Scheduling in Centralized Cognitive Radio Networks for Energy Efficiency

Suzan Bayhan and Fatih Alagöz

***Abstract*—With growing concern on environmental issues and emerging green communications paradigm, cognitive radio (CR) networks have to be considered from energy efficiency perspective. In this work, we focus on scheduling in CR networks (CRNs) in which cognitive base station (CBS) makes frequency allocations to the CRs at the beginning of each frame. A cognitive scheduler must consider the diversity among CRs' queues and channel capacities in terms of number of bits as well as the channel switching cost from one frequency to another. Taking all these into account, we formulate the scheduling problem as energy efficiency maximization problem which is a nonlinear integer programming (NLP) problem and thereby hard to solve. We seek for alternate computationally easier solutions. To this aim, we propose a polynomial time heuristic algorithm, *energy-efficient heuristic scheduler*, which allocates each idle frequency to the CR that attains the highest energy efficiency at this frequency. Next, we reformulate the original problem first as throughput maximization problem subject to energy consumption restrictions and next, as energy consumption minimization problem subject to minimum throughput guarantees. These two schedulers have also the power to provide fairness in resource allocation. We analyze the energy efficiency and successful transmission probability of the proposed schedulers under both contiguous and fragmented spectrum scenarios. Performance studies show that compared to a pure opportunistic scheduler with a throughput maximization objective, proposed schedulers can attain almost the same throughput performance with better energy efficiency.**

***Index Terms*—Cognitive radio (CR), energy efficiency, channel switching, fragmented spectrum.**

I. INTRODUCTION

Cognitive radio networks (CRNs) enable the radio spectrum to be utilized effectively owing to their opportunistic transmission and dynamic spectrum access (DSA) capabilities. Moreover, CRs promise advanced functionalities which will require advanced information processing capabilities. On the other hand, CRs need powerful energy sources to afford all these functionalities. However, there is a lag between the advances in battery technology and semiconductor technologies; the former being significantly slower than the latter. As a result, current battery technology cannot meet the tremendous increase in power consumption related to the increasing traffic flow resulting from the improvement in fast semiconductor technologies [1]. Thus, energy efficiency may become a limiting factor in the development of advanced wireless communications technologies which makes energy efficiency a crucial issue for wireless networks.

Quest for higher energy efficiency is primarily due to three reasons: cost-effectiveness, longer battery lifetime and environmental concerns. Energy costs are constantly increasing and energy expenditure of a wireless network is a significant fraction (20 to 30 per cent [2]) of total operator expenditures (site rental, licensing etc.). Hence, energy should be consumed effectively for cost-effective systems. Reducing energy consumption and energy-efficient operation are thereby at the interest of the operators. From the user viewpoint, energy efficiency means longer battery lifetime. It is a fact that short durations between two battery charging annoy the users and reduce the practicality of wireless communications. Thus, energy efficiency is vital for both actors of wireless communications. Another driving factor for increasing energy efficiency of communications is the environmental concerns. Emissions due to Information and Communication Technologies (ICT) is estimated to be around 2% of the worldwide CO_2 emissions [3], [4]. Regarding wireless communications as a principal component of ICT, CO_2 emissions are expected to increase with the exponential growth in wireless traffic and fast penetration of smart mobile devices. Therefore, analysis of energy efficiency and design of energy-efficient systems in wireless communications have become more essential.

In the CRN literature, limited work has been done to address energy efficiency. Most of the prior research is on the energy efficiency of spectrum sensing and accordingly on spectrum access [5]–[8]. Since spectrum sensing is mostly treated as a task required to ensure a certain degree of primary user (PU) detection reliability and during this period transmission is paused, mostly this period is desired to be minimized for both throughput efficiency and energy consumption concerns. However, as the throughput attained in transmission duration is a function of the total discovered spectrum opportunities and collision rate with the PU traffic, achieved throughput is affected by the sensing duration. Therefore, most of the research considered this tradeoff between sensing and transmission to design throughput-efficient CR systems with low energy consumption. Works in [9]–[11] focus on cooperative sensing and devise energy-efficient solutions by trading-off between energy consumption and cooperative detection performance.

Centralized resource allocation in CRNs, also referred to as *scheduling*, has been well-investigated mostly under throughput efficiency perspective [12], [13]. Besides, fairness and quality-of-service (QoS) issues are also considered in some of the works [13], [14]. To the best of our knowledge, energy efficiency is neglected as a design criteria in CRN scheduling.

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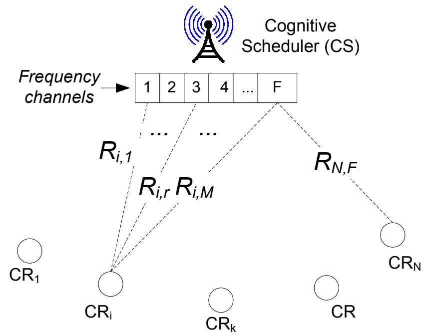
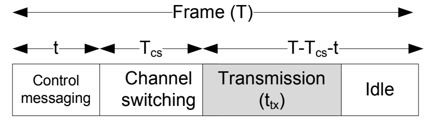


Fig. 1. Each CR_i maintains a link with the CBS for each frequency f denoted by $l_{i,f}$, $i \in \{1,..,N\}$ and $f \in \{1,..,F\}$.



(a) CRs selected for transmission, i.e, $\text{CR}_i \in \mathcal{A}$, switch to the related channel and transmit through that channel.

(b) CRs stay in idle mode if not assigned a frequency.

Fig. 2. Frame organization.

As CRs are expected to possess operation capability within a wide range of spectrum owing to power-intense spectrum sensing tasks, they are expected to operate with high energy efficiency. Furthermore, with the emerging green communications paradigm, CRs are desired to be greener. Hence, cognitive protocols must also be designed with an energy efficiency perspective. In this sense, a cognitive scheduler located at the cognitive base station (CBS) should consider the energy efficiency while determining a schedule.

Contributions of our work can be summarized as follows: we formulate the scheduling problem in CRNs as an energy efficiency maximization problem which is a nonlinear programming (NLP) problem. To overcome this computational complexity, we propose a polynomial time heuristic algorithm, *energy-efficient heuristic scheduler* (EEHS), as a solution to this problem. Next, we study scheduling problem not only from an energy efficiency perspective but also from throughput efficiency perspective. We revise our problem formulation and present two approaches: (1) maximization of throughput in a frame while meeting energy consumption restriction and (2) minimization of energy consumption in a frame while ensuring a desirable throughput performance. The first scheduler is referred to as TMER and the second as EMTG. Both TMER and EMTG incorporate the ratio of traffic successfully sent by a CR as a fairness criteria in their objective functions. We compare performance of EEHS, TMER and EMTG with the throughput maximizing scheduler that only aims to increase the total throughput of the CRN. Numerical analysis show that all the proposed schemes improve energy efficiency of the CRN while not sacrificing drastically from the throughput performance. As EEHS has no consideration of fairness, it may lead to starvation in some CRs. On the contrary, EMTG and TMER can support a fair, throughput and energy-efficient spectrum allocation. Different from previous works in the literature, we also consider a realistic scenario where the wireless spectrum is fragmented into various frequency bands which are spectrally distant from each other. To the best of our knowledge, our work is the only work in the literature that considers a fragmented spectrum rather than spectrum as a collection of contiguous bands.

The rest of this paper is organized as follows. Section II presents the system model and assumptions. Next, Section III introduces the problem formulation and proposed solutions for the formulated NLP problem. Section IV demonstrates the performance analysis of each scheduler derived from the simulations. For each scheduling scheme, energy efficiency, throughput, bandwidth of channel switchings, and energy consumption are analyzed. Finally, Section V concludes the paper.

II. System Model and Assumptions

We consider a centralized CRN serving N CRs as in Fig. 1. The primary network (PN) has F non-overlapping orthogonal frequencies. Occupancy state of each primary channel is modeled as a two-state Markov chain [15], two states representing the *idle* and *busy* state of the channel. The probability of a channel's being idle is p_{idle}. Both PN and CRN operate in a time-synchronized manner, the latter being synchronized with the former. We assume that PU spectrum occupancy is retrieved by cognitive base station (CBS) from an external entity such as a *white space database* [16]. With the latest regulations [17], such database based CR systems have gained noticeable interest due to its higher potential for turning CRs into practical networks. The retrieved information is assumed to be reliable, and CRs access the assigned frequency without performing spectrum analysis.

Let $l_{i,f}$ denotes the channel between CR_i and CBS at frequency f. At the beginning of each frame, each CR sends its state to the CBS as $[\mathbf{R}_i, Q_i]$. $\mathbf{R}_i = [R_{i,f}]$ is the vector denoting the number of bits that can be transmitted in a frame through each $l_{i,f}$, and Q_i is the number of bits in CR_i's buffer. As all information is gathered at CBS, it determines a transmission schedule applying its scheduling policy and broadcasts it to the CRs. All these transactions are completed in control messaging period which takes t units of time. We assume that control messaging period is significantly shorter compared to other periods. Hence, for the sake of simplicity, we trait it as if $t = 0$. Let $\mathcal{A}$ denotes the set of CRs that are assigned a frequency. CRs in $\mathcal{A}$ tune their antennas to the assigned frequencies and begin transmission while others stay in idling state till the end of frame. CRs switch to idling state after completion of transmission. Fig. 2 depicts frame organization for these two cases.

A. Link Capacity Calculation with Channel Switching Cost

Capacity of $l_{i,f}$ depends on the bandwidth of the channel (W) and signal-to-noise ratio (SNR) of the link. In addition, number of bits that can be sent through this link in a frame is determined by the time spent for tuning the CR's RF front-end to this frequency. In the literature, total time spent during all these necessary RF front-end hardware configurations is referred to as *channel switching latency* and it is considered as a linear function of total frequency distance between the former (f') and the latter frequencies (f) [18]–[21]. Accordingly, channel switching latency denoted by T_{cs} is calculated as follows:

$$T_{cs} = t_{cs}|f - f'| \tag{1}$$

where t_{cs} represents the delay for switching unit bandwidth.

Let $B_{i,f}$ be the channel capacity of $l_{i,f}$ calculated by Shannon's formula and $R_{i,f}$ be the maximum number of bits that can be sent by CR$_i$ at link $l_{i,f}$ during a frame. $B_{i,f}$ and $R_{i,f}$ are calculated as follows:

$$B_{i,f} = W \log_2(1 + SNR_{i,f}) \qquad \text{bits/second,} \tag{2}$$

$$R_{i,f} = B_{i,f}(T - T^{i,f}_{cs}) \qquad \text{bits} \tag{3}$$

where W is the channel bandwidth, $SNR_{i,f}$ is the signal-to-noise ratio of $l_{i,f}$, T is the frame duration, and $T^{i,f}_{cs}$ is the channel switching time for CR$_i$ to switch to frequency f. However, CR$_i$ cannot transmit more than the number of bits in its buffer. Hence, effective rate of $l_{i,f}$ denoted by $C_{i,f}$ is restricted by both $R_{i,f}$ and number of bits in CR$_i$'s buffer. $C_{i,f}$ is calculated as follows:

$$C_{i,f} = \min(R_{i,f}, Q_i) \text{ bits.} \tag{4}$$

We calculate total CRN throughput as follows:

$$R = \sum_{f=1}^{F} \sum_{i=1}^{N} X_{i,f} C_{i,f} \text{ bits} \tag{5}$$

$X_{i,f}$ standing for the binary decision variable that represents the allocation state of CR$_i$ at frequency f, i.e. $X_{i,f} = 1$ if f is assigned to CR$_i$, and $X_{i,f} = 0$ otherwise.

B. Energy Consumption Modeling

Considering the frame organization depicted in Fig. 2, we can model energy consumption of a CRN. If CR$_i$ is assigned a frequency (CR$_i \in \mathcal{A}$), first it tunes its antenna to the assigned frequency which takes T_{cs} time units. Next, CR begins transmission. As the transmission is completed, it switches to the idling state and keeps idle till the end of the frame. If CR$_i$ is not assigned a frequency (i.e., CR$_i \notin \mathcal{A}$), CR$_i$ waits idle in this frame.

Since wireless interfaces are the dominant sources of energy consumption in a wireless device [22], we ignore energy consumption due to information processing. Energy consumption of a CR in such a CRN setting is due to various tasks and components:

1) Transmission (E_{tx}): The CRs that are scheduled for transmission consume transmission energy while those that are not assigned any frequencies stay in *idling* state. The transmission power (P_{tx}) is assumed to be constant. Energy consumption during transmission (E_{tx}) is proportional to the transmission duration and P_{tx}. Transmission duration of CR$_i$ at frequency f denoted by $t^{i,f}_{tx}$ is calculated as follows:

$$t^{i,f}_{tx} = \frac{C_{i,f}}{B_{i,f}} \text{ seconds.} \tag{6}$$

Consequently, E_{tx} is calculated as $E_{tx} = P_{tx} t^{i,f}_{tx}$.

2) Circuitry (E_c): Power consumed by electronic circuits (e.g. digital-to-analog converters, mixers, filters, etc.) of a mobile device during transmission is referred to as *circuit power* (P_c). It is almost constant and assumed to be independent of the transmission rate. Energy consumption due to circuitry equals to $P_c t^{i,f}_{tx}$.

3) Channel switching (E_{cs}): E_{cs} represents the energy consumed for configuring the hardware from current transmission frequency (f') to the assigned transmission frequency (f). We model total energy consumption due to channel switching (E_{cs}) as follows:

$$E_{cs} = P_{cs} T^{i,f}_{cs} \text{ Joules} \tag{7}$$

where P_{cs} is the power dissipation for switching and $T^{i,f}_{cs} = t_{cs}|f - f'|$. Due to channel switching, transmission duration is decreased to $T - T^{i,f}_{cs}$ seconds.

4) Idling (E_d): As mentioned above, CRs that are not selected for transmission stay idle. Hence, they consume idling power (P_d) for a duration of T which results in energy consumption $E_d = P_d T$. Moreover, the CRs selected for transmission switch to idling state till the end of the frame once they complete transmission of all the bits in their buffers. In this case, idling time is $T - T^{i,f}_{cs} - t^{i,f}_{tx}$ seconds.

Taking all the above states into account, energy consumption of CR$_i$ at frequency f is formulated as follows:

$$E_{i,f} = (P_{tx} + P_c) t^{i,f}_{tx} + P_d(T - T^{i,f}_{cs} - t^{i,f}_{tx}) + P_{cs} T^{i,f}_{cs}. \tag{8}$$

In the above formulation, the first term is due to transmission, whereas the second is due to idling and the third due to channel switching. Consequently, total energy consumption of a CRN in a frame is calculated as follows:

$$E = \sum_{\substack{\forall i, \\ CR_i \in \mathcal{A}}} \sum_{f=1}^{F} E_{i,f} X_{i,f} + \sum_{\substack{\forall i, \\ CR_i \notin \mathcal{A}}} P_d T \text{ Joules.} \tag{9}$$

In the above formula, the first term is due to CRs that are assigned a frequency and the second term is due to CRs that do not transmit.

III. Energy-Efficient Scheduling in CRNs

Formally, energy efficiency is defined as the throughput obtained per unit energy consumed in an observation period T. Directly derived from this formal definition, *bits-per-Joule* capacity [23] serves as a metric for measuring energy efficiency of a network. Using (5) and (9) to compute total CRN throughput (R) and total CRN energy consumption (E)

respectively, we can calculate the energy efficiency of the CRN as follows:

$$\eta = \frac{R}{E} \qquad \text{bits/Joule.} \tag{10}$$

Subsequently, we formulate the energy efficiency maximization problem as follows:

$$\mathbf{P1}: \quad \max_{\vec{x}} \ \eta \tag{11}$$

$$s.t. \quad \sum_{f=1}^{F} X_{i,f} \leqslant 1 \ , \ i \in \{1,..,N\} \tag{12}$$

$$\sum_{i=1}^{N} X_{i,f} \leqslant 1 \ , \ f \in \{1,..,F\} \tag{13}$$

$$X_{i,f} \in \{0,1\} \tag{14}$$

where $\vec{x} = [X_{i,f}, \ i \in \{1,..,N\} \ , \ f \in \{1,..,F\}]$ is the allocation vector with elements $X_{i,f}$. Constraint (12) ensures that each CR is assigned to at most one frequency due to our assumption that CRs all have a single antenna. We consider an overlay model in which only one CR is active at a frequency at a specific time. Constraint (13) guarantees this by preventing simultaneous transmissions in a frequency band. Constraint (14) denotes $X_{i,f}$ is a binary variable.

The scheduler solves **P1** (11) at the beginning of each frame and broadcasts the scheduling decision $\vec{x}$. In sequel, CRs tune their antennas to the assigned frequencies if they are selected for transmission. However, **P1** is not computationally easy to solve due to the nonlinear objective function. The optimal solution of **P1** can be discovered by exhaustive search for small instances of the problem. However, such a solution approach is inappropriate for practical networks with many CRs and frequencies. For example, for $F = 20$ idle frequencies and $N = 40$ CRs with a transmission request, the search space consisting of all possible assignments has $\sum_{i=0}^{F} \frac{F!}{(F-i)!i!} \frac{N!}{(N-i)!}$ elements. Scheduling should be both efficient and computationally easy. Therefore, we propose *Energy-Efficient Heuristic Scheduler* (EEHS) which is a polynomial time heuristic algorithm for **P1**. Furthermore, it may be subject to low throughput performance since it does not explicitly aim to ensure high throughput performance. Therefore, we can reorganize the problem in (11) such that throughput is maximized with some restrictions on energy consumption per frame, and alternatively we can define an energy consumption minimization problem with minimum throughput guarantees. In the following subsections, we define these scheduling schemes.

A. Energy-Efficient Heuristic Scheduler (EEHS)

Let $\mathcal{C}_{idle}$ denotes the set of idle frequencies, $\mathcal{R} = \{C_{i,f}\}$ be the set of effective rate of each link $l_{i,f}$, and $\mathcal{N}_{tx}$ be the set of CRs with a transmission request (i.e., CR$_i$ with $Q_i > 0$). Let $\mathcal{E} = \{E_{i,f}\}$ denotes the set of energy consumption values if CR$_i$ is assigned to frequency f and transmits at this frequency. The cardinality of $\mathcal{C}_{idle}$ denoted by $|\mathcal{C}_{idle}|$ equals to the number of idle frequencies. Number of CRs with a transmission request is $N_{tx} = |\mathcal{N}_{tx}|$.

Let $\eta_{i,f}$ be the resulting energy efficiency of CR$_i$'s transmission through f. $\eta_{i,f}$ is formulated as:

$$\eta_{i,f} = \frac{C_{i,f}}{E_{i,f}}. \tag{15}$$

The energy-efficient heuristic scheduler (EEHS) greedily assigns each idle frequency to the CR that can attain the maximum energy efficiency at this frequency, i.e. highest $\eta_{i,f}$. EEHS operates applying the steps listed in Algorithm 1. Briefly, if there are more CRs than the number of idle frequencies (Line 1), then the *best CR* denoted by CR_{i*} for each idle frequency is selected in channel assignment. We call the CR achieving the highest energy efficiency at a frequency *the best CR* for f (i.e., CR$_{i*}$ where $i* = \arg\max_i \eta_{i,f}$ in Line 4). In case of ties, CR with higher effective rate, i.e., larger $C_{i,f}$, is selected for this frequency. If there are plenty of frequencies (Line 8), then the *best frequency* denoted by f^* is selected for each CR in $\mathcal{N}_{tx}$. The frequency at which CR$_i$ maintains the highest energy efficiency is the best frequency for this CR. After a frequency is assigned to a CR, it is removed from the set of idle frequencies (Line 13). Likewise, if CR$_i$ is assigned a frequency, it is removed from $\mathcal{N}_{tx}$ (Line 6).

Algorithm 1 Energy-efficient heuristic scheduler: EEHS

Require: $\mathcal{C}_{idle}$, $\mathcal{R}$, $\mathcal{E}$.
Ensure: Assignment vector $\vec{x} : [(f, CR_i)]$, $f \in \mathcal{C}_{idle}$ and CR$_i \in \mathcal{N}_{tx}$.

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1:  if |C_idle| < N_tx then
2:      for all f ∈ C_idle do
3:          η_{i,f} = C_{i,f} / E_{i,f},  ∀ CR_i ∈ N_tx
4:          i* ← arg max_i η_{i,f}
5:          Add (f, CR_{i*}) to the assignment vector
6:          N_tx ← N_tx \ CR_{i*}
7:      end for
8:  else
9:      for all CR_i ∈ N_tx do
10:         η_{i,f} = C_{i,f} / E_{i,f},  ∀f ∈ C_idle
11:         f* ← arg max_f η_{i,f}
12:         Add (f*, CR_i) to the assignment vector
13:         C_idle ← C_idle \ f*
14:     end for
15: end if
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The above algorithm operates in polynomial time for a constant F. More particularly, it is in the order of $O(Fp_{idle}N_{tx})$ complexity where Fp_{idle} is the expected number of idle channels. As N_{tx} is a function of number of CRs (N), complexity of EEHS can be written as $O(FN)$.

B. Throughput Maximizing scheduler with an Energy consumption Restriction (TMER)

Instead of formulating the centralized resource allocation problem as an energy efficiency maximization problem, we can formulate it as a throughput maximization problem with a restriction on energy consumption (TMER). Let assume that E_{max} is the maximum allowed energy consumption for a frame. It is a constant value determined by the scheduler at each frame and can be tuned for the desired operation point. Let K be the number of CRs in transmission, α the average number of channel switchings per user, and T_d be the average idling time of CRs after transmission. Accordingly, E_{max} is calculated as follows:

$$E_{max} = \beta(K[(P_{tx} + P_c)(T - \alpha t_{cs} - T_d) + P_d T_d + P_{cs}\alpha t_{cs}] + (N - K)P_d T) \quad (16)$$

In the above formula, $\beta \in (0, 1]$ is the energy-throughput tradeoff parameter. Number of CRs in transmission is simply the minimum of number of CRs with a transmission request (N_{tx}) and number of idle channels ($|\mathcal{C}_{idle}|$):

$$K = \min(N_{tx}, |\mathcal{C}_{idle}|). \quad (17)$$

Next, average idling time of CRs after transmission (T_d) is computed as follows:

$$T_d = T - \alpha t_{cs} - T_{avg} \quad (18)$$

where T_{avg} is the average transmission time of a CR. T_{avg} is the time required for transmitting all bits in the CR's buffer. However, as this time may be greater than the effective time available for transmission, i.e., $T - \alpha t_{cs}$, we take the minimum of these values as below:

$$T_{avg} = \min(\frac{Q_{avg}}{R_{avg}}, T - \alpha t_{cs}) \quad (19)$$

$$Q_{avg} = \frac{\sum_i Q_i}{N_{tx}} \qquad i, CR_i \in \mathcal{N}_{tx} \quad (20)$$

$$R_{avg} = \frac{\sum_i \sum_f B_{i,f}}{|\mathcal{C}_{idle}| N_{tx}} \qquad f \in \mathcal{C}_{idle}. \quad (21)$$

Q_{avg} in (20) and R_{avg} in (21) denote the average queue size of CRs with transmission request and average rate of idle channels, respectively.

As a scheduler is desired to be fair in resource allocation, we define a metric called *satisfaction ratio* (ω_i) which is simply the ratio of CR$_i$'s transmitted traffic to its total generated traffic up to current time. We use satisfaction ratio as a kind of fairness criteria in our scheduler. Therefore, $(1 - \omega_i)$ in the objective serves to ensure a notion of fairness and favor the CRs with lower ω_i. TMER can be formulated as below:

$$\textbf{P2:} \quad \max_{\vec{x}} \sum_{i=1}^{N} \sum_{f=1}^{F} (1 - \omega_i) X_{i,f} C_{i,f} \quad (22)$$

$$\text{s.t.} \quad \sum_{\substack{\forall i,\\ CR_i \in \mathcal{A}}} \sum_{f=1}^{F} E_{i,f} X_{i,f} + \sum_{\substack{\forall i,\\ CR_i \notin \mathcal{A}}} P_d T \leqslant E_{max} \quad (23)$$

$$K_1 \leqslant \sum_{i=1}^{N} \sum_{f=1}^{F} X_{i,f} \leqslant K \quad (24)$$

and subject to Constraints (12), (13) and (14). Constraint (24) ensures that at least K_1 CRs are allocated an idle frequency. Setting $K_1 = K$, we can ensure that all idle channels are allocated to CRs, or all CRs with a transmission request are assigned a frequency if $N_{tx} < |C_{idle}|$. Recall $K = \min(N_{tx}, |\mathcal{C}_{idle}|)$. Otherwise, this scheduler may leave some channels unused although being idle. **P2** is a variant of **P1** which is a linear integer programming (LP) problem, and can be solved using an optimization software such as CPLEX [24].

C. Energy consumption Minimizing scheduler with a Throughput Guarantee constraint (EMTG)

Similar to **P2**, we can formulate an energy consumption minimization problem with minimum throughput guarantees (EMTG) as follows:

$$\textbf{P3:} \quad \min_{\vec{x}} \sum_{i=1}^{N} \sum_{f=1}^{F} \omega_i X_{i,f} E_{i,f} \quad (25)$$

$$\text{s.t.} \quad R_{min} \leqslant \sum_{i=1}^{N} \sum_{f=1}^{F} X_{i,f} C_{i,f} \quad (26)$$

$$R_{min} = \beta K T_{avg} R_{avg} \quad (27)$$

$$K_2 \leqslant \sum_{i=1}^{N} \sum_{f=1}^{F} X_{i,f} \leqslant K \quad (28)$$

and subject to Constraints (12), (13) and (14). Constraint (26) ensures at least R_{min} throughput is attained in a frame while energy consumption is minimized. Similar to E_{max}, R_{min} is a constant value determined by the scheduler as in (27). By Constraint (28), at least K_2 CRs are assigned a frequency in a frame.

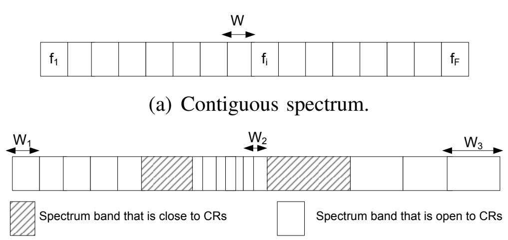
Both TMER and EMTG schedulers can be changed into schedulers ignoring fairness by setting $\omega_i = 0$ for TMER, and $\omega_i = 1$ for EMTG. Regarding computational complexity of TMER and EMTG, both solve an LP problem. If we model the frequency assignment problem using bipartite graphs (CRs as vertices in V_1 and frequencies in the other vertex group V_2, $V_1 \cap V_2 = \emptyset$), throughput maximization corresponds to *maximum weighted matching* in this bipartite graph. In this model, $(1 - \omega_i)C_{i,f}$ is the weight of the edge between vertex i and vertex f. Likewise, frequency assignment in EMTG can be modeled using *minimum weighted bipartite matching*. However, we have additional energy consumption (Constraint in 23) and minimum throughput constraint (Constraint in 26). In the literature, there are various algorithms running in polynomial time for maximum/minimum weighted bipartite matching, e.g. $O(|F|^3)$ as in Hungarian algorithm [25]. Using the solutions in the literature and dealing with the additional constraints, EMTG and TMER optimization problems can be solved efficiently.

IV. Performance Evaluation

Basic performance metrics are probability of success (P_s), energy consumption, and energy efficiency (η). Probability of success represents the fraction of the generated CR traffic that is delivered successfully. We use it as a means to evaluate throughput performance. First, we deactivate fairness in TMER and EMTG schedulers by appropriately setting ω values. In the last set of scenarios, we evaluate the fairness of each scheduler. Simulations are performed on our discrete event simulator developed in Java while ILOG CPLEX [24] is used for solving optimization problems **P2** and **P3**.

TABLE I
SUMMARY OF SYMBOLS AND BASIC SIMULATION PARAMETERS

Symbol	Description	Value/metric
$X_{i,f}$	Binary decision variable denoting whether CR$_i$ is assigned to frequency f	$\{0, 1\}$
$B_{i,f}$	Achievable rate of $l_{i,f}$ if used by CR$_i$	bits/second
$R_{i,f}$	Number of bits that can be transmitted at $l_{i,f}$ in a frame if used by CR$_i$	bits/frame
$C_{i,f}$	Effective rate of $l_{i,f}$ if CR$_i$ transmits at f	bits
Q_i	Number of bits in CR$_i$'s buffer	bits
T	Frame duration	100 ms
W	Channel bandwidth	5 MHz
F	Number of frequencies	[5,50]
N	Number of CRs	[5,40]
P_{tx}	Transmission power	1980 mW
P_d	Idling power	990 mW
P_c	Circuit power	210 mW
P_{cs}	Channel switching power	1000 mW
t_{cs}	Channel switching latency	0.1 ms/MHz
λ	Average number of packets generated by a CR in a frame	4.7 packets
α	Average number of channel switching	F/10
β	Energy-throughput tradeoff parameter	(0,1]
E_{max}	Maximum allowed energy consumption in a frame	mJ
R_{min}	Minimum throughput to be achieved in a frame	bits



(a) Contiguous spectrum.

(b) Fragmented spectrum.

Fig. 3. Spectrum organization.

As benchmark, we also present performance of maximum rate heuristic scheduler (MRHS) in the following scenarios. MRHS is a well-known and commonly applied heuristic scheduler that aims to maximize total throughput of the CRN in a frame. Simply, MRHS assigns each idle frequency f to the CR with maximum effective rate ($C_{i,f}$) as opposed to EEHS which assigns frequency f to the CR which will attain maximum energy efficiency ($\frac{C_{i,f}}{E_{i,f}}$) at frequency f. Similar to EEHS, MRHS has polynomial time complexity, i.e. linear in N and F. Performance improvement in energy efficiency achieved by a scheduler S over the reference scheduler (i.e., MRHS) can be computed as *energy saving ratio* (ESR). It is calculated as follows:

$$ESR_S = (\frac{\eta_S}{\eta_{MRHS}}) \tag{29}$$

where η_S is the energy efficiency achieved by S.

Two spectrum occupancy scenarios are analyzed. In the first (Fig. 3(a)), CRN operates on a contiguous spectrum of F bands all with equal bandwidth, whereas in the second (Fig. 3(b)) frequency bands are fragmented. The second scenario is more realistic: since some of the spectrum is for the exclusive use of PUs such as military bands, that part of the spectrum is closed for CR access. Moreover, spectrum is divided into bands with various bandwidths, e.g. GSM has 200 kHz bands while WLAN has 22 MHz channels. Thus, spectrum for CRN's use becomes collection of various frequency bands with non-identical bandwidth and spectrally separated from each other. Actual location of an opportunity is important since channel switching is a function of spectral separation of two frequencies. In our analysis, we only consider fragmented spectrum of identical bandwidth channels for analyzing the effect of spectral distance in the fragmented scenario and ignore any other factors.

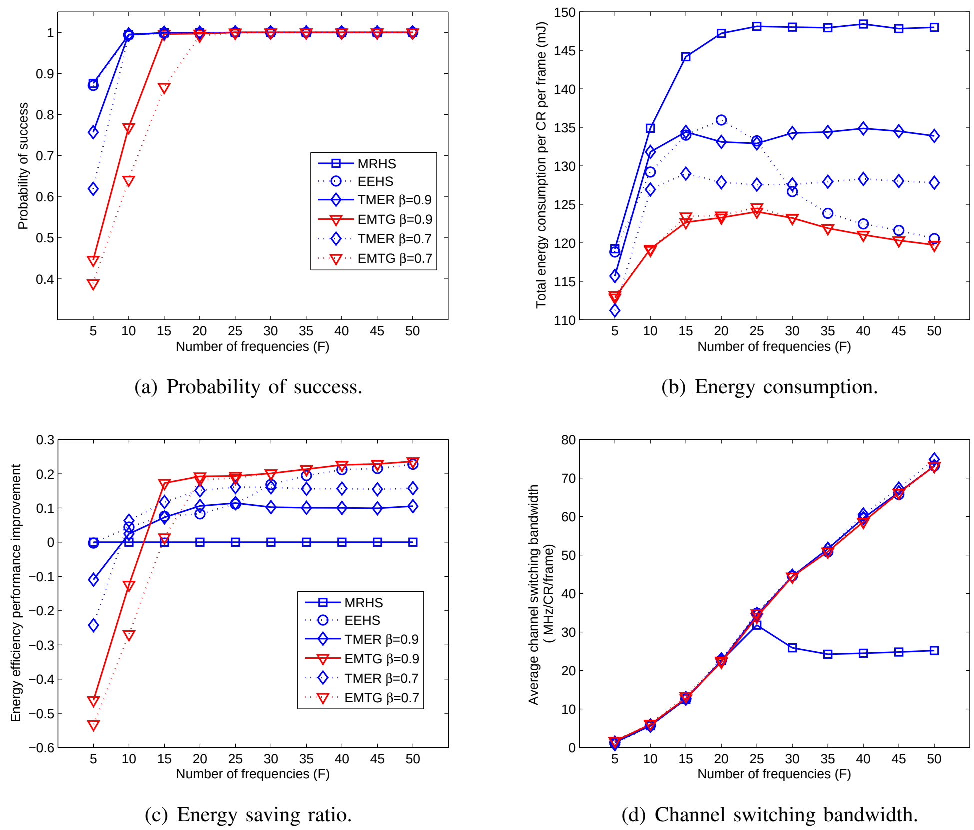
We assume CR traffic follows a batch Bernoulli process. In the literature [18], generally CRs are assumed to have infinite queue backlogs, i.e. they can transmit as much as the link capacity lets. This approach simplifies the analysis and facilitates the mechanisms to be assessed under full capacity without being restricted by the CR traffic process, however it is not realistic. In our simulations, each CR probabilistically generates i packets with probability p_i which makes $\lambda = \sum_i ip_i$ packets in a frame on the average.

In the following, results are collected from ten independent runs for scheduling performed over 200 consecutive frames. In our runs, we set $\lambda = 4.7$ packets/frame for each CR and each packet is assumed to be 60 Kb. We set $\alpha = F/10$. In all scenarios, channel switching latency t_{cs} is set to $0.1ms/1MHz$. SNR of a link is assumed to follow an exponential process with mean SNR=2.5dB. Table I summarizes the symbols and basic simulation parameters. Note that relationship among power values is as follows: $P_d < P_{cs} < P_{tx}$. We utilize the power consumption profile of a WLAN interface [1] to determine these power consumption components. To the best of our knowledge, there is not any specification denoting the power consumption of channel switching. Therefore, we assume that P_{cs} is larger than idling power and smaller than transmission power. In order to avoid infeasible solutions, we set $K_1 = K - 2$ and $K_2 = K$ for contiguous spectrum and $K_1 = K/2$ and $K_2 = 0$ for fragmented spectrum.

A. Contiguous Spectrum

In this scenario, first we set $N = 20$ and analyze the effect of increasing F. Next, we set $F = 20$ and analyze the effect of increasing N.

Fig. 4 illustrates the effect of increasing number of frequencies on the performance of schedulers. The CR traffic load changes from 2.2 (for $F = 5$) to 0.22 (for $F = 50$). As shown in Fig. 4(a), increase in F also leads to an increase in success probability. TMER and EEHS perform as good as MRHS almost for all F values while EMTG schedulers are close to MRHS in throughput performance for $F \geqslant 20$. For $F \geqslant 20$, although all schedulers achieve similar throughput performance (i.e., $P_s = 1$), they differ in total energy consumption. As Fig. 4(b) depicts, EMTGs have the lowest energy consumption while MRHS always consumes the highest energy. For increasing F, energy consumption increases for a while which is caused by more CRs having



(a) Probability of success.

(b) Energy consumption.

(c) Energy saving ratio.

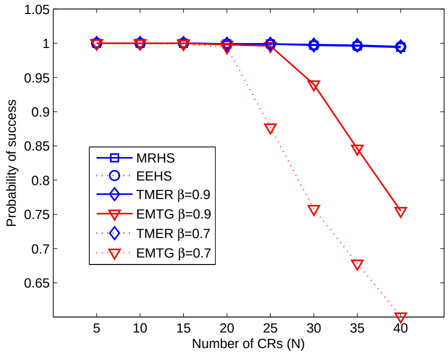
(d) Channel switching bandwidth.

Fig. 4. Performance figures of scheduling schemes with increasing F under contiguous spectrum.

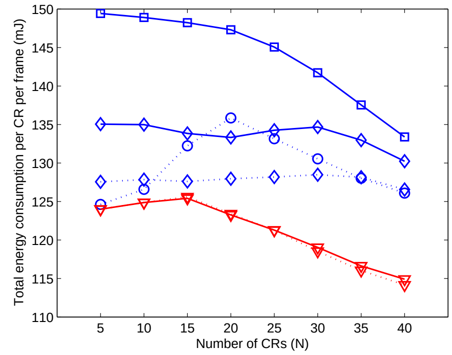
chance to transmit. After some point (e.g. $F = 20$ for EEHS), energy consumption of proposed schedulers decreases with increasing F. Since there exists a huge amount of available resources, proposed schedulers assign the frequency that will lead to lower energy consumption. Moreover, since more frequencies are available, CRs' queues are shorter in general. That is, CRs can transmit quickly and switch to low-energy-consuming idling state. On the other hand, energy consumption in MRHS does not change significantly as it lacks an energy consumption perspective. Regarding ESR in Fig. 4(c), EEHS has always better performance than MRHS and it attains significant improvement in energy efficiency for $F \geqslant 25$. To be more exact, for $F = 25$ EEHS transmits 9% more bits with the same energy consumption compared to MRHS. Its ESR changes from -0.002 to 0.23. For high load (low F), EMTGs have low throughput performance leading to low energy efficiency. However, as there are more resources available in the system, EMTGs become more favorable owing to their lower operation energy costs. ESR changes from -0.53 (significantly lower energy efficiency) to 0.24 for EMTG. We observe that P_s values for TMER and EMTG with $\beta = 0.9$ are higher than their counterparts with $\beta = 0.7$ only for low F. For $F \geqslant 10$, TMER with $\beta = 0.9$ and $\beta = 0.7$ have the same throughput performance. Similarly, for $F \geqslant 20$, EMTG with $\beta = 0.9$ and $\beta = 0.7$ attain similar throughput. On the other hand, achieved improvement in energy efficiency by TMER with $\beta = 0.9$ is lower than TMER with $\beta = 0.7$ while there is not a significant difference between EMTG with $\beta = 0.9$ and $\beta = 0.7$. Hence, CBS can set $\beta = 0.7$ for TMER in order to attain higher energy efficiency. However, β parameter does not significantly affect EMTG scheduler for $F \geqslant 20$. Performance of TMER and EMTGs directly depend on our estimate of expected energy consumption and expected throughput, i.e, E_{max} and R_{min}, respectively. Hence, appropriate estimation of E_{max} and R_{min} is paramount. Considering the throughput performance in Fig. 4(a), it is seen that our estimations are appropriate for $F \geqslant 20$.

Time and energy spent on channel switching depends on the number of frequencies in the system. Channel switching bandwidth increase with increasing F for the proposed schedulers. For $F = 50$, average channel switching distance is around 75 MHz. While it follows the same trend for MRHS for $F < 25$, channel switching bandwidth begins to decrease after that point. This is caused by the fact that for $N = 20$ and $F > 25$ each CR can be assigned a frequency for transmission without switching to very distant frequencies. Given that $t_{cs} = 0.1ms/MHz$, total channel switching time is around 7.5 ms ($T_{cs} = 75MHz \times 0.1ms/MHz$) for TMERs, EMTGs and EEHS, and shorter for MRHS. For $T = 100$ ms, 92.5% of the frame is effectively useable. Since spectrum is contiguous and t_{cs} is small, channel switching does not noticeably affect the performance of the schedulers.

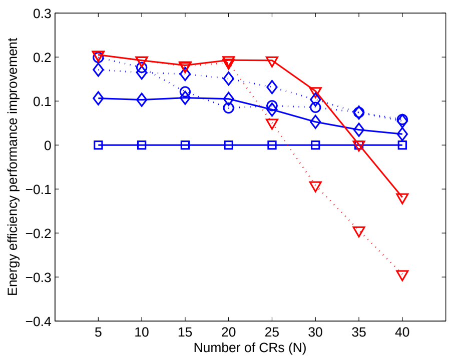
Given the fact that CR operators ensure a certain degree of success rate by various admission control techniques, a typical operation scenario is that CR load is kept at reasonable values. Therefore, in such scenarios, e.g. $F \geqslant 20$ corresponding to



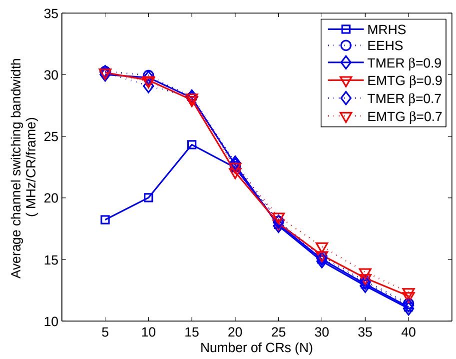
(a) Probability of success.



(b) Energy consumption.



(c) Energy saving ratio.



(d) Channel switching bandwidth.

Fig. 5. Performance figures of scheduling schemes with increasing F under contiguous spectrum.

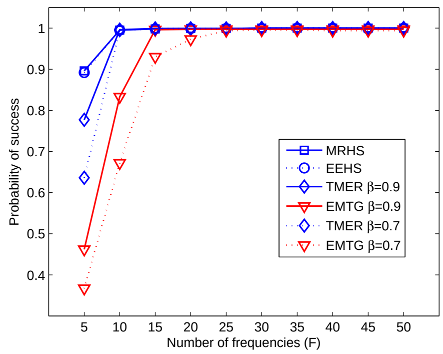
0.56 CR load, success rates attained by EEHS, EMTG and TMERs are the same as that of MRHS and energy efficiencies are higher. Hence, any of EEHS, TMER or EMTG should be the choice for energy-efficient CRN scheduling. For small F, in case a slight throughput sacrifice is tolerable, EEHS and TMER schedulers can be the choice since they consume lower energy compared to MRHS. Performance of EEHS is also compared to the optimal solution of problem **P1** in [26]. We showed that EEHS has comparable performance to that of the optimal solution. As EEHS has low complexity, we consider it as an efficient solution for maximum energy-efficiency scheduling problem.

Fig. 5 demonstrates the performance of schedulers with increasing number of CRs for $F = 20$. This scenario is similar to the previous scenario in a way that increase in N represents the increase in CR traffic load (and corresponds to decrease in F). For low number of CRs (as in high F), all schedulers have higher energy efficiency performance than that of MRHS while EMTGs consume the lowest energy. Throughput and energy efficiency performance of EMTG drastically decrease with increasing N. However, note that for $N = 40$ traffic load is 1.1 which is much more higher than that would be allowed in operational networks. A typical operation point would be $N = 20$ for $F = 20$ corresponding to load of 0.56. At this point, EMTGs are more energy-efficient and have the same throughput performance as MRHS. In all schemes, average channel switching bandwidth decreases with increasing N. This is not surprising since there are many CRs requesting frequency, and the ones which will require lower channel switching are in general more favorable in terms of throughput and energy efficiency. ESR of EEHS changes from 0.20 to 0.06 while it changes from 0.21 to -0.12 for EMTGs and 0.18 to 0.06 for TMERs.

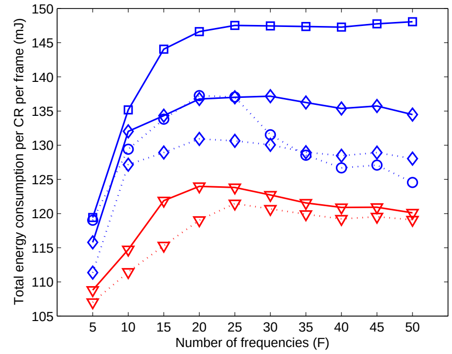
B. Fragmented Spectrum

In the previous scenarios, we have contiguous block of spectrum bands. As an example, for $F = 20$ and $W = 5$ MHz, there is totally 100 MHz bandwidth as spectrum resource for CRN's use. In this scenario, let us have the same total bandwidth but in a fragmented way. Let assume CRN can use ten channels at 470-520 MHz, five channels at 600-625 MHz and thirty channels at 2400-2575 MHz bands. We refer each block of channels as *spectrum fragment* in the following. We assume all channels have 5 MHz bandwidth. Moreover, all channels have exactly the same two-state model leading to identical probability of being idle values (p_{idle}=0.7).

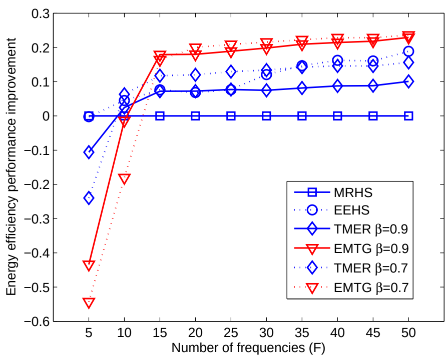
Fig. 6 summarizes the performance figures of schedulers under fragmented spectrum for increasing F. The results agree with the previous runs in which contiguous spectrum is considered. MRHS has lower energy efficiency than that of EEHS and TMERs. Average channel switching bandwidth is around 20-30 MHz for EMTGs and MRHS whereas it is around 50 MHz for TMERs and EEHS, lower than the contiguous case. Comparing these results with the contiguous spectrum case,



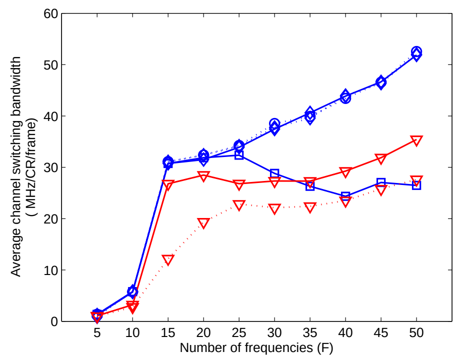
(a) Probability of success.



(b) Energy consumption.



(c) Energy saving ratio.



(d) Channel switching bandwidth.

Fig. 6. Performance figures of scheduling schemes with increasing F under fragmented spectrum.

we conclude that each scheduler tries to allocate the CRs to its close frequency bands in the same fragment. Therefore, despite the spectrum being fragmented, average channel switching bandwidth is lower than the contiguous spectrum case. Fig. 7 corroborates this explanation.

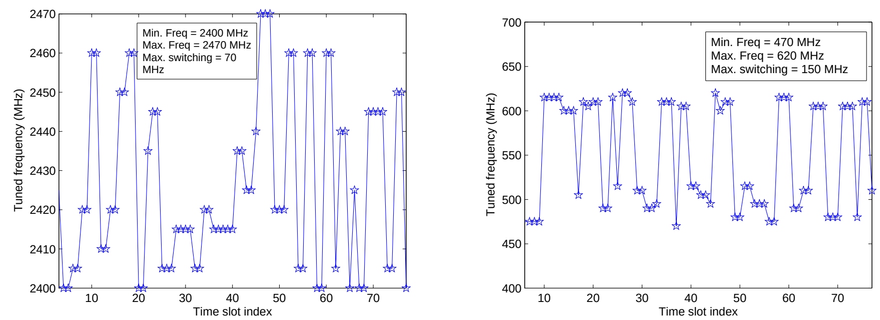
We randomly select a CR and record its antenna configuration, i.e., the frequency it is tuned to, through the simulation duration for each frame for $F = 50$ under EEHS. Fig. 7 depicts the frequencies for both contiguous and fragmented spectrum. Minimum and maximum operation frequencies are also written on the figures. The scheduler behaves as if CRs are partitioned in three classes, and each CR in a class is usually assigned a frequency in the corresponding spectrum fragment. For the fragmented spectrum scenario (Fig. 7(b)), this CR operates in the first and second fragment, and never hops to the 2400 MHz fragment. This CR mostly switches to the frequencies in the same fragment which are only tens of MHz distant. As we set $t_{cs} = 0.1ms/MHz$ and perform channel switching only before transmission, CRs cannot hop between fragments of the spectrum due to *infeasibility* of switching. For $F = 50$, spectrum consists of 470-520 MHz (ten channels), 600-625 MHz (5 channels) and 2400-2575 MHz (35 channels) bands. Switching from the first fragment to the second is feasible whereas it is not to switch to the 2400 MHz bands. Frequency separation is around [2400-625 MHz, 2425-600 MHz] and it requires channel switching time in the interval [177.5 ms, 182.5 ms] which is much longer than the frame duration. Hence, such assignments are accepted as *infeasible* and are avoided by the scheduler.

With the developments in the hardware technologies, channel switching cost may become negligible. However, current systems incur channel switching cost that may sometimes be comparable to other energy consumption costs. Therefore, it is vital to implement scheduling schemes, especially for operation in the fragmented spectrum, that combats this cost. For instance, if CRs have the ability to tune their antennas in an intelligent way during their idling periods, this switching delay can be hidden with careful scheduling and subsequently operation in all parts of the spectrum becomes possible. However, it still incurs the energy consumption overhead.

To sum up, spectrum fragmentation does not noticeably affect the CRN performance if considered from a network-wide perspective since scheduling schemes tackle fragmentation via careful frequency allocation. If considered from the viewpoint of a single CR, spectrum resources a CR can use is decreased to a smaller portion which may deteriorate the performance of this CR. On the other hand, the set of CRs competing with this CR may be reduced to a smaller set as some CRs are restricted to another portion of the spectrum. Considering these two points, we can conclude that fragmentation, on the average, does not affect the individual CR performance.

C. Fairness in Scheduling

In this section, we analyze each scheduling scheme in terms of fairness criteria. Ensuring a degree of fairness is desirable even if fairness objective may conflict with the objective of



(a) Tuned frequency under contiguous spectrum. (b) Tuned frequency under fragmented spectrum.

Fig. 7. A CR is randomly selected and frequency to which its antenna is tuned is recorded for each frame, $F = 50$, EEHS scheme.

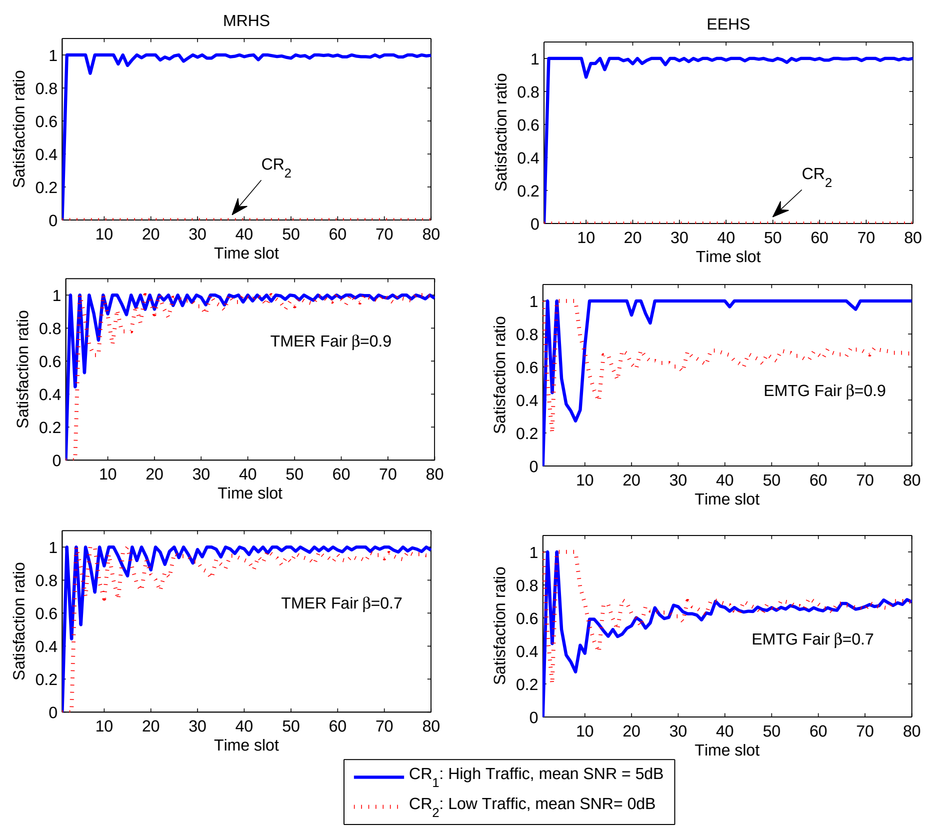


Fig. 8. Change of satisfaction ratios versus time. CR_1 has almost four-fold high traffic compared to CR_2. Additionally, mean SNR of the links associated with CR_1 is 5dB whereas it is 0dB for CR_2.

throughput maximization. Otherwise, some users starve while others may be over allocated. As in opportunistic scheduling, MRHS and EEHS favor CRs leading to higher throughput and higher energy efficiency, respectively. However, ω_i in TMER and EMTG schedulers enable fairness in resource allocation. We interpret fairness in our system in terms of mean satisfaction ratio. In an informal way, we can say that a scheme is more fair than the other if it can keep satisfaction ratios of CRs closer to each other. Formally, we evaluate fairness in terms of *Gini index*. Gini index computes how much resource allocation deviates from the ideal fair allocation [27]. Hence, it can be considered as a measure of inequality. A perfectly fair allocation scheme has Gini index 0 whereas a highly unfair allocation has high Gini index. Let F_{Gini} denotes this index, and it is calculated as follows:

$$F_{Gini} = \frac{1}{2N^2\bar{\omega}} \sum_{i=1}^{N} \sum_{k=1}^{N} |\omega_i - \omega_k| \tag{30}$$

$$\bar{\omega} = \frac{\sum_{i=1}^{N} \omega_i}{N} \tag{31}$$

where ω_i is the satisfaction ratio of CR_i and $\bar{\omega}$ is the mean satisfaction ratio of CRs at the end of the simulation.

For a clear understanding of the behavior of schedulers, we focus on a scenario where CRs have non-homogenous traffic density and non-uniform SNR conditions [27]. Assume that half of the CRs are close to the CBS and therefore have good

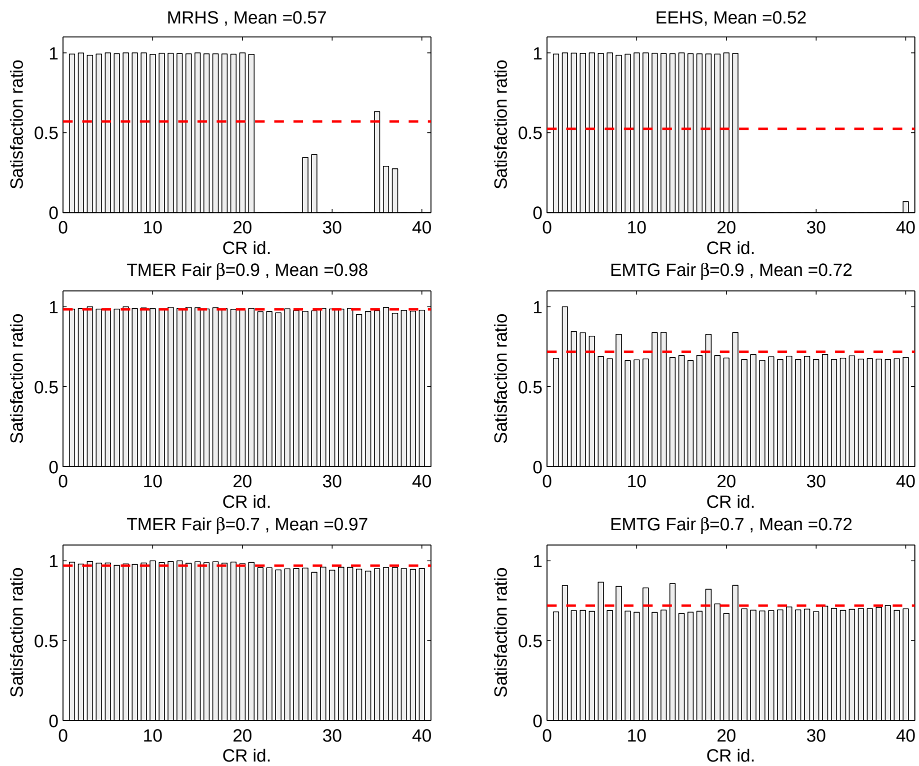


Fig. 9. Satisfaction ratios of CRs under various scheduling schemes.

channel conditions. We reflect this by setting mean SNR = 5 dB for these CRs. In addition, these CRs generate high traffic. The other half (say CRs with identities $\lfloor N/2 \rfloor$,$\lfloor N/2 \rfloor$+1,. . ., N) have lower SNR (SNR=0 dB) and generate low traffic. We assume CRs in the first group generates four-fold traffic that of the second group. There are 40 CRs and 20 frequencies in this setting. For low traffic, each scheme can satisfy a certain degree of fairness since non-served CRs have longer queues (i.e. Q_i) leading to higher $C_{i,f}$ values. Therefore, these CRs are also served. However, for high, non-identical traffic, and non-identical link conditions, scheduling schemes may fall short of providing fairness.

Fig. 8 illustrates the change of satisfaction ratios of two CRs; CR_1 from the first group and CR_2 from the second group. Since CR_2 has bad channel conditions, MRHS and EEHS never allocate frequency to this CR. On the other hand, TMER and EMTG assign a frequency to the CR when its satisfaction ratio decreases for a while. Therefore, satisfaction ratios of CRs are close to each other in TMER and EMTG. The unfairness of MRHS and EEHS can also be seen in Fig. 9. CRs in the first group are always favored in MRHS and EEHS whereas TMER and EMTG distribute resources more fairly.

Table II includes TMER and EMTGs both with and without fairness notion and summarizes the performance of all schedulers for $N = 10$, $N = 30$ and $N = 40$. Please recall that mean satisfaction in the first column is not a metric evaluating the user perceived quality but is simply a representation of the average satisfaction of all CRs and a representation of the throughput performance. For low N, all schedulers have the same throughput and fairness performance (i.e., $P_s = 1$ and $F_{Gini} = 0$). Nevertheless, they differ in energy efficiency profiles. EMTGs yield the highest energy efficiency among all schedulers. Furthermore, we also observe that there is a marginal decrease in energy efficiency when fairness is enabled in TMERs. For $N = 30$, energy efficiencies are lower in general compared to the performance for $N = 10$. This is due to the CRs that stay in idling mode which only contribute to the energy consumption but have no throughput. In this case, TMER Fair schedulers have slightly higher energy efficiencies compared to their counterparts with no fairness notion. As $F < N$, some CRs cannot be assigned frequencies. F_{Gini} values are higher compared to $N = 10$. For $N = 40$, regarding the probability of success results, it can be seen that enabling fairness in TMERs and EMTGs also has a positive effect on throughput performance. Fair schemes compared to the unfair counterparts have higher probability of success and energy efficiency performance for this particular setting. This result conflicts with the general expectation that enabling fairness may deteriorate the throughput performance. On the other hand, the dynamic operation of TMER and EMTGs which depends on both satisfaction ratios (ω_i) and effective channel rates ($C_{i,f}$) challenges such a straightforward conclusion. For instance, TMER tries to maximize weighted sum of the CR throughput but at the same time it has to meet the constraint on energy consumption. Hence, it is not trivial to have a direct generalization that fairness has a positive or negative effect on throughput and energy efficiency performance of TMERs and EMTGs. Since MRHS and EEHS cannot serve CRs in a fair way, F_{Gini} is very high for these schemes. However, for TMERs with fairness enabled it is a perfectly fair system with

TABLE II
SUMMARY OF SIMULATION RESULTS FOR CONTIGUOUS SPECTRUM, HETEROGENOUS CR TRAFFIC AND NON-UNIFORM LINK SNRS, $F = 20$.

	N = 10			N = 30			N = 40		
	P_s	η	F_{Gini}	P_s	η	F_{Gini}	P_s	η	F_{Gini}
MRHS	1.00	2680.21	0.00	0.99	2495.72	0.03	0.85	2350.89	0.40
EEHS	1.00	3027.54	0.00	0.92	2541.96	0.21	0.83	2460.90	0.46
TMER $\beta = 0.9$	1.00	2789.00	0.00	1.00	2622.23	1.00	0.87	2449.94	0.36
TMER Fair $\beta = 0.9$	1.00	2714.28	0.00	1.00	2702.92	0.00	1.00	2720.82	0.00
EMTG $\beta = 0.9$	1.00	3042.45	0.00	0.85	2527.02	0.22	0.68	2066.76	0.34
EMTG Fair $\beta = 0.9$	1.00	3042.23	0.00	0.94	2528.81	0.02	0.78	2117.01	0.02
TMER $\beta = 0.7$	1.00	2945.82	0.00	1.00	2691.24	0.00	0.87	2481.05	0.36
TMER Fair $\beta = 0.7$	1.00	2854.80	0.00	1.00	2733.90	0.00	1.00	2801.39	0.00
EMTG $\beta = 0.7$	1.00	3042.41	0.00	0.75	2212.48	0.21	0.60	1825.42	0.34
EMTG Fair $\beta = 0.7$	1.00	3042.31	0.00	0.89	2364.02	0.03	0.75	2037.88	0.02

$F_{Gini} = 0$. For EMTGs, F_{Gini} is higher than TMER, but still very close to zero.

V. CONCLUSIONS

In this work, we have formulated an energy efficiency maximizing scheduler for cognitive radio networks. First, we have presented EEHS, a heuristic algorithm running in polynomial time, for energy-efficient resource allocation. As EEHS may fall short of throughput efficiency, we have re-formulated resource allocation as throughput maximization problem subject to energy consumption restrictions (TMER) and as an energy consumption minimization problem subject to throughput guarantees (EMTG). TMER and EMTG also have the power to provide fairness among the CRs owing to the satisfaction parameter in their objective functions. Satisfaction ratio of a CR represents the fraction of traffic transmitted by this particular CR up to current time. CRs with lower satisfaction are favored in frequency allocation resulting in their satisfaction ratio to increase, and in turn facilitating less satisfied CRs to be favored in the subsequent frames.

We have evaluated the performance of these schedulers and compared them with the commonly-known throughput maximizing scheduler (MRHS). Moreover, we have focused our attention on the spectrum organization. Spectrum available for CRN's use may consist of either contiguous bands or it may be a composition of spectrally distant frequency bands (also called fragments). Frequency separation in the second case determines the range of frequencies that can be assigned to a CR since channel switching time and energy consumption depend on frequency separation between the two frequency bands. MRHS has lower energy efficiency performance compared to EEHS, TMER and EMTG. Besides, throughput performance of our proposals under practical operation conditions (e.g. sufficient number of frequencies) are similar. Therefore, schedulers with energy efficiency or energy consumption concerns should be the preferred scheduling scheme for energy-efficient CRNs. Considering fairness, for low traffic load and homogeneous conditions, all schemes serve CRs almost equally as expected. On the other hand, under non-homogeneous traffic and link quality conditions, EEHS and MRHS as opportunistic schedulers cannot provide fairness among CRs. On the contrary, EMTG and TMER provide a good balance in resource allocation among CRs. We have also showed that the proposed schedulers can combat the spectrum fragmentation by considering the cost of channel switching and avoiding hopping between distant frequency bands.

In this work, we have focused on a CRN that acquires sensing information from a white space database considering the latest trends on geolocation databases. However, as spectrum sensing is the principal step for real autonomous CRNs, we plan to work on the energy-efficient scheduling problem for a CRN that performs spectrum sensing internally. Moreover, we will incorporate transmission power adaptation into our scheme in our future work.

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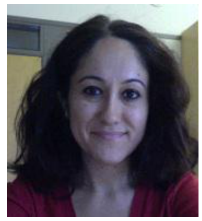

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