Cooperative Adaptive Spectrum Sharing in Cognitive Radio Networks

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***Abstract*—The cognitive radio (CR) paradigm calls for open spectrum access according to a predetermined etiquette. Under this paradigm, CR nodes access the spectrum opportunistically by continuously monitoring the operating channels. A key challenge in this domain is how the nodes in a CR network (CRN) cooperate to access the medium in order to maximize the CRN throughput. Typical multichannel MAC protocols assume that frequency channels are adjacent and that there are no constraints on the transmission power. However, a CRN may operate over a wide range of frequencies, and a power mask is often enforced on the transmission of a CR user to avoid corrupting the transmissions of spectrum-licensed primary-radio (PR) users. To avoid unnecessary blocking of CR transmissions, we propose a novel *distance-dependent* MAC protocol for CRNs. Our protocol, called DDMAC, attempts to maximize the CRN throughput. It uses a novel probabilistic channel assignment mechanism that exploits the dependence between the signal's attenuation model and the transmission distance while considering the traffic profile. DDMAC allows a pair of CR users to communicate on a channel that may not be optimal from one user's perspective, but that allows more concurrent transmissions to take place, especially under moderate and high traffic loads. Simulation results indicate that, compared to typical multichannel CSMA-based protocols, DDMAC reduces the blocking rate of CR requests by up to 30%, which consequently improves the network throughput.**

***Index Terms*—Cognitive radio networks (CRNs), distance awareness, MAC protocols, spectrum access, traffic awareness.**

I. INTRODUCTION

SPECTRUM measurements by the FCC and other organizations (e.g., XG DARPA initiative) indicate significant temporal and geographical variations in the utilization of the licensed spectrum, ranging from 15% to 85% [1]. These measurements motivated the need for a new technology that improves spectrum utilization without degrading the performance of licensed primary radio networks (PRNs). To cope with the rising demand in unlicensed wireless services, cognitive radio (CR) technology has been proposed. This technology allows an open access to the spectrum subject to a predetermined etiquette. In a cognitive radio network (CRN), users are aware of the radio frequencies used by existing legacy networks, and they opportunistically adapt their communication parameters to be able to communicate without affecting active PR users.

A CRN has unique characteristics that distinguish it from traditional multichannel wireless networks. Unlike traditional wireless networks, which typically occupy contiguous bands [2]–[4], a CRN is expected to operate over a set of widely separated noncontiguous frequency bands. Communication on such bands exhibits different RF attenuation and interference behaviors. It is well known that signal attenuation increases with the distance between the two communicating users and also with the carrier frequency used for communication [5]. Therefore, when assigning transmission channels in a CRN, it is necessary to consider the signal attenuation model and the interference conditions to improve spectrum utilization. Another characteristic of a CRN is that users must operate using a relatively low transmission power (i.e., abide by a power mask) to avoid degrading the performance of the PR users [4]. These peculiar characteristics call for new MAC protocols that efficiently utilize the available spectrum while improving the overall network throughput.

A. Motivation

Channel assignment mechanisms in traditional multichannel wireless networks typically select the "best" channel, or set of channels, for a given transmission (e.g., [3], [6], and [7]). In these mechanisms, the *best* channel is often defined as the one that supports the highest rate. We refer to this approach as the *best multichannel* (BMC) approach. When the BMC approach is employed in a CRN, the blocking probability for CR transmissions, defined as the percentage of CR packet requests that are blocked due to the unavailability of a feasible channel assignment, can increase, leading to a reduction in the network throughput. To illustrate, consider an environment in which two PRNs and one CRN coexist. PRN 1 operates over a low-frequency band $(CH1)$, while PRN 2 operates over a high-frequency band $(CH2)$. Suppose that PRN 2 introduces a higher average PR-to-CR interference. Consequently, a CR receiver experiences a higher average signal-to-interference-plus-noise ratio (SINR) over $CH1$ than over $CH2$. Assume that two CR users A and C need to send data to CR users B and D, respectively (see Fig. 1). Also assume that the distance between A and B (d_{AB}) is less than that between C and D (d_{CD}). Fig. 1(a) shows that when the CR users employ the BMC approach, the transmission $A \rightarrow B$ uses $CH1$, whereas the transmission $C \rightarrow D$ uses $CH2$. $A \rightarrow B$ is allowed to proceed because it operates over a low carrier-frequency channel with low PR-to-CR interference for a short transmission distance.

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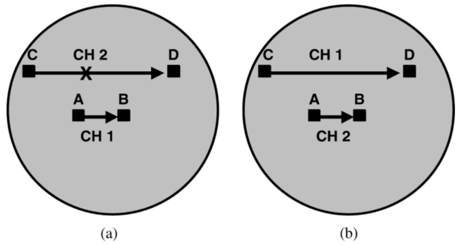

Fig. 1. Scenarios in which two CR transmissions can/cannot proceed simultaneously. (a) BMC channel assignment. (b) Distance-dependent channel assignment.

On the other hand, $C \rightarrow D$ requires relatively higher transmission power to overcome the high attenuation associated with the high-frequency/high-interference channel and the long transmission distance. If the required transmission power exceeds the specified power mask, $C \rightarrow D$ cannot proceed. However, both $A \rightarrow B$ and $C \rightarrow D$ have much better chances of proceeding simultaneously if each CR transmitter selects channels while keeping in mind the constraining power mask of the other transmitter [Fig. 1(b)].

As a numerical example, assume that PRN 1 and PRN 2 operate in the 900-MHz and 2.4-GHz bands, respectively. Assume that $d_{AB} = 10$ m and $d_{CD} = 50$ m. Also assume that a CR transmission is successful if the received SINR over the selected channel is greater than the SINR threshold. For both channels, we set the SINR threshold and the interference mask to 5 dB and 60 mW, respectively. Assume that CR receivers B and D experience the same level of total interference over both channels (0.05 μW). Given the above parameters and using the propagation model in [8] with path loss exponent of 2, the required transmit powers over $CH1$ and $CH2$ for $A \rightarrow B$ are 2.2 and 16 mW, respectively. For $C \rightarrow D$, these powers are 56.18 and 399.5 mW. According to the BMC scheme [Fig. 1(a)], $A \rightarrow B$ can proceed over $CH1$ (the power mask is not violated), whereas $C \rightarrow D$ cannot proceed over $CH2$ (the required transmit power exceeds the power mask). On the other hand, if $A \rightarrow B$ uses $CH2$ and $C \rightarrow D$ uses $CH1$, both transmissions can proceed simultaneously [Fig. 1(b)].

It is worth mentioning that in a given (one-hop) neighborhood, the *optimal* channel assignment that maximizes the number of simultaneous CR transmissions can be formulated as an integer linear programming (ILP) problem [9], [10]. Since computing the optimal solution for the ILP problem grows exponentially with the size of the network [9], heuristic algorithms with suboptimal performance are needed. Such algorithms should attempt to compute channel assignment with reasonable computational/communication overhead.

B. Contributions

In this work, we develop a novel CSMA-based MAC protocol that aims at enhancing the throughput of the CRN subject to a power mask constraint. The proposed protocol (DDMAC) employs an intelligent stochastic channel assignment scheme that exploits the dependence between the RF signal attenuation model and the transmission distance while taking into consideration the local traffic conditions. The channel assignment scheme accounts for the interference conditions and the power constraints at different bands. In particular, the scheme assigns channels with lower average SINR to shorter transmission distances, and vice versa. In addition, our scheme associates more preferable channels to the most frequent transmission distances and less preferable channels to the less frequent distances. In other words, the assignment process identifies a "preferable" channel list for each CR user. Such a list indicates which channels are preferable to use depending on the estimated distance between the transmitter and the receiver. We propose two variants for the channel assignment scheme. The first variant is suitable for offline planning of spectrum sharing in networks with known deployment and traffic patterns. In this case, there is no need for distance-traffic pattern prediction. The second variant is suitable for online dynamic network operation with unknown traffic patterns. To estimate the distance-traffic pattern in a given neighborhood, the second variant employs a stochastic learning technique that adapts to network dynamics (i.e., mobility, interference conditions, and traffic conditions). The primary advantage of our assignment scheme is that it is based on passive learning. This is because in DDMAC, CR users always listen to the control channel in order to overhear control-packet exchanges, including those not destined to them. CR users use the control information to identify the preferable channels.

DDMAC has the following attractive features:

- It does not make any assumptions about the activity patterns of the underlying networks or about user distribution.
- It is easy to implement in practical settings, and its processing overhead is small.
- It is transparent to PR users, i.e., does not require coordination with them.
- It inherently improves the fairness among CR users compared to typical multichannel CSMA-based protocols.
- Under low load and several available channels, DDMAC gracefully degrades to the BMC approach.

To evaluate the performance of DDMAC, we conduct simulations over a dynamic CRN with mobile users. Our simulation results show that by being distance- and traffic-aware, DDMAC significantly improves network throughput while preserving fairness. The results also indicate that compared with typical multichannel CSMA-based protocols, DDMAC decreases the connection blocking rate in a CRN by up to 30%. By injecting artificial errors into the estimated distances, our evaluation reveals that DDMAC is robust against estimation errors.

It should be noted that selecting a preferable channel list was also proposed in the MMAC protocol [11]. However, MMAC does not support multiple-channel assignment (it is limited to one channel per user). Specifically, the channel selection criterion in MMAC is to use a channel with the lowest count of source–destination pairs that have selected the channel. In DDMAC, the preferable channel list per node is constructed by accounting for the challenges associated with CRs (i.e., low transmit power, presence of PR users, widely separated non-contiguous available bands). Unlike DDMAC, the objective in MMAC was not to address spectrum sharing while improving the overall throughput, but rather to handle multichannel hidden terminals using a single transceiver and to balance the channel usage over all available channels. In addition, MMAC requires global network synchronization, which is not a requirement in DDMAC.

C. Organization

The rest of this paper is organized as follows. Section II gives an overview of related work. In Section III-A, we introduce our system model and state the main assumptions. The SINR analysis is presented in Section III-B. Section III-C illustrates the effect of the carrier frequency and transmission distance on the path loss. In Section IV, we formulate the optimal channel assignment problem. Section V introduces our proposed distance- and traffic-aware channel assignment algorithm. Section VI describes the proposed DDMAC protocol and outlines its benefits and associated overhead. We evaluate DDMAC in Section VII. Finally, Section VIII gives concluding remarks.

II. Related Work

Recently, several attempts were made to develop MAC protocols for CRNs (e.g., [6] and [12]–[16]). In [6], the authors developed a CRN MAC protocol with a common control channel. This protocol jointly optimizes the channel/power/rate assignment, assuming a given power mask on CR transmissions. DC-MAC [12] is a cross-layer distributed scheme for spectrum allocation/sensing. It provides an optimization framework based on partially observable Markov decision processes, assuming that PR and CR users share the same slotted transmission structure. In [13], the authors investigated continuous-time Markov models for dynamic spectrum access in open spectrum wireless networks. Using such models, a distributed random access protocol is proposed to achieve airtime fairness between dissimilar unlicensed users.

The FCC defined the *interference temperature model* [17], which provides a metric for measuring the interference experienced by licensed receivers. In [14], the authors studied the issue of spectrum sharing among a group of spread-spectrum users subject to constrains on the SINR and on the interference temperature. In [18], the interference temperature model was used for optimal selection of spectrum and transmission powers for CR users. In [16], the authors proposed a decentralized channel-sharing mechanism for CRNs based on a game-theoretic approach for both cooperative and noncooperative scenarios. In [19], the concept of a time-spectrum block is introduced to model spectrum reservation in a CRN. Based on this concept, the authors presented centralized and distributed CRN protocols with a common control channel for spectrum allocation.

The above protocols were designed without exploiting the dependence of the number of allowable CR transmissions on the carrier frequency and the transmission distance. They are limited to the analytical aspects of MAC design, with no complete operational details. To the best of our knowledge, DDMAC is the first CRN MAC protocol that aims at improving the CRN throughput by exploiting the dependence on the RF signal's attenuation model and the transmission distance while considering the prevailing traffic and interference conditions.

III. Preliminaries

A. Network Model

We consider a CRN with decentralized control (i.e., an ad hoc network). This CRN coexists geographically with M different PRNs. PR users are legacy radios that cannot be controlled by the CRN. Fig. 2 shows a conceptual view of the scenario under consideration with $M = 2$. The PRNs are licensed to operate over nonoverlapping frequency bands. We assume that all the PRN bands have the same bandwidth (BW). In reality, a PRN may occupy multiple noncontiguous frequency bands. Such a PRN can be easily represented in our setup by using multiple equal-bandwidth virtual PRNs, each operating over its own carrier frequency. For the ith PRN, we denote its carrier frequency by f_i. As shown in Fig. 3, the available bandwidth (BW) of a PRN is divided into L adjacent but nonoverlapping frequency channels each of Fourier bandwidth W (in Hz). Such L channels are collectively referred to as a band. Let N denote the total number of channels in all bands; $N = LM$.

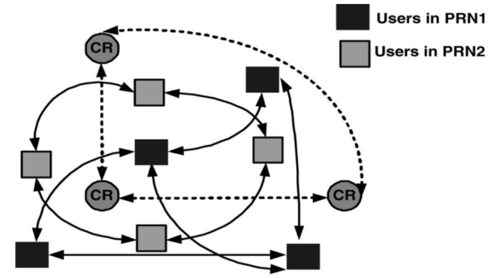

Fig. 2. Example of an opportunistic CRN that coexists with two PRNs.

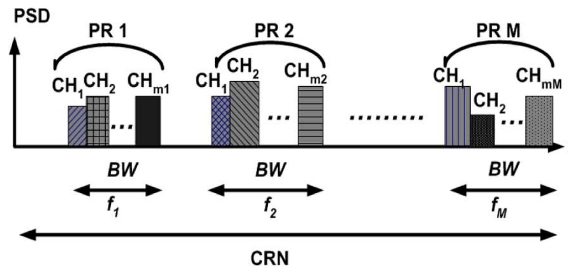

Fig. 3. Operating spectrum in the hybrid network.

Without loss of generality, we assume that BW is sufficient to support at least one CR transmission. This is an acceptable assumption in many wireless systems that are built to operate in the unlicensed bands, including IEEE 802.11/a/b/g-compliant devices. Each CR user is equipped with n_t radio transceivers, $1 \leq n_t \leq L$, that can be used simultaneously. In theory, a CR user can transmit over an arbitrary segment of the available bandwidth by using tunable filters. In practice, however, a CR typically implements a bank of fixed filters, each tuned to a given carrier frequency with fixed bandwidth, allowing the CR user to choose from a fixed number of channels. In our setup, we assume the latter (more practical) capability, which can be used to approximate the tunable filter scenario.

To avoid corrupting the transmissions of licensed users, a mask is enforced on the transmission power of a CR user over each band, i.e, $P_t^{(i)} \leq P_{\text{mask}}^{(i)}$, $i = 1, 2, \ldots, M$. The determination of an appropriate power mask is an important topic, which has been investigated under certain simplifying assumptions (e.g., [18] and [20]). The spectrum sharing protocols in [18] and [20] were designed such that the maximum transmission powers of CR users over various bands are dynamically computed based on the PR's interference margins (set by the FCC) and local traffic conditions. In [20], the authors provided a *neighborhood-dependent* adaptive power mask on CR transmissions that ensures a statistical (soft) guarantee of the outage probability of PRNs (the probability that the total interference power at a PR receiver exceeds the maximum tolerable interference). The authors provided closed-form expressions for the resulting power mask. For our purposes, we assume that a similar mechanism for determining the power mask is in place. A CR user transmits data to other CR users using the maximum allowable power vector $\mathbf{P}_{\text{mask}}$. When not transmitting, a CR user is capable of measuring the total noise-plus-interference $I^{(i)}$ over all bands $i = 1, 2, \ldots, M$.[1] This requires a wideband sensing capability with a narrowband resolution. The technology to support such capability is readily available through a wideband antenna, a power amplifier, adaptive filters, and a DSP technique called cyclostationary feature detection [21], [22]. Thus, a CR user can simultaneously sense several GHz-wide bands and estimate the instantaneous interference over each band [22]. Alternatively, a sequential partial sensing approach can be employed at the cost of negligible switching/sensing overhead [21], [23]. It is worth mentioning that off-the-shelf wireless cards can readily serve as a fully functional wideband multichannel CR interface. Such an interface enables a CR user to perform analysis of the RF spectrum (i.e., sensing) in real time.

B. *Analysis of the Average SINR*

Based on the aforementioned characteristics of the CRN, the average measured SINR ($\overline{\text{SINR}}$) at a CR receiver at a given time over band i is mainly determined by: 1) the path loss associated with that band ($P_L(f_i)$); 2) the average interference over that band ($\overline{I}^{(i)}$), which can be estimated based on the sensing history and the spectrum occupancy statistics (e.g., using the techniques in [12] and [24]; and 3) the enforced power mask $P^{(i)}_{\text{mask}}$. Formally, $\overline{\text{SINR}}^{(i)}(dB)$ is given by

$$\overline{\text{SINR}}^{(i)}(dB) = P^{(i)}_{\text{mask}}(dB) - P_L(f_i)(dB) - \overline{I}^{(i)}(dB). \quad (1)$$

Note that in [25] and [26], it was shown that for a given CRN and due to PRN's activity, CR users that are far away from each other can experience different average interference $\overline{I}^{(i)}$, which may vary with time. On the other hand, CR users in close proximity typically share the same view of the surrounding RF environment.

Table I summarizes the main notation used in the paper.

C. *Carrier Frequency and Distance Effects on Path Loss*

In this section, we discuss the effect of the carrier frequency and transmission distance on the path loss. For a given carrier frequency f, let $d_o(f)$ be the close-in distance, i.e., the distance from the transmitter after which the RF channel can be approximated by the free-space model; $d_o(f)$ can be determined from measurements or can be estimated by [8]

$$d_o(f) = \max\left\{\frac{2D_a^2 f}{c}, D_a, \frac{c}{f}\right\} \quad (2)$$

[1]The quantity $I^{(i)}$ includes the PR-to-CR interference as well as the thermal noise.

TABLE I
SUMMARY OF NOTATIONS USED IN THE PAPER

M	Number of PRNs
L	Number of channels in a PRN
$N, \mathcal{N}$	N is the total number of channels, $\mathcal{N} = \{1, \ldots, N\}$
BW, W	Bandwidth of a band and a channel, respectively
n_t	Number of transceivers per CR user
${P_t}^{(i)}$	CR transmit power
$P^{(i)}_{mask}$	Interference power mask on channel i
$I^{(i)}$	Noise-plus-interference over channel i
$\text{SINR}^{(i)}_j$	Measured SINR over band i at receiver j
$P_L(f_i)$	Path loss associated with band i
$P_r(f_i)$	Received power at a CR receiver over band i
d	Transmitter-receiver distance
$\mathcal{J}$	Set of all CR transmission requests in a locality
$c^{(i)}_j$	ith selected channel's data rate for transmission j
C_j	Rate demand of the jth CR transmission
μ^*_i	SINR threshold over channel i
m_j	Number of selected channels for the jth transmission
$\mathcal{M}_j$	$\mathcal{M}_j$ is the set of m_j selected channels for the jth transmission
R	Random variable represents the distance to the intended receiver
R_c , r_c	R_C is the transmission region, $R_c = \pi r_c^2$
R_i	ith ring around a CR in static channel assignment
r_i, r_{i-1}	Radii that define R_i, $i = 1, \ldots M$
D_i	ith ring around a CR in dynamic channel assignment
d_i, d_{i-1}	Radii that define D_i
m	Number of non-overlapping D_i rings
T_{win}	Observation window time
$p_i(t)$	Probability of D_i at time t
$\widetilde{p}_i(t)$	Weighted average of $p_i(t)$
α	Forgetting factor
$\Omega_i(A)$, K	CR A's preferable channel list for region i, $i = 1, \ldots, K$
$CCL(A, B)$	Common channel list available for $A \rightarrow B$ transmission
$\Phi(A, B)$	Preferable available channels for $A \rightarrow B$ transmission

where D_a is the antenna length of the transmitter and c is the speed of light. Let $P_o(f)$ and $P_t(f)$ respectively denote the received power at the close-in distance and the CR transmit power. Then, $P_o(f)$ can be estimated as follows [8]:

$$P_o(f) = \frac{c^2 G_t(f) G_r(f)}{(4\pi d_o(f))^2 f^2} P_t(f) \quad (3)$$

where $G_t(f)$ and $G_r(f)$ are the transmit and receive antenna gains, respectively. Let $P_r(f)$ denote the received power at distance d from the transmitter, $d \geq d_o(f)$. Then

$$P_r(f) = P_o(f)\left(\frac{d_o(f)}{d}\right)^n \quad (4)$$

where n is the path loss exponent (typically, $2 \leq n \leq 6$). Note that, in practice, $d_o(f)$ is of the same order of magnitude as the node's dimensions. For example, for a mobile phone operating in the 900-MHz band with $D_a = 5$ cm, $d_o(f) = 33$ cm. For an 802.11 WLAN card operating in the 2.4-GHz band and the same antenna size, $d_o(f) = 12$ cm. Accordingly, it is reasonable to assume that the probability that d is less than $d_o(f)$ is very small (i.e., $\Pr(d < d_o(f)) \approx 0$).

Using (2)–(4), the path loss $P_L(f)$ can be expressed as

$$P_L(f) = 10 \log \frac{P_t(f)}{P_r(f)}$$
$$= -10 \begin{cases} \log \frac{c^2 \gamma D_a^{n-2}}{f^2 d^n}, & \forall f \text{ s.t. } D_a \geq \max\left\{\frac{c}{f}, \frac{2D_a^2 f}{c}\right\} \\ \log \frac{c^n \gamma}{f^n d^n}, & \forall f \text{ s.t. } \frac{c}{f} \geq \max\left\{D_a, \frac{2D_a^2 f}{c}\right\} \\ \log \frac{c^{4-n}\gamma\left(2D_a^2\right)^{n-2}}{f^{4-n} d^n}, & \forall f \text{ s.t. } \frac{2D_a^2 f}{c} \geq \max\left\{D_a, \frac{c}{f}\right\} \end{cases} \quad (5)$$

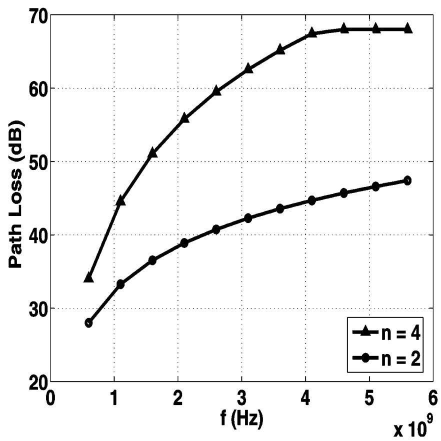

Fig. 4. Path loss versus carrier frequency for two path loss exponents ($D_a = 5$ cm, $G_t(f) = G_r(f) = 1$).

where

$$\gamma \stackrel{\text{def}}{=} \frac{G_t(f)G_r(f)}{(4\pi)^2}. \tag{6}$$

Note that the dependence of $P_L(f)$ on d (i.e., $\frac{1}{d^n}$) is the same for any given carrier frequency.

Fig. 4 depicts the path loss for a wide range of carrier frequencies and two values of n at a distance $d = 1$ m. This figure and (5) reveal that the signal attenuation increases as the distance between the two communicating users increases and as the frequency used for communication increases. These observations provide the motivation for our distance-dependant channel assignment, discussed in Section V.

IV. Optimal Channel Assignment Problem

Our objective is to maximize the number of simultaneous CR transmissions and, consequently, the overall network throughput. Toward this end, we define the term *local spectrum utilization* as the total number of simultaneous CR transmissions that can be supported in a given (one-hop) locality while meeting a predefined power mask. Before formulating the problem, we discuss the requirements for a successful CR transmission.

A. CRN Transmission Requirements

Within a given neighborhood, multiple CR users may contend for access to one or more of the available channels. Let $\mathcal{N}$ and $\mathcal{J}$ denote the set of all N channels and the set of all CR transmission requests in the local neighborhood at a given time, respectively. We assume that the jth CR transmission $(j \in \mathcal{J})$ is successful if both of the following conditions are met:

- It is possible to find m_j available channels from the set $\mathcal{N}$ such that $\sum_{i=1}^{m_j} c_j^{(i)} \geq C_j$, where $c_j^{(i)}$ is the data rate of the ith selected channel and C_j is the total rate demand for the jth CR transmission.
- Let $\mathcal{M}_j$ be the set of m_j selected channels. Then, the received SINR of every $i \in \mathcal{M}_j$ $\left(\text{SINR}_j^{(i)}\right)$ must be greater than the SINR threshold (μ_i^*) that is required at the CR receiver to achieve a target bit error rate over channel i.

B. Maximizing the Utilization of Local Spectrum

Let $\delta_j^{(i)}$ be a binary variable denoting whether or not channel i is assigned for transmission j. Formally

$$\delta_j^{(i)} = \begin{cases} 1, & \text{if channel } i \text{ is assigned for transmission } j \\ 0, & \text{otherwise.} \end{cases} \tag{7}$$

Similar to [10] and [27], the problem of maximizing the total number of simultaneous CR transmissions in a given neighborhood can be formally stated as follows:

$$\max_{\delta_j^{(i)} \in \{0,1\}} \sum_{j \in \mathcal{J}} \mathbf{1}\left[\sum_{i \in \mathcal{N}} \delta_j^{(i)} c_j^{(i)} \geq C_j\right] \tag{8}$$

$$\sum_{j \in \mathcal{J}} \delta_j^{(i)} \leq 1, \quad \forall\, i \in \mathcal{N} \tag{9}$$

$$\sum_{i \in \mathcal{N}} \delta_j^{(i)} \leq n_t, \quad \forall\, j \in \mathcal{J} \tag{10}$$

$$\text{SINR}_j^{(i)} \geq \mu_i^*, \quad \forall\, j \in \mathcal{J}, \ \text{s.t. } \delta_j^{(i)} = 1 \tag{11}$$

where $\mathbf{1}[\cdot]$ is the indicator function. The constraint in (9) ensures that a channel cannot be assigned to more than one CR transmission in the same vicinity. The constraint in (10) ensures that at most n_t channels can be assigned to a CR transmission. For an *ad hoc* CRN, the above optimization problem must run in a distributed manner at each CR user in the network. This implies that each CR user must exchange instantaneous SINR and rate demand information with neighboring CR users before selecting channels, which incurs high control overhead and delay (i.e., information may not be up to date). Even if perfect knowledge of the SINR of each link and the rate demands are available, the above ILP problem belongs to the class of NP-hard problems [9]. In this paper, we develop a heuristic channel assignment scheme that provides a suboptimal solution with low complexity and good spectrum utilization. Our heuristic exploits distance and traffic awareness. The key idea behind it is to assign channels with low $\overline{\text{SINR}}$ to short-distance transmissions. Also, local traffic information is used to assign more channels to more likely transmission distances.

V. Distance-Dependent Channel Assignment Algorithm

In this section, we describe our proposed channel assignment mechanism. The assignment process identifies a "preferable" channel list for each CR user. Such a list indicates which channels are preferable to use depending on the estimated distance between the transmitter and the receiver. It is worth mentioning that many techniques for estimating the transmitter–receiver distance in wireless networks have been proposed in the literature, including the Received Signal Strength Indicator (RSSI), the Time of Arrival (ToA), and the Time Difference of Arrival (TDoA) [28]. For our purposes, any of these schemes can be used. In Section VII, we investigate the robustness of our scheme under inaccurate distance estimation, which is mainly caused by mobility, multipath propagation, reflection, and fading effects.

Two variants of the channel assignment mechanism are proposed. The first variant is suitable for offline planning of spectrum sharing in networks with known traffic patterns, whereas the second variant is for online spectrum allocation in dynamic (mobile) networks with unknown traffic patterns.

A. Spectrum Assignment for Known Traffic Profiles

Given a CR user with a packet to transmit, let r be the estimated distance to the intended receiver; $r \leq r_c$, where r_c is the maximum transmission range. r_c represents the largest distance from a CR transmitter over which the transmission at maximum power can be correctly decoded over all selected channels in the absence of interference from other terminals (CR or PR users). Let $F_R(r) \stackrel{\text{def}}{=} \Pr\{R \leq r\}$. The functional form of F_R depends on both node distribution as well as the distance traffic profile, which for now we assume to be given. Given F_R, the channel assignment process is conducted as follows:

- The available bands are divided according to their measured $\overline{\text{SINR}}$ [given in (1)][2] into M sets $S_1, S_2, \ldots, S_M$, where each band consists of multiple channels. The set S_1 contains the frequency channels of the band that has the highest $\overline{\text{SINR}}$, S_2 contains the next highest $\overline{\text{SINR}}$, and so on.
- A CR user, say A, divides its maximum transmission region $R_c \stackrel{\text{def}}{=} \pi r_c^2$ into M nonoverlapping "rings" $R_1, \ldots, R_M$. The ith ring contains the CR users whose distances to A fall in $(r_{i-1}, r_i]$, where $i = 1, \ldots, M$ and $0 = r_0 \leq r_1 \leq r_2 \leq \cdots \leq r_M = r_c$. The rings are divided such that the probability of communicating with a CR receiver that falls within any of the M rings is the same, i.e.,

$$F_R(r_i) - F_R(r_{i-1}) = \frac{1}{M}, \quad i = 1, \ldots, M. \tag{12}$$

  User A computes the radii $r_i, i = 1, \ldots M$, by substituting for $F_R(r_i)$ in (12) and solving for r_i.
- Finally, A constructs a preferable channel list for each ring by assigning channels with lower $\overline{\text{SINR}}$ to shorter transmission distances and channels with higher $\overline{\text{SINR}}$ to longer transmission distances, i.e., assign S_M to R_1, S_{M-1} to $R_2, \ldots$, and S_1 to R_M.

To illustrate the idea, we consider a uniformly distributed CRN and assume that a CR transmitter randomly chooses a destination for its data from within R_c. Therefore, $F_R(r)$ is given by

$$F_R(r) = \begin{cases} \frac{r^2}{r_c^2}, & r \leq r_c \\ 1, & r \geq r_c. \end{cases} \tag{13}$$

Using (12) and (13), and noting that $r_0 = 0$, we arrive at the following expression for r_i:

$$r_i = \sqrt{\left(\frac{1}{M} + \frac{r_{i-1}^2}{r_c^2}\right)}\, r_c = \sqrt{\frac{i}{M}} r_c. \tag{14}$$

Fig. 5 illustrates the nonoverlapping rings around a CR transmitter when $M = 4$. Within these rings, other CR and PR users may exist. Assume $r_c = 100$ m. Then, $r_1, \ldots, r_4$ are given by 50, 70.71, 86.6, and 100 m, respectively.

[2]Note that P_L's dependence on d is the same for all bands. Thus, for the purpose of $\overline{\text{SINR}}$ comparison, we set $d = 1$ meter.

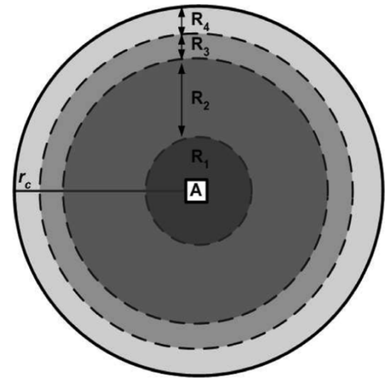

Fig. 5. Four regions around a CR transmitter for assigning channels.

B. Spectrum Assignment for Unknown Traffic Profiles

For offline spectrum planning, we assumed in the previous section a fixed network and prior knowledge of the distance-traffic pattern (i.e., the form of F_R). During network operation, however, the distance-traffic pattern may change with time, depending on network dynamics and user mobility. Because users only possess local knowledge of their neighborhoods, it is difficult to maintain the optimal network performance. Nevertheless, we can develop a stochastic learning algorithm that performs well and uses only localized information. Stochastic learning techniques have been widely used in wireless networks for online traffic prediction, tracking, and power control [29], [30]. Our proposed learning approach is a distributed algorithm that runs at each CR user in the network. A CR user, say A, evenly divides its maximum transmission region R_c into m nonoverlapping regions, where $m \gg M$. The ith region, D_i, forms a ring, defined by the area $\{(x,y) : d_{i-1}^2 < x^2 + y^2 \leq d_i^2\}$, where $d_i = i\frac{r_c}{m}$, and $d_{i-1} < d_i$ $i = 1, \ldots, m$. CR user A maintains an m-entry transmission distance table. The ith entry in that table corresponds to the region D_i and contains the number of overheard CR packet requests during the recent observation window T_{win} for which the transmitter-receiver distances fall in the range $(d_{i-1}, d_i]$ (how to convey transmitter–receiver distance information will be discussed later). Note that the proper setting of T_{win} depends on the dynamics of the network. The effect of T_{win} is studied in Section VII.

To initialize the assignment algorithm, all CR users employ the BMC scheme discussed in Section I. At any time t, CR user A constructs its transmission distance table based on control packets it overheard during the observation window $[t - T_{\text{win}}, t]$. Using the transmission distance table, A estimates the current probability mass function (pmf) $p_i(t)$ of the distance r at time t (see Fig. 6). It then computes an exponentially weighted average of $p_i(t)$

$$\widetilde{p_i}(t) = \alpha p_i(t) + (1 - \alpha)\widetilde{p_i}(t - T_{\text{win}}) \tag{15}$$

where α is a forgetting factor, $0 < \alpha \leq 1$. Once $\widetilde{p_i}(t)$ is computed, A computes the preferable channel list for each ring. Let $\Omega_i(A)$ denote the preferable channel list for ring D_i at CR user A (how to construct $\Omega_i(A)$ will be given later). The new preferable channel lists will be used during the next observation window time. The proposed channel assignment process merges the D_i's into K regions according to $p_i(t)$, where $K \leq M$. It

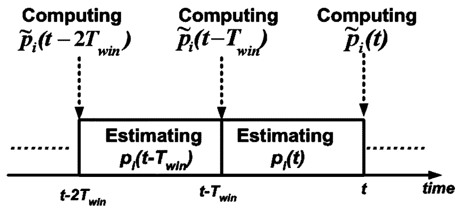

Fig. 6. Time diagram of pmf's updating process.

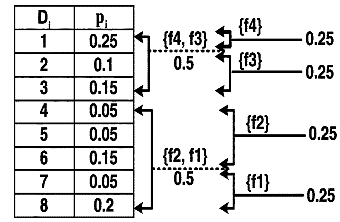

Fig. 7. Example that illustrates the channel assignment process in a dynamic CRN.

then assigns preferable channels for each region. The process is now described in detail.

1) User A determines the integer k such that $|\sum_{i=0}^{k-1} \tilde{p}_i(t) - \sum_{i=k}^{m} \tilde{p}_i(t)|$ is minimized, i.e., it divides the regions into two groups: short-distance and long-distance groups. The probabilities of the short-distance and long-distance groups are given by

$$P_{\text{short}} = \sum_{i=0}^{k-1} \tilde{p}_i(t) \tag{16}$$

and

$$P_{\text{long}} = \sum_{i=k}^{m} \tilde{p}_i(t). \tag{17}$$

2) User A divides the M bands into two frequency sets: low $\overline{\text{SINR}}$ frequency set and high $\overline{\text{SINR}}$ frequency set. It assigns the low $\overline{\text{SINR}}$ frequency set to the short-distance group and the high $\overline{\text{SINR}}$ frequency set to the long-distance group. The numbers of bands in the high (n_{H}) and low (n_{L}) frequency sets depend on P_{short} and P_{long}, as follows:

$$\begin{aligned} n_{\text{H}} &= \left\lceil \frac{P_{\text{short}}}{P_{\text{short}} + P_{\text{long}}} M \right\rceil \\ n_{\text{L}} &= M - n_H \end{aligned} \tag{18}$$

where $\lceil \cdot \rceil$ is the ceiling function.

3) Steps 1 and 2 are repeated for every group until either only one band is assigned to that group or the group contains only one region. Note that when repeating the above process for a group, m in (17) and M in (18) are replaced by the number of regions in that group and the number of channels assigned to that group, respectively.

Using this recursive procedure, the preferable channel list $\Omega_i(A)$, for all i, is computed for one observation window.

C. Complexity

1) Claim 1: The worst-case complexity for selecting the preferable channel list $\Omega_i(A)$, for all i, may be obtained using the above recursive procedure in $\mathcal{O}(mK)$ time, where $K \approx \min[N, m]$.

Proof: In the worst case, our proposed algorithm requires $\mathcal{O}(m)$ comparisons to perform one iteration (steps 1 and 2). In addition, it requires at most $K = \min[N-1, m-1]$ iterations to obtain $\Omega_i(A)$, for all i. Hence, $\Omega_i(A)$, for all i, may be obtained using the proposed algorithm with a complexity of $\mathcal{O}(mK)$, where $K \approx (m \min[N, m])$. For $N \geq m$, $K \sim \mathcal{O}(m)$. On the other hand, for $N < m$, $K \sim \mathcal{O}(N)$.

D. Illustrative Examples

We illustrate the previously discussed channel assignment process using the following examples.

1) Example 1: Consider four PRNs and one CRN. Each PRN occupies two adjacent nonoverlapping channels. The PRNs are labeled such that $f_1 < f_2 < f_3 < f_4$. Consider a CR user A with $\overline{\text{SINR}}^{(1)} > \overline{\text{SINR}}^{(2)} > \overline{\text{SINR}}^{(3)} > \overline{\text{SINR}}^{(4)}$. Suppose that A divides its transmission region R_c into eight rings, $D_1, D_2, \ldots, D_8$. At a given time t, assume that the weighted average pmf $\{\tilde{p}_i(t) : i = 1, \ldots, 8\}$ is given by $\{0.25, 0.1, 0.15, 0.05, 0.05, 0.15, 0.05, 0.2\}$. Fig. 7 shows how the proposed channel assignment process is conducted. The outcome of this process is as follows:

- Band 4, which includes two channels, is assigned to all CR transmissions whose distances are in D_1 (i.e., $\Omega_1(A) = \{4\}$).
- Band 3, which includes two channels, is assigned to all CR transmissions whose distances are in D_2 and D_3 (i.e., $\Omega_2(A) = \Omega_3(A) = \{3\}$).
- Band 2, which includes two channels, is assigned to all CR transmissions whose distances are in D_4, D_5, and D_6 (i.e., $\Omega_4(A) = \Omega_5(A) = \Omega_6(A) = \{2\}$).
- Band 1, which includes two channels, is assigned to all CR transmissions whose distances are in D_7 and D_8 (i.e., $\Omega_7(A) = \Omega_8(A) = \{1\}$).

2) Example 2: Consider eight PRNs and one CRN. The PRNs are labeled such that $f_1 < f_2 < \cdots < f_8$. Suppose that A divides its transmission region into two rings. At a given time t, assume that the weighted average pmf $\{\tilde{p}_i(t) : i = 1, 2\}$ is given by $\{0.25, 0.75\}$. Then, the outcome of our preferable channel assignment is as follows:

- Channels 1 and 2 (total of two channels are assigned to all CR transmissions whose distances are in D_1).
- Channels $3, \ldots, 8$ (total of six channels are assigned to all CR transmissions whose distances are in D_2).
- The above example reveals that our algorithm assigns more preferable channels (total of six channels) to the more frequently used transmission distances (D_2, $\tilde{p}_2(t) = 0.75$).

VI. DDMAC Protocol

Based on the channel assignment process presented in Section V, we now propose a distributed, asynchronous MAC protocol for CRNs. The proposed DDMAC is a CSMA/CA-based scheme that uses contention-based handshaking for exchanging control information. It is worth mentioning that the most common configuration for upcoming CRNs is to use CSMA/CA-like MAC access [6], [19], [20],

[23], [25], [26], [31]. Thus, in designing the channel access in DDMAC, we focus on extending the CSMA/CA scheme due to its maturity and wide deployment in many wireless packet networks. Note that the handshaking procedure is essential in multichannel systems. Besides mitigating the hidden-terminal problems, there are two other main objectives for the use of RTS/CTS: 1) conducting and announcing the channel assignment; and 2) prompting both the transmitter and the receiver to tune to the agreed on channels before transmission commences. Before describing our protocol in detail, we first state our main assumptions.

Assumptions

In designing DDMAC, we make the following assumptions:

- For each frequency channel, the channel gain is stationary for the duration of three control packets and one data and ACK packet transmission periods. As explained in [32], this assumption holds for typical mobility patterns and transmission rates.
- Channel gains between two CR users are symmetric. This is a typical assumption in any RTS/CTS-based protocol, including the IEEE 802.11 scheme.
- CR transmissions use the maximum allowable power vector ($\mathbf{P}_{\rm mask}$). The key idea behind this choice is as follows. It is well-known that using as many channels as possible for a transmission reduces the CR-to-PR interference [6] due to the reduction in transmission power. However, because DDMAC enforces an exclusive channel occupancy, which prevents two neighboring CR users from using common channels,[3] such a channel assignment policy may lead to channel overassignment, which reduces the opportunity for finding available channels by other neighboring CR transmitters (thus reducing the CRN's throughput). Therefore, in DDMAC, we tackled the CR-to-PR interference problem by assuming a given power mask to protect PR users while trying to use the least possible number of selected channels per transmission. This can be done by transmitting at the highest possible transmission power over each selected channel, which results in less number of assigned channels per CR transmission. This increases the opportunity for finding available channels by other neighboring CR transmitters.
- The total rate demand of a CR user A (denoted by C_A) is met by aggregating the transmission rates of several selected channels. Note that C_A can vary from one packet to another.
- A prespecified control channel with Fourier bandwidth B_c is available, where $B_c \ll B$. This channel does not need to be reserved for the CRN. It can, for example, be one of the subchannels in an ISM band.
- Contending CR users follow similar interframe spacings and collision avoidance strategies of the 802.11 protocol (over the control channel) by using physical-carrier sensing and back off before initiating control packet exchanges. We also assume that data packet sizes are significantly larger than control packets, and therefore, the use of the RTS/CTS handshake is justified.

[3]The exclusive channel occupancy excludes *CR-to-CR* interference, although it still allows for the typical cochannel PR-to-CR interference, thus largely simplifying the *CR-to-PR* interference management process.

RTS	Transmitter ID	Receiver ID	Packet size	Rate demand (C_A)	Available channel list
PCA/ EPCA	Transmitter ID	Receiver ID	TX duration	Distance (d)	Assigned channel list
NCA/ ENCA	Transmitter ID	Receiver ID	Distance (d)		

Fig. 8. Formats of DDMAC control packets.

A. Channel Access in DDMAC

The channel access mechanism allows the CR transmitter and receiver to agree on the set of channels to use for communication and to allocate their rates. Rate is allocated in a manner that ensures that the power mask and the rate demands are met. A CR user A views its transmission region as K nonoverlapping regions, where each region is associated with a preferable channel list $\Omega_i(A)$, $i = 1, \ldots, K$, determined according to Section V. This user maintains an N-entry channel list and an m-entry transmission distance table (as described in Section V). The jth entry of the channel list indicates the status of the jth channel; 1 if the channel is available, and 0 if the channel is occupied or reserved by any of A's CR neighbors. Recall that each CR user is equipped with n_t transceivers. One of these transceivers is tuned to the control channel, while the other $n_t - 1$ transceivers can be tuned to any data channels. As a result, CR users can always hear control messages over the common control channel even when they are transmitting/receiving data over other data channels. Thus, every CR user listens to the control channel and accordingly updates its channel list and transmission distance table.

Suppose that CR user A has data to transmit to another CR user B at an aggregate rate demand C_A. Then, A reacts as follows:

- If user A does not sense a carrier over the control channel for a random duration of time, it sends an RTS message at the maximum (known) power $P_{\max}$. This $P_{\max}$ is constrained by the power mask imposed on the prespecified control channel. The RTS includes C_A, the packet size (in bytes), and the list of all available channels at A (see Fig. 8).
- The neighbors of A (other than B) that can correctly decode the RTS refrain from accessing the control channel until they receive one of two possible control packets, denoted by EPCA and ENCA (explained below).
- Upon receiving the RTS packet, B estimates the distance between A and B (d_{AB}) (using one of the techniques described in Section V). It identifies the preferable channel list $\Omega_i(B)$ that corresponds to d_{AB}. Based on the available channels at A and B, and the instantaneous interference level over these channels as measured at B, user B removes any channel that has a received SINR less than its threshold SINR and determines the *common channel list* that is potentially available for $A \rightarrow B$ transmission, denoted by $CCL(A,B)$. User B then computes the intersection between $\Omega_i(B)$ and $CCL(A,B)$ to identify a preferable set of channels for $A \rightarrow B$ ($\Phi(A,B)$). To achieve

good throughput, B sorts the channels in $\Phi(A,B)$ in a descending order of their maximum possible data rate (calculated according to Shannon's formula[4]). Then, user B appends the rest of the common available channels that are not in $\Phi(A,B)$ $\left(\text{i.e., } CCL(A,B) \bigcap \overline{\Phi(A,B)}\right)$, also listed in a descending order of their maximum possible data rate, to the bottom of the sorted preferable channels. User B cumulatively adds channels from the top of the new sorted list until either the aggregate rate C_A is satisfied or the list is exhausted, i.e., no feasible channel assignment is found.

- If there is no feasible channel assignment, then B responds by sending a Negative-Channel-Assignment (NCA) message that includes the distance d_{AB} (see Fig. 8). The purpose of this packet is to help B's neighbors estimate the network distance-traffic pattern and prompt A to back off and retransmit later. If B can find a set of available channels that can support a total demand C_A, it sends a Positive-Channel-Assignment (PCA) message to A, which contains the assigned channels for the transmission $A \to B$, the distance d_{AB}, and the duration needed to hold the assigned channels for the ensuing data transmission and corresponding ACK packet. The PCA packet implicitly instructs B's CR neighbors to mark the set of assigned channels as unavailable for the indicated transmission duration. It also helps these neighbors estimate the network distance-traffic pattern.
- Depending on which control message is received, user A reacts as follows:
  - If A receives a NCA message, it responds by sending an Echo-NCA (ENCA) message, which includes the distance d_{AB}. The purpose of this packet is to help A's neighbors estimate the network distance-traffic pattern.
  - If A receives a PCA message, it replies back with an Echo-PCA (EPCA) message, informing its neighbors of the selected channel list, the distance d_{AB}, and the transmission duration. This EPCA also announces the success of the control packet exchange between A and B to A's neighbors, which may not have heard B's PCA.
- Once the RTS-PCA-EPCA exchange is completed, the data transmission $A \to B$ proceeds. Once completed, B sends back an ACK packet to A over the best assigned channel, i.e., the channel that has the highest rate. A time diagram of the RTS-PCA-EPCA-DATA-ACK exchange is depicted in Fig. 9.

It is worth mentioning that there is no interference between data and control packet transmissions because the two are separated in frequency. Therefore, a CR user that hears the RTS packet from A defers its attempt to access the control channel until it receives an EPCA or a ENCA packet from A. In addition, a CR user that receives only a PCA or a NCA should defer its attempt to access the control channel for the expected time of the EPCA/ENCA packet (to avoid a collision between control packets). This allows for more parallel transmissions to take place in the same neighborhood (see Fig. 9).

Remark: DDMAC's channel assignment is performed on a per-packet basis, with the channels assigned to different interfaces dynamically changing. This type of channel assignment requires channel switching to occur at a very small time scale, which is in the range of microseconds.[5]

[4]Other rate-versus-SINR relationships, such as a staircase function, can be used for calculating the achievable data rates.

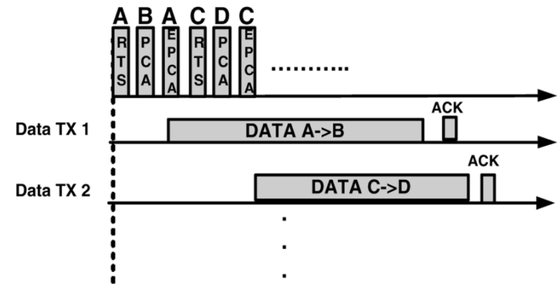

Fig. 9. RTS-PCA-EPCA-DATA-ACK packet exchange.

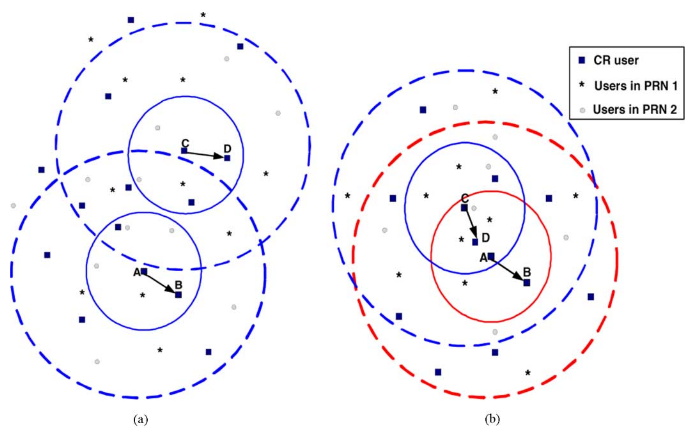

Fig. 10. Scenarios in which a CR transmitter C can/cannot reuse the channels assigned to A. Solid circles indicate data-transmission ranges, whereas dashed circles indicate control-transmission ranges. (a) Allowed channel reuse. (b) Unallowed channel reuse.

B. Spatial Reuse and DDMAC

We consider a CSMA/CA-based multihop CRN environment, which consists of multiple contention regions (neighborhoods) that permit spatial reuse. Specifically, nonneighboring CR users may access the same channel on different contention domains. To illustrate the idea of spatial reuse, Fig. 10 depicts two scenarios for the operation of DDMAC. In the first scenario [Fig. 10(a)], the two transmitters A and C cannot hear each other's control packets. Therefore, according to CSMA/CA, the transmissions $A \to B$ and $C \to D$ can overlap in their data channels, i.e., the assigned channels for $A \to B$ transmission are reserved only within the area of A's and B's control range (spatial reuse case). In Fig. 10(b), node C falls in the control region of node A (and vice versa). The exclusive channel occupancy policy prevents A and C from using common channels. However, the two transmissions can proceed simultaneously if A and C can find two nonintersecting sets of channels to support their rates.

C. Worst-Case Scenarios for DDMAC

We illustrate two extreme scenarios under which the DDMAC protocol gracefully degrades into the BMC scheme. Recall that a CR receiver A divides its transmission range into m regions.

[5]Current radio technology allows channel switching to be done in a few microseconds (i.e., < 10 μs [23], [33]).

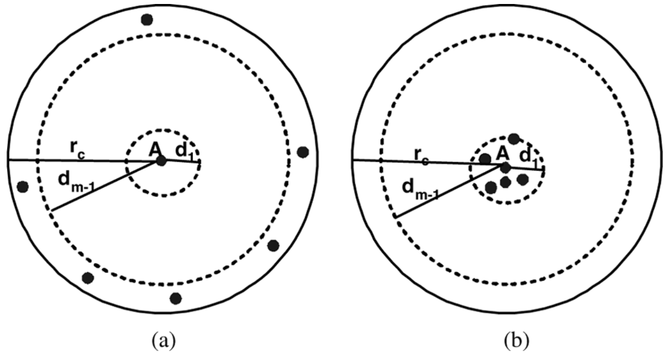

Fig. 11. Illustration of two worst-case scenarios in DDMAC. (a) Scenario I. (b) Scenario II.

- **Scenario I:** At a given time t, assume that the weighted average pmf $\{\widetilde{p_i}(t) : i = 1, \ldots, m\}$ has a value of 1 at $i = m$, and 0 otherwise (i.e., most likely, transmission distances are within D_m). This scenario represents the case when all of A's neighbors are located near the border of A's transmission range [Fig. 11(a)]. According to the channel assignment algorithm, the preferable channel list is identified as follows:

$$\Omega_i(A) = \phi : i = 1, \ldots, m-1.$$
$$\Omega_i(A) = \mathcal{N} : i = m.$$

Recall that $\mathcal{N}$ denotes the set of available channels. In other words, no channels will be assigned to ring, i, $i = 1, 2, \ldots, m-1$, and all channels will be assigned to the mth ring.

- **Scenario II:** At a given time t, assume that the weighted average pmf $\{\widetilde{p_i}(t) : i = 1, \ldots, m\}$ has a value of 1 at $i = 1$, and 0 otherwise (i.e., most likely, transmission distances are within D_1). This scenario represents the case where all A's neighbors are located close to A [Fig. 11(b)]. According to the proposed channel assignment algorithm, the preferable channel list is identified as follows:

$$\Omega_i(A) = \mathcal{N} : i = 1.$$
$$\Omega_i(A) = \phi : i = 2, \ldots, m.$$

According to DDMAC, the sorted channel list from which a CR user assigns channels to its transmission is constructed by appending the common sorted available channels that are not in the sorted preferable channels to the bottom of the sorted preferable channels list. Thus, for the above two scenarios and depending on the transmitter–receiver distance, the sorted channel list of DDMAC is as follows:

- If the distance falls in the range $(d_{m-1}, d_m = r_c]$ or $(0, d_1]$, the preferable channel list is the set of all available channels. Therefore, the sorted channel list of DDMAC is the same as that of the BMC scheme. Consequently, DDMAC gracefully degrades into the BMC scheme.
- If the distance falls within the transmission range R_c but not in the range $(d_{m-1}, d_m]$ or $(0, d_1]$, the preferable channel list is empty, whereas the available channel list contains all the available common channels. Therefore, the sorted channel list of DDMAC is the same as that of BMC. Consequently, DDMAC gracefully degrades into the BMC scheme.

D. Protocol Overhead

1) Claim 2: DDMAC and BMC have comparable overheads.

Proof: Both DDMAC and BMC use a three-way handshake to send one data packet. Thus, DDMAC does not introduce any additional control message overhead.

VII. Protocol Evaluation

We now evaluate the performance of the DDMAC via simulations and compare it with CSMA/CA variants. Our results are based on simulation experiments conducted using CSIM (a C-based, process-oriented, discrete-event simulation package [34]). Each CR user generates packets according to a Poisson process with rate λ (in packet/time slot), which is the same for all users. For simplicity, data packets are assumed to be of a fixed size (2 kB). Each CR user requires an aggregate transmission rate of 5 Mb/s. We divide time into slots, each of length 3.3 ms. A time slot corresponds to the transmission of one CR packet at a rate of 5 Mb/s. We set the CRN SINR threshold to 5 dB and the thermal noise to $P_{\rm th}^{(i)} = 10^{-21}$ W/Hz for all channels. Because DDMAC and the compared with CSMA/CA-based protocols have the same maximum transmission ranges and use the same channel access mechanism, it is reasonable to assume that all protocols achieve the same forward progress per hop. Consequently, our performance metrics are: 1) one-hop throughput, i.e., the destination of a packet is restricted to one hop from the source; 2) connection blocking rate; and 3) the fairness index [35]. The connection blocking rate is defined as the percentage of CR packet requests that are blocked due to the unavailability of a feasible channel assignment. We use Jain's fairness index [35] to quantify the throughput fairness of a scheme.[6] Fairness index values closer to 1 indicate better fairness. The signal propagation model in (4) is used with $n = 4$, the antenna length (D) is 5 cm, and $G_t(f) = G_r(f) = 1$ for every carrier frequency f.

A. Single-Hop Scenarios

1) Simulation Setup: We first simulate a small-scale network for the purpose of highlighting the advantages and operational details of DDMAC. DDMAC is compared with three multichannel CSMA-based protocols that use different channel selection schemes: an optimal scheme (which uses exhaustive search), the BMC scheme [3] (which is based on a *greedy strategy* that selects the best available channels for a given transmission), and a naive scheme (which always tries to select high-frequency channels if available for a given transmission while leaving low-frequency channels for other users). Specifically, we consider a single-hop CRN, where all users can hear each other. This CRN coexists with two PRNs in a 100×100 m^2 field. The PRNs operate in the 600-MHz and 2.4-GHz bands. Each PRN band consists of one channel of bandwidth 1.5 MHz. The number of PR users in each PRN is 50. Each user in the ith PRN acts as an ON/OFF source, where it is ON while transmitting, and OFF otherwise. We define the "activity factor" α_i as the fraction of time in which the ith-type PR

[6]For our simulation setup, CR user demands are uniform. The destination CR user is uniformly selected from the one-hop neighbors, and the packet generation rate is the same for all CR users. Thus, Jain's fairness index provides a meaningful metric for comparing the fairness of DDMAC and BMC.

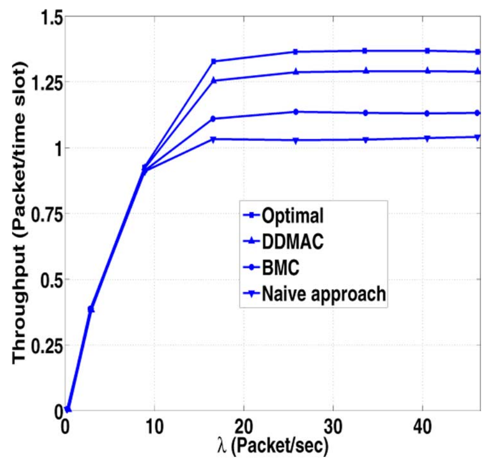

Fig. 12. Throughput versus λ for a small-scale network (comparison with the optimal scheme).

user is ON (i.e., the probability that the source is in the ON state). The source is further characterized by the distribution of its ON and OFF periods, which are both taken to be exponential. We set the average ON period to be the duration of one time slot. In other words, traffic correlations are captured using a two-state Markov model. The appropriateness of the two-state ON/OFF model has been demonstrated in several previous works, e.g., [6], [13], [20], [36], and [37]. In essence, theON/OFF behavior is attributed to the bursty nature of many types of network traffic, including voice traffic and VBR video streaming. Note that one potential PRN is a cellular network that transports voice traffic. We set the α_i probabilities for the two PRNs to 0.5 and 0.3, respectively. The transmission power for each PR user is 0.5 W.

For the CRN, we consider 40 mobile users. The random waypoint model is used for mobility, with the speed of a CR user uniformly distributed between 0 and 2 m/s. This results in dynamic, time-varying topologies. We assume that a CR user can use up to two data channels simultaneously. We set the interference mask to $P_{\text{mask}}^{(1)} = P_{\text{mask}}^{(2)} = 50$ mW. We also set the forgetting factor α to 0.6, the observation window $T_{\text{win}} = 0.5$ s, and the number of rings around a CR user $m = 12$. For a fair comparison, we let all schemes use the maximum allowable power vector $\mathbf{P}_{\text{mask}}$.

2) Results: Under the above setup, Fig. 12 shows that DDMAC improves the one-hop throughput by up to 25% (compared to BMC) and 34% (compared to the naive approach). More importantly, its throughput is within 7% of the optimal throughput, obtained via exhaustive search. Note that the exhaustive search implies that the instantaneous SINR values, location information, and rate demands are known to the decision-making entity that assigns channels to CR users (i.e., such search requires global information). Even if perfect knowledge of the SINR of each link and the rate demands are available, for large-scale networks, finding the optimal solution requires exhaustive search over a large state space, which grows exponentially with the number of CR users and the available channels.

B. Multihop Scenarios

1) Simulation Setup: We now evaluate the performance of DDMAC in more realistic (large-scale) network scenarios and contrast it with a typical multichannel CSMA-based protocol that uses BMC for channel selection [3]. We consider four PRNs and one CRN. Users in each PRN are uniformly distributed over a 500×500 m^2 area. The PRNs operate in the 600-MHz, 900-MHz, 2.4-GHz, and 5.7-GHz bands, respectively. Each PRN band consists of three nonoverlapping 1-MHz channels. The number of PR users in each PRN is 300. The α_i probabilities for the four PRNs are 0.5, 0.3, 0.3, and 0.1, respectively. The transmission power for each PR user is 0.5 W.

For the CRN, we consider a *random-grid* topology,[7] where 225 mobile CR users are placed within the 500×500 m^2 field. The field is split into 225 smaller squares, one for each CR user. The location of a mobile user within the small square is selected randomly. For each generated packet, the destination is selected randomly from the one-hop neighbors. Within each small square, the random waypoint model is used for CR mobility, with the speed of a CR user uniformly distributed between 0 and 2 m/s. We assume that a CR user can use up to three data channels simultaneously. We set the interference mask to $P_{\text{mask}}^{(1)} = P_{\text{mask}}^{(2)} = \cdots = P_{\text{mask}}^{(12)} = 50$ mW. The reported results are the average of 100 experiments. In our design, we assume an exclusive channel occupancy policy on CR transmissions (i.e., no CR–CR interference). However, hidden-terminal problem can still occur in this scenario due to imperfect control. Our simulations relax these assumptions and account for all sources of interference, including those that are far away from a receiver and use common channels.

Remark: Our simulations only address the MAC layer aspects and assume that route computations have already been carried out. Taking the destination from a node's one-hop neighbors is intended only to convey the need for channel access. A "destination" in this context could be the next hop where a packet is to be forwarded to or the final packet destination. Randomly selecting a neighbor as a destination is realistic in terms of packet forwarding, especially when multiple flows (like file transfers, messaging, or VoIP) pass through a node.

2) Results: We first compare the performance of DDMAC to that of the BMC scheme. For a fair comparison, we let both schemes use the maximum allowable power vector $\mathbf{P}_{\text{mask}}$. We set α to 0.6, T_{win} to 0.5 s, and m to 12. Fig. 13(a) and (b) show that under moderate and high traffic loads, DDMAC significantly reduces the connection blocking rate and improves the overall one-hop throughput by up to 30%. This improvement is attributed to the increase in the number of simultaneous transmissions in DDMAC. Note that under low traffic load, the throughput of DDMAC gracefully degrades to that of BMC due to the availability of a sufficient number of channels. The system performance under Raleigh channel model (i.e., varying channel conditions) is also investigated in Fig. 13(b). We consider normalized random variables to capture the fading processes [8]. The results show that, under such varying channel conditions, the same trends that were noticed for the AWGN channel are observed here. Fig. 13(b) shows that the impact on throughput is almost the same under AWGN and Raleigh channel models. Similar observations have also been reported in an experimental study in [38] for IEEE 802.11b wireless LAN. In [38], the authors showed that the impact on throughput and packet error

[7]Random-grid is a realistic topology that models constrained scenarios. For example, a building could have various offices, where each office may contain several wireless devices.

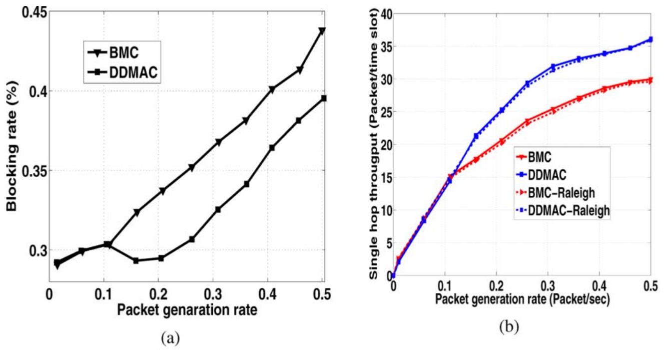

Fig. 13. Performance of a CRN. (a) Blocking rate versus λ. (b) Throughput versus λ (with and without a Raleigh fading component).

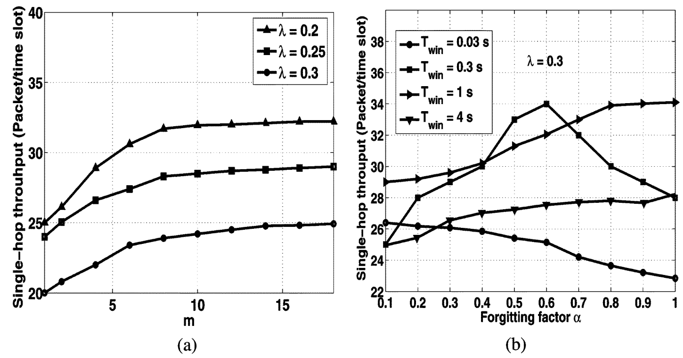

Fig. 15. Performance of DDMAC. (a) Throughput versus number of rings (m) around a CR user. (b) Throughput versus α for different $T_{\rm win}$ values.

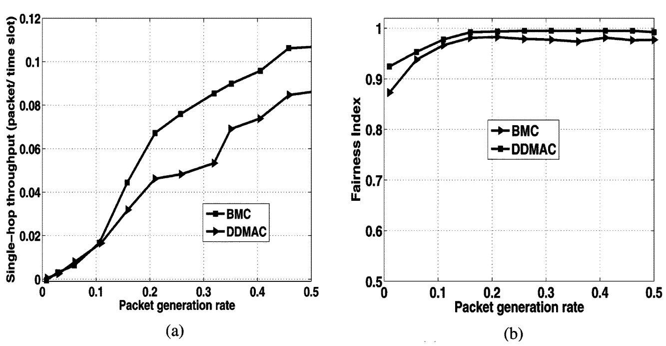

Fig. 14. Per-user throughput and fairness performance. (a) Per-user single-hop throughput. (b) Fairness index versus λ.

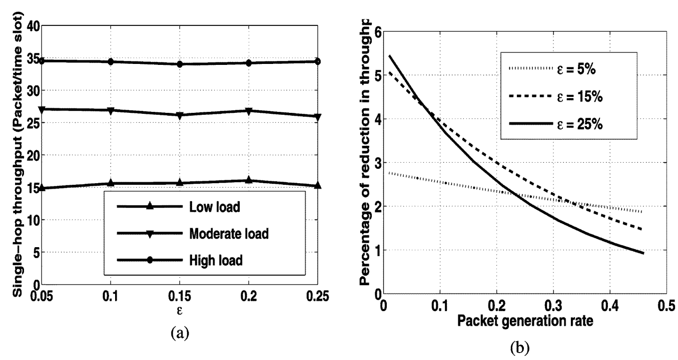

Fig. 16. Impact of inaccurate distance estimation in DDMAC. (a) Throughput versus ϵ. (b) Percentage of reduction in throughput versus λ.

rate were virtually identical under AWGN and Raleigh channel models.

In Fig. 14(a), we focus on the per-user throughput performance under DDMAC.[8] As shown in this figure, although DDMAC requires a pair of CR users to communicate over a set of channels that may not be optimal from one user's perspective, the *per-user* throughput of DDMAC under moderate and high traffic loads is still greater than that of the BMC scheme. This is because DDMAC attempts to serve a given CR transmission first using the preferable channel list and preserves the "better" channels for other transmissions. However, if the aggregate rate of this transmission cannot be satisfied using the preferable list, DDMAC attempts to serve this transmission using the remaining available channels.

Next, we compare the fairness index of DDMAC to that of BMC. Compared to BMC, Fig. 14(b) shows that DDMAC slightly improves the network fairness and preserves long-term fairness properties. This improvement occurs because DDMAC motivates cooperation among neighbors to maximize their network-wide benefit.

The effect of dividing the transmission range of a CR user is depicted in Fig. 15(a) for different values of λ. As m increases, the throughput increases up to a certain point. For $m \geq 12$, no significant improvement is observed in the network throughput. This is because the preferable-channel assignment mechanism merges the m regions into $K \leq m$ regions, i.e., oversplitting R_c is not useful.

[8]This figure shows the average worst-case throughput performance among all CR users.

TABLE II
PERFORMANCE OF DDMAC AT THE OPTIMAL α AS A FUNCTION OF $T_{\rm win}$

Scheme	α^*	Best throughput (packet/slot)
BMC	-	25
DDMAC($T_{win} = 0.03$ s)	0.1	26
DDMAC($T_{win} = 0.3$ s)	0.6	33.6
DDMAC($T_{win} = 0.4$ s)	0.6	33.85
DDMAC($T_{win} = 1$ s)	0.8	33.89
DDMAC($T_{win} = 4$ s)	1.0	28

In Fig. 15(b), we study the impact of α and $T_{\rm win}$ on the performance of DDMAC. We set $\lambda = 0.3$ packet/slot. The network throughput versus α for different values of $T_{\rm win}$ is shown in the figure. It is clear that the throughput depends on the choice of α and $T_{\rm win}$. As $T_{\rm win}$ increases, α should increase to give much more importance to recent observations without entirely discarding older observations. Table II shows the best throughput performance and the associated optimal value of α (α^*), obtained from simulation, for different values of $T_{\rm win}$. It is clear that if $T_{\rm win}$ is too small or too large, the throughput reduces significantly.

We also investigate the robustness of DDMAC under inaccurate distance estimation, which is mainly caused by mobility, multipath propagation, reflection, and fading effects. The estimated distance $\widetilde{d}$ is given by $(1+\xi)\,d$, where ξ is a uniform estimation error ($\xi \sim \mathrm{Uniform}[-\epsilon,\epsilon]$). Fig. 16(a) shows the effect of inaccurate distance estimation on throughput as a function of ϵ under different traffic loads. It can be observed that there are no significant changes in the throughput for different values

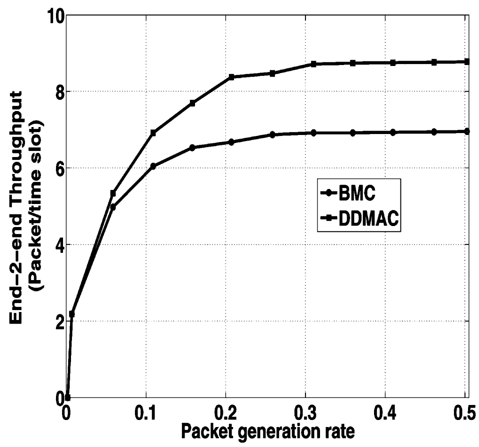

Fig. 17. End-to-end throughput versus λ.

of ϵ. Fig. 16(b) gives the percentage reduction in throughput due to inaccurate d as a function of λ for different values of ϵ. This figure shows that the maximum percentage of reduction in throughput due to inaccurate estimation of d is less than 6%.

The results in Fig. 16 indicate that channel assignment in DDMAC is quite robust to distance estimation errors. This is because DDMAC requires only rough estimates of user distribution, distances among users, and local traffic conditions in order to dynamically adapt channel assignments to current network traffic.

Finally, we study the end-to-end throughput for both BMC and DDMAC. Specifically, for each generated packet, the destination node is randomly selected to be any node in the network. We use a min-hop routing policy, but we ignore the routing overhead. For both schemes, the next-hop candidates are nodes that are within the transmission range of the transmitter. Fig. 17 shows that under moderate and high traffic loads, DDMAC significantly improves the overall network throughput [in line with the results in Fig. 13(b)].

VIII. Conclusion

In this paper, we proposed an opportunistic distance-dependent MAC protocol for CRNs (DDMAC). DDMAC improves the CRN throughput through cooperative channel assignment, taking into consideration the nonadjacency of frequency channels and the imposed power masks. We presented a heuristic stochastic channel assignment scheme that dynamically exploits the dependence between the signal attenuation model and the transmission distance. Our scheme accounts for traffic dynamics. It assigns channels with lower average SINR to shorter transmission distances to increase the number of simultaneous transmissions. We integrated the channel assignment process in the design of DDMAC. We compared the performance of DDMAC with that of a reference multichannel MAC protocol that is designed for typical multichannel systems (BMC). We showed that, under moderate and high traffic loads, DDMAC achieves about 30% increase in throughput over the BMC scheme, with manageable processing overhead. Although DDMAC requires a pair of CR users to communicate on a channel that may not be optimal from a user's perspective, we showed that the average per-user throughput of DDMAC under moderate and high traffic loads is greater than that of the BMC scheme. Furthermore, DDMAC preserves (even slightly improves) throughput fairness relative to BMC. In summary, DDMAC provides better spectrum utilization by reducing the connection blocking probability and increasing the system throughput. To the best of our knowledge, DDMAC is the first CRN MAC protocol that utilizes the radio propagation characteristics to improve the overall network throughput.

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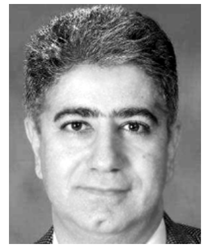

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