Energy Efficient Cooperative Spectrum Sensing in Cognitive Radio Sensor Network Using FPGA: a Survey

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Abstract—**Cognitive Radio Sensor Network (CRSN) is a network of deployed wireless sensor nodes integrated with Cognitive Radio (CR) capability. It is a most promising technology to resolve spectrum scarcity resources, coexistence with another network in ISM band, and prolonging the lifetime in Wireless Sensor Networks (WSN). One of the major challenges in CRSN is the energy consumption due to the inherited limited energy from its traditional WSN. Cooperative Spectrum Sensing (CSS) is utilized used to improve the sensing performance in multipath fading, shadowing and receiver uncertainty. In this paper, we present the basic difference between the conventional WSN and the CRSN, a comprehensive overview of non-cooperative spectrum sensing methods and state-of-the-art research of EE in CRSN. Furthermore, we introduce the most commonly utilized platforms and the appropriate tools in CR field.**

I. INTRODUCTION

As a result of the global growth in wireless services and the need for higher data rates, an enormous increase in energy consumption in communications has been recently reported, which has a considerable environmental effect. Energy resources, energy consumption, and the spectrum scarcity are serious challenges from the wireless view that have recently attracted a plenty of research interest [1]. An innovative technique like CR is considered to be a solution for the spectrum scarcity and green communication [2], [3]. It permits the unlicensed user (secondary user (SU) or cognitive user (CU)) to opportunistically exploit temporally and spatially unused licensed spectrum of the primary user (PU) without interfering with it [4]. CR is a development of the software defined radio (SDR) which is characterized by the following tasks [5]:

- Multiband Operation.
- Multistandard support.
- Multiservice support.
- Multichannel support.

CR is a single device that can adapt in the middle of a communication session with radios of different technologies when necessary [6] and performs the cognitive cycle with four steps as illustrated in Fig. 1 [7].

- Spectrum sensing: The first step in this cycle, SU monitors the available spectrum and detects the spectrum holes (temporarily unused spectrum).
- Spectrum analysis: It utilizes the information obtained from the first step to understand the characteristics of the spectrum holes.
- Decision: Then, appropriate spectrum band will be chosen according to the spectrum characteristics and the user requirement.
- Action: Finally, it enables the radio to be dynamically programmed.

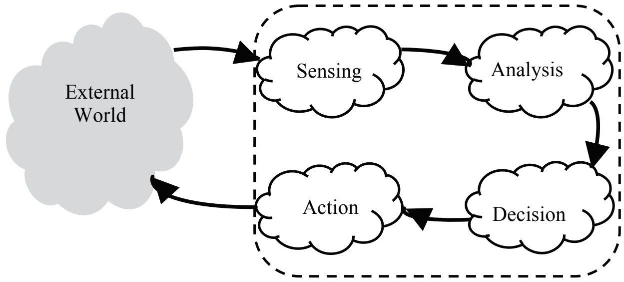

Fig. 1. Cognitive radio cycle

In contrast, WSN has triggered a significant amount of research for several decades. Its application domain has dispersed beyond the military field to the commercial field in areas such as in building or home automation, lighting control, energy management, to name just a few. In general, it can be defined as a distributed network comprising a large number of nodes deployed throughout the sensor field. It operates in the industrial scientific medical (ISM) band as an unlicensed band with limited battery energy. Its short lifetime and spectrum scarcity coinciding with the coexistence of different networks such as WiFi and Bluetooth have become an obstacle preventing the evolution of WSN [8]. In order to overcome these limitations, CR technology has been added to the traditional WSN in two approaches, either sensor network assisted CR network which is called SENDORA (Sensor Network for Dynamic and cOgnitive Radio Access) [9] or

CRSN [10]. In the first proposed approach, the information on spectrum occupancy is provided with a separate sensor network through a single sink and multi-hops to the CR network. In the other approach, where the traditional wireless sensor nodes are equipped with the CR technology.

The realization of CRSN relies on processing difficult challenges which are introduced by the individual features of both CR and WSN and the combining between them lead to exacerbate the issue. Usually, spectrum sensing is a crucial step in CR network, because all the next steps depend on its result. Many spectrum sensing techniques available in the literature. One of those techniques is the energy detection technique that has gained more interest because of the low computational and implementation complexity. In addition, it does not require any prior information about PU [11]. However, in multipath fading, shadowing and the hidden node problem, it suffers from unreliable estimation. To this end, CSS uses the spatial diversity in monitoring of spatially isolated of SU's nodes can be used to dramatically improve the sensing performance [12]. Admittedly, CSS technique has been demonstrated as a good candidate for improving the detection sensitivity in CRN [13]. However, when CSS is used, more energy will be consumed in local sensing and reporting the result as compared to the single SU case, especially in wireless sensor nodes, which are characterized by its limited energy.

Hence, the main challenges in CRSN are the energy efficient communications to extend the lifetime of the network and protect the PU from the prohibited interference [14]. In the literature, different metrics in CSS have been used to assess its performance, such as detection accuracy, energy consumption, and achievable throughput, as illustrated below [15]:

A collection of the detection probability (P_d) and the false-alarm probability (P_{fa}) performs the detection accuracy. P_d is defined as the probability of deciding the licensed spectrum is busy, while P_{fa} is defined as the probability of deciding the idle spectrum is busy [16]. Certainly, the detection accuracy is calculated through the probability of error that is defined as the aggregating of the false alarm and miss detection probabilities.

Then, the consumed energy in CSS is related to the average energy consumed through the local sensing, results' reporting and data transmission by all the CUs in CSS. It is a function of the cooperating CUs numbers, the sensing time and the detection accuracy.

The achievable throughput is defined as the average quantity of the successfully forwarded data by the slated CU. It deserves mentioning that it is directly impacted by the detection accuracy. Finally, EE is represented by the average successfully transmitted data normalized by the energy consumption and it combines all the aforementioned performance metrics. Therefore, the EE has been agreed as an overall metric and essential indicator for a good quality in cognitive transmission [17]. A significant amount of literature published on CRN and CRSN topics has been concentrated on the theoretical and simulation results, such as [51], [59], and [63], with a few works done on implementing those results. Accordingly, it is necessary to speed up the research and the evolution of CR technologies from simulation to practical implementations. Thus far, there has been a lack in implementing a CRN platform to meet the demand of wireless engineers and researchers in implementing algorithms, protocols, real-time elucidation of CR and CRSN concepts, progression, and validation of networking results for future research.

According to standard digital hardware (HW) options, three features: namely flexibility, performance and power consumption must be taken into account in designing a CRN platform. Obviously, Field Programmable Gate array (FPGA) is characterized by such features and it is favored to be used in implementing the CR due to:

- Flexibility: reconfigures itself in order to suit user demand.
- Performance: It has a high degree of parallelism i.e. all used logic blocks execute at the same time, rather than sequentially.
- Power consumption: it has less power dissipation than the digital signal processors.

On the other hand, FPGA faces challenge in energy consumption, especially when low power is required simultaneously with real-time [18], [19].

By using the appropriate methodology in the design flow, many problems could be obviated. Therefore, it is indispensable to employ tools that provide a good design methodology and supply convenient assessments of project performance, cost and design shutting early in the design stage.

For this reason, researchers are seeking tools that can offer quickened design productivity with a significant degree of reliability [20]. One of these tools is High-Level Synthesis (HLS) tool ready for FPGA. It generates a register transfer level RTL code from a function written in high-level languages such as C, C++, or Matlab. HLS with FPGA make a perfect productivity improvement for fast modeling and a quick time to market [21], [22].

II. Spectrum sensing in CRSN

In generally, spectrum sensing, namely spectrum holes' detection is considered as one of the significant techniques in CRSN. The basic difference between CRSN and the traditional WSN is the sensing as depicted in Fig.2 and Fig.3 [23].

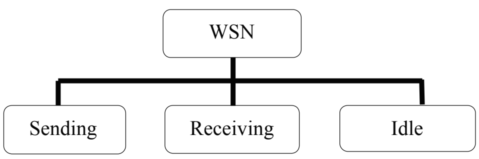

Fig.2. States in WSN

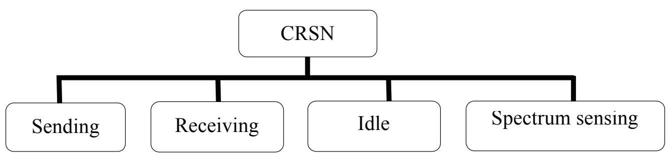

Fig.3. States in CRSN

Spectrum sensing technique is classified into (a) non-cooperative (or signal processing technique) (b) cooperative spectrum sensing. Non-cooperative spectrum sensing technique can be divided further into matched filter, energy detector, cyclostationary feature detector and interference temperature. Similarly, cooperative spectrum sensing can be divided further into two different parts as following: centralized and distributed spectrum sensing [24]. As an illustration, Table I. gives an overview of non-cooperative spectrum sensing.

While in CSS, SUs collaborate to perform the sensing, each node individually performs sensing by using one of the aforementioned signal processing techniques and reports local sensing results, which are processed to make a final decision about the spectrum occupancy [33], [48], and [49]. CSS in CRN is different from the CSS in CRSN because the latter is required a good detection performance and a considered EE within[50].

TABLE I. AN OVERVIEW FOR NON-COOPERATIVE TECHNIQUE

Type	Description	Advantages	Limitation	Field of application	Relevant Ref.
Matched filter	By convolving the unknown signal with a conjugated time-reversed version of the template. It is a coherent detection.	Short time detection. Robustness to noise uncertainty. Moderate computational complexity.	High computational complexity and consume large power.	Perfect Knowledge of PU needed.	[11], [24], [25], [26], [27], [28].
Energy detector	Treats the primary signal as noise and decides on the presence or absence of the primary signal based on the energy of the observed signal.	Simple, low computational and implementation complexity.	Cannot differentiate a primary user from the other signal source, poor performance in low SNR, cannot be used in spread spectrum signals and requires long detection time.	Does not require prior knowledge of PU signal.	[29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39].
Cyclostationary feature detector	Exploits the periodicity in the received PU signal to identify the presence of it.	Better performance even in low SNR.	High implementation complexity and higher accuracy requires a longer length of known sequences that result in low spectrum efficiency.	Requires prior Knowledge of PU signal.	[40], [41], [42], [43], [44].
Interference temperature	Concentrates on measuring interference at the receiver.	Wide range.	High implementation complexity.	Requires prior information of PU location.	[45], [46], [47].

III. ENERGY EFFICIENCY OF CSS IN CRSN

Undoubtedly, EE is an essential requirement in CRSN to prolong the network lifetime and perform high sensing accuracy as in [50], [51]. There are several approaches targeting at enhancing the EE in CRSN have been presented in the literature. In this section, we review these approaches. Based on the CSS stages, which are targeted at the optimization. For instance, they can be categorized as following: EE approaches for local sensing stage, EE approaches for the reporting stage and EE approaches for the decision-making stage as illustrated in Fig. 4.

A. Energy efficient approaches for the local sensing

During the local sensing, the energy consumed is equal to the product of CRs' number, the sensing time and the power, which is consumed in this stage. Correspondingly, decreasing energy consumption in this stage can be achieved by two different methods; either reducing the CRs' number or by shortening the sensing time.

1) User selection

This is dependent on the fact that decreasing the number of the sensing users leads to a decreasing in all the following stages and the optimal number of sensors in CSS that satisfy the constraints in detection performance lead to saving energy.

In [51], Energy Efficient Sensor Selection (EESS) algorithm is proposed where the CUs are divided into subsets such that only the subset that has the lowest cost function (demonstrated by the network's energy consumption) and satisfies the desired detection accuracy (two constraints on detection and false alarm probabilities) is chosen. The algorithm is solved using convex optimization method and compared with various algorithms such as RSSA (Random Sensor Selection Algorithm), MEA (Minimum Energy Algorithm) and MDPA (Maximum Detection Probability algorithm). Only the OR fusion rule is used in this algorithm. The sensing channel (the channel between the sensor and the PU) considers the effects of fading and shadowing but the reporting channel (the channel between the sensor and the fusion center) is an ideal channel, unlike the real situation. The achievable throughput is not considered by the authors.

In [52], an algorithm is presented based on preventing the CUs that have high correlated spectrum sensing outcomes. The proposed algorithm is supposed that each CU has the ability to overhear the sensing outcomes of other CUs. Thus, when each CU calculates its correlation within a passable range, it will take part in the sensing stage. Otherwise, the corresponding CU will not take part. Besides its additional complication, the ability to overhear the sensing outcomes of other CUs is always impossible.

Another approach of choosing the sensing CUs but jointed with modulation constellation size is presented in [53]. The authors concerned on the total energy consumption of the sensors in the CRSN which comprises the sensing energy and the transmitting energy. The latter has two components: the first component is the transmitter electronics energy and the other is the energy spent for the amplification required to satisfy the receiver sensitivity level. The amplification energy has been formulated as a function of the constellation size and the transmission distance. The proposed algorithm is built based on multiple antennae for sensing and the equal gain combining (EGC) technique. They are assumed various transmission distances and for each distance, optimal constellation size is selected to minimize the energy consumption. Although the simulation results of this algorithm show a good energy reduction, it does not discuss the EE of the network.

2) Sensing Time

In a bid to boost the EE of CRSN, the authors in [54] used a Markov model in order to find an optimal sensing time interval and describe the state change of channel. Then, the energy-efficient problem was formulated as that of guessing the state of the Markov model. Lastly, using Markov model-based state prediction, they derived thresholds on the spectrum sensing time interval for the action policy, which specifies the optimum action to accomplish minimum energy consumption. Two cases of energy consumption for the SUs have been assumed: without spectrum sensing (the SUs transmit data with enough spectrum resource (namely, ISM frequency) so there is no need to sense) and with spectrum sensing. This means that SUs have not enough spectrum resource so that they need to sense licensed spectrum to transmit data. In simulation results, it has a big drawback that they have compared their results with another reference's results that deals with CRN and not CRSN.

In [55], optimizing the sensing time is presented in proposed algorithm by using SLC (Square Law Combining) technique and the probability of detection and false alarm constraints to optimize sensing time and reduce energy consumption. The results demonstrate an improvement of 17.6%, 16.6%, 15.7% and 13.6% in the cognitive network comprising of 2, 8, 4 and 6 users respectively at -5dB average received SNR (signal to noise ratio). It is worth mentioning that the attention in this paper has been focused on the energy consumption not on the EE.

B. Energy efficient approaches for the result's reporting stage

As usual, the result's reporting stage is the second stage in CSS, where SUs transmit their local sensing results to the FC. The energy consumption to transmit the local result in a sensor node is higher than the consumed energy in the sensing stage [56]. Several works have studied techniques to reduce the energy consumption during reporting the results.

1) Censoring

Censoring is a promising approach that can significantly reduce the reporting SUs. In this approach, a CU does not report its sensing outcome unless it lies outside a specific area [57], [58]. Optimizing the censoring thresholds to shorten the energy consumption with constraints on the detection accuracy has been introduced in [59]. Two setups for the availability of the prior information about the probability of spectrum occupancy are taken into account, specifically, blind setup and knowledge aided setup. In contrast, considering the EE maximization as a targeted problem instead of energy consumption minimization is more effective.

Another approach of censoring with double threshold has been evaluated in [60], [61], and [62] by using only hard decision in the former and the hard and soft decision in the latter under Rayleigh faded sensing and reporting channels. Two types of censoring such as rank-based and threshold-based are considered to choose the CU based on the quality of the R-channel. They found that the censoring threshold has significant effect on average missed detection performance and relying on the channel and network parameters, an optimal censoring threshold is existed, which is yielded minimum average missed detection probability. The analytical and simulation results do not discuss the performance of their proposed method in terms of EE. In [63], censoring and truncated sequential sensing are integrated to minimize the energy consumption in CSS in CRSN. In detail, the spectrum is sequentially sensed, and after the accumulated energy of the sensed samples lies outside a certain part, the sensing is stopped and a binary decision is transmitted to the FC. If the sequential sensing process carries on until a timeout, censoring is applied and no decision is transmitted. The thresholds of the censoring part are optimized in order to minimize the maximum energy consumption per CU undergo to a constraint on the detection accuracy. AND and OR rules are utilized as fusion rules rather than considering the general *K-out-of-N* FR. No systematic solution for the censored sequential problem formulation has been investigated to solve the problem. Moreover, no collection of their proposed scheme with sleeping as in [59], in order to produce more energy saving.

As well as, a combination of censoring scheme and sleeping schedule in CRSN to achieve energy efficient for CSS has been considered in [64] by using a fast-multi-objective differential evolution algorithm. Simulation results

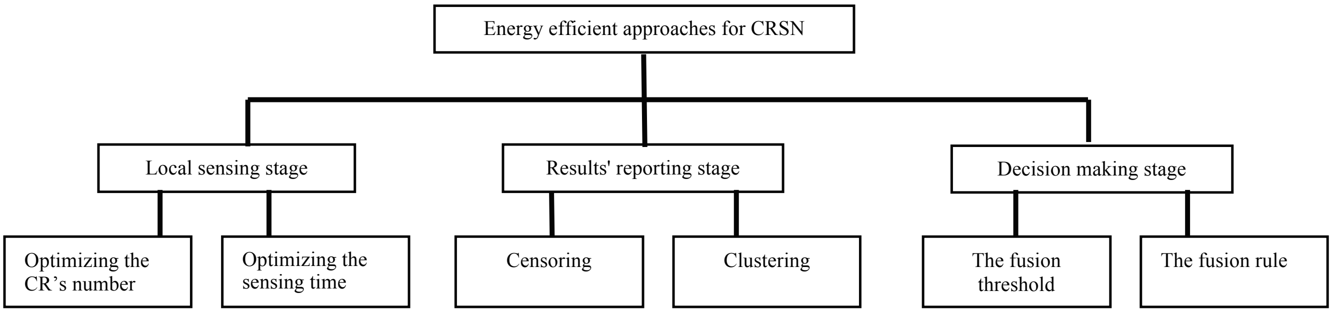

Fig. 4. Classification of energy efficient approaches in CRSN

of the proposed algorithm show that it not only can reduce the average node's energy consumption, but also can improve the global probability of spectrum sensing. A comparison has been presented with widely used multi-objective evolutionary algorithms such as Differential evolution (DE), nondominated sorting genetic (NSGA-II) and opposite-based differential evolution (ODE) to demonstrate that the performance of the proposed algorithm is better than the other algorithms. The authors did not consider the fading and shadowing in their algorithm.

2) Clustering

Clustering approach is considered as an effective method in CSS to address the performance deterioration in spectrum sensing due to fading and shadowing of reporting channel, and also to decrease the control channel overhead when the cooperative users' number becomes huge [65]. In clustering, CUs are splitted into groups based on that, all the nodes must exist in the transmission range of the others, in addition to share a common communication channel among them. In addition, one from each cluster is elected as a cluster-head, who is responsible for collecting sensing results from the cluster-members and reporting a cluster-decision to the FC. Although WSN's clustering algorithms primarily focus on routing and energy consumption issues, they may not be suitable for CRSN due to the dynamic nature of the channels. This necessitates the need for a clustering algorithm that will address both energy issues and spectrum holes' detection issues in CRSN.

In [66], Spectrum Aware clustering algorithm based on Reinforcement Learning to enhance spectrum holes' detection and minimize network energy consumption in CRSN has been suggested to achieve EE. The main objective of the proposed algorithm is to achieve an optimal policy for selecting optimal cluster or clusterhead that satisfies the pairwise constraint conditions, minimizes cooperative channel sensing energy consumption and data communication energy consumption while enhancing spectrum holes' detection. The simulation results imply that, compared with groupwise constraint-based algorithm, the introduced approach has better performance in terms of the energy consumption about 9%, computational complexity and sensing performance. In [67], a pairing among sensor nodes and switches between Awake and Sleep modes in clustering is proposed and a developed algorithm for configuring Awake and Sleep modes for coupled nodes in their scheme has been presented. The authors consider their result has significant improvement as compared with distributed energy-efficient clustering (DEEC) protocol that is used with WSN and not with CRSN.

Even though clustering shortens the reported information to the FC, it generates further energy consumption during results interchanging inside the cluster itself. Furthermore, creating clustering is a sophisticated process that adds extra complexity to the CRNs, particularly in mobile CUs scenario [17].

C. Decision making

Unquestionably, every CSS ends by making a global decision about the spectrum occupancy. The global decision is made by addressing the received local results/decisions with certain fusion rule (FR) in the FC. Despite the configuration of the received results, a predefined fusion threshold is required to make a decision.

In [68], implicit-OR (I-OR) and implicit-AND (I-AND) aggregation rules in CRSN are introduced, by using randomized channel sensing, implicit cooperation and simplified aggregation. The proposed schemes are built to reduce energy consumption. The results demonstrate saving more than half the consumed energy and reducing the required abilities of the aggregating node to be as easy as any normal node because the low complication of implicit collecting. Thus, I-OR is favoured at low Primary Network (PN) because of its good miss-detection performance. On the other hand, at high PU activity above 60%, I-AND is further saving energy.

In [69], a soft-hard combination scheme, called SHC scheme, for cooperative spectrum sensing in CRNs has been proposed. In this scheme, a cluster based network has been spread in which Likelihood Ratio Test (LRT)-based soft combination (SC) is applied at each cluster, and weighted decision fusion rule-based hard combination (HC) is used at FC. By the scheme's structure, the complexity of cooperative detection, which is an inherent restriction of SC schemes, is reduced. In this paper, effects of large scale fading on different users in the wide area network is considered. The simulation results show that the SHC scheme can achieve better sensing performance compared to the conventional HC schemes by using the weighted decision fusion rule since the fusion center can distinguish the corresponding contributions of different cluster heads, while the SHC scheme requires a long period of reporting time than the traditional HC schemes. The proposed scheme does not discuss the consumed energy and its effect on EE.

TABLE II. EE APPROACHES IN CRSN

Ref. No.	Constraints	Fading and shadowing sensing channel	Reporting channel type	Utilized Energy metric
[51]	Detection probability	Yes	Noiseless	Energy in joule
[52]	False alarm probability	AWGN with log-normal shadowing.	Noiseless	Energy in joule
[53]	Detection probability, false alarm probability and constellation size	Yes	Free space path loss model	Energy consumption ratio.
[54]	Sensing time interval	No	No	Energy efficiency(bits/J)
[55]	Probability of detection and probability of false alarm	AWGN channel	AWGN	Energy consumption in Joule
[59]	Probability of detection and probability of false alarm	No	Free space path loss model	Energy in Joule
[60]	No	Faded channel	Faded channel	No. of users
[62]	No	Faded channel	Faded channel	No. of users
[63]	Probability of detection and probability of false alarm	Faded channel	No	Average energy consumption
[64]	Sleeping rate, censoring rate	No	No	Energy consumption in Joule
[65]	No	No	No	Energy consumption in Joule
[66]	No	No	No	Energy consumption in Joule
[67]	No	No	No	Network lifetime
[68]	No	Faded channel	Faded channel	Energy consumption in Joule

In summary, EE is achieved by minimizing the energy consumption that is normally joined with constraint(s) in detection probability, false alarm probability, and/or other conditions as can be seen in Table II.

IV. CR, CRN AND CRSN PLATFORMS

Due to the great role of the CR in a future radio technology which is represented by resolving the spectrum scarcity problem and the green communication problem, it is necessary to build a platform or a testbed that enable and promote this promising technology. Yet, many published literatures on CR or CRSN themes have been achieved in theoretical and simulation results with few works done on experimental reality of these results. Therefore, it is important to the researchers and academic community accelerating the research and evolution of CR and CRSN technologies from simulation only to practical applications.

Consequently, a large number of software defined radios (SDRs) and CR platforms are evolved universally to assist experimental- based-research and to fast-track the deployment of CR systems. Some of them are built on open source SDR software (SW) packages and inexpensive HW, and they are easy to use for free (SW only) [70]. According to the literatures [70], [71], some of these platforms are reviewed as follows:

1) Universal Software Radio Peripheral (USRP)

The USRP is evolved by Ettus Research [72] and is one of the most significantly used HW for CR platform evolution. It forms a motherboard and at least one daughterboard with selectable RF and most of them connected to the host computer through a link. The main calculating power on the motherboard comes from the FPGA. According to USRP's interface, it is classified to three various series: Gigabit Ethernet networked (USRP N2xx), USB bus (USRP B1xx) and Embedded (USRP E1xx) series which is designed for the application that needs stand-alone fashion. The utilization of USRPs is effortless and inexpensive. However, it has drawbacks, such as poor RF performance, narrowband operation and it bases on FPGA that is hard to upgrade or repair its fixed program.

2) eFalcon

University of Duisburg-Essen in Germany [73] developed eFalcon as a flexible HW CR platform. To process the FPGA's drawback for debugging the implemented signal processing algorithms, eFalcon's core components complies a Texas Instruments triple-core digital signal processor (DSP) (TMS320C6474 running at 1 GHz system clock) integrated with an FPGA. The DSP has 256 MB of double data rate (DDR2) random access memory (RAM) to enable the implementation of memory-intensive applications. It has multiple serial high-speed interfaces such as Gigabit Ethernet link, three full duplex OBSAI (open base station architecture initiative), usually referred to as antenna interface, and a Serial Rapid Input Output (SRIO) link. Even though, eFalcon is not widely used, it combines the advantage of both digital processors running software and programmable logic permitting enormous parallelization to ensure real-time operation.

3) Wireless open-Access Researcher Platform (WARP)

WARP is designed by the Rice University [74] as a scalable, programmable and extensible SDR platform developed. One of its goals was to realize both HW and software required for research, build and prototype high performance next-generation wireless networks. This is enabling the researchers to focus on enhancing one aspect of a wireless system without having to implement, or even understand, everything required to enable real world communications. WARP's HW is comparable to the USRP approach. The HW uses FPGAs for DSP-optimized development, where a number of FPGAs can be scaled as required by allowing additional processing resources to be allocated when the computational power of a single processor proves insufficient. It assists different packages to be developed to give functionality at four levels, such as Low-Level Support, Logic-PowerPC Support, Peripherals Support and Board-to-Board Support. In [75], Neyman-Perarson (NP) criteria based energy detection spectrum sensing algorithm in CR has been implemented using WARP platform.

4) Berkeley Emulation Engine (BEE2)

University of California at Berkeley Wireless Research Center developed BEE2, which assists up to 500 Giga-operations per second by dividing the load among its multiple FPGAs. It supplies a unique multiuser environment, much like that in a traditional PC cluster, where many users can share a common pool of computing resources with ensured computational throughput [76]. The BEE2 HW is absolutely built out of commercial common-off-the-shelf (COTS) components. It is a demonstrator and not a mass production machine. Thus, this platform is not available for sale.

In [77], Authors' platform is built at Tennessee Technological University as a CRN testbed and differs from the aforementioned platforms. It overcomes the shortcomings of the existing hardware platforms in power computing, time delay and prices. The proposed architecture of motherboard for one node in CRN comprises two FPGAs, i.e., a Xilinx Virtex-6 LX FPGA and a Xilinx Virtex-5 FX FPGA, that are utilized as core components on the motherboard with low latency connection. The proposed motherboard is able to supply sufficient and upgradable computing resources for nodes of CRN testbed. The FPGAs' time delay is uninfluential. This motherboard is connected with one or two RF board either reused from USRP or WARP or customized board. Multiple nodes form a CRN which are linked using Gigabit Ethernet to one or more console computers via one or more Ethernet switches. The proposed testbed can be utilized for CRN and other application like smart grid and wireless tomography.

In [78], a CR prototyping platform has been shown based on hybrid Xilinx Zynq FPGA that combine the modification of the HW level with a computational ability in the processing system by implementing the baseband in hardware and the MAC in software rather than implementing them in software as the most SDR platforms. The proposed platform merges the high-speed partial reconfiguration controller to permit radio reconfiguration of the baseband with less latency. Simulation results have been tabled in this paper for two scenarios of digital video broadcasting (DVB) cable (DVB-C) and satellite (DVB-S) standards. The results show that the resources utilization was over the half and the End-to-end latency of the Data Plane at 100 MHz was tripled faster than the normal blocking reconfiguration control.

In fact, none of the previous platform can be used to implement the CRSN nodes since most of them based on the SDR [72], [74], and [76] or on CRN [73] which are not compatible with CRSN requests. In contrast, in [79] a CRSN wireless test-bed with three various ISM band has been proposed. It comprises two elements, the first one is the cognitive New Generation Device (cNGD) which interfaced with aforementioned bands and the latter is a modified Castalia's structure to assist the CR in simulation because network's spreading with a high number of real devices is not easy and expensive.

V. High level synthesis (HLS) tools

It is an essential phase in the designing of the electronic circuit since it generates RTL code from a high-level language as mentioned earlier. It demonstrates great benefits such as reducing the time consuming in rewriting the RTL code, making the design productivity better, and the generated design has less amount of error as compared with the handcraft RTL code [80]. It has opened the floodgates for an enormous amount of software engineer, who need expertise in hardware design, to effectively contribute in the process of hardware system architecting and synthesizing side by side with their FPGA counterpart. At the same time, it enables the hardware engineers to explore the design space quickly and more realistically. It is crucial in the designing especially for FPGA design, where different applications can be readily produced, spread on the objective architecture and estimated the similarity or the difference between them.

Generally, many HLS tools has been presented, but in this survey, we specifically review the widely known in the CR field namely Xilinx System Generator (XSG) and Synphony model compiler(SMC) as explained below:

- **Xilinx System Generator (XSG)** is one of the HLS tool that facilitates FPGA hardware design. It uses Matlab's Simulink as a graphical programming environment [81]. Hardware co-simulation of Xilinx system generator in Xilinx Virtex2pro XC2VP30 (FFG896-7) FPGA has been utilized in both works [82], [83], in the first work, a 7-node of CSS technique is implemented by using AND, OR as a hard decision and equal gain combining (EGC) as a soft decision in the fusion center. The local sensing is accomplished in each node by energy detection technique for a primary signal as a DVB-T signal with 16,32,64 sample size under AWGN channel and Rayleigh fading channel which is entered from the Matlab workspace. The implementation results show that there are increasing in the resource utilization as the number of nodes in CSS increased and the changing in the operating frequency is neglected as compared with considerable improvement in probability of detection. While in the latter work, aforementioned FPGA with Xilinx system generator has been used to perform the energy detector spectrum sensing technique for different modulation types of a primary signal characterized by different sample size under AWGN and Rayleigh fading channel. According to those results, obviously, the estimated resource architecture needs 1641 slices, 3233 flip flops, 1681 LUTs, 817 IOBs and 64 embedded multipliers for 64 sample size data, and as the sample size increases the operation frequency decreases. In [84], orthogonal frequency division multiplexing (OFDM) cognitive radio transmitter is implemented in FPGA vertex-5 device XC5VLX50 using Xilinx system generator.

- **Synphony Model Compiler tool (SMC**) [85], [86] is Another HLS tool that is placed inside the Matlab's Simulink environment [87]. Energy detection spectrum sensing technique for a generated DVB-T primary signal in various samples observation's number under a modeled FPGA of AWGN and Rayleigh fading environment has been executed by using SMC tool in Stratix II EP2S180 FPGA board. The results demonstrate that the consumed resources in system synthesis are completely less than 20% and 2% of the hardware resource is used to accomplish the energy detector. In [88], SU of Selection Combining (SC) and EGC reception diversity techniques under Rayleigh fading channel with 2 and 3 antennas has been implemented in FPGA testbed using SMC tool. The implemented results show that the used hardware resources are around 40% and the detection probability is improved when applying the diversity techniques in low SNR.

VI. CONCLUSION

The realization of energy efficient communication in CRSN by optimizing the CSS stages is an effective method so as to extend the lifetime of this network and prevent the PU from the unlawful interference. Additionally, the designing of an efficient CRSN platform is important to meet the demand of the researchers in implementing a real-time demonstration of CRSN concepts, algorithms, protocols, development and establishment of the networking results for future studies.

In this survey, an overview of the non-cooperative technique is presented, EE approaches in CRSN based on the CSS stages and show a summary of the constraint (s) that should be considered in the EE approaches with the utilized energy metrics. Also, a general review of some platforms that are used to implement CRN and CRSN. Furthermore, a demonstration of the HLS benefits in designing the electronic circuit is introduced and a reviewing of the most common HLS tools which are used in CR field. This paper may be used as a starting point for the future studies that deals with a practical implementation of EE especially for the software engineers who combine between the simulation and the practical implementation.

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