Multidisciplinary : Rapid Review : Open Access Journal

Digital Object Identifier

Spectrum Assignment in Hardware-constrained Cognitive Radio IoT Networks under Varying Channel-quality Conditions

HAYTHEM BANY SALAMEH[1], (Senior, IEEE), SAHAM AL-MASRI[1], ELHADJ BENKHELIFA[2]. JAIME LLORET [3], (Senior, IEEE)

[1]Yarmouk university, Irbid, Jordan (e-mail: haythem@yu.edu.jo, saham@yu.edu.jo)
[2]Staffordshire University, UK (e-mail: E.Benkhelifa@staffs.ac.uk)
[3]Universitat Politecnica de Valencia, Spain (e-mail: jlloret@dcom.upv.es)

ABSTRACT The integration of cognitive radio (CR) technology with future Internet-of-Things (IoT) architectures is expected to allow effective massive IoT deployment by providing huge spectrum opportunities to IoT devices. Several communication protocols have been proposed for CR networks while ignoring the adjacent channel interference (ACI) problem by assuming sharp filters at the transmit and receive chains of each CR device. However, in practice, such an assumption is not feasible for low-cost hardware-constrained CR-capable IoT (CR-IoT) devices. Specifically, when large number of CR-IoT devices are operating in the same vicinity, guardband channels (GBs) are needed to mitigate the ACI problem. Introducing GB constraint spectrum efficiency and protocol design. In this paper, we develop a channel assignment mechanism for hardware-constrained CR-IoT networks under time-varying channel conditions with GB-awareness. The objective of our assignment is to serve the largest possible number of CR-IoT devices by assigning the least number of idle channels to each device subject to rate demand and interference constraints. The proposed channel assignment in this paper is conducted on a per-block basis for the contending CR-IoT devices while considering the time-varying channel conditions for each CRIoT transmission over each idle channel such that spectrum efficiency is improved. Specifically, our channel assignment problem is formulated as a binary linear programming (BLP) problem, which is NP hard. Thus, we propose a polynomial-time solution using a sequential fixing algorithm that achieves a suboptimal solution. Simulation results demonstrate that our proposed assignment provides significant increase in the number of served IoT devices over existing assignment mechanisms.

INDEX TERMS Cognitive Radio, Guard-band, Variable Rate, Adjacent-channel Interference, Binary Linear Programing.

I. INTRODUCTION

Internet-of-things (IoT) is the key future networking paradigm that defines the interconnection and interaction of any device (thing) that can connect to the Internet and be able to communicate with other devices and networks. Many of the IoT devices are mobile, small and located in scattered locations. Hence, wireless networking is represented as the most appropriate communication paradigm that effectively connects these devices with each other and other networks [1]–[9]. However, enabling massive wireless-based IoT deployment is expected to place a massive pressure on wireless spectrum resources. To meet the high spectrum demand of the huge number of IoT wireless devices, cognitive radio (CR) technology has been proposed [10]–[19]. CR technology allows the unlicensed CR-capable IoT (CR-IoT) devices to dynamically and opportunistically utilize the licensed portion of spectrum while providing performance guarantees to legacy primary radio users (PUs) [20]–[23].

The main intelligence feature of CR-IoT networks is the ability to alleviate spectrum scarcity by conducting efficient channel assignment decisions. This intelligence in spectrum management and assignment were well studied in the context of CR networks (CRNs) assuming very sharp filters on the transmit and receive chains of each CR device [24],

[25]. However, low-cost IoT CR-enabled devices may not be equipped with such sharp (near ideal) transmit/receive filters, so existing spectrum assignment for CRNs are not directly applicable to CR-IoT networks. Specifically, most of existing channel assignment designs for CRNs [24], [25] did not consider the harmful interference introduced to PUs and ongoing CRs due to the adjacent channel interference (ACI) issue. ACI is known as the power leakage to adjacent channels due to imperfect transmit/receive filters in communicating devices [26], [27]. Limited number of CRN protocols have dealt with the ACI problem in their design by adding GB channels between adjacent channels that are assigned to different CR links (e.g., [28]–[32], [34]–[36]). These protocols have been designed without considering the multi-channel diversity and interference heterogeneity in CRNs by assuming that each channel can support a fixed average-data rate. Such assumption is limited to wireless networks that implement sophisticated power-control strategies to achieve such fixed data rate per idle frequency channel. This can significantly limit the achieved rate per channel as distinct idle channels can support different data rates depending on the time-varying link-quality and interference conditions over each idle channel. Assuming that each idle channel can support a fixed average data rate greatly simplifies the channel assignment design, but can significantly degrade network performance by wasting available spectrum opportunities through unnecessary assigning more channels for CR-IoT devices [21]. Hence, new GB-aware spectrum sharing algorithms for CR-IoT networks that effectively utilize the available spectrum while accounting for the hardware-limitation of the IoT devices and the frequencies/time-varying nature of the channel quantities of CR-IoT links are needed.

This paper proposes an adaptive GB-aware spectrum assignment scheme for hardware-constrained CR-IoT networks under time-varying channel-quality conditions. The proposed scheme conducts the channel assignment on a per-block basis for a given CR-IoT transmission while considering the time-varying channel conditions over each idle channel between the communicating devices such that spectrum efficiency is improved. Specifically, the channel assignment problem is formulated as an optimization problem that attempts at minimizing the total number of reserved data-plus-GB channels (maximizing spectrum efficiency) subject to aggregate rate demand, channel-quality and maximum allowable transmit power constrains. The formulation constitutes a binary-linear programming (BLP) problem, which is known as NP-hard. Thus, we propose a polynomial-time algorithm that achieves a sub-optimal solution using a sequential-fixing algorithm. It is worth mentioning that performing channel assignment for multiple CR-IoT links at the same time (batch approach) can provide better performance than performing the assignment sequentially (i.e., one CR-IoT link at a time). For a single collision domain (all devices can hear each other), the batch method is practical. However, the batch approach is not practical in a multi-hop CR-IoT environment, as it incurs high control overhead and delay. Therefore, in this paper, our design follows an asynchronous Carrier Sense Multiple Acces with Collision Avoidance (CSMA/CA)-like random access strategy, that ensure only one link (a transmitter-receiver CR-IoT pair) can access the control channel at any given time. Simulation results are demonstrated to demonstrate the effectiveness of the proposed channel assignment scheme compared to previously proposed assignment schemes (i.e., [29], [32]).

The rest of this paper is organized as follows. Section II reviews the related work. In Section III, we present the network model. Then, the problem statement, formulation and proposed solution of the channel assignment problem are described in Section IV. In Section V, we provide the simulation results and discussions. Finally, the conclusion remarks are given in Section VI.

II. RELATED WORK

Several studies have been conducted to design spectrum access protocols that address the unique features of CR environment assuming very sharp filters on the transmit and receive chains of each CR device (ignoring the ACI issue) [24], [25]. Very few CRN protocols have been proposed to deal with the ACI issue (e.g., [29], [31], [32], [35]). In [29], the authors investigated the ACI with the objective of finding the best channel assignment that results in minimum number of newly introduced GBs. They considered both channel bonding and aggregation with per-link channel assignment. However, they did not consider the multi-channel diversity by assuming a fixed data-rate per idle channel. In [31], [35], the authors proposed a batch-based GB-aware spectrum assignment for CRNs. It considers batching, in which multiple assignment decisions can be made simultaneously. In [32], the authors proposed a GB-aware per-block channel assignment algorithm for a multi-channel single-link CRNs with average fixed transmission rate per channel. Unlike the works in [29], [31], [35] that perform the channel assignment on a per-channel basis, the proposed scheme in [32] selects channels on a per-block basis, where at most one GB channel will be added on each side of a block for each CR transmission. The authors showed that the channel selection based on per-block basis provides better network performance compared to the per-channel assignment. In summary, most spectrum access protocols for CRNs were designed assuming ideal (or very sharp) transmit/receive filters and fixed data-rate per channel. Such designs are not suitable for low-cost hardware-constrained CR-IoT networks operating over heterogeneous time-varying wireless channels. Therefore, new communication protocols for CR-IoT networks are needed that account for the ACI issue and the time-varying nature of channel conditions. To the best of our knowledge, this is the first work that considers assigning channels to CR-IoT devices in a per-block basis while accounting for the ACI issue and the time-varying nature of channel conditions between communicating devices.

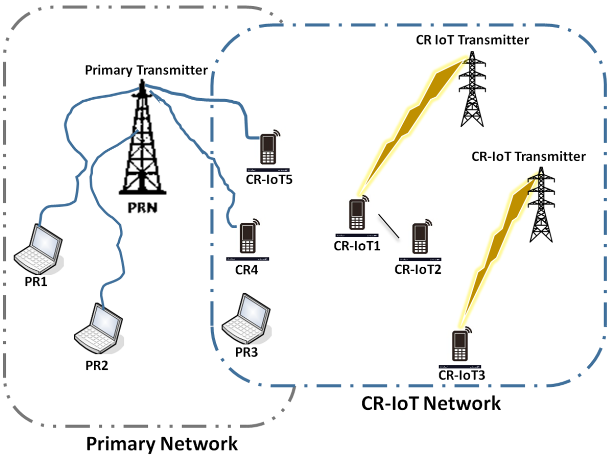
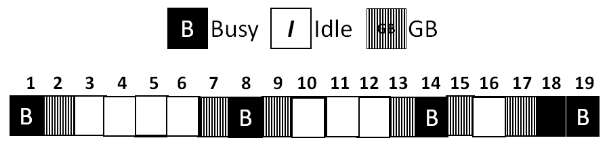


FIGURE 1. An illustration of PU and CR-IoT networks coexistence.

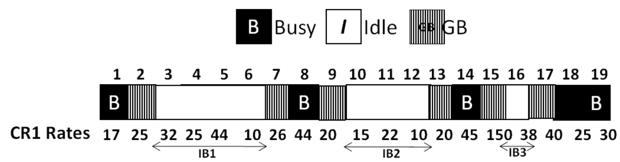
III. NETWORK MODEL

We consider a CSMA/CA-based wireless CR-capable IoT network that coexists geographically with several PU networks as shown in Figure 1 (e.g., the CR-IoT network can be a wireless sensor network that is deployed for monitoring hazard environment as illustrated in [**?**]). The PUs are licensed to transmit over a set of orthogonal non-overlapping channels. Let $\mathcal{M} = \{1, 2 \ldots M\}$ represent the set of all PU channels, where each channel has a Fourier bandwidth of W (in Hz). CR-IoT devices can persistently scan the available spectrum to identify potential spectrum opportunities (idle PU channels) in order to access them. Considering the spectrum availability status in Figure 2(a). Figure 2(b) illustrates that each set of contiguous idle channels is grouped into a"frequency block". The spectrum is divided into: (1) idle blocks, (2) busy blocks and (3) data blocks. An idle channel can be used as a GB between frequency data blocks of different CR-IoT transmissions or reserved as data channel. Note that for each identified idle block, the first and last channels in that block are reserved as GBs if their adjacent channels, which do not belong to the block, are reserved for PR users. Note that, already existing GBs can be reused by potential CR transmissions such that no additional GBs are needed. To exchange control information among CR-IoT devices, we assume the existence of a common control channel that is available to all CR-IoT devices. Such channel is pre-specified but not necessarily dedicated to the CR-IoT network. The existence of a dedicated common control channel is a characteristic of many communication protocols designed for CRNs (e.g., [5], [21], [29], [32]. We note here that other coordination mechanisms can also be used for our purposes including: (1) spread spectrum-based techniques, (2) dynamic local cluster-based techniques, or (3) frequency hopping-base techniques [37], [38].

Each idle channel k of a given CR transmission can support time-variant transmission rate of $r_t^{(k)}$ Mbps. Specifically, the transmission rate over channel k for a CR link is determined according to the maximum possible transmit power (determined by the FCC) over channel k, and the current channel state information (CSI) of that channel. Note that the transmission rate over channel k can be calculated based on the received signal-to-noise ratio (SNR) over channel k ($\mathrm{SNR}^{(\mathrm{k})}$) as $r_t^{(k)} = W\log_2(1+\mathrm{SNR}^{(\mathrm{k})})$, where W is the channel bandwidth $\frac{\mathcal{P}^{(k)}}{W\mathcal{N}_o}$, $\mathcal{N}_o$ is the thermal noise power and $\mathcal{P}^{(k)}$ denotes the received power over the kth channel depending on the transmitting power $\mathcal{P}_t^{(k)}$. The power $\mathcal{P}_t^{(k)}$ over each channel k is set to the maximum allowable transmission power. This results in achieving the maximum possible data rate over channel k. We define an idle frequency block as the set of contiguous idle channels that are grouped into one block. For each idle block i, denoted by $IB(i)$, we define $S^{(i)}$ as the size of that block. We assume that at any given time t, $|\mathcal{N}_t| = N$ different idle frequency blocks are identified depending on the PU activities, where $\mathcal{N}_t$ is the set of all idle blocks at time t. Let $R_t^{(i)} = \sum_{k\in\mathfrak{B}^{(i)}} r_t^{(k)}$ denote the supported rate of the i^{th} block ($IB(i)$), where $\mathfrak{B}^{(i)}$ represents the idle channels set belonging to block i, for $i = \{1, \ldots, N\}$. We note here that one GB channel on each side of a frequency block assigned to a CR-IoT transmission is sufficient to mitigate the ACI [34], [36], [39].



(a) Channel availability status.



(b) Idle block formation

FIGURE 2. Illustrative example of channel vs. block formation with 19 channels.

IV. PROBLEM STATEMENT, FORMULATION AND SOLUTION

A. PROBLEM STATEMENT

At a given time t, our problem statement is as follows: given a CR-IoT transmitting pair, all idle channels (idle blocks), and the supported transmission rate of each channels and each block, our main objective is to compute the optimal frequency-block assignment $\Omega_B^{(*)}$ that reserved the minimum number of idle channels subject to:

- Rate demand constraint: each CR-IoT device requires a demand rate d.
- Total transmit power constrain: for each CR-IoT transmission, the total transmission power $\sum_{i=1}^{N} \mathcal{P}_t^{(i)}$ over the selected blocks is limited to $\mathcal{P}_{\max}$, where $\mathcal{P}_{\max}$ and

$\mathcal{P}_t^{(i)}$ are the maximum power that can be supported by the CR battery and the needed transmit power over block i).
- Per-Channel individual transmit power constrain: the transmit power over each channel k is limited to the maximum permissible transmission power ($P_{\max}^{(k)}$) determined by the FCC. This constraint is ensured by setting the transmit power over each channel k to $P_{\max}^{(k)}$.

We note here the following two observations: (1) assigning channels to CR-IoT devices based on per-block basis adds at most two extra GB channels, and (2) when smaller size blocks are selected, less number of channels is reserved, which saves more channels for future potential CR-IoT devices. Based on the above observation, we conclude that using per-block assignment with the objective of selecting the minimum size blocks that serve the CR-IoT demand can result in improved network performance. We note here that our design considers both channel bonding and aggregation. Specifically, our design first bonds the adjacent idle channels into frequency blocks then it attempts to aggregate the minimum number of frequency blocks (each block contains a set of bonded channels) to serve the required demands of each CR-IoT transmission.

B. PROBLEM FORMULATIONS

To proceed in our formulation, a new $0/1$-decision variable $X^{(i)}$ is introduced as follows:

$$X^{(i)} = \begin{cases} 1, & \text{if block } i \text{ is reserved by the CR}-\text{IoT device} \\ 0, & \text{otherwise.} \end{cases} \tag{1}$$

Mathematically, our proposed assignment is written as:

$$\begin{aligned} \min_{X^{(i)},\in\{0,1\}} & \left\{\sum_{i=1}^{N} S^{(i)} \;\; X^{(i)}\right\} - \frac{R^{(i)}}{\sum_{i=1}^{N} R^{(i)}} \\ \text{s.t.} & \sum_{i=1}^{N} R^{(i)} X^{(i)} \geq d \text{ or } \sum_{i=1}^{N} R^{(i)} X^{(i)} = 0 \\ & \sum_{i=1}^{N} \mathcal{P}_t^{(i)} X^{(i)} \leq \mathcal{P}_{\max}. \end{aligned} \tag{2}$$

Recall that d is the required rate demand, $S^{(i)}$ is the size of each idle frequency block, and N is the number of idle frequency blocks. Note that the first part of the objective function attempts at minimizing the total size of the assigned blocks (reducing the number of assigned data-plus-GB channels) while the second part $\frac{R^{(i)}}{\sum_{i=1}^{N} R^{(i)}}$ ensures that for any two feasible channel assignments $\Omega_B^{(*)}(1)$ and $\Omega_B^{(*)}(2)$ with the same size $S_{\Omega_B^*(1)} = S_{\Omega_B^*(2)}$, our problem formulation selects the one that supports the higher rate. Note that, if $S\ (\Omega_B^{(*)}(1))$ $< S\ (\Omega_B^{(*)}(2))$, our formulation always selects $\Omega_B^{(*)}(1)$ over $\Omega_B^{(*)}(2)$, irrespective of the supported rate of each assignment $R^{(i)}$. To Proceed in our analysis, the either/or constraint in (2) can be expressed in more tractable form by using an auxiliary binary variable y as follows:

$$\begin{aligned} & \sum_{i=1}^{N} -R^{(i)} X^{(i)} \leq -d - \Gamma y \\ & \sum_{i=1}^{N} R^{(i)} X^{(i)} \leq -\Gamma\, y + \Gamma \end{aligned} \tag{3}$$

where Γ is a very large constant $\gg 1$ and y is given by:

$$y = \begin{cases} 0\,, & if\ \sum_{i=1}^{N} R^{(i)} X^{(i)} \geq d \\ 1\,, & if\ \sum_{i=1}^{N} R^{(i)} X^{(i)} = 0. \end{cases} \tag{4}$$

Therefore, the optimization in (2) becomes:

$$\begin{aligned} \min_{X^{(i)},y,\in\{0,1\}} & \left\{\sum_{i=1}^{N} S^{(i)} \;\; X^{(i)}\right\} - \frac{R^{(i)}}{\sum_{i=1}^{N} R^{(i)}} \\ \text{s.t.} & \sum_{i=1}^{N} -R^{(i)} X^{(i)} \leq -d - \Gamma y \\ & \sum_{i=1}^{N} R^{(i)} X^{(i)} \leq -\Gamma\, y + \Gamma \\ & \sum_{i=1}^{N} \mathcal{P}_t^{(i)} X^{(i)} \leq \mathcal{P}_{max}. \end{aligned} \tag{5}$$

The above formulation is a BLP problem that can be written in matrix form as: $\min_{\mathcal{X}} \ \{\mathrm{c}^{\mathrm{T}}\mathcal{X} :\ \mathrm{A}\mathcal{X} \geq \mathrm{b},\ \mathcal{X} \in \{0,1\}\}$, where $\mathbf{c}=\ [\,S^{(1)}\ S^{(2)} \ldots S^{(N)}\ 0]_{1\times(N+1)}$ is the objective vector, $\mathbf{b}=\ [-d\ \ \Gamma\ \ \mathcal{P}_{\max}]_{3\times 1}^{T}$ represents the right-hand-side of the design constraints, and $[\mathcal{X}\ y]$ is the vector containing all decision variables,

$$A = \begin{bmatrix} -R^{(1)} & -R^{(2)} & \ldots\ldots -R^{(N)} & \Gamma \\ R^{(1)} & R^{(2)} & \ldots\ldots R^{(N)} & \Gamma \\ \mathcal{P}_t^{(1)} & \mathcal{P}_t^{(2)} & \ldots\ldots \mathcal{P}_t^{(N)} & 0 \end{bmatrix}_{3\times(N+1)} \tag{6}$$

is the linear constraints matrix. It is worth mentioning that the BLP problems are, in general, NP-hard problems. Thus, we develop a polynomial-time suboptimal algorithm to solve our optimization in (5). This optimization can be solved using an efficient polynomial-time sequential-fixing linear programming (SFLP) procedure that was previously introduced in [27], [29] to solve BLP problems, where effective suboptimal solutions were reported. The optimization problem provides the least number of frequency blocks that satisfy the rate demand, such that if any of the assigned block is removed the demand rate constrain will be violated, which results in infeasible solution. Therefore, a post-processing phase is needed after solving the optimization in (5) to remove the extra channels from one of the assigned block such that the rate demand is still achieved. Let $\mathcal{R}_s$ be the achieved rate of the optimal assignment $\Omega_B^{(*)}$ resulting from solving (5). Given $\mathcal{R}_s > d$, channels with ($\mathcal{R}_s\ - d$) rates can be released without violating the rate demand constraint.

C. THE PROPOSED CHANNEL ASSIGNMENT SCHEME

Our proposed channel assignment algorithm consists of two phases: (1) Block Assignment Phase, where the problem in (5) is solved using the SFLP mechanism and (2) Releasing the extra channels post-processing phase. The main objective of BAP is assigning the minimum number of blocks that provides aggregate rate that is greater than the demand d while the second phase is intended to spare the extra channels.

1) The Block Assignment Phase Using SFLP

The SFLP was used in [29], [35] to tackle BLP problems in polynomial time, where a suboptimal solution was demonstrated. The SFLP is executed as follows: it first uses a linear relaxation approach that allows each binary variable to take any real value in $[0, 1]$ interval. Then, the relaxed linear programming problem can be solved in polynomial-time (thee associated block is assigned to the CR-IoT device). From all $X^{(i)}$'s of the provided solution of the relaxed problem, the one with the highest value is fixed to 1 and after that the feasibility of the problem is checked. The above process is repeated until a feasible channel assignment that achieves the rate demand is found or no feasible assignment is declared, in which all the idle blocks cannot support the rate demand.

2) Relaxing the Extra Channels Post-processing Phase

According to the post-processing phase, our algorithm determines the block with maximum size from the selected blocks for the CR transmission. Then, it starts releasing the maximum number of channels starting from the left sided GB of the block, such that the aggregate transmission rate after removing the rate of the released channels still satisfies the rate demand. In this case, one GB is added to the right of the last reserved data channel of the selected block. This spares the extra channels, in which they are grouped into a new block for potential future CR-IoT transmissions. Hence, network performance is improved.

V. PERFORMANCE EVALUATION

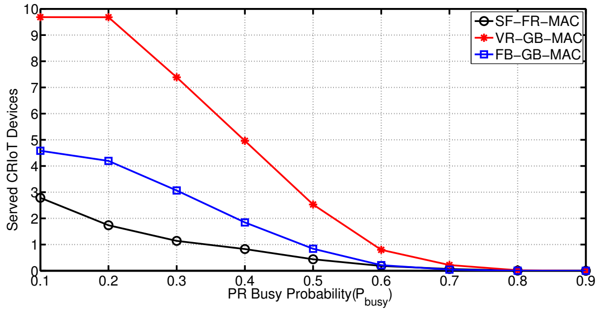
A. SIMULATION SETUP

We evaluate the performance of our proposed channel assignment scheme using MATLAB simulations [40]. We consider a CR-IoT network that opportunistically share the available licensed spectrum with a number of PRNs, where the number of PU channels is set to M. The status of each PU channel follows a 2-state Markov model with IDLE and BUSY periods. The BUSY channel imposes that some PUs are transmitting over that channel. Each channel is busy with probability P_{busy}. The carrier frequency of each PU channel $k \in \mathcal{M}$ is computed as: $f_k = 900 + k$ MHz. We consider a Rayleigh fading channel model with path-loss exponent n between any two communicating CR-IoT devices over the different channels. We set the transmission power of each CR-IoT device to the FCC maximum permissible transmit power level over each idle channel. The total transmission power of a CR-IoT device over all selected channels is limited to 1 watt and the thermal noise power density over each channel is fixed to 10^{-12} W/Hz. The network performance is investigated as a function of the total number of channels M, the demand rate d, path-loss exponent n and the PR activity P_{busy}.

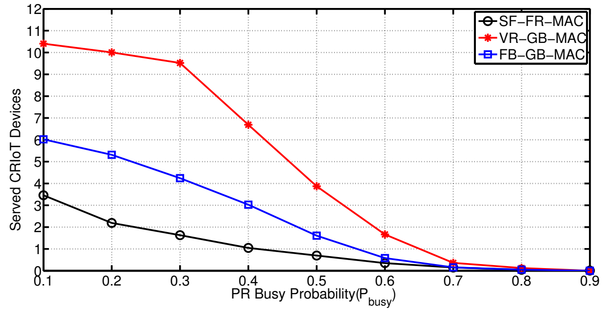
B. SIMULATION RESULTS

The performance of the proposed scheme, denoted by VR-GB-MAC, is compared with two other schemes: the fixed-block-GB-MAC (referred to as FB-GB-MAC) scheme [32] and the sequential fixing-fixed rate-MAC (referred to as SF-FR-MAC) scheme [29]. The FB-GB-MAC and SF-FR-MAC schemes employ a power control to achieve a fixed average transmission rate per channel. FB-GB-MAC attempts at maximizing spectrum efficiency by performing fixed block assignment that introduces the minimum number of GBs [32]. On the other hand, SF-FR-MAC scheme attempts at reducing the number of newly added GBs while achieving the demand rate by performing per channel assignment [29], but with a main objective of reducing the number of newly added GBs while minimizing the total needed power. Note that, in general, the transmission rate over each channel of a CR link depends on the CSI of that link over that channel. Figure 3 shows the number of severed CR-IoT devices versus P_{busy} for different n (3 and 4), different d (20 and 30 Mbps), $M = 23$ channels, $BW = 5$ MHz and 20 CR-IoT communicating links. For $n = 3$ and $n = 4$, we set the achieved average rates to 20 and 10 Mbps, respectively. This figure shows that, for all scheme, as P_{busy} increases the chances of finding idle channels to serve larger number of CR-IoT devices decreases. It also reveals that the proposed channel assignment provides significant performance improvement compared to the other two channel assignment schemes, irrespective of d and n. It can also observed that the number of served users is higher at lower values of n. This is due to the better channel conditions and higher achieved data rates at lower values of n (for $n = 4$ and $d = 30$ Mbps, 3 channels are needed to serve one user, however for $n = 3$ and $d = 30$, only one channel is needed) [41]. Figure 4 plots the number of served IoT devices versus d with $BW = 5$ MHz for both $P_{busy} = 0.5$ and 0.3. The number of served CR-IoT when $P_{busy} = 0.3$ is larger than that when $P_{busy} = 0.5$. This is because that at smaller P_{busy} more available idle blocks exist and more CR-IoT transmissions can be activated. Figure 4 reveals that at larger rate demands, our proposed assignment serves more CR-IoT devices and achieves higher network throughput compared to the other two channel assignment schemes.

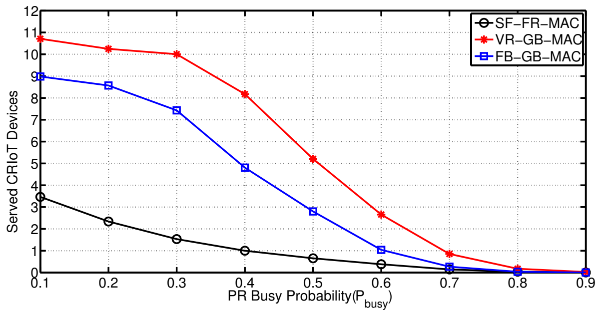
Figure 5(a) demonstrates the overall network throughput as a function of P_{busy} for $d = 12$ Mbps and $n = 3$. When P_{busy} increases, the achieved network throughput decreases due to the fact that as P_{busy} increases the number of idle blocks decreases and the chance of finding idle blocks that can achieve the required d decreases. Figure 5(b) plots the spectrum efficiency, defined as the ratio between the total number of reserved data channels and the number of reserved data-plus-GB channels. This figure indicated that the proposed VR-GB-MAC achieves higher spectrum efficiency



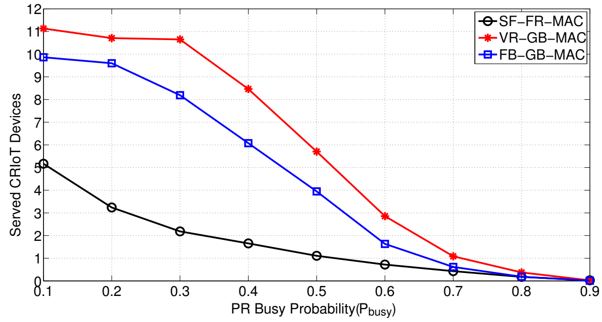
(a) $d = 30$ Mbps, $n = 4$.



(b) $d = 20$ Mbps, $n = 4$.



(c) $d = 30$ Mbps, $n = 3$.



(d) $d = 20$ Mbps, $n = 3$.

FIGURE 3. Number of served CR-IoT devices vs. P_{busy} for $M = 23$ and 24 links.

with respect to the other two schemes. Figure 5(b) also shows that the spectrum efficiency decreases as P_{busy} increases.

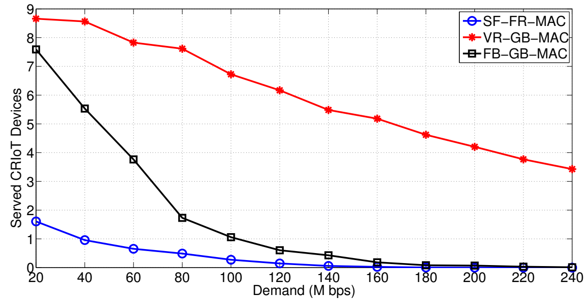
Figure 6 plots the overall network throughput versus P_{busy} for different number of channels M (i.e., M=10, 20, and 30 channels). It can be observed that as M increases, higher throughput performance is achieved. This can be explained as follows as the number of PU channels increases, the chance of finding larger idle blocks that can serve the rate demand for the CR-IoT devices increases. Thus, more CR-IoT transmissions can be served. Figure 6 also reveals that as the number of CR-IoT contending devices increases, the overall network throughput is enhanced.

The number of reserved channels per CR-IoT transmission is demonstrated in Figure 7(a). It is clear that our proposed scheme needs smaller number of channels to serve each CR-IoT device. Figure 7(b) shows the number of introduced GBs served CR-IoT devices as a function of P_{busy}. This figure shows that our proposed scheme introduces less number of GB per CR-IoT transmission. This is due to our employed appropriate block assignment that is aware of rate demand of each CR-IoT device.

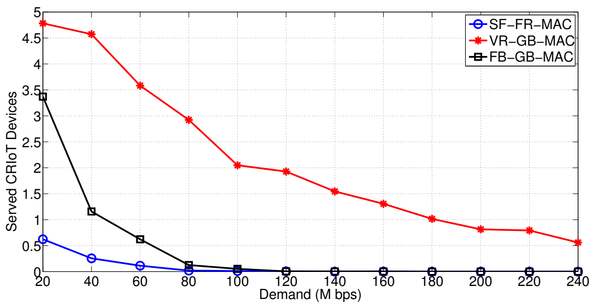
Figure 8 plots the number of served CR-IoT devices versus the number of contending CR-IoT transmissions for different values of maximum transmission power P_t under different PUs' activities (i.e., $P_{busy} = 0.5$, $P_{busy} = 0.3$ and $P_{busy} = 0.9$). Note that at high P_{busy}, significant decrease in network performance is observed for all schemes. Figure 8 reveals that the overall number of served CR-IoT users is larger at smaller P_{busy} as the chances of finding more available idle blocks/channels is higher. This figure also shows that as P_t increases, the number of served CR-IoT devices increases. This is because increasing the power increases the achieved rate of each channel. Finally, Figure 8(c) shows that at lower values of P_{busy} irrespective of P_t, the three schemes have comparable performance. This is expected as at low P_{busy} the chances of finding idle blocks with high rates that can achieve the rate demand for the CR-IoT devices, irrespective of P_t.

VI. CONCLUSIONS

This paper presented a GB-aware channel assignment scheme for time-varying CR-IoT networks with adaptive rate. The proposed assignment assigns channels to CR-IoT devices in a per-block basis. Our scheme attempts to maximize the achieved network throughput by reducing the number of assigned data-plus-GB channels subject to required rate demand, link quality and total transmit power constrains. The problem is formulated as a BLP, which is, in general, an NP-hard problem. Thus, we developed a polynomial-time suboptimal algorithm procedure using the sequential fixing linear programming (SFLP). The performance of our proposed channel assignment scheme is compared with that

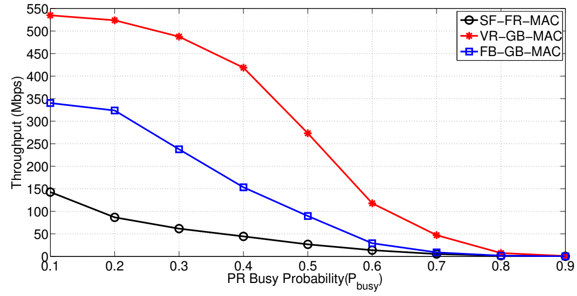


(a) $P_{busy} = 0.3$.

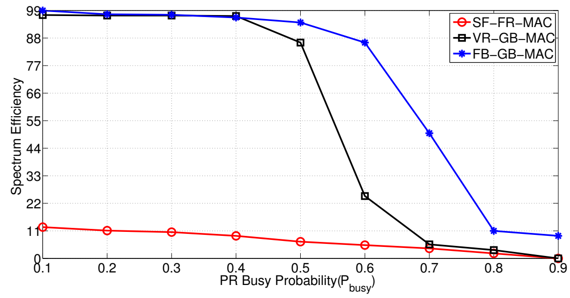


(b) $P_{busy} = 0.5$.

FIGURE 4. Number of served CR-IoT devices vs. d for $M = 23$, n=3 and $BW = 5$ MHz.



(a) Throughput Performance.



(b) Spectrum Efficiency Performance.

FIGURE 5. Throughput and Spectrum Efficiency Performance Performance vs. P_{busy} for $d = 12$ Mbps, $n = 3$ and $N = 24$ links.

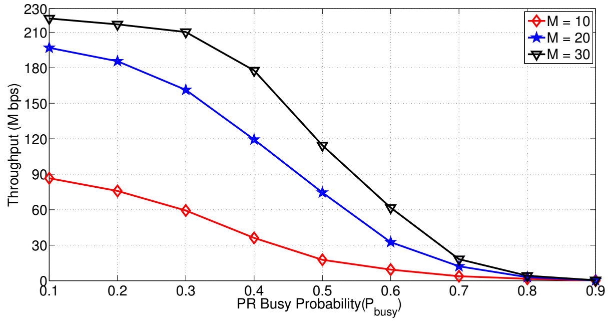
of sequential fixing per-channel assignment and the fixed rate per-block assigned schemes. Simulation results showed that the proposed scheme significantly outperforms the reference schemes. The results also indicated that a significant increase in networks throughput can be realized by considering multi-channel diversity when assigning frequency blocks to CR-IoT devices, in which the blocks with highest data rates and smaller sizes are selected. As future work, the proposed approach can be extended to support simultaneous channel assignment decisions for several CRIoT nodes such that the overall network throughput is improved.

ACKNOWLEDGEMENTS

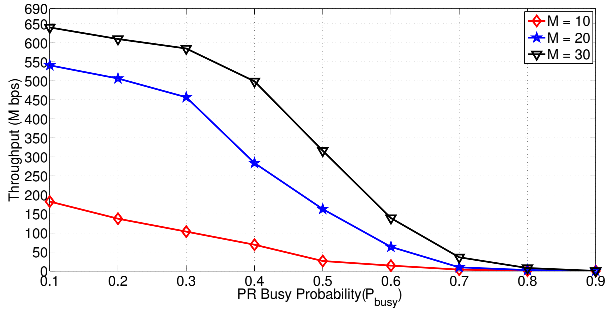
This research was supported in parts by the QR Global Challenges Research Fund (GCRF), Staffordshire University, Staffordshire UK. An abridge version of this paper was presented at the IEEE SDS' 18 Conference, Bercelona, Spain.

REFERENCES

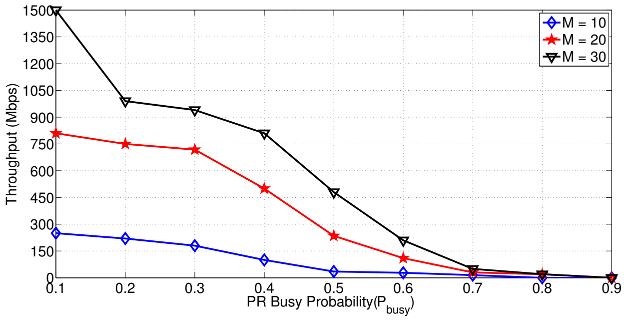
[1] T. Li, J. Yuan and M. Torlark, "Network Throughput Optimization for Random Access Narrow-band Cognitive Radio Internet of Things (NB-CR-IoT)", *IEEE Internet of Things Journal*, vol.5, no.3, 2018.
[2] W. Yu et al., "A Survey on the Edge Computing for the Internet of Things," *in IEEE Access*, vol. 6, pp. 6900-6919, 2018.
[3] R. Atat, L. Liu, H. Chen, J. Wu, H. Li and Y. Yi, "Enabling cyber-physical communication in 5G cellular networks: challenges, spatial spectrum sensing, and cyber-security," in IET Cyber-Physical Systems: Theory Applications, vol. 2, no. 1, pp. 49-54, 4 2017.
[4] J. An, K. Yang, J. Wu, N. Ye, S. Guo and Z. Liao, "Achieving Sustainable Ultra-Dense Heterogeneous Networks for 5G," *in IEEE Communications Magazine*, vol. 55, no. 12, pp. 84-90, Dec. 2017.
[5] H. Bany Salameh, S. Almajali, M. Ayyash and H. Elgala, "Spectrum Assignment in Cognitive Radio Networks for Internet-of-Things Delay-sensitive Applications under Jamming Attacks", *IEEE Internet of Things Journal*, vol. 5, no. 3, pp. 1904-1913, March 2018.
[6] R. Atat, L. Liu, J. Wu, G. Li, C. Ye, Y. Yi, "Big Data Meet Cyber-Physical Systems: A Panoramic SurveyâĂİ, *IEEE Access*, vol. 6, pp. 73603-73636, 2018.
[7] M. Wang, F. Tseng and M. Ku, "Cooperative SWIPT Transmission in Overlay Multi-antennas Hierarchical Cognitive Radio Networks," *in IEEE Access*, 2018.
[8] M. Jia, Z. Yin, Q. Guo, G. Liu and X. Gu, "Downlink Design for Spectrum Efficient IoT Network," *in IEEE Internet of Things Journal*, vol. 5, no. 5, pp. 3397-3404, Oct. 2018.
[9] E. Benkhelifa, T. Welsh and W. Hamouda, "A Critical Review of Practices and Challenges in Intrusion Detection Systems for IoT: Toward Universal and Resilient Systems," *in IEEE Communications Surveys & Tutorials*, vol. 20, no. 4, pp. 3496-3509, 2018.
[10] M. Jia, X. Gu, Q. Guo, W. Xiang and N. Zhang, "Broadband Hybrid Satellite-Terrestrial Communication Systems Based on Cognitive Radio toward 5G," *in IEEE Wireless Communications*, vol. 23, no. 6, pp. 96-106, 2016.
[11] M. Zheng, L. Chen, W. Liang, H. Yu and J. Wu, "Energy-Efficiency Maximization for Cooperative Spectrum Sensing in Cognitive Sensor Networks," *in IEEE Transactions on Green Communications and Networking*, vol. 1, no. 1, pp. 29-39, March 2017.
[12] A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari, and M. Ayyash, "Internet of Things: A survey on enabling technologies, protocols, and applications," *IEEE Communication Surveys and Tutorials*, vol. 17, no. 4, pp. 2347-2376, 2015.
[13] P. Rawat, K. Singh, and J. Bonnin, "Cognitive radio for M2M and Internet of Things: A survey," *Computer Communications*, vol. 94, pp. 1-29, Nov. 2016.



(a) Low number of links $N = 10$.



(b) Moderate number of links $N = 30$.



(c) High number of links $N = 50$.

FIGURE 6. Throughput performance vs. P_{busy} for $d = 16$ Mbps, $n = 4$ and different number of channels M.

[14] FCC, "Second memorandum opinion and order in the matter of unlicensed operation in the TV broadcast bands (ET Docket No. 04-186)", Additional Spectrum for Unlicensed Devices Below 900 MHz and in 3 GHz Band, Washington, DC, USA, (EC Docket No. 02-380), Sep. 23, 2010.

[15] I. Kakalou, D. Papadopoulou, T. Xifilidis, K. Psannis, K. Siakavara and Y. Ishibashi, "A Survey on Spectrum Sensing Algorithms for Cognitive Radio Networks", *Proceedings of the International Conference on Modern Circuits and Systems Technologies (MOCAST'18)*, 2018, Thessaloniki, Greece.

[16] G. A. Akpakwu, B. J. Silva, G. P. Hancke and A. M. Abu-Mahfouz, "A Survey on 5G Networks for the Internet of Things: Communication Technologies and Challenges," *in IEEE Access*, vol. 6, pp. 3619-3647, 2018.

[17] I. Khan, MH. Zafar, MT. Jan, J. Lloret, M Basheri, D Singh, "Spectral and Energy Efficient Low-Overhead Uplink and Downlink Channel Estimation for 5G Massive MIMO Systems", *Entropy*, vol. 20, no. 2, 2018.

[18] H. Bany Salameh, "Efficient Resource Allocation for Multicell Heterogeneous Cognitive Networks With Varying Spectrum Availability," *in IEEE Transactions on Vehicular Technology*, vol. 65, no. 8, pp. 6628-6635, Aug. 2016.

[19] J. Lloret Mauri, KZ. Ghafoor, D. Rawat, J. Perez, Cognitive networks: Applications and deployments, CRC Press. 2014

[20] P. Smith, R. Senanayake and P. Dmochowski, "Novel Distributed Spectrum Sensing Techniques for Cognitive Radio Networks", *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC'18)*, Barcelona, Spain, 2018.

[21] H. Bany Salameh, S. Almajali and M. Ayyash, "Security-aware channel assignment in IoT-based cognitive radio networks for time-critical applications", *Proceedings of the Fourth International Conference on Software Defined Systems (SDS'17)*, Spain, May 2017.

[22] M. Jia, X. Liu, X. Gu, and Q. Guo, " Joint cooperative spectrum sensing and channel selection optimization for satellite communication systems based on cognitive radio",. Int. J. Satell. Commun. Netw. vol35, no. 2, pp. 139-150, 2017.

[23] M. Jia, X. Liu, Z. Yin, Q. Guo, X. Gu, "Joint cooperative spectrum sensing and spectrum opportunity for satellite cluster communication networks," *Ad Hoc Networks*, Volume 58, pp 231-238, 2017.

[24] Y. Li, L. Zhao, C. Wang, A. Daneshmand, and Q. Hu, "Aggregation based spectrum allocation algorithm in cognitive radio networks," *Proceedings of the IEEE Networking Operation and Management Symposium*, 2012, pp. 506-509.

[25] J. Jia, J. Zhang, and Q. Zhang, "Cooperative Relay for Cognitive Radio Networks", *Proceedings of the IEEE INFOCOM*, pp. 794-802, 2009.

[26] E. Ahmed, A. Gani et al., "Channel Assignment in Cognitive Radio Networks: Taxonomy, Open Issues, and Challenges", *IEEE Communication Surveys and Tutorials*, October, 2014.

[27] A. Zubow, R. Sombrutzki, "Adjacent channel interference in IEEE 802.11n", *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC'12)*, 2012, pp.1163-1168.

[28] M. Javad, N. Oliaee and B. Hamdaoui, "Analysis of Guard-band-aware Spectrum Bonding and Aggregation in Multi-Channel Access Cognitive Radio Networks", *Proceedings of the IEEE ICC Conference*, 2016.

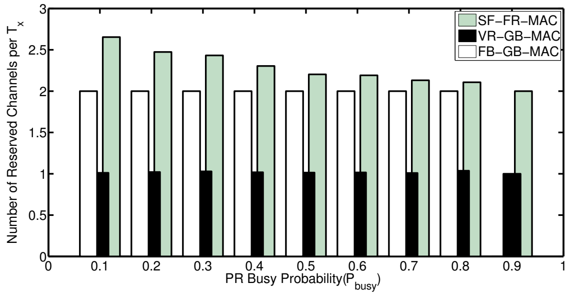
[29] H. Bany Salameh, M. Krunz, and D. Manzi, "Spectrum bonding and aggregation with guard-band awareness in cognitive radio networks", *IEEE Transactions on Mobile Computing*, vol. 13, no. 3, pp. 569-581, Mar. 2013.

[30] S. Bukhari, S. Siraj and M. Rehmani, "PRACB: A Novel Channel Bonding Algorithm for Cognitive Radio Sensor Networks," *in IEEE Access*, vol. 4, pp. 6950-6963, 2016.

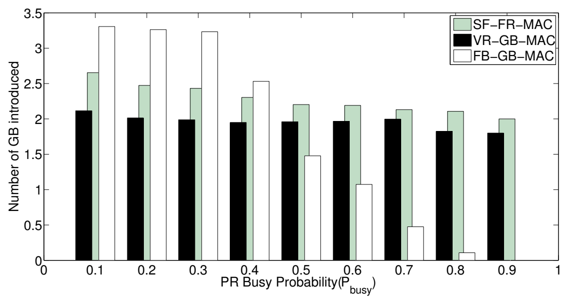
[31] H. Bany Salameh, H. Kasasbeh and B. Harb, "A Batch-Based MAC Design With Simultaneous Assignment Decisions for Improved Throughput in Guard-Band-Constrained Cognitive Networks", *IEEE Transactions on Communications*, vol. 64, no. 3, pp. 1143-1152, Jan 2016.

[32] G. S. Uyanik, M. J. Abdel Rahman and M. Krunz, "Optimal Guardband-aware Channel Assignment with Bonding and Aggregation in Multichannel Systems", *Proceeding of the IEEE Globecom'13 Workshops*, 2013, Atlanta, GA, USA.

[33] H. Bany Salameh and M. Dhainat,"Event-driven hybrid MAC protocol for a two-tier cognitive wireless sensor network: design and implementation", *Int. J. High Perform. Comput. Netw.*, vol. 9, no. 4, pp. 271-280, 2016.

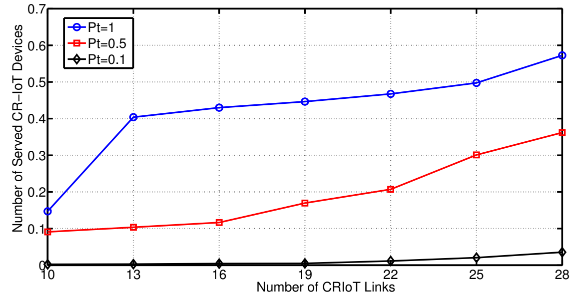


(a) Number of reserved channels per transmission CR-IoT vs. P_{busy}.

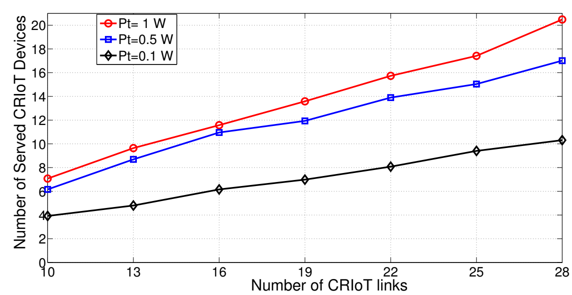


(b) Number of introduced GBs. vs. P_{busy}.

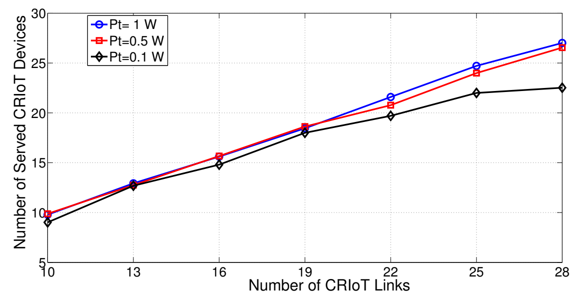
FIGURE 7. Number of reserved channels vs. P_{busy} for $BW = 5$ MHz, $d = 35$ Mbps and $n = 3$.



(a) $P_{busy} = 0.9$ (High PR activity).



(b) $P_{busy} = 0.5$ (Moderate PR activity).



(c) $P_{busy} = 0.1$ (Low PR activity).

FIGURE 8. Number of served CR-IoT devices vs. Number of contending transmissions for $d = 100$ Mbps, and $M = 23$.

[34] M. Abdel-Rahman and, M. Krunz, “Stochastic guard-band-aware channel assignment with bonding and aggregation for DSA networks", *IEEE Transactions on Wireless Communications*, vol. 14, no. 7, pp. 3888-3898, 2015.

[35] H. Bany Salameh, H. Kasasbeh and B. Harb, “An Opportunistic Guard-band-aware Channel Assignment: A batch-based Approach", *Proceeding of the IEEE Wireless Communications and Networking Conference (WCNC'16)*, Qatar, April 2016.

[36] M. Abdel-Rahman, F. Lan, and M. Krunz, ”Spectrum-efficient stochastic channel assignment for opportunistic networks," *Proceeding of the IEEE GLOBECOM'13 Conference*, Atlanta, GA, USA, 2013, pp. 1272âĂŞ1277.

[37] H. Bany Salameh, “Spread spectrum-based coordination design for spectrum-agile wireless ad hoc networks", *Journal of Network and Computer Applications*, vol. 57, pp. 192-201, 2015.

[38] H. Bany Salameh and M. El-Attar, “Cooperative OFDM-Based Virtual Clustering Scheme for Distributed Coordination in Cognitive Radio Networks," *in IEEE Transactions on Vehicular Technology*, vol. 64, no. 8, pp. 3624-3632, Aug. 2015.

[39] A. Hassan, “Brief Overview of the Cognitive Radio Technologies", *International Journal of Advanced Research in Computer Science and Software Engineering*, vol. 5, pp. 21-28, 2015.

[40] Math Works [Online], http://www.mathworks.com.

[41] O. Olaleye, A. Ali, K. Khalil, “Spectrum-Awareness-based Performance and Scalability of Cognitive Radio Network", *Proceeding of the IEEE ICC Workshops*, 2018, MO, USA.

HAYTHEM A. BANY SALAMEH (M'06-SM'16) received the Ph.D. degree in electrical and computer engineering from the University of Arizona, Tucson, AZ, USA, in 2009. He is currently a Professor of telecommunication engineering with Yarmouk University (YU), Irbid, Jordan. He was the Director of the Queen Rania Center for Jordanian Studies and Community Service from June 2014 to June 2018. From January 2011 to June 2014, he was the Director of the Academic Entrepreneurship Center of Excellence, YU. In August 2009, he joined YU, after a brief postdoctoral position with the University of Arizona. His current research interests include optical communication technology and wireless networking, with emphasis on dynamic spectrum access, radio resource management, energy-efficient networking, and distributed protocol design. His research covers a wide variety of wireless systems, including cognitive radio networks, Internet-of-things (IoT)-based networks, wireless sensor networks, ad hoc networks, and cellular networks. He is a recipient of the Jordan Science Research Support Foundation prestigious award for Distinguished Research in ICT sector, 2016. He is also the recipient of the Best Researcher Award for Scientific Colleges in Yarmouk University for the year 2015/2016. Dr. Bany Salameh has served and continues to serve on the Technical Program Committee of many international conferences and serves as a Reviewer for many international conferences and journals. In the summer of 2008, he was a member of the RD Long-Term Evolution Development Group, QUALCOMM, Inc., San Diego, CA, USA.

SAHAM ALMASRI received the B.A. degree in communications engineering and the M.A. degree in wireless communications engineering from Yarmouk University, Irbid, Jordan, in 2015, and 2019, respectively. She is currently working as a creative design and innovation teacher in Al Maseera public school in Al Ain, UAE. Her research interests include cognitive radio networks, guard-band awareness assignment under time-varying conditions and Internet of Things.

ELHADJ BENKHELIFA is a Full Professor of Computer Science at Staffordshire University, UK, with an extensive experience in working with industry on real world business problems. Elhadj was (2014-2016) the Faculty Director of the Mobile Fusion Applied Research Centre (45 PhD students and 15+ Staff). Over the past years, Elhadj has built a rich portfolio of successful collaborative cutting edge research projects, and he is currently the University Lead for REF (Research Exercise Framework) UoA11 (Computing Informatics). Elhadj is the Founding Head of the Cloud Computing and Applications Research Lab and the Cybersecurity Research Lab, leading a team of 8 PhD Students and Research Staff. Elhadj has a strong research publications and dissemination track record and a co-founding chair of several pioneering conferences/workshops. Elhadj research is very contemporary to cover many aspects of Cloud Computing including security, Mobile Cloud, Software Defined Systems, Cloud Forensics, IOT and Cloud, Fog and Mobile Edge Computing, Cloud computing resilience, Social Network Analysis, Collaborative software development, security as a service, testing as a service to mention but the most recent work. He has served as a guest Editor of many journals Special Issues, IEEE Trans Cloud Computing, Cluster Computing, Future Generation Computer System etc., and chaired several international conferences and workshops. Elhadj delivered several keynote lectures at different prestigious venues. Elhadj is a Director at YottaLaborattories Ltd and he is a Senior RD Advisor to several companies in the UK and a member of several panels and committees within the UK and internationally.

JAIME LLORET received his M.Sc. in Physics in 1997 at University of Valencia and he finished a postgraduate Master in Corporative networks and Systems Integration from the Department of Communications in 1999. Later, he received his M.Sc. in Electronic Engineering in 2003 at University of Valencia and his Ph.D. in telecommunication engineering (Dr. Ing.) at the Polytechnic University of Valencia in 2006. Before concluding his PhD. Thesis he obtained the first place given by the Spanish Agency for Quality Assessment and Accreditation for the Campus of Excellence in the New Technologies and Applied Sciences Area. He was awarded the prize of the best doctoral Student in the Telecommunications area in 2006 according to the Social Council of the Polytechnic University of Valencia. He is a Cisco Certified Network Professional Instructor of the regional academy "Universidad PolitÃl’cnica de Valencia" in the Cisco Networking Academy Program (CNAP) and he is the Legal Main Contact of UPV-ADIF (local academy of the CNAP). He teaches Local Area Networks and Systems Integration in the "Escuela Politecnica Superior de Gandia" from the Polytechnic University of Valencia. He has been working as a network designer and administrator in several companies. His academic interests and research are P2P networks, Wireless Local Area Networks, Sensor Networks and Routing Protocols. He also researches on educational approaches and strategies.