A Multi-Channel Diversity Based MAC Protocol for Power-Constrained Cognitive Ad Hoc Networks

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Abstract—One of the major challenges in the medium access control (MAC) protocol design over cognitive Ad Hoc networks (CAHNs) is how to efficiently utilize multiple opportunistic channels, which vary dynamically and are subject to limited power resources. To overcome this challenge, in this paper we first propose a novel diversity technology called Multi-Channel Diversity (MCD), allowing each secondary node to use multiple channels simultaneously with only one radio per node under the upperbounded power. Using the proposed MCD, we develop a MCD based MAC (MCD-MAC) protocol, which can efficiently utilize available channel resources through joint power-channel allocation. Particularly, we convert the joint power-channel allocation to the Multi-Choice Knapsack Problem, such that we can obtain the optimal transmission strategy to maximize the network throughput through dynamic programming. Simulation results show that our proposed MCD-MAC protocol can significantly increase the network throughput as compared to the existing protocols.

I. INTRODUCTION

COGNITIVE RADIO is a promising yet challenging technology to solve wireless-spectrum underutilization problem caused by the traditional static spectrum allocation strategy [1]. Built upon the cognitive radio (CR) technology, cognitive Ad Hoc networks (CAHNs), playing a critically important role in future wireless networks, have attracted a great deal of research attention. In CAHNs, MAC protocols are responsible for dynamically accessing opportunistic channel for packet transmission. Correspondingly, one of the most important targets in cognitive MAC protocol design is how to efficiently use available channels and limited power budget to increase the network throughput and guarantee QoS, where QoS provisioning is one of the most important issues in next-generation wireless networks [1-12].

Diversity technologies are widely used to improve the throughput of Ad Hoc networks. Three main diversity technologies have been extensively investigated in recent research, namely Channel Diversity [2], Link Diversity [3], and Multi-Radio Diversity [4]. However, some drawbacks in these diversity technologies prevent the network throughput from being further improved. In particular, since channel diversity and link diversity only use one channel for packet transmissions, they cannot sufficiently utilize available channel resources.

Although multi-radio diversity can use multiple channels simultaneously, mobile nodes need to be equipped with multiple radios, increasing the implementation cost and power consumption. In addition to these diversity technologies, Game Theory [5-7] and Water-filling Algorithm [8-9] have been also applied into CAHNs for resource allocation. These two types of methods aim at identifying the optimal transmission rate to maximize the network throughput. In these two methods, the transmission rate can vary continuously, which, however, cannot be implemented in practical systems. For example, IEEE 802.11b only supports four different transmission rates, which are equal to 1, 2, 5.5, and 11 Mbps, respectively, and 802.11a only supports eight rates ranging from 6 to 54 Mbps. Moreover, these two methods yield high computational complexity, making them less attractive for practical CAHNs.

In order to efficiently use available channel resources, which vary dynamically with time, under limited power resources, we first propose a novel diversity technology called Multi-Channel Diversity (MCD). Our proposed diversity technology is based on the software-defined radio (SDR), which needs only one radio per secondary node and allows secondary nodes to use multiple channels simultaneously through channel aggregation. Using the MCD, we develop a MAC protocol, called MCD based MAC (MCD-MAC) in power-constrained cognitive Ad Hoc networks. In our proposed protocol, control packets are exchanged on the common control channel (CCC). Each node pair that successfully finishes the control packets exchange will perform joint power-channel allocation and continuously transmit multiple data packets. In order to maximize the network throughput, we convert the joint power-channel allocation to the Multiple-Choice Knapsack Problem and obtain the optimal allocation scheme through dynamic programming. In addition, we also design a mechanism to guarantee the transmission-time fairness for different node pairs.

The rest of this paper is organized as follows. Section II presents the network model. Section III defines the Multi-Channel Diversity and proposes the MCD-MAC protocol. Section IV theoretically analyzes the performance of MCD-MAC. Simulation results are given in Section V. The paper concludes with Section VI.

II. NETWORK MODEL

Suppose that the CAHN contains one Common Control Channel (CCC) and N Data Channels (DCs). The CCC with central frequency $f_0$ belongs to the CAHN, which is used to
exchange control packets. The DCs with central frequencies \( \{f_1, \cdots, f_R\} \) are licensed to Primary Users (PUs). The CAHN can only use those opportunistic DCs which are not occupied by PUs.

We use the ON/OFF model to characterize the channel-usage statuses of PUs, as shown in Fig. 1. Specifically, DCs are divided into synchronized Channel Slots (CSs). The shaded rectangle areas denote the channels used by PUs, and the white rectangle areas represent the available channels which can be used by the CAHN. At the beginning of each CS, PUs independently select which DCs they will use and the channel usage status of PUs remain unchanged in each CS.

In the CAHN, control packets are transmitted with basic rate \( R_{\text{basic}} \). The set of data-packet transmission rate is denoted by \( \mathcal{R} = \{R_1, R_2, \cdots, R_Q\} \), where \( Q \) is the cardinality of \( R \) and \( R_1 < R_2 < \cdots < R_Q \). The corresponding set of Signal-to-Noise Ratio (SNR) is denoted by \( \mathcal{SNR} = \{SNR_1, SNR_2, \cdots, SNR_Q\} \), where \( SNR_1 < SNR_2 < \cdots < SNR_Q \). The maximum transmit power for each node is denoted by \( P_{\text{max}} \). The radio propagation model between two nodes follows the two-ray model \[^{[4]}\]. Then, the received power is given by

\[
P_r(d) = P_l G_t G_r h_t^2 h_r^2 / (d^4 L),
\]

where \( G_t \) and \( G_r \) are the gains of transmitter and receiver antennas, \( h_t \) and \( h_r \) are the height of transmitter and receiver antennas, \( L \) is the system loss factor, and \( d \) is the distance between transmitter and receiver. Moreover, each node is equipped with two radios, called control radio and data radio, respectively. The control radio is devoted to operating on the CCC for control packet exchanges. The data radio works on the data channels for sensing, transmitting and receiving. The data radio is based on the software-defined radio (SDR) so that it can realize channel aggregation and use multiple channels with different transmit power simultaneously.

III. MCD-MAC PROTOCOL

A. Multi-Channel Diversity

In recent researches, there are three main diversity technologies, which are Channel Diversity, Link Diversity, and Multi-Radio Diversity respectively. Although above diversity technologies can efficiently improve the network throughput, there are still some drawbacks in them. For channel diversity and link diversity, as only one channel is allowed for packet transmission, they cannot sufficiently utilize available channel resources, which will prevent the throughput from further increasing. For multi-radio diversity, several channels can be used simultaneously, but nodes in the network have to be equipped with several radios, which will increase the cost payment and power consumption.

Therefore, in order to efficiently use available channel resources and not to bring additional cost, we introduce a novel diversity technology named Multi-Channel Diversity. The proposed diversity can be described as: there are several available channels between source and destination, the node pair first decides the channels and corresponding power that they will use through exchanging control packets, then the source continuously transmits multiple packets to the destination according to the allocation result of channel and power with only one radio and limited transmitting power.

B. Protocol Description

The MCD-MAC protocol divides each CS into two parts, named Sensing Period and Data Transmission Period. In sensing period, nodes sense all DCs to determine opportunistic DCs that PUs do not use in current CS. In data transmission period, nodes compete for these opportunistic DCs to transmit data packets through exchanging control packets on CCC.

Each node maintains one Data Channel Usage List (DCUL). The list records an item for each DC, and each item contains five parts, which are “Channel Number \( k \)”, “PU Status”, “Neighbor Status”, “Sensed Interference \( P_{\text{sensed}}(k) \)”, and “Maximal Allowed Transmitting Power \( P_{\text{max}} - \cdot \cdot \cdot (k) \)”. “PU Status” and “Neighbor Status” represent whether the \( k \)-th DC is occupied by PUs or neighbor nodes.

In the MCD-MAC protocol, node pairs compete for the opportunistic DCs through three control packets, which are RTS, CTS, and RES. If one node pair won the competition, then the two nodes determine the DCs that they will use for packet transmission, and finish their packet transmission on those DCs. Suppose the source and destination nodes are \( S \) and \( D \) respectively. The transmission process is shown in Fig. 2.

1) Sending RTS: \( S \) first overhears on CCC. If the CCC is busy, then \( S \) chooses a backoff time and defer its transmission. If the CCC is idle for a duration of one DIFS after the backoff time, then a RTS packet that contains the DCUL of \( S \) is sent to \( D \).

2) Sending CTS: If \( D \) successfully receives the RTS, then it compares its DCUL with that of \( S \). If common available DCs, which mean such DCs are not occupied by PUs for both \( S \) and \( D \), exist in the two DCULs, \( D \) first computes the channel gain between itself and \( S \) on CCC through (2):

\[
h_{SD}^0 = p_{\text{receiver power of the RTS}} / P_{\text{max}},
\]

where \( p_{\text{receiver power of the RTS}} \) is the receiving power of the RTS.

Suppose there are \( M \) common available channels with central frequencies \( \{f_1, \cdots, f_M\} \) between \( S \) and \( D \), then channel gains on these channels can be acquired through (3):

\[
h_{SD}^m = h_{SD}^0 \times (f_0/f_m)^4, \quad m = 1, \cdots, M.
\]

Then \( D \) processes the joint power-channel allocation based on the information of the two DCULs, and decides the number of data packets that can be transmitted in the following transmission process. Finally, a CTS, which contains the information of the result of power-channel allocation and the number of data packets for transmitting, is sent to \( S \).

3) Sending RES: If \( S \) successfully receives the CTS, then a RES that contains the same content with the CTS is sent.
4) Data packets transmission: After exchanging control packets, S and D switch to the corresponding DCs, and finish their packet transmission.

Furthermore, nodes that overhear CTS or RES packets also need to modify the information contained in DCUs.

Suppose S and D will transmit N_{SD} packets with transmission rate R_{SD}, and the power allocation is \{P_{SD}^{1}, \ldots, P_{SD}^{M}\}. If node I overheard the CTS sent by D, I first computes the channel gains h_{ID}^{0} and \{h_{ID}^{1}, \ldots, h_{ID}^{M}\}. Then for each channel \(m = 1, \ldots, M\), node I computes the interference caused by the ACK packets transmission and updates the total interference according to (4):

\[
\begin{aligned}
P_{\text{inf}}^{m}(m) &= P_{\text{inf}}^{m} / h_{ID}^{m}, \\
P_{\text{inf}}(m) &= P_{\text{inf}}(m) + P_{\text{inf}}^{m}(m).
\end{aligned}
\]

Then the maximum allowed power can be got through (5):

\[
P_{\text{max}} - s(m) = P_{\text{inf}}^{m} / h_{ID}^{m}, \quad m = 1, \ldots, M,
\]

where \(P_{\text{inf}}^{m}\) is the maximum interference power that neighbor nodes can tolerate. Finally, node I updates the Network Allocation Vector (NAV) of the CTS through (6):

\[
NAV_{cts} = L_{res} / R_{\text{basic}} + N_{SD} L_{\text{data}} / R_{SD} + (2N_{SD} + 1)T_{\text{sifs}}.
\]

The same way can be used for those nodes that overheard the RES packet to update correlative information.

C. Transmission-Time Fairness

As the MCD-MAC protocol allows node S continuously transmits several packets to node D, we must avoid that one node pair occupies DCs for a long time, which will harm the fairness of the protocol. Therefore, we use (7) to define the maximum transmission time, which represents the time that nodes transmit one data packet with basic rate on CCC and is also used in [2]

\[
T_{\text{max}} = L_{\text{data}} / R_{\text{basic}}.
\]

Besides, as varying channel gains will affect power-channel allocation, the transmission time cannot exceed the coherent time of DCs. Therefore, the transmission time should satisfy the following inequality:

\[
T_{SD} \leq \min \{CT(f_{1}), \ldots, CT(f_{M})\} = CT_{\text{min}},
\]

where \(CT(f_{m})\) is the coherent time of DC with central frequency \(f_{m}\). Therefore, the transmission time \(T_{SD}\) has to satisfy:

\[
T_{SD} \leq \min \{CT_{\text{min}}, T_{\text{max}}\}.
\]

As the transmission time can be acquired as (10), the number of data packets \(N_{SD}\) that node pair is allowed to transmit must hold the condition shown in (11):

\[
T_{SD} = (2N_{SD} - 1)T_{\text{sifs}} + N_{SD}(L_{\text{data}} + L_{\text{ack}}) / R_{SD},
\]

\[
N_{SD} \leq \frac{R_{SD} \left( \min \{CT_{\text{min}}, T_{\text{max}}\} + T_{\text{sifs}} \right)}{L_{\text{data}} + L_{\text{ack}} + 2T_{\text{sifs}} R_{SD}},
\]

where \(L_{\text{data}}\) and \(L_{\text{ack}}\) are the lengths of data and ACK packets, \(T_{\text{sifs}}\) are the the duration of Short Inter-Frame Space (SIFS), and \([\cdot]\) is the floor function.

D. Joint Power-Channel Allocation

In this section, we first convert the joint power/channel allocation to the Multiple-Choice Knapsack Problem, then obtain the optimal allocation scheme through dynamic programming.

Suppose the number of common available channels for S and D is M and the corresponding channel gains are \(\{h_{SD}^{1}, \ldots, h_{SD}^{M}\}\). Construct the matrix of available transmission rates:

\[
\mathbf{R} = \begin{bmatrix} R_{1} & \cdots & R_{M} \end{bmatrix}^{T},
\]

where \(\mathbf{R}^{m} = [R_{m,1}, \ldots, R_{m,Q}]\) is available transmission rate vector of the \(m\)th DC and satisfies \(R_{m,q} = R_{q},\ \forall m \in \{1, \ldots, M\}\) and \(q \in \{1, \ldots, Q\}\). Construct the matrix of transmit power:

\[
\mathbf{P}_{SD} = \begin{bmatrix} P_{SD}^{1} & \cdots & P_{SD}^{M} \end{bmatrix}^{T},
\]

where \(\mathbf{P}_{SD}^{m,q} = \mathbf{P}_{SD}^{m,1} / h_{SD}^{m}\). For \(\forall m \in \{1, \ldots, M\}\) and \(q \in \{1, \ldots, Q\}\), \(\mathbf{P}_{SD}^{m,q}\) is the transmit power that S sends data packets with rate \(R_{q}\) on the \(m\)th DC and can be calculated as:

\[
\mathbf{P}_{SD}^{m,q} = SINR_{q} \frac{P_{\text{inf}} + P_{\text{inf}}(m)}{h_{SD}^{m}},
\]

where \(P_{n}\) is the noise power.

Problem Description: Source S selects transmit power on the M DCs from vectors \(\mathbf{P}_{SD}^{1}, \ldots, \mathbf{P}_{SD}^{M}\), and at most one power can be chosen from each vector. The optimization objective is to maximize the transmission rate \(R_{SD}\) under the constraints that the total transmit power and the power used for the \(m\)th DC are no larger than \(P_{\text{max}}\) and the maximum allowed transmit power \(P_{\text{max}} - s(m)\), respectively.

The above problem is the Multiple-Choice Knapsack Problem and its mathematical description is

\[
\begin{aligned}
&\max_{\{x^{m,q}\}} \sum_{m \in M} \sum_{q \in Q_{m}} R_{m,q} x^{m,q}, \\
&\text{s.t.} \quad \sum_{m \in M} \sum_{q \in Q_{m}} \mathbf{P}_{SD}^{m,q} x^{m,q} \leq P_{\text{max}}, \\
&\quad \mathbf{P}_{SD}^{m,q} x^{m,q} \leq P_{\text{max}} - s(m), \quad m \in M, \ q \in Q_{m}, \\
&\quad \sum_{q \in Q_{m}} x^{m,q} \leq 1, \quad m \in M, \\
&\quad x^{m,q} \in \{0, 1\}, \quad m \in M, \ q \in Q_{m}.
\end{aligned}
\]

where \(M = \{1, \ldots, M\}\) and \(Q_{m} = \{1, \ldots, Q\}, \forall m \in M\).
For ∀i ∈ Q_m, if P_{SD}^{m,i} > P_{\text{max}}, then i is said to be IP-infeasible and can be deleted from Q_m. For ∀i, j ∈ Q_m, i is said to IP-dominate j if and only if P_{SD}^{m,i} ≤ P_{SD}^{m,j} and R_{SD}^{m,i} ≥ R_{SD}^{m,j}, then j can be deleted from Q_m. If i is not IP-dominate by any other j ∈ Q_m, then i is said to be IP-efficient. Let Q_m^* contains the IP-feasible and IP-efficient indices of Q_m.

we use dynamic programming to solve above problem [10]. In this method, multiple-choice knapsack problem can be solved through M stages. While solving the L-stage subproblem (L ∈ M), denoted as SP(L), we only consider to use the first L DCs (denoted as L = {1, · · · , L}) for transmission. The mathematical description of SP(L) is

\[
\max_{(x^{l,q}, D)} \sum_{l \in \mathcal{L}} \sum_{q \in \mathcal{Q}_l} R_l^{x^{l,q}, D} \cdot l \leq P_{\text{max}},
\]

\[
\text{s.t.} \left\{ \begin{array}{l}
\sum_{l \in \mathcal{L}} \sum_{q \in \mathcal{Q}_l} P_{SD}^{l,q} \cdot l \leq P_{\text{max}}, \\
P_{SD}^{l,q} \leq P_{\text{max}}^{s(l)}, l \in \mathcal{L}, q \in \mathcal{Q}_l, \\
\sum_{q \in \mathcal{Q}_l} x_l^{q} \cdot l \leq 1, l \in \mathcal{L}, \\
x_l^{q} \in \{0, 1\}, l \in \mathcal{L}, q \in \mathcal{Q}_l.
\end{array} \right.
\]

A solution to SP(L) can be uniquely characterized by a vector g with g[l] ∈ Q_l and x_l^{g[l]} = 1, l ∈ L. Let X_L^0 denote a subset of the set of solutions of SP(L). For each x ∈ X_L^0, (R(x), P(x)) is said to be a DP-state, which can be calculated as

\[
(R(x), P(x)) = \left( \sum_{l \in \mathcal{L}} R_l^{x^{l,q}, D}, \sum_{l \in \mathcal{L}, q \in \mathcal{Q}_l} P_{SD}^{l,q} \right).
\]

If P(x) > P_{\text{max}}, the partial solution x is said to be DP-infeasible and can be deleted from X_L^0. Let X_L^f denote a subset of the set of DP-feasible solutions of SP(L). If for ∀x^d, x^e ∈ X_L^f, which satisfy

\[
P(x^e) \leq P(x^d) \text{ and } R(x^e) \geq R(x^d),
\]

the partial solution x^d is said to be DP-dominated by x^e and can be deleted from X_L^f. If x^e is not DP-dominated by any other element of X_L^f, x^e is said to be DP-efficient. Let X_L^e denote the set of DP-feasible and DP-efficient solutions of SP(L). After solving M subproblems, we can obtain the final power allocation \( P_{SD} = [P_{SD}^1, \cdots, P_{SD}^M] \). In summary, the joint power-channel allocation algorithm is described as the dynamic programming algorithm shown in Fig. 3.

IV. PERFORMANCE ANALYSIS

Considering a node pair with source S and destination D with M common available channels. The channel gains are \( \{h_{SD}^1, \cdots, h_{SD}^M\} \). The sets of available data transmission rate and corresponding SNR threshold are the same as those described in section III. Moreover, the corresponding set of transmission radius on the mth DC is denoted by \( r_{m} = \{r_{m}^1, r_{m}^2, \cdots, r_{m}^Q\} \), where \( r_{m}^1 > r_{m}^2 > \cdots > r_{m}^Q \). We only consider the path loss component.

**Dynamic programming algorithm: Joint power-channel allocation.**

1) Initialization: \( L = 1, X_{L}^0 = N_c^0 \);
2) DP-dominance:
   i) Construct \( X_{L}^f \) by eliminating all DP-infeasible elements of \( X_{L}^0 \);
   ii) Construct \( X_{L}^e \) by eliminating all DP-infeasible elements of \( X_{L}^f \);
3) If \( L = M \), stop;
   Otherwise, \( L = L + 1 \), construct \( X_{L}^e = X_{L-1}^e \times N_c^f \) and goto 2).

![Fig. 3. Dynamic programming algorithm for joint power-channel allocation.](image)

A. Data Transmission Rate Analysis

Suppose that node S transmits on the mth DC with rate \( R_q \). When the interference caused by other nodes is absence, the SNR of node D which is apart from S with \( r_q^m \) can be expressed as

\[
SNR_q = \frac{P_n \cdot (r_q^m)}{P_n} = \frac{G_{t} (f_m) G_{r} (f_m) h_{SD}^2 h_{SE}^2}{(r_q^m + 1) \cdot L \cdot P_n} P_{max},
\]

where \( P_n \) is the noise power, and \( f_m \) is the central frequency. While considering the interference caused by other nodes, if the distance between S and D is \( d_{SD} \) and the transmit power on the mth channel is \( P_t^m \), then the SINR at D, denoted by \( SINR^m(d_{SD}) \), is

\[
SINR^m(d_{SD}) = \frac{G_{t} (f_m) G_{r} (f_m) h_{SD}^2 h_{SE}^2}{d_{SD}^4 \cdot L \cdot (P_n + P_{inf})} P_t^m,
\]

where \( P_t^m(d_{SD}) \) is the receiving power, and \( P_{inf} \) is the interference power on the mth channel detected by D. If S can use rate \( R_q \) for transmission on the mth DC, the inequation \( SINR^m(d_{SD}) \geq SNR_q \) must be held. Substituting (19) and (20) into the inequation, we can obtain the relationship between \( P_t^m \) and \( P_{\text{max}} \), shown as

\[
P_t^m \geq \left( \frac{d_{SD}^4 \cdot L \cdot (P_n + P_{inf})}{P_n} \right) P_{\text{max}}.
\]

Suppose that the data transmission rate used by S on the mth channel is \( R_q(m) \) (\( m \in M \) and \( q(m) \in Q_m \)), then the inequation, which is shown as

\[
\sum_{m \in M} P_t^m = \sum_{m \in M} \frac{d_{SD}^4 \cdot L \cdot (P_n + P_{inf})}{P_n} P_{\text{max}} \leq P_{\text{max}},
\]

must be satisfied. From the above inequation, we can get the condition that \( d_{SD} \) must hold, which is given by

\[
d_{SD} \leq \left[ \sum_{m \in M} \left( \frac{d_{SD}^4 \cdot L \cdot (P_n + P_{inf})}{P_n} \right) \right]^{-\frac{1}{4}}.
\]

If we denote the set of transmission radius on the CCC as \( r = \{r_1, \cdots, r_Q\} \), the relationship between \( r_q^m \) and \( r_q \) is

\[
r_q^m = (f_m / f_0) r_q.
\]
From (24) into (23), the constraint for \( d_{SD} \) can be written as
\[
d_{SD} \leq \left[ \sum_{m \in M} \left( \frac{1}{r_q} \cdot \frac{f_0}{f_m} \right)^4 \frac{P_n + P_m^m}{P_{inf}} \right]^{\frac{1}{4}}.
\] (25)

The total data transmission rate \( R_{SD} \) can be calculated as:
\[
R_{SD} = \sum_{m \in M} R_q(m).
\] (26)

From (25) and (26), we get the relationship between the distance and the total data transmission rate. If the transmission rate on each channel is given and the interference is measured, the required distance between source and destination can be calculated. Since the number of total transmission rate is \( Q^M \), the number of corresponding distance is also \( Q^M \), which provide more adaptability for transmission rate.

### B. Throughput Analysis

Suppose that the power allocation of node \( S \) and \( D \) is \( P_{SD} = [P_{SD}^1, \cdots, P_{SD}^M] \). For the \( m \)-th \( (m \in M) \) channel, the probability that \( S \) can use rate \( R_q \) \( (q \in \{1, \cdots, Q-1\}) \) for transmission on the channel is
\[
Pr\{R_{SD}^m=R_q\} = Pr\{SNR_q \leq SINR_{SD}^m < SNR_{q+1}\} \tag{27}
\]
where \( R_{SD}^m \) is the transmission rate on the \( m \)-th channel and \( SINR_{SD}^m \) is the SINR of node \( D \) on the channel. Substituting (19) and (20) into the above equation, we can obtain
\[
Pr\{R_{SD}^m = R_q\} = \Pr\{\Gamma_m r_q^{m+1} \leq d_{SD} < \Gamma_m r_q^m\}, \tag{28}
\]
where \( \Gamma_m = [P_{SD}^m P_n/P_{max} (P_n + P_{inf})]^{1/4} \). Through similar approach, we can obtain the probabilities that \( S \) uses rate \( R_Q \) for transmission and gives up using this channel, respectively, which are shown as
\[
Pr\{R_{SD}^m = R_Q\} = \Pr\{SINR_{SD}^m \geq SNR_Q\} = \Pr\{d_{SD} \leq \Gamma_m r_q^m\}, \tag{29}
\]
\[
Pr\{R_{SD}^m = 0\} = \Pr\{SINR_{SD}^m < SNR_1\} = \Pr\{d_{SD} > \Gamma_m r_q^m\}. \tag{30}
\]

If the distribution of nodes is given, we can obtain the probability density function (pdf) of the distance \( d_{SD} \) and calculate the probabilities shown in (28)-(30). For example, if the nodes are uniformly distributed, then the pdf of \( d_{SD} \) is \( f(d_{SD}) = 2d_{SD} \). Therefore, (28)-(30) become
\[
Pr\{R_{SD}^m = R_q\} = \int_{\Gamma_r r_q^{m+1}}^{\Gamma_m r_q^m} f(d_{SD})d(d_{SD}) = (\Gamma_m)^2[(r_q^m)^2 - (r_q^{m+1})^2], \tag{31}
\]
\[
Pr\{R_{SD}^m = R_Q\} = \int_0^{\Gamma_m r_q^m} f(d_{SD})d(d_{SD}) = (\Gamma_m r_q^m)^2, \tag{32}
\]
\[
Pr\{R_{SD}^m = 0\} = 1 - \sum_{q=1}^{Q} Pr\{R_{SD}^m = R_q\} = 1 - (\Gamma_m r_q^m)^2. \tag{33}
\]

Therefore, the expected average transmission rate is
\[
\mathbb{E}\{R_{SD}\} = \sum_{m=1}^{M} \sum_{q=0}^{Q} Pr\{R_{SD}^m = R_q\} R_q. \tag{34}
\]

Using \( \mathbb{E}\{R_{SD}\} \) instead of \( R_{SD} \) in (11), we can get the expected average number of data packets \( \mathbb{E}\{N_{SD}\} \) that can be transmitted during one transmission process. Then, using \( \mathbb{E}\{N_{SD}\} \) and \( \mathbb{E}\{R_{SD}\} \) instead of \( N_{SD} \) and \( R_{SD} \) in (10), the expected average transmission time for one transmission process, denoted by \( \mathbb{E}\{T_{SD}\} \) can be calculated.

Finally, we can get the expected average throughput between \( S \) and \( D \):
\[
\mathbb{E}\{\psi_{SD}\} = \mathbb{E}\{N_{SD}\} L_{data}/\mathbb{E}\{T_{SD}\}. \tag{35}
\]

### V. Simulation Results

Suppose each node supports three different data transmission rates which are 2, 5.5, and 11Mbps, respectively. The corresponding transmission radii of the CCC are 250, 200, and 100m, respectively. The control packets are exchanged on the CCC with basic rate 2Mbps. Each data packet contains 1000 Bytes.

Fig. 4 shows the data transmission rate gains of the MCD-MAC protocol with different number of data channels over the data rate with one data channel. From the result, we can find that the data transmission rates with multiple data channels are significantly larger than that with one data channel, and the obtained gains are the most notable when the distance between source and destination is small. The reason is that the required transmitting power is small with the small distance, therefore, nodes can utilize all the data channels under the total power limitation. The simulation result also shows, no matter how many channels are available, the obtained data rate gains decrease as the distance between the two nodes increases.

The reason is that the propagation loss will become larger with longer distance, in order to finish their transmission, the source has to decrease its transmission rate to guarantee the SINR at the destination. Although the data transmission rate with multiple data channels equals that with one channel under extremely long distance, the multi-channel diversity can still significantly improve the data transmission rate in most of the distance range.

Fig. 5 shows the average node throughput of the MCD-MAC protocol as a function of number of available data channels under different interference power. From the result we can find, no matter how many channels can be used, the average node throughput decreases as the interference power increases. This is because larger transmit power is needed to guarantee that the SINR at the destination is larger than the threshold when interference exists, which causes the source node has to use less data channels or choose lower transmission rate because of the limited transmit power resources. However, given the interference power, the average node throughput with multiple data channels is larger than that with one channel. In particular, the more data channels are used, the more obvious the improvement is, which shows the advantage of multi-channel diversity.

Fig. 6 shows the average network throughput of MCD-MAC, OMMC [4] with power limitation and MOAR [2].
as a function of number of flows. In our simulation, nodes are uniformly distributed in a circular area with a diameter of 250m, and any node randomly chooses one of its neighbors as its destination. The network contains six data channels. In order to simulate the PUs’ activities, the probability that each channel is occupied by PUs in each CS is 0.5, which means half of channels can be used statistically. The simulation result shows that the average network throughput of the MCD-MAC protocol obviously exceeds those of MOAR and OMMAC with total power limitation. The main reason is that the MCD-MAC protocol uses multi-channel diversity, which can help nodes to efficiently and fully utilize available opportunistic DCs for data transmission. Moreover, the most suitable number of channels that they will use and the corresponding power allocation can be dynamically adjusted by joint channel/power allocation according to the distance between source and destination as well as the interference caused by their neighbor nodes. Furthermore, because of the power control brought by the multi-channel diversity, the mutual interference among neighbor nodes is reduced, and the space reuse efficiency is improved, which are benefit for the throughput improvement.

VI. CONCLUSION

In this paper, we first propose the multi-channel diversity (MCD), which allows each secondary node to utilize multiple channels simultaneously with only one radio per node and upperbounded transmit power. Then, using the proposed MCD, we develop a novel MAC protocol, named MCD-MAC. The protocol can efficiently utilize available channel resources through joint power-channel allocation. Particularly, we convert the joint power-channel allocation to the multiple-choice knapsack problem such that the optimal transmission strategy can be obtained through dynamic programming. In addition, we also design a mechanism to guarantee the transmission-time fairness for different node pairs. Simulation results show that our proposed MCD-MAC protocol outperforms the existing protocols.

REFERENCES

[1] J. Mitola and G.Q. Maguire, “Cognitive Radio: Making Software Radios More Personal,” IEEE Personal Commun., vol. 6, no. 4, pp. 13-18, Aug. 1999.
[2] A. Sabharwal, A. Khoshnevis, V. Kanodia, and E. Knightly, “Opportunistic spectral usage: bounds and a multi-band CSMA/CA protocol,” IEEE/ACM Trans. Netw., vol. 15, no. 3, pp.533-545, Jun. 2007.
[3] J.F. Wang, H.Q. Zhai, Y.G. Fang, J.M. Shea, and D.P. Wu, “OMAR: Utilizing Multuser Diversity in Wireless Ad Hoc Networks,” IEEE Trans. Mobile Computing, vol. 5, no. 12, pp. 1764-1779, Dec. 2006.
[4] F. Chen, H.Q. Zhai, and Y.G. Fang, “An Opportunistic Multiradio MAC Protocol in Multirate Wireless Ad Hoc Networks,” IEEE Trans. Wireless Commun., vol. 8, no. 5, pp. 2642-2651, May, 2009.
[5] F. Wang, M. Krunz, and S.G. Cui, “Price-Based Spectrum Management in Cognitive Radio Networks,” IEEE J. Select. Topics in Signal Process., vol. 2, no. 1, pp. 74-87, Feb., 2008.
[6] S.K. Jayaweera, and T.M. Li, “Dynamic Spectrum Leasing in Cognitive Radio Networks via Primary-Secondary User Power Control Games,” IEEE Trans. Wireless Commun., vol. 8, no. 6, pp. 3300-3310, Jun. 2009.
[7] H. He, J. Wang, J. Zhu, and S.Q. Li, “Optimal Policy of Cross-Layer Design for Channel Access and Transmission Rate Adaptation in Cognitive Radio Networks,” EURASIP J. Advances in Signal Process., vol. 2010, pp. 1-12, 2010.
[8] G. Bansal, M.J. Hossain, and V.K. Bhargava, “Optimal and Suboptimal Power Allocation Schemes for OFDM-based Cognitive Radio Systems,” IEEE Trans. Wireless Commun., vol. 7, no. 11, pp. 4710-4718, Nov. 2008.
[9] X. Kang, H.K. Garg, Y.L. Liang, and R. Zhang, “Optimal power allocation for OFDM-based cognitive radio with new primary transmission protection criteria,” IEEE Trans. Wireless Commun., vol. 9, no. 6, pp. 2066-2075, Jun. 2010.

[10] H. Su and X. Zhang, “Cross-Layer Based Opportunistic MAC Protocols for QoS Provisionings Over Cognitive Radio Wireless Networks,” IEEE J. Selec. Areas Commun., vol.26, no. 1, pp. 118-129, Jun. 2008.

[11] M.E. Dyer, W.O. Riha, and J. Walker, “A Hybrid Dynamic Programming/Branch-and-Bound Algorithm for the Multiple-Choice Knapsack Problem,” J. Computational and Applied Mathematics, vol. 58, no. 1, pp. 43-54, Mar. 1995.

[12] X. Zhang and H. Su, “CREAM-MAC: Cognitive Radio-Enabled Multi-Channel MAC Protocol Over Dynamic Spectrum Access Networks,” IEEE J. Selec. Topics Signal Process., vol.5, no. 1, pp. 118-123, Feb. 2011.

[13] M. Maskery, V. Krishnamurthy, and Q. Zhao, “Decentralized Dynamic Spectrum Access for Cognitive Radios: Cooperative Design of a Non-Cooperative Game,” IEEE Trans. Commun., vol.57, no. 2, pp. 459-469, Feb. 2009.

[14] K.Q. Liu and Q. Zhao, “Indexability of Restless Bandit Problems and Optimality of Whittle Index for Dynamic Multichannel Access,” IEEE Trans. Inf. Theory, vol. 56, no. 11, pp. 5547-5567, Nov. 2010.

[15] Y.C. Wang, P.Y. Ren, and G.E. Wu, “A throughput-aimed MAC protocol with QoS provision for cognitive Ad Hoc networks,” IEICE Trans. Commun., vol. E93-B, no. 6, Jun. 2010.

[16] J. Tang and X. Zhang, “Quality-of-service driven power and rate adaptation over wireless links,” IEEE Trans. Wireless Commun., vol. 6, no. 8, pp. 3058-3068, Aug. 2007.

[17] J. Tang and X. Zhang, “Cross-Layer-Model Based Adaptive Resource Allocation for Statistical QoS Guarantees in Mobile Wireless Networks,” IEEE Transactions on Wireless Communications, vol. 7, no. 6, pp. 2318–2328, June 2008.

[18] X. Zhang and K. G. Shin, D. Saha, and D. Kandlur, “Scalable flow control for multicast ABR services in ATM networks,” IEEE/ACM Trans. on Networking, vol. 10, no. 1, pp. 67-85, Feb. 2002.

[19] J. Tang and X. Zhang, “Cross-Layer Resource Allocation Over Wireless Relay Networks for Quality of Service Provisioning,” IEEE Journal on Selected Areas in Communications, vol. 25, no. 4, pp. 645–657, May 2007.

[20] X. Zhang, J. Tang, H.-H. Chen, S. Ci, and M. Guizni, “Cross-layer-based modeling for quality of service guarantees in mobile wireless networks,” IEEE Commun. Mag., pp. 100-106, Jan. 2006.

[21] X. Zhang and Q. Du, “Cross-Layer Modeling for QoS-Driven Multimedia Multicast/Broadcast over Fading Channels,” IEEE Communications Magazine, vol. 45, no. 8, pp. 62–70, August 2007.