Research Article

Survey on Improving QoS of Cognitive Sensor Networks using Spectrum Availability based routing techniques

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Abstract: Cognitive Sensor Networks (CSNs) are significantly different from the traditional WSNs in terms of Cognitive Radio (CR) technology. According to the surrounding environment interaction, the modification of transmitter parameters is required for CSNs. However, routing is one of the important components and routing schemes are distinctive for other networks based on the spectrum-aware capability. The changeable spectrum resources should understand by the routing scheme to establish a reliable forwarding path. Because of spectrum unavailability, packet drops and the nodes' connectivity impacts seriously by the buffer overflows. The prolonging of packet dropping impacts the data delivery rate and network lifetime. In the routing phase, this drawback addresses to improve the lifetime of a network. Based on the spectrum links power dissipation and packet drop ratio, we have studied various routing techniques for cognitive sensor networks. These methods will help in reducing the drop ratio and ensure the data that would handle using low dropping ratio nodes. Thus, the network lifetime and energy efficiency will improve.

Keywords: Cognitive Sensor Networks, Packet dropping, Data delivery, Network lifetime, Packet drop ratio, Energy efficiency.

1. Introduction

The Internet of Things (IoT) has become an essential networking paradigm that allows the communication among physical objects. The industrial, offices, and household devices will have a capability of sensing, communicating, and processing the data in the future [1]. Due to the enormous increment of number of wireless devices, IoT solutions need to face various challenges of scarcity in spectrum and energy. In IoT, spectral and energy efficient techniques have required for a range of sensing devices that facing these challenges. As a potential solution, the utilization of opportunistic spectrum sharing is considered and spectral efficiency achieves [2]-[4]. A large number of connected devices can be supported for various applications. For coexisting with a licensed network (primary network), unlicensed devices (secondary users) have allowed using the cognitive radio (CR) as a key technology for opportunistic spectrum sharing [1], [2], [5]. Here, primary users (PUs) refer to the people who subscribe for primary network. All non-continuous spectrum can be used in CR sensor networks (CRSN) for making it spectrum efficient [6]. From radio frequency (RF) signals, energy supply can provide by wireless energy harvesting that improve network lifetime and energy efficiency. The received RF signal converts into DC power by sensor nodes in the wireless energy harvesting and data transmits and perform other tasks. For wireless energy harvesting, two possible cases are involved such as: i) the energy harvesting can process from ambient RF signals by sensor nodes, and ii) deploying the dedicated energy transmitters in the sensor nodes vicinity. For IoT, energy efficient solutions have considered by various research efforts [7]-[10].The prototype mentioned in [11] implements at the sensor nodes that power by an ambient RF energy.

In [12], the RF energy harvesting proposes in body area networks, where energy harvests from the spectrum band of radio signals ranging from 3 KHz to 300 GHz. For managing the energy, a work-on-demand protocol proposes. In [13]-[15], the schemes of energy harvesting have presented that harvests the energy from ambient RF signals for achieving sensor nodes' requirements in terms of energy. For IoT, CRSN can use alternative solutions for spectrum resources and improve the usage of spectrum [16]. To evaluate the performance of CRSN for IoT, various deployment patterns have considered [17] and presented the performance comparison. To gain the advantages of user requirements and network efficiency, intelligence and cognition have developed and utilized in CRSN [18], [19]. The processing of spectrum sharing and spectrum sensing tasks have required higher energy for sensor nodes in CRSN along with the traditional functionalities [20]. For addressing these demands and improving energy efficiency, energy harvesting can use in CRSN. Based on the energy variations(difference between the energy consumption and harvested energy), the channel assignment and sensor node selection schemes should redesign for incorporating the energy harvesting in CRSNs for achieving better performance in spectral variations and power management.

Based on spectrum sensing, the unoccupied channels can identify by sensor nodes in the licensed bands in CRSN and communication channel estimates based on spectrum decision. When PUs have arrived on the communication channel, the operating channels modify the spectrum hand-off. In a dynamic spectrum environment, the nodes collaboration with their neighbouring nodes carried out in multi-hop way for delivering event data from source to the destination. The limitations of energy and hardware problems that adapted from WSN have imposed by CRSN in despite of addressing the challenges of dynamic spectrum by CR functionalities. The earlier existing solutions have not considered CR functionalities and not addressing the challenges of dynamic spectrum for WSNs. The hardware and energy challenges don't consider in the proposed solutions for CRN. To address these issues, we required to determine new techniques. Its need to research more on the area CRSN as it receives interest lately from the research community. The connectivity, clustering, and path formation have focused in the recent works [21], [22]. In sensor networks, one of the significant research fields is clustering where sensor nodes integrate in groups for management of system topology to obtain the increased stability of a system. For wireless ad-hoc networks and WSNs, various reported researches on clustering are provided [23], [24], [25], [26], [27]. The whole network divides into self-organized clusters by clustering in the existing schemes where each cluster controls using one of the cluster member, known as cluster head (CH) which can be acted as a cluster's central entity. In prior to the forwarding of collected data to the next node to sink in a routing path, it aggregate from other member nodes of a cluster. Using the residual energy of nodes, CH elects using the clustering schemes for WSNs [28]. The clustering schemes can include two nodes within a cluster only in case of availability of one common channel and they can't be exploited for CRSN. As re-clustering has occurred owing to the dynamic radio environment, the schemes alone don't ensure the stability. The distributed and energy efficient event-driven cluster based routing method proposes that focuses on making robust for PU activities with CRSN. Based on inter and intra-cluster communication, the CRSN features adapt in a routing protocol that transmits the event samples to the sink from detecting nodes. The clusters' optimal number is estimated for reducing the power consumption of communication.

The intra-cluster aggregation uses through CHs in the spectrum aware clustered structure and efficient inter-cluster relaying has performed based on the gateways by considering the issue of energy consumption. For reducing the intra-cluster communication power and intra-cluster distances, the clustering utilizes under the constraint of spectrum aware. By using the parameters of available channels, nodes' residual energy, and distance to sink node, CHs have chosen for each cluster and gateway nodes select for inter-cluster connectivity. These CRSNs have powered up by the dynamic spectrum access (DSA) through which required performance can provide in the applications based on the dynamical changing of operating parameters and adaption with the channels condition. A three step process, called cognitive cycle has to be gone through in CRSN node1 which has some data to transmit for PR nodes that are priority nodes [29]. To understand the current channel condition, the channel sensing performs primarily. To choose the suitable channel or tuning to make decisions by CRSN node, channel sensing results have considered for communication. Both unlicensed and licensed bands can be accessed using the CRSN nodes and they provide opportunistically that not creating interference for PR nodes. The CRSN node is required to leave the channel instantly for PR communication when any PR node display on the same channel in the CRSN communication. For WSNs, CR capability allows to invoke certain challenges for using the effective spectrum. To prevail the CRSNs future, the challenges should address. For achieving the data rate requirements in CRSNs, large bandwidth is needed as multimedia is being an integral part in all applications and seamless communication provides by CRSNs for those applications based on the unlicensed opportunistic access [30]. To get access the advantages of multiple contiguous channels which are free from PR activity, CRSNs enhance based on CB by providing a large bandwidth to opportunistic users. In high bandwidth applications, the multiple contiguous channels have used that integrate using the CB. The various interfaces equip at the devices that performs the parallel sensing of spectrum holes for multiple networks and use them whenever require [31]. The necessary performance can provide by CB only if it decides accurately based on the PR activity although CB is a prominent method used for CRSNs, CRNs, WLANs, and WSNs. PR nodes approximate the spectrum usage in the Primary Radio (PR) activity. Using channel sensing process, the channel is chosen. If the CRSN nodes, they sense the channels which can be used for CB. If any PR node is appearing on any channel of bond, the CRSN nodes make the channel sensing periodically during the communication. The communication has to be stopped by the CR node, break the bond, and leave the channel. Before detecting the PR node by the CRSN node, it will have to face the challenge of interference. Due to the bonds breaking and frequent making, a great disruption causes in the CRSN transmissions. The certain network requirements meeting is difficult for CRSN nodes. However, RIT importance highlights. The QoS requirements and reduction of PR nodes' harmful interference can meet using the CRSN nodes if channels have chosen that include longest RIT with higher probability. For CRSN nodes, the channels are suited with longest remaining idle time. The harmful interference can reduce and certain requirements of QoS can meet using CRSN nodes.

The recent network paradigms requirements like IoT can be fulfilled by associating 5G technologies and cognitive radio undoubtedly. The billions of devices can connect to the people or other machines. For benefit of reporting, monitoring, and controlling the plethora of applications status that focus on the automation of human life aspects, the IoT paradigm connects the devices over the Internet. A large bandwidth requires that need to be provided through millimetre wave spectrum (60 GHz) [32] along with the under-utilized lower frequency spectrum (below 6 GHz). For various applications, direct communication requires between IoT devices. The limitation on the power has resulted in 5G that can overcome using the efficient spectrum sharing. The unlicensed users can use the spectrum sharing for reducing the interference with licensed ones. As a result, the unlicensed users (SUs) transmission range can reduce for the spectrum below 6 GHz. The short transmission range should mandate in the millimetre wave spectrum propagation characteristics [33]. For future CRNs, multi-hop communication is inevitable that shares the spectrum with 5G networks. To create a partly static infrastructure-based wireless mesh network [34] or a self-configuring ad-hoc network [35], the concept of cognitive radio can implement for multi-hop wireless networks. To obtain a complete spectrum awareness environment, a spectrum allotment map can establish and the neighbourhood can discover fully in an infrastructure based CRN. The availability of upholding tools can access in the network like central control entities, which control the spectrum allocation and accessing and geo-location databases. At each cognitive node, the information about spectrum accessibility is built location as we assuming the state of being away from supporting tools. The cooperation schemes require in the local spectrum awareness medium. The communication parameters like frequency and modulation should be adjusted flexibly using the CRN-based devices.

By not considering a source of interference to the primary users (PUs), the available spectrum gaps harnessing can perform efficiently which should mandate to allow the SUs. After detecting a PU transmission, the higher priority has given to the PUs transmission by an SU through the deferring of its transmissions to achieve the objective in overlay spectrum access. The energy limited devices can implement in various IoT applications. Such type of multi-hop CRNs lead to the serious challenges because the nodes in a network that depend on each other for data forwarding and a serious challenge imposes in such kind of multi-hop CRNs. To limit the exposure of a network to energy degradation that leads to the severe impact on connectivity, the nodes that are suffered from energy exhaustion should avoid by the selected route. For future multi-hop CRNs, an efficient routing scheme should implement for providing the available capacity of a per-node that anticipates the increasing number of devices to realize the machine-to-machine (MCM) and a multitude of IoT applications. A lightweight cognitive radio-based routing protocol has to devise in this research that suits IoT devices. These devices can act as SUs using the proposed protocol and they communicate each other based on multi-hop connections through a licensed radio channel. By reducing the communication overhead and number of hops, the proposed method has focused on (1) balancing the energy consumption among SUs, (2) achieving the highest possible per-node capacity (lowest end-to-end latency), and (3) reducing the consumption of energy through the minimization of communication overhead and number of hops. The remaining energy of a node is considered in the fully distributed route discovery which reduces the number of hops to the destination. At the times of forwarding nodes' energy depletion or improved PU activities, a fast route repair procedures invokes. To save the consumed energy in channel sensing, a sensing back off duration triggers by any PU activity for SU nodes. During the PUs activity, the back off process repeats for a particular number of retires. According to the surrounding PUs activity duration history, both the number of sensing retires and duration of sensing backoff have configurable. As the exchanging of routing messages has performed over the data channel, lightweight protocol proposes without common control channel (CCC). In the PUs frequency band, a cost-effective and simple medium access control (MAC) to be employed by following the IEEE 802.11 distributed coordination function (DCF) [36]. As the routing messages flooding is not exploited, low routing overhead considers. The stationary IoT environment or M2M applications like smart city environment monitoring, and industrial automation process (example, industrial elements monitoring and fault diagnosis like heaters and pumps) can adapt the pre-configurable node locations.

2. Literature survey

In [21], the authors have presented the energy management and its associated challenges for IoT overview. Energy management classifies into two different types for IoT such as energy harvesting operations and energy-efficient solutions. The optimal scheduling involves for energy-efficient solutions for lightweight protocol design, predictive models, and sleep and idle states for energy consumption. In [37], the energy harvesting sources, their benefits, and applications with a comprehensive survey have presented. In [38], two receiver architectures have introduces such as power splitting and time switching. The received signal selects either as an energy harvesting or information by the sensor node and the received signals separate into two streams, one of which for RF energy harvester and the other for information receiver. In [39], an integrated architecture proposes for energy harvesting and spectrum to handle the challenges of data rate requirements that poses in the sophisticated and modern applications. The energy scarcity overcomes by considering energy harvesting for CR networks. In [40], energy harvesting introduces for CR networks in which an optimal spectrum sensing mechanism proposes for improving the throughput under the energy causality constraints and collision for spectrum access. A cooperative mechanism proposes in [41] for wireless energy harvesting and spectrum sharing of 5G networks. For improving a throughput, an optimization problem formulates for both SUs and PUs with the conditions of energy harvesting and data rate. In [42], the authors propose a channel selection technique in CR networks to retrieve the higher throughput for SUs in the fading channel and energy neutrality constraints. Based on slotted mode, a CR system has proposed by considering the harvesting of energy by SU from the ambient environment. For the trade-off between 'harvesting sensing and throughput', system parameters can optimized. In CR networks, guard and harvesting zones introduce in [44]. The energy harvests if a node locates inside the zone of harvesting and the data transmit in case it is in outside the guard zone.

The energy balancing doesn't achieve by the proposed scheme but it optimizes the throughput. In the channel allocation, the PU behaviour doesn't consider. In the cluster-based CRSNs, different protocols have studied for effective energy management. In [45], channel pairing scheme, and two level residual energy and channel quality aware sensor node classification scheme have proposes for RF energy harvesting based CRSN. They can be used to choose the best sensor node for reporting. The algorithm of low-energy adaptive cluster hierarchy (LEACH) adapts in [46] for CRSN that elects the cluster head (CH) rotationally to achieve the energy management among various sensor nodes. Energy efficiency doesn't achieve with the irregular distribution of CHs even though the algorithm complexity is low. In [47], the authors have investigated a reinforcement learning-based trust and reputation model to choose the CH in CR networks that detects the malicious SUs. For CRSNs, an event-driven spectrum aware clustering proposes and determine the candidate sensor nodes for CH according to the sensor nodes' distance from the event and sink [48]. According to the distance from the sink, node degree, and available channels, CH chooses among the candidate nodes. The strategies of CH selection have proposed to choose the CH based on weight in [49] and [50]. The energy efficiency improves with the dynamic channel access in the cluster-based CRSNs has investigated in [51]. For both inter-cluster and intra-cluster data transmission, the sequential channel sensing and accessing schemes have proposed for CRSNs to achieve energy efficiency. In [52]-[54], the schemes of probability based channel idle time estimation have demonstrated. The future availability determines using various probabilistic models. The idle time prediction limits using these schemes but they perform better results in the predictability.

In [55], the existing node clustering scheme with performance comparison has presented with a detailed survey. In [56], an energy efficient and learning inspired channel decision technique has implemented for CSNs that allowing the accessing of CRSN sensor nodes based on previous data relevant to the energy consumption rate and energy efficiency. In [57], the network lifetime and energy efficiency development discusses for multi-channel CRSN. In addition to the allocation of energy aware channel for sensor nodes, the packet size adapts in the scheme. The modelling of primary users' behaviour has processed like a two-state Markov chain and a maximum-likelihood uses for determining the transition probabilities. In [58], a spectrum aware cluster based routing protocol (SCR) proposes. To being part in the establishment of route by sensor nodes has limited for reducing the power consumption. The clusters create in the network under the constraint of spectrum aware as SCR is not an event-driven routing protocol that leads to the re-clustering frequently in the dynamic radio environment. A distributed spectrum aware clustering scheme proposes for CRSN [59]. The constrained clustering uses for clustering of CRSN nodes in the spectrum aware conditions. In [60], an energy and cognitive radio aware routing scheme (ECR) designs using the principle of on-demand distance vector (AODV). The presented concept in [62] extends for mobile scenario [61]. Different channels are available in SUs at different locations [63]. The sensing accuracy can suffer from the shadowed and fading environments which is one of the challenges for spectrum sensing. For addressing the performance degradation, the Cooperative Spectrum Sensing (CSS) has used [64], [65], and [66]. To decide the appropriate grouping of SUs and allocation of SUs to use the PU channels for inter-cluster and intra-cluster communication, the allocation problem is focused in CRSN. A distributed event-driven cluster based routing proposes for addressing the associated challenges with CRSN to reduce the energy consumption. Here, the clusters are formed by reducing the frequency of re-clustering while establishing the network based on more number of common channels between and within clusters. The reliable gateway nodes have chosen that include higher energy with neighbouring clusters and more common channels and they are closer to the sink node among candidate nodes. The CB utilization in CRNs, WSNs, and WLANs has discussed. While developing the CRSNs, the CB challenges have described.

For providing a larger bandwidth for users, the multiple contiguous channels combine by CB using RIT based CB in WSNs and WLANs [67]. To provide the continuous seamless support for users, the wireless local area networks (WLANs) have deployed. WLAN has powered all wireless devices that get support from the vendors. The internet support can provide to the users who are locating everywhere either in market, hospital, office, home, etc. The performance can improve through the CB as WLANs have used to provide an internet access to the users.

For providing large bandwidth to the users, the new standard supports CB for IEEE 802.11n WLAN. The equal sharing of sources is performed by all users in WLAN and the bond size will vary based on the available number of users. To provide more users with the internet, the bond size will reduce when more users are there and network resources are required. The bond size can increase when there are less number of users. In [68], the bandwidth improves by considering different ways in wireless networks and the CB approach effectiveness has highlighted. Some particular event senses by deploying the WSNs and its parameters transmit in a multi-hop manner for the actuator or central station [69]. As WSNs have particular range of communication and lifetime, the deployment of WSNs has performed densely. WSNs lifetime can increase with the short communication range. By default, IEEE 802.15.4 doesn't support which is the current standard for WSNs. To limit the interference, an effective utilization of spectrum is required as WSNs have used the industrial, scientific, and medical (ISM) band for communication.

In CRNs, RIT based CB are opportunistic nodes that use ISM and licensed band for the communication. The co-existing of CR nodes with the licensed nodes is performed in a CR based network that means CR nodes shouldn't create interference for licensed users. The data transmit using a CR node and a PR node has tried to get access the similar frequency band for transmission. For preventing the PR-CR interference, the communication of CR node stop and it should leave the band in this case and PR activity data is needed. The presence or absence of PR node estimates using PR activity model. The scarce spectrum usage improves using the CR technique. The spectrum opportunities (white spaces) use in a network by the CR nodes while restricting the harmful interference. To use the opportunities in a better way, CR node uses that provides using the intelligent decision. In [70], the method of intelligent channel utilization is relied on the total number of CR nodes. The required performance can provide by the probability based channel selection when lower CR traffic is involved in the network, but better results can be provided by sensing based channel selection for high CR traffic to choose the required channels. For CR based networks, the channel prediction methods importance have highlighted in [71]. To compute the channels' stability for CR nodes, multiple methods have used that can switch the CR nodes to those channels which providing longer idle slots based on the coordination of a network [72]. The prediction based schemes have demonstrated in [73] for users activity of PR that improve the performance of CR node while reducing the switching of number of channels. To estimate the forthcoming PR activities, the previous histories about a channel can use by the CR nodes and the harmful interference can reduce effectively [74]. The power consumption is an essential parameter if adding CR capabilities to WSN node. If a CR node includes some data for transmission, the channel sensing is the best way to improve the CR based wireless sensor node lifetime effectively. However, the battery resources can save remarkably. By setting out the interference below a threshold level, the larger bandwidth provides to CR nodes for CB in CR based networks. For providing more bandwidth to CR nodes, the emerging CR based standard IEEE 802.22 has supported [75]. In [76], we have proposed a new concept known as CB in CRSNs. The harmful interference can reduce by the CB in CRSNs based on effective channel selection. The routing protocols in CRNs address in various research works based on different models, techniques, and routing parameters. The existence of multiple channels is assumed in these research proposals. The overall network capacity becomes more with the using of more network resources. The multiple radios employ in the multiple channels that results in more hardware-expensive nodes, which don't fit for the devices which use in M2M or IoT applications. The time-to-rendezvous (TTR) increases based on multiple channels with single radio that means the amount of time requires for maintaining or establishing a communication link between SU pairs. Thus, the degradation of throughput has resulted owing to the number of times the SU requires for switching various channels in the transmission of data.

Extra energy consumes by secondary nodes for channel switching [77] and it considers a crucial issue for CRNs that have energy-limited devices. We have focused on the routes that reduce energy consumption and improve the throughput of per-node (reduce packet transfer latency) for stationary applications and environments for M2M and IoT networks. The most related protocols have reviewed that use both latency and energy for route selection or consumption of energy considers to estimate the performance of latency. As routing protocols are not considering the characteristics of CRN, such as the PUs activity, which affect the stability of a route greatly, they don't consider the addressing of static and mobile ad-hoc networks. An on-demand routing protocols introduces by the authors in [78] and the route chooses in a way that the remaining energy improves over the chosen path and the end-to-end delay reduces. It's assume that the nodes are fully aware of the spectrum holes. Without considering the duration or probability of PU activity, the channel status determines using the MAC layer. An energy-based and delay spectrum aware routing protocol proposes in [79]. The flooding technique uses in an ad-hoc on-demand distance vector protocol (AODV) for the route discovery [80]. To determine the route that has the smallest weight for each level, Dijkstra's algorithm has utilized by depending on a central controller (BS) for collecting and communicating the information of channel availability with SU nodes. A quasi-cooperative multi-agent learning schemes proposes based on a stochastic game [81]. The scheme provides a tradeoff between transmission delay and energy efficiency. The prior knowledge about the transmission range of PU is required in the route selection that has considering the overlap in the transmission coverage area between SUs and PUs. For disseminating the information of channel availability to SUs through the periodic beaconing, the protocol depends on a TDMA-based common control channel (CCC) and a synchronization mechanism is needed. In [82], the SER protocol has made trails on choosing the energy-efficient routes based on AODV via balancing the energy consumption of a node. A frame structure has used for data transmission and CCC beaconing. It incorporates in TDMA-based MAC for data messages and contention-based MAC for control messages. It focuses on improving the throughput based on channel-time slot allocation and efficient rate selection. A CCC uses and the traffic distributes across the time slots and channels.

As similar as mentioned in [83], a perfect synchronization is needed for SER protocol among SU nodes but it's very hard in providing in a distributed fashion for a CRN. AODV has modified using the proposed protocol by depending on the multiple unlicensed channels, a CCC, one licensed channel, and a piggybacking mechanism for conveying the information about the spectrum availability and the collected residual energy. The scheme complexity increases and the packet delivery ratio reduces although the route selects through a variety of parameters. A routing protocol proposes by the authors [84] for 802.15.4 based IoT networks using a learning process that creates proactive actions through the exchanged messages history. The nodes that using half of the initial energy and increase the distance to the next hop don't involve in the proposed protocol. The end-to-end latency minimizes for CRNs using other routing protocols by not considering the energy efficiency for selecting a routing path. The switching and queuing delays minimize using OSDRP [85] based DSR which improve the route stability. The PU activity probability has taken into account with opportunistic service differentiation for different traffic priorities. IEEE 802.11 incorporates in the protocol as a MAC but a CCC has used. When estimating the end-to-end delay, the channel characteristics, protection of PU receiver, and sender's activity of PU, and backup routes have considered in the routing protocol of ETED_BEST [86]. In [87], DMACO-RPL proposes for CR advanced metering infrastructure (AMI) networks in smart grid ecosystems. In choosing the route, QoS and protection of PU receiver of delay-sensitive applications have considered. In [88], the relative advancement considers for advancement of the destination node that helps to reduce the interference between coexisting SUs and PUs and improve the throughput via beamforming. A balance between efficiency and simplicity has tried to achieve using the proposed routing protocol. For SUs and PUs, a single licensed channel uses without BS or CCC. It has assumed that the prior information about available spectrum holes doesn't require. A simple medium access mechanism (IEEE 802.11 DCF) uses and synchronization is not required. For future distributed CRNs with the energy capabilities and limited processing devices, the low operation overhead is suitable.

Ref.no	Author name	Title	Proposed method	Limitations
2	W. Ejaz and M. Ibnkahla	Machine-to-machine communications is considered for cognitive cellular systems.	The WCETT protocol includes a randomness feature for the existing protocol that extends using a drop factor. Each router or intermediary nodes amid source nodes and destination nodes decides either forwarding or dropping the RREQ towards the destination during a route discovery.	For data analytics and ground and aerial connectivity, communication technologies have considered. In this area, several open researches are there.
7	N. Kaur and S. K. Sood,	An energy efficient architecture designs for the Internet of Things (IoT)	Energy efficient routing methods such as multi-path routing techniques and cluster architectures have employed	IoT implementation in energy sector has faced some challenges such as objects detection, connectivity issues, and big data management, and subsystems integration, uncertainty, standardization, energy requirements, security, privacy, and architectural design.
13	P. Kamalinejad, C. Mahapatra,	Wireless energy harvesting applies for IoT	The technologies for efficient WEH with an overview has given and	The size and cost requirements should comply with the devices

	Z. Sheng, S. Mirabbasi, V. Leung, and Y. L. Guan		WEH-enabled IoT devices lifetime analyses.	which are being an integral part of WEH. Another crucial issue is the efficiency for a WEH system. By considering limited power due to the interference and health constraints based on the dedicated source, high efficiency becomes relevant increasingly.
14	M. Gorlatova, J. Sarik, G. Grebla, M. Cong, I. Kymissis, and G. Zussman	Movers and shakers: Kinetic energy harvesting considers for IoT.	A wireless energy harvesting node model considers various designs of practical IoT nodes. Based on the collected motion energy traces, the online, optimal, and approximated energy allocation algorithms have designed and their performances evaluated.	Additional human participants and their motions should include. The new wearable devices appear by expanding the study for additional motions that target particular activities like jumping and dancing.
17	W. Li, C. Zhu, V. C. Leung, L. T. Yang, and Y. Ma,	The cognitive radio sensor networks performance compare for industrial IoT that includes various deployment patterns.	The learning methods demonstrate to improve the SS performance by considering both cooperative and local sensing scenarios.	Various challenges are included such as switching protocols between CR functioning nodes, channel coding for interference sensing, strategy access for IoT or WSN networks, sensing the spatial dimension for CR towards intelligent spectrum sensing, and, exchange protocol of SS data for WSN or IoT.
41	H. Gao, W. Ejaz, and M. Jo	In 5G networks, cooperative wireless energy harvesting and spectrum sharing have discussed.	By integrating a power control-based SI mitigation scheme, a novel communication framework proposes for enabling CST in DSS systems and the performance analysis of proposed framework in terms of throughput is presented.	It's a crucial problem of obtaining spectrum occupancy data about the surrounding environment within a time frame.
51	J. Ren, Y. Zhang, N. Zhang, D. Zhang, and X. Shen,	For improving energy efficiency, dynamic channel access in cognitive radio sensor networks.	A four-step analysis is considered for a proposed solution: i) energy consumption for intra-cluster data transmission, ii) optimized transmission time allocation for intra-cluster data transmission, iii) channel sensing and switching decision analysis for intra-cluster data transmission, and iv) channel switching and sensing decision analysis	To support the cognitive radio techniques, a study should conduct on rechargeable CRSNs, where stochastic harvested energy can leverage.

			for inter-cluster data transmission.	
61	M. Ozger, E. Fadel, and O. B. Akan	In mobile cognitive radio sensor networks, event-to-sink spectrum-aware clustering proposes.	To build the coordination between the sink and the event, a two phase clustering protocol proposes. The intermediate eligible nodes estimation between the sink and the event is included in the first phase. Whereas in the second phase, the spectrum-aware clusters form using the nodes in this corridor with their one-hop neighbours. Until the end of event, cluster maintenance is considered.	The average probability of re-clustering and how the approach will reduce the probability have required to investigate.
67	Bukhari, S. H. R., Rehmani, M. H., &Siraj, S	The channel bonding for WSNs and guidelines of channel bonding for futuristic cognitive radio sensor networks have studied.	The effectiveness of spectrum usage with CR nodes can determine by the PR activity pattern in CR based networks. The efficient channel utilization is achieved using the important spectrum decision schemes.	Because of the changes in software and hardware at transmitter and receiver, the limitations can incur. Single MPDU transmits to various channels as CB applies at physical layer, but separate modulators require for each channel that should be bonded together. A larger bandwidth includes than a single channel as it includes a single bit-interleaver for all channels.
74	Agarwal, S., & De, S	Dynamic spectrum access implements for energy-constrained CR: single channel vs switched multichannel	In CRNs, the energy efficiency of fixed single channel access (SCA) and switched or probabilistic multichannel access (pMCA) are compared. The channel switches with certain probability using a secondary user in pMCA when a busy channel encounters.	In a dynamic PU traffic scenario, the limitations include using the multiuser CR MAC protocol with tradeoffs between pMCA and SCA for optimal energy.
88	A., Karmoose, M., Habak, K., El-Nainay, M., & Youssef, M	Cognitive radio networks with cooperation-based multi-hop routing protocol has implemented.	A cross layering routing protocol proposes by integrating the physical layer methods in the routing layer (layer 3). For data transmission, the cooperating groups and beamforming use when primary users are active and existed.	Mobile PUs is assumed for extending this work. This change accommodates by remembering top k groups and one of them has chosen based on the locations of PUs.
81	Appel, Titus, Rafael Fierro, Brandon	In unstructured environment, a learning strategy	A source tracking problem is formulated by learning a robot to navigate towards a light source.	The reactions of robots in narrow areas include in the limitations.

	Rohrer, Ron Lumia, and John Wood	develops for source tracking.	Based on the Robot Operating System and the ROS, the light-following problem implements in the hardware simulation.	

3. Different methods in Routing techniques of cognitive sensor networks :

The state-of-the-art routing protocols have reviewed for CRNs. By relying on the operation of a protocol, the routing protocols have classified into different types such as tree-based, reactive source-based, spectrum aware-based, local coordination-based, and multipath-based routing methods. The summary of a protocol presents in the form of tables.

4.1 Dynamic Spectrum-aware Routing

For effective utilization of unallocated wireless spectrum, CR technologies enable by dynamic spectrum-aware routing protocols. Route discovery employs with spectrum sensing in such routing protocols. The establishment and maintenance of route across various available spectrums is the main objective of such protocols. These protocols summarize in the remaining sub sections and their benefits and routing techniques have highlighted. At the end of each protocol, the summary of a protocol presents in the table.

4.1.1 Spectrum-Aware Routing (SPEAR)

In [89], a routing protocol which supporting the transmission of packets with higher throughput in the spectrum heterogeneity availability has investigated. The performance of end-to-end delay reduces with the integration of link-based and flow based methods. For reducing the interference, different channels assign to the sinks and utilize optimally by combining the route discovery and spectrum discovery. A list of unoccupied available local channels maintains by each node and they neither reserve by nearby neighbours nor occupy with primary users. A message of Route Request (RREQ) on common control channel broadcasts in SPEAR route discovery and IP addresses of receiver and sender being detect these messages. As this message receives by an intermediate node, whether a common channel with the earlier node is verified and its own id appends and broadcasting the information about received message for an available channel set. Based on the link quality, minimum end-to-end latency (minimum hop count), and maximum throughput, the best path chooses by the destination node. The channel reservation message that contains time-to-live ad timeout field broadcasts by the node periodically during the transmission. The sending reservation messages is notified at the communication nodes along a route.

4.1.2 Spectrum Aware Mesh Routing (SAMER)

In [90], a routing protocol proposes for mesh CRNs that deals with the channel availability diversity and balance between short-term route and long-term route stability. Based on the data transmission over the route with higher availability of spectrum, the available white spaces use in the SAMER. To compute the routing parameter, the spectrum availability uses for long-term routes. Through the establishment of a runtime forwarding route mesh, the balance between short-term and long-term routes is achieved. The periodical updating of mesh is performed and a set of candidate routes to the destination is provided. Across the mesh, the packets route towards the destination. By collaborating the MAC and PHY layer, the routing decisions are considered. The candidate forwarding mesh, dynamic candidate, and opportunistic forwarding have built by SAMER.

Table 1: Comparison of SPEAR& SAMER Routing Protocols.

	SPEAR		SAMER	
Objective and features		**Technique**		**Technique**
End-to-end throughput	Yes	Link-based and flow-based approaches integration.	Yes	Path with long-term stability, high spectrum availability, and short-term usage of spectrum

Route discovery		RREQ message broadcasting and control channel.		Link state packets
Routing decisions		PHY and MAC layers collaboration		MAC and PHY layers integration
Route nature		On demand		Periodical
Mobility handling	Yes	Timeout field in periodic channel reservations messages	No	
Communication overhead	Yes	Route setup, route tear down	Yes	The cost to destination computes by each node
Computational Complexity	Low		Low	
Route discovery packet size	Variable	Available channel set and identifier append using each node	Fixed	Estimation of hop-to-hop
Best path selection	Yes	Link quality, maximum throughput, and minimum hop count	Yes	Spectrum availability and minimum hop count

4.1.3 Spectrum-aware On-Demand routing protocol (SORP)

SORP refers to an on demand routing protocol that establishes neither on multi-channel nor centralized spectrum allocation. Owing to the lack of shared data, the protocol nature is relied. Ma, H. and Zheng et al., [91] has proposed a routing method for choosing best suitable RF bands along the route for each node. By using minimum cumulative delay, the RF band selection is performed. To determine the routing path cumulative delay, the judging parameters like intersecting flow and the path have considered that cause the switching and back-off delay. For RF band selection, the routing performs using a spectrum aware on demand framework and RF band selection is carried out by multi-flow multi-frequency scheduling. By including the spectrum opportunity inconsistency, an adhoc on demand distance vector routing (AODV) [98] has modified slightly based on some assumptions for routing technique as follows:

A traditional wireless interface along with the CR transceiver is contained at each node to create a common control channel. Based on the cross layer design, the information about spectrum sensing is provided by each node to routing protocol.

The basic methods of AODV with modified Route Request (RREQ) inherit by SORP for route discovery. RREQ messages piggyback the SORP spectrum opportunity (SOP) data when determining the intersection between the RREQ and its own by the node. All nodes' SOP distribution along the path receives by the destination node and RF band allocates to the CR transceiver by RF band. The source node and intermediate nodes receive this RF band data via Route Reply (RREP) message. Based on this received RREP, all nodes assign the RF band along the routing path.

4.1.4 Multi-hop Single-transceiver Cognitive Radio Networks Routing Protocol (MSCRP):

In [92], MSCRP approach proposes not considering the control channel. Without common control channel, the messages of a routing protocol are exchanged. MSCRP is an on-demand protocol which develops using the ad-hoc on-demand distance vector (AODV).

To deal with the problem of available channel set, AODV modifies by Ma et al and the available channel set of other nodes doesn't understand by each node in a network. In [92], a new problem introduces known as 'deafness', owing to the nodes' channel switching. Switching state is not involved in two consecutive nodes in a flow to limit the problem of deafness. To inform the working channel of neighbours, LEAVE/JOIN messages use by MSCRP switching node to overcome the complication of communication with a switching node. In a wide range of RF spectrum, the tuning of CR transceiver can assume by MSCRP but operating on the smaller and limited range of CR and RF transceiver which works on single channel only at any time. The spectrum aware routing's core functionality implements by a cross layer protocol known as MSCRP which detects the six system functions which include:

Three of these functions involve in the physical layer such as estimation of available channels quality, detection of active primary user, and spectrum sensing. The other two includes in the network layer: scheduling and routing in the multi-channel and multi-flow environment. The last remaining one involves in the link layer i.e. IEEE 802.11 DCF which uses as the MAC protocol.

Table 2: Comparison of SORP & MSCRP Routing Protocols.

	SORP		MSCRP	
Objective and features		**Technique/ explanation**		**Technique/ explanation**
End-to end throughput	Yes	Multi-flow multi-frequency scheduling and spectrum aware on demand routing	Yes	Spectrum aware routing and leave or join messages
Route discovery		RREQ messages broadcasting		Instead of a single channel, RREQ message on all available channels
Routing decisions		MAC and network layers collaboration		The physical, network, and MAC layers integrated.
Route nature		On demand		On demand
Link failure handling	No		Yes	Leave/join messages
Communication overhead		Both back off and switching delay introduce using path cumulative based RF band selection		Because of the channel switching, extra delay introduces by deafness to RREQ and RREQ messages broadcasting on all available channels that results in extra overhead.

Route discovery packet size	Variable	A list of SOP appends using each node	Variable	The state information and available channel set append at all intermediate nodes.
Best path selection	Yes	Path delay and node delay (switching and back off delay)	Yes	Each channel's number of flows consider
Control channel	Yes	The routing protocol messages exchanging	No	The protocol messages routing using data channel

4.2Reactive Source-Based Routing

The data transmission over the network is specified using a source node in the reactive source based routing method. It computes the path from source to destination node. A reactive source-based routing protocol with a summary including its benefits and routing technique is provided in the remaining sub section.

4.2.1 Routing in Opportunistic Cognitive Radio Networks

Khalife et al., [93] proposes a reactive source-based routing protocol for CRNs and a novel routing parameter uses. It implements using a probabilistic definition of the available channel capacity. Although the most probable path (MPP) doesn't give a guarantee on satisfying the bandwidth demand, it determines using the routing parameter. An augmentation phase uses in this case where augmenting the bottleneck links with additional channels. The bandwidth demand meets by the resulting path using a given probability.

The available capacity measures as the PR probability distribution to the user interference of CR over a channel at any node.

For node coordination, the control channel uses and the source will initiate if an application requests a demand of capacity. All probabilities of links have determined based on the demand. To determine a route to the destination, Dijkstra-like algorithm implements by the source after estimating all links' weights. MPP includes the higher probability of satisfying the demand and stability. When Dijkstra-like algorithm reaches to one of the below two states, it stops computation.

1. Compared to the demand, the total capacity will be more on MPP's each link.
2. Any path is not suitable for the destination when the total estimated capacity on two nodes of all channels will not fulfil the demand after processing the augmentation. Thus, it is not reachable.

Table3: Description of Reactive Source based Routing Protocol.

Objective and features		Technique /explanation
End-to-end throughput	Yes	The application capacity demand is fulfilled by choosing MPP path
Route discovery		The route computes using OSPF and Dijkstra-like algorithm
Routing decisions		Does not base on cross layer
Route nature		On demand
Data structure		Graph
Link weight assignment	Yes	Using available link capacity
link failure handling	No	
Route discovery packet size	Fixed	Hop-to-hop communication

Best path selection	Yes	A routing parameter uses by considering the probabilistic definition about available channel capacity
Control channel	Yes	

4.3Local Coordination-Based Routing

The local coordination is implemented on the intersecting of nodes on a routing path and it is a kind of enhancement scheme. If nodes are evaluating both the flow accommodation and redirection workflow, the local coordination is initiated. Based on the neighbourhood interaction and evaluation results, the flow redirection or accommodation chooses by the nodes.

A local coordination-based routing protocol with the summary involving the benefits and its routing method is described in the remaining sub sections.

4.3.1 Local Coordination Based Routing and Spectrum Assignment in Multi-hop Cognitive Radio Networks:

Yang et al., [94] proposes an on demand routing and spectrum assignment protocol which interacts with multi-frequency scheduling and exchanges the local spectrum data at each node. To restrict the SOP inconsistency, AODV modifies to create a mechanism on common control channel to exchange the SOP among nodes. At each node, traversing flows are detected and RF band utilization is determined for scheduling of multi-flow multi-frequency. The back off and switching delays show by the node delay and path delay along the path and the path cumulative delay estimates. For load balancing on intersecting nodes, a local coordination scheme uses for multi-frequency traffic. To ensure the routing messages successful delivery at each node, it equips with traditional wireless interface along with the CR transceiver in despite of the frequency bands inconsistency. The SOP data provides by each node to its network layer. On each node of multi-hop CRNs, the local coordination implements.

Table 4: Description of LCB Routing Protocol.

Objective and features		Technique /explanation
End-to-end delay	Less	Cooperate the adaptive relay with routing protocol
End-to-end performance		The flow redirects to other neighbouring nodes and the flow accommodates.
Route discovery		RREQ messages broadcasting
Routing decisions		Perform joint decisions using network and MAC layers
Route nature		On demand
Link failure handling	Yes	Flow redirects to another neighbour
Protocol overhead		
Route discovery packet size	Variable	SOP list appends using each intermediate node
Best path selection	Yes	Based on the path cumulative delay
Load balancing	Yes	Utilizes a local coordination scheme
Network topology		Full mesh
Control channel	Yes	Spectrum opportunity exchanges among network nodes

Neighbor discovery	Yes	Beacon broadcasting and channel scanning

4.4Multi-path Routing

Various routes discover for any destination in multi-path routing and some of the best routes choose among discovered route using multiple parameters. The advantages of reducing primary to secondary user interference and improved bandwidth have provided by multi-path routing. A multipath routing protocol with a summary is discussed in the remaining sub section.

4.4.1 Multipath Routing and Spectrum Access (MRSA)

Since existing multi-path routing protocols neither considering the coexistence of primary and secondary users and nor the diversity in spectrum availability, they can't be adapted for traditional WSNs in CRNs. The primary multi-path protocol is MRSA [95] which implements for CRNs to reduce the interference and inter path contention. Based on the each traffic flow distribution over multiple paths, the primary users' interruption has overcome with reduced degradation.

The round robin fashion is used for traffic distribution but it's not an effective one. When multiple paths don't include any interfering bands between them, the concept of 'spectrum wise disjointness' is revised in MRSA and these paths are disjointed spectrum wise. A total of N channels is assumed for data traffic and signalling delivers over the channels that together with data traffic in MRSA. The dynamic source routing (DSR) [99] has used for route discovery and the RREQ message with new RREQ_ID broadcasts by the source node and its band radio usage table (BRT) attaches. Whether RREQ_ID is new one or not is verified if RREQ receives by an intermediate node before forwarding. If not, the hop count is counted from source. RREQ will append its BRT when it has fewer hop count compared to the previous RREQ and forwards it. From multiple paths, same RREQ will receive by the destination. Band and radio assign to each link primarily and all candidate paths evaluate using available bandwidth. To overcome the primary users' sudden arrival, RERR message of DSR extends which is being a part of route recovery.

Table 5: Description of MRSA Routing Protocol.

Objective and features	Technique /explanation	
End-to end throughput	Yes	Multipath and multi-radios have used
Route discovery		Controlling RREQ message transmission and channel
Routing decisions		Not based on cross layer
Route nature		Periodical
Path failure handling	Yes	RERR messages used
Communication overhead	Yes	Multiple flows on single radio and band switching for each individual flow
Route discovery packet size	Variable	Appends each node BRT and ID
Best path selection	Yes	Minimum hop count
Data striping	Yes	Round robin fashion
Network topology		Mesh

4.5Tree Based Routing

Based on a root configuration, a tree structured network enables in the tree based routing protocol. A single network entity known as Base Station controls the tree based routing which is a centralized routing scheme. Based on the configuration of a cognitive BS as root, the network topology can construct among CR station. The tree based routing protocol with its benefits and routing method details have described in the rest of the sub section.

4.5.1 Cognitive Tree-based Routing (CTBR)

A tree based routing protocol (TBR) proposes for wireless mesh networks [96] which is an extended protocol of cognitive tree based routing (CTBR) [97]. For determination of a route, local and global decision schemes have used. The route with the best global end-to-end metric chooses using the global decision scheme and the best interface with the least load has chosen by the local decision scheme. For same destination, multipath paths can exist with the same global end-to-end metric. The local decision scheme has used to select the end-to-end path based on the load measurement.

TBR routing procedure has used by CTBR and it sends the message of Root Announcement (RANN) using a root periodically for formulating a tree. The node caches and receives the RANN, whom it receives RANN is considered as the potential parent and RANN rebroadcasts with updated cumulative parameter. From all potential parents, a parent node will choose using a node based on the best parameter i.e. hop count for the path to root. Each node includes a known path to root and sends route reply (RREP) to register with root. Based on the RREP source node selection as its destination, the message transmits by any intermediate node which receives REEP to its parent node and update the routing table as well. A tree constructs finally as it learns all network nodes. However, a link quality introduces for making adaptable the TBR for CRNs.

Table 6: Description of CTBR Routing Protocol.

Objective and features		Technique /explanation
End-to-end delay		Five times better than hop count scheme
Route discovery		Broadcasting Root Announcement (RANN) message
Routing decisions		Not based on cross layer
Route nature		Periodical
link failure handling	No	
Protocol overhead	Yes	Transmit additional control bytes
Route discovery packet size	Fixed	A single field ‘cumulative metric’ updates using every node
Best path selection	Yes	Path chooses based on the local and global decision schemes
Centralize	Yes	Single point of failure
Network topology		Tree

Conclusion

Based on the existing links’ drop factor between nodes, different novel routing methods have investigated and computed the drop factor based on the average hop count link and random number generated at each node. The control packets broadcast by the PUs in a network. The links that have lower drop factor decide using the PU’s upon receiving the control packets and verifies the spectrum availability and connects with the target nodes. We have concluded that these novel routing techniques will reduce the energy consumption and improve network lifetime. By implementing additional algorithms at the nodes, the overhead minimizes in a network using these routing methods for CSNs.

References

1. El-Mougy, M. Ibnkahla, G. Hattab, and W. Ejaz, "Reconfigurable wireless networks," *Proceedings of the IEEE*, vol. 103, no. 7, pp. 1125– 1158, Jul. 2015.
2. W. Ejaz and M. Ibnkahla, "Machine-to-machine communications in cognitive cellular systems," in *IEEE International Conference on Ubiquitous Wireless Broadband (ICUWB)*. Montreal, QC: IEEE, Oct. 2015, pp. 1–5.
3. M. Ibnkahla, *Cooperative Cognitive Radio Networks: The Complete Spectrum Cycle*. CRC Press, 2014.
4. G. Hattab and M. Ibnkahla, "Multiband spectrum access: Great promises for future cognitive radio networks," *Proceedings of the IEEE*, vol. 102, no. 3, pp. 282–306, Mar. 2014.
5. W. Ejaz, N. Ul Hasan, and H. S. Kim, "Distributed cooperative spectrum sensing in cognitive radio for ad hoc networks," *Computer Communications*, vol. 36, no. 12, pp. 1341–1349, Jul. 2013.
6. El-Mougy and M. Ibnkahla, "A cognitive framework for WSN based on weighted cognitive maps and Q-learning," *Ad Hoc Networks*, vol. 16, pp. 46–69, 2014.
7. N. Kaur and S. K. Sood, "An energy-efficient architecture for the Internet of Things (IoT)," *IEEE Systems*, vol. PP, no. 99, pp. 1–10, Oct. 2015.
8. J.-M. Liang, J.-J. Chen, H.-H. Cheng, and Y.-C. Tseng, "An energyefficient sleep scheduling with QoS consideration in 3GPP LTEadvanced networks for Internet of Things," *IEEE Journal on Emerging and Selected Topics in Circuits and Systems*, vol. 3, no. 1, pp. 13–22, Mar. 2013.
9. R. J. Carbajales, M. Zennaro, E. Pietrosemoli, and F. Freitag, "Energyefficient Internet of Things monitoring with low-capacity devices," in *IEEE 2nd World Forum on Internet of Things (WF-IoT)*. Milan: IEEE, Dec. 2015, pp. 305–310.
10. Burdett, "Ultra-low-power wireless systems: energy-efficient radios for the Internet of Things," *IEEE Solid-State Circuits Magazine*, vol. 7, no. 2, pp. 18–28, Jun. 2015.
11. Nishimoto, Y. Kawahara, and T. Asami, "Prototype implementation of ambient RF energy harvesting wireless sensor networks," in *IEEE Sensors*. Kona, HI: IEEE, Nov. 2010, pp. 1282–1287.
12. X. Zhang, H. Jiang, L. Zhang, C. Zhang, Z. Wang, and X. Chen, "An energy-efficient ASIC for wireless body sensor networks in medical applications," *IEEE Transactions on Biomedical Circuits and Systems*, vol. 4, no. 1, pp. 11–18, Feb. 2010.
13. P. Kamalinejad, C. Mahapatra, Z. Sheng, S. Mirabbasi, V. Leung, and Y. L. Guan, "Wireless energy harvesting for the Internet of Things," *IEEE Communications Magazine*, vol. 53, no. 6, pp. 102–108, Jun. 2015.
14. M. Gorlatova, J. Sarik, G. Grebla, M. Cong, I. Kymissis, and G. Zussman, "Movers and shakers: Kinetic energy harvesting for the Internet of Things," *IEEE Journal on Selected Areas in Communications*, vol. 33, no. 8, pp. 1624–1639, Aug. 2015.
15. Roselli, N. Borges Carvalho, F. Alimenti, P. Mezzanotte, G. Orecchini, M. Virili, C. Mariotti, R. Goncalves, and P. Pinho, "Smart surfaces: Large area electronics systems for Internet of Things enabled by energy harvesting," *Proceedings of the IEEE*, vol. 102, no. 11, pp. 1723–1746, Nov. 2014.
16. Aijaz and A. H. Aghvami, "Cognitive machine-to-machine communications for Internet-of-Things: a protocol stack perspective," *IEEE Internet of Things Journal*, vol. 2, no. 2, pp. 103–112, Apr. 2015.
17. W. Li, C. Zhu, V. C. Leung, L. T. Yang, and Y. Ma, "Performance comparison of cognitive radio sensor networks for industrial IoT with different deployment patterns," *IEEE Systems Journal*, vol. PP, no. 99, pp. 1–11, Dec. 2015.
18. Ibnkahla, *Wireless sensor networks: a cognitive perspective*.CRC Press, 2012.
19. Hu and M. Ibnkahla, "A MAC protocol with mobility support in cognitive radio ad hoc networks: Protocol design and analysis," *Ad Hoc Networks*, vol. 17, pp. 114–128, Jun. 2014.
20. W. Ejaz, G. A. Shah, H. S. Kim *et al.*, "Energy and throughput efficient cooperative spectrum sensing in cognitive radio sensor networks," *Transactions on Emerging Telecommunications Technologies*, vol. 26, no. 7, pp. 1019–1030, Jul. 2015.
21. G. A. Shah and O. B. Akan, "Spectrum-aware cluster-based routing for cognitive radio sensor networks," in *2013 IEEE International Conference on Communications (ICC)*, pp. 2885–2889, IEEE, 2013.
22. H. Zhang, Z. Zhang, H. Dai, R. Yin, and X. Chen, "Distributed spectrumaware clustering in cognitive radio sensor networks," in *Global Telecommunications Conference (GLOBECOM 2011), 2011 IEEE*, pp. 1–6, IEEE, 2011.

23. W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, “Energyefficient communication protocol for wireless microsensor networks,” in *System sciences, 2000. Proceedings of the 33rd annual Hawaii international conference on*, pp. 10–pp, IEEE, 2000.
24. Lindsey and C. S. Raghavendra, “Pegasis: Power-efficient gathering in sensor information systems,” in *Aerospace conference proceedings, 2002. IEEE*, vol. 3, pp. 3–1125, IEEE, 2002.
25. Manjeshwar and D. P. Agrawal, “Apteen: A hybrid protocol for efficient routing and comprehensive information retrieval in wireless sensor networks.,” in *Ipdps*, vol. 2, p. 48, 2002.
26. Y.-F. Wen and W. Liao, “On qos routing in wireless ad-hoc cognitive radio networks,” in *Vehicular Technology Conference (VTC 2010-Spring), 2010 IEEE 71st*, pp. 1–5, IEEE, 2010.
27. L. Ding, T. Melodia, S. N. Batalama, J. D. Matyjas, and M. J. Medley, “Cross-layer routing and dynamic spectrum allocation in cognitive radio ad hoc networks,” *IEEE Transactions on Vehicular Technology*, vol. 59, no. 4, pp. 1969–1979, 2010.
28. O. Younis and S. Fahmy, “Heed: a hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks,” *IEEE Transactions on mobile computing*, vol. 3, no. 4, pp. 366–379, 2004.
29. J. Abolarinwa, N. M. A. Latiff, and S. K. Syed, “Energy-efficient, learning-inspired channel decision and access technique for cognitive radio-based wireless sensor networks,” *development*, vol. 10, no. 2, 2015.
30. Akan, O. B., Karli, O. B., &Ergul, O. (2009). Cognitive radiosensor networks. IEEE Network, 23(4), 34–40.
31. Lin, Z., Ghosh, M., &Demir, A. (2013). A comparison of MACaggregation vs. PHY bonding for WLANs in TV white spaces. In 24th international symposium on personal, indoor and mobile radio communications: MAC and cross-layer design track (pp. 1829–1834).
32. Yong, S. K., & Chong, C.-C. (2007). An overview of multigigabit wireless through millimeter wave technology: Potentials and technical challenges. *EURASIP Journal on Wireless Communications and Networking,2007*(1), 1–10.
33. Hu, F., Chen, B., & Zhu, K. (2018). Full spectrum sharing in cognitive radio networks toward 5G: A survey. *IEEE Access,6*, 15754–15776.
34. Chowdhury, K. R., & Akyildiz, I. F. (2008). Cognitive wireless mesh networks with dynamic spectrum access. *IEEE Journal on Selected Areas in Communications,26*(1), 168–181.
35. Akyildiz, I. F., Lee, W. Y., & Chowdhury, K. R. (2009). CRAHNs: Cognitive radio ad hoc networks. *Ad Hoc Networks,7*(5), 810–836.IEEE Standards Association. (2016). IEEE Std 802.11-2016, IEEE Standard for Local and Metropolitan Area Networks—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications.
36. W. Ejaz, M. Naeem, A. Shahid, A. Anpalagan, and M. Jo, “Efficient energy management for Internet of Things in smart cities,” *IEEE Communications Magazine (in press)*, vol. 55, no. 1, pp. 84–91, Jan. 2017.
37. S. Sudevalayam and P. Kulkarni, “Energy harvesting sensor nodes: Survey and implications,” *IEEE Communications Surveys & Tutorials*, vol. 13, no. 3, pp. 443–461, Sep. 2011.
38. R. Zhang and C. K. Ho, “MIMO broadcasting for simultaneous wireless information and power transfer,” *IEEE Transactions on Wireless Communications*, vol. 12, no. 5, pp. 1989–2001, May 2013.
39. Y. Liu, Y. Zhang, R. Yu, and S. Xie, “Integrated energy and spectrum harvesting for 5G wireless communications,” *IEEE Network*, vol. 29, no. 3, pp. 75–81, Jun. 2015.
40. S. Park, H. Kim, and D. Hong, “Cognitive radio networks with energy harvesting,” *IEEE Transactions on Wireless communications*, vol. 12, no. 3, pp. 1386–1397, Mar. 2013.
41. H. Gao, W. Ejaz, and M. Jo, “Cooperative Wireless Energy Harvesting and Spectrum Sharing in 5G Networks,” *IEEE Access*, vol. 4, pp. 3647– 3658, Jul. 2016.
42. S. S. Kalamkar, A. Banerjee *et al.*, “Energy harvesting cognitive radio with channel-aware sensing strategy,” *IEEE Communications Letters*, vol. 18, no. 7, pp. 1171–1174, Jul. 2014.
43. S. Yin, Z. Qu, and S. Li, “Achievable throughput optimization in energy harvesting cognitive radio systems,” *IEEE Journal on Selected Areas in Communications*, vol. 33, no. 3, pp. 407–422, Mar. 2015.
44. S. Lee, R. Zhang, and K. Huang, “Opportunistic wireless energy harvesting in cognitive radio networks,” *IEEE Transactions on Wireless Communications*, vol. 12, no. 9, pp. 4788–4799, Sep. 2013.
45. S. Aslam and M. Ibnkahla, “Optimized node classification and channel pairing scheme for RF energy harvesting based cognitive radio sensor networks,” in *12th International Multi-Conference on Systems, Signals & Devices (SSD)*. SakietEzzitSfax, Tunisia: IEEE, Mar. 2015, pp. 1–6.
46. N. Panahi, H. O. Rohi, A. Payandeh, and M. S. Haghighi, “Adaptation of leach routing protocol to cognitive radio sensor networks,” in *Sixth International Symposium on Telecommunications (IST)*. Tehran, Iran: IEEE, Nov. 2012, pp. 541–547.

47. M. H. Ling and K.-L. A. Yau, "Reinforcement learning-based trust and reputation model for cluster head selection in cognitive radio networks," in *9th International Conference for Internet Technology and Secured Transactions (ICITST)*. London, UK: IEEE, Dec. 2014, pp. 256–261.
48. M. Ozger and O. B. Akan, "Event-driven spectrum-aware clustering in cognitive radio sensor networks," in *IEEE INFOCOM*. Turin, Italy: IEEE, Apr. 2013, pp. 1483–1491.
49. J.-S. Leu, T.-H. Chiang, M.-C. Yu, and K.-W. Su, "Energy efficient clustering scheme for prolonging the lifetime of wireless sensor network with isolated nodes," *IEEE communications letters*, vol. 19, no. 2, pp. 259–262, Feb. 2015.
50. M. Mishra, C. R. Panigrahi, B. Pati, and J. L. Sarkar, "ECHS: An energy aware cluster head selection algorithm in Wireless Sensor Networks," in *International Conference on Man and Machine Interfacing (MAMI)*.Bhubaneswar, India: IEEE, Dec. 2015, pp. 1–4.
51. J. Ren, Y. Zhang, N. Zhang, D. Zhang, and X. Shen, "Dynamic channel access to improve energy efficiency in cognitive radio sensor networks," *IEEE Transactions on Wireless Communications*, vol. 15, no. 5, pp. 3143–3156, Jan. 2016.
52. Y. Liu, N. Kundargi, and A. Tewfik, "Channel idle time statistics based spectrum accessing strategies with CSMA based primary networks," *IEEE Transactions on Signal Processing*, vol. 62, no. 3, pp. 572–582, Feb. 2014.
53. S. Cacciapuoti, M. Caleffi, L. Paura, and M. A. Rahman, "Channel availability for mobile cognitive radio networks," *Journal of Network and Computer Applications*, vol. 47, pp. 131–136, Oct. 2015.
54. N. Jiang, J. Hua, Z. Shang, and K. Yang, "A new method for channel availability analysis and the associated policy design for selection of channel sensing order in CRNs," *IEEE Transactions on Signal Processing*, vol. 64, no. 9, pp. 2443–2458, May 2016.
55. G. P. Joshi and S. W. Kim, "A survey on node clustering in cognitive radio wireless sensor networks," *Sensors*, vol. 16, no. 9, p. 1465, 2016.
56. J. Abolarinwa, N. M. A. Latiff, and S. K. Syed, "Energy-efficient, learning-inspired channel decision and access technique for cognitive radio-based wireless sensor networks," *development*, vol. 10, no. 2, 2015.
57. X. Li, D. Wang, J. McNair, and J. Chen, "Dynamic spectrum access with packet size adaptation and residual energy balancing for energyconstrained cognitive radio sensor networks," *Journal of Network and Computer Applications*, vol. 41, pp. 157–166, 2014.
58. G. A. Shah and O. B. Akan, "Spectrum-aware cluster-based routing for cognitive radio sensor networks," in *2013 IEEE International Conference on Communications (ICC)*, pp. 2885–2889, IEEE, 2013.
59. H. Zhang, Z. Zhang, H. Dai, R. Yin, and X. Chen, "Distributed spectrumaware clustering in cognitive radio sensor networks," in *Global Telecommunications Conference (GLOBECOM 2011), 2011 IEEE*, pp. 1–6, IEEE, 2011.
60. H. Oey, I. Christian, and S. Moh, "Energy-and cognitive-radio-aware routing in cognitive radio sensor networks," *International Journal of Distributed Sensor Networks*, vol. 2012, 2012.
61. M. Ozger, E. Fadel, and O. B. Akan, "Event-to-sink spectrum-aware clustering in mobile cognitive radio sensor networks," *IEEE Transactions on Mobile Computing*, vol. 15, pp. 2221–2233, Sept 2016.
62. M. Ozger and O. B. Akan, "Event-driven spectrum-aware clustering in cognitive radio sensor networks," in *INFOCOM, 2013 Proceedings IEEE*, pp. 1483–1491, IEEE, 2013.
63. P. Bahl, R. Chandra, T. Moscibroda, R. Murty, and M. Welsh, "White space networking with wi-fi like connectivity," *ACM SIGCOMM Computer Communication Review*, vol. 39, no. 4, pp. 27–38, 2009.
64. Song and Q. Zhang, "Cooperative spectrum sensing with multichannel coordination in cognitive radio networks," in *Communications (ICC), 2010 IEEE International Conference on*, pp. 1–5, IEEE, 2010.
65. X. Sun, L. Chen, and D. H. Tsang, "Energy-efficient cooperative sensing scheduling for heterogeneous channel access in cognitive radio," in *Computer Communications Workshops (INFOCOM WKSHPS), 2012 IEEE Conference on*, pp. 145–150, IEEE, 2012.
66. W. Zhang, Y. Yang, and C. K. Yeo, "Cluster-based cooperative spectrum sensing assignment strategy for heterogeneous cognitive radio network," *IEEE Transactions on Vehicular Technology*, vol. 64, no. 6, pp. 2637– 2647, 2015.
67. Bukhari, S. H. R., Rehmani, M. H., &Siraj, S. (2016). A surveyof channel bonding for wireless networks and guidelines of channel bonding for futuristic cognitive radio sensor networks. IEEE Communications Surveys & Tutorials, 18(2), 924–948.
68. Ramaboli, A. L., Falowo, O. E., & Chan, A. H. (2012). Bandwidth aggregation in heterogeneous wireless networks: A survey of current approaches and issues. Journal of Network and Computer Applications, 35(6), 1674–1690.

69. Akyildiz, I. F., Su, W., Sankarasubramaniam, Y., & Cayirci, E.(2002). Wireless sensor networks: A survey. Computer Networks, 38(4), 393–422.
70. Wang, C.-W., Wang, L.-C., & Adachi, F. (2009). Modeling andanalysis of multi-user spectrum selection schemes in cognitive radio networks. In IEEE 20th international symposium on personal, indoor and mobile radio communications (pp. 828–832). IEEE.
71. Li, X., &Zekavat, S. A. R. (2009). Traffic pattern prediction based spectrum sharing for cognitive radios. Den Haag: INTECH Open Access Publisher.
72. Song, Y., & Xie, J. (2010). Common hopping based proactivespectrum handoff in cognitive radio ad hoc networks. In Global telecommunications conference (GLOBECOM) (pp. 1–5). IEEE.
73. Li, X., &Zekavat, S. A. (2008). Traffic pattern prediction andperformance investigation for cognitive radio systems. In IEEE wireless communications and networking conference (pp. 894–899). IEEE.Yang, L., Cao, L., & Zheng, H. (2008). Proactive channel accessin dynamic spectrum networks. Physical Communications Journal, 1, 103–111.
74. Agarwal, S., & De, S. (2016). Dynamic spectrum access for energy-constrained CR: Single channel versus switched multichannel. *IET Communications,10*(7), 761–769.
75. Rehman, R. A., &Byung-Seo, K. (2014). L2ER: Low-latency and energy-based routing protocol for cognitive radio ad hoc networks. *International Journal of Distributed Sensor Networks*. https: //doi. org/10.1155/2014/96320 2
76. Rehman, R. A., Sher, M., & Afzal, M. K. (2012). Efficient delay and energy based routing in cognitive radio ad hoc networks. In *2012 international conference on emerging technologies*, Islamabad.
77. Liang, Y., & Wang, J. (2012). A flexible delay and energy-efficient routing protocol for cognitive radio network. In *2012 third international conference on intelligent control and information processing*, Dalian.
78. Du, Y., Chen, C., Ma, P., &Xue, L. (2019). A cross-layer routing protocol based on quasi-cooperative multi-agent learning for multi-hop cognitive radio networks. *Sensors,19*(1), 151.
79. Habachi, O., Hayel, Y., & El-Azouzi, R. (2018). Optimal energydelaytradeoff for opportunistic spectrum access in cognitive radio network. *Telecommunication Systems,67*(4), 763–780.
80. [80] Perkins, A., Belding-Royer, E., & Das, S. (2013). *Ad hoc ondemand distance vector (AODV) routing* (Online). Retrieved August 2013, from http://www.ietf.org/rfc/rfc35 61.txt.
81. Appel, Titus, Rafael Fierro, Brandon Rohrer, Ron Lumia, and John Wood. "A Learning Strategy for Source Tracking in Unstructured Environments." *LEARNING AND APPROXIMATE DYNAMIC PROGRAMMING*
82. Yadav, Ram Narayan, Rajiv Misra, and Divya Saini. "Energy aware cluster based routing protocol over distributed cognitive radio sensor network." *Computer Communications* 129 (2018): 54-66.*OR FEEDBACK CONTROL* (2013): 582
83. Khan, Athar Ali, Mubashir Husain Rehmani, and Martin Reisslein. "Cognitive radio for smart grids: Survey of architectures, spectrum sensing mechanisms, and networking protocols." *IEEE Communications Surveys & Tutorials* 18, no. 1 (2015): 860-898.
84. Stephan, Thompson, Fadi Al-Turjman, K. Suresh Joseph, BalamuruganBalusamy, and Sweta Srivastava. "Artificial intelligence inspired energy and spectrum aware cluster based routing protocol for cognitive radio sensor networks." *Journal of Parallel and Distributed Computing* 142 (2020): 90-105.
85. How, K. C., Ma, M., & Qin, Y. (2010). An opportunistic service differentiation routing protocol for cognitive radio networks. In *2010 IEEE global telecommunications conference (GLOBECOM 2010)*, Miami, FL.
86. Yousofi, A., Sabaei, M., & Hosseinzadeh, M. (2019). Design a novel routing criterion based on channel features and internal backup routes for cognitive radio network. *Telecommunication Systems,71*(3), 339–351.
87. Yang, Z., Ping, S., Aijaz, A., & Aghvami, A. (2018). A global optimization-based routing protocol for cognitive-radio-enabled smart grid AMI networks. *IEEE Systems Journal,12*(1), 1015–1023.
88. Guirguis, A., Karmoose, M., Habak, K., El-Nainay, M., & Youssef, M. (2018). Cooperation-based multi-hop routing protocol for cognitive radio networks. *Journal of Network and Computer Applications,110,* 27–42.
89. Sampath, A. and Yang, L. and Cao, L. and Zheng, H. and Zhao," High Throughput Spectrumaware Routing for Cognitive Radio Networks.
90. Pefkianakis, I. and Wong, S.H.Y. and Lu," SAMER: Spectrum Aware Mesh Routing in Cognitive Radio Networks", 3rd IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks, 2008. DySPAN 2008.

91. Cheng, G. and Liu, W. and Li, Y. and Cheng," Spectrum aware on-demand routing in cognitive radio networks", 2nd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, 2007. DySPAN 2007.pp.571—574.
92. Ma, H. and Zheng, L. and Ma, X. and Luo," Spectrum-aware routing for multi-hop cognitive radio networks with a single transceiver", Proceedings of the Cognitive Radio Oriented Wireless Networks and Communications (CrownCom) 2008.
93. Khalife, H. and Ahuja, S. and Malouch, N. and Krunz," Routing in Opportunistic Cognitive Radio Networks".
94. Yang, Z. and Cheng, G. and Liu, W. and Yuan, W. and Cheng."Local coordination based routing and spectrum assignment in multi-hop cognitive radio networks", Mobile Networks and Applications 2008.
95. Wang, X. and Kwon, T.T. and Choi," A multipath routing and spectrum access (MRSA) framework for cognitive radio systems in multi-radio mesh networks" Proceedings of the 2009 ACM workshop on Cognitive radio networks 2009.
96. A. Raniwala and T. C. Chiueh, "Architecture and algorithms for an IEEE802.11-based multi-channel wireless mesh network," in Proc. IEEE INFOCOM Conf., pp.2223-2234, 2005
97. B. Zhang, Y. Takizawa, A. Hasagawa, A. Yamauchi, and S. Obana, "*Tree-based routing protocol for cognitive wireless access networks,"* in Proc. of IEEE Wireless Communications and Networking Conference2007.
98. N1: C. E. Perkins and E. M. Royer, "Ad hoc on-demand distance vector routing," in Proc.of IEEE Workshop on Mobile Computing Systems and Applications, 1999.
99. N2: D. B. Johnson, D.A. Maltz and Y. C. Hu, "The Dynamic Source Routing for mobile ad hoc networks,", draft-ietf-manet-dsr-09.txt, 2003.