Survey on Energy-Efficient and Energy-Balanced WSN Routing Protocols

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Abstract

Wireless sensor network (WSN) is a network comprised of tiny sensor nodes. These sensors are characterized by limited memory, low processing capacity, limited power, and transmission bandwidth. The limited energy constraints inherent in WSNs have triggered an extensive research effort to develop Energy-efficient (EE) and Energy-balanced (EB) routing protocols to prolong the lifetime of the network. This study aims to investigate the overall research productivity and trends of the state-of-the-art research in energy-efficient and energy-balanced routing protocols designed for WSNs. The classification of energy-efficient and energy-balanced routing protocols is also a vital aim of this study. As a result, we conducted a selected relevant study with strict adherence to the pre-defined systematic mapping methodology to ensure unbiased inclusion of the relevant studies. This research provides great insight into the focus of the research community, tools being used, and taxonomies of research conducted in EE and EB WSN protocols for the past decade. In the end, this article also provides a comprehensive discussion of the challenges and future directions.

Keywords—Energy-balanced, Energy-efficient, Routing protocol, Systematic mapping, Wireless sensor network

1 Introduction

Wireless sensor networks (WSNs) technology is receiving a great deal of interest throughout industries as an empowering technique applied in emerging pervasive computing areas [1]. The merger of sensing with wireless communication has upsurged the development of WSNs. At present, it has been used for extensive sort of applications including battlefield surveillance, environmental monitoring, inventory control, health monitoring, ecological control, and target tracking [2, 3]. Thus, the large-scale and commercial application of WSNs is expected to increase considerably.

Generally, WSNs consist of sensor nodes (SNs) with limited energy sources, like batteries. In addition, SNs are installed in an area of interest(AoI) to collect and communicate the information to know the condition of an AoI. This information is to be transferred efficiently to the base station (BS) without relying on any support from pre-existing infrastructure [4]. Because, in some installations, AoI, the battery replacement may become impossible, especially in unfriendly environments such as battlefields, earthquakes, and so on [5]. The SNs in WSNs communicate their sensed data to the BS based on the adopted routing protocol (RP) [6]. An RP defines how the SNs communicate among themselves and enables them to choose the cost-efficient way to deliver their sensed information to the BS. A cost-efficient RP must as much as possible be scalable, robust, and delay-sensitive [6]. Most especially, the RP must be energy conscious to achieve reasonable network duration. This means that it must minimize energy consumption to prolong the lifetime of the network as much as possible. This makes the development of RP a challenging issue as it must try to achieve balance in all these mentioned requirements. Adhering to the rising interest of researchers in optimizing the energy consumption in WSN, a plethora of energy-efficient (EE) and/or energy-balanced (EB) routing techniques have emerged over the years, with many numbers of studies reported in this domain. In addition, there are several review studies on EE/EB

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RPs in the literature that offer various taxonomies, trends, classifications, and challenges. However, most of these aforementioned reviews are limited in coverage, obsolete, or address only specific issues. For example, Singh, Singh [7] reviews only energy-efficient hierarchical cluster-based routing. Similarly, Ogundile and Alfa [6] surveyed EE and EB RPs from 2013 to 2016. But, to the best of our knowledge, systematic mapping studies in this domain are non-existent.

To fill in this research gap, it is very crucial to understand the current state-of-the-art (SoA) research on EE/EB RPs for WSNs to identify areas that need further research effort to support a variety of application domains. To identify the key challenges in this area, we systematically examined the existing protocols/algorithms and provided a comprehensive summarization. As a result, we surveyed selected relevant studies with stick adherence to the pre-defined systematic mapping methodology to ensure unbiased inclusion of the relevant studies. Petersen, Feldt [8] suggested a well-defined evidence-based, and repeatable systematic mapping stage starting from the search approach, inclusion or exclusion criteria, selection procedure, data extraction, and synthesis, which we adopted in this study. This is done by conducting an extensive analysis of the relevant studies published in this domain over the last 10 years (2014 - 2023) to enable new researchers to understand the current trends in terms of the most or least utilized EE/EB routing techniques, most used validation methods and the most used evaluation metrics. In addition, it also enables new researchers to understand the categories of the research facet provided by the selected studies and their distributions, the type of research contributions provided in the selected studies, the most utilized simulation tools, and publication demographics which provides an understanding about the research trends in this domain.

1.1 Research Methodology

1.1.1 Data sources

Four electronic libraries were considered in this study of one decade which are IEEE Xplore, ACM, Springer, and Science Direct. Google Scholar was not considered in this study owing to its low precision and overlapping results from other sources. The list of digital databases and their URLs is given in Table 1.

TABLE 1: Data sources

Digital Library Name	URL
IEEE Xplore	https://ieeexplore.ieee.org/
Science Direct	https://www.sciencedirect.com/
ACM Digital Library	https://dl.acm.org/
SpringerLink	https://link.springer.com

1.1.2 Search terms

To facilitate the collection of the relevant studies, it is essential to formulate effective search strategies.

Given this, our study employed searching strategies suggested by Kitchenham, and Pearl Brereton [9] called population, intervention, and outcome viewpoints. The population refers to technology-related terms such as wireless sensor networks, wireless body networks, etc. The intervention addresses specific issues in WSN such as routing, security, etc. The outcome describes the factors that are of importance to the network practitioners, which include, energy-efficiency, load balancing etc. The strategies have been used by several systematic literature reviews (SLRs). Listed in Table are the relevant terms for our study.

TABLE 2: Search term

SN.	Term	Relevant term
1	Population	Wireless sensor networks
2	Interventions	Routing protocol, routing algorithm
3	Outcome	Energy-efficient, energy-balanced

Following the Kitchenham strategies, generic search terms are formulated to maintain consistency across the multiple digital libraries. (((Wireless sensor networks) AND (Routing protocol OR Routing algorithm)) AND (Energy-efficient OR Energy-balanced)) Our contribution is this study is summarized below. We conducted a systematic mapping study on EE/EB RPs designed for WSNs.

- We presented a taxonomy of the selected studies according to the techniques in which EE/EB RPs are designed to achieve energy efficiency and/or energy balancing.
- We identified some research challenges that essentially be focused on by the researchers in the future.
- Recommendations for future research work are provided.

The rest of the paper is organized as follows. Section 2 presents a review of the related work. The discussion of our findings is presented in section 3. The conclusion is described in section 4.

2 Related Work

Considering energy constraint, which is one of the major characteristics of WSNs, developing EE/EB RPs for WSNs is crucial. Several research efforts are

ongoing to design EE/EB RPs for WSNs. In addition, there have been several survey studies on EE/EB RPs in the literature that offer various taxonomies, trends, classifications, and challenges [10]. This section discusses some of the existing reviews on EE/EB RPs and highlights on the differences between our work and existing surveys in the literature.

An extensive survey on energy-efficient (EE) RPs is carried out in [11]. In this survey, EE RPs were classified according to network topology, reliability, model type for communication, and architecture. In addition, the techniques used by EE RPs to deliver messages were explored. This is done by taking into consideration the energy consumed by each protocol and how it achieved minimized energy consumption. Moreover, the strengths and weaknesses of each protocol are discussed using some metrics such as scalability, mobility support, route metric, and so on.

Dhiman and Singh [12] conducted an in-depth survey on EE RPs in 2015. In this survey, EE RPs were classified according to path establishment, network structure, protocol operation, and swarm intelligence. A brief description of protocols in each category was provided. Moreover, a review of recent advances in EE RPs was presented in [13]. In this survey, EE RPs are classified into two categories according to their orientation and mobility support. According to orientation, EE RPs were classified into homogeneous and heterogeneous. Accordingly, Yan, and Zhou [13] classified EE RPs according to mobility support into static and mobile routing. In addition, the characteristics, limitations, and application of each category were summarized.

Furthermore, in [6], a survey of the various SoAs on energy-efficient and load-balanced energy RPs was presented. In this survey, Ogundile and Alfa [6] presented a taxonomical classification of EE/EB RPs in terms of their modes of communication to BS (i.e., multi-hop communication method and single-hop communication method). In addition, this survey highlighted the strengths and weaknesses of the decision variables used in the design of EE and EB RPs. Moreover, RPs were classified according to the solution types used to solve energy consumption optimization problems. Similarly in [14], a survey was carried out on EE RPs with a specific focus on network structure-based RPs. In this review, the pros and cons of each protocol were highlighted. Akila and Mehswari Akila [15] conducted a survey on recent techniques for energy-efficient routing in WSN. The focus of this survey was on recent approaches adopted to avoid energy consumption. Recently, a comprehensive review of EE hierarchical RPs was presented in [16]. In this review, EE hierarchical RPs were classified based on their design approach into classical and swarm intelligence-based protocols. The summary of the protocol in each category was based on energy efficiency, data aggregation, quality of service (QoS), and so on. However, this survey is limited to only hierarchical RPs. Considering the above-highlighted surveys, it is evident that to the best of our knowledge systematic mapping studies have not been carried out in this domain. Moreover, in the aforementioned surveys, the selected studies were arbitrarily chosen without following evidence-based and repeatable procedures. Furthermore, these surveys have not provided an overview of EE/EB RPs in terms of the most used routing techniques, validation methods, most used evaluation metric, the distribution of research facets, contribution type, the most utilized simulation tools, publication demographics, and so on. In addition, none of the existing reviews provide a reference point to authors of high influence, relevant conferences, and journal sources in this area. Table 3 below summarizes the existing reviews.

2.1 Taxonomy of contribution types

Firstly, the selected studies were classified into research types following the existing classification scheme suggested by Petersen, Feldt [8]. Where, the classification scheme categorized relevant studies based on the existing design approach into validation, evaluation, solution, philosophical, opinion, and experience research. The detailed description of each research type is highlighted in Table 4. However, considering the unique nature of the research topic, validation, evaluation, and solution research types are found to be relevant to our study.

In Table 5, the selected studies were also classified according to the type of contribution they provide following the classification scheme highlighted by Petersen, Feldt [8]. Due to the characteristics of this study area, only method/technique, process, specific solution, and evaluation/comparison classifications are found suitable for our study.

2.2 Taxonomy of techniques

Secondly, the selected studies were classified according to the techniques in which the protocol is designed to achieve energy efficiency and energy balancing as shown in Fig. 1. Several techniques have been used to design RPs to achieve energy efficiency and energy-balancing in WSNs. These techniques include Cluster-based (clustering), multihop, duty-cycling, multi-path, energy harvesting, multi-sink, sink-mobility, and hybrid techniques. Accordingly, this study classified

TABLE 3: Related literature summary

Study	Year	Contribution
[11]	2012	• Provide survey on energy-efficient RPs • Classified routing energy-efficient RPs according to network structure, communication mode, topology, and reliability • The strengths and weaknesses of energy-efficient RPs are discussed based on scalability, mobility support, route metrics, etc.
[14]	2015	• Provides review on energy-efficient RP for wireless sensor networks • Classified energy-efficient RPs according to path establishment, network structure, protocol operation, and swarm intelligence • Provides a brief description of protocols in each category.
[13]	2016	• Provides a review of recent advances in energy-efficient RPs for wireless sensor networks • Classified energy-efficient RPs according to their orientation and mobility support • Discussion on the characteristics, limitations, and application of each category is provided
[6]	2017	• Provides a survey on an energy-efficient and energy-balanced RP for wireless sensor networks • Presented a taxonomical classification of EE/EB RPs in terms of their modes of communication to BS • Highlights the strengths and weakness of the decision variables used in the design of EE/EB RPs
[14]	2017	Provides a survey on energy-efficient RPs with a specific focus on network structure-based RPs Highlights the pros and cons of each protocol
[15]	2018	Provides a survey on recent issues in energy efficiency issues in WSN with a focus on recent approaches to avoiding energy consumption.
[16]	2019	• Provides a comprehensive review on energy efficient hierarchical RPs for WSN • Classified energy-efficient hierarchical RPs based on their design approach into classical and swarm intelligence-based protocols • Provides a summary of the protocol in each category according to energy efficiency, data aggregation, QoS, and so on.
[17]	2020	• Provides a detailed systematic literature review on energy-efficient RP in WSN. • Revealed that energy consumption is the most fundamental issue in the WSN environment • And identify the reasons that may contribute to consuming more power.
[18]	2020	• Provides investigation about the energy saving schemes, which can contribute to achieving reduced energy consumption • Antennas topology control and transmission power controls were also discussed
[19]	2021	• Provides nine categories of protocols and discusses their advantages and disadvantages, and performed simulation of LEACH, Mod-LEACH, iLEACH, E-DEEC, multichain-PEGASIS, and M-GEAR protocols on NS3 simulator
[20]	2022	• Provides review about cluster-based energy-efficient RPs.
[21]	2022	• Provides survey about the algorithms which have an optimum location in WSN environment • It also focuses on energy consumption and increased PDR which is also achieved through optimum location finding in the WSN environment.
[22]	2023	• This paper proposes a Fuzzy-based Energy Efficient Routing Protocol (E-FEERP) utilizing Particle Swarm Optimization (PSO) for clustering. • The protocol considers factors such as average distance from the Base Station (BS), node density, energy, and communication quality to optimize data transmission. • The E-FEERP, combining PSO and Fuzzy logic, achieves improved network performance in terms of packet delivery ratio, Residual Energy (RE), throughput, energy consumption, load balancing ratio, and network lifetime.
[23]	2023	• This work focuses on improving the network lifetime of wireless sensor networks (WSNs) in 5G networks by implementing a novel routing protocol-based modified power line system. • The proposed technique minimizes energy usage during data transmission and increases the number of alive nodes compared to existing methods such as LEACH, EEUC, and CH LEACH, leading to significant energy savings and extended WSN lifetimes in 5G networks.

TABLE 4: Research types

Classification	Description
Validation	The techniques examined are innovative but have not yet been implemented in practice. This means that the validation of the techniques is only conducted in the lab
Evaluation	Researches that illustrate how the techniques can be implemented in practice and its evaluation is provided. The consequences of the implementation in terms of advantages and disadvantages are highlighted.
Solution	Research conducted to solve specific a problem or its application to a specific problem is illustrated by showing examples or reasonable explanation
Philosophical	Researches that illustrate a new way of viewing existing things by structuring the field inform of classification or conceptual framework
Opinion	Researches that express the opinion of someone explaining whether a certain technique is good or bad. This type of research does not rely on the related work or follow a standard research methodology.
Opinion	Articles written based on the personal experience of the author explaining how things are done in practice.

TABLE 5: Contribution type

Contribution type	Description
Technique	Description of a method or procedure
Process	Sequence of independent methods as well as linked procedures
Notation	A formal language or pictorial notation to support a method
Tool	A specific implemented tool using a certain technique
Specific solution	Solution for a specific application problem, for instance, the result of an application-specific analysis, evaluation, or comparison.

EE/EB RPs according to these techniques as shown in Fig. 1. The description of each technique with its advantages and disadvantages is given below.

Multi-sink: The multi-sink technique seeks to improve network performance by evenly sending the network traffic over multiple sinks to achieve load balancing. With the multi-sink technique, the density of the many-to-one correspondence traffic pattern in a single sink scenario is distributed, in multiple directions, towards the multiple sinks. However, the main challenge with the multi-sink is that the many-to-one correspondence traffic pattern that leads to hot spot problems cannot be eliminated. Moreover, if the sinks are not evenly distributed, the sensor nodes closer to the nearby sink will be overburdened.

1) Multihop-based: In a large-scale network WSN that uses static BS, the multihop routing technique is more appropriate because of the weak links characteristics of wireless channels [24]. It is better and more energy-efficient to let the sensor nodes collaborate to pass on their data to the BS. With the multihop technique, the energy consumption of the sensor nodes that are located far away from the BS is minimized. However, the many-to-one correspondence traffic pattern leads to a hotspot problem when a multi-hop routing technique is adopted among the sensor nodes [24]. Since the sensor nodes near neighbors of static BS are more exploited with heavy traffic relays along their own generated traffic loads. Therefore, the BS neighboring area becomes a trouble spot. The nodes in the neighboring area of BS deplete their energy rapidly and ultimately die much ahead of the rest of the nodes available on any network.
2) Cluster-based technique: the sensor nodes are arranged into several disjoint clusters. Here, a leader named cluster head (CH) is nominated based on certain predetermined criteria. The rest of the nodes in the cluster become cluster members (CMs), which are liable for capturing the data about the region of interest and sending the data to CH, which will in turn perform data aggregation and forward it to BS for further actions. Clustering tasks include selection of CH, formation of balanced clusters, minimizing clustering overhead, cluster head rotation, etc. With clustering the size of the routing table is minimized, with a reduction of maintenance in the network topology. When the sensor nodes are purely involving their interaction with the CH. The Cluster-based routing also jams the communication bandwidth by reducing inter-cluster and intra-cluster communications [25]. The cluster head performs data collection to mitigate duplicate data from several sources and sends the compressed data to the BS. This is the most effective technique for WSNs to save energy. Clustering techniques allow the rotation of CH. This rotation mechanism is performed either at the cluster level or globally

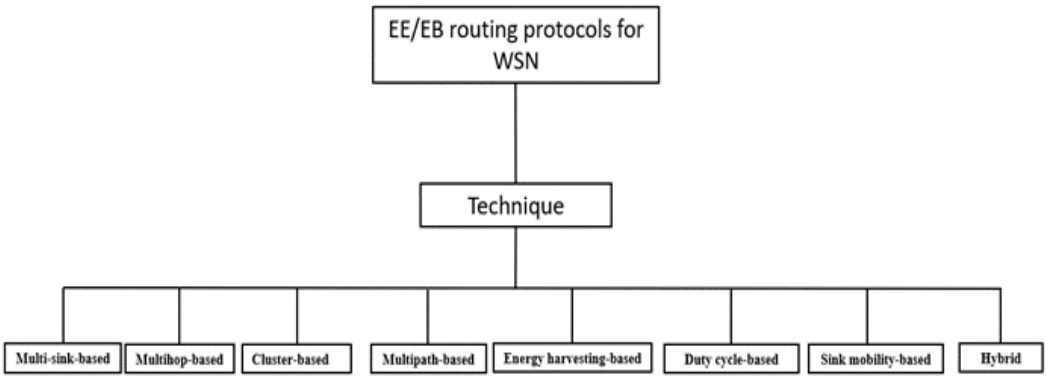

Fig. 1: Taxonomy of energy-efficient and energy-balanced RPs

through re-clustering, allowing the network to handle topological changes such as changes in node density due to node demise or mobility. In contrast, the several pros of cluster-oriented routing techniques, have many limitations. One of the disadvantages of cluster-based routing is considerable energy overhead during the cluster formation process. In addition, the time wasted during cluster formation setup could be used for data transmission to the BS.

3) Multipath technique: The multipath technique seeks to improve network performance by sending network traffic over multiple paths with respect to the cost of data transmission along these paths [26]. Multipath routing promotes efficient utilization of the network resources such as load balancing, minimum delay, and throughput. However, maintaining multiple paths in multipath routing in the network requires sort of periodic messages at some time intervals to keep paths alive which leads to significant energy consumption within the network [27].
4) Energy harvesting-based: Energy harvesting is a method used to generate energy from network ambient environs in order to provide a continuous power supply for a specific sensor node and for the overall WSN [28]. The goal of the energy harvesting technique is to shift the paradigm from battery-powered WSN to perpetual WSN that relies on the energy harvested from the ambient environment. However, the main challenge with the use of energy harvesting mechanisms in WSN is the lack of systems that can generate enough power for the sensor nodes and their associated interfaces suitable for various application areas [29-33].
5) Duty cycle-based: The duty-cycling is an energy-saving technique in WSNs. It solves the issue of excessive energy utilization because of the sensor nodes' idle state [34]. In duty cycling, when sensing and communication activities are not required, then the sensor node turns its radio off and goes to sleep to save energy, wakes up at specific intervals senses the surroundings, and checks channel activity. Duty-cycling saves a great amount of node's energy; however, duty-cycling comes with great disadvantages to the design of energy-efficient/energy-balanced routing solutions for WSNs. The energy saved by duty cycling may be overshadowed by the overhead complexities involved in the dissemination of the scheduling information, synchronization with neighboring nodes, and MAC layer handshaking for packet forwarding [5].
6) Sink Mobility-based: The mobile sink is mostly attached to moving objects such as people, robots, vehicles, and so on. With a mobile sink, the heavy data traffic relaying tasks near the BS or sink can be distributed to different numbers of sensor nodes as the sinks move and change their neighbors [35]. Therefore, the energy dissipation is spread more uniformly which leads to prolong network lifetime. However, sink mobility incurs extra signaling overheads to update the routing paths about the direction and location of the mobile sink as they move, which leads to significant energy consumption across the network [35].
7) Hybrid: RPs that combine more than one technique, for example, clustering and multihop routing, cluster-based and duty cycling, single hop and multihop, etc. This technique of routing can inherit the strengths and weaknesses of the two or more combined techniques to achieve energy efficiency and load balancing.

Accordingly, the selected were examined to classify them according to the above-mentioned tech-

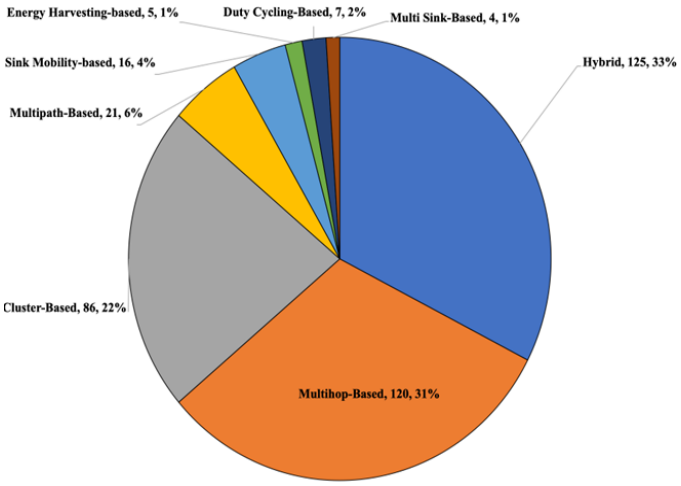

Fig. 2: Distribution of routing techniques

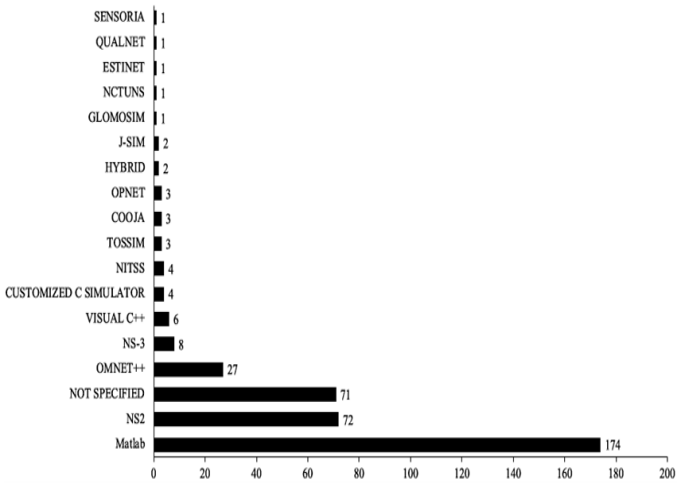

Fig. 3: Simulation tools

niques. This study identified eight techniques as shown in Fig. 2.

2.3 Taxonomy of simulation tools

Fig. 3 shows the distribution of usage of the simulation tools. Our study identified 16 simulation tools across the selected studies, however, 17 categories in Fig. 3 show the unspecified where authors didn't specify any tool and 18th is where authors used customized simulators. It was found that 174 of the selected studies used the MATLAB simulation tool, 72 papers used NS-2, 27 papers used OMNeT++ and 8 papers used NS-3 from the selected studies. MATLAB provides an environment suitable for implementing WSNs routing algorithms and it is also compatible with techniques written in other programming languages, such as C, C++, etc. Hence, MATLAB is widely accepted and used by industries and academia.

NS-2 is the second most used simulation tool instead of NS-3 which rolled out in July 2008 [39]. This can be attributed to the following reasons: the recent version of NS-2 roll-out in late 2011 (NS-2.35) with significant enhancements and remains compatible with the older version. For NS-2 and NS-3, the differences between them are quite many since NS-2 scripts are not compatible with NS-3.
This makes it difficult for the researchers who are used to NS-2 to switch to NS-3 as it requires studies and adaptations, which take a long period of time. Even though NS-3 has enhanced models, NS-2 is still adopted by many researchers to test their models and algorithms. The OMNeT++ as depicted in Fig. 3 is the third most used simulation tool. For the use of multiple simulation tools, we identified two papers [40, 41] that used more than one simulation tool. In the selected papers, the detail of the simulation setup is provided but the specific name of the simulation tool used has not been mentioned. So, we found it difficult to identify the exact name of the simulation tools used in those studies. Some of the papers in the selected studies that did not specify the simulation tools used can be found here[42-44].

3 Research challenges and direction for future work

After careful analysis of the selected studies, some of the research challenges that need to be addressed by the research community in the future were identified. It was noticed that a greater number of the proposed EE/EB routing protocols are only validated using simulation. These proposed protocols are expected to be deployed in a real environment. However, simulations have been proven not to capture the exact characteristics of real deployment [45]. Since the real hardware can set a boundary on some parameters which may be difficult to verify on simulators. Moreover, even though the simulation is a less expensive technique for validation, more important than simulations, the real implementation on testbed or case studies can validate with the real devices or in the real environment, the reliability of the proposed solution. It was also observed that the use of theoretical analysis to corroborate the convergence of the proposed solution has not been used by most of the papers. To give a broader perspective of the proposed solution and to achieve a fair comparison between standard protocols, the simulation activity needs to be accompanied by theoretical (mathematical) modeling. It was observed that most of the researches on EE/EB routing protocol focus more on validation research.

However, it was observed that there were fewer research efforts on evaluation research and solution research in the literature. Therefore, more evaluation and solutions research on EE/EB routings are needed in the future. Moreover, research on EE/EB routing protocols contributed more to the method/technique. Little attention is noticeably given to specific solutions research. However, the development of application-specific EE/EB routing solutions should be given much emphasis. The development of routing protocols with specific applications could increase research acceptability across industries and funding agencies.
We also identified only a few papers (specifically two [40, 41]) in the selected studies that used multiple simulators for validation. Some simulation tools are suitable at the network layer level but might not be suitable at the physical layer level and vice versa. To fully validate the correctness of the proposed EE/EB routing protocol, it is recommended the use of multiple simulation tools.

4 Conclusion

Generally, WSNs involve SNs that have limited power sources like batteries. Moreover, SNs are usually installed to communicate and capture information about the condition of an AoI. The main goal is to deliver the information efficiently to the BS without relying on any existing foundation support. Furthermore, in some installations, the substitute of power source is almost impossible, especially in unfavorable AoI such as battlefield, earthquake, etc. Therefore, developing EE/EB RPs for this network scenario has become a challenging issue. This has triggered an extensive research effort to develop energy-efficient and energy-balanced RPs to optimize the lifetime of the network. A plethora of EE/EB routing techniques have emerged over the years, and many studies have been reported in this domain. However, it is of paramount importance for the new researchers and network designers involved in the development of EE/EB RPs for WSNs to understand the existing EE/EB RPs, trends, and demographics. The results show that the research on energy efficiency and energy-balanced routing is gaining more attention recently. The results also show that validation research is the most practiced research facet in the domain. This means that the greater number of the proposed EE/EB RP in the selected studies are only carried out in the laboratories and have not been implemented in practice. The study also shows that researchers focused more on contributing methods/techniques and processes in the domain. Little attention is noticeably given to application-specific solutions research. We also found that the majority of the proposed EE/EB RPs are only validated using simulation. We have also discovered that hybrid routing is the most frequently used technique (32%), followed by multihop (31%), and cluster-based (22%) techniques, with the remaining techniques having lower adoption rates.

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