Spectrum Assignment in Hardware-Constrained Cognitive Radio IoT Networks Under Varying Channel-Quality Conditions

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ABSTRACT The integration of cognitive radio (CR) technology with the future Internet-of-Things (IoT) architecture is expected to allow effective massive IoT deployment by providing huge spectrum opportunities to the IoT devices. Several communication protocols have been proposed for the 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 a large number of CR-IoT devices are operating in the same vicinity, guard-band channels (GBs) are needed to mitigate the ACI problem, introducing GB adds constraints on the efficient use of spectrum and protocol design. In this paper, we develop a channel assignment mechanism for the 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 problem, which is NP-hard. Thus, we propose a polynomial-time solution using a sequential fixing algorithm that achieves a suboptimal solution. The 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

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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]). Salameh *et al.* [29] 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. Salameh *et al.* [31], [35] proposed a batch-based GB-aware spectrum assignment for CRNs. It considers batching, in which multiple assignment decisions can be made simultaneously. Uyanik *et al.* [32] 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], and [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
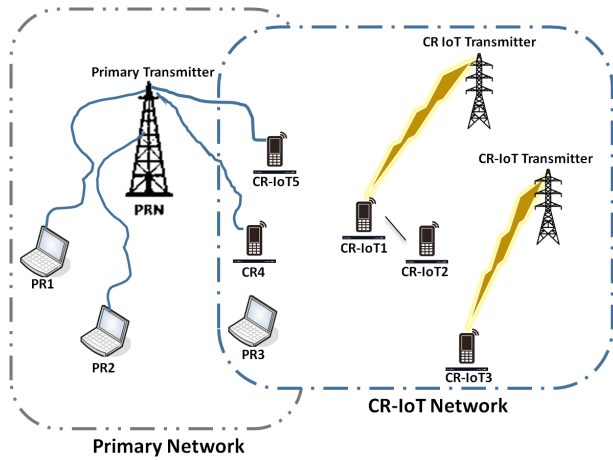
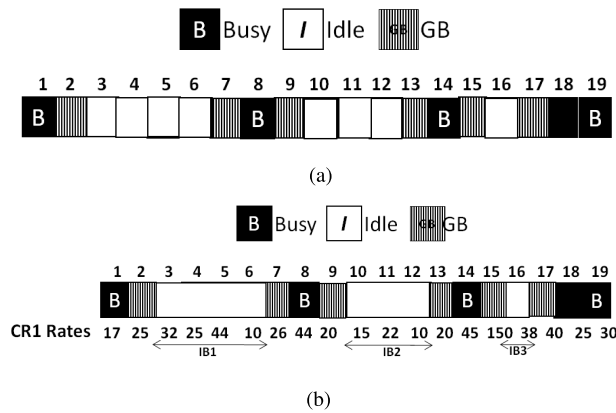**FIGURE 1.** An illustration of PU and CR-IoT networks coexistence.

FIGURE 2. Illustrative example of channel vs. Block formation with 19 channels. (a) Channel availability status. (b) Idle block formation.

ACI issue and the time-varying nature of channel conditions between communicating devices.

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 ($\text{SNR}^{(k)}$) as $r_t^{(k)} = W \log_2(1 + \text{SNR}^{(k)})$, 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 ith 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].

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:

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

(1)

Mathematically, our proposed assignment is written as:

$$\min_{X^{(i)}, \in \{0,1\}} \left\{ \sum_{i=1}^{N} S^{(i)} \, X^{(i)} \right\} - \frac{R^{(i)}}{\sum_{i=1}^{N} R^{(i)}}$$

$$\text{s.t.} \sum_{i=1}^{N} R^{(i)} X^{(i)} \geq d \text{ or } \sum_{i=1}^{N} R^{(i)} X^{(i)} = 0$$

$$\sum_{i=1}^{N} \mathcal{P}_t^{(i)} X^{(i)} \leq \mathcal{P}_{max}.$$

(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 $S\left(\Omega_B^{(*)}(1)\right) < S\left(\Omega_B^{(*)}(2)\right)$, 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:

$$\sum_{i=1}^{N} -R^{(i)} X^{(i)} \leq -d - \Gamma y$$

$$\sum_{i=1}^{N} R^{(i)} X^{(i)} \leq -\Gamma y + \Gamma$$

(3)

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

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

(4)

Therefore, the optimization in (2) becomes:

$$\min_{X^{(i)}, y, \in \{0,1\}} \left\{ \sum_{i=1}^{N} S^{(i)} \, X^{(i)} \right\} - \frac{R^{(i)}}{\sum_{i=1}^{N} R^{(i)}}$$

$$\text{s.t.} \sum_{i=1}^{N} -R^{(i)} X^{(i)} \leq -d - \Gamma y$$

$$\sum_{i=1}^{N} R^{(i)} X^{(i)} \leq -\Gamma y + \Gamma$$

$$\sum_{i=1}^{N} \mathcal{P}_t^{(i)} X^{(i)} \leq \mathcal{P}_{max}.$$

(5)

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

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

(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] and [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] and [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 (the 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
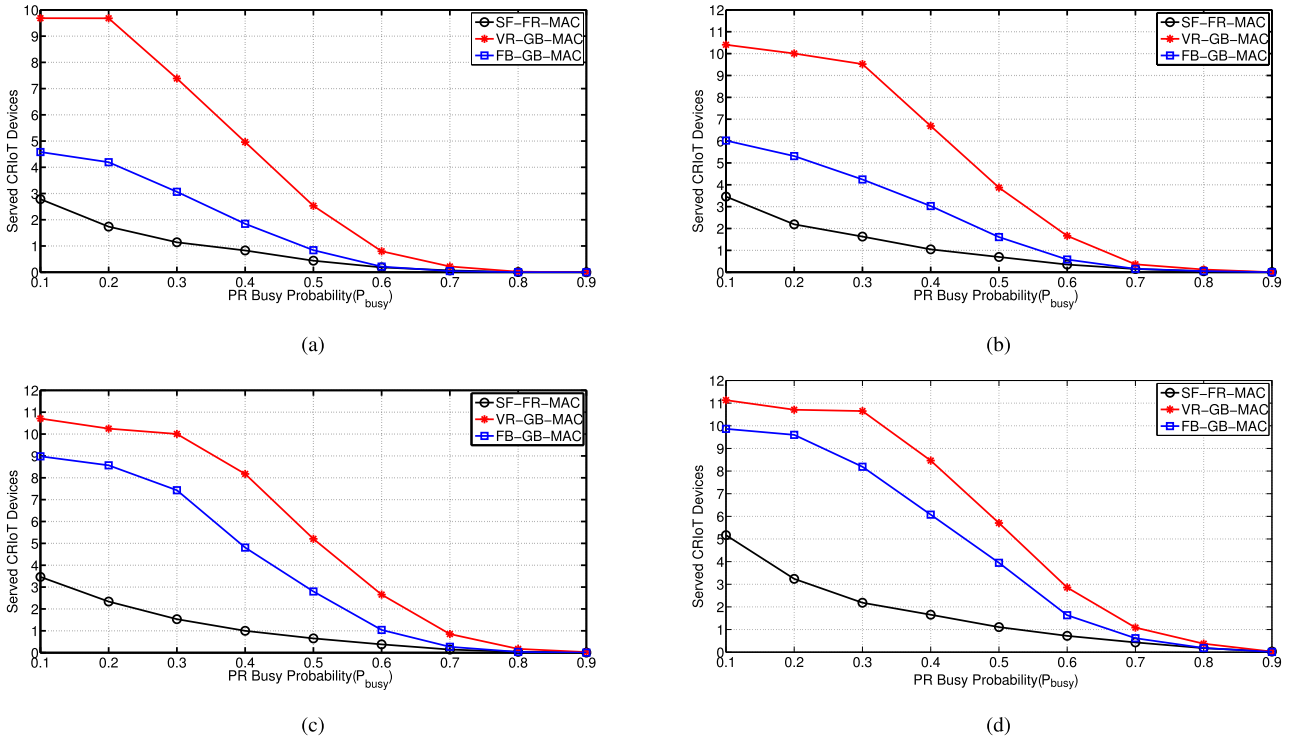
FIGURE 3. Number of served CR-IoT devices vs. P_{busy} for $M = 23$ and 24 links. (a) $d = 30$ Mbps, $n = 4$. (b) $d = 20$ Mbps, $n = 4$. (c) $d = 30$ Mbps, $n = 3$. (d) $d = 20$ Mbps, $n = 3$.
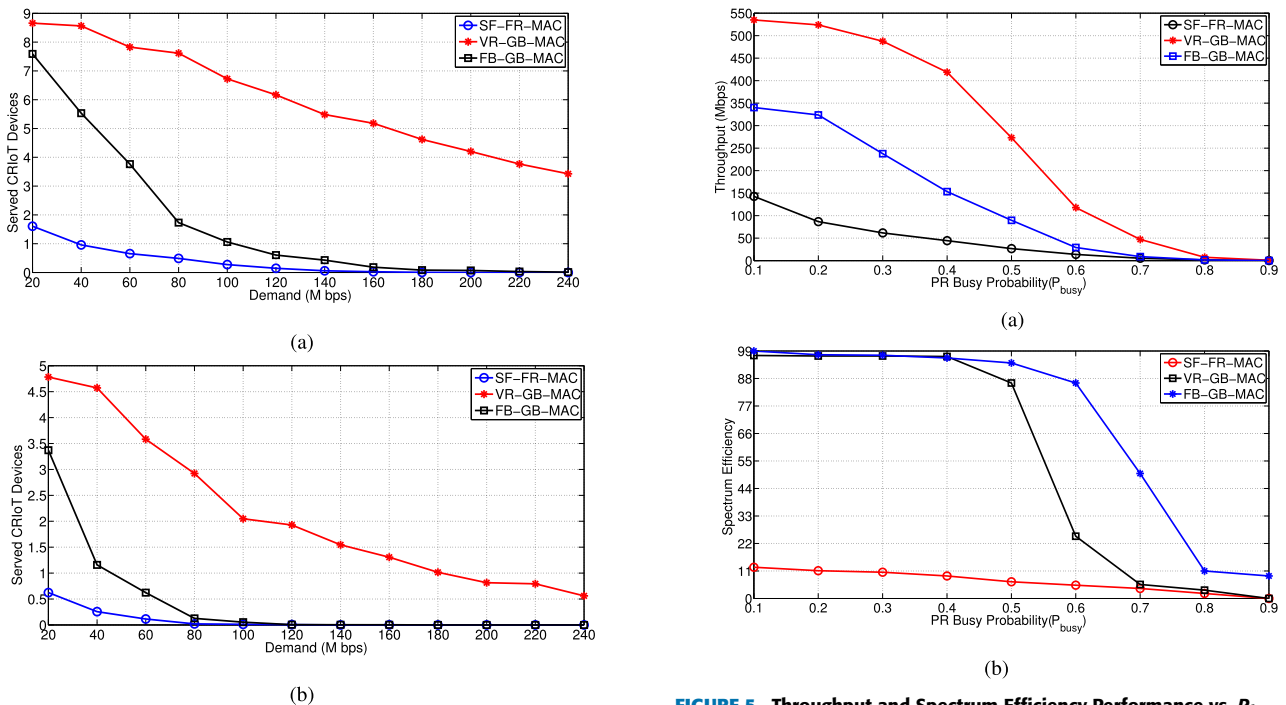

FIGURE 4. Number of served CR-IoT devices vs. d for $M = 23$, n=3 and $BW = 5$ MHz. (a) $P_{busy} = 0.3..$ (b) $P_{busy} = 0.5$.

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

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

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., $M = 10, 20,$
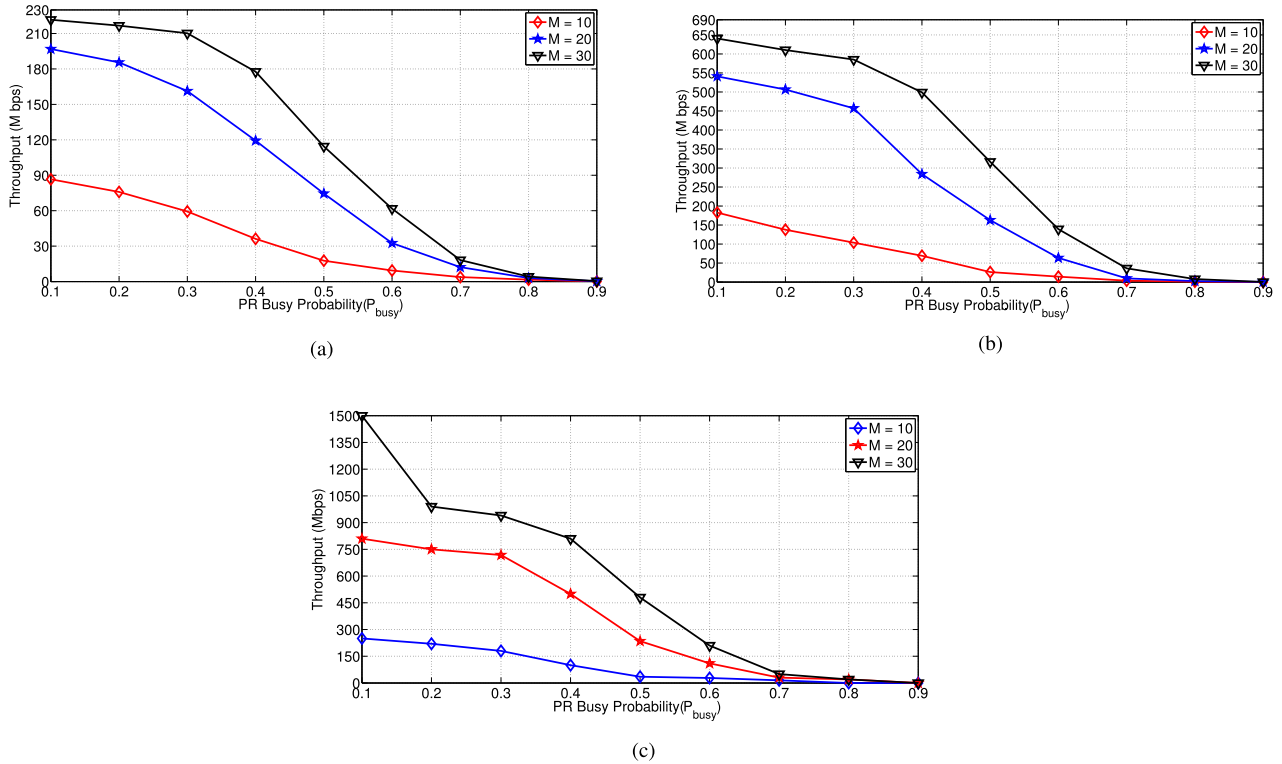
(a)

(b)

(c)

FIGURE 6. Throughput performance vs. P_{busy} for d = 16 Mbps, n = 4 and different number of channels M. (a) Low number of links N = 10. (b) Moderate number of links N = 30.

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
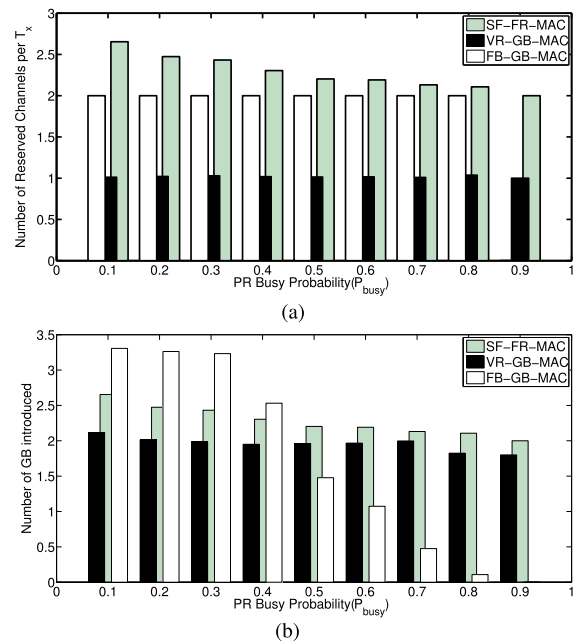

(a)

(b)

FIGURE 7. Number of reserved channels vs. P_{busy} for BW = 5 MHz, d = 35 Mbps and n = 3. (a) Number of reserved channels per transmission CR-IoT vs. P_{busy}. (b) Number of introduced GBs. vs. P_{busy}.

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
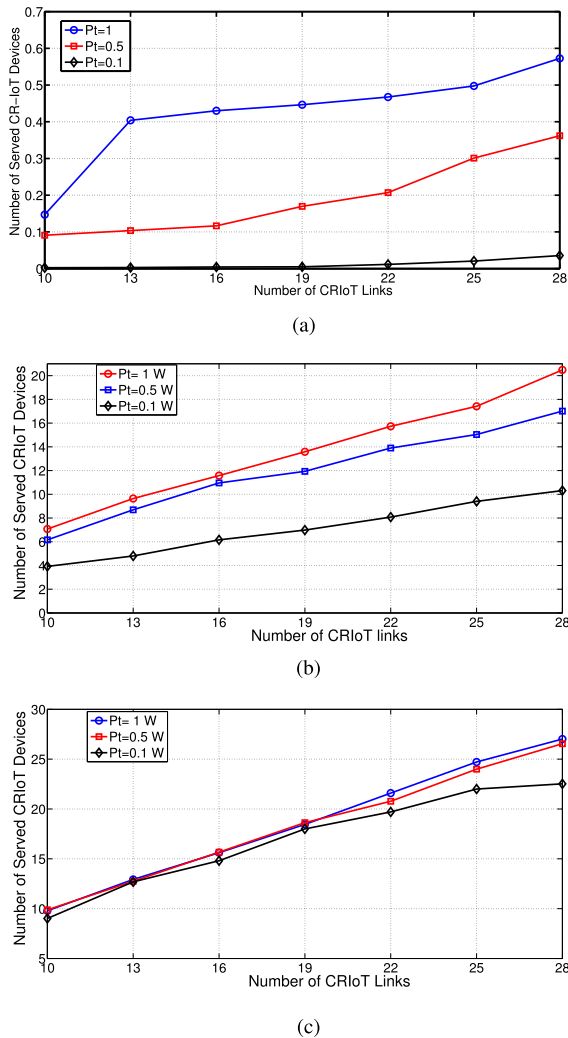
FIGURE 8. Number of served CR-IoT devices vs. Number of contending transmissions for d = 100 Mbps, and M = 23. (a)P_{busy} = 0.9 (High PR activity). (b) P_{busy} = 0.5 (Moderate PR activity). (c) P_{busy} = 0.1 (Low PR activity).

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 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.

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