Distance- and Traffic-Aware Channel Assignment in Cognitive Radio Networks

Haythem Bany Salameh and Marwan Krunz
Department of Electrical and Computer Engineering
University of Arizona, Tucson, AZ 85721
Email: {haythem,krunz}@ece.arizona.edu

Ossama Younis
Applied Research, Telcordia Technologies, Inc.
Piscataway, NJ 08854
Email: oyounis@research.telcordia.com

Abstract— **The scarcity of unlicensed spectrum has triggered great interest in cognitive radio (CR) technology as a means to improve spectrum utilization. An important challenge in this domain is how to enable nodes in a CR network (CRN) to access the medium opportunistically. Multi-channel MAC protocols for typical ad hoc networks assume that frequency channels are adjacent and that there are no strict constraints on the transmission power. However, a CRN may occupy a wide range of frequencies. In addition, a power mask is often enforced on the transmission power of a CR user to avoid corrupting the transmissions of spectrum-licensed primary-radio (PR) users. Obviously, CR users operating in different licensed bands will be subject to different PR-to-CR interference conditions. To avoid unnecessary blocking of CR transmissions under these constraints, we propose a novel *distance-dependent* MAC protocol for CRNs (DDMAC) that attempts to maximize the CRN throughput. DDMAC introduces a novel suboptimal probabilistic channel assignment algorithm that exploits the dependence between the signal's attenuation model and the transmission distance while considering the traffic profile. The protocol 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 transmissions to take place simultaneously, especially under moderate to high traffic loads. Simulation results indicate that compared to typical multi-channel CSMA-based protocols, DDMAC decreases the connection blocking rate of CR transmission requests by up to 30%, which improves the network throughput at no additional cost in energy consumption. On the whole, our protocol is simple yet effective. It can be incorporated into existing multi-channel systems with little extra processing overhead.**

I. Introduction

The enormous growth in the number of unlicensed wireless applications resulted in crowding the unlicensed portion of the frequency spectrum (e.g., the ISM bands). While this is happening in the unlicensed bands, the FCC Spectrum Policy Task Force (SPTF) indicated that at any given time and in any geographic locality, less than 10% of the licensed spectrum is being utilized [1]. These two factors motivated the need for a new spectrum-adaptive technology that improves the spectrum efficiency without degrading the performance of licensed PR networks (PRNs). To cope with the rising demand in the unlicensed services, the cognitive radio (CR) technology has been proposed as a means to improve the spectrum utilization by allowing an open access policy subject to a predetermined etiquette. In a CRN, users are aware of the radio frequencies used by existing legacy networks. 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 multi-channel wireless communication networks. Unlike traditional wireless networks, which typically occupy contiguous bands [2]–[4], a CRN is expected to operate over a set of highly separated non-contiguous frequency bands, which exhibit 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 channels for its transmissions, it is necessary for a CRN to consider the signal attenuation model and the interference conditions so as to improve the utilization of the spectrum. Another characteristic of a CRN is that users must operate using a relatively low transmission power (i.e., subject to power mask) to avoid degrading the performance of the PR users [6], [7]. These peculiar characteristics call for new MAC protocols that can efficiently utilize the available spectrum and improve the overall network throughput.

Channel assignment approaches in traditional multi-channel wireless networks typically try to select the "best" set of channels for a given transmission (e.g., [2], [4], [7], [8])[1]. We refer to this approach as the *best multi-channels* (BMC) scheme. When BMC is employed in a CRN, the blocking probability for CR transmissions can actually 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 at a low frequency band (CH 1), while PRN 2 operates at a high frequency band (CH 2). Suppose that PRN 2 introduces a higher average PR-to-CR interference (i.e., it has higher activity factor and transmission power). Consequently, a CR receiver experiences a higher average signal-to-interference-plus-noise ratio (SINR) over CH 1 than over CH 2. Assume that two CR users A and C need to send data to CR users B and D, respectively (see Figure 1). Also assume that the distance between A and B is less than that between C and D. Figure 1(a) shows that when the CR users employ the BMC scheme, the transmission $A \rightarrow B$ uses CH 1, whereas the transmission $C \rightarrow D$ uses CH 2. The transmission $A \rightarrow B$ is allowed to proceed because it operates over a low carrier-frequency channel (CH 1) with low PR-to-CR interference for a short transmission distance. On the other hand, the transmission $C \rightarrow D$ 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

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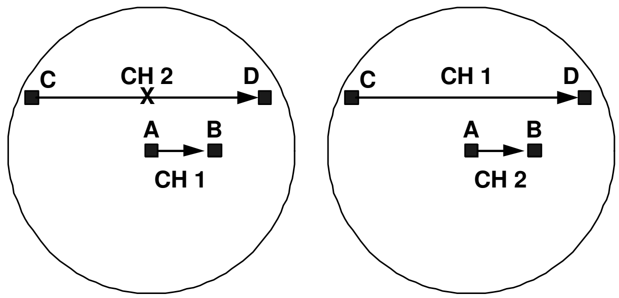
[1] The best channel is often defined as the one that supports the highest rate.

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 on the other transmitter (Figure 1(b)).



(a) BMC channel assignment

(b) Distance-dependent channel assignment

Fig. 1. Scenarios in which two CR transmissions can/cannot proceed simultaneously.

It is worth mentioning that in a given (one-hop) neighborhood, the optimal channel assignment that maximizes the total number of simultaneous CR transmissions can be structured as an integer linear programming (ILP) problem. Due to the high (exponential) complexity of computing the optimal solution for this ILP [9], [10], heuristic algorithms that attempt to compute suboptimal assignments with reasonable computational complexities are needed.

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 heuristic stochastic channel assignment scheme that exploits the dependence between the RF signal's attenuation model and the transmission distance while considering the prevailing local traffic conditions. The proposed channel assignment scheme accounts for the interference conditions and the power constraints at different PRN bands. In particular, the proposed scheme assigns channels with lower average SINR to shorter transmission distances, and vice versa. In addition, our scheme assigns more preferable channels to the most frequent transmission distances and less preferable channels to the less frequent ones. We propose two variants of the channel assignment mechanism in DDMAC. The first variant is suitable for static networks with known traffic patterns, while the other variant is for dynamic networks with unknown traffic patterns. The second variant employs a stochastic learning technique that adapts to network dynamics. DDMAC has several attractive features. First, it does not make any assumptions about the activities of the underlying networks or about user distributions. Second, the operation of DDMAC is simple and thus its processing overhead is very small. This makes it suitable for practical implementations. In addition, DDMAC does not require any coordination with PR users. Finally, under low load and many available channels, DDMAC gracefully degrades into the BMC scheme.

In our performance evaluation, we conduct simulations over a dynamic CRN with mobile users. Our simulation results show that distance and traffic awareness significantly improves network throughput. The results also indicate that compared with typical multi-channel CSMA-based protocols, the proposed 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.

The rest of the paper is organized as follows. Section II overviews related work. In Section III-A, we introduce our system model and state our assumptions. The average SINR for CRN is discussed 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-aware traffic-aware channel assignment algorithm. Section VI describes the proposed DDMAC protocol and outlines its benefits and 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., [7], [11]–[17]). In [7], 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 [11] 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 [12], the authors investigated continuous-time Markov models for dynamic spectrum access in open spectrum wireless networks. Using such models and the homo-egualis anthropological model, they proposed a distributed random access protocol that is shown to achieve airtime fairness.

The FCC defined the *interference temperature model* [18], which provides a metric for measuring the interference experienced by licensed receivers. In [13], 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 [14], the interference temperature model was used for optimal selection of spectrum and transmission powers for CR users. AS-MAC [16] is a spectrum-sharing protocol for a CRN that coexists with a GSM network. In AS-MAC, the GSM network is assumed to provide input to the CRN over a broadcast channel. Each CR user selects channels based on the CRN's control packets and information from the GSM network. Thus, explicit coordination with the PRNs is required. In [17], the authors proposed a decentralized channel-sharing mechanism for CRNs based on a game-theoretic approach for both cooperative and non-cooperative scenarios.

The above protocols were designed without exploiting the dependence of the number of allowable CR transmissions on the carrier frequency and the transmission distance. In addition, these protocols do not account for the traffic and PR-to-CR interference conditions. 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 decentralized CRN that coexists geographically with M different PRNs. PR users are legacy radios

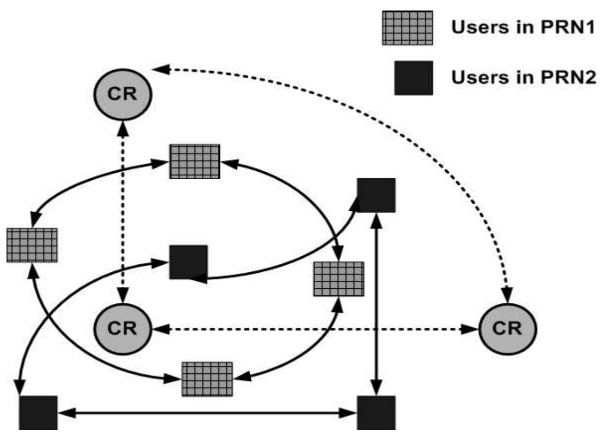


Fig. 2. Example of an opportunistic CRN that coexists with two PRNs.

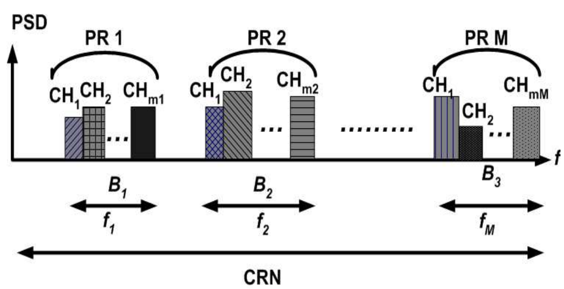


Fig. 3. Operating spectrum in the hybrid network.

that cannot be controlled by the CRN. Figure 2 shows a conceptual view of the scenario under consideration. The PRNs are licensed to operate over non-overlapping frequency bands. We assume that all the PRN bands have the same bandwidth (B). In reality, a PRN may occupy multiple, non-contiguous, unequal 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 Figure 3, the available bandwidth (B) of a PRN is divided into L adjacent but non-overlapping frequency channels 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; $N = LM$.

Without loss of generality, we assume that B 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 $n_t \leq L$, 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, $P_t^{(i)} \leq P_{mask}^{(i)}$, $i = 1, 2, \ldots, M$. The determination of $\overrightarrow{P}_{mask} \stackrel{\text{def}}{=} \{P_{mask}^{(1)}, P_{mask}^{(2)}, \ldots, P_{mask}^{(M)}\}$ is certainly an important topic, but is out of the scope of this paper. Here, we simply assume that $\overrightarrow{P}_{mask}$ is given. A CR user transmits data to other CR users using the maximum allowable power vector $\overrightarrow{P}_{mask}$. When not transmitting, a CR user is capable of measuring the total noise-plus-interference[2] $I^{(i)}$ over all bands $i = 1, 2, \ldots, M$. This requires the CR user to have 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* [6], [19], [20]. Thus, a CR user can simultaneously sense several GHz-wide bands and estimate the instantaneous interference over each band [20]. Alternatively, a sequential partial sensing approach can be employed at the cost of negligible switching/sensing overhead [19], [21]. It is worth mentioning that off-the-shelf wireless cards (e.g., ICS-572 products [22]) can readily serve as a fully functional wideband multi-channel 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 ($\overline{\text{SINR}}$) over band i is mainly determined by: (1) the path loss associated with that band ($P_L(f_i)$); (2) the average value of the measured $I^{(i)}$ over that band ($\overline{I}^{(i)}$), which can be estimated based on the sensing history and the spectrum occupancy statistics [11], [23]; and (3) the enforced power mask $P_{mask}^{(i)}$. Formally, $\overline{\text{SINR}}^{(i)}(dB)$ is given by:

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

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 [24]:

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

where D is the antenna length of the transmitter and c is the speed of light. Let $P_o(f)$ denote the received power at the close-in distance. Then, $P_o(f)$ can be estimated as follows [24]:

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

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, $2 \leq n \leq 6$).

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

Using (2), (3), and (4), the path loss $P_L(f)$ can be expressed as:

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

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

Note that the dependence of the path loss on d (i.e., $\frac{1}{d^n}$) is the same, irrespective of the carrier frequency.

Figure 4 depicts the path loss for a wide range of carrier frequencies and two values of n at a distance $d = 1$ meter. This figure and equation (5) reveal that the signal attenuation increases as the distance between 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.

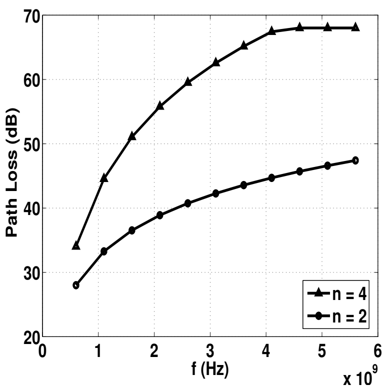


Fig. 4. Path loss vs. carrier frequency for two path loss exponents ($D = 5$ cm, $G_t(f) = G_r(f) = 1$).

IV. Formulation of Optimal Channel Assignment

Our objective is to maximize the number of simultaneous CR transmissions, and consequently the overall network throughput, by the means of optimal channel assignment. 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 of 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 say the jth CR transmission ($j \in \mathcal{J}$) is successful if both of the following two 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 $i \in \mathcal{M}_j$ ($\text{SINR}_j^{(i)}$) 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 Local Spectrum Utilization

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

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

Similar to [10], [25], the problem of maximizing the total number of simultaneous CR transmissions in a given neighborhood can be formally stated as follows:

$$\max_{\delta_j^{(i)} \in \{0,1\}} \sum_{j\in\mathcal{J}} \mathbf{1}\left[\sum_{i\in\mathcal{N}} \delta_j^{(i)} c_j^{(i)} \geq C_j\right] \quad (8)$$
$$\sum_{j\in\mathcal{J}} \delta_j^{(i)} \leq 1, \forall i \in \mathcal{N} \quad (9)$$
$$\sum_{i\in\mathcal{N}} \delta_j^{(i)} \leq n_t, \forall j \in \mathcal{J} \quad (10)$$
$$\text{SINR}_j^{(i)} \geq \mu_i^*, \forall j \in \mathcal{J}, \text{ s.t. } \delta_j^{(i)} = 1 \quad (11)$$

where $\mathbf{1}[.]$ 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). Worse yet, even with perfect knowledge of the SINR of each link and the rate demands, the above ILP problem belongs to the class of NP-hard problems [9]. In our paper, we develop a heuristic channel assignment scheme that provides a suboptimal solution with lower complexity while still achieving 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. Two variants of the channel assignment mechanism are proposed. The first variant is suitable for static networks with known traffic patterns, whereas the second one is for dynamic (mobile) networks with unknown traffic patterns.

A. Assignment for a Static CRN with Known Traffic Patterns

Given s CR user with a packet to transmit, let r be the distance to the intended receiver; $r \leq r_c$, where r_c is the maximum transmission range[3]. Let $F_R(r) \stackrel{\text{def}}{=} \Pr\{R \leq r\}$. The

[3]This is 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).

functional form of F_R depends on both the distribution of users as well as the traffic profile, which we now 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))[4] 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 non-overlapping 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 $0 = r_0 \leq r_1 \leq r_2 \leq \ldots \leq r_M = r_c$. 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, ..., and S_1 to R_M.

To illustrate the idea, we consider a uniformly distributed CRN. We assume that a CR transmitter chooses a destination for its data randomly 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:

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

Figure 5 illustrates the non-overlapping rings around a CR transmitter for $M = 4$. Within these rings, other CR and PR users exist.

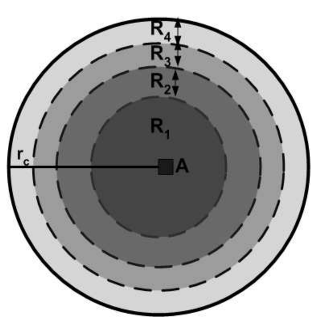


Fig. 5. Different rings for assigning channels around a CR transmitter ($M = 4$).

[4]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.

B. Assignment for a Dynamic CRN with Unknown Traffic Patterns

In the previous analysis, we assumed a fixed network and prior knowledge of the traffic pattern (i.e., the form of F_R). In practice, the traffic pattern may change with time, depending on the network dynamics and user mobility. Because users can only possess local knowledge of their neighborhoods, it is hard to reach and maintain the optimal network performance. Nevertheless, we can develop a stochastic learning algorithm that performs well with only localized information. Stochastic learning techniques have been widely used in wireless networks for online traffic prediction, tracking, and power control [26], [27]. 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 non-overlapping 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. It 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$(d_{i-1}, d_i]$. 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).

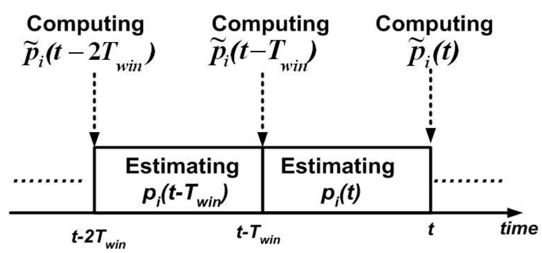


Fig. 6. Time diagram of pmf's updating process.

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 that have been overheard during the observation window $[t - T_{win}, t]$. Using the transmission distance table, A estimates the current probability mass function $p_i(t)$ of the distance r at time t (see Figure 6). It then computes an exponentially weighted average of $p_i(t)$:

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

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

1) User A chooses k such that $|\sum_{i=0}^{k-1} \widetilde{p}_i(t) - \sum_{i=k}^{m} \widetilde{p}_i(t)|$ 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:

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

and

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

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:

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

where $\lceil x \rceil$ is the smallest integer $\geq x$.

3) Step 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 with the number of regions in that group and the number of channels assigned to that group, respectively.

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

C. Example

We illustrate the previously discussed channel assignment process via a simple example. Consider four PRNs and one CRN. Each PRN occupies two adjacent non-overlapping 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 8 rings, $D_1, D_2, \ldots, D_8$. At a given time t, assume that the weighted average pmf $\{\widetilde{p}_i(t) : i = 1, \ldots, 8\}$ is given by $\{0.25, 0.1, 0.15, 0.05, 0.05, 0.15, 0.05, 0.2\}$. Figure 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., $\Omega_7(A) = \Omega_8(A) = \{1\}$).

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 uses contention-based handshaking for exchanging control information. We first state our main assumptions. Then, we describe our protocol in detail.

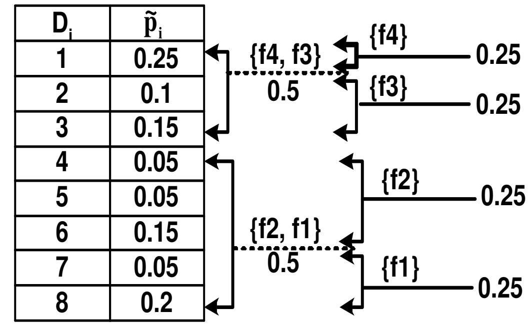


Fig. 7. Example that illustrates the channel assignment process in a dynamic CRN.

A. Assumptions

For each frequency channel, we assume that the channel gain is stationary for the duration of a few control and one data packet transmission periods. This assumption holds for typical mobility patterns and transmission rates [28]. We assume symmetric channel gains between two CR users. This is a typical assumption in any RTS/CTS-based protocol, including the IEEE 802.11 scheme. We also assume that a CR user transmits data to other CR users at a fixed rate using the maximum allowable power vector ($\overrightarrow{P}_{mask}$). Finally, we assume the availability of a prespecified control channel with Fourier bandwidth B_c, where $B_c \ll B$. This channel need not to be reserved for the CRN. It can, for example, be one of the subchannels in an ISM band.

B. Channel Access Mechanism

The purpose of the channel access mechanism is to allow the CR transmitter and receiver to agree on the set of channels to use for communication and to determine the rate allocation across these selected channels in a manner that ensures that the power mask and the rate demand are met. A CR user A views its transmission region as K non-overlapping regions, where each region is associated with a preferable channel list $\Omega_i(A)$, $i = 1, \ldots, K$, determined according to the discussion in 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. It maintains a value of 1 if the channel is available and 0 if the channel is occupied or reserved by any of A's CR neighbors. 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 a constant aggregate rate demand R_A, which corresponds to the aggregate rate for the $A \rightarrow B$ communication over all selected channels. 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 R_A and the list of all available channels at A. The RTS message is sent even if A's channel list contains no free channels. In this case, the purpose of the RTS is to help CR users predict the network traffic pattern.

- 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 uses the received signal strength of the RTS to estimate the distance between A and B (d_{AB}). 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 the preferable set of available channels for the $A \rightarrow B$ communication ($\Phi(A, B)$). 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 the Shannon's formula) and then 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.[5] Then, B cummulatively adds channels from the top of the new sorted list until either the aggregate rate R_A is satisfied or the list is exhausted (i.e., no feasible channel assignment can be found).
- User B determines whether or not there exists a feasible set of channels that can support the aggregate rate R_A. If not, then B responds by sending a Negative-Channel-Assignment (NCA) message that includes the distance d_{AB}. The purpose of this packet is to help B's neighbors estimate the network 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 R_A, it sends a Positive-Channel-Assignment (PCA) message to A, which contains the assigned channels for the transmission $A \rightarrow B$, the distance d_{AB}, and the duration needed to hold the assigned channels for the ensuing data transmission and corresponding ACK packet. The PCA 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 in estimating the network traffic pattern.
- Depending on which control message is received, user A reacts as follows:
  - If A receives an 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 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 $A \rightarrow B$ proceeds. Once completed, B sends back an ACK packet to A over the best assigned channel that has the highest rate.

[5]As demonstrated in [6], [7], minimizing the number of assigned channels results in the best throughput performance.

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 an ENCA packet from A. In addition, a CR user that receives only a PCA or an NCA should defer its attempt to access the control channel until the expected time for the EPCA/ENCA packet expires (to avoid collision of control packets). This allows for more parallel transmissions to take place in the same neighborhood.

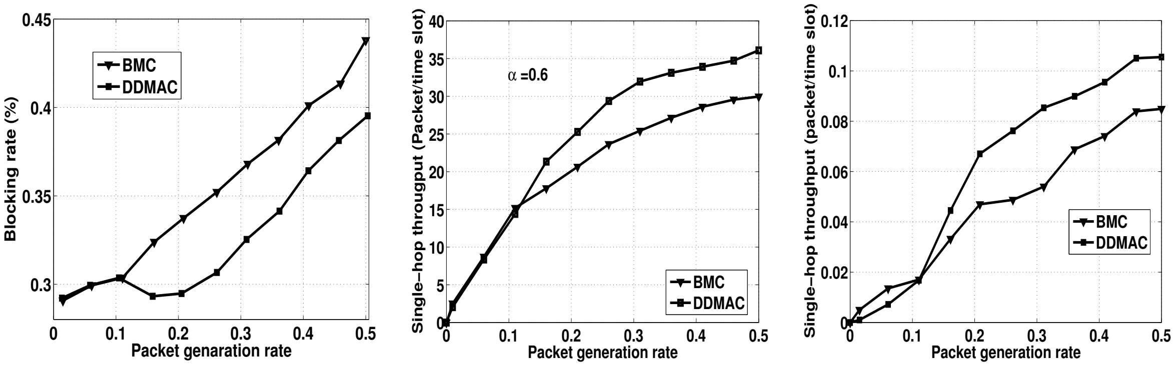
VII. Protocol Evaluation

We now evaluate the performance of the DDMAC protocol and contrast it with the BMC approach. Our results are based on simulation experiments conducted using CSIM programs (CSIM is a C-based process-oriented discrete-event simulation package [29]). For simplicity, data packets are assumed to be of a fixed size (2 Kbytes). Since the maximum transmission ranges under the DDMAC and BMC protocols are the same, it is safe to assume that both protocols achieve the same forward progress per hop. Consequently, our performance metrics are the one-hop throughput, i.e., the packet destination is restricted to one hop from the source, and the connection blocking rate. The latter metric is defined as the percentage of CR packet requests that are blocked due to the unavailability of a feasible channel assignment. The signal propagation model in (4) is used with $n = 4$ and $G_t(f) = G_r(f) = 1$ for every carrier frequency f.

A. Simulation Setup

We consider four PRNs and one CRN. Users in each PRN are uniformly distributed over a 500×500 meters^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 non-overlapping 1-MHz channels. The number of PR users in each PRN is 300. We divide the time into slots, each of length 3.3 ms. A time slot corresponds to the transmission of one CR packet at a fixed data rate (5 Mbps). In any given slot, each PR user in the ith PRN attempts to transmit over its own band with probability α_i. The probabilities for the four PRNs are $0.5, 0.3, 0.3, 0.1$, respectively. The transmission power for each PR user is 0.5 Watt, and the antenna length (D) is 5 cm.

For the CRN, we consider a *random-grid* topology, where 225 mobile CR users are placed within the 500×500 meters^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. Each CR user generates packets according to a Poisson process with rate λ (same for all users) and requires an aggregate transmission rate of 5 Mbps. The random waypoint model is used for mobility, with the speed of a CR user uniformly distributed between 0 and 2 meters/sec. We set the CRN SINR threshold to 5 dB and the thermal noise to $P_{th}^{(i)} = 10^{-21}$ Watt/Hz for all channels. We assume that a CR user can use up to three data channels simultaneously. We set the interference mask to $P_{mask}^{(1)} = P_{mask}^{(2)} = \ldots = P_{mask}^{(12)} = 50$ mW, which results in a maximum transmission range of $r_c = 75$ meters. The reported results are the average of 100 experiments.



(a) Blocking rate vs. λ.

(b) Throughput vs. λ.

(c) Per-user single-hop throughput.

Fig. 8. Performance of a CRN.

B. Results

We first compare the performance of DDMAC to that of the BMC scheme. We set the forgetting factor to $\alpha = 0.6$, the observation window to $T_{win} = 0.5$ second, and the number of rings around a CR user to $m = 12$. For a fair comparison, we let both schemes use the maximum allowable power vector $\overrightarrow{P}_{mask}$. Figures 8(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 due to the proper channel assignment algorithm. Note that under low traffic load, a minor reduction in the throughput of DDMAC may occur compared with BMC. This is mostly attributed to the larger control overhead of DDMAC.

In Figure 8(c), we focus on the performance of one CR user under DDMAC (other CR users depicted similar behaviors). This figure shows that, 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 greater than that of the BMC scheme. This is attributed to the fact that 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.

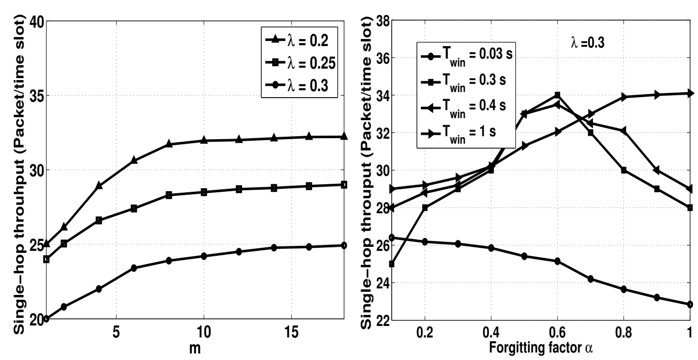
The effect of dividing the CR user's transmission range is depicted in Figure 9(a) for different values of λ. As m increases, the throughput also increases up to a certain point. For $m \geq 12$, no significant improvement is observed in the CRN throughput. This is because our proposed channel assignment merges the m regions into $K \leq m$ regions. Thus, increasing m beyond a certain value (over-dividing R_c) becomes unnecessary.

In Figure 9(b), we study the impact of α and T_{win} on the performance of DDMAC. We set $\lambda = 0.3$ packet/slot. The throughput versus α for different values of T_{win} is shown in the figure. It is clear the throughput depends on the choice of α and T_{win}. As T_{win} increases, α should increase to give much more importance to recent observations without entirely discarding older observations. Table I shows the best throughput performance and the associated optimal value of α (α^*) for different values of T_{win}. It is clear that if T_{win} is too small or too large, the throughput reduces significantly.

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

TABLE I

PERFORMANCE OF DDMAC AT THE OPTIMAL α AS A FUNCTION OF T_{win}.

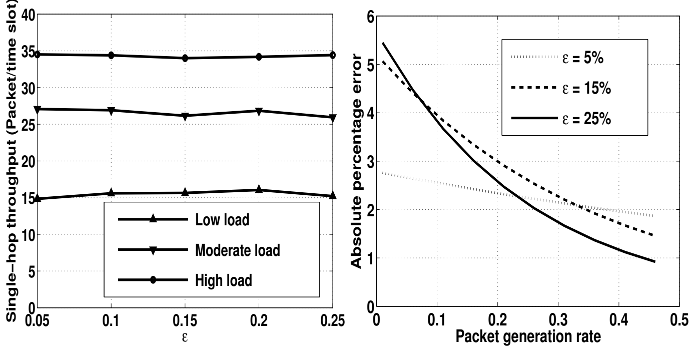


(a) Throughput vs. number of rings (m) around a CR user.

(b) Throughput vs. α for different T_{win} values.

Fig. 9. Performance of DDMAC.

Finally, we investigate the robustness of DDMAC to inaccurate distance estimation, which mainly results from multipath propagation, reflection, and fading effects. We introduce uniform estimation errors ($\xi \sim$ Uniform$[-\epsilon, \epsilon]$) into the distance d. Thus, the estimated distance $\widetilde{d}$ is given by $\widetilde{d} \longmapsto (1 + \xi)\, d$. Figure 10(a) shows the effect of inaccurate distance estimation on the perceived throughput as a function of ϵ under different traffic loads. As the figure indicates, there are no significant difference in the throughput for different values of ϵ.



(a) Throughput vs. ϵ. (b) Relative error vs. λ.

Fig. 10. Impact of inaccurately estimating d on performance.

Furthermore, Figure 10(b) shows that the maximum throughput reduction due to inaccurate d is less than 6%.

Our results suggest that the assignment is reasonably robust against estimation errors. This robustness arises from the fact that DDMAC does not need accurate distances but only the rough user distributions and local traffic conditions in order to dynamically adapt the channel assignment to transmission distances and prevailing traffic conditions.

VIII. Conclusions

In this paper, we proposed a novel distance-dependent MAC protocol for opportunistic CRNs, known as DDMAC. DDMAC improves the CRN throughput through a proper channel assignment process. We presented a heuristic stochastic channel assignment scheme that dynamically exploits the dependence between the frequency's signal attenuation model and the transmission distance, while considering the prevailing traffic conditions, to enhance the throughput. The proposed scheme assigns channels with lower average SINR to shorter transmission distances. We integrated the proposed channel assignment process in the design of DDMAC. 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 under interference mask constraints. We compared the performance of DDMAC with an optimum multi-channel MAC protocol that is designed for typical multi-channel systems (BMC). We showed that, under moderate and high traffic loads, DDMAC achieves about 30% increase in throughput over the BMC scheme. 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. In summary, our simulation results showed that DDMAC provides better spectrum utilization in terms of smaller connection blocking probability and larger system throughput.

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