Cognitive Radio Sensor Networks

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***Abstract*—The increasing demand for wireless communication introduces efficient spectrum utilization challenge. To address this challenge, cognitive radio has emerged as the key technology, which enables opportunistic access to the spectrum. The main potential advantages introduced by cognitive radio are improving spectrum utilization and increasing communication quality. These appealing features match the unique requirements and challenges of resource-constrained multi-hop wireless sensor networks (WSN). Furthermore, dynamic spectrum access stands as very promising and spectrum-efficient communication paradigm for WSN due to its event-driven communication nature, which generally yields bursty traffic depending on the event characteristics. In addition, opportunistic spectrum access may also help eliminate collision and excessive contention delay incurred by dense deployment of sensor nodes. Clearly, it is conceivable to adopt cognitive radio capability in sensor networks, which, in turn yields a new sensor networking paradigm, i.e., cognitive radio sensor networks (CRSN). In this paper, the main design principles, potential advantages and application areas, and network architectures of CRSN are introduced. The existing communication protocols and algorithms devised for cognitive radio networks and WSN are discussed along with the open research avenues for the realization of CRSN.**

***Index Terms*—Cognitive radio, sensor networks, opportunistic spectrum access, efficient spectrum sensing.**

I. INTRODUCTION

INCREASING usage of wireless communications triggered the development of dynamic spectrum access schemes. The key enabling technology providing dynamic, i.e., opportunistic, spectrum access is the cognitive radio (CR) [1]. Cognitive radio has the capability to sense the spectrum and determine the vacant bands. By dynamically changing its operating parameters, cognitive radio can make use of these available bands in an opportunistic manner surpassing the traditional fixed spectrum assignment approach in terms of overall spectrum utilization.

With these capabilities, cognitive radios can operate in licensed bands as well as in unlicensed bands. In licensed bands, wireless users with a specific license to communicate over the allocated band, i.e., the primary user (PU), has the priority to access the channel. Cognitive radio users, called secondary users (SU), can access the channel as long as they do not cause interference to the PU. Upon the natural habitants of a specific frequency band, i.e., PU, start communication; the cognitive radio users must detect the potentially vacant bands, i.e., spectrum sensing. Then, they decide on which channels to move, i.e., spectrum decision. Finally, they adapt their transceiver so that the active communications are continued over the new channel, i.e., spectrum handoff. This sequence of operation outlines a typical cognitive cycle [2], which can also be applied over an unlicensed band by all cognitive radio users with the same priority to access the channel.

The capabilities of cognitive radio may provide many of the current wireless systems with adaptability to existing spectrum allocation in the deployment field, and hence improve overall spectrum utilization. Among many others, these features can also be used to meet many of the unique requirements and challenges of wireless sensor networks (WSN), which are, traditionally, assumed to employ fixed spectrum allocation and characterized by resource constraints in terms of communication and processing capabilities of low-end sensor nodes. In fact, a WSN comprised of sensor nodes equipped with cognitive radio may benefit from the potential advantages of the salient features of dynamic spectrum access such as:

- *Opportunistic channel usage for bursty traffic:* Upon the detection of an event in WSN, sensor nodes generate a traffic of packet bursts. At the same time, in densely deployed sensor networks, a large number of nodes within the event area try to acquire the channel. This increases probability of collisions, and hence, decreases the overall communication reliability due to packet losses leading to excessive power consumption and packet delay. Here, sensor nodes with cognitive radio capability may opportunistically access to multiple alternative channels to alleviate these potential challenges.
- *Dynamic spectrum access:* In general, the existing WSN deployments assume fixed spectrum allocation. However, WSN must either be operated in unlicensed bands, or a spectrum lease for a licensed band must be obtained. Generally, high costs are associated with a spectrum lease, which would, in turn, amplify the overall cost of deployment. This is also contradictory with the main design principles of WSN [3]. On the other hand, unlicensed bands are also used by other devices such as IEEE802.11 wireless local area network (WLAN) hotspots, PDAs and Bluetooth devices as shown in Table I. Therefore, sensor networks experience crowded spectrum problem [4]. Hence, in order to maximize the network performance and be able to co-operate efficiently with other types of users, opportunistic spectrum access schemes must be utilized in WSN as well.
- *Using adaptability to reduce power consumption:* Time varying nature of wireless channel causes energy con-

TABLE I
OPERATING SPECTRUM BANDS OF COMMERCIAL WSN TRANSCEIVERS AND OVERLAPPING WIRELESS SYSTEMS.

Sensor node platforms	**Radio chip**	**Operating bands**	**Overlapping wireless systems**
Bean [5], BTnode [6], Mica2 [7], MANTIS Nymph [8]	Chipcon (TI Norway) CC1000	315, 433, 868, 915 MHz	Fixed, Mobile, Amateur, Satellite, Radiolocation, Broadcasting, Telemetry, ZigBee
IMote [9], MicaZ [10], SenseNode [11], XYZ [12], Sentilla Mini [13], TelosB [14]	Chipcon (TI Norway) CC2420	2.4 GHz	Fixed, Mobile, Amateur Radio as secondary, 802.11b/g/n, Telemetry, Bluetooth, ZigBee
Mica [7], weC	RF Monolithics TR1000	916.3 - 916.7 MHz	Fixed, Mobile, Broadcasting, Telemetry, ZigBee
ANT [15]	Nordic nRF24AP1	2.4 GHz	Fixed, Mobile, Amateur Radio as secondary, Telemetry, 802.11b/g/n, Bluetooth, ZigBee
EyesIFX v1 and v2 [16]	Infineon TDA5250	868 - 870 MHz	Fixed, Mobile, Broadcasting, Telemetry, ZigBee
Iris [17]	Atmel AT86RF230	2.4 GHz	Fixed, Mobile, Amateur Radio as secondary, Telemetry, 802.11b/g/n, Bluetooth, ZigBee

sumption due to packet losses and retransmissions. Cognitive radio capable sensor nodes may be able to change their operating parameters to adapt to channel conditions. This capability can be used to increase transmission efficiency, and hence, help reduce power used for transmission and reception.

- *Overlaid deployment of multiple concurrent WSN:* With the increased usage of sensor networks, one specific area may host several sensor networks deployed to operate towards fulfilling specific requirements of different applications. In this case, dynamic spectrum management may significantly contribute to the efficient co-existence of spatially overlapping sensor networks in terms of communication performance and resource utilization.
- *Access to multiple channels to conform to different spectrum regulations:* Each country has its own spectrum regulation rules. A certain band available in one country may not be available in another. Traditional WSN with a preset working frequency may not be deployed in cases where manufactured nodes are to be deployed in different regions. However, if nodes were to be equipped with cognitive radio capability, they would overcome the spectrum availability problem by changing their communication frequency.

Therefore, it is conceivable to provide wireless sensor networks with the capabilities of cognitive radio and dynamic spectrum management. This defines a new sensor network paradigm, i.e., Cognitive Radio Sensor Networks (CRSN). In general, a CRSN can be defined as *a distributed network of wireless cognitive radio sensor nodes, which sense an event signal and collaboratively communicate their readings dynamically over available spectrum bands in a multi-hop manner ultimately to satisfy the application-specific requirements*.

While the above potential advantages and the definition of CRSN stand as a significant enhancement of traditional sensor networks, the realization of CRSN depends on addressing many difficult challenges, posed by the unique characteristics of both cognitive radio and sensor networks, and further amplified by their union. Among many others, inherent resource constraints of sensor nodes, additional communication and processing demand imposed by cognitive radio capability, design of low-cost and power-efficient cognitive radio sensor nodes, efficient opportunistic spectrum access in densely deployed sensor networks, multi-hop and collaborative communication over licensed and unlicensed spectrum bands are primary obstacles to the design and practical deployment of CRSN.

Despite the extensive volume of research results on WSN [3] and considerable amount of ongoing research efforts on cognitive radio networks [2], CRSN is vastly unexplored field. In [18], an energy-efficient and adaptive modulation technique is introduced for CRSN in order to achieve high power efficiency towards maximizing the lifetime of resource-constrained sensor networks. In [19], CRSN is discussed for applications such as health care and tele-medicine, which require timely delivery of critical information. Authors propose a centralized spectrum allocation scheme with game theoretic approach in order to achieve fair allocation of spectrum bands with maximum spectrum utilization and energy efficiency. Potential of dynamic spectrum access in sensor networks is shown in [20] to achieve high power efficiency in sensing applications by reducing interference of concurrent transmissions through distributed channel selection and power allocation.

Clearly, only a handful of studies reviewed above do not suffice to open the road towards the realization of cognitive radio networks. The abovementioned fundamental challenges and many others need to be precisely determined and effectively addressed in order to exploit the potential advantages of CRSN. In this paper, we introduce the main design challenges and principles, potential advantages and application areas, and network architectures of CRSN. The existing communication protocols and algorithms devised for cognitive radio networks as well as WSN are explored from the perspective of CRSN and the open research avenues for the realization of CRSN are highlighted. Our objective is to provide a clear picture of potentials of cognitive radio sensor networks, the current state-of-the-art and the research issues on this timely and exciting topic.

The remainder of the paper is organized as follows. In Section II, we present the CRSN architecture including cognitive radio sensor node structure, and possible architectural topologies of CRSN. Potential applications of CRSN are explored

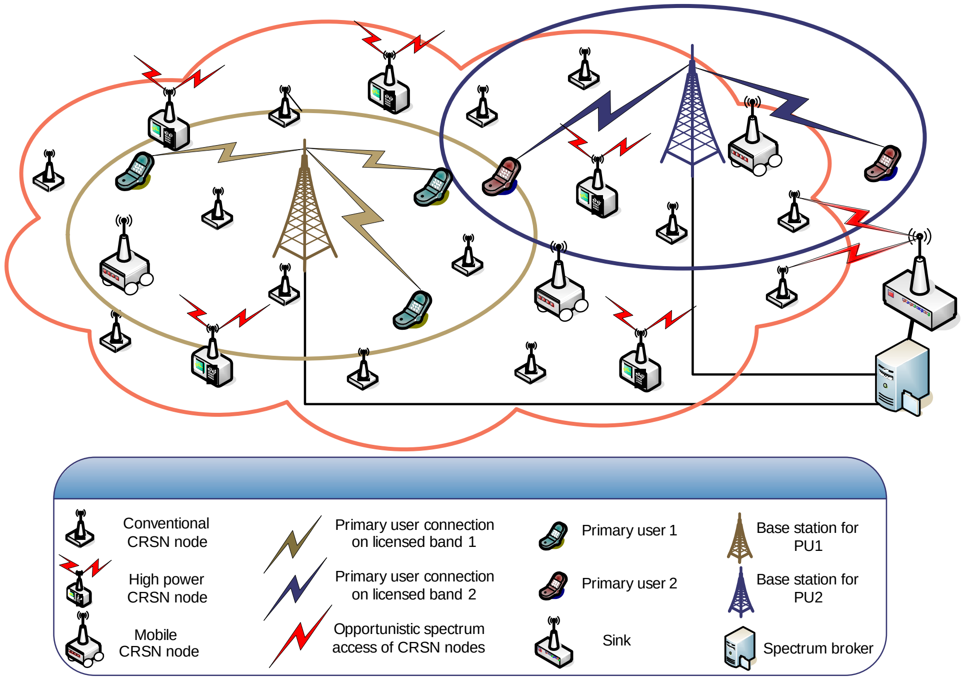

Fig. 1. A typical cognitive radio sensor network (CRSN) architecture.

in Section III. The existing work on dynamic spectrum access and cognitive radio ad hoc networks are explored in Section IV along with the open research challenges for dynamic spectrum management in CRSN. In Section V, we discuss the communications layers of CRSN in bottom-up approach and present the open research issues for the design of CRSN communication protocols. Finally, we state the concluding remarks in Section VI.

II. CRSN ARCHITECTURE

Cognitive radio sensor nodes form a wireless communication architecture of CRSN as shown Fig. 1 over which the information obtained from the field is conveyed to the sink in multiple hops. The main duty of the sensor nodes is to perform sensing on the environment. In addition to this conventional sensing duty, CRSN nodes also perform sensing on the spectrum. Depending on the spectrum availability, sensor nodes transmit their readings in an opportunistic manner to their next hop cognitive radio sensor nodes, and ultimately, to the sink. The sink may be also equipped with cognitive radio capability, i.e., cognitive radio sink. In addition to the event readings, sensors may exchange additional information with the sink including control data for group formation, spectrum allocation, spectrum handoff-aware route determination depending on the specific topology.

A typical sensor field contains resource-constrained CRSN nodes and CRSN sink. However, in certain application scenarios, special nodes with high power sources, i.e., actors, which act upon the sensed event, may be part of the architecture as well [21]. These nodes perform additional tasks like local spectrum bargaining, or acting as a spectrum broker. Therefore, they may be actively part of the network topology. It is assumed that the sink has unlimited power and a number of cognitive transceivers, enabling it to transmit and receive multiple data flows concurrently.

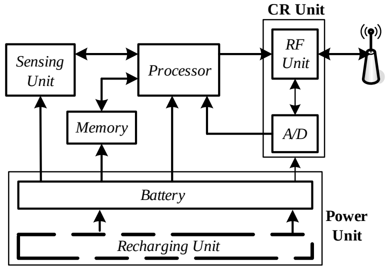

Fig. 2. Hardware structure of a cognitive radio sensor node.

A. CRSN Node Structure

CRSN node hardware structure is mainly composed of sensing unit, processor unit, memory unit, power unit, and cognitive radio transceiver unit as abstracted in Fig. 2. In specific applications, CRSN nodes may have mobilization and localization units as well. The main difference between the hardware structure of classical sensor nodes [3] and CRSN nodes is the cognitive radio transceiver of CRSN nodes. As discussed in Section V-A, cognitive radio unit enables the sensor nodes to dynamically adapt their communication parameters such as carrier frequency, transmission power, and modulation.

CRSN nodes also inherit the limitations of conventional sensor nodes in terms of power, communication, processing and memory resources. These limitations impose restrictions on the features of cognitive radio as well. For example, as will be discussed in Section IV-A, CRSN nodes may perform spectrum sensing over a limited band of the spectrum due to processing, power, and antenna size constraints. Consequently, CRSN nodes are generally constrained in terms of the degree of freedom provided by the cognitive radio capability as well.

B. CRSN Topology

According to the application requirements, cognitive radio sensor networks may exhibit different network topologies as explored in the following.

1) Ad Hoc CRSN: Without any infrastructural element, inherent network deployment of sensor networks yields an ad hoc cognitive radio sensor network as shown in Fig. 1. Nodes send their readings to the sink in multiple hops, in an ad-hoc manner.

In ad hoc CRSN, spectrum sensing may be performed by each node individually or collaboratively in a distributed way. Similarly, spectrum allocation can also be based on the individual decision of sensor nodes. This topology imposes almost no communication overhead in terms of control data. However, due to hidden terminal problem, spectrum sensing results may be inaccurate, causing performance degradation in the primary user network.

2) Clustered CRSN: In general, it is essential to designate a common channel to exchange various control data, such as spectrum sensing results, spectrum allocation data, neighbor discovery and maintenance information. Most of the time, it may not be possible to find such common channel available throughout the entire network. However, it has been shown in [22] that finding a common channel in a certain restricted locality is highly possible due to the spatial correlation of channel availability. Therefore, a cluster-based network architecture as in Fig. 3(a) is an appropriate choice for effective operation of dynamic spectrum management in CRSN.

In this case, cluster-heads may also be assigned to handle additional tasks such as the collection and dissemination of spectrum availability information, and the local bargaining of spectrum. To this end, new cluster-head selection and cluster formation algorithms may be developed for CRSN which jointly consider the inherent resource constraints as well as the challenges and requirements of opportunistic access in CRSN.

3) Heterogeneous and Hierarchical CRSN: In some cases, CRSN architecture may incorporate special nodes equipped with more or renewable power sources such as the actor nodes in wireless sensor and actor networks (WSAN) [21]. These nodes may have longer transmission ranges, and hence, be used as relay nodes much like the mesh network case. This forms a heterogeneous and multi-layer hierarchical topology consisting of ordinary CRSN nodes, high power relay nodes, e.g., cognitive radio actor nodes, and the sink as shown in Fig. 3(b).

While the presence of capable actor nodes may be exploited for effective opportunistic access over the CRSN, the associated heterogeneity brings additional challenges. Among the others, sensor and actor deployment, increased communication overhead due to hierarchical coordination, and the need for cognitive radio capability over the actor nodes need to be addressed.

4) Mobile CRSN: When some or all of the architectural elements of a CRSN are mobile, this yields a more dynamic topology, i.e., a mobile CRSN. For example, the sensor nodes, actors if exist, and even the sink might be mobile depending on the specific application and deployment scenario.

Clearly, mobility amplifies the existing challenges on most of the aspects of CRSN. First of all, the dynamic nature of the topology requires mobility-aware dynamic spectrum management solutions over resource-constrained CRSN nodes. Moreover, cognitive radio communication protocols for CRSN must consider mobility as well. Therefore, this specific CRSN architecture needs a thorough investigation of the challenges and solution techniques.

In general, the physical characteristics of a CRSN node and diverse set of CRSN network topologies discussed above yield many open research issues outlined as follows.

- *CRSN node development:* Clearly, one of the fundamental issues for the realization of CRSN is the development of efficient and practical cognitive radio sensor nodes. Considering the basic design principles and objectives of sensor networks, and hence, the inherent limitations of sensor nodes, hardware and software design for sensor nodes with cognitive radio capability must be extensively studied.
- *Node deployment strategies:* In cases where primary user statistics are available, node deployment strategies considering spectrum availability characteristics may provide considerable improvements on the lifetime and transmission efficiency of the network. Therefore, the mathematical analysis for optimal node deployment in CRSN topologies, and hence, practical yet efficient deployment mechanisms must be investigated.
- *Clustering in CRSN:* Clustering and forming hierarchy incur additional communication overhead in the network. This overhead may be amplified due to node mobility or spectrum handoff which vary the neighboring constellation of nodes. Hence, for the applications requiring cluster-based and hierarchical CRSN topologies, dynamic spectrum aware group formation and maintenance techniques must be developed.
- *Coordinated vs. uncoordinated network operation:* Spectrum sensing, spectrum detection and allocation, spectrum handoff as well as medium access may be performed either individually by the nodes or cooperatively in CRSN. A detailed efficiency analysis for the comparison of coordinated and uncoordinated schemes is required for various network topologies.
- *Optimal network coverage:* Spatial locations of CRSN nodes may vary even in case of manual uniform deployment due to node failures and primary user activities rendering some of the cognitive radio nodes disconnected. Hence, to maintain maximum network coverage, certain nodes may have to transmit with more radio power, which in turn, increases power consumption. On the other hand, connectivity at longer ranges may be achieved with lower frequencies which also help save transmission power. Therefore, optimal network coverage must be analyzed considering dynamic spectrum management, and new

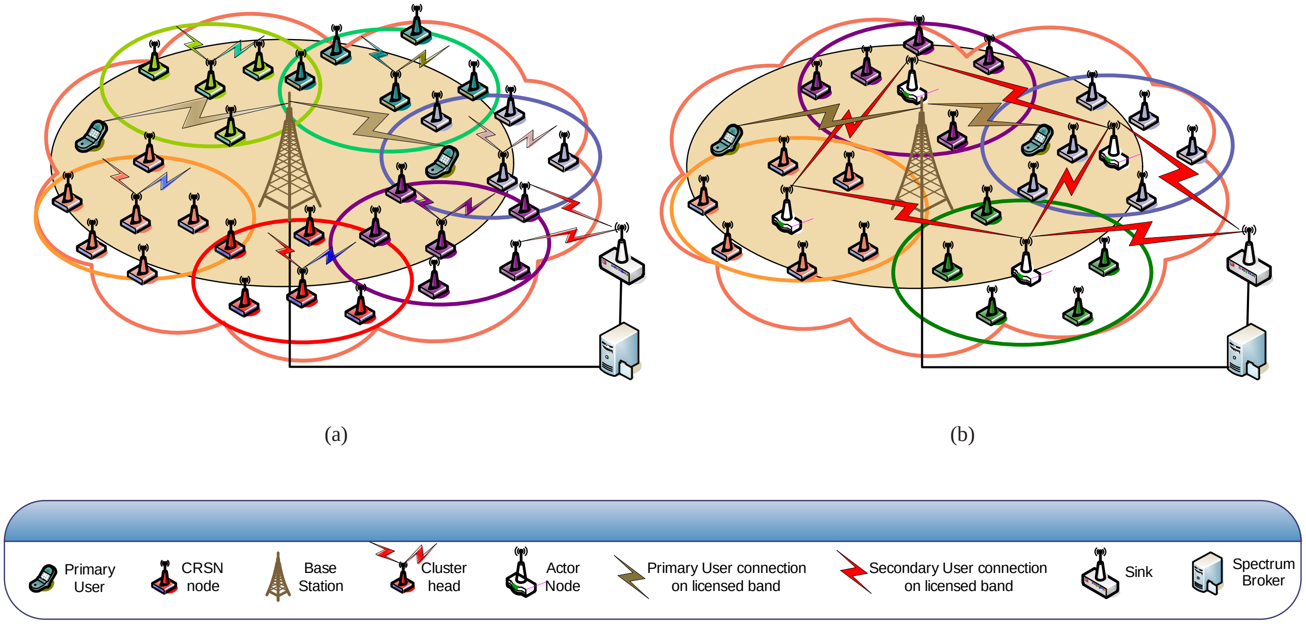
(a)
(b)

Fig. 3. Possible network topologies for CRSN (a) Clustered (b) heterogeneous hierarchical.

topology formation schemes which address the tradeoff between network lifetime and communication coverage must be introduced.

III. POTENTIAL APPLICATION AREAS OF CRSN

Traditional sensor networks already have a diverse range of application domains from smart home with embedded sensor and actuators to large-scale real-time multimedia surveillance sensor networks. With the ingression of cognitive radio capability to sensor networks regime, CRSN might be the preferred solution for some specific application domains explored below due to its potential advantages introduced in Section I.

A. Indoor Sensing Applications

Indoor applications, e.g., tele-medicine [19], home monitoring, emergency networks, factory automation, generally require the deployment of many sensor nodes within a small area. In some cases, such as industrial operation automation, smart building, actor nodes may be also part of the deployment.

The main problem with indoor sensing applications is that the unlicensed bands, e.g., ISM bands, for indoor usage are extremely crowded [4]. Consequently, conventional sensor networks may experience significant challenges in achieving reliable communication due to packet losses, collisions and contention delays. Here, opportunistic spectrum access of CRSN may help mitigate these challenges due to crowded spectrum and extreme node density. For example, with the cognitive radio capability, emergency networks may coexist with other indoor wireless systems. Critical information, which requires real-time reliable communication, may exploit the potential advantages of dynamic spectrum management even in crowded environments.

B. Multimedia Applications

Reliable and timely delivery of event features in the form of multimedia, e.g., audio, still image, video, over resource-constrained sensor networks is an extremely challenging objective due to inherent high bandwidth demand of multimedia [23]. At the same time, the capacity provided by the sensor network varies with the temporal and spatial characteristics of the channel.

Unlike the traditional sensor networks, CRSN may provide the sensor nodes with the freedom of dynamically changing communication channels according to the environmental conditions and application-specific quality-of-service (QoS) requirements in terms of bandwidth, bit error rates, and access delay. Hence, for multimedia communication over sensor networks, CRSN may improve the performance of multimedia communication as well as overall spectrum utilization. For example, as the packet travels through multiple hops, each relaying node may use higher frequencies and the highest possible data rate to provide required bandwidth.

Furthermore, when multiple nodes need to transmit at the same time, they try to acquire the same channel which increases the contention delay in WSN. However, nodes in a CRSN have access to multiple available channel and can send their data through different channels concurrently. Therefore, CRSN is more suitable to sensing applications that involve in multimedia communication.

C. Multi-class Heterogeneous Sensing Applications

Some applications may require multiple sensor networks with distinct sensing objectives to coexist over a common area [24]. Various information gathered from these networks may be fused to feed a single decision support. Similarly, in a single sensor network, different sensor nodes may be deployed over the same area to sample the event signal over multiple dimensions including scalar measurements, e.g., heat, humidity, location, motion, as well as audio visual readings of the target being monitored.

Clearly, readings of these heterogeneous sensor networks impose heterogeneity in terms of communication requirements as well. For example, a multimedia sensor node, providing streaming video data, has more bandwidth requirement and less delay tolerance compared to a magnetic sensor. With the help of dynamic spectrum management, multi-class heterogeneous sensor networks may overlap with minimum interference to each other. Furthermore, through the coordination and cooperative spectrum management among these multiple cognitive radio sensor networks, their individual performance as well as the overall spectrum utilization may be improved.

D. *Real-time Surveillance Applications*

Real-time surveillance applications like target detection and tracking require minimum channel access and communication delay. In traditional WSN with fixed spectrum allocation, this objective may not be always achieved, especially if the operating spectrum band is crowded. Furthermore, additional communication latency may occur in WSN in case of rerouting due to a link failure caused by degrading channel conditions.

In CRSN, sensor nodes may opportunistically access to the available channel in order to maintain minimum access and end-to-end communication delay for effective real-time surveillance applications. As discussed in Section V-C, with the development of new delay-constrained joint spectrum allocation and routing algorithms for CRSN, performance of real-time sensing applications may be further improved. At the same time, statistical information of primary user over the spectrum band in use can be exploited in order to minimize the probability of spectrum handoff so as to avoid increasing communication delay due to frequent spectrum mobility.

One typical real-time sensing application example is military surveillance applications which are highly delay-sensitive and also require high reliability. In general, tactical sensor networks are densely deployed to assure network connectivity and maximize reliability within a certain delay bound. As mentioned above, such dense deployment can also exploit the potential advantages of dynamic spectrum access. Furthermore, with the spectrum handoff capability, tactical surveillance CRSN may be less susceptible to interception and jamming threats.

IV. DYNAMIC SPECTRUM MANAGEMENT IN CRSN

The realization of cognitive radio sensor networks primarily require an efficient spectrum management framework to regulate the dynamic spectrum access of densely deployed resource-constrained sensor nodes. The major challenges and open research issues regarding such dynamic spectrum management framework for CRSN are explored in this section.

A. *Spectrum Sensing*

Spectrum sensing is one of the major functionalities distinguishing CRSN from traditional WSN. Since nodes can operate on spectrum bands of the licensed primary users in an opportunistic manner, they must gather spectrum usage information via spectrum sensing prior to transmission. In the literature, there exist various spectrum sensing methods, which are examined below in terms of how they can apply to CRSN.

- *Matched filter:* It has been shown that the optimal spectrum sensing method for the cognitive radio with the presence of Gaussian noise is the matched filter method [25]. However, this approach requires a priori knowledge about the transmission of the primary user. Since it is a coherent detection method, it requires synchronization with the primary user. In cases, where PU transmission characteristics are available, matched filter-based detection may be employed. However, most of the time, such assumption is unrealistic. Furthermore, CRSN nodes need additional dedicated circuitry for each encountered primary user type. This considerably increases the cost and complexity for low-end sensor nodes.
- *Energy detection:* Inherent constraints of CRSN nodes mandate for a simpler spectrum sensing technique such as energy detection method. This method is popular even in cognitive radio networks, where nodes are typically less power constrained and have more computational power [26]. The idea is to measure the received energy on the specific portion of the spectrum, i.e., channel, for a certain period of time. If the measured energy is below a threshold value, the channel is considered available. Its simplicity and low signal processing requirement make this method very attractive for CRSN. However, it has a number of drawbacks. Energy detection requires longer measurement duration to achieve a certain performance level compared to matched filter method. Furthermore, the performance of this method highly depends on variations of the noise power level. Therefore, in case of a small increase in detected energy, it is impossible to understand whether the reason is a primary user activity or an increase noise power level.
- *Feature detection:* This method can be used when certain features of the primary user transmission such as carrier frequency and cyclic prefixes are known [27]. Feature detection method takes advantage of the cyclo-stationary features of the PU signal. Unlike noise, the PU signal has spectrum correlation due to its inherent cyclo-stationarity. By making use of this correlation, the PU signal inside the noise can be detected. Thus, feature detection method is very robust against variations of noise. However, this additional capability comes with the cost of increased complexity, which typical CRSN nodes may not be able to provide. Hence, feature detection is more suitable to special CRSN cases where the network includes nodes with greater computational power.
- *Interference temperature:* The sensing method introduced by the FCC is the interference temperature measurement method [28]. An interference temperature level above

TABLE II
OVERVIEW OF SPECTRUM SENSING METHODS.

Spectrum sensing Method	**Disadvantages**	**Advantages**
Matched Filter [25]	Requires a priori info on PU transmissions, and extra hardware on nodes for synchronization with PU.	Best in Gaussian noise. Needs shorter sensing duration (less power consumption)
Energy detection [26]	Requires longer sensing duration (high power consumption). Accuracy highly depends on noise level variations	Requires the least amount of computational power on nodes.
Feature detection [27]	Requires a priori knowledge about PU transmissions. Requires high computational capability on nodes.	Most resilient to variation in noise levels.
Interference temperature [28]	Requires knowledge of location PU and imposes polynomial calculations based on these locations.	Recommended by FCC. Guarantees a predetermined interference to PU is not exceeded.

the noise floor is determined. CRSN nodes calculate how much interference they would cause at the primary user receiver. Then, they adjust their power such that their interference plus the noise floor is not greater than the interference temperature level. This method requires CRSN nodes to know the locations of the primary users for precise interference measurement. Furthermore, it may be too computationally intense for a low-end sensor node.

Following these main approaches above as outlined in Table II, there is a substantial amount of work in literature on spectrum sensing methods for cognitive radio. Clearly, most of these methods are not suitable for CRSN as they are designed without considering the unique challenges posed by the resource constraints of sensor nodes as follows:

- *Hardware limitations* - It is not feasible to equip CRSN nodes with highly capable processors and A/D units. Thus, complex detection algorithms cannot be used. Spectrum sensing must be performed with limited node hardware.
- *Minimum sensing duration* - Keeping the transceiver on even just for spectrum listening causes excessive power consumption. While sensing accuracy increases with duration, spectrum sensing must be achieved in short sensing duration.
- *Reliable sensing* - Secondary users can operate on licensed bands, unless they do not interfere with primary users. For avoiding interference on primary user, spectrum sensing must be reliable.

The first two of these challenges are unique to CRSN. The last one is a concern for cognitive radio networks too; however, due to limitations of the cognitive radio sensor node, techniques developed for cognitive radio networks cannot be directly applied to CRSN. Therefore, additional research must be conducted on spectrum sensing for CRSN along the following open research issues:

- *Hybrid sensing techniques:* A possible way to obtain spectrum information with minimum sensing duration and low computational complexity is to use hybrid sensing techniques, which is a balanced combination of the sensing approaches above. For example, energy detection may be used on a broader band to have an idea about which portions of the spectrum may be available. Based on this information, more accurate sensing methods can be performed over selected potential channels. Therefore, hybrid sensing techniques addressing the trade off between sensing accuracy and complexity must be investigated.
- *Cooperative sensing:* When nodes rely only on their own spectrum sensing results, they may not be able to detect the primary user due to shadowing. Spectrum sensing duty may be distributed among the nodes to increase sensing accuracy [26]. Achieving sensing in a distributed manner is called *cooperative sensing* [29], [22]. While cooperative sensing yields better sensing results, it also imposes additional complexity and communication overhead. New cooperative sensing method, requiring minimum amount of extra packet transmission and having minimum impact on the sleep cycles of the node, is an open research issue.
- *Sensing based on collaborative PU statistics:* If it is possible to obtain channel usage statistics of the primary users, it may be possible to develop more efficient sensing methods. Even if PU statistics are not available, nodes may collectively obtain these statistics by continuously sharing their distributed spectrum sensing results. Intelligent and collaborative methods, which estimate and then make use of primary user channel usage statistics, must be studied.

B. Spectrum Decision

CRSN nodes must analyze the sensing data and make a decision about channel and the transmission parameters, e.g., transmission power and modulation. Spectrum decision methods proposed for cognitive radio networks consider power consumption as a secondary issue and the amount of extra control packets to transmit is almost never taken into account. Furthermore, nodes in a cognitive radio network have more memory and computational power. More complicated schemes for coordination of spectrum decision, which incur higher communication overhead, may be used in cognitive radio networks. However, these solutions are not feasible for CRSN due to additional challenges posed by the ad hoc multi-hop nature as well as the inherent constraints of sensor nodes.

First, in any given locality, it has been shown that the spectrum sensing results will be similar [22]. Thus, most of the time, spectrum decisions of the nodes, which are close to each other, will be the same. If nodes try to access the channel depending only on their individual spectrum decision results, collision probability increases. Furthermore, since nodes run the same algorithm, when a collision occurs, they all try to switch to another channel, leaving the previous channel empty and colliding again on the new channel. This negates the advantage of multiple channel availability brought by the cognitive radio capability. Therefore, spectrum decision in CRSN must be coordinated to increase overall utilization and maximize power efficiency.

Coordination can be handled by a centralized method. Nodes send their spectrum sensing results to the sink along with their event samples and sink decides on optimal spectrum usage. Based on this decision, corresponding sharing rules are sent to the nodes. Furthermore, centralized methods are also suitable for hierarchical topology given in Section II-B3. Centralized methods may yield optimal spectrum utilization since central decision unit has global network information which enables it to perform global optimization methods over the multi-hop paths from the event field to the sink. However, the additional traffic imposed on the nodes may result in excessive power consumption.

An alternate is to use distributed coordination approaches, where nodes share their spectrum sensing and decision results only with their immediate neighbors or within small clusters. Such distributed methods are more suitable for ad hoc and mobile topologies discussed in Sections II-B1 and II-B4. Based on shared local spectrum availability information, nodes follow simple rules to decide on spectrum usage on their own. Even though this method yields suboptimal utilization, compared to the centralized approach, it is considerably simpler to implement and incurs less communication and hence power overhead as data is shared among a small number of nodes. In [22], authors propose a distributed spectrum decision scheme based on a clustered architecture and show that the provided suboptimal solution is indeed close to the global optimal solution. This proves that properly designed distributed solutions may also yield performance close to the optimal.

Clearly, there exist many open research issues for the development of new spectrum decision techniques for CRSN as outlined below.

- *Spectrum decision parameters:* Determining which parameters to include in the decision process is essential. Parameters such as signal to noise ratio, path loss and channel capacity of the channel are easier to obtain. On the other hand, parameters such as wireless link errors, link layer delays and holding times of PU may be more challenging to obtain by constrained sensor nodes. Therefore, parameters to use in spectrum decision for CRSN must be explored and new algorithms, which yield optimal spectrum decision based on these parameters as well as application-specific requirements, must be developed.
- *New decision methods handling heterogeneity:* In heterogeneous networks with more than one sensor node type, some of the channel parameters may be more important than others. For example, for a multimedia sensor node which provides streaming video data, channel capacity is more important than path loss. Hence, novel decision schemes which consider heterogeneity in energy-efficient manner must be developed.
- *Distribution of control data:* Coordinated spectrum decision schemes also need mechanisms to share essential control data. The method vastly used in conventional multi-channel networks is to use a common control channel. However, in general, CRSN do not have channels allocated specifically to them. It was shown in [22] that most of the time, finding a channel that is available through the whole network may be impossible for a secondary user. On the other hand, finding such a channel within a given locality has a large probability and small local group based approaches, in which each group has its own local control channel may be more practical. Therefore, energy efficient central and distributed methods of sharing spectrum decision data must be investigated. Furthermore, analysis and comparison of these central and distributed methods must be studied.

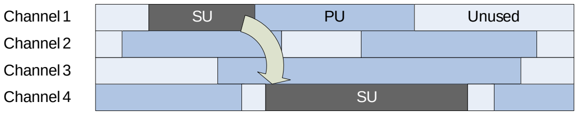

Fig. 4. Spectrum handoff in CRSN.

C. Spectrum handoff

When a PU starts using a previously available channel, CRSN nodes must detect primary user activity within a certain time through spectrum sensing methods as discussed in Section IV-A. Then, as illustrated in Fig. 4, they immediately move to another available channel decided by an effective spectrum decision mechanism as explored in Section IV-B, even if they have ongoing transmission. Nodes may also want to switch channels if channel conditions get worse, reducing communication performance. This fundamental functionality of cognitive radio is called as *spectrum handoff* [30].

When spectrum handoff is needed, first an alternate channel must be determined. Then, receiver-transmitter handshake must be performed on the new channel. Only then can nodes continue their transmissions. All of these additional operations incur long delays, and hence, buffer overflows which lead to packet losses, degradation in reliability, and ultimately resource waste in CRSN.

Various spectrum handoff methods have been proposed in literature for cognitive radio [31], [32]. There are also studies on the analysis of the effect of spectrum handoff on overall communication [33], [34]. However, none of these works consider the challenges posed by the inherent limitations of CRSN.

In [19], a central spectrum allocation scheme, which tries to minimize spectrum handoff, has been proposed for CRSN. However, this single work clearly comes short in addressing other fundamental issues pertaining to spectrum handoff in CRSN. First, minimizing the effect of spectrum handoff on various communication layers must be analyzed. For example,

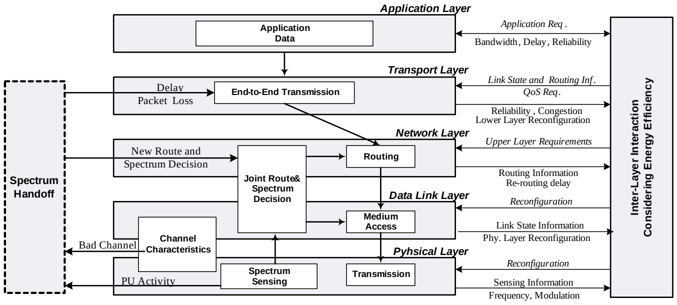

Fig. 5. Interaction between the communication and dynamic spectrum management functionalities.

at the time of spectrum handoff queuing of packets in a memory limited node is an open issue to be researched. At the same time, the development of central and distributed spectrum handoff solutions for CRSN must be investigated. In addition, precautions must be taken to meet QoS requirements over multi-hop paths from the event field to the sink when spectrum handoff occurs. Hence, methods must be developed to move control traffic to another channel in case of primary user arrival to control channel.

V. COMMUNICATION IN CRSN

The performance of communication in CRSN is tightly coupled with how effectively dynamic spectrum management issues discussed in Section IV are addressed. There exists a close relation and interaction between the requirements and functionalities of dynamic spectrum management and communication techniques in CRSN as illustrated in Fig. 5.

In this section, we investigate the specific design considerations of each communication layer, and explore the existing networking solutions of cognitive radio and wireless sensor networks along with the open research issues for effective communication in CRSN.

A. Physical Layer

Physical layer regulates interaction between data link layer and physical wireless medium. It is also responsible for spectrum sensing and reconfiguration of the transmission parameters according to spectrum decisions in CRSN.

A CRSN node can reconfigure its operating frequency, modulation, channel coding and output power without hardware replacement. This is the most significant difference between cognitive radio sensor network and wireless sensor network physical layer. Software defined radio (SDR) based RF front-end transmitters and receivers [35] are required for reconfigurability of cognitive radio sensor nodes. However, implementing RF front-end for cognitive radio sensor node is a significant challenge due to low cost and resource-constrained nature of sensor nodes.

On the other hand, limited capabilities of A/D converters used in the nodes and heavy-weight signal processing algorithms, make spectrum sensing a challenging issue as well. Detecting weak signals, and hence, presence of PU, while there are secondary users, are significant sensing problems in CRSN [36].

Furthermore, unlike in conventional SDR, it is impossible to support different waveforms, since cognitive radio sensor node has limited memory and baseband signal processing capability. Similarly, wide-band spectrum sensing, advanced modulation schemes and cognitive learning capabilities cannot be fully realized in a CRSN node due to its limited computational power.

Clearly, the realization of CRSN depends on the development of effective, energy-efficient, and yet practical cognitive radio for sensor nodes. However, there exist many fundamental open research issues on the physical layer design for CRSN as outlined below:

- Software defined radio-based transceivers providing energy-efficient dynamic spectrum access must be designed for CRSN.
- Low-cost and practical digital signal processing (DSP) hardware and algorithms must be developed for wide-band spectrum sensing and reliable detection of primary user overlapping with CRSN.
- Since fully capable SDR is not feasible for CRSN, multiple waveforms cannot be maintained in hardware. Hence, design of an optimal waveform, which can be adaptively used in multiple channels with different transmission parameters, needs to be studied.
- Adaptive methods, which address the trade-off between transmission power and interference, must be designed to solve the interference problem that may arise in densely deployed CRSN.
- Methods to map application-specific QoS requirements to adaptable transmission parameters of the physical layer must be investigated.

B. Data Link Layer

Data link layer is responsible for reliable transmission and reception of frames between sensor nodes. In general, efficient medium access control (MAC), and error control and correction are the main functionalities of link layer to achieve its goals. In CRSN, these objectives must be achieved in accord with the principles of dynamic spectrum management and in an energy-efficient manner.

1) Error Control: The main error control schemes assumed by WSN are forward error correction (FEC), and automatic repeat request (ARQ). Despite the simplicity of ARQ approaches, its retransmission-based mechanism causes extra energy consumption and reduces bandwidth utilization. Therefore, similar to traditional WSN, FEC schemes are promising for resource-constrained cognitive radio sensor nodes.

In FEC approaches, a certain amount of redundancy is included in the packet to be used by the receiver to recover bit errors. The amount of error that can be corrected depends on the complexity of the error correction algorithm and the amount of redundancy. In addition to reduced channel utilization due to redundancy, CRSN have further challenges for error control because of its multiple frequency access ability. Since each channel may have different conditions, a fixed FEC scheme may not yield optimal results for every channel. Furthermore, when channel conditions are good, ARQ may

TABLE III
OVERVIEW OF MAC APPROACHES DEVELOPED FOR MULTI-CHANNEL AD HOC NETWORKS.

MAC approach	**Disadvantages in CRSN**	**Reasons to adopt for CRSN**	**Open research issues**
On-demand negotiation [37]	Contention due to single channel for all negotiations	On-demand reservation is suitable for bursty traffic	Coordination of multiple control channels required for heavy traffic
Home channel [39]	Multiple transceiver requirement	Does not require negotiation for each packet (helps power conservation)	Mechanisms to make this scheme work with single transceiver needed
Time division-based negotiation [38]	Requires network-wide synchronization for negotiation intervals	Simple and very few rules imposed on nodes	Need for network-wide synchronization must be eliminated

yield better performance compared to FEC schemes. Hence, the error correction method should consider this trade-off and may use a combination of both schemes.

2) Medium Access Control: In general, a MAC protocol aims to provide the sensor nodes with means to access the medium in a fair and efficient manner. This is a challenging objective considering the resource limitations of the nodes, dense network deployment, and application-specific QoS requirements.

In CRSN, according to the specific CRSN topology as explored in Section II, sensor nodes may perform handshake to negotiate on the channel before transmitting packets. Both topology forming and channel negotiations require some control packet exchange. Therefore, compared to conventional WSN, MAC layer of a cognitive radio sensor node must handle additional challenges due to the coordination of dynamic spectrum access as outlined below.

- *Silent periods* - CRSN nodes need to perform spectrum sensing in regular intervals. When a node performs sensing on a channel, other nodes must refrain from transmitting on that channel to avoid inaccurate spectrum sensing. Therefore, special control messaging may be employed to inhibit potential transmission of other nodes that are close to the node currently sensing the spectrum. These sensing periods are called *silent periods*. For efficient medium access control and spectrum sensing, these silent periods must be coordinated among neighboring nodes.
- *Broadcasting* - Due to opportunistic medium access in CRSN, broadcasting cannot be done by conventional means. At time of broadcast, neighbors may have their transceivers tuned to various other channels. Hence, acquiring the channel and successful transmission without collision do not necessarily imply the successful reception of the packet by the neighbor nodes. Second, as pointed out earlier, assumption of a common channel globally available throughout the whole network is not practical in cognitive radio networks. Thus, broadcast messages cannot simply be forwarded through the received channel. Clearly, an efficient MAC layer scheduling is imperative so that all nodes can switch to a local broadcast channel in the time of transmission.
- *Distribution of spectrum sensing and decision results* - If cooperative methods for spectrum sensing and decision mentioned in Section IV are to be used to increase sensing accuracy and sharing efficiency, extra control information should be shared among nodes. In such cases, MAC protocol must include mechanisms to distribute sensing results and sharing information with higher priority.

Unfortunately, there exists no complete MAC solution which addresses above requirements for CRSN. The existing MAC solutions for WSN are not designed for dynamic spectrum access, and hence, they simply cannot address above issues. On the other hand, the previous work on ad hoc cognitive radio networks can be broadly divided into three categories based on how they perform channel reservation as outlined in Table III.

In on-demand reservation approach, a channel, i.e., the *control channel*, is used to exchange channel reservation information on demand. Then, nodes switch to the negotiated data channel for transmission [37]. The main problem with this approach is that, it cannot handle cases where large number of nodes attempt to transmit in a short amount of time. Since a single channel is used for channel reservations, it gets congested very quickly. In fact, this is highly likely in CRSN due to its bursty traffic nature and dense deployment. Furthermore, this approach causes a high end-to-end latency due to contention delay. Since CRSN generally operates in a multi-hop manner, this delay may exceed tolerable delay bound of some applications.

One of the challenges for on-demand approaches is to provide means to move control channels smoothly and in an energy-efficient manner in case of PU arrival. Having multiple control channels can also improve the performance for these cases such that the rest of the control channels can be used until a new vacant band is found for the effected control channel.

The second approach is to use each available channel as the *home channel* of one or several nodes [39]. This approach assumes nodes to have more than one transceiver. One of these transceivers is fixed to its home channel. When a node wants to send data to another node it switches its non-fixed transceiver to the home channel of the destination node and send the data. However, multiple transceiver assumption is not practical for CRSN. The main challenge for this approach would be to realize the core idea of the home channel method without multiple transceiver requirement.

The third approach is based on the use of time division techniques to divide time into frames, in which nodes transmit their data in a round-robin fashion [38]. Channel reservations are made at the beginning of each frame and nodes perform their transmission in their reserved slots. Due to network-wide strict synchronization requirement, this approach cannot be

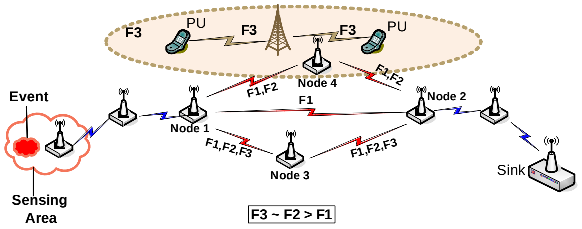

Fig. 6. Effect of spectrum availability on potential routing paths.

directly employed by a CRSN. Moreover, as the number of nodes increase the reservation time at the beginning of each frame increases, leading to overall performance degradation.

Clearly, none of these existing approaches can be directly employed in CRSN. Hence, the main open research issues for data link layer in CRSN are outlined as follows.

- When a degradation in channel conditions is detected, FEC schemes with more redundancy may be used to decrease the error rate. Therefore, dynamic spectrum FEC schemes with minimum energy consumption must be developed. Furthermore, impact of packet size on the transmission efficiency, and hence optimal packet size for CRSN must be analyzed under varying channel characteristics.
- Adaptability to the channel conditions enable CRSN to employ novel error prevention schemes. For example, if channel availability permits, transmission bandwidth and constellation size can be changed, keeping the bit rate constant while decreasing error probability. Hence, dynamic spectrum access based novel error control mechanism must be investigated.
- Novel MAC solutions, which can handle the additional challenges above and make full use of the multiple alternative channel availability, must be developed.
- Home channel-based MAC seems to be promising as it requires minimum communication overhead for channel negotiation. However, it is not feasible for CRSN since it requires two transceivers. Methods to adopt home channel idea with a single transceiver in CRSN must be studied.
- Another issue that must be addressed by the link layer is the power saving methods as CRSN nodes have limited power like in WSN [2]. However, due to frequency agility of cognitive radio sensor nodes new challenges arise. One is the coordination of spectrum sensing with sleep/wake up cycles. Another challenge is to provide connectivity to a sensor node after it wakes up. Since there is no fixed channel to transmit, new duty cycle methods jointly considered with neighbor discovery, and spectrum sensing and allocation must be investigated.

C. Network Layer

CRSN inherits major network layer issues from WSN such as ad hoc and multi-hop networking, the need for energy-efficient data-centric routing, attribute-based addressing, and location-awareness.

Existing ad hoc cognitive radio routing schemes [48], [43], [30] aim to provide joint spectrum and routing decisions, however, do not consider the inherent resource constraints of CRSN. At the same time, routing schemes developed for WSN mainly aim to minimize energy consumption [42] and do not handle dynamic spectrum access.

In fact, there are various energy efficient routing algorithms proposed for WSN with fixed allocation scheme [42]. However, predetermined routing is not suitable for dynamic topology caused by opportunistic channel access. Hence, on-demand routing is advised for cognitive radio networks [43]. Despite the communication overhead and increased contention, dynamic spectrum-aware on-demand routing can be investigated for CRSN.

CRSN are also energy-constrained, hence, hop count is an important metric to be minimized in routing process. However, spectrum mobility introduces additional challenges. Hop-based channel characteristics like channel access delay, interference, operating frequency, and bandwidth are new metrics. Therefore, new route determination algorithms, which consider both opportunistic spectrum access and sensor networks metrics, are required. In addition, number of channel switches along a path between source to sink affects route decision since switching from one channel to another does not have zero delay. Hence, routing algorithms should select minimum channel switching paths [30].

On the other hand, spectrum decision can change neighboring status of CRSN node as path loss changes with operating frequency [40]. Therefore, spectrum decision and assignment is directly related to route determination. In [41], it is shown that joint route and spectrum selection outperforms discrete route and spectrum selection in cognitive radio networks. In Fig. 6 this situation is depicted, where primary and secondary users are in the sensing area. Here, 3 frequencies, i.e., F_1, F_2, F_3, with different transmission ranges, R_1, R_2, and R_3, such that $R_1 > R_2, R_3$, are available. F_3 is used by primary users. Hence, if node 1 selects F_1 for transmission, it connects to node 2 directly, or over nodes 3 and 4. However, if it selects F_2, it can only connect to node 2 over nodes 3 or 4. If it selects F_3, it connects to node 2 over node 3 as path over node 4 cannot be used due to PU activity. Therefore, unlike traditional WSN, frequency selection is directly related and must be jointly considered with route determination in CRSN.

In addition, spectrum handoff introduces re-routing challenges in CRSN. Due to spectrum handoff, routes may be obsolete during new spectrum sensing and assignment phases. After spectrum assignment, variation in channel characteristics mandates for re-calculation of routes according to the metrics in use. Unlike cognitive radio network, re-routing algorithms should also be highly energy-efficient in CRSN. For example, flooding over control channel during the spectrum handoff, or pre-determined route establishment with pre-spectrum handoff signaling may be incorporated into new network layer solutions for CRSN.

Furthermore, as discussed in Section V-B, the absence of a global common channel makes neighbor discovery and messaging for route establishment quite challenging for CRSN. Therefore, heavy-weight and high maintenance routing algorithms may not be practical for CRSN.

Clearly, there is a need for extensive research for the development of effective network layer solutions addressing the challenges above for CRSN along the open issues outlined below.

- New energy-efficient cognitive radio multi-hop routing protocols as in Fig. 5, which consider the requirements and challenges of both dynamic spectrum access and sensor networks such as spectrum mobility, resource constraints, dense deployment, must be developed.
- Unlike conventional WSN, on-demand routing may be employed in CRSN. Hence, energy-efficient on-demand multi-hop cognitive radio sensor network routing protocols must be investigated.
- Analytical framework for routing optimization in terms of efficiency and complexity in conjunction with opportunistic spectrum access must be studied, which would lead to optimal networking solutions for CRSN.
- Adaptive and priority-based routing schemes, which also consider application-specific QoS requirements for varying channel conditions, need to be designed for real-time multimedia surveillance CRSN.

D. Transport Layer

In sensor networks, transport layer is mainly responsible for end-to-end reliable delivery of event readings and congestion control to preserve scarce network resources while considering application-based QoS requirements. With the detection of an event, sensor nodes inject high and bursty traffic into the network. To achieve successful detection and tracking of an event signal, sufficient number of event readings must be reliably delivered to the sink. At the same time, if the capacity of multi-hop network is exceeded, this would lead to congestion which wastes power and communication resources in sensor networks.

Clearly, there is a delicate balance between reliability and energy-efficiency, which has been the main focus of transport layer solutions proposed for sensor networks thus far [44]. While the same balance is also inherited by CRSN, dynamic spectrum management brings additional factors affecting this trade-off as outlined below.

- There is no fixed frequency set over the path from the sensing node to the sink in CRSN, which may significantly vary the channel characteristics, e.g., link delay, channel bit error rate, capacity, over each hop.
- At the time of the spectrum handoff, performance degradation may occur due to extra delays, buffer overflows and packet losses. Furthermore, spectrum mobility during active communication or along the path may incur large variances and inaccuracy in end-to-end delay and packet loss measurements.
- CRSN nodes must sense spectrum periodically to control PU activity. Since, nodes in the spectrum sensing phase cannot transmit and receive; extra sensing delay and buffer overflows may trigger additional packet losses.

Furthermore, some applications such as target tracking and surveillance may also impose additional real-time delay bounds on the reliable communication requirements. Above challenges posed by opportunistic spectrum access render this objective extremely challenging. In addition to the event-to-sink forward path, effective transport layer solutions are also required for reliable delivery of packets in the reverse path, i.e., from the sink to the sensors, in CRSN. Delivery of queries, commands, and code updates may impose even tighter reliability requirements, which are difficult to handle with conventional fixed solutions due to large variations of channel characteristics over the entire CRSN.

Although there exist several transport layer solutions for WSN [45], [46], [47], which address reliable delivery with minimum energy consumption and congestion avoidance, none of them considers dynamic spectrum access. At the same time, there exists no transport layer solution for ad hoc cognitive radio networks either. Hence, all of the challenges elaborated above, which are inherited from WSN and amplified by cognitive radio, must be addressed through the design of novel dynamic spectrum-aware CRSN transport protocols. To this end, the open research issues for transport layer in CRSN can be outlined as follows.

- New reliability definitions, objectives, and metrics must be studied in order to incorporate the fundamental variables of dynamic spectrum access.
- Adaptive, energy-efficient spectrum-aware transport protocols, which can effectively handle opportunistic spectrum usage challenges, must be developed for both event-to-sink and sink-to-sensor communication in CRSN.
- Analytical modeling of communication capacity, reliability, congestion, and energy consumption should be studied for CRSN. Furthermore, queuing and network information theoretical analysis of reliable communication must be explored for CRSN.
- Cross-layer interactions with spectrum management and congestion control mechanisms must be investigated to address large variations in channel characteristics over multi-hop paths.
- Adaptive real-time transport solutions must be developed to address real-time reliability requirements and application-specific QoS needs under varying spectrum characteristics.
- New mechanisms to exploit the multiple channel availability towards reliable energy-efficient communication in CRSN must be developed.

E. Application Layer

Application layer algorithms in sensor networks mainly deal with the generation of information and extracting the features of event signal being monitored to be communicated to the sink. Other services provided by the application layer include methods to query sensors, interest and data dissemination, data aggregation and fusion [2].

Clearly, each of these services must utilize the capabilities of cognitive radio sensor network while conforming to its limitations. Therefore, existing application layer protocols must be revisited with these capabilities and limitations in mind. For example, in a CRSN, solutions regulating queries must consider broadcast limitations of CRSN due to unavailability of a global common channel as discussed in Section IV.

As stated in Section III, CRSN has a wide range of application areas. However, there is no application-layer protocol developed specifically for CRSN. One of the potential areas that needs an application layer protocol is overlay, multi-class heterogeneous sensor networks described in Section III-C. In such applications, multiple kinds of sensor nodes coexist over the sensor field, each collecting data with different communication requirements. An application layer protocol that analyzes and organizes user queries in a heterogeneous network for efficient transmission is needed. Similarly, for multimedia sensor applications an open research issue is adaptive coding schemes which can employ various coding methods depending on the channel conditions and handoff rate.

On the other hand, there is a significant amount of research in the literature on data aggregation and fusion techniques for WSN [49], [50], [51], [52], [53]. Data aggregation and fusion techniques are employed to increase estimation performance at the cost of communication and computational complexity. The justification in terms of energy consumption is that computation at a node consumes almost always less energy than communication [54]. Since data aggregation and fusion reduce the number of transmissions or the transmitted packet length, these techniques help improve energy efficiency and network utilization.

However, in CRSN, transceivers of the nodes may be tuned to different channels, thus, a node cannot hear all transmitted data around it. This makes data aggregation and fusion a challenging task. New aggregation and fusion techniques which address CRSN limitations and take advantage of its additional capabilities must be investigated. Cooperative schemes, which let the node with aggregated data to use the best available channel, are example of such mechanisms taking advantage of CRSN capabilities.

Another open research issue is developing schemes to perform sampling of the event signal and to gather sensing data based on spectrum availability. If sensing results are sent to the sink periodically, mechanisms to schedule sampling and sensing based on spectrum availability must be investigated. If sensing data is sent based on queries from the sink, new query methods which take spectrum availability into account must be developed.

For task-based applications and distributed data processing applications, work load on nodes can be distributed based on channel conditions of the nodes. The nodes with better channel availability can send and receive more data in a more reliable manner. Thus, these nodes can be assigned more tasks. In addition priorities may be assigned to the nodes based on their tasks and spectrum availability to achieve fairness enabling nodes with less channel availability to access better channels.

VI. CONCLUSIONS

Cognitive radio increases spectrum utilization and communication quality with opportunistic spectrum access capability and adaptability to the channel conditions. These salient features can also be exploited in resource-constrained sensor networks. Moreover, multiple channel availability provided by cognitive radio capabilities can be used to overcome the problems caused by the dense deployment and bursty communication nature of sensor networks. In this paper, we investigated cognitive radio sensor networks; a new sensor networking paradigm formed by adopting cognitive radio capabilities in wireless sensor networks. We discussed advantages and limitations of CRSN and explored the applicability of the existing networking solutions for cognitive radio and sensor networks in CRSN along with their shortcomings. Even though cognitive radio and wireless sensor networks have individually been studied extensively, there exist significant challenges for the realization of CRSN. We anticipate that this paper will provide better understanding of the potentials for CRSN and motivate research community to further explore this promising paradigm.

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