CAD-MAC: A Channel-Aggregation Diversity Based MAC Protocol for Spectrum and Energy Efficient Cognitive Ad Hoc Networks

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***Abstract*—In cognitive Ad Hoc networks (CAHN), because the contentions and mutual interferences among secondary nodes are inevitable as well as secondary nodes usually have limited power budget, spectrum efficiency and energy efficiency are critically important to the CAHN, especially for the medium access control (MAC) protocol design. Aiming at improving both spectrum and energy efficiencies, we in this paper propose a diversity technology called Channel-Aggregation Diversity (CAD), through which each node can utilize multiple channels simultaneously and efficiently allocate the upper-bounded power resource with only one data radio. Based on the proposed CAD technology, we further develop a CAD-based MAC (CAD-MAC) protocol, which enables the secondary nodes to sufficiently use available channel resources under the upper-bounded power and transmit multiple data packets in one transmission process subject to the transmission-time fairness constraint. In order to improve the performance of CAHNs, we propose two joint power-channel allocation schemes. In the first scheme, we aim at maximizing the data transmission rate. By converting the joint power-channel allocation to the Multiple-Choice Knapsack Problem, we derive the optimal allocation policy through dynamic programming. In the second scheme, our objective is to optimize the energy efficiency and we obtain the corresponding allocation policy through fractional programming. Simulation results show that our proposed CAD-MAC protocol can efficiently increase the spectrum and energy efficiencies as well as the throughput of the CAHN compared with existing protocols. Moreover, the energy efficiency of the CAHN can be further improved by adopting the energy efficiency optimization based resource allocation scheme.**

***Index Terms*—Cognitive radio, Ad Hoc networks, medium access control (MAC), joint power-channel allocation.**

I. Introduction

With the rapid development of wireless communication technologies, the radio spectrum has become one of the most scarce resources. The critical factor that prevents wireless communication networks from further development is the traditional static spectrum allocation policy, which leads to a significantly low spectrum utilization efficiency. Because cognitive radio (CR) is able to detect the occupancy of licensed spectrum and perform opportunistic spectrum access, it has been regarded as a promising yet challenging technology to solve the wireless spectrum underutilization problem and has been extensively investigated in past years [1]–[4].

Being built upon the CR technology, cognitive Ad Hoc networks (CAHN), playing a critically important role in future wireless networks, have attracted a great deal of research attention. In CAHNs, the medium access control (MAC) protocol, which is responsible for dynamically accessing opportunistic channels and performing resource allocation, has been extensively researched in the last decade [5]–[20]. The existing MAC protocols for CAHNs can be classified according to different criteria [5], [6], such as spectrum sharing modes (overlay or underlay), spectrum allocation behaviors (cooperative or non-cooperative), spectrum access modes (contention-based, time slotted, or hybrid), the usage of common control channel (CCC) (dedicated CCC or non-dedicated CCC), number of radios (single radio or multi-radios), spectrum usage strategies (single channel or multi-channels), spectrum sensing techniques (local sensing or cooperative sensing), etc.

Although a number of classifications are available, 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. Fortunately, diversity technology is the widely used approach to achieve this goal for Ad Hoc networks. In recent researches, three main diversity technologies have been investigated, namely Channel Diversity [23], Link Diversity [24], and Multi-Radio Diversity [25]. 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.

Although increasing the throughput is an important target for the cognitive MAC protocol design, spectrum efficiency and energy efficiency are also two critically crucial performance metrics to CAHNs and should be carefully considered in MAC protocols due to the following reasons. First, the contentions and mutual interferences among secondary nodes are inevitable. Second, the secondary node usually has limited

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power budget. Third, the available channel resources are dynamically varied with the activities of primary users (PU). Consequently, not only increasing the throughput, but also improving the spectrum efficiency and energy efficiency should be jointly considered in the CAHNs. Moreover, although the throughput and spectrum efficiency of one secondary node can be improved by using larger transmit power, it can cause severe interference to its neighbor nodes, which will result in the degradations of the network throughput and energy efficiency. Therefore, there is an urgent need to develop a MAC protocol for CAHNs, which can not only increase the network throughput, but also improve the network spectrum and energy efficiencies by efficiently utilizing dynamically varied channel resources and limited transmit power budget.

To achieve the aforementioned goals, in this paper, a novel diversity technology called *Channel-Aggregation Diversity* (CAD) is proposed. Our proposed CAD technology, which is based on the well-know software-defined radio (SDR), allows each node to simultaneously utilize a group of channels with only one data radio. The upper-bounded power resource can also be efficiently allocated across the selected channels by performing joint power-channel allocation. In this way, the channel and power resources can be sufficiently utilized and mutual interferences among secondary nodes can be efficiently controlled. Thus, the spectrum efficiency and energy efficiency can be improved. Based on the proposed CAD technology, we further develop a CAD-based MAC (CAD-MAC) protocol. In our developed protocol, the secondary node can sufficiently use available channel resources under the upper-bounded transmit power by applying the CAD technology. Moreover, secondary nodes are allowed to transmit multiple data packets in one transmission process while the transmission-time fairness constraint is guaranteed. Thus the network throughput can also be improved. As the resource allocation is incorporated into our proposed CAD-MAC protocol, in order to improve the performance of the CAHN, we further propose two joint power-channel allocation schemes. In the first scheme, we aim at maximizing the data transmission rate of the source and destination node pair. By converting the joint power-channel allocation to the Multiple-Choice Knapsack Problem, we derive the optimal allocation policy through dynamic programming. In the second scheme, our objective is to optimize the energy efficiency of secondary nodes and we obtain the corresponding allocation policy through fractional programming.

The rest of this paper is organized as follows. Section II defines the network model under consideration. Section III presents in details the multi-channel diversity and the proposed CAD-MAC protocol. Moreover, in this section, we develop two joint power-channel allocations schemes, which can optimize the data transmission rate and energy efficiency of the source-destination nodes pair, respectively. Section IV theoretically analyzes the performances of the proposed CAD-MAC protocol. 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 orthogonal frequency data channels

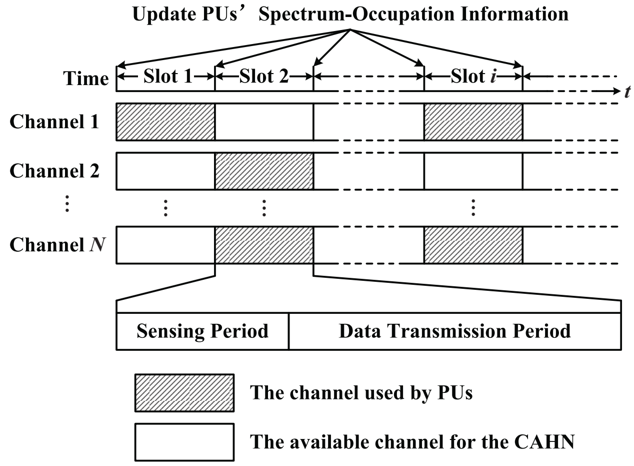


Fig. 1. ON/OFF model for the CAHN.

(DC). The CCC with central frequency f_0 belongs to the CAHN, which is used to exchange control packets. The DCs with central frequencies $\{f_1, \cdots, f_N\}$ are licensed to primary users (PU). The CAHN can only access those DCs which are not occupied by PUs.

In this paper, we employ the well-known ON/OFF model to describe PUs' channel-usage patterns [5]–[7], [9]–[11], [16], [17], as shown in Fig. 1. Specifically, all DCs are divided into synchronized channel slots (CS). At the beginning of each CS, PUs independently select which channels they will use in current CS. The PUs' channel-occupation statuses remain unchanged in each CS. As depicted in Fig. 1, the shaded rectangle areas denote the channels occupied by PUs and the white rectangle areas represent the available channels which can be used by the CAHN.

In order to efficiently protect PUs from being interfered by the CAHN, all secondary nodes in the CAHN are synchronized and have the same time slot division with PUs[1]. Moreover, each CS is further divided into two parts by the CAHN, which are sensing period and data transmission period, respectively, as shown in Fig. 1. In the sensing period, all secondary nodes simultaneously sense all DCs to find which channels are not occupied by PUs, through which available channel resources in current CS can be determined[2]. In the data transmission period, secondary nodes compete for the opportunistic DCs to transmit data packets through exchanging control packets, which will be discussed in detail in Section III. In the sensing period, lots of sensing methods can be utilized and cooperative spectrum sensing can also be incorporated [7], [8], [16], [18], [19]. As we mainly focus on designing how SUs efficiently access and utilize limited spectrum resources to improve the CAHN's performance, such as throughput, spectrum efficiency, and energy efficiency, we assume that SUs can obtain reliable sensing results at the end of the sensing period.

In the CAHN, control packets are transmitted with the predefined basic rate, denoted by R_{basic}. The set of data-packet

[1]This is the widely accepted assumption in existing literatures [7]–[10], [13], [16], [17] and can be easily implemented by utilizing Global Positioning Systems (GPS).

[2]Available DCs for different SUs may not be the same, because different SUs may be affected by different PUs.

transmission rate is denoted by $\mathbf{R} \triangleq \{R_1, \cdots, R_Q\}$, where Q is the cardinality of $\mathbf{R}$ and $R_1 < R_2 < \cdots < R_Q$. The corresponding set of Signal-to-Interference plus Noise Ratio (SINR) is denoted by $\mathbf{SINR} \triangleq \{SINR_1, \cdots, SINR_Q\}$, where $SINR_1 < SINR_2 < \cdots < SINR_Q$. The maximum transmit power of each node is denoted by $P_{\max}$. The radio propagation model between two nodes follows the two-ray model [5]. Then, the received power is given by

$$P_r(d) = \frac{h_t^2 h_r^2}{d^4 L} G_t(f) G_r(f) P_t, \tag{1}$$

where d is the distance between the transmitter and receiver, L is the system loss factor, h_t and h_r are the heights of the transmitter and receiver antennas, respectively, $G_t(f)$ and $G_r(f)$ denote the gains of the transmitter and receiver antennas, respectively. According to [28], the gains of the transmitter and receiver antennas can be written as

$$\begin{cases} G_t(f) &= 4\pi A_e^t f^2/c^2, \\ G_r(f) &= 4\pi A_e^r f^2/c^2, \end{cases} \tag{2}$$

where A_e^t and A_e^r represent the efficient areas of the transmitter and receiver antennas, c is the speed of light, and f is the carrier center frequency.

Each node is equipped with one data radio, which works on the DCs for sensing, transmitting and receiving. The data radio is based on the software-defined radio (SDR) so that it can realize channel aggregation, which allows the secondary node to use multiple channels with different transmit power simultaneously[3]. In order to help secondary nodes establish communication links, each secondary node is equipped with an additional radio, called the control radio, which is dedicated to operating on the CCC for control packet exchanges.

III. CAD-MAC Protocol

A. Channel Aggregation Diversity

Diversity technology has been widely used to improve the throughput of Ad Hoc networks. In recent researches, there are three main diversity technologies, named channel diversity, link diversity, and multi-radio diversity, respectively. In the channel diversity [23], there are several available channels between the source and destination nodes, but only one channel with the best quality is used for transmission. In the link diversity [24], for a given source node, there are several destination nodes on a given channel. The source chooses only one destination node between which the channel condition is the best for transmission. In the multi-radio diversity [25], there are several available channels and radios for a given source node. The source can communicate with several destination nodes simultaneously through different radios and channels. 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.

As discussed previously, network throughput, spectrum efficiency, and energy efficiency are critically important performance metrics to the CAHN. Intuitively, the network throughput can be improved by increasing the transmit power. However, it is not true in the CAHN and will decrease the network spectrum and energy efficiencies due to the following reasons. As there is no central control entity in the CAHN, the mutual interference and packets collisions are unavoidable. If one node increases the transmit power, its neighbor nodes will suffer more serious interference. Then, its neighbor nodes can only transmit with lower rates, which will degrade the network throughput. Moreover, using larger transmit power will cause more packets collisions, which is also harmful to the network throughput. When the throughput gain cannot match the power consumption, increasing transmit power will also cause the degradation of spectrum and energy efficiencies. Furthermore, the CAHN cannot constantly increase the transmit power due to upper-bounded power budget. Consequently, we need to develop an efficient approach to improve the network performances in terms of throughput, spectrum and energy efficiencies, under the limited power resource.

In order to achieve this goal, we propose a novel diversity technology, called *Channel Aggregation Diversity* (CAD). The proposed CAD allows the secondary node to select a group of channels from multiple available channels, which are not occupied by PUs, and allocate the upper-bounded transmit power for the selected channels based on the channel qualities and suffered interferences through joint power-channel allocation. Then, based on the joint power-channel allocation policy, the node can use the channel aggregation technology to utilize the selected group of channels simultaneously for data transmission and transmit multiple data packets during one transmission process under the transmission-time fairness constraint. Compared with the existing diversity schemes, such as channel diversity, link diversity, and multi-radio diversity, our proposed channel aggregation diversity can efficiently utilize multiple channels simultaneously under power limitation, which can increase the network throughput and reduce the implementation cost as well as the power consumption.

B. Protocol Description

In order to maximize each node's throughput under the constraint that ongoing transmissions of other nodes cannot be interfered, each node maintains one Data Channel Usage List (DCUL), which will be dynamically updated. The list records five entries for each DC, which are as follows: (i) "Channel Index k"; (ii) "PU Status"; (iii) "Neighbor Status"; (iv) "Suffered Interference $P_{\inf}(k)$"; and (v) "Maximal Allowed Transmit Power $P_{\max-s}(k)$. "PU Status" and "Neighbor Status" represent whether the kth DC is occupied by PUs or neighbor secondary nodes, respectively.

In the CAD-MAC protocol, node pairs compete for the opportunistic DCs through exchanging control packets in the data transmission period, which are Ready-To-Send (RTS), Clear-To-Send (CTS), and REServation (RES), respectively. After

[3]In order to avoid the cross-channel interference, several techniques can be adopted, such as discontiguous orthogonal frequency division (D-OFDM) [22] and using a group of software-tunable filters [21].

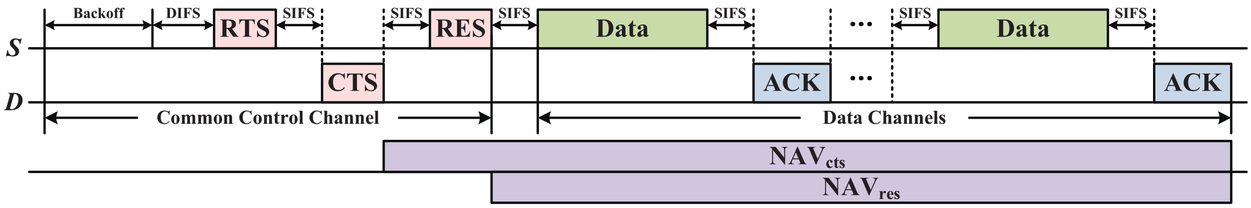


Fig. 2. Transmission process of CAD-MAC.

successful RTS-CTS-RES three-way handshakes, a group of DCs and transmission rate can be determined. Then, the source and destination node pair can finish their data transmissions on the selected DCs. Denote the source and destination nodes as S and D, respectively. The transmission process is shown in Fig. 2 and is described as follows.

1) Sending RTS Packet: S first overhears on the CCC. If the CCC is busy, then S chooses a backoff time and defers its transmission. Otherwise, if the CCC is idle for a duration of one Distributed Coordination Function Inter-Frame Space (DIFS) after the backoff time, a RTS packet that contains the DCUL of S will be sent to D.

2) Sending CTS Packet: If D successfully receives the RTS packet, then it compares its DCUL with that of S. If common available DCs, which are regarded as the opportunities by both S and D, exist, the channel power gain between S and D on the CCC, denoted by h_{SD}^0, will be calculated by

$$h_{SD}^0 = \frac{P_{\mathrm{r}}^{\mathrm{RTS}}}{P_{\max}}, \tag{3}$$

where $P_{\mathrm{r}}^{\mathrm{RTS}}$ is the received power of the RTS packet and $P_{\max}$ denotes the maximum transmit power. We suppose that all control packets are transmitted with $P_{\max}$. From Eqs. (1) and (2), the channel power gain of a given channel with the central frequency f between nodes S and D, denoted by $h_{SD}(f)$, can be written as

$$h_{SD}(f) = \frac{G_t(f)\, G_r(f)\, h_t^2 h_r^2}{d_{SD}^4 \cdot L} = \frac{16\pi^2 A_e^t A_e^r h_t^2 h_r^2 f^4}{d_{SD}^4 \cdot L \cdot c^2}, \tag{4}$$

where d_{SD} is the distance between S and D. Therefore, suppose that there are M common available channels with central frequencies $\{f_1, \cdots, f_M\}$ between S and D, based on Eqs. (3) and (4), the channel gain of the mth common available channel, denoted by h_{SD}^m, can be calculated by

$$h_{SD}^m = h_{SD}^0 \times \left(\frac{f_0}{f_m}\right)^4, \quad m = 1, 2, \cdots, M. \tag{5}$$

Then D performs the joint power-channel allocation and decides the number of data packets that can be transmitted in the following transmission process. Finally, a CTS packet is sent to S, which contains the above information.

3) Sending RES packet: If node S successfully receives the CTS packet, then a RES packet that contains the same information with the CTS packet is sent. The purposes of transmitting the RES packet are twofold. On the one hand, it can be used to confirm the successful reception of the CTS packet. On the other hand, it can notify the neighbor nodes of S to update the information recorded in their DCULs.

4) Transmitting Data Packets: After exchanging control packets, S and D switch to the corresponding DCs and finish their packet transmission according to the power-channel allocation policy.

Furthermore, those nodes that overheard CTS or RES packets need to update the information contained in their DCULs. Suppose S and D will transmit N_{SD} packets with the transmission rate R_{SD}, and the power allocation is $\{P_{SD}^1, \cdots, P_{SD}^M\}$. If node I overhears the CTS packet sent by D, I first computes the channel gains h_{ID}^0 and $\{h_{ID}^1, \cdots, h_{ID}^M\}$. Then for each channel m ($m = 1, \cdots, M$), node I computes the interference caused by the ACK packets sent by node D and updates the total interference according to

$$\begin{cases} P_{\mathrm{inf}}^D(m) &= P_{SD}^m \cdot h_{ID}^m, \\ P_{\mathrm{inf}}(m) &= P_{\mathrm{inf}}(m) + P_{\mathrm{inf}}^D(m), \end{cases} \tag{6}$$

where $P_{\mathrm{inf}}^D(m)$ is the received interference power on the mth channel caused by the ACK packet transmission of node D, P_{SD}^D denotes the transmit power of node D on the mth channel, and h_{ID}^m represents the channel gain of the mth channel between nodes I and D. Then, the maximum allowed transmit power of node I on the mth channel, denoted by $P_{\max-\mathrm{s}}(m)$, can be written as

$$P_{\max-\mathrm{s}}(m) = \frac{P_{\min}^{\mathrm{inf}}}{h_{ID}^m}, \quad m = 1, 2, \cdots, M, \tag{7}$$

where $P_{\min}^{\mathrm{inf}}$ is the maximum interference power that neighbor nodes can tolerate. Finally, node I updates the Network Allocation Vector (NAV) of the CTS packet, denoted by NAV_{cts}, through the following equation,

$$NAV_{\mathrm{cts}} = \frac{L_{\mathrm{res}}}{R_{\mathrm{basic}}} + N_{SD}\frac{L_{\mathrm{data}} + L_{\mathrm{ack}}}{R_{SD}} + (2N_{SD} + 1)\, T_{\mathrm{sifs}}, \tag{8}$$

where L_{res}, L_{data}, and L_{ack} denote the lengths of the RES, data, and ACK packets, respectively, and T_{sifs} is the duration of the Short Inter-Frame Space (SIFS). The same way can be used for those nodes that overheard the RES packet to update corresponding information. The only difference is the NAV, which can be written as

$$NAV_{\mathrm{res}} = N_{SD}\frac{L_{\mathrm{data}} + L_{\mathrm{ack}}}{R_{SD}} + 2N_{SD}T_{\mathrm{sifs}}. \tag{9}$$

C. Transmission-Time Fairness

To prevent a single secondary link from occupying the channels for a very long time period, we introduce the *maximum transmission time* to keep the fairness among secondary users. In particular, the maximum transmission time represents the time period that a node transmits one data packet with the basic rate on CCC, which is given by

$$T_{\max} = \frac{L_{\mathrm{data}}}{R_{\mathrm{basic}}}. \tag{10}$$

Besides, the transmission time cannot exceed the coherent time of DCs. Therefore, the transmission time should satisfy the following inequality:

$$T_{SD} \leq \min\left\{CT\left(f_1\right), CT\left(f_2\right), \cdots, CT\left(f_M\right)\right\} = CT_{\min}, \tag{11}$$

where $CT\left(f_m\right)$ is the coherent time of DC with central frequency f_m. Therefore, the transmission time T_{SD} needs to satisfy:

$$T_{SD} \leq \min\left\{CT_{\min}, T_{\max}\right\}, \tag{12}$$

As the transmission time can be obtained by

$$T_{SD} = (2N_{SD} - 1)T_{\text{sifs}} + \frac{N_{SD}(L_{\text{data}} + L_{\text{ack}})}{R_{SD}}, \tag{13}$$

the number of data packets N_{SD} that the node pair is allowed to transmit needs to satisfy:

$$N_{SD} \leq \left\lfloor \frac{R_{SD}\left(\min\{CT_{\min},\ T_{\max}\}\right) + T_{\text{sifs}}}{L_{\text{data}} + L_{\text{ack}} + 2T_{\text{sifs}}R_{SD}} \right\rfloor, \tag{14}$$

where $\lfloor\cdot\rfloor$ is the floor function.

D. Joint Power-Channel Allocation

In order to increase the throughput of each node pair, we expect that the node pair can transmit more data packets during the upper-bounded transmission time. We can clearly observe from Eq. (14) that the number of data packets N_{SD} that the node pair is allowed to transmit is closely related with the total transmit rate R_{SD}. As $\min\left\{CT_{\min}, T_{\max}\right\} \gg T_{\text{sifs}}$, N_{SD} can be increased by optimizing the total transmission rate R_{SD}. Moreover, the energy efficiency and spectrum efficiency can also be improved. Consequently, in order to maximize the throughput of the node pair as well as improve the energy and spectrum efficiencies, in this section, we maximize the total transmission rate of the node pair by performing joint power-channel allocation.

Suppose the number of common available channels for *S* and *D* is *M* and the corresponding channel gains are $\left\{h_{SD}^1, \cdots, h_{SD}^M\right\}$. Construct the matrix of available transmission rates

$$\overline{\mathbf{R}} = \left[\overline{\mathbf{R}}^1, \overline{\mathbf{R}}^2, \cdots, \overline{\mathbf{R}}^M\right]^T, \tag{15}$$

where $\overline{\mathbf{R}}^m = \left[\overline{R}^{m,1}, \overline{R}^{m,2}, \cdots, \overline{R}^{m,Q}\right]$ is the available transmission rate vector of the *m*th DC and satisfies $R^{m,q} = R_q$, $\forall m \in \{1, \cdots, M\}$ and $q \in \{1, \cdots, Q\}$. Construct the matrix of transmit power

$$\overline{\mathbf{P}}_{SD} = \left[\overline{\mathbf{P}}_{SD}^1, \overline{\mathbf{P}}_{SD}^2, \cdots, \overline{\mathbf{P}}_{SD}^M\right]^T, \tag{16}$$

where $\overline{\mathbf{P}}_{SD}^m = \left[\overline{P}_{SD}^{m,1}, \overline{P}_{SD}^{m,2}, \cdots, \overline{P}_{SD}^{m,Q}\right]$ is the transmit power vector corresponding to $\overline{\mathbf{R}}^m$. For $\forall m \in \{1, 2, \cdots, M\}$ and $q \in \{1, 2, \cdots, Q\}$, $\overline{P}_{SD}^{m,q}$ is the transmit power that *S* can send data packets with rate R_q on the *m*th DC and can be calculated by

$$\overline{P}_{SD}^{m,q} = SINR_q \frac{P_n + P_{\inf}(m)}{h_{SD}^m}, \tag{17}$$

where P_n is the noise power.

Problem Description: Source *S* selects transmit power on the *M* DCs from vectors $\overline{\mathbf{P}}_{SD}^1, \cdots, \overline{\mathbf{P}}_{SD}^M$, 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 $P_{\max}$ and the maximum allowed transmit power $P_{\max-\mathrm{s}}(m)$, respectively. Then, the optimization problem can be mathematically formulated by

$$\text{(P1)} \max_{\{x_{m,q}\}} \sum_{m\in\mathcal{M}} \sum_{q\in\mathcal{Q}_m} R^{m,q} x_{m,q},$$

$$\text{s.t.} \begin{cases} \sum\limits_{m\in\mathcal{M}} \sum\limits_{q\in\mathcal{Q}_m} \overline{P}_{SD}^{m,q} x_{m,q} \leq P_{\max}, \\ \overline{P}_{SD}^{m,q} \leq P_{\max-\mathrm{s}}(m),\ m \in \mathcal{M},\ q \in \mathcal{Q}_m, \\ \sum\limits_{q\in\mathcal{Q}_m} x_{m,q} \leq 1, \quad m \in \mathcal{M}, \\ x_{m,q} \in \{0, 1\}, \quad m \in \mathcal{M},\ q \in \mathcal{Q}_m, \end{cases} \tag{18}$$

where $\mathcal{M} = \{1, \cdots, M\}$ and $\mathcal{Q}_m = \{1, \cdots, Q\}$, $\forall m \in \mathcal{M}$. The problem (P1) can be regarded as the Multiple-Choice Knapsack Problem and thus can be solved by dynamic programming [29]. After solving problem (P1), we can obtain the optimal power-channel allocation scheme, denoted by $\mathbf{P}_{SD}^* = \left[P_{SD}^{*1}, \cdots, P_{SD}^{*M}\right]$.

E. Energy Efficiency Optimization Under Our Framework

In Section III-D, we have developed a data transmission rate optimization based power-channel allocation scheme which can maximize the throughput of the CAHN. Our proposed CAD-MAC protocol employs a flexible resource allocation framework. It means that we can optimize different performance metrics through employing different resource allocation policies, such as throughput, delay, spectrum efficiency, energy efficiency, etc. As secondary nodes usually have limited power budget, energy efficiency is critically important to the CAHN. Consequently, in this section, we investigate an energy efficiency optimization based joint power-channel allocation scheme to maximize the energy efficiency of our proposed CAD-MAC protocol.

We also suppose that there are M common available channels for source node S and destination node D. The channel gain for the M channels are denoted by $\left\{h_{SD}^1, \cdots, h_{SD}^M\right\}$. The matrices of available transmission rates and transmit power are given by Eqs. (15) and (16), respectively. The required transmit power on the mth DC with rate R_q is calculated by Eq. (17). As we aim at maximizing the energy efficiency of nodes S and D, our optimization problem can be mathematically formulated as

$$\text{(P2)} \max_{\{x_{m,q}\}} \frac{\sum\limits_{m\in\mathcal{M}} \sum\limits_{q\in\mathcal{Q}_m} R^{m,q} x_{m,q}}{\sum\limits_{m\in\mathcal{M}} \sum\limits_{q\in\mathcal{Q}_m} \overline{P}_{SD}^{m,q} x_{m,q}}, \tag{19}$$

$$\text{s.t.} \begin{cases} \sum\limits_{m\in\mathcal{M}} \sum\limits_{q\in\mathcal{Q}_m} \overline{P}_{SD}^{m,q} x_{m,q} \leq P_{\max}, \\ \overline{P}_{SD}^{m,q} \leq P_{\max-\mathrm{s}}(m),\ m \in \mathcal{M},\ q \in \mathcal{Q}_m, \\ \sum\limits_{q\in\mathcal{Q}_m} x_{m,q} \leq 1, \quad m \in \mathcal{M}, \\ x_{m,q} \in \{0, 1\}, \quad m \in \mathcal{M},\ q \in \mathcal{Q}_m, \end{cases} \tag{20}$$

where $\mathcal{M} = \{1, \cdots, M\}$ and $\mathcal{Q}_m = \{1, \cdots, Q\}$. However, the above optimization problem cannot directly solved by dynamic programming as the objective function given by Eq. (19) is the ratio of two additive functions. Fortunately, fractional programming is a powerful approach to deal with optimization problem with ratio-type function [30]. Specifically, we define a new optimization problem, which is given by

$$\begin{aligned}(\text{P3}) \qquad & \max_{\{x_{m,q}(\lambda)\}} \mathcal{J}\left(x_{m,q}(\lambda); \lambda\right) \\ = & \max_{\{x_{m,q}(\lambda)\}} \sum_{m\in\mathcal{M}} \sum_{q\in\mathcal{Q}_m} G_{m,q}\left(x_{m,q}(\lambda); \lambda\right) \end{aligned} \tag{21}$$

subject to the constraints given by Eq. (20), where $G_{m,q}\left(x_{m,q}(\lambda); \lambda\right) = \left(R^{m,q} - \lambda \overline{P}_{SD}^{m,q}\right) x_{m,q}(\lambda)$ and $\lambda \geq 0$ is the predefined parameter. The objective function $\mathcal{J}\left(x_{m,q}(\lambda); \lambda\right)$ can be regarded as the total reward of the joint power-channel allocation process. Clearly, the optimization problem (P3) can be solved by dynamic programming, which is similar with problem (P1).

We can find from Eq. (21) that parameter λ will affect the power-channel allocation policy $\{x_{m,q}(\lambda)\}$. Consequently, we need to determine the relationship between the original problem (P2) and problem (P3). We denote the optimal values of the objective functions for problems (P2) and (P3) as γ_e^* and $\mathcal{J}\left(x_{m,q}^*(\lambda^*); \lambda^*\right)$, respectively. Then, we show the relationship between problems (P2) and (P3) in the following proposition.

Proposition 1. *Denote the optimal parameter λ and allocation policies for problem* (P2) *and* (P3) *as λ^*, $\left\{x_{m,q}^*\right\}$, and $\left\{x_{m,q}^*(\lambda^*)\right\}$, respectively. Then, we have $\gamma_e^* = \lambda^*$ if and only if $\mathcal{J}\left(x_{m,q}^*(\lambda^*); \lambda^*\right) = 0$.*

Proof. If $\gamma_e^* = \lambda^*$, we have

$$\gamma_e = \frac{\sum_{m\in\mathcal{M}} \sum_{q\in\mathcal{Q}_m} R^{m,q} x_{m,q}}{\sum_{m\in\mathcal{M}} \sum_{q\in\mathcal{Q}_m} \overline{P}_{SD}^{m,q} x_{m,q}} \leq \lambda^*$$

and

$$\gamma_e^* = \frac{\sum_{m\in\mathcal{M}} \sum_{q\in\mathcal{Q}_m} R^{m,q} x_{m,q}^*}{\sum_{m\in\mathcal{M}} \sum_{q\in\mathcal{Q}_m} \overline{P}_{SD}^{m,q} x_{m,q}^*} = \lambda^*.$$

As $\sum_{m\in\mathcal{M}} \sum_{q\in\mathcal{Q}_m} \overline{P}_{SD}^{m,q} x_{m,q} \geq 0$, $\mathcal{J}\left(x_{m,q}(\lambda^*); \lambda^*\right) = \left(R^{m,q} - \lambda^* \overline{P}_{SD}^{m,q}\right) x_{m,q}(\lambda^*) \leq 0$ must be hold and the maximum value $\mathcal{J}\left(x_{m,q}^*(\lambda^*); \lambda^*\right) = 0$ can be achieved by using policy $\left\{x_{m,q}^*(\lambda^*)\right\}$.

If $\mathcal{J}\left(x_{m,q}^*(\lambda^*); \lambda^*\right) = 0$, then

$$\sum_{m\in\mathcal{M}} \sum_{q\in\mathcal{Q}_m} G_{m,q}\left(x_{m,q}(\lambda^*); \lambda^*\right) \leq 0$$

and

$$\sum_{m\in\mathcal{M}} \sum_{q\in\mathcal{Q}_m} G_{m,q}\left(x_{m,q}^*(\lambda^*); \lambda^*\right) = 0$$

must be hold. As $\sum_{m\in\mathcal{M}} \sum_{q\in\mathcal{Q}_m} \overline{P}_{SD}^{m,q} x_{m,q} \geq 0$, we have $\gamma_e \leq \lambda^*$ and the maximum energy efficiency $\gamma_e^* = \lambda^*$ is achieved by using policy $\{x_{m,q}(\lambda^*)\}$. $\square$

Proposition 1 tells us that if we can obtain λ^* such that the maximum value of problem (P3) is 0, the optimal solution $\left\{x_{m,q}^*(\lambda^*)\right\}$ for problem (P3) is also optimal for problem (P2). The following proposition can help us determine λ^* for problem (P3).

Proposition 2. *The maximum value $\mathcal{J}\left(x_{m,q}^*(\lambda); \lambda\right)$ of is monotonously decreasing with parameter λ.*

Proof. For any given λ_1 and λ_2 ($\lambda_1 < \lambda_2$), we denote the corresponding optimal solutions by $\left\{x_{m,q}^*(\lambda_1)\right\}$ and $\left\{x_{m,q}^*(\lambda_2)\right\}$, respectively. Then, we have

$$\begin{aligned} & \mathcal{J}\left(x_{m,q}^*(\lambda_2); \lambda_2\right) \\ = & \sum_{m\in\mathcal{M}} \sum_{q\in\mathcal{Q}_m} G_{m,q}\left(x_{m,q}^*(\lambda_2); \lambda_2\right) \\ < & \sum_{m\in\mathcal{M}} \sum_{q\in\mathcal{Q}_m} G_{m,q}\left(x_{m,q}^*(\lambda_2); \lambda_1\right) \\ \leq & \max_{\{x_{m,q}(\lambda_1)\}} \sum_{m\in\mathcal{M}} \sum_{q\in\mathcal{Q}_m} G_{m,q}\left(x_{m,q}(\lambda_1); \lambda_1\right) \\ = & \sum_{m\in\mathcal{M}} \sum_{q\in\mathcal{Q}_m} G_{m,q}\left(x_{m,q}^*(\lambda_1); \lambda_1\right) \\ = & \mathcal{J}\left(x_{m,q}^*(\lambda_1); \lambda_1\right) \end{aligned} \tag{22}$$

Now we proved that the maximum value $\mathcal{J}\left(x_{m,q}^*(\lambda); \lambda\right)$ of is monotonously decreasing with parameter λ. $\square$

Based on the monotonicity of $\mathcal{J}\left(x_{m,q}^*(\lambda); \lambda\right)$, λ^* can be readily obtained by the bisection algorithm. Then, we can obtain the optimal joint power-channel allocation scheme that maximizes the energy efficiency of one node pair.

IV. Performance Analyses

In this section, we will theoretically analyze the performances of the CAD-MAC protocol. First, we analyze the data transmission rate and energy efficiency. Then, the throughput analyses under two scenarios, which are contention-free scenario and contention scenario, respectively, are provided.

A. Data Transmission Rate and Energy Efficiency

We denote the source and destination nodes as S and D, respectively. There are M common available channels with channel gains $\left\{h_{SD}^1, \cdots, h_{SD}^M\right\}$ and central frequencies $\{f_1, \cdots, f_M\}$. The sets of available data transmission rate and the corresponding SINR threshold are the same as those described in Section II. Moreover, the corresponding set of transmission radius on the mth DC is denoted by $r^m = \left\{r_1^m, r_2^m, \cdots, r_Q^m\right\}$, where $r_1^m > r_2^m > \cdots > r_Q^m$.

Suppose that node S transmits on the mth DC with rate R_q. When the interference caused by other nodes is absence, the Signal-to-Noise Ratio (SNR) threshold, denoted by SNR_q, can be expressed by

$$SNR_q = \frac{G_t\left(f_m\right) G_r\left(f_m\right) h_t^2 h_r^2}{\left(r_q^m\right)^4 \cdot L \cdot P_n} P_{\max}, \tag{23}$$

where r_q^m is the distance between S and D and f_m is the central frequency of the mth DC. If we take the interferences caused by other neighbor nodes into consideration, the SINR of the received signal, denoted by $SINR^m(d_{SD})$, is

$$SINR^m\left(d_{SD}\right) = \frac{G_t\left(f_m\right) G_r\left(f_m\right) h_t^2 h_r^2}{d_{SD}^4 \cdot L \cdot \left(P_n + P_{\text{inf}}^m\right)} P_t^m, \tag{24}$$

where d_{SD} is the distance between S and D, P_t^m denotes the transmit power of S on the mth DC, and $P_{\inf}^m$ 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

$$SINR^m(d_{SD}) \geq SNR_q \tag{25}$$

must be satisfied. Substituting Eqs. (23) and (24) into inequation (25), we can obtain that the transmit power P_t^m on the mth DC must satisfy

$$P_t^m \geq \left(\frac{d_{SD}}{r_q^m}\right)^4 \frac{P_n + P_{\inf}^m}{P_n} P_{\max}. \tag{26}$$

Suppose that the data transmission rate used by S on the mth channel is $R_{q(m)}$ ($m \in \mathcal{M}$ and $q(m) \in \mathcal{Q}_m$), then the following inequation

$$\sum_{m\in\mathcal{M}} P_t^m = \sum_{m\in\mathcal{M}} \left(\frac{d_{SD}}{r_{q(m)}^m}\right)^4 \frac{P_n + P_{\inf}^m}{P_n} P_{\max} \leq P_{\max}, \tag{27}$$

must be satisfied. From the above inequation, we have

$$d_{SD} \leq \left[\sum_{m\in\mathcal{M}} \left(\frac{1}{r_{q(m)}^m}\right)^4 \frac{P_n + P_{\inf}^m}{P_n}\right]^{-\frac{1}{4}}. \tag{28}$$

The above inequation is the constraint that the distance d_{SD} should be held if the transmission rate policy is $\{R_{q(1)}, R_{q(2)}, \cdots, R_{q(M)}\}$. If we denote the set of transmission radius on the CCC as $r = \{r_1, r_2, \cdots, r_Q\}$, the relationship between r_q^m and r_q is determined by

$$r_q^m = \left(\frac{f_m}{f_0}\right) r_q. \tag{29}$$

Substituting Eq. (29) into inequation (28), the constraint that d_{SD} must be held can also be written as

$$d_{SD} \leq \left[\sum_{m\in\mathcal{M}} \left(\frac{1}{r_q} \cdot \frac{f_0}{f_m}\right)^4 \frac{P_n + P_{\inf}^m}{P_n}\right]^{-\frac{1}{4}}. \tag{30}$$

Then the total transmission rate R_{SD} can be calculated by

$$R_{SD} = \sum_{m\in\mathcal{M}} R_{q(m)}. \tag{31}$$

From Eqs. (30) and (31), 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.

Energy efficiency, which is defined as the ratio of total transmission rate and total consumed transmit power, is another crucial metric for the CAHNs. Based on the above analysis, the energy efficiency of our proposed CAD-MAC protocol, denoted by γ_e, can be written as

$$\gamma_e = \sum_{m=1}^{M} R_{q(m)} \Bigg/ \sum_{m=1}^{M} P_t^m. \tag{32}$$

The energy efficiency γ_e represents the number of bits transmitted per unit of power consumption. The larger the ratio is, the more efficient the transmit power is utilized.

B. Throughput Analysis under Contention-Free Scenario

In this section, we analyze the maximum throughput of our proposed CAD-MAC protocol that one source-destination pair can achieve. In this scenario, we only consider one source-destination pair, denoted by S and D, respectively. As we do not consider the contentions among the secondary nodes, we can derive the maximum achievable throughput of the CAD-MAC protocol for one source-destination pair.

Suppose the power-channel allocation policy is $\mathbf{P}_{SD} = [P_{SD}^1, \cdots, P_{SD}^M]$. For the mth ($m = 1, \cdots, M$) channel, the probability that S can use rate R_q ($q = 1, \cdots, M-1$) for transmission is determined by

$$\begin{aligned} & \Pr\{R_{SD}^m = R_q\} \\ = \; & \Pr\{SINR_q \leq SINR_{SD}^m < SINR_{q+1}\} \\ = \; & \Pr\left\{\left(\frac{P_{SD}^m}{P_{\max}}\right)^{\frac{1}{4}} r_{q+1}^m < d_{SD} \leq \left(\frac{P_{SD}^m}{P_{\max}}\right)^{\frac{1}{4}} r_q^m\right\}. \end{aligned} \tag{33}$$

where R_{SD}^m is the transmission rate on the mth channel and $SINR_{SD}^m$ is the SINR of the signal received by node D on the channel. Through the similar approach, we can obtain the probabilities that node S uses rate R_Q for transmission and gives up accessing the mth channel, respectively, which can be calculated by

$$\begin{aligned} \Pr\{R_{SD}^m = R_Q\} &= \Pr\{SINR_{SD}^m \geq SINR_Q\} \\ &= \Pr\left\{d_{SD} \leq \left(\frac{P_{SD}^m}{P_{\max}}\right)^{\frac{1}{4}} r_Q^m\right\} \end{aligned} \tag{34}$$

and

$$\begin{aligned} \Pr\{R_{SD}^m = 0\} &= \Pr\{SINR_{SD}^m < SINR_1\} \\ &= \Pr\left\{d_{SD} > \left(\frac{P_{SD}^m}{P_{\max}}\right)^{\frac{1}{4}} r_1^m\right\}, \end{aligned} \tag{35}$$

respectively. Therefore, the average transmission rate can be written as

$$\mathbb{E}\{R_{SD}\} = \mathbb{E}\left\{\sum_{m=1}^{M} R_{SD}^m\right\} = \sum_{m=1}^{M}\sum_{q=0}^{Q} \Pr\Big\{R_{SD}^m = R_q\Big\} R_q, \tag{36}$$

where $R_0 = 0$ represents that the node S does not use the corresponding DC. Based on Eqs. (13), (14), and (36), the average number of data packets that one source-destination pair can be transmitted during one transmission process can be written as

$$\mathbb{E}\{N_{SD}\} = \left\lfloor \frac{\mathbb{E}\{R_{SD}\}(\min\{CT_{\min}, T_{\max}\}) + T_{\text{sifs}}}{L_{\text{data}} + L_{\text{ack}} + 2T_{\text{sifs}}\mathbb{E}\{R_{SD}\}} \right\rfloor \tag{37}$$

and the average transmission duration for one transmission process is determined by

$$\mathbb{E}\{T_{SD}\} = \frac{(2\mathbb{E}\{N_{SD}\} - 1)T_{\text{sifs}} + \mathbb{E}\{N_{SD}\}(L_{\text{data}} + L_{\text{ack}})}{\mathbb{E}\{R_{SD}\}}. \tag{38}$$

Finally, the average throughput for nodes S and D can be written as

$$\mathbb{E}\left\{\Psi_{SD}\right\} = \frac{\mathbb{E}\left\{N_{SD}\right\} L_{\text{data}}}{\mathbb{E}\left\{T_{SD}\right\}}. \tag{39}$$

C. Throughput Analysis Under Contention Scenario

In order to calculate the throughput of the contention scenario, we first determine the transmission range, carrier sensing (CS) range, and interference range on the CCC.

The transmission range, denoted by r_t, is defined as the maximum transmitter-receiver distance within which the packet can be successfully received when the interference is absence. Therefore, the transmission range r_t must satisfy

$$SINR\left(r_t\right) = \frac{G_t\left(f_0\right) G_r\left(f_0\right) h_t^2 h_r^2}{r_t^4 \cdot L \cdot P_n} P_{\max} \geq SINR_b, \tag{40}$$

where $SINR\left(r_t\right)$ denotes the SINR of the signal received by the destination node when the source-destination distance is r_t and $SINR_b$ represents the SINR threshold. Through solving inequality (40), we can obtain the transmission range r_t, which is given by

$$r_t \leq \left[\frac{G_t\left(f_0\right) G_r\left(f_0\right) h_t^2 h_r^2}{SINR_b \cdot L \cdot P_n} P_{\max}\right]^{\frac{1}{4}}. \tag{41}$$

The CS range, which mainly depends on the sensitivity of the receiver and the radio propagation properties and is denoted by r_c, is defined as the range within which the neighbor nodes can detect the transmission of the transmit node. Consequently, we have

$$P_r\left(r_c\right) = \frac{G_t\left(f_0\right) G_r\left(f_0\right) h_t^2 h_r^2}{r_c^4 \cdot L} P_{\max} \geq \eta, \tag{42}$$

where $P_{\mathrm{r}}(r_c)$ is the received signal power of the neighbor node when the distance between itself and the transmitter is r_c and η is the predetermined CS threshold. Following inequality (42), we derive the CS range, which can be written as

$$r_c \leq \left[\frac{G_t\left(f_0\right) G_r\left(f_0\right) h_t^2 h_r^2 P_{\max}}{L \cdot \eta}\right]^{\frac{1}{4}} = \left[\frac{SINR_b P_n}{\eta}\right]^{\frac{1}{4}} r_t. \tag{43}$$

We can find from (43) that the transmission range r_t and CS range r_c are related with respect to the CS threshold η.

The interference range, denoted by r_i, is defined as the maximum distance at which the receiver will be interfered by another source's transmission, implying the packet loss. Therefore, the following inequality

$$\frac{G_t\left(f_0\right) G_r\left(f_0\right) h_t^2 h_r^2}{d_{SD}^4 \cdot L \cdot \left(P_n + P_{\mathrm{r}}\left(r_i\right)\right)} P_{\max} < SINR_b \tag{44}$$

must hold, where d_{SD} is the source-destination distance and $P_{\mathrm{r}}(r_i)$ denotes the interference power received by the destination node. According to Eq. (1), $P_{\mathrm{r}}(r_i)$ is determined by

$$P_{\mathrm{r}}\left(r_i\right) = \frac{G_t\left(f_0\right) G_r\left(f_0\right) h_t^2 h_r^2}{r_i^4 \cdot L} P_{\max}. \tag{45}$$

Plugging (45) into (44), the interference range r_i can be written as

$$r_i < \left[\frac{G_t\left(f_0\right) G_r\left(f_0\right) h_t^2 h_r^2 SINR_b}{G_t\left(f_0\right) G_r\left(f_0\right) h_t^2 h_r^2 L - d_{SD}^4 SINR_b L^2 P_n} P_{\max}\right]^{\frac{1}{4}}. \tag{46}$$

From (46), we can find that r_i is closely related with d_{SD}. In particular, r_i increases as d_{SD} increases, and vice versa.

As the control packets collisions on the CCC are inevitable, we still need to calculate the probabilities of a series of collisions, including RTS, CTS, RES, DATA, and ACK packets collisions. We denote the source and destination nodes as S and D, respectively.

1) RTS Packets Collision: When S sends the RTS packet to D, two kinds of collisions may happen. The first kind RTS collision is caused by the nodes which locate in the intersection of the interference range of D and the CS range of S, i.e., the area S_{1234} in Fig. 3(a). If the nodes that locate in this area initiate their transmissions at the same time with node S, the collision at node D will happen. Consequently, the probability that such collision happens, denoted by p_{rts}^1, can be written as

$$p_{\text{rts}}^1\left(d_{SD}\right) = \tau\left[1 - (1-\tau)^{N_1\left(d_{SD}\right)}\right], \tag{47}$$

where τ denotes the probability that a secondary node transmits at the beginning of each slot and $N_1(d_{SD})$ is the number of nodes located in this area. If we denote the average node density of the CAHN as ρ, $N_1(d_{SD})$ can be calculate by

$$N_1\left(d_{SD}\right) = \rho \cdot A_1\left(d_{SD}\right), \tag{48}$$

where $A_1(d_{SD}) = \theta_1 r_c^2 + \theta_2 r_i^2 - r_c \sin\theta_1\left(r_c \cos\theta_1 + r_i \cos\theta_2\right)$ is the area of S_{1234}. From the geometry knowledge, θ_1 and θ_2 are determined by

$$\begin{cases} \theta_1 = \cos^{-1}\left(\frac{r_c^2 + d_{SD}^2 - r_i^2}{2 r_c d_{SD}}\right), \\ \theta_2 = \cos^{-1}\left(\frac{r_i^2 + d_{SD}^2 - r_c^2}{2 r_i d_{SD}}\right). \end{cases} \tag{49}$$

The second kind RTS collision is caused by such nodes located in the interference range of D but not in the CS range of S, i.e., area S_{1534} in Fig. 3(a). If one of these nodes in this area initiates any transmission during the period of RTS transmission, D will be interfered. The probability of this kind of RTS collision, denoted by p_{rts}^2, can be written as

$$p_{\text{rts}}^2\left(d_{SD}\right) = \tau\left[1 - (1-\tau)^{N_2\left(d_{SD}\right)\frac{T_{\text{rts}}}{T_{\text{avg}}}}\right], \tag{50}$$

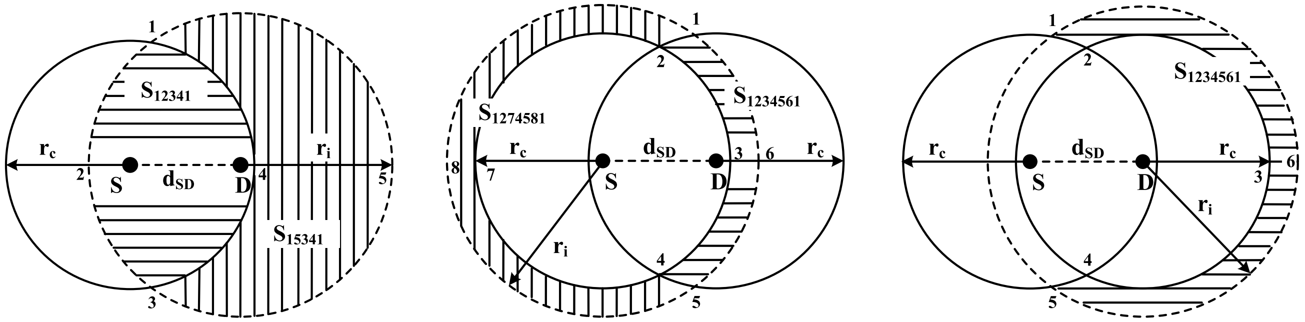
where $N_2(d_{SD})$ is the number of secondary nodes located in area S_{1534} and T_{avg} denotes the expected time interval between the beginning instants of two consecutive transmissions. Therefore, the probability that the RTS packets collision happens, denoted by p_{rts}, can be calculated by

$$p_{\text{rts}}\left(d_{SD}\right) = 1 - \left(1 - p_{\text{rts}}^1\left(d_{SD}\right)\right)\left(1 - p_{\text{rts}}^2\left(d_{SD}\right)\right). \tag{51}$$

As the probability of the RTS packets collision is the function of d_{SD}, the average RTS packets collision probability is

$$p_{\text{rts}} = \int_0^{r_t} f\left(d_{SD}\right) p_{\text{rts}}\left(d_{SD}\right) d\, d_{SD}. \tag{52}$$

2) CTS Packet Collision: In the CTS packet transmission process, the collision may happen at D. A CTS packet collision occurs when the interference nodes of S initiate their transmissions during the CTS packet transmission process and there are two kinds of CTS packet collision. The first kind CTS packet collision is caused by the nodes located in the



(a) RTS collision (b) CTS collision (c) RES collision

Fig. 3. RTS, CTS, and RES collisions

interference range of S and the CS range of D but not in the CS range of S, i.e., the are $S_{1234561}$ in Fig. 3(b). If one of these nodes initiates the transmission at the same time with D, a collision occurs at S and the probability of such kind collision, denoted by $p^1_{\text{cts}}(d_{SD})$, can be written as

$$p^1_{\text{cts}}(d_{SD}) = \tau\left[1-(1-\tau)^{N_3(d_{SD})}\right], \tag{53}$$

where $N_3(d_{SD})$ is the number of secondary nodes located in area $S_{1234561}$. The second CTS collision is caused by the nodes located in the interference range of S but not in the CS ranges of both S and D, i.e., the area $S_{1274581}$ in Fig. 3(b). If these nodes initiate their transmissions during the CTS packet transmission process, the collision occurs. The probability of the second kind CTS packet collision, denoted by $p^2_{\text{cts}}(d_{SD})$, is determined by

$$p^2_{\text{cts}}(d_{SD}) = \tau\left[1-(1-\tau)^{N_4(d_{SD})\frac{T_{\text{cts}}}{T_{\text{avg}}}}\right], \tag{54}$$

where $N_4(d_{SD})$ is the number of nodes located in area $S_{1274581}$. Consequently, the probability that the CTS packet collision happens, denoted by $p_{\text{cts}}(d_{SD})$, is given by

$$p_{\text{cts}}(d_{SD}) = 1-\left(1-p^1_{\text{cts}}(d_{SD})\right)\left(1-p^2_{\text{cts}}(d_{SD})\right). \tag{55}$$

We can use the same method to obtain the average CTS packet collision probability p_{cts}.

3) RES Packet Collision: A RES collision happens when the interference nodes initiate their transmissions during the RES packet transmission process. There is only one kind of RES collision which is caused by the nodes located in the interference range of D but not in the CS ranges of both S and D, i.e., the area $S_{1234561}$ in Fig. 3(c). If these nodes initiate their transmissions during the RES packet transmission process, a collision occurs. The probability of the RES packet collision, denoted by p_{res}, is given by

$$p_{\text{res}}(d_{SD}) = \tau\left[1-(1-\tau)^{N_5(d_{SD})\frac{T_{\text{res}}}{T_{\text{avg}}}}\right], \tag{56}$$

where $N_5(d_{SD})$ is the number of nodes located in area $S_{1234561}$. We can use the same method to obtain the average RES collision probability p_{res}.

4) DATA and ACK Packets Collisions: If RTS, CTS, and RES packets are successfully exchanged, the power allocation, denoted by $\mathbf{P}_{SD} = \left[P^1_{SD}, P^2_{SD}, \cdots, P^M_{SD}\right]$, is completed. The DATA packets transmitted on the mth channel may be interfered by the nodes located in the interference range of D but not in the transmission range of D. If these nodes choose the same channel for transmission, a collision may occur. Denoted I as the interference node, the probability that a DATA collision caused by I occurs on the mth channel can be written as

$$p^m_I = p^2_{\text{PU}}\Pr\left\{d_{ID} \leq \left[\frac{G_t(f_m)\,G_r(f_m)\,h^2_t h^2_r P^m_I}{L\cdot P^{\text{inf}}_{\min}}\right]^{\frac{1}{4}}\right\}, \tag{57}$$

where p_{PU} denots the probability that the channel will be occupied by PUs, P^m_I is the transmit power of I on the mth channel, and d_{ID} is the distance between I and D. Consequently, the probability that the DATA packet collision happens, denoted by $p_{\text{data}}(d_{SD})$, can be written as

$$p_{\text{data}}(d_{SD}) = 1-\left[\prod_{m=1}^{M}\left(1-p^m_I\right)\right]^{N_6(d_{SD})\frac{\mathbb{E}\{N_{SD}\}T_{\text{data}}}{T_{\text{avg}}}}, \tag{58}$$

where $\mathbb{E}\{N_{SD}\}$ is the average number of DATA packets that can be transmitted during one transmission process and $N_6(d_{SD})$ denotes the number of nodes that locate in the interference range but not in the transmission range of D.

Similar approach can be applied to obtain the probability of the ACK packet collision $p_{\text{ack}}(d_{SD})$, which can be written as

$$p_{\text{ack}}(d_{SD}) = 1-\left[\prod_{m=1}^{M}\left(1-p^m_I\right)\right]^{N_6(d_{SD})\frac{\mathbb{E}\{N_{SD}\}T_{\text{ack}}}{T_{\text{avg}}}}. \tag{59}$$

By using the same method, we can obtain the average DATA collision probability and the average ACK collision probability, denoted by p_{data} and p_{ack}, respectively.

In order to derive the throughput between S and D, we also need to calculate the expected time interval, denoted by T_{avg}, between the beginning instants of two consecutive transmissions, which is determined by

$$T_{\text{avg}} = p_i T_i + p_c T_c + p_s T_s \tag{60}$$

where p_i, p_c, and p_s are the probabilities that channel is idle, collisions happen, and transmission is successful, respectively, and T_i, T_c, and T_s are the durations that channel is idle, collisions happen, and transmission is successful, respectively.

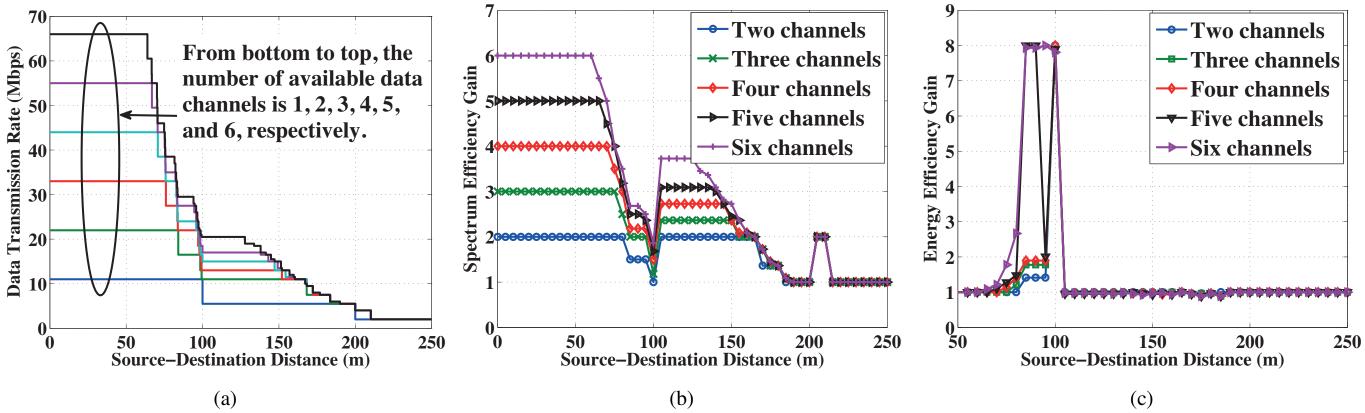


Fig. 4. Performance evaluation of the CAD-MAC protocol. (a) Data transmission rate versus the source-destination distance under different number of available data channels. (b) Spectrum efficiency gain normalized over the spectrum efficiency with one data channel. (c) Energy efficiency gain obtained by utilizing multiple data channels for transmission over the case only using one data channel for transmission versus the source-destination distance.

Moreover, p_i, p_c, P_s, T_i, T_c, and T_s can be calculated by

$$\begin{cases} p_i &= (1-\tau)^{N_1(d_{SD})+1}, \\ T_i &= \sigma, \\ p_c T_c &= p_{\text{rts}} T_c^{\text{rts}} + (1-p_{\text{rts}})\, p_{\text{cts}} T_c^{\text{cts}} \\ &\quad + (1-p_{\text{rts}})(1-p_{\text{cts}})\, p_{\text{res}} T_c^{\text{res}}, \\ p_s &= (1-p_{\text{rts}})(1-p_{\text{cts}})(1-p_{\text{res}}) \\ &\quad (1-p_{\text{data}})(1-p_{\text{ack}}), \\ T_s &= T_{\text{rts}} + T_{\text{cts}} + T_{\text{res}} + \mathbb{E}\{N_{SD}\}(T_{\text{data}} + T_{\text{ack}}) \\ &\quad + 2(\mathbb{E}\{N_{SD}\}-1)\, T_{\text{sifs}} + T_{\text{difs}}, \end{cases} \tag{61}$$

where T_c^{rts}, T_c^{cts}, and T_c^{res} denote the durations for the RTS, CTS, and RES collisions, respectively, and can be written as

$$\begin{cases} T_c^{\text{rts}} = T_{\text{rts}} + T_{\text{difs}}, \\ T_c^{\text{cts}} = T_{\text{rts}} + T_{\text{cts}} + T_{\text{sifs}} + T_{\text{difs}}, \\ T_c^{\text{res}} = T_{\text{rts}} + T_{\text{cts}} + T_{\text{res}} + 2T_{\text{sifs}} + T_{\text{difs}}. \end{cases} \tag{62}$$

Based on the above analyses, the throughput for one source and destination node pair under the contention scenario, denoted by $\mathcal{T}$, is determined by

$$\mathcal{T} = \frac{p_s \cdot \mathbb{E}[N_{SD}] \cdot L_{\text{data}}}{T_{\text{avg}}}. \tag{63}$$

V. Simulation Results

In this section, we evaluate the performances of the proposed CAD-MAC protocol through simulations. Specifically, in Section V-A, we evaluate the data transmission rate, spectrum efficiency, and energy efficiency to show the advantage of our proposed CAD technology. In section V-B, we provide the throughput simulation under the contention-free scenario. In Section V-C, we compare the network average throughput of our proposed CAD-MAC protocol with that of the OM-MAC protocol [25] and the MOAR protocol [23] under the contention scenario to verify the advantage of the CAD-MAC protocol. Note that in above simulations, we focus on evaluating the performances of the data rate optimization based joint power-channel allocation scheme developed in Section III-D. Furthermore, in Section V-D, we evaluate the performances of the energy efficiency optimization based power-channel allocation scheme investigated in Section III-E to study the tradeoff between the throughput and energy efficiency of our proposed CAD-MAC protocol.

In our simulations, the simulation parameters are set similar to the IEEE 802.11b standard. Specifically, each secondary node supports three different data rates, which are 2, 5.5, and 11Mbps, respectively. The corresponding transmission radius are 250, 200, and 100m, respectively. Secondary nodes can only exchange control packets on the CCC with rate 2Mbps. The RTS packet contains 160bits. Both of the CTS and RES packets contain 112bits. Each data packet contains 1000bytes. Moreover, the durations of SIFS and DIFS are $10\mu s$ and $50\mu s$, respectively.

A. Data Rate, Spectrum Efficiency, and Energy Efficiency

Figure 4(a) shows the data transmission rate of our proposed CAD-MAC protocol as a function of the distance between the source and destination when different number of DCs are available. Note that when there is only one available DC, the data transmission rate of the CAD-MAC protocol is the same with that of the OMMAC protocol with only one radio. We can find from Fig. 4(a) that the data transmission rate of our proposed CAD-MAC protocol can be significantly improved as the number of available DCs increases. This is because that the CAD technology can more efficiently utilize limited power resource and multiple available DCs through the joint power-channel allocation. Moreover, we can also observe from Fig. 4(a) that, as the number of the available DCs increases, the number of available transmission rates correspondingly increases. For example, when the number of DCs are 1, 2, 3, 4, 5, and 6, respectively, the number of available transmission rates are 3, 8, 15, 24, 35, and 47, respectively. Consequently, the CAD can provide the secondary node more adaptivity and the secondary node can always perform the transmission with the highest rate because the available channel resources and upperbounded transmit power can be sufficiently utilized. Furthermore, We can find from Fig. 4(a) that no matter how many data channels are available, the data transmission rate decreases as the distance between the source and destination nodes increases. The reason for this phenomenon is that the propagation loss will become larger with longer distance and the transmit power can not be continuously increased to satisfy the SINR threshold of higher transmission rate. Therefore, in order to finish their transmission, the source node has to decrease its transmission rate to guarantee that the SINR at the destination is larger than the predetermined threshold.

In order to evaluate the advantage brought by our proposed CAD technology to the spectrum efficiency, Fig. 4(b) illustrates the spectrum efficiency gain of one source-destination pair obtained by utilizing multiple channels for data transmission over the case only using one channel for transmission versus the source-destination distance. We can find from Fig. 4(b) that the spectrum efficiency with multiple DCs are significantly larger than that with only one DC, and the more the data channels, the larger the spectrum efficiency gain can be derived. This is because the CAD technology can help secondary nodes efficiently utilize the channel and power resources through the joint power/channel allocation. In particular, the derived spectrum efficiency gain is the most obvious when the distance between the source and destination is not extremely large. The reason is that when the source-destination distance is short, the secondary node only needs to use smaller transmit power. Consequently, the source and destination nodes can use more DCs under the total power limitation and thus help the secondary nodes achieve higher spectrum efficiency. When the distance between the source and destination nodes are large, the obtained spectrum efficiency gain decreases, which is because that larger transmit power is needed for longer source-destination distance and thus only less DCs can be used simultaneously due to the limited transmit power. Moreover, we can find from Fig. 4(b) that the derived spectrum efficiency gain fluctuates as the source-destination distance varies. The reason for this phenomenon is that there are only three available data transmission rates for one channel, i.e., 11Mbps for the distance that is less than 100m, 5.5Mbps for the distance that is between 100m and 200m, and 2Mbps for the distance that is larger than 200m, respectively. However, when multiple channels can be used simultaneously, there are several available data rates that can be achieved for each of the three distance ranges, as shown in Fig. 4(a), and these data rates decrease as the distance increases. Therefore, the spectrum efficiency gain fluctuates with the distance.

As discussed previously, the energy efficiency, which is used to evaluate whether the power resource is efficiently utilized, is another critically important metric for the CAHN. Fig. 4(c) shows the energy efficiency gain obtained by utilizing multiple data channels for transmission over the case only using one data channel for transmission versus the source-destination distance. W can find from Fig. 4(c) that the energy efficiency with different number of available DCs are the same when the source-destination distance is large. However, the data transmission rate and the spectrum efficiency are improved by using multiple data channel (as shown in Figs. 4(a) and 4(b)). Therefore, the transmit power is not wasted by the our proposed CAD. Moreover, we also observe from Fig. 4(c) that the energy efficiency can be obviously improved for short source-destination distance and the more DCs are available, the larger energy efficiency gain can be derived. Compared Fig. 4(c) with Fig. 4(b), we can find that when the energy efficiency is increased, we can also obtain higher spectrum efficiency, which means that the limited power resource is more efficiently utilized by our proposed CAD technology.

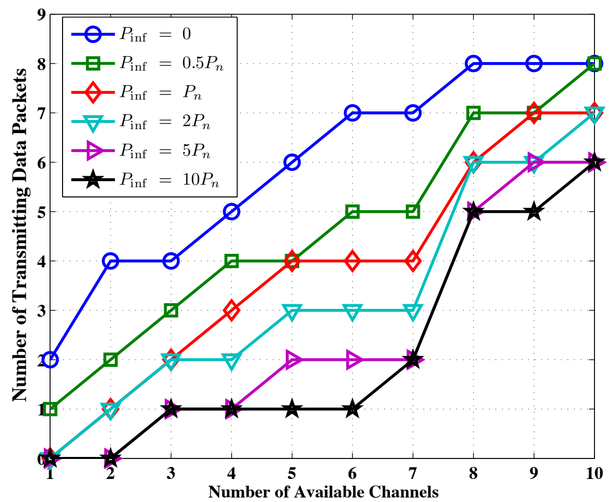


Fig. 5. Number of data packets that can be transmitted during one transmission process versus different number of available data channels under different interference power.

B. *Contention-Free Scenario*

In the contention-free scenario, the contentions among the secondary nodes are not taken into consideration. Consequently, we can evaluate the maximum throughput that can be achieved by our proposed CAD technology.

Figure 5 shows the number of data packets that can be transmitted during one transmission process as a function of number of available DCs under different interference power. We can find from Fig. 5 that no matter how many channels can be used, the number of data packets that can be transmitted in one transmission process decreases as the interference power increases. This is because that larger transmit power is needed to guarantee that the SINR at the destination node is larger than the threshold when interference exists, which causes that the source node has to use less channels or choose lower transmission rate due to the total power limitation. Therefore, the number of data packets that can be transmitted during one transmission process will be decreased. However, under the given interference power, the number of data packets with multiple DCs is larger than that with one channel. In particular, the more DCs can be used, the more obvious the improvement is, which shows the advantage of the CAD technology.

Figure 6 presents the average throughput of one source-destination pair as a function of the number of available DCs under different interference power. We can find from Fig. 6 the similar phenomenon as Fig. 5. Specifically, although the average throughput decreases while increasing the interference power, the average throughput with multiple channels can

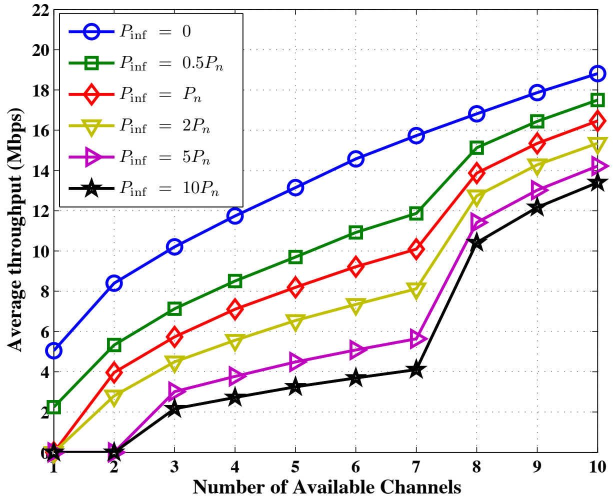


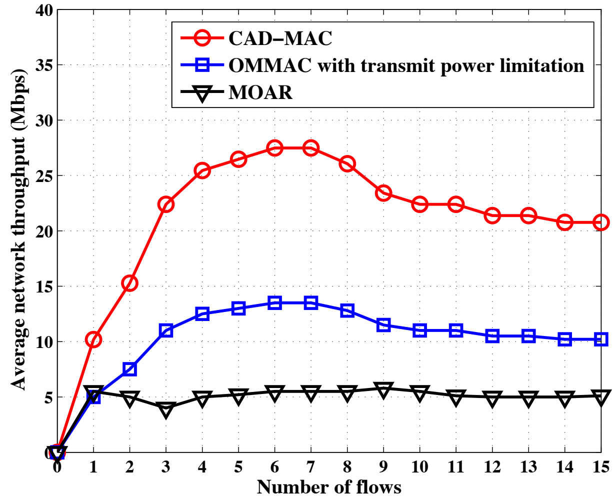
Fig. 6. Average throughput of one source-destination pair versus different number of available data channels under different interference power.

be significantly improved compared with the case that only one channel can be used. Therefore, the CAD technology can efficiently reduce the impact of the interference on the node's performance. Moreover, compared Fig. 5 with Fig. 6, an interesting phenomenon can be observed, i.e., the number of data packets that can be transmitted in one transmission process is a nondecreasing function of the number of DCs, but the average throughput is a strictly increasing function of the number of DCs. The reason is that, although the numbers of data packets that can be transmitted under different number of available DCs are the same, utilizing multiple DCs can efficiently increase the data transmission rate and thus reduce the time duration for transmitting the same number of data packets. Consequently, the average throughput for one node pair is increased.

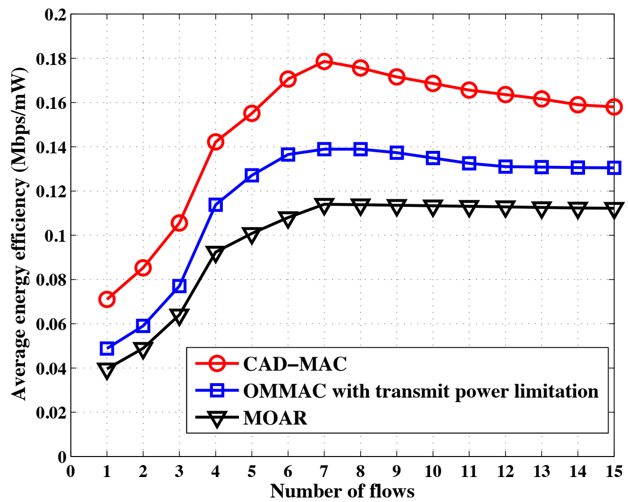
C. Contention Scenario

In this section, we use the MATLAB simulator to evaluate the average network throughput and energy efficiency in the contention scenario.

Figure 7(a) shows the average network throughput of CAD-MAC, OMMAC and MOAR protocols as a function of the number of flows. Because the OMMAC allows one secondary node to use multiple radios for data transmission simultaneously, in order to guarantee the comparison fairness, we suppose that the OMMAC protocol also has to satisfy the total power limitation. We can find from Fig. 7(a) that the average network throughput of the CAD-MAC protocol obviously exceeds those of the MOAR and OMMAC protocols. The main reason is that the CAD-MAC protocol uses the CAD technology, which can help secondary nodes efficiently and sufficiently utilize available opportunistic DCs for data transmissions. Moreover, the optimal number of channels that the secondary nodes use and the corresponding power allocations can be dynamically adjusted by the joint channel-power allocation scheme. Therefore, the CAD-MAC protocol can efficiently increase the data transmission rate and thus



(a) Average network throughput



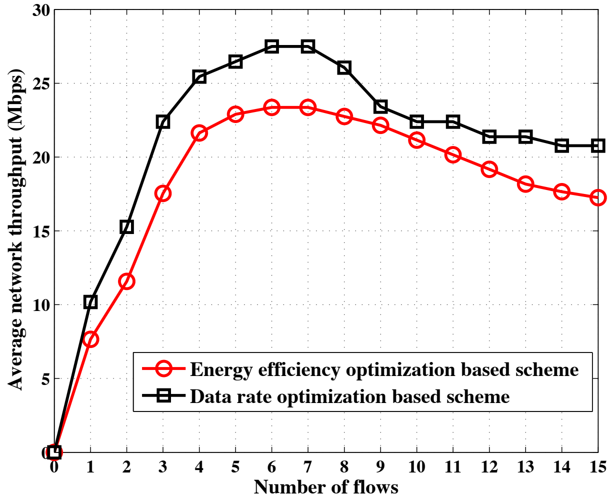
(b) Average energy efficiency

Fig. 7. Network performances of CAD-MAC, OMMAC, and MOAR protocols versus the number of flows.

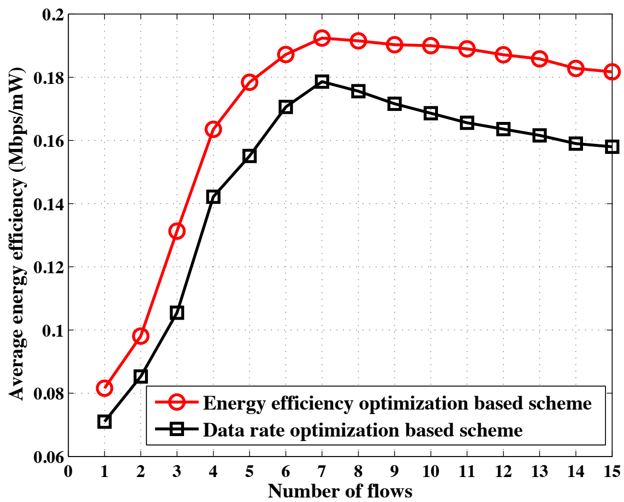
improve the average network throughput. The second reason is that both OMMAR and MOAR protocols can only use one data channel for transmission, which seriously degrades the network throughput. Furthermore, because of the power control brought by the CAD technology, the mutual interference among neighbor nodes is reduced and the space reuse efficiency is improved, which are benefit for the throughput improvement. Fig. 7(b) plots the average network energy efficiency of CAD-MAC, OMMAC, and MOAR protocols versus the number of flows. We can observe from Fig. 7(b) that, although the energy efficiency of our proposed CAD-MAC protocol reduces when the number of flows is larger than 6, our proposed CAD-MAC protocol still outperforms the OMMAC and MOAR protocols. Such phenomenon can also be ascribed to our developed CAD technology, through which the multi-channel can be sufficiently utilized, data transmission rate can be optimized, and mutual interference among neighbor nodes can be restrained.

D. Tradeoff Between Throughput and Energy Efficiency Under Our Proposed CAD-MAC Protocol

In Sections III-D and III-E, we developed two joint power-channel allocation schemes, which aim at optimize the throughput and energy efficiency of the CAHN, respectively. As the optimization objective of the two schemes are different, in this section, we provide the performance comparison between the two schemes to study the tradeoff between the throughput and energy efficiency of the CAHN. Fig. 8(a) shows the average network throughput of the CAD-MAC protocol achieved by the data transmission rate and energy efficiency optimization based power-channel allocation schemes versus the number of flows. We can observe from Fig. 8(a) that the data rate optimization based power-channel allocation scheme can derive better throughput than the energy efficiency optimization based power-channel allocation scheme. The main reason is that, the former scheme aims at maximizing the transmission rate, but the latter scheme focuses on optimizing the energy efficiency. Thus, secondary nodes may use lower rate for transmission as higher rate could cause much more power consumption. Although the throughput of the energy efficiency optimization based power-channel allocation scheme degrades, its average network energy efficiency is improved, which is shown in Fig. 8(b). Consequently, our proposed CAD-MAC protocol can be viewed as a flexible framework and can be modified by utilizing different resource allocation schemes. Specifically, if we mainly focus on the network throughput, we can use the joint power-channel allocation scheme developed in Section III-D; but if we want better energy efficiency, the resource allocation scheme designed in Section III-E can be employed.



(a) Average network throughput



(b) Average energy efficiency

Fig. 8. Network performances of CAD-MAC protocol with different joint power-channel allocation schemes versus the number of flows.

VI. Conclusions

In this paper, we proposed a new diversity technology called Channel-Aggregation Diversity (CAD). The proposed CAD technology, which aims at improving both the spectrum and energy efficiencies, allows each node to utilize multiple channels simultaneously and allocates the upper-bounded power resource across the selected group of channels through the joint power-channel allocation with only one data radio. Based on the proposed CAD technology, we further developed a CAD-based MAC (CAD-MAC) protocol, in which the secondary nodes can sufficiently use available channel resources under the upper-bounded transmit power and transmit multiple data packets in one transmission process subject to the transmission-time fairness. In order to optimize the performance the CAHN, we developed two joint power-channel allocation schemes, which aim at maximizing the data transmission rate and energy efficiency of the CAHN, respectively, and obtained the corresponding optimal resource allocation policies. Simulation results showed that our proposed CAD-MAC protocol can efficiently increase the spectrum efficiency, energy efficiency, and average throughput of the CAHN compared to the existing protocols.

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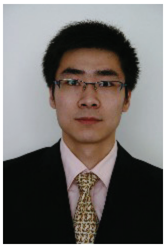

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