jan. 2008, pp. 775–778.
[25] I. Stoianov, L. Nachman, S. Madden, and T. Tokmouline, "PIPENETa wireless sensor network for pipeline monitoring," in *Proc. 6th Int. Conf. Inf. Process. sensor Netw.*, 2007, pp. 264–273.
[26] T. Robles, R. Alcarria, D. Martín, A. Morales, M. Navarro, R. Calero, S. Iglesias, and M. López, "An Internet of Things-based model for smart water management," in *Proc. 28th Int. Conf. Adv. Inf. Netw. Appl. Workshops*, May 2014, pp. 821–826, doi: 10.1109/WAINA.2014.129.
[27] X. Fang, S. Misra, G. Xue, and D. Yang, "Smart grid—The new and improved power grid: A survey," *IEEE Commun. Surveys Tuts.*, vol. 14, no. 4, pp. 944–980, 4th Quart., 2012, doi: 10.1109/SURV.2011.101911.00087.
[28] H. Gharavi and R. Ghafurian, "Smart grid: The electric energy system of the future [scanning the issue]," *Proc. IEEE*, vol. 99, no. 6, pp. 917–921, Jun. 2011, doi: 10.1109/JPROC.2011.2124210.
[29] B. A. Akyol, H. Kirkham, S. L. Clements, and M. D. Hadley, "A survey of wireless communications for the electric power system," Pacific Northwest Nat. Lab. (PNNL), Richland, WA, USA, Tech. Rep. PNNL-19084, 2010.
[30] H. E. Brown and S. Suryanarayanan, "A survey seeking a definition of a smart distribution system," in *Proc. 41st North Amer. Power Symp.*, Oct. 2009, pp. 1–7.
[31] J. F. Buford, G. Jakobson, J. Erickson, W. J. Tolone, and W. Ribarsky. (Apr. 2010). *Cyber Security, Situation Management, and Impact Assessment II; and Visual Analytics for Homeland Defense and Security II*. Accessed: Aug. 25, 2019. [Online]. Available: http://adsabs.harvard.edu/abs/2010SPIE.7709E.B
[32] E. Fadel, V. C. Gungor, L. Nassef, N. Akkari, M. G. A. Malik, S. Almasri, and I. F. Akyildiz, "A survey on wireless sensor networks for smart grid," *Comput. Commun.*, vol. 71, pp. 22–33, Nov. 2015, doi: 10.1016/j.comcom.2015.09.006.
[33] A. Ghosal and M. Conti, "Key management systems for smart grid advanced metering infrastructure: A survey," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 3, pp. 2831–2848, 3rd Quart., 2019, doi: 10.1109/COMST.2019.2907650.
[34] V. C. Gungor and F. C. Lambert, "A survey on communication networks for electric system automation," *Comput. Netw.*, vol. 50, no. 7, pp. 877–897, May 2006.
[35] R. Hassan and G. Radman, "Survey on smart grid," in *Proc. IEEE SoutheastCon*, Mar. 2010, pp. 210–213.
[36] Y. Kabalci, "A survey on smart metering and smart grid communication," *Renew. Sustain. Energy Rev.*, vol. 57, pp. 302–318, May 2016, doi: 10.1016/j.rser.2015.12.114.
[37] J. Rodríguez-Molina and D. M. Kammen, "Middleware architectures for the smart grid: A survey on the state-of-the-art, taxonomy and main open issues," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 4, pp. 2992–3033, 4th Quart., 2018, doi: 10.1109/COMST.2018.2846284.
[38] S. Rohjans, M. Uslar, R. Bleiker, J. González, M. Specht, T. Suding, and T. Weidelt, "Survey of smart grid standardization studies and recommendations," in *Proc. 1st IEEE Int. Conf. Smart Grid Commun.*, Oct. 2010, pp. 583–588.
[39] N. Shaukat, S. M. Ali, C. A. Mehmood, B. Khan, M. Jawad, U. Farid, Z. Ullah, S. M. Anwar, and M. Majid, "A survey on consumers empowerment, communication technologies, and renewable generation penetration within smart grid," *Renew. Sustain. Energy Rev.*, vol. 81, pp. 1453–1475, Jan. 2018, doi: 10.1016/j.rser.2017.05.208.
[40] J. Vasconcelos, "Survey of regulatory and technological developments concerning smart metering in the European Union electricity market," Eur. Univ. Inst. Badia Fiesolana, Robert Schuman Centre Adv. Studies, Italy, Tech. Rep. EUI-PP RSCAS 2008/01, 2008.
[41] M. Vogt, F. Marten, and M. Braun, "A survey and statistical analysis of smart grid co-simulations," *Appl. Energy*, vol. 222, pp. 67–78, Jul. 2018, doi: 10.1016/j.apenergy.2018.03.123.
[42] W. Wang, Y. Xu, and M. Khanna, "A survey on the communication architectures in smart grid," *Comput. Netw.*, vol. 55, no. 15, pp. 3604–3629, Oct. 2011.
[43] J. M. Sinopoli, *Smart Buildings Systems for Architects, Owners and Builders*. Oxford, U.K.: Butterworth-Heinemann, 2009.
[44] P. K. D. Pramanik, B. Mukherjee, S. Pal, T. Pal, and S. P. Singh, "Green smart building: Requisites, architecture, challenges, and use cases," in *Green Building Management and Smart Automation*. Hershey, PA, USA: IGI Global, 2020, pp. 1–50. [Online]. Available: https://www.igi-global.com/chapter/green-smart-building/284813, doi: 10.4018/978-1-5225-9754-4.ch001.
[45] S. Sony, S. Laventure, and A. Sadhu, "A literature review of next-generation smart sensing technology in structural health monitoring," *Struct. Control Health Monitor.*, vol. 26, no. 3, p. e2321, Mar. 2019. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/stc.2321
[46] H. Wang, S. Wang, and R. Tang, "Development of grid-responsive buildings: Opportunities, challenges, capabilities and applications of HVAC systems in non-residential buildings in providing ancillary services by fast demand responses to smart grids," *Appl. Energy*, vol. 250, pp. 697–712, Sep. 2019, doi: 10.1016/j.apenergy.2019.04.159.
[47] S. Nižetić, N. Djilali, A. Papadopoulos, and J. J. P. C. Rodrigues, "Smart technologies for promotion of energy efficiency, utilization of sustainable resources and waste management," *J. Cleaner Prod.*, vol. 231, pp. 565–591, Sep. 2019, doi: 10.1016/j.jclepro.2019.04.397.

[48] P. Sundaravadivel, E. Kougianos, S. P. Mohanty, and M. K. Ganapathiraju, "Everything you wanted to know about smart health care: Evaluating the different technologies and components of the Internet of Things for better health," *IEEE Consum. Electron. Mag.*, vol. 7, no. 1, pp. 18–28, Jan. 2018, doi: 10.1109/MCE.2017.2755378.

[49] K. Ullah, M. A. Shah, and S. Zhang, "Effective ways to use Internet of Things in the field of medical and smart health care," in *Proc. Int. Conf. Intell. Syst. Eng. (ICISE)*, Jan. 2016, pp. 372–379.

[50] S. P. Mohanty, *Nanoelectronic Mixed-Signal System Design*. New York, NY, USA: McGraw-Hill, 2015.

[51] O. Hamdi, M. A. Chalouf, D. Ouattara, and F. Krief, "EHealth: Survey on research projects, comparative study of telemonitoring architectures and main issues," *J. Netw. Comput. Appl.*, vol. 46, pp. 100–112, Nov. 2014.

[52] M. Hassanalieragh, A. Page, T. Soyata, G. Sharma, M. Aktas, G. Mateos, B. Kantarci, and S. Andreescu, "Health monitoring and management using Internet-of-Things (IoT) sensing with cloud-based processing: Opportunities and challenges," in *Proc. IEEE Int. Conf. Services Comput.*, Jun. 2015, pp. 285–292.

[53] M. M. Mahmoud, J. J. Rodrigues, and K. Saleem, "Cloud of things for healthcare: A survey from energy efficiency perspective," in *Proc. Int. Conf. Comput. Inf. Sci.*, 2019, pp. 1–7.

[54] M. M. Dhanvijay and S. C. Patil, "Internet of Things: A survey of enabling technologies in healthcare and its applications," *Comput. Netw.*, vol. 153, pp. 113–131, Apr. 2019, doi: 10.1016/j.comnet.2019.03.006.

[55] (Oct. 1, 2012). *Preview: IBM i2 Intelligent Law Enforcement*. Accessed: Aug. 27, 2019. [Online]. Available: http://www-01.ibm.com/common/ssi/showdoc.wss

[56] A. Clemente, J. Martínez-de Dios, and A. O. Baturone, "A WSN-based tool for urban and industrial fire-fighting," *Sensors*, vol. 12, no. 11, pp. 15009–15035, Nov. 2012, doi: 10.3390/s121115009.

[57] C. Park and J. Lee, "Intelligent traffic control based on IEEE 802.11 DCF/PCF mechanisms at intersections," in *Proc. IEEE Veh. Technol. Conf. (VTC Fall)*, Sep. 2011, pp. 1–4, doi: 10.1109/VETECF.2011.6093043.

[58] J. Pérez, F. Seco, V. Milanés, A. Jiménez, J. C. Díaz, and T. De Pedro, "An RFID-based intelligent vehicle speed controller using active traffic signals," *Sensors*, vol. 10, no. 6, pp. 5872–5887, Jun. 2010, doi: 10.3390/s100605872.

[59] S. Djahel, R. Doolan, G.-M. Muntean, and J. Murphy, "A communications-oriented perspective on traffic management systems for smart cities: Challenges and innovative approaches," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 1, pp. 125–151, 1st Quart., 2015, doi: 10.1109/COMST.2014.2339817.

[60] A. Andrae and T. Edler, "On global electricity usage of communication technology: Trends to 2030," *Challenges*, vol. 6, no. 1, pp. 117–157, Apr. 2015, doi: 10.3390/challe6010117.

[61] F. Creutzig, G. Baiocchi, R. Bierkandt, P.-P. Pichler, and K. C. Seto, "Global typology of urban energy use and potentials for an urbanization mitigation wedge," *Proc. Nat. Acad. Sci. USA*, vol. 112, no. 20, pp. 6283–6288, May 2015.

[62] C. Harrison, B. Eckman, R. Hamilton, P. Hartswick, J. Kalagnanam, J. Paraszczak, and P. Williams, "Foundations for smarter cities," *IBM J. Res. Develop.*, vol. 54, no. 4, pp. 1–16, Jul. 2010, doi: 10.1147/JRD.2010.2048257.

[63] P. Liu and Z. Peng, "China's smart city pilots: A progress report," *Computer*, vol. 47, no. 10, pp. 72–81, Oct. 2014.

[64] L. Helali and M. N. Omri, "A survey of data center consolidation in cloud computing systems," *Comput. Sci. Rev.*, vol. 39, Feb. 2021, Art. no. 100366, doi: 10.1016/j.cosrev.2021.100366.

[65] J. Gubbi, R. Buyya, S. Marusic, and M. Palaniswami, "Internet of Things (IoT): A vision, architectural elements, and future directions," *Future Gener. Comput. Syst.*, vol. 29, no. 7, pp. 1645–1660, Sep. 2013, doi: 10.1016/j.future.2013.01.010.

[66] R. Gantassi, Z. Masood, and Y. Choi, "Enhancing QoS and residual energy by using of grid-size clustering, K-means, and TSP algorithms with MDC in LEACH protocol," *IEEE Access*, vol. 10, pp. 58199–58211, 2022, doi: 10.1109/ACCESS.2022.3178434.

[67] Y. Mehmood, F. Ahmad, I. Yaqoob, A. Adnane, M. Imran, and S. Guizani, "Internet-of-Things-based smart cities: Recent advances and challenges," *IEEE Commun. Mag.*, vol. 55, no. 9, pp. 16–24, Sep. 2017, doi: 10.1109/MCOM.2017.1600514.

[68] J. Lin, W. Yu, N. Zhang, X. Yang, H. Zhang, and W. Zhao, "A survey on Internet of Things: Architecture, enabling technologies, security and privacy, and applications," *IEEE Internet Things J.*, vol. 4, no. 5, pp. 1125–1142, Oct. 2017, doi: 10.1109/JIOT.2017.2683200.

[69] M. Leo, F. Battisti, M. Carli, and A. Neri, "A federated architecture approach for Internet of Things security," in *Proc. Euro Med Telco Conf. (EMTC)*, Nov. 2014, pp. 1–5.

[70] K. Finkenzeller, *RFID Handbook: Fundamentals and Applications in Contactless Smart Cards, Radio Frequency Identification and Near-Field Communication*. Hoboken, NJ, USA: Wiley, 2010.

[71] X. He, "The two-dimensional bar code application in book management," in *Proc. Int. Conf. Web Inf. Syst. Mining*, vol. 1, Oct. 2010, pp. 409–411.

[72] R. Muniz, L. Junco, and A. Otero, "A robust software barcode reader using the Hough transform," in *Proc. Int. Conf. Inf. Intell. Syst.*, 1999, pp. 313–319.

[73] X. Du, Y. Xiao, M. Guizani, and H.-H. Chen, "An effective key management scheme for heterogeneous sensor networks," *Ad Hoc Netw.*, vol. 5, no. 1, pp. 24–34, Jan. 2007, doi: 10.1016/j.adhoc.2006.05.012.

[74] J. Nakamura, *Image Sensors and Signal Processing for Digital Still Cameras*. Boca Raton, FL, USA: CRC Press, 2017.

[75] Y. Xiao, V. K. Rayi, B. Sun, X. Du, F. Hu, and M. Galloway, "A survey of key management schemes in wireless sensor networks," *Comput. Commun.*, vol. 30, nos. 11–12, pp. 2314–2341, Sep. 2007.

[76] F.-J. Wu, Y.-F. Kao, and Y.-C. Tseng, "From wireless sensor networks towards cyber physical systems," *Pervas. Mobile Comput.*, vol. 7, no. 4, pp. 397–413, Aug. 2011.

[77] L. D. Xu, W. He, and S. Li, "Internet of Things in industries: A survey," *IEEE Trans. Ind. Informat.*, vol. 10, no. 4, pp. 2233–2243, Nov. 2014, doi: 10.1109/TII.2014.2300753.

[78] K. Latif, N. Javaid, and M. Saqib, "Energy hole minimization techniques in wireless sensor networks," COMSATS Inst. Inf. Technol. Islamabad, Islamabad, Pakistan, Tech. Rep. CIIT/SP12-PCS-001/ISB, 2016, doi: 10.13140/RG.2.2.32778.77762.

[79] B. Tong, G. Wang, W. Zhang, and C. Wang, "Node reclamation and replacement for long-lived sensor networks," *IEEE Trans. Parallel Distrib. Syst.*, vol. 22, no. 9, pp. 1550–1563, Sep. 2011.

[80] A.-F. Liu, P.-H. Zhang, and Z.-G. Chen, "Theoretical analysis of the lifetime and energy hole in cluster based wireless sensor networks," *J. Parallel Distrib. Comput.*, vol. 71, no. 10, pp. 1327–1355, Oct. 2011, doi: 10.1016/j.jpdc.2011.05.003.

[81] X. Jiang, J. Polastre, and D. Culler, "Perpetual environmentally powered sensor networks," in *Proc. 4th Int. Symp. Inf. Process. Sensor Netw.*, 2005, p. 65.

[82] A. Kansal, J. Hsu, S. Zahedi, and M. B. Srivastava, "Power management in energy harvesting sensor networks," *ACM Trans. Embedded Comput. Syst.*, vol. 6, no. 4, p. 32, Sep. 2007.

[83] M. Rahimi, H. Shah, G. S. Sukhatme, J. Heideman, and D. Estrin, "Studying the feasibility of energy harvesting in a mobile sensor network," in *Proc. IEEE Int. Conf. Robot. Automat.*, Sep. 2003, pp. 19–24.

[84] T. Voigt, H. Ritter, and J. Schiller, "Utilizing solar power in wireless sensor networks," in *Proc. 28th Annu. IEEE Int. Conf. Local Comput. Netw.*, Oct. 2003, pp. 416–422.

[85] A. Kurs, A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher, and M. Soljačić, "Wireless power transfer via strongly coupled magnetic resonances," *Science*, vol. 317, no. 5834, pp. 83–86, Jul. 2007.

[86] L. Xie, Y. Shi, Y. T. Hou, and H. D. Sherali, "Making sensor networks immortal: An energy-renewal approach with wireless power transfer," *IEEE/ACM Trans. Netw.*, vol. 20, no. 6, pp. 1748–1761, Dec. 2012.

[87] I. Talzi, A. Hasler, S. Gruber, and C. Tschudin, "PermaSense: Investigating permafrost with a WSN in the Swiss Alps," in *Proc. 4th workshop Embedded networked sensors*, Jun. 2007, pp. 8–12.

[88] G. Anastasi, M. Conti, M. Di Francesco, and A. Passarella, "Energy conservation in wireless sensor networks: A survey," *Ad Hoc Netw.*, vol. 7, no. 3, pp. 537–568, May 2009.

[89] K. C. Barr and K. Asanović, "Energy-aware lossless data compression," *ACM Trans. Comput. Syst.*, vol. 24, no. 3, pp. 250–291, Aug. 2006.

[90] G. J. Pottie and W. J. Kaiser, "Wireless integrated network sensors," *Commun. ACM*, vol. 43, no. 5, pp. 51–58, May 2000.

[91] W. Ejaz, M. Naeem, A. Shahid, A. Anpalagan, and M. Jo, "Efficient energy management for the Internet of Things in smart cities," *IEEE Commun. Mag.*, vol. 55, no. 1, pp. 84–91, Jan. 2017, doi: 10.1109/MCOM.2017.1600218CM.

[92] J. N. Al-Karaki and A. E. Kamal, "Routing techniques in wireless sensor networks: A survey," *IEEE Wireless Commun.*, vol. 11, no. 6, pp. 6–28, Dec. 2004, doi: 10.1109/MWC.2004.1368893.

[93] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks," in *Proc. 33rd Annu. Hawaii Int. Conf. Syst. Sci.*, 2000, p. 10, doi: 10.1109/HICSS.2000.926982.

[94] W. B. Heinzelman, A. P. Chandrakasan, and H. Balakrishnan, "An application-specific protocol architecture for wireless microsensor networks," *IEEE Trans. Wireless Commun.*, vol. 1, no. 4, pp. 660–670, Oct. 2002, doi: 10.1109/TWC.2002.804190.

[95] O. Younis and S. Fahmy, "HEED: A hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks," *IEEE Trans. Mobile Comput.*, vol. 3, no. 4, pp. 366–379, Oct. 2004, doi: 10.1109/TMC.2004.41.

[96] S. Sasirekha and S. Swamynathan, "Cluster-chain mobile agent routing algorithm for efficient data aggregation in wireless sensor network," *J. Commun. Netw.*, vol. 19, no. 4, pp. 392–401, Aug. 2017.

[97] K. Du, J. Wu, and D. Zhou, "Chain-based protocols for data broadcasting and gathering in the sensor networks," in *Proc. Int. Parallel Distrib. Process. Symp.*, Apr. 2003, pp. 1–8.

[98] Y. Xue, X. Chang, S. Zhong, and Y. Zhuang, "An efficient energy hole alleviating algorithm for wireless sensor networks," *IEEE Trans. Consum. Electron.*, vol. 60, no. 3, pp. 347–355, Aug. 2014.

[99] N. Jan, A. R. Hameed, B. Ali, R. Ullah, K. Ullah, and N. Javaid, "A wireless sensor networks balanced energy consumption protocol," in *Proc. 31st Int. Conf. Adv. Inf. Netw. Appl. Workshops (WAINA)*, Mar. 2017, pp. 730–736, doi: 10.1109/WAINA.2017.122.

[100] N. Jan, N. Javaid, Q. Javaid, N. Alrajeh, M. Alam, Z. A. Khan, and I. A. Niaz, "A balanced energy-consuming and hole-alleviating algorithm for wireless sensor networks," *IEEE Access*, vol. 5, pp. 6134–6150, 2017.

[101] H. Xin and X. Liu, "Energy-balanced transmission with accurate distances for strip-based wireless sensor networks," *IEEE Access*, vol. 5, pp. 16193–16204, 2017.

[102] N. Javaid, T. Hafeez, Z. Wadud, N. Alrajeh, M. S. Alabed, and N. Guizani, "Establishing a cooperation-based and void node avoiding energy-efficient underwater WSN for a cloud," *IEEE Access*, vol. 5, pp. 11582–11593, 2017, doi: 10.1109/ACCESS.2017.2707531.

[103] R. Yarinezhad and A. Sarabi, "Reducing delay and energy consumption in wireless sensor networks by making virtual grid infrastructure and using mobile sink," *AEU-Int. J. Electron. Commun.*, vol. 84, pp. 144–152, Feb. 2018.

[104] L. Kong, K. Ma, B. Qiao, and X. Guo, "Adaptive relay chain routing with load balancing and high energy efficiency," *IEEE Sensors J.*, vol. 16, no. 14, pp. 5826–5836, Jul. 2016.

[105] I. Azam, N. Javaid, A. Ahmad, W. Abdul, A. Almogren, and A. Alamri, "Balanced load distribution with energy hole avoidance in underwater WSNs," *IEEE Access*, vol. 5, pp. 15206–15221, 2017, doi: 10.1109/ACCESS.2017.2660767.

[106] X. Liu and P. Zhang, "Data drainage: A novel load balancing strategy for wireless sensor networks," *IEEE Commun. Lett.*, vol. 22, no. 1, pp. 125–128, Jan. 2018, doi: 10.1109/LCOMM.2017.2751601.

[107] P. Chatterjee, S. C. Ghosh, and N. Das, "Load balanced coverage with graded node deployment in wireless sensor networks," *IEEE Trans. Multi-Scale Comput. Syst.*, vol. 3, no. 2, pp. 100–112, Apr. 2017, doi: 10.1109/TMSCS.2017.2672553.

[108] H. H. Ekal, J. Abdullah, A. Jamil, L. Audah, and R. Alias, "Energy balance mechanism for improving the lifetime in dense centric wireless sensor networks," in *Proc. IEEE 7th Annu. Inf. Technol., Electron. Mobile Commun. Conf. (IEMCON)*, Oct. 2016, pp. 1–7, doi: 10.1109/IEMCON.2016.7746088.

[109] A. Ghosal and S. Halder, "Lifetime optimizing clustering structure using archimedes' spiral-based deployment in WSNs," *IEEE Syst. J.*, vol. 11, no. 2, pp. 1039–1048, Jun. 2017, doi: 10.1109/JSYST.2015.2434498.

[110] W. K. Lai and C.-S. Fan, "Novel node deployment strategies in corona structure for wireless sensor networks," *IEEE Access*, vol. 5, pp. 3889–3899, 2017, doi: 10.1109/ACCESS.2017.2681124.

[111] Y. Zhou, N. Wang, and W. Xiang, "Clustering hierarchy protocol in wireless sensor networks using an improved PSO algorithm," *IEEE Access*, vol. 5, pp. 2241–2253, 2017, doi: 10.1109/ACCESS.2016.2633826.

[112] G. Chen, C. Li, M. Ye, and J. Wu, "An unequal cluster-based routing protocol in wireless sensor networks," *Wireless Netw.*, vol. 15, no. 2, pp. 193–207, Feb. 2009.

[113] T. Liu, Q. Li, and P. Liang, "An energy-balancing clustering approach for gradient-based routing in wireless sensor networks," *Comput. Commun.*, vol. 35, no. 17, pp. 2150–2161, Oct. 2012.

[114] H. Li, Y. Liu, W. Chen, W. Jia, B. Li, and J. Xiong, "COCA: Constructing optimal clustering architecture to maximize sensor network lifetime," *Comput. Commun.*, vol. 36, no. 3, pp. 256–268, Feb. 2013, doi: 10.1016/j.comcom.2012.10.006.

[115] G. Smaragdakis, I. Matta, and A. Bestavros, "SEP: A stable election protocol for clustered heterogeneous wireless sensor networks," in *Proc. 2nd Int. Workshop Sensor Actor Network Protocols Appl. (SANPA)*, vol. 3, Aug. 2004.

[116] L. Qing, Q. Zhu, and M. Wang, "Design of a distributed energy-efficient clustering algorithm for heterogeneous wireless sensor networks," *Comput. Commun.*, vol. 29, no. 12, pp. 2230–2237, Aug. 2006.

[117] B. Elbhiri, R. Saadane, S. El fldhi, and D. Aboutajdine, "Developed distributed energy-efficient clustering (DDEEC) for heterogeneous wireless sensor networks," in *Proc. 5th Int. Symp. I/V Commun. Mobile Netw.*, Sep. 2010, pp. 1–4.

[118] N. Javaid, T. N. Qureshi, A. H. Khan, A. Iqbal, E. Akhtar, and M. Ishfaq, "EDDEEC: Enhanced developed distributed energy-efficient clustering for heterogeneous wireless sensor networks," *Proc. Comput. Sci.*, vol. 19, pp. 914–919, Jan. 2013.

[119] R. Gantassi, A. B. Yagouta, and B. B. Gouissem, "Improvement of the LEACH protocol in load balancing and energy-association conservation," in *Proc. Int. Conf. Internet Things, Embedded Syst. Commun. (IINTEC)*, Oct. 2017, pp. 53–59, doi: 10.1109/IINTEC.2017.8325913.

[120] R. Gantassi, Z. Masood, S. Lim, Q. A. Sias, and Y. Choi, "Performance analysis of machine learning algorithms with clustering protocol in wireless sensor networks," in *Proc. Int. Conf. Artif. Intell. Inf. Commun. (ICAIIC)*, Feb. 2023, pp. 543–546, doi: 10.1109/ICAIIC57133.2023.10067019.

[121] R. Gantassi, B. B. Gouissem, and J. B. Othmen, "Routing protocol LEACH-K using K-means algorithm in wireless sensor network," in *Web, Artificial Intelligence and Network Applications* (Advances in Intelligent Systems and Computing), L. Barolli, F. Amato, F. Moscato, T. Enokido, and M. Takizawa, Eds. Cham, Switzerland: Springer, 2020, pp. 299–309, doi: 10.1007/978-3-030-44038-1_27.

[122] R. Gantassi, B. B. Gouissem, and J. B. Othman, "The use of grid-sizes clustering and K-means algorithms to enhance the QoS in LEACH protocol," in *Proc. IEEE Int. Conf. Commun.*, Jun. 2021, pp. 1–6, doi: 10.1109/ICC42927.2021.9500383.

[123] R. Gantassi, B. B. Gouissem, and J. B. Othman, "Combination of MDC and K-means to improve LEACH," in *Proc. IEEE Int. Conf. Commun.*, Jun. 2021, pp. 1–5, doi: 10.1109/ICC42927.2021.9500909.

[124] R. Gantassi, Z. Masood, and Y. Choi, "Smart mobile data collectors to enhance quality of service in wireless sensor networks," Chonnam Nat. Univ., South Korea, Tech. Rep. rs-2156988, Oct. 2022, doi: 10.21203/rs.3.rs-2156988/v1.

[125] K. Koosheshi and S. Ebadi, "Optimization energy consumption with multiple mobile sinks using fuzzy logic in wireless sensor networks," *Wireless Netw.*, vol. 25, no. 3, pp. 1215–1234, Apr. 2019, doi: 10.1007/s11276-018-1715-2.

[126] S. Kumar, P. R. Gautam, A. Verma, R. Verma, and A. Kumar, "Energy efficient routing using sectors based energy-hole reduction in WSNs," in *Proc. Int. Conf. Electr., Electron. Comput. Eng. (UPCON)*, Nov. 2019, pp. 1–4, doi: 10.1109/UPCON47278.2019.8980254.

[127] R. Vishnuvarthan, R. Sakthivel, V. Bhanumathi, and K. Muralitharan, "Energy-efficient data collection in strip-based wireless sensor networks with optimal speed mobile data collectors," *Comput. Netw.*, vol. 156, pp. 33–40, Jun. 2019, doi: 10.1016/j.comnet.2019.03.019.

[128] D. R. Edla, A. Lipare, R. Cheruku, and V. Kuppili, "An efficient load balancing of gateways using improved shuffled frog leaping algorithm and novel fitness function for WSNs," *IEEE Sensors J.*, vol. 17, no. 20, pp. 6724–6733, Oct. 2017, doi: 10.1109/JSEN.2017.2750696.

[129] A. Shukla and S. Tripathi, "An effective relay node selection technique for energy efficient WSN-assisted IoT," *Wireless Pers. Commun.*, vol. 112, no. 4, pp. 2611–2641, Jun. 2020, doi: 10.1007/s11277-020-07167-8.

[130] F. Zhu and J. Wei, "An energy-efficient unequal clustering routing protocol for wireless sensor networks," *Int. J. Distrib. Sensor Netw.*, vol. 15, no. 9, Sep. 2019, Art. no. 1550147719879384, doi: 10.1177/1550147719879384.

[131] N. M. Shagari, M. Y. I. Idris, R. B. Salleh, I. Ahmedy, G. Murtaza, and H. A. Shehadeh, "Heterogeneous energy and traffic aware sleep-awake cluster-based routing protocol for wireless sensor network," *IEEE Access*, vol. 8, pp. 12232–12252, 2020.

[132] N. Gharaei, Y. D. Al-Otaibi, S. A. Butt, G. Sahar, and S. Rahim, "Energy-efficient and coverage-guaranteed unequal-sized clustering for wireless sensor networks," *IEEE Access*, vol. 7, pp. 157883–157891, 2019, doi: 10.1109/ACCESS.2019.2950237.

[133] L. Yang, Y.-Z. Lu, Y.-C. Zhong, and S. X. Yang, "An unequal cluster-based routing scheme for multi-level heterogeneous wireless sensor networks," *Telecommun. Syst.*, vol. 68, no. 1, pp. 11–26, May 2018.

[134] N. Sharmin, A. Karmaker, W. L. Lambert, M. S. Alam, and M. S. A. Shawkat, ''Minimizing the energy hole problem in wireless sensor networks: A wedge merging approach,'' *Sensors*, vol. 20, no. 1, p. 277, Jan. 2020, doi: 10.3390/s20010277.

[135] (2019). *An Energy-Efficient Unequal Clustering Routing Protocol for Wireless Sensor Networks—Fang Zhu, Junfang Wei*. Accessed: Jun. 17, 2022. [Online]. Available: https://journals.sagepub.com/doi/full/10.1177/1550147719879384

[136] *Heterogeneous Energy and Traffic Aware Sleep-Awake Cluster-Based Routing Protocol for Wireless Sensor Network | IEEE Journals & Magazine | IEEE Xplore*. Accessed: Jun. 17, 2022. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/8954708

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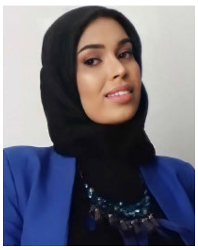

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