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A Survey on Routing Protocols for Delay and Energy-Constrained Cognitive Radio Networks

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ABSTRACT The ever-growing demand for higher network data rates, lower delay, and conservative energy consumption at reduced costs, to support Internet-of-things (IoT) communications, has pushed wireless technologies into a new frontier. The growing demand for such technologies can be attributed to several factors, such as the massive number of the upcoming bandwidth-hungry IoT applications and the enormous number of – often battery-powered – devices expected to connect to the network. Cognitive Radio Networks (CRNs) can play a significant role in future generations of mobile-communication technologies by providing dynamic access to underutilized licensed bands. However, battery-operated devices, which communicate delay-sensitive data over multihop links, impose serious energy-delay limits. In such CRN-based IoT communications, as one device depletes its energy, network disconnectivity may arise, which can degrade the network efficiency. Therefore, building a reactive routing protocol to recover from any sudden link breakage is necessary to maintain prolonged network connectivity. This paper provides a comprehensive survey of CRN routing protocols that are based on two essential metrics, namely, packet delay, energy consumption, or both, while excluding all other CRN routing protocols. The survey is meant to support the designers of future CRN-based IoT communication frameworks with a detailed comparative survey, which targets the most relevant proposed routing protocols, including the specifics of the routing metrics, implemented spectrum awareness strategy, and employed medium-access control standard along with the simulator tool used for performance evaluation. In addition, this survey finds that the majority of cognitive radio routing protocols address either delay or energy consumption, but only a few consider a joint delay-energy metric, which suits delay-sensitive IoT applications running on energy-constrained devices.

INDEX TERMS Cognitive radio, delay, energy, Internet-of-Things, routing, sensor network.

I. INTRODUCTION

The rapid expansion of wireless devices has enabled the extensive use of various real-time applications. Some of these applications serve classified information for the military, while others serve the civil defense, fire systems, healthcare, home appliances, and e-commerce transactions. Several applications serve multimedia communications such as video conferencing, Internet telephony, and chatting, while others serve online gaming and entertainment communications. Some of these applications have delay and energy constraints due to the urgency of the carried information and the energy-limited devices used. Users of such applications often seek to avoid service disruption and depletion of their device battery while – at the same time – assuring immediate information transfer at a high delivery rate.

The Internet-of-things (IoT) paradigm [1], [2] enables the interaction between devices from several application domains that include – but not limited to mobile phones, routers, game consoles, printers, pacemakers, telephone systems, refrigerators, and Automatic Teller Machines (ATMs). Applications running on such devices interact with each other using Wireless Sensor Network (WSN) technologies such as Zigbee, LPWAN, LTE-M, Wireless HART, Wireless networks for Industrial Automation-Process Automation (WIA-PA). They often communicate in a multihop environment, either as Machine-to-Machine (M2M) or Human-to-Machine (H2M) [3], to meet the diverse user demands and Quality of Service (QoS) requirements. Service unavailability due to energy depletion of devices or service delay due to packet latency can lead to deferral or, in many cases, denial of

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service, which can have severe consequences in many sensitive sectors, such as health-care and the stock-market.

The suitability of future wireless network technologies to work under different environments and provide equal coverage for billions of high-traffic devices sets high expectations to be met in IoT networks. This also refers to its capability to prolong the batteries of devices and offer them high speed with small latency at low cost [4]–[6]. The use of wireless PCs, smartphones, tablets, smart home devices, wearables, and IoT devices shows a significant worldwide expansion from about 2 billion devices in the year 2008 to 26 billion in the year 2018. This massive growth is expected to reach 35 billion by the year 2020 [5], which poses the pressing global problem of frequency spectrum scarcity.

ITU-R, the Radio Communication Sector of the International Telecommunication Union (ITU), has categorized the world into three regions to attain a global non-interference usage of the radio spectrum, where region One mainly covers Europe and Africa, region Two covers Asia, and region Three covers the Americas [7]. Based on these regions, the FCC publishes a yearly updated Table of Frequency Allocations [8] that shows the number of offered services around the world. According to [8], the reported number is enormous, which leads to complications in managing the spectrum allocation for the forthcoming technology trends. It also shows the overwhelming amount of spectrum bands statistically dedicated to primary (licensed) services, which are partially utilized with an average that varies from 15% to 85% [9]. A proper settlement to spectrum scarcity is the use of Cognitive Radio (CR) to take advantage of the underutilized licensed spectrum-bands.

CR is an extension of Software Defined Radio (SDR) [10], [11] that outlets unlicensed Secondary Users (SUs) to opportunistically utilize the spectrum bands when not being used by Primary Users (PUs) or share the spectrum with PUs while the latter are thoroughly protected. Figure 1 depicts a scenario where three communication channels are available and accessible by In the presence of PUs. When a PU is not using a channel, an SU can have access to the channel and therefore sharing it with the PU. To form a CR multihop network [12], SUs rely on each other in a partially static infrastructure-based mesh network. Figure 2 (a) shows two base stations that connect a few mobile devices using multihop communication, whereas Figure 2 (b) depicts a completely self-configuring ad-hoc network. Typically, SUs in a CR Mesh Network (CRMN) [13] or a CR Ad-Hoc Network (CRAHN) [14] scatter across different primary radio regions. Moreover, a single-hop infrastructure-based network, as illustrated in Figure 2 (c), can also make use of the CR paradigm.

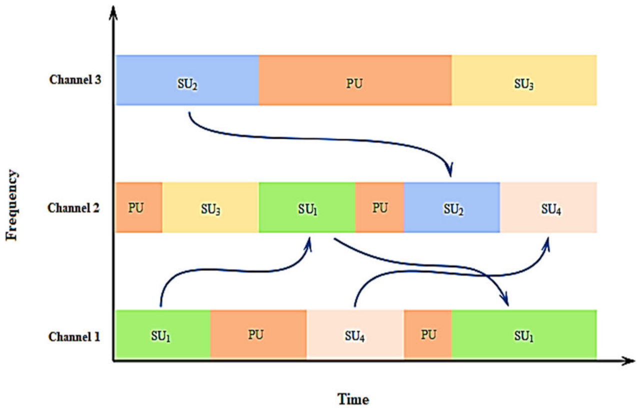
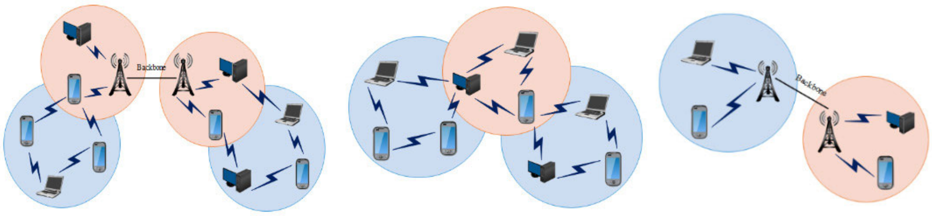


FIGURE 1. CR spectrum access opportunities in a system of one PU and four SUs.

Comparing the wireless CR multihop with single-hop networks, the former extends network coverage and leads to less transmission power consumption compared to the power required over long single-hop links. Besides, multihop CRNs can provide multiple paths. This results in higher network throughput, bottleneck avoidance, and robustness by providing backup paths to confront any unexpected PU appearance or any exhaustion in the network energy-limited devices. However, multihop routing that depends on transmitting packets through a single-path outperforms multihop multi-path routing in which packets of the same source follow different paths to reach the destination. The former requires less computational overload (during route discovery and maintenance) and lower routing state storage while achieving higher load balancing [15], [16]. The anticipated number and density of IoT devices in an IoT network suggest that multihop communication shall represent a dominating paradigm for these networks.

IoT devices are different in their internal structures as they vary from simple wireless sensor nodes to more sophisticated computer boards that can make decisions and take actions based on a variety of measurements obtained via sensors. Providing sensor networks with CR communication mainly leads to what is called CR Sensor Networks (CRSNs). CRSNs commonly differ from other CRNs in their energy and memory limitations [17]. Typically, the nodes sense the event signals and cooperatively report the sensed information in a multihop environment to fulfill application demands.

Generally, building a fully operational multihop CRN is a complex and challenging task. An efficient CR routing protocol should consider timely route discovery and maintenance phases, which meet different criteria (metrics) to enhance data transmission performance. Figure 3 illustrates the two phases. During the route discovery phase, the best route is selected according to available spectrum holes and intended routing metrics. The other phase (route maintenance) should take into account the possibility of route breakage due to having nodes depleted of energy, or – mobility – i.e., some nodes are no longer in range, channel degradation, channel switching (spectrum mobility). During the route maintenance phase, broken routes should be promptly recovered whenever possible; otherwise, route recovery fails, and remaining packets are dropped. The routing metrics vary depending on the SUs' QoS requirements that the protocol aims to satisfy,



(a) (b) (c)

FIGURE 2. Communications in (a) multihop infrastructure-based mech networks with base stations and mobile devices along with stationary devices, (b) multihop self-configuring ad-hoc network with nine devices, (c) single-hop infrastructure-based with two base stations and four devices.

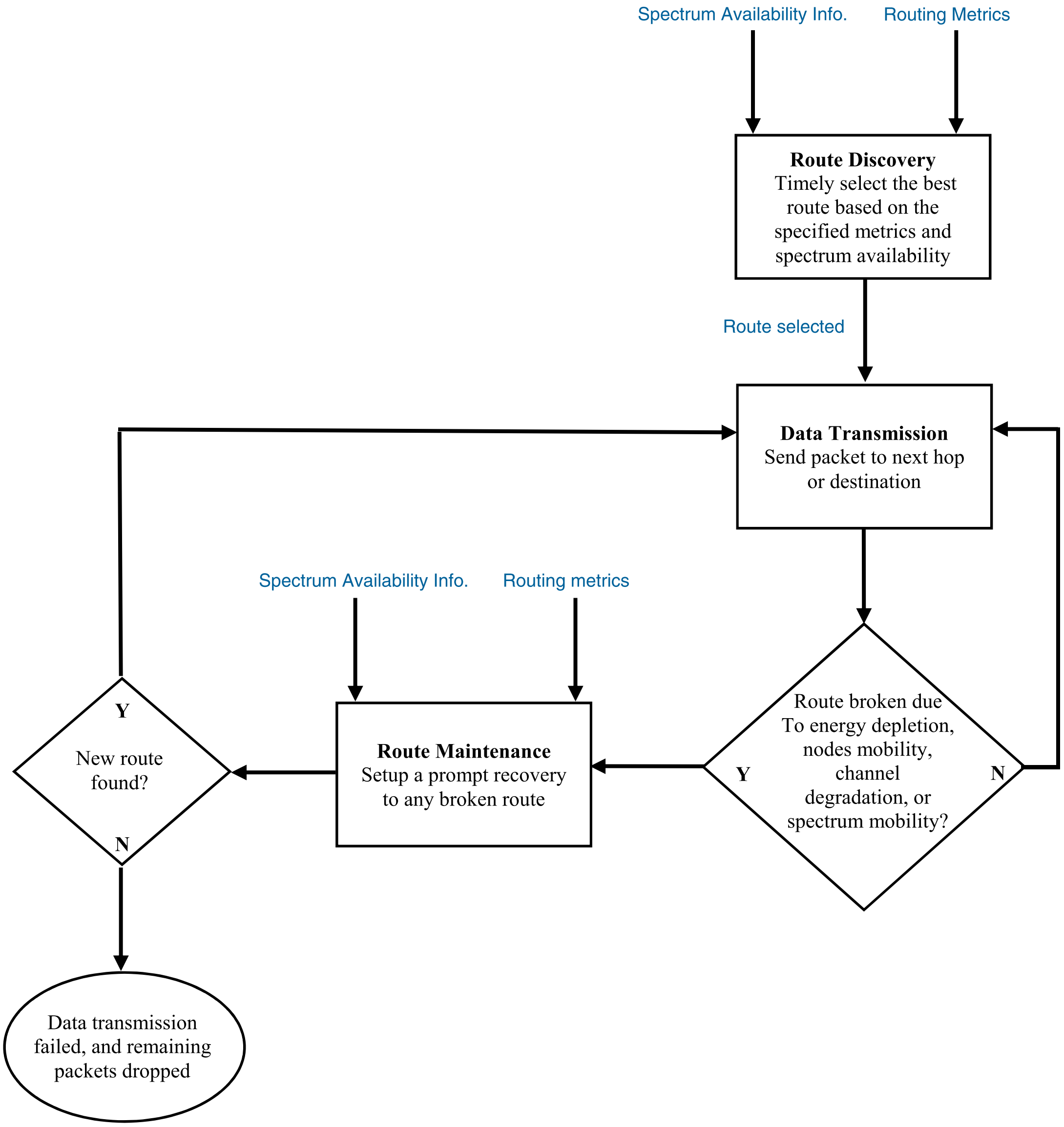


FIGURE 3. Phases of an efficient CRN routing protocol.

such as higher throughput, lower latency, and more extended network availability.

Routing metrics are used to rate the available links, which leads to selecting the most suitable route. Some protocols are built by considering only one metric, and others are based on a tradeoff between two or more metrics. SAMER [18] and SPEAR [19] are examples of throughput-based protocols, while SEARCH [20] and [21] are location-based protocols that attempt to minimize the distance to the destination by considering hop count. RSRA [22] and STOD-RP [23]

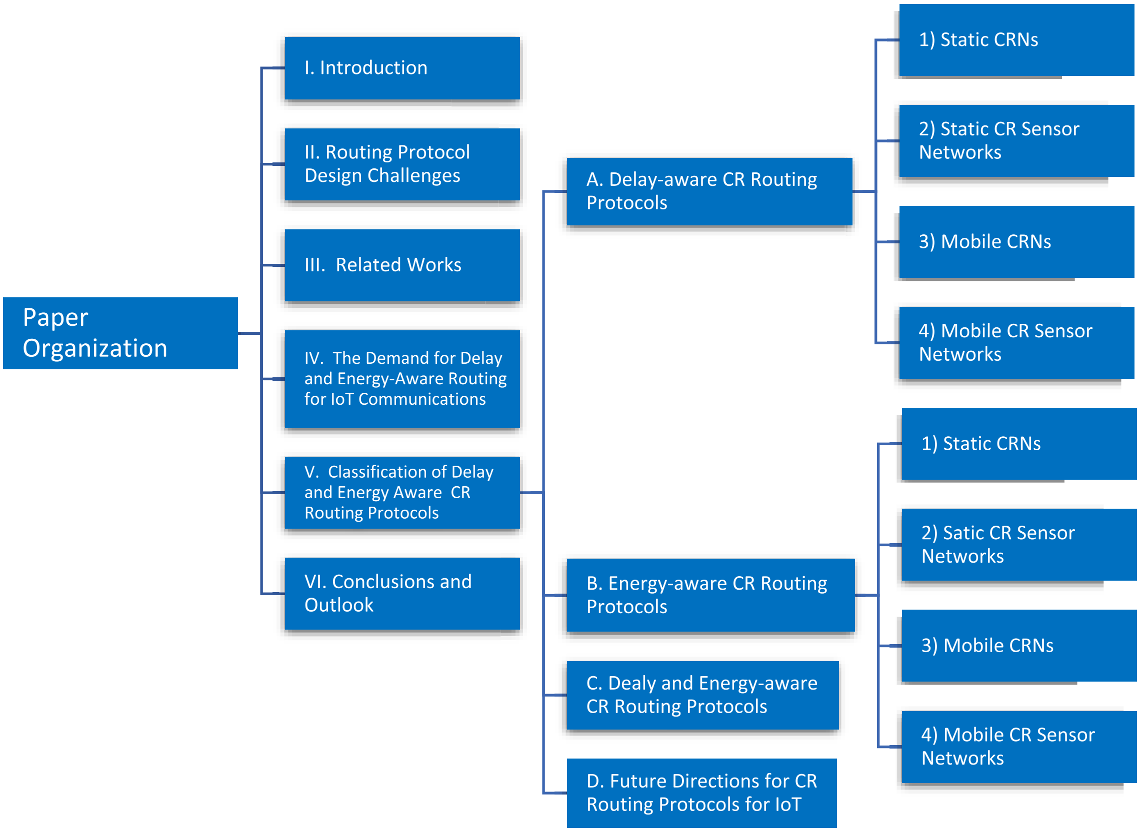


FIGURE 4. **Paper organization.**

consider link stability in route selection. The Coolest Path [24] and [25] protocols are PU activity probability-based and PU interference probability-based, respectively.

This survey thoroughly covers different routing protocols for single-path CRNs and the metrics considered in their route selection. We provide an insight into the works published in the CR field in the current decade to highlight the challenges in fulfilling the requirements of IoT-based networks, and in particular, of devices with limited-energy and/or stringent response-delay constraints running information-critical SUs' applications.

The paper is organized as in Figure 4. Section II details the design challenges of building routing protocols for multihop CRNs. Section III describes the survey method along with the material and methods used. Besides, it covers the relevant surveys in the literature and offers a compassion between them and this work. The need of developing delay-aware and energy-aware protocols for IoT applications is discussed in section IV. As Figure 4 reveals, Section V is divided into four main subsections, where the first two subsections survey the routing protocols using either delay or energy as a metric for route discovery. The other two subsections review the research works focusing on joint delay and energy metrics and the publications addressing IoT applications. The four main subsections are further partitioned according to the CRN network model (either stationary or mobile) and node type considered (general or sensor) where research works of all possible combinations are surveyed. The paper is concluded in section VI with final remarks.

II. CRN ROUTING PROTOCOL DESIGN CHALLENGES

The consequences of exploiting traditional routing protocols in CRNs without adapting them to accommodate the dynamic spectrum environment can lead to significant delay, low throughput, and high probability of packet loss. Since the environment is ruled by the restrictions imposed by spectrum availability, building a single-path CRN routing protocol must encompass considerations for best route selection, route maintenance due to the various route failures, coordination between layers, route quality, and deafness problem [26] [27]. In addition, it is imperative to account for the long-established difficulties associated with wireless networks such as the shortage of radio channels, interference, nodes limited battery life, mobility, and characteristics of the wireless channel such as error rates and Signal-to-Noise ratio (SNR) [28].

On the other hand, implementing services efficiently in an IoT environment with M2M communication requires addressing many challenges, mainly when such devices belong to a CRN. IoT and M2M applications are anticipated to demand massive wireless network bandwidth to provide uninterruptable Internet connectivity. Thus, there is a need for further studies to develop CR routing protocols that address different design challenges such as route instability, efficient use of battery-powered devices, network connectivity issues due to node and spectrum mobility, the unpredictability of PU intervention (activity), additional resources to acquire spectrum knowledge, deafness problem, and the use of multiple channels. The following subsections provide more details about these challenges.

A. ROUTE INSTABILITY

Route instability in CRNs owes to the probability that a transmission may be disrupted or disconnected mainly due to PUs' activity in addition to other common factors, such as channel degradation, node mobility, and energy depletion. Indeed, route failure negatively affects IoT-network performance as it increases the network overhead, energy dissipation, and packet delivery latency. Thus, it is a necessity to employ a reactive (on-demand) routing protocol that is resilient to such failures to achieve and maintain reliable information dissemination, especially in health-monitoring applications. AODV [44] and DSR [45] are examples of such reactive protocols.

B. ENERGY EFFICIENCY

Limited-energy M2M resources could lead to frequent node failures and network disconnectivity. Reaching high availability of IoT services requires the efficient use of battery-powered devices. A CRN routing protocol should consider prolonging device battery lifetime by reducing frequent charging as much as possible through selecting routes with high residual energy and low overall path energy.

C. SPECTRUM MOBILITY

As the dearth in the wireless spectrum drifts IoT communications towards CRNs, spectrum mobility is considered a big issue in such networks due to its impact on network connectivity and performance. Spectrum fluctuations due to PUs' activity force SUs to free the channel being used and switch to another channel to continue their transmission. Therefore, a spectrum availability analysis must precede route selection and route maintenance phases to check for the available spectrum, as shown in Figure 3. Since route failures significantly degrade the network efficiency, quick recovery is needed with minimum decision-making and tuning times. As a result, the network layer should stand on the information gathered at the lower layers [46]. Several routing metrics, such as delay, energy consumption, stability, throughput [28], have to be used to fulfill the route quality requirements according to SU demands, noting that the use of multiple metrics can lead to better network performance and stability.

D. LICENSED USERS ACTIVITY

The degree of PU activity plays a significant role in determining the routing scheme to be used as the activity may be static, dynamic, or highly dynamic, causing different levels of spectrum mobility [47]. Specifying the best scheme based on the degree of PU activity is a challenging task. A robust CRN routing protocol must quickly adapt to these spectrum changes while consuming the minimum amount of available resources (i.e., bandwidth and energy).

E. SPECTRUM KNOWLEDGE

In infrastructure-based CRN, full-spectrum awareness is often supported by resources such as base stations (BSs), geo-location databases, and central control entities. Nodes become fully informed with the spectrum availability using these resources as BSs coordinate the available spectrum bands among SUs, whereas control entities collect the required information from network nodes to establish spectrum association maps. In the absence of such resources, as in M2M networks, cooperation schemes are needed to locally assemble the spectrum information by every machine in the network and hence, taking the responsibility of allotting itself a spectrum share.

F. NODE MOBILITY

Mobility is essential in many IoT applications, but it is a big challenge in multihop CRNs. As channel availability varies over time and space, routing protocols should be aware of nodes' mobility in a distributed fashion to control rerouting degree and energy consumption and to increase the channel access time.

G. DEAFNESS PROBLEM

The deafness problem arises as a result of directional antennas communication failure [27] when using a fixed low-frequency Common Control Channel (CCC) to exchange control messages between network nodes. The CCC helps nodes locate their neighbors as well as be aware of their active transmissions. However, its acquisition is somewhat difficult. Also, it increases the overhead in such a dynamic environment and the possibility to form a bottleneck. Alternatively, data packets can be sent on all channels to be accessible by targeted nodes, which can exhaust all network resources and lead to excessive overhead. Another option is to use routing schemes with channel synchronization [28].

H. CHANNEL SCOPE

The decision to consider spectral opportunities through a single-channel or multiple-channel assignment is critical in CRNs used to support IoT applications. Although switching between several channels increases system throughput, it also increases time-to-rendezvous (TTR), the time needed to establish a connection between SU pairs. The number of channels used must be carefully selected because the multiple times the SU switches between channels affect network throughput and end-to-end delay [48]. Furthermore, switching channels forces secondary nodes to consume extra energy, a valuable resource in IoT networks as many nodes are battery-powered devices.

On the other hand, confining to a single-channel imposes additional delays on SUs when the channel is not available, but reduces energy consumption, and therefore, enhances

TABLE 1. Comparison summary of related works.

Related Works	Summary of Contributions
[17]	Study of the relation between WSNs, CRAHNs and cross-layer design of CRSNs
[28] [29] [30] [31] [32] [33] [34]	Routing protocols built on metrics such as energy and delay
[35]	Routing protocols based on AODV and/or DSR
[36] [37] [28]	Routing protocols built on energy and delay metrics for a broad range of CRN, but no CRSN
[38]	Focused on protocols that jointly consider routing and channel selection
[39]	Comprehensive survey on routing and link-layer protocols for wireless multimedia CRNs considering security, cross-layer design, and spectrum sensing issues.
[40]	A presentation of challenges in vehicular CRNs, performance metrics, and field demand
[41]	A comparison between CRAHNs and CRSNs in addition to the challenges facing CRSNs, their applications, and sensing schemes.
[42]	A comparison of clustering algorithms in CRSNs and WSNs considering specific objectives, metrics, performance enhancements, and complexity analysis
[43]	A comparison of clustering algorithms in CRSNs and WSNs
This Survey	Comprehensive list of CR energy and/or delay-aware routing protocols in CRMNs, CRAHNs, CRSNs, and IoT. Comparison of existing protocols with key comparison elements such as routing metrics, spectrum awareness, MAC type, base protocol, supporting resources, simulation tools used, performance metrics and protocols compared with

network lifetime and connectivity. Relying on a single channel also minimizes the cost and complexity of operating the network and equipping the SUs with sensing hardware. These factors have a high impact on the decision to use single or multiple channels in CRNs even though the higher utilization the former scheme offers [49].

III. RELATED WORKS

A. EXISTING SURVEYS

Numerous surveys exist in the CR field. Some focus on CR functionalities such as [50], [51], while others focus on medium access control (MAC) and network layer challenging issues with guidance on how to tackle those issues [52]. The practical imperfections that forcibly take a part of the CR environment are studied in [53], along with an overview of the possible ways to overcome such inconveniences. In addition to presenting the CR functionalities, [54] compares the diverse DSA models and methods.

The surveys [28]–[34] describe techniques of a collection of routing protocols built on specific metrics including energy and delay-aware protocols, while [35] focuses on routing protocols that are built on AODV and/or DSR. Similar works are presented in [28], [36]–[38] for a broader range of CRN protocols with no coverage for CRSNs. The authors in [38] concentrate on the various protocols that jointly consider routing and channel selection. A comprehensive survey on routing and link-layer protocols for wireless multimedia

CRNs is offered in [39] with related security, cross-layer design, and spectrum sensing issues.

Unlike other surveys, the authors in [40] present the challenges in vehicular CRNs and the performance metrics used, alongside the field demand in such networks.

Despite the prevalence of IoT technology using sensor devices in smart cities, industry, retail, healthcare, finance, and manufacturing, only a few authors cover the CRSNs in their surveys. The relation between WSNs, CRAHNs, and cross-layer design of CRSNs is studied in [17]. The researchers in [41] compare between CRAHNs and CRSNs. The challenges facing CRSNs, their applications, and sensing schemes are also considered. As clustering algorithms play a significant role in CRSNs, thorough surveys are presented in [42], [43] to compare between WSNs and CRSNs clustering algorithms. The algorithms based on specific objectives, metrics, performance enhancements, and complexity analysis are discussed in [42].

To the best of the authors' knowledge, none of the surveys available in the CR field present a comprehensive work of the CR routing protocols that consider energy limitations and delay sensitivity in CRMNs, CRAHNs, and CRSNs.

This survey covers a wide range of CR routing protocols listing their characteristics, infrastructure requirements, delay and/or energy-related metrics used, and the considered degree of mobility. Table 1 is a comparison summary of related published surveys.

B. SURVEY METHODOLOGY

1) SCOPE AND OBJECTIVE

The paper addresses the following research question: Does the current literature of cognitive radio routing protocols support the diverse requirements of different IoT applications in terms of delay-awareness, energy-awareness, or joint delay-energy awareness? The question is essential to support IoT applications running on energy-constrained devices, which are supposed to grow in number to reach billions in the coming years. This, in turn, adds a considerable demand for the scarce wireless bandwidth, which promotes the usage of the underutilized spectrum by the aid of multihop cognitive radio networks. Thus, the paper surveys the current cognitive radio routing literature and provides an outlook for further studies.

2) MATERIALS AND METHODS

The literature search is conducted using the Google Scholar database because it indexes a much larger number of articles than many databases [55]. We covered the technical articles published between 2000 and 2019 since 2000 marks the appearance of cognitive radio as an extension to its enabling technology, namely, software-defined radio. Searching Google Scholar using the set of keywords "cognitive radio, routing, delay, energy" lead to around 380 relevant articles when the "most relevant" ordering option is selected. Only Scopus-indexed English-written original research articles, which are either journals or conference proceedings, are considered for the technical content of the survey. Also, the publications that propose using routing metrics other than packet delay or energy consumption are excluded. Moreover, the research works that introduce a routing algorithm without specifying routing protocol messages are omitted.

The surveyed articles are manually categorized by the authors into three categories, namely, delay-aware, energy-aware, delay, and energy-aware routing protocols. Delay-aware and energy-aware categories are further classified as either CRN or CRSN for stationary and mobile networks. Manual categorization is often more accurate than using tools since some research articles do not explicitly state the employed metric. Figure 5 (a) and Figure 5 (b) show the total number of articles and the number of articles per each category, respectively, with the year of publication.

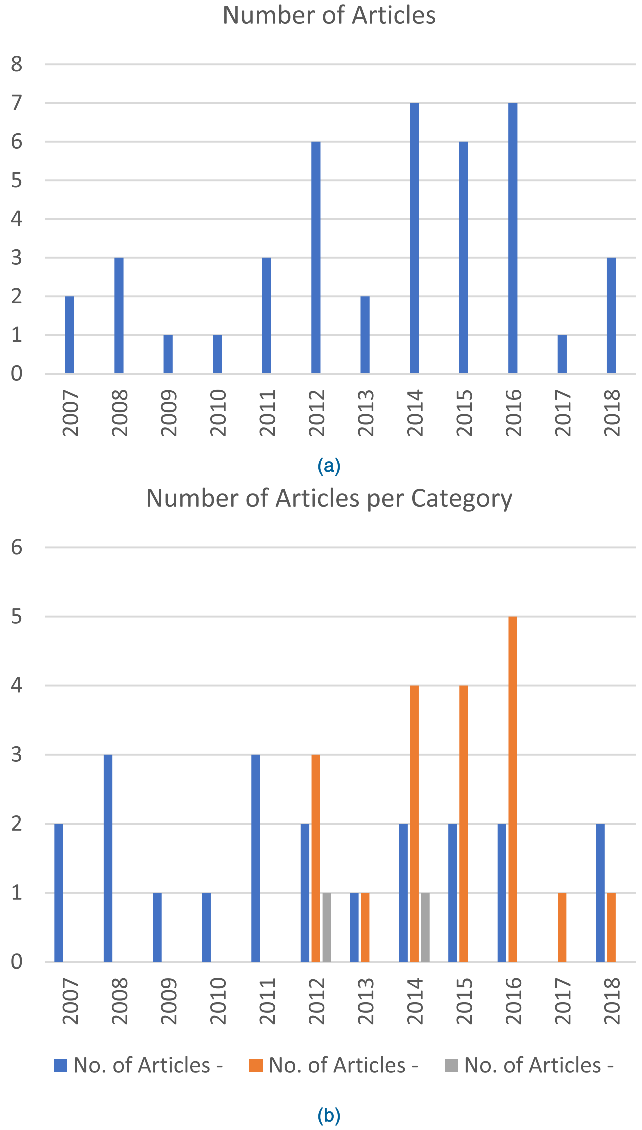


FIGURE 5. Number of articles, (a) combined delay, energy, and delay-energy routing protocols (b) per category.

IV. THE DEMAND FOR DELAY AND ENERGY-AWARE ROUTING FOR IoT COMMUNICATIONS

With the fast pervasion of wireless devices and applications, users of wireless networks expect everlasting continuous Internet connectivity. The limited-energy batteries of IoT devices and the requirements of delay-sensitive applications inflict time-delay limits. Indeed, not all IoT applications are delay-sensitive, which implies they can satisfactorily run on multihop CRNs using energy-aware cognitive radio routing protocols. On the other hand, some IoT devices are not energy-constrained because either they are not battery-powered or their batteries can be recharged [56], [57], and they run delay-sensitive applications such as in smart grids. This implies that a delay-aware cognitive radio routing protocol can support running these applications on such devices. However, some devices are energy-constrained and run delay-sensitive applications such as factory and process automation [58], where latency in the order of 50 ms is required. In CRNs, as one device depletes its energy, a network disconnectivity may arise, which will degrade the network efficiency. Therefore, building a reactive protocol to recover from sudden link breakage is essential to maintain a prolonged connecting environment.

Considering network nodes' residual energy during route constructions positively affects the routing protocol performance to a great extent. Likewise, minimizing the energy consumption per transmission conserves the resource-limited batteries and hence extends the network lifetime, which reflects favorably on the packet delivery ratio and network throughput. Moreover, balancing energy consumption is a necessity since the nodes along the path can be heavily loaded, thus prone to energy depletion despite the presence

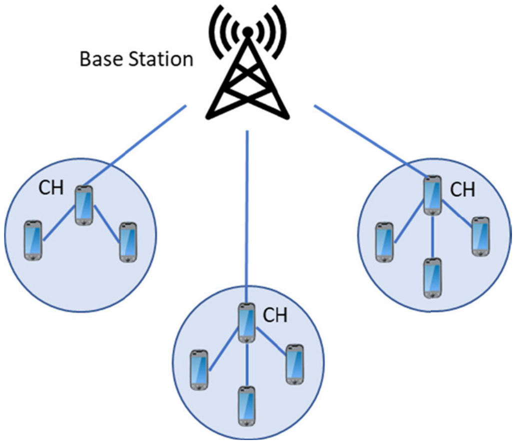


FIGURE 6. An example of a three cluster CRSN.

of other nodes with enough energy that could have been used instead. Energy balancing is crucial in any CR-based IoT network that uses CRSN clustering schemes since the highly capable Cluster Heads (CHs) use direct links to transmit to a BS, as illustrated in Figure 6, where three clusters are shown with each having its own CH. Communication among the devices can be made via CHs to reduce transmission power because the nodes are normally closer to the CHs than the Base Station. This may accelerate the energy consumption of distant heads, causing imbalance among all CHs. Consequently, efficient energy protocols should aim to reduce and balance energy consumption to endure network connectivity. This can be achieved in multiple ways, such as adopting an energy threshold value to distribute, to some extent, the nodes consumption, deploying more nodes, controlling the transmitting power [59].

On the other hand, if a proposed routing protocol for IoT devices running over a CRN ignores all considerations except the energy of the nodes along the route, a prolonged end-to-end delay will be observed, which is unacceptable for time-sensitive IoT applications. The number of times the SU switches the channel affect the end-to-end network delay. The network delay comprises delays due to channel switching, MAC backoff, queuing, processing, transmission, and signal propagation. Switching delay occurs when the node switches between channels, while backoff delay is related to the node waiting time when the channel is blocked. Queueing delay is the time the queued data packets wait before being transmitted, whereas processing delay is the time the node spends in processing the packet. The time the node needs to transmit the whole packet into the medium and the time the packet needs to reach the next node represent transmission and propagation delays, respectively.

These aforementioned delay components have to be considered to avoid possible massive overload that could subsequently exhaust the network and decrease its efficiency. This is because queues fill up quickly, leading to a high packet delay and a possible overflow and hence a decline in throughput and packet delivery ratio.

As a rule, SUs have to balance energy consumption to obtain efficient data transmission and end-to-end packet delay to minimize the cost of delivering a payload. Combining several atomic metrics (hybrid) enhances the route selection process leading to better route stability and network performance.

V. CLASSIFICATION OF DELAY AND ENERGY AWARE CR ROUTING PROTOCOLS

The unexpected intervention of PUs, alongside the mobility and energy depletion of SUs during route discovery and maintenance, can negatively influence the network performance (delay, throughput, and packet delivery ratio) and sustain additional energy consumption. As a consequence, careful route selection is vital to avoid any network performance degradation and disconnectivity.

Proposed protocols for CRNs should be evaluated in an environment that supports spectrum mobility to guarantee the optimization of spectrum efficiency. Several network simulators exist with different supportive CR modules to emulate the CR environment. The open-source Network Simulator (NS), with its different versions, supports several MAC standards such as IEEE 802.11, IEEE 802.16, IEEE 802.15.3, and IEEE 802.15.4. The most popular one is the NS-2 [60]. It offers users an interface for different layer configurations to implement various wireless network scenarios. An extension to NS-2 is the Cognitive Radio Cognitive Networks (CRCN) simulator [61], which provides a reconfigurable multi-radio multi-channel physical layer.

Global Mobile Information System Simulator (GLOMOSIM) [62] is a scalable network simulation tool designed using the parallel programming language Parsec [63]. It supports a large number of network models in a parallel simulation environment. The Optimized Network Engineering Tools simulator (OPNET) [64] is another network modeler with graphical and programmable features. Matrix Laboratory (Matlab) [65] is also a widely-used tool by researchers. Some researchers favor building their simulators based on programming languages such as C, C++, and JAVA, while others prefer to use other simulators such as the open-source Objective Modular Network Testbed in C++ (OMNeT++) [66] and the NetSim network simulator [67].

Several performance metrics are commonly used to evaluate the efficiency of routing protocols:

- End-to-end delay (cumulative delay): It is the time a generated data packet takes to travel from source to destination.
- Throughput: It is the amount of successfully received data packets in a specified period.
- Hop count: It is the number of intermediate hops a data packet has to pass through from a source to a destination node.
- Routing overhead: It is the ratio of routing bytes (control packets) to the total number of routing and data bytes.

- Packet delivery ratio: It is the ratio of the received data packets (at the destination) to the generated data packets (by the source).
- Network lifetime: It is the network operational time until the first occurrence of a network partition.
- Energy consumption: It is the amount of energy consumed by network nodes.

This section introduces a comparative survey of CRN routing protocols that are based on packet delay and/or energy metrics. The majority of these protocols are designed with no IoT-specific design requirements in mind. We introduce them in this survey as they use CRN-tailored routing techniques. CRSNs are also addressed as they are somewhat close to some IoT networks in terms of node density and limitations on node energy and processing power. We also dedicated a part of this section to address the few CR routing protocols in the literature that targets IoT networks and applications. The survey covers different aspects of each routing protocol, including spectrum awareness, MAC protocol type, supporting resources, and the deployed network simulator.

A. DELAY-AWARE CR ROUTING PROTOCOLS

Since network delay can be split into several components, it helps researchers to appropriately develop routing solutions by considering the different delay components to design an efficient IoT network with reliable communications, which is crucial to make appropriate decisions and avoid undesirable scenarios [68]. Various parameters can be communicated from monitoring systems for medical and other purposes using smart devices with the different applications available on various operating systems. For example, water network monitoring could be performed using IoT devices to assure drinking water quality. Sensors measure critical water parameters, which could avoid accidental contamination [69].

1) STATIC CRNs

CRNs can serve the above-mentioned applications with static (stationary) secondary nodes. Table 2 shows the delay-aware routing protocols for static CRNs. The researchers in SORP [70] and DORP [71] have developed an approach that calculates the cumulative path delay considering the nodal and path delays. Switching and channel backoff delays are considered to evaluate the route selection in both. However, DORP with queuing delay consideration is at an advantage. In both protocols, the route that experiences the minimum cumulative delay is selected. A node-analytical model is offered to cover the channel assignment process using a polling policy. The cross-layer routing provides SUs with full knowledge of spectrum holes. The work in [72] is an extension of the DORP protocol with the addition of a local coordination scheme. A relay node can locally decide to proceed with the selected flow or to redirect it in case other nodes provide better packet delay. Such a redirection mechanism offers load balancing among all intermediate nodes and their neighbors.

MSCRN [73] utilizes network capacity to a great extent by considering a switching/backoff delay algorithm. When switching channels, the time the node spends to broadcast a LEAVE message on its current channel and a JOIN message on the new channel, alongside the hardware switching delay, are all considered. The work shows constraints under which channel assignment has to be performed to avoid the deafness problem. The comparison is held with a single channel AODV protocol to show the difference between the two environments.

OSDRP protocol [74] selects the route with minimum switching and queuing delays with maximum stability. The protocol presents four modules: Route Discovery, Route Decision, Opportunistic Routing with Transmit Power Control, and Route Maintenance. The probability of PU activity with opportunistic service differentiation for various traffic priorities is considered. A mobility scenario is tested to examine its influence on OSDRP and the protocols with which they compared their work.

DARP-NND protocol [75] is based on neighbor node discovery (NND), where delays are an estimate of the combined channel switching and MAC layer backoff delays. Channel switching delay is the time it takes a node to switch from one channel to another, while the backoff delay is calculated using a formula that depends on the number of contending nodes, the contention probability, and the smallest size contention window. The next-hop node is selected based on the accumulated estimated delay for a given route. SU neighbor nodes exchange control information using neighbor nodes discovery messages (NDMs) and acknowledgments (ACKs). The work assumes a sensing operation to collect information about accessible channels and PUs' activities. The surrounding neighbors are detected using node discovery control messages with no CCC presence. The protocol is built on top of AODV with the incorporation of delay and neighbor node discovery operations. The same AODV route request (RREQ) and route reply (RREP) are adopted. A source node that wants to transmit data to a destination node initiates route discovery by broadcasting the RREQ packet to all close-by neighboring nodes. The intermediate nodes estimate the channel delay and forward the packet to the node with minimum delay. This is repeated until it reaches the destination node. The destination node responds by sending back the RREP packet, which travels back to the source node with the routing information. After route discovery, data packets are sent to the destination using the established route; and if a PU becomes active, the affected SU node pauses current transmission, queues packets to the destination, and sends a channel switch (CS) packet to both the previous and next-hop nodes in the transmission route. The previous-hop node switches to the newly selected channel, while the next-hop node initiates a CS-REP (change channel-Reply) packet. When a node receives CS-REP packet, it resumes transmission after updating the routing table accordingly.

OCR protocol [76] is a multi-hop routing protocol where multiple PUs and SUs share several orthogonal channels with

TABLE 2. Delay-aware routing protocols for static CRNs.

Protocol Name	Routing Metric(s)	Spectrum Awareness	MAC Type	Base Protocol	Supporting Resources	Simulator Used	Performance Metric(s)	Protocols Compared with
SORP [70]	Switching delay, backoff delay	Fully aware of spectrum holes	IEEE 802.11	AODV	CCC	GloMoSim	Cumulative delay	Switch-aware [79] [80], K-hop distinct [81]
DORP [71]	Switching delay, backoff delay, queuing delay	Fully aware of spectrum holes	IEEE 802.11	AODV	CCC	GloMoSim	Cumulative delay, number of switchings	SORP [71], Switch-aware [79], [80], K-hop distinct [81]
[72]	Switching delay, backoff delay, queuing delay	Fully aware of spectrum holes	IEEE 802.11	AODV	CCC	MATLAB	Cumulative delay, queuing delay, generalized cost, end-to-end delay	Switch-aware [79] , [80], K-hop distinct [81]
MSCRN [73]	Switching delay, backoff delay	PU probability of activity follows 1-0 distribution	IEEE 802.11	AODV	-----	OPNET	Throughput	AODV [45]
OSDRP [74]	Switching delay, queuing delay, link stability	Mean time of Idle and Busy states follows an exponential distribution	IEEE 802.11a	DSR	CCC	OPNET	Number of hops, end-to-end delay, throughput, routing overhead	ccDSR [75], DORP [72], SAMER [82]
DARP–NND [75]	Switching delay, backoff delay	-----	IEEE 802.11a	AODV	-----	NS-2	Throughput, end-to-end delay	MRSED [83]
OCR [76]	Hop transmission delay, distance	ON/OFF durations follow exponential distributions	IEEE 802.11	-----	CCC	C/C++ based simulator	End-to-end delay, packet delivery ratio, performance	SEARCH [20] , GOR [84], Geographic routing, different versions of OCR
CSRP [77]	Switching delay, probability of channel availability	ON/OFF durations follow an exponential distribution	-----	AODV	CCC	-----	End-to-end delay, data delivery rate	TDRP [85] , PUC-JRCA [86]
STOD-RP [23]	Switching delay, link stability	Statistical history of PU activity	IEEE 802.11	AODV	-----	NS-2	End-to-end delay, overhead	CTBR [87], Multi-channel multi-interface-AODV, different versions of STOD-RP
BCCCS [86]	Switching delay, link stability	Statistical history of PU activity	IEEE 802.11	AODV	-----	MATLAB	Percentage of connectivity	Single-channel approach
E-D2CARP [87]	Link delay, packet loss	PU activity is modeled based on the ON/OFF switching cycle	IEEE 802.11	-----	-----	NS-2	Percentage of packet loss, throughput, end-to-end delay, Jitter	D2CARP [90]

a CCC. The protocol adapts to network dynamics based on a distributed opportunistic routing algorithm involving spectrum sensing at the physical layer and spectrum sharing at the MAC layer. A SU uses a half-duplex cognitive radio for data transmissions and a different half-duplex regular radio as the CCC. Relay nodes are selected based on their geographical locations – i.e., preference is given to closer nodes, and channel usage statistics information obtained through periodic sensing. The source node selects an unoccupied channel and broadcasts a sensing invitation message using the CCC to inform neighboring nodes of its selection. The performance of the protocol is measured based on a new metric called Cognitive Transport Throughput (CTT), which is defined to be the expected next-hop bit rate advancement. To obtain an optimal end-to-end network performance, the CTT is maximized along the path from the source to the destination while considering multiple channels with each channel having its own expected bit advancement rate. An efficient heuristic search algorithm is proposed to reduce the calculation complexity of finding a global optimum CTT.

CSRP [77] is a joint channel selection and routing protocol that uses a technique based on channel switching delay and PU probability of availability to select the route with the shortest end-to-end delay. The AODV-established route increases the probability of data delivery with minimum delay and low interference with PUs. The channel availability is estimated by PUs' activity history. The records of

TABLE 3. Delay-aware routing protocols for static CRSNs.

Protocol Name	Routing Metric(s)	Spectrum Awareness	MAC Type	Base Protocol	Supporting Resources	Simulator Used	Performance Metric(s)	Protocols Compared with
BUD [89]	Unrelated degree between routes, data transmission delay, switching delay	-----	-----	-----	-----	C++ based simulator	Delay	Different schemes proposed in the work
[90]	Common channels, neighboring nodes, switching delay, backoff delay, queuing delay	-----	Contention - based	-----	-----	NS-2	Delay, throughput	-----

channel-availability probability are preserved in secondary nodes, using diffusion spectrum sensing technology.

STOD-RP [23] is a combination of tree-based proactive routing and on-demand (reactive) AODV-based route discovery. It combines route stability and channel switching delay in calculating the route cost. Statistical history of PU activity specifies the route stability. The CR users establish a one-time tree in each spectrum band where one node acts as a root for that tree that keeps the necessary information about the spectrum-tree topology. Subsequently, proactive paths are used to locate the spectrum band in which the destination resides. Intra-spectrum routing is performed wherever the source and destination nodes are in the same spectrum tree. When the source and the destination reside in different spectrum trees with a common root, inter-spectrum routing is used. The proactive routing is not required if an overlapping node exists between the two spectrum trees. To better utilize channels and network capacity, BCCCS [86] makes use of the metric in STOD-RP [23]. It considers the deafness problem and avoids rerouting by locally applying a route recovery in case of PU activity. This is performed by assigning an extra channel as a backup. A channel list is stored in each node to show channels' availabilities and priorities, depending on the metric used. Each node selects the least-used channel by assigning it the highest priority. When sudden channel unavailability occurs, a channel switch to the one with the second-highest priority in the list is performed.

As an enhancement to D2CARP [88], E-D2CARP [87] presents an Expected Path Delay (EPD) metric that considers link delay and packet loss probability in establishing high-quality routes while circumventing PUs regions. A node refuses to join the route if it is located within these regions. The request sent by the source is broadcasted through all channels unaffected by PU activity. Therefore, the destination replies to all received requests, and hence, multi-channel replies could reach the source.

2) STATIC CR SENSOR NETWORKS

On the other hand, for reliable routing in CRSNs, as Table 3 shows, [89] offers a quick recovery mechanism by selecting a backup route in the event of PU appearance. The routing algorithm selects the route with the minimum transmission and channel switching delays as a primary route. This is performed using the advanced Depth First Search (DFS) algorithm. A backup route is selected according to the delay and the "unrelated" degree, which depends on the number of common nodes the two routes share. A large number of common nodes expose both routes to failure. In [90], the node with the largest Cluster Head (CH) Determination Factor (CHDF) among its neighbors selects itself as a CH. The other nodes join the cluster with the highest CHDF among all CHs. The number of free common channels and the number of neighboring nodes are the CHDF dependent factors, which are needed to maximize the number of channels per cluster. The largest CHDF node in each cluster is selected by the CH to be a Secondary CH (SCH) to avoid re-clustering in case of CH unavailability. One-hop intra-communications occur, while relay nodes take part in the inter-communications. Multiple paths to the destination node are inspected. In the end, the source selects the path with the least delay.

3) MOBILE CRNs

Since IoT devices can be mobile, we survey here research works addressing routing protocols for mobile CRNs. Delay-aware routing protocols that support mobility are listed in Table 4. The greedy location-based routing protocol SEARCH [20] selects the lowest-cost route by considering the nodes that are in the nearest geographical region of the target. The destination makes the route selection decision. This minimizes the hop count and, therefore, minimizes the end-to-end path latency. The protocol depends on the information shared among channels about the PU activity. To handle PU interruptions, a different mode of operation is used in which the request messages detour around the PU activity region to avoid the channels influenced by the PU activity. Alternative routes are then discovered. For mobility support, beacons are periodically sent to keep locations updated.

Another greedy location-aided routing protocol LAUNCH [21] finds the stable route among nodes based on

TABLE 4. Delay-aware routing protocols for mobile CRNs.

Protocol Name	Routing Metric(s)	Spectrum Awareness	MAC Type	Base Protocol	Supporting Resources	Simulator Used	Performance Metric(s)	Protocols Compared with
SEARCH [20]	Switching delay, location, route stability, hop count	PU activity is modelled using an exponential ON/OFF process	IEEE 802.11	GPSR	-----	NS-2	End-to-end delay, packet delivery ratio, number of hops	GPSR [96]
LAUNCH [21]	Switching delay, location, PU activity	ON/OFF durations follow exponential distributions	IEEE 802.11	GPSR	CCC	NS-2	End-to-end delay, loss ratio, number of routing packets	SEARCH [20], AODV [45], CLCR [97]
CRP [91]	Switching delay, bandwidth, spectrum characteristics, PU protection, hop count	ON/OFF PU activity model with ON duration follows an exponential distribution	Adopted version of IEEE 802.11b	-----	CCC	NS-2	Path latency, path length, goodput, collision risk ratio, interference-time product, mobility induced path disruption time	SOP [73]
CoRoute [92]	Expected transmission time	Primary access points	IEEE 802.11b	-----	CCC	Qualnet, VanetMobiSim	Delivery ratio	Single-channel Route [94], CoAODV [94], AODV [45]
[93]	Switching delay, backoff delay, queuing delay, number of hops, throughput	-----	IEEE 802.16e	AODV	Geo-location database	NS-2	Delay, number of hops, packet delivery ratio, packet drop ratio, throughput, network lifetime, node lifespan, remaining and consumed energy, complementary cumulative distribution function	DRAND [98], different versions proposed in the work
RARE [97]	Switching delay, backoff delay, queuing delay	PU traffic is modeled using Semi-Markov ON/OFF process	Proposed MAC	-----	CCC	NS-2	Number of clusters, re-clustering effects, simulation execution time, channels per cluster, delay, overhead, throughput	Cluster-based approach [100], SOC approach [101], Node contraction approach [102], CogMesh [103]
JRCA [102]	Media access delay, transmission delay	-----	-----	-----	CCC	NS-2	End-to-end delay	STOD-RP [23], WCETT [105]

stochastic PUs activities, switching delay, and how close the next hop is to the destination. The protocol avoids short-lived routes despite their advantage. The preferable route is the stable route that supports low delay and stays operational for a longer time. This is achieved by estimating the latency period when rerouting happens due to the presence of PU activity.

A set of metrics is used in CRP [91] to assign different levels of PUs protection and SUs end-to-end latency. Based on the desired level of protection and user demands, the protocol either prioritizes the PUs protection from interference or minimizes the end-to-end latency while maximizing the network performance. It protects PU transmitters as well as the hardly detected PU receivers due to the weak leakage power in the reception circuit. The protection is obtained by avoiding the zones where the PUs reside.

Researchers in [92] propose CoRoute protocol for vehicles in urban areas. Each node has a forwarding set consisting of nodes near the destination. This is performed with the help of a CCC. The route with the minimum expected transmission time is selected based on the estimated channel status and the least disturbance to PUs.

The protocol in [93] selects the route based on packet delay, throughput, and the number of hops while offering an adaptive traffic-oriented mechanism to save nodes energy. However, it does not consider energy as a metric; instead, it analyses secondary nodes incoming traffic and associates sleep-time duration for each to preserve energy according to the Fibonacci-based Backward Traffic Difference(F-BTD) scheme. The packets are cached into the one-hop neighboring nodes along its route to uphold the incoming packets to a node in a sleep state. When neighboring nodes are unavailable,

TABLE 5. Delay-aware routing protocols for mobile CRSNs.

Protocol Name	Routing Metric(s)	Spectrum Awareness	MAC Type	Base Protocol	Supporting Resources	Simulator Used	Performance Metric(s)	Protocols Compared with
DCAR [104]	One-hop transmission delay, hop count	Channel idle time ratio is compared with a predefined threshold value	IEEE 802.11	-----	CCC	NS-2	Packet delivery ratio, packet dissemination ratio, end-to-end delay	Different approaches proposed in the work

TABLE 6. Energy-aware routing protocols for static CRNs.

Protocol Name	Routing Metric(s)	Spectrum Awareness	MAC Type	Base Protocol	Supporting Resources	Simulator Used	Performance Metric(s)	Protocols Compared With
[105]	Energy, spectrum availability, distance	PU activity is modelled as an exponential ON/OFF process	CSMA/CA, CDMA (PUs)	-----	CCC	C++ based simulator	Throughput, end-to-end delay	GPSR [96], OCR [108]
[107]	Energy, PU protection, load balancing, hop count	PU activity is modelled as an ON/OFF with probability of 0.5	TDMA/ CSMA/CA	-----	CCC	OPNET	End-to-end delay, goodput, aggregate interference	SER [110]
SEER [109]	Energy, network lifetime	Poisson distribution with exponential time duration mean of 500 slots	-----	-----	CCC	Java-based simulator	Energy per packet, network lifetime, throughput, end-to-end delay	Minimum total transmission power routing, min–max battery cost routing

packets are stored in the relay-node buffer as long as it has sufficient capacity. PU activity probability is considered in their performance evaluation (i.e., end-to-end delay).

RARE protocol [97] proposes a MAC super-frame structure with four periods, namely, beacon, spectrum sensing, neighbor discovery, and data. It also incorporates cross-layering through the fusion of the Network Layer with the MAC Layer, in addition to a delay-aware clustering mechanism. Similar to [90], CHDF is used to select the CH, then the route with the least delay among all available routes. Re-clustering solutions are also provided to handle spectrum and nodes mobility by exploiting the highest number of reserved channels and maintaining an SCH. In the case of spectrum mobility, new clusters can be formed with the possibility of excluding old members and including new ones.

The delay prediction model in JRCA [102] is used to minimize delay based on channel collision probability. The model predicts transmission time and media access time to detect any channel interference among different primary and secondary nodes. The channel set of each node changes according to its mobility and PU appearance. Therefore, interference may occur if the multiple nodes start using the same channel. The protocol discovers the minimum-delay routes and assigns channels accordingly.

4) MOBILE CR SENSOR NETWORKS

The routing protocols shown in Table 5 address mobile CRSNs. The gateways in [104] collect data in a closer-first mechanism using CSMA/CA contention-based mode. The gateway declares the accessible channels via the CCC. Accordingly, a sensor node constructs a route to the gateway and sends its data to different working channels. The gateway, in turn, either sends the message to the destination or floods it in the case of multiple sensor destinations. The work follows an upstream to downstream channel assignment (downstream node is the one using itself as the next-hop node to the gateway). The delay includes both propagation and queuing delays occurred at all hops along the path to the gateway. The work is evaluated using two cases, when all sensor nodes utilize the same channel, and when each node randomly selects channels.

B. ENERGY-AWARE CR ROUTING PROTOCOLS

In CRN-based IoT networks with limited-energy devices, the efficient use of energy plays a significant role in preventing network disconnectivity and sustaining high network performance. The section addresses the CRN routing protocols that use the device energy as a routing metric either for stationary or mobile networks. Since a large body of the proposed energy-aware CRN routing research is found in the CRSN-related literature, we dedicate separate parts of the section to address the works pertained to static and dynamic CRSNs.

1) STATIC CRNs

Table 6 shows the energy-aware routing protocols for static CRNs. A distributed and localized algorithm has been proposed in [105], that benefits from both underused (grey) spectrum and unused (white) spectrum. A node selects the appropriate spectrum depending on the PU presence, PU-SU distance, its location, in addition to its residual energy. The node that supports the largest link capacity is selected as a next-hop in underlay routing (i.e., both PUs and SUs transmit on the same spectrum, but SUs avoid interfering with PUs) that makes use of underused spectrum. On the other hand, the node that can support largest transmission distance with higher residual energy is selected in overlay routing (i.e., SUs transmit only in spectrum holes) that makes use of unused spectrum. Combining the two techniques allows packets to follow different routes to reach their target, which maximizes network utilization.

Similar to CRP [91], but in a static environment, the route discovery in [107] is performed based on nodes' geographical locations. The objective is to reduce the end-to-end delay and energy consumption by restricting the number of downstream nodes participating in the route discovery process. The route request is broadcasted to all upstream neighbors that are closer to the destination than the source. The priority can be given to one of two classes, either PU protection or network performance maximization. Zones with the least overlap between SUs and PUs transmission ranges should be used to pass the route through. This route detour provides some protection to PU receivers, which may reside in the overlapped region. For both classes, the protocol considers increasing network survivability by balancing the energy levels at each node and choosing the route with the highest minimal residual energy node. Synchronization schemes among SUs are needed to distribute the channel availability information periodically. SEER protocol [109] considers the power consumed over the link and the energy consumed by nodes. The number of packets queued at each node is used to estimate the energy each node will consume to forward these packets. The remaining energy, in turn, is used to find the expected residual lifetime. The route with the minimum required the destination selects transmission power and the maximum lifetime.

2) STATIC CR SENSOR NETWORKS

Table 7 shows several energy-aware protocols for CRSNs. Researches in ROR [110] present five phases: route request, route selection, virtual contention group (VCG) formation, VCG-based initiative-determination forwarding, and route management phases. The hop and channel switching counts are the route selection metrics. After route selection, the sink broadcasts a VCG formation packet along the selected route to the source node, including the data rate required by the application layer. Each node forwarding the request packet or receiving the formation packet applies VCG eligibility operation, depending on the node residual energy, to ensure its capability to forward the packet or join the virtual cluster. The protocol considers PU activity in performance evaluation.

BECHR [112] maintains the system lifetime by evenly dividing the energy consumption among all sensor nodes. As all nodes send their locations and energy levels to the BS, initial clustering, based on the Euclidean distance, is specified by the BS. Nodes at the borders of each cluster could be arranged to balance clusters' energy evenly. The energy level is considered high or low relative to a threshold value. The highest-energy node in each cluster is initially selected as a CH. The CH is replaced only if its energy level drops below the threshold value. Every CH receives data in a TDMA manner and then transmits them to the remote BS, after performing the required signal processing.

The work in [114] presents an adaptation to the LEACH protocol [113]. Three-level threshold values are used to select a CH and a backup CH. The probability of a node to be selected as a CH is related to the node energy level relative to the cumulative residual energy of the network. A specified distance between adjacent CHs is enforced. The number of clusters is related to the total number of sensor nodes within the network area, the CH-BS distance, and the amount of energy used by transmission amplifiers. Remaining nodes stay in the sleep-state waiting for their turn in a TDMA manner. As each CH broadcasts an advertisement message using CSMA, every node selects the cluster based on the signal strength of the advertisement messages it receives. It chooses the CH with the maximum signal strength (minimum communication energy).

The work in [115], ECR, is an energy and a CR awareness protocol that enhances the mobile AODV protocol to work in a CR environment. It assumes the use of 802.11 MAC with several unlicensed channels and one licensed. The residual energy and channel availability information are collected and disseminated using the DSR-adopted piggybacking mechanism. The destination selects the route with available licensed channels, the highest average residual energy, the highest number of shared unlicensed channels, and the lowest number of hops. The energy computation involves the energy consumed in broadcasting the request packets, unicasting reply packets, receiving packets, transmitting data packets, switching channels, and sensing each channel once before information transfer. PU channel occupancy is taken into consideration to find the system throughput.

The protocol (ERP) [116] introduces an event-driven clustering formation and routing solution. The qualified clustering nodes are chosen based on their locations and remaining energy levels. The CHs are elected from the eligible nodes based on their available channels, neighbors, remaining energy levels, and distance to the target. Communication between clusters is made through gateway nodes. The probability of PUs presence affects the selection of clusters' common data channels. The protocol reduces distributive clustering and re-clustering formation and selects a shared data channel based on PU probability of presence estimated through periodic monitoring. Different values of PUs channel occupancy percentage are investigated to show the impact on several performance metrics.

For CR multimedia sensor networks, SCEEM [111] is proposed to minimize distortion in multimedia transmissions dealing with latency and packet loss. Periodic energy rank is given to each sensor node to reflect its energy level relative to the neighboring node, which has the maximum residual energy. Clusters are formed with the arrangement of nonadjacent available spectrum bands for a persistent transmission. The node with the highest rank is chosen as a CH, which

TABLE 7. Energy-aware routing protocols for static CRSNs.

Protocol Name	Routing Metric(s)	Spectrum Awareness	MAC Type	Base Protocol	Supporting Resources	Simulator Used	Performance Metric(s)	Protocols Compared with
ROR [110]	Energy, hop count, switching count, buffer occupancy level, distance, SNR, channel availability	PU activity is modelled as an ON/OFF Poisson process	CSMA	AODV	CCC	MATLAB	Throughput, goodput, latency, loss rate, energy efficiency	SCEEM [113]
BECHR [112]	Energy, distance	-----	TDMA	-----	-----	MATLAB	Number of dead nodes, residual energy, energy distribution	LEACH [115]
[114]	Energy	-----	TDMA, CSMA	-----	CCC	-----	Energy, SNR	LEACH [115]
ECR protocol [115]	Energy, common channels, probability of using licensed and unlicensed channels, number of hops	Channel availability and unavailability follow 1-0 distribution	IEEE 802.11. IEEE 802.15.4	AODV, DSR	CCC	MATLAB, NS-2	Network-wide energy consumptions, number of alive nodes, number of cumulative packets received, packet delivery ratio	AODV [45]
ERP [116]	Energy, distance, channels availability, neighbors	Estimation of PU appearance probability and idle time	CSMA/CA	-----	CCC	NS-3	Cluster Data channel stability, packet delivery ratio, throughput, end-to-end delay, network lifetime, overhead	ESAC [119], SCR [120]
SCEEM [111]	Energy, Channel statistics	PU traffic is modelled as an exponential ON/OFF process	802.11 CSMA, TDMA	-----	CCC	NS-2	Number of optimal clusters, video quality, delay, channel usage time, energy consumption, delivery ratio	SEARCH [20]
LEAUCH [119]	Available channels, residual energy, location	-----	TDMA		CCC	MATLAB	CH energy consumption, network load balance, network lifetime	LEACH [122], DSAC [123], CogLEACH [124], EEUC [125]
CogLEACH-C [124]	Available channels, residual energy, location	PU traffic is modelled using Semi-Markov ON/OFF process	TDMA	-----	CCC	MATLAB	Round of first node death, alive nodes	CogLEACH [124]
CRC [125]	Energy, location information, number of hops, channel commonality, presence of a licensed channel	-----	-----	-----	-----	MATLAB	Time taken for first node death, number of alive nodes, energy consumption,	ECR [117]
ECS [126]	Energy	-----	TDMA, CSMA/CA	-----	-----	MATLAB	Number of dead and alive nodes, number of packets to FC, Number of CHs	DEEC [129]
ECHS [128]	channel availability, initial energy	PU traffic is modelled using Semi-Markov ON/OFF process	TDMA	-----	CCC	MATLAB	Average Number of bits to BS per round, average number of alive nodes	EC [131], CogEC (a modified version of CogLEACH [124])
EACRP [130]	Energy, distance, channels availability	PU traffic is modelled as an exponential ON/OFF process	TDMA, CSMA	------	CCC	NS-2	End-to-end delay, energy consumption, stability of gateway nodes, packet delivery ratio	ECR [117], ESAC [119], ERP [118]
EARP [131]	Energy	-----	-----	-----	-----	MATLAB	Energy consumption, number of alive nodes, loss rate	LEACH [122]

is responsible for establishing routes and forwarding. Since CHs are involved in route establishment, proactive routing is performed. TDMA is used for intra-cluster communication, while CSMA is used for routing between clusters. Balancing energy consumption is performed through the continuous re-forming of clusters based on the rank. In addition, a node in idle-state switches to the CCC without having to sense the channel, which helps in balancing the energy consumption. The channel statistics history is used to find the average channel available time.

The work in [119] presents an algorithm, LEAUCH, which offers reduced and balanced energy consumption. The node is promoted to be a CH candidate if it has several idle channels with a probability greater than 0.4. The other nodes stay in a sleeping mode while the CH decision is being made. Each candidate node creates a competition message to broadcast its ID, competition radius (computed based on the distance from the sink), and residual energy. Based on these messages, each candidate CH decides to become a CH if its residual energy is higher than the neighboring candidate CHs'. The remaining nodes join clusters that impose minimum energy consumption penalty. The balance in energy consumption comes from driving the clusters close to the sink, which has fewer cluster members to dedicate part of their energy to help further clusters to communicate with the sink. CogLEACH-C [124] is based on the Low Energy Adaptive Clustering Hierarchy protocol, LEACH [120], and its extension, the spectrum aware algorithm CogLEACH [122]. Through intensive signaling, the BS assigns a CH. The probability of being a CH depends on the node's available channels, locations, and residual energy levels. The CH, in turn, waits for joining messages from the other nodes sent over the CCC to the BS.

In CRC [125], a BS divides the region containing sensor nodes into sectors. This is presumed to locally categorize the sensor nodes based on their locations by assigning each node a sector number. The BS specifies the appropriate sector number based on the node signal strength and angle of reception. Synchronization between sensor nodes and the BS is required. Chains are formed to include the node with higher residual energy from each cluster that does not reside in any other chain. The chain formation considers the minimum number of nodes from adjacent sectors taking into account the presence of a licensed channel and common channels. Energy reduction and load balancing are implemented by reducing the hops forming each chain, re-chaining, and shifting the computing load towards the BS to balance the traffic load. Forwarding data packets is handled through time slots.

ECS [126] selects the CH according to the residual energy of the awake nodes. The probability of being a CH depends on the random number the node picks from [0,1], which must be less than a particular value. The selected CH broadcasts a message to inform the awake nodes of its presence. After that, the node chooses the CH to join based on the received signal strength. The joining request to a CH is transmitted via the CSMA/CA MAC protocol and contains the node distance (from the CH) and energy level. As a result, the node with the highest energy level is selected by the CH as an SCH. The non-cluster nodes transmit their data to the CH in TDMA slots. Energy conservation is achieved in the network by applying sleep rounds to reduce the energy consumed in sensing and in connecting to the CH.

The probability of being a CH in ECHS [128] relies on channel availability similar to some previous works but depends on the initial node energy instead of its residual energy. The aim is to reduce the number of interchanged messages to reduce energy consumption. As each node calculates this probability, it randomly selects a number in [0,1] and then considers itself a candidate to be a CH if this number is less than the calculated probability. All candidate CHs broadcast their residual energy levels to their neighbors. A candidate CH declares itself a CH, if it does not receive any broadcast from its neighbors or if it has the highest residual energy among its neighbors. Balancing the traffic load around the sink is performed by shrinking the transmission range of nodes around the sink to add more clusters. Each CH, in turn, broadcasts its ID and the used frequency, in an area within double its transmission range, over the CCC. Non-CHs select the nearest CH with which it shares a frequency. Intra-transmissions are performed in a TDMA schedule.

EACRP [130] aims at reducing energy consumption using short-distance intra-cluster communications through CHs and inter-cluster relaying communications through gateways. The event samples are routed from the event-detecting nodes to the sink. The selection of CHs and gateways is made based on the nodes' residual energy levels, channels' availability, and distance to the sink. The optimum number of clusters is calculated based on the relation between the number of nodes, the sensing results, and the energy consumption. As an event occurs, every node considers itself a disjoint cluster. In each round, all CHs collect the information regarding the cluster size and common channels unless the optimal number of clusters has been reached. In addition, the distance between their clusters and the others is calculated. Subsequently, a decision is made by each CH to merge one of the neighboring clusters based on the collected information. The merge is done if the two CHs swap the merge requests, and hence, a new CH is assigned. In the case of merge failure, a CH replacement takes place. Similar to other CRSNs, CHs use intra-cluster TDMA and inter-cluster CSMA MAC protocols. Gateway nodes are chosen according to their positions relative to other clusters.

Two energy threshold values are assumed in EARP [131] to indicate the normal, warning, and danger stages. The route request packet contains the relative residual energy value of all nodes, in addition to the minimum residual energy value among all nodes along the route. As a result, the destination selects the route based on the link energy stage. A prediction process is adopted by nodes to locally start a maintenance strategy in advance to avoid route failures. A node selects the next-hop with the highest residual energy among its neighbors as long as the next-hop node has a residual energy level higher than the minimum residual energy level of the sink.

TABLE 8. Energy-aware routing protocols for mobile CRNs.

Protocol Name	Routing Metric(s)	Spectrum Awareness	MAC Type	Base Protocol	Supporting Resources	Simulator Used	Performance Metric(s)	Protocols Compared with
SER [108]	Energy, hop count	PU activity is modeled using an ON/OFF process	CSMA	DSR	CCC	-----	Throughput, message delay, survival nodes ratio, routing success rate, normalized routing overhead, consumed energy per packet, consumed energy for control overhead ratio, network lifetime	Baseline energy-aware routing, Baseline shortest path routing

TABLE 9. Energy-aware routing protocols for mobile CRSNs.

Protocol Name	Routing Metric(s)	Spectrum Awareness	MAC Type	Base Protocol	Supporting Resources	Simulator Used	Performance Metric(s)	Protocols Compared with
[132]	Energy	PU activity is modelled using Markov ON/OFF process	TDMA	-----	CCC	-----	Consumed energy, end-to-end delay, normalized residual energy, mean squared error, probability of detection	SENDORA [135], LEACH-C [122]
mESAC [134]	Node degree, nodes speed, available channels, remaining energy, location	PU traffic is modelled using Semi-Markov ON/OFF process	-----	-----	CCC	MATLAB	Number of data and control packet transmissions, time steps for clustering, connectivity, energy consumed for clustering, ratio of re-clustered CHs in terms of nodes speed and weight	DSAC [123], SOC [101], MNB [137]

3) MOBILE CRNs

Various energy-aware CR routing protocols have been proposed to support mobility, as shown in Table 8. A scheme for channel-time slot allocation is proposed in [108], SER protocol. The traffic load is distributed among available channels and time slots with minimum hop-count consideration. The strategy aims at selecting energy-efficient paths to guarantee a long network lifetime. Synchronization between SUs is needed during the Ad-hoc Traffic Indication Messages (ATIM) window dedicated to the CCC. The protocol is applicable for single-path and multi-path routing to offer fast recovery in case of route failure with no need for route rediscovery.

4) MOBILE CR SENSOR NETWORKS

Cluster-based protocols for CRSNs are shown in Table 9. In [132], sensor nodes surrounding the cognitive mobile stations, which act as CHs, save energy in different ways. The low-consumed sensing energy is considered because of the periodic sensing performed in short intervals. Once a sensor node receives a broadcasted advertisement message from multiple cognitive stations, it responds by sending its energy level and SNR. The response is directed towards the closest cognitive station to consume the least transmission energy. In the case of multiple cognitive stations with identical closest distance, the response is directed towards the station with the smallest number of registered nodes to reduce the waiting time needed to send the sensing result. Subsets are formed in clusters by gathering the nodes that surround the cluster region with minimum overlap. The highest residual energy node is used to start forming the subsets to prolong the network lifetime. For spectrum sensing, the subset with the maximum total energy is selected to receive the beacon messages sent by the cognitive station in a TDMA schedule, which gives priority to nodes based on its SNR. The other subsets in the cognitive station region stay in a sleep mode for a number of consecutive slots specified by the PU history.

mESAC [134] proposes reducing energy consumption in CRSNs by forming clusters upon events in an iterative

TABLE 10. Delay and energy-aware routing protocols for static CRNs.

Protocol Name	Routing metric(s)	Spectrum awareness	MAC type	Base protocol	Supporting resources	Simulator used	Performance metric(s)	Protocols compared with
FDRP [136]	Packet transmission time, energy	Channel-availability probability follows [0,1] uniform distribution	-----	-----	CCC, BS	MATLAB	Transmission delay, remaining energy	Traditional shortest delay algorithm
L2ER [137]	Switching delay, backoff delay, queuing delay, energy	Free/non-free channel provided by MAC layer	-----	AODV	-----	NS-2	End-to-end delay, throughput, number of exhausted nodes, packet delivery ratio	SER [110], DORP [72]

manner and disbanding the clusters once data is transmitted. It also offers stability against spectrum variations and nodes mobility by selecting the node with the highest weight to be the CH. The weights are assigned according to eligible one-hop neighbors availability, available channels, residual energy, distance to the sink, and speed. In the case of CH movement, a new CH is selected following the same criteria. Inter-communication between clusters is performed through gateways. The vacant channel parameter considered in the selection of CH leads to a high probability of having common channels between the neighboring CHs, and hence, energy consumption due to channel switching is avoided.

C. DELAY AND ENERGY-AWARE CR ROUTING PROTOCOLS

1) DELAY AND ENERGY-AWARE ROUTING PROTOCOLS FOR STATIC CRNs

CR protocols should jointly consider delay and energy metrics to satisfy the latency requirements of delay-sensitive applications in a network with limited-energy devices (e.g., real-time monitoring and fault diagnosis of industrial elements such as pumps and heaters). Table 10 shows the few hybrid-metric (joint delay and energy-aware) routing protocols proposed for static CRNs. Based on user demand, the required delay performance level in FDRP [136] is reconfigurable. It breaks up upper layer applications into energy and delay levels. The levels are organized according to the d'ata transmission requirements and the amount of network energy to be saved. The highest level serves delay-sensitive applications, whereas the lowest levels save network energy consumption. For general (non-sensitive) delay applications, the protocol reaches a balance from both delay and energy perspectives. In this case, the route with the smallest weight, found by Dijkstra's algorithm, is selected. Channel availability probability has been considered to show its effect on average packet delay.

A route decision is made based on the AODV protocol in the full spectrum-aware L2ER [137]. It is a reactive protocol that selects the route that reduces the end-to-end delay and the number of exhausted nodes. The route with the maximum residual energy sum and minimum delay is selected. The MAC layer provides channel information.

D. FUTURE DIRECTIONS FOR CR ROUTING PROTOCOLS FOR IoT

In the literature, a few CR routing protocols are declared by their authors to fit the nature of IoT networks. SpEED-IoT [138] is an energy-aware routing protocol for device-to-device IoT communication that depends on the existence of a spectrum map available through the usage of spectrum sensors. The protocol uses power control-based selective flooding for route requests and a dynamic learning algorithm to discover conflict-free paths. The protocol addresses only optimizing throughput and energy minimization over the discovered paths. The authors of [139] propose an AODV CR routing protocol to transfer the IoT aggregate data from an IoT gateway to the final destination over a non-constrained CRN via the usage of directional antennas. Thus, the proposed protocol is not used to route the data among IoT nodes. In [140], the authors propose a spectrum-aware clustering mechanism for CRNs with non-uniform node distribution, such as in IoT networks. They also propose a routing protocol that works proactively for intra-cluster routing and reactively for inter-cluster routing. The path selection of the proposed routing protocol is a multi-objective optimization problem that takes into account packet delay, data rate, and the number of hops of the selected path, but it does not consider node energy as a routing metric. Zhang *et al.* [141] propose an on-demand CRN routing protocol that takes into account statistical and instant spectrum availability in choosing a route based on average transmission delay and packet delivery probability allowing only one retransmission if an SU transmission is interrupted by a PU. However, the work in [141] does not take node energy consumption into account. In [142], the authors propose a light-weight routing protocol for CRNs of energy-constrained devices that can fit IoT networks and achieve low latency. However, the protocol uses only the remaining energy as a metric for path discovery.

The IoT paradigm is anticipated to span a wide variety of applications in industrial automation, environment monitoring, e-health, video surveillance, to name a few. This makes an IoT network distinct in nature as it is expected to cover a wide area with a high device density to serve real-time and non-real-time applications, while the majority of the devices are energy-constrained (battery-powered). Besides, the integration of mobile SUs complicates the search for spectrum holes and increases the energy consumption as the SUs have the additional overhead of continuously sensing the channel for any PU appearance. Thus, the surveyed literature includes only a few multi-metric CR routing protocols that can jointly address both delay and energy consumption, and hence tackle the aforementioned challenges pertaining to the nature of IoT networks serving delay-sensitive applications running on energy-limited devices.

VI. CONCLUSIONS AND OUTLOOK

Integrating IoT devices in CRNs is one viable solution to provide such devices with the massive spectrum opportunities they require. As these battery-operated devices are connecting IoT applications, a communication environment that meets the QoS requirements of such applications is essential. This paper surveys the most recent CRN protocols that focus on either delay, energy, or both as metrics. Challenges facing CR routing protocol design are identified and discussed. Moreover, to enable future research in developing delay and energy-aware routing protocols, existing protocols with key comparison elements are presented. It is shown that the majority of existing delay-aware routing protocols for static CRNs are based on AODV and use different simulation tools, such as GloMoSim, MATLAB, OPNET, NS-2, and C/C++ based, while most protocols for mobile CRNs use NS-2 simulation tool and only very few are based on AODV. Almost all static and mobile delay-aware protocols assume the availability of a Common Control Channel (CCC). On the other hand, energy-aware protocols rarely depend on AODV, use different simulation tools, and the majority of them also assume the availability of a CCC. Indeed, the expected massive demand for wireless network bandwidth by IoT and M2M applications mandates uninterruptable Internet connectivity. Besides, for these applications that run on energy-limited devices and require real-time low-latency data transfer, there is still a need for further studies to develop light-weight CR routing protocols that combine packet delay and energy consumption metrics.

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