Harnessing Frequency Domain for Cooperative Sensing and Multi-channel Contention in CRAHNs

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***Abstract*—It is known that current fixed spectrum assignment policy has made the spectrum resource significantly underutilized. As a promising solution, cognitive radio emerges and shows its advantages. It allows the unlicensed users to opportunistically access the spectrum not used by the licensed users. To ensure that the unlicensed users can identify the vacate spectrum fast and accurately without interfering the licensed users, cooperative sensing is explored to improve the sensing performance by leveraging spatial diversity. However, cooperation gain can be compromised dramatically with cooperation overhead. Furthermore, when sensing decisions are made, contention on spectrum access also contributes a lot to the control overhead, especially in the distributed networks. Motivated by this, we propose a novel MAC design, termed Frequency domain Cooperative sensing and Multi-channel contention (FCM) for Cognitive Radio Ad Hoc Networks (CRAHNs). FCM is proposed for OFDM (Orthogonal Frequency Division Multiplexing) modulation based communication systems, which moves cooperative sensing and multi-channel contention from time domain into frequency domain. Therefore, control overhead caused by cooperation and contention can be significantly reduced. Meanwhile, the sensing and access performance can be both guaranteed. Extensive simulation results show that FCM can effectively reduce the control overhead, and improve the average throughput by 220% over Traditional Cooperative MAC for CRAHNs.**

***Index Terms*—OFDM modulation, cooperative sensing, cognitive radio network.**

I. INTRODUCTION

WITH the rapid growth of wireless communications and high demand on the deployment of new wireless services, the unlicensed bands, most in the 900MHz and the 2.4GHz, are getting more and more congested. Meanwhile, several licensed bands are shown to be extremely underutilized, such as TV broadcast frequencies below 700MHz [1]. Due to the poor spectrum utilization of fixed spectrum assignment policy enforced today, cognitive radio (CR) technology has recently been receiving significant research interest both from academia and industry. CR is envisaged to solve this critical spectrum inefficiency problem. It enables the access of the intermittent periods of vacant spectrum in the licensed band for the unlicensed users (CR users), without affecting the performance of the licensed or primary users (PUs).

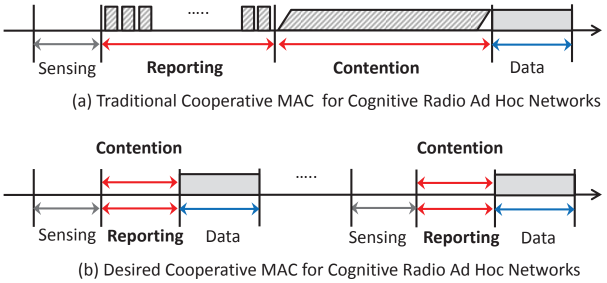

Fig. 1: (a) An example of Traditional Cooperative MAC that conducts cooperation and contention in time domain; (b) Desired Cooperative MAC that conducts cooperation and contention in frequency domain.

Although CR network is a promising paradigm to improve the spectrum usage efficiency, its design imposes unique challenges due to the high fluctuation in the vacant spectrum and the opportunistic access among CR users. The first challenge is to accurately identify the available spectrum in real-time through spectrum sensing, while vacate the spectrum once a PU is detected. This sensing accuracy is compromised with many factors, such as multi-path fading and shadowing [10]. Recently, cooperative spectrum sensing has shown its superiority to improve the sensing accuracy by exploiting spatial diversity. After exchanging sensing information among spatially located CR users, each of them makes a combined decision, which can be more accurate than individual ones. However, cooperation overhead increases dramatically and comprises the sensing performance, especially in distributed networks, e.g., Cognitive Radio Ad Hoc Networks (CRAHNs). The second challenge is to share the available spectrum among different CR users once the sensing decisions have been made. As the available spectrum and node density increases, coordination overhead and transmission delay raise up accordingly, resulting in a significant performance degradation. These challenges necessitate efficient designs that can simultaneously address extensive communication problems raised up in CR networks.

In order to solve the above-mentioned challenges and minimize the control overhead of cooperation and contention for CR networks, we need to design a cost-effective MAC protocol, which consumes fewer resources on control transmission, and meanwhile ensures accurate and real-time spectrum usage information for data transmission. Recently, some works leverage OFDM (Orthogonal Frequency Division Multiplexing)

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modulation to move the channel contention from time domain into frequency domain, in order to improve the efficiency of 802.11 MAC [11] [13] [14]. Motivated by the researches using frequency domain for channel contention, we propose a novel MAC protocol for CRAHNs, termed FCM (Frequency domain Cooperative sensing and Multi-channel contention). As illustrated in Fig. 1, FCM combines both cooperative sensing and multi-channel contention in frequency domain. Specifically, we allow CR users to exchange and share their sensing information in a portion of OFDM subcarriers, and meanwhile contend for spectrum access in the other portion of subcarriers to construct an access order. With the available spectrum and access order at hand, CR users can undertake data transmission simultaneously in different available spectrum. Since decision sharing and multi-channel contention can be finished in the same short period, the coordination overhead and transmission delay are significantly reduced. To summarize, the main contributions of this paper over existing protocols in CRAHNs are as follows:

- We present a cost-effective MAC protocol FCM, which moves cooperative sensing and multi-channel contention from time domain into frequency domain. To the best of our knowledge, it is the first of this kind in the literature to address the control overhead problem in CRAHNs.
- We conduct extensive simulations, which verify the effectiveness of FCM, and indicate that FCM can achieve throughput gain of 220% over Traditional Cooperative MAC for CRAHNs.

The rest of this paper is organized as follows. In Sec. III, we give a brief introduction on cooperative sending in CR networks. The detailed design of FCM is presented in Sec. IV, including *hierarchical subcarrier structure*, *full-duplex Meta Reporting Channel* and *receiver declared contention*. In Sec. V, we analyze the performance FCM by extensive experiments and simulations. Sec. II gives the related work, and Sec. VI concludes the paper and provides some suggestions for future research.

II. RELATED WORK

Cognitive radio spectrum access has become a hot topic these days [5] [6] [7]. Extensive dynamic spectrum access methods have been proposed. [8] proposes a spatial spectrum access game on directed interference graphs. This framework well models the interference relationship for cognitive radio networks. In [9], multiple operators are enabled in cooperative cognitive networks. These operators involve SUs as the cooperative relays for their PUs. As a consequence, the SUs have the opportunities to access the spectrum for their own transmission. The cooperative transmission model enables efficient designs to enhance the performance of cognitive radio networks.

Among which, many researches have been presented by minimizing the coordination overhead in common control channel for cooperative sensing. In [15], a censoring method is proposed to solve the bandwidth constraint in control channel, where a decision can be reported only after local test. In this way, unnecessary report can be effectively avoided. In [16], the authors design an efficient combination scheme that allows reporting data to be superposed at the FC side. Therefore, the bandwidth of the reporting channel is fixed no matter how many cooperative users there are. [18] utilizes the pricing model in cognitive radio networks, and allows the SUs to strategically adjust their uplink transmission power levels to maximize their own throughput. In [17], the authors define a metric for energy efficiency of cooperative sensing, and optimize the parameters that will affect the energy efficiency, including the fusion rule threshold, the number of cooperating SUs and so on. In [19], the authors handle cooperative sensing problem under an attack scenario, where the SUs can effectively identify the attack and exclude the attackers. However, none of the above approaches takes contention overhead together into consideration, and reduces the control overhead in frequency domain. On the contrary, FCM jointly consider both contention and cooperative sensing overhead, and utilize frequency domain OFDM subcarriers to reduce these overhead.

Recently, some works [11] [12] [13] leverage OFDM modulation to improve the efficiency of 802.11 MAC by moving the contention into frequency domain. FICA [11] utilizes OFDM subchannel for concurrently transmissions in centralized networks. While T2F [12] reduces the backoff overhead by counting contention using subcarriers in distributed networks. REPICK [13] extends the usage of subcarrier to represent ACK in frequency domain, in the meantime addresses most of the overhead in 802.11 DCF. Another type of work, like Side channel [22], uses "interference pattern" to represent the control message, and leverage interference cancellation to decode such control message, which greatly reduces the control overhead. Our previous work, *h*jam [23] and FAST [24] both utilize interference cancellation to transmit control information and data packets concurrently, aiming to reduce the control overhead without degrade the effective throughput of the data transmission. However, none of the above works considers to utilize OFDM modulation in frequency domain to reduce the cooperation and contention overhead in CR networks, which is the main target of FCM.

III. PRELIMINARY

In cognitive radio, spectrum sensing plays a key role to identify the availability of the licensed band. Owing to multipath fading and shadowing, a CR user sometimes is not able to receive signal strong enough from the PU. Cooperative sensing can help improve individual sensing performance, since a CR user can take sensing decisions from others for reference.

Fig. 2 illustrates two types of cooperative sensing. In centralized networks, there exists a central identify called Fusion Center (e.g. Base Station). The role of Fusion Center is to collect the local sensing information from cooperative CR users, make a combined decision on the presence of PUs, and diffuse the decision back to them. While in distribute networks (e.g. CRAHNs), since there is no central identity, CR users make cooperative decision by themselves. Each of them sends its own sensing data to others, combines its data with received sensing data, and then makes cooperative decision on the presence of PUs.

However, cooperative sensing can incur extensive cooperation overhead, resulting in a great performance degradation on

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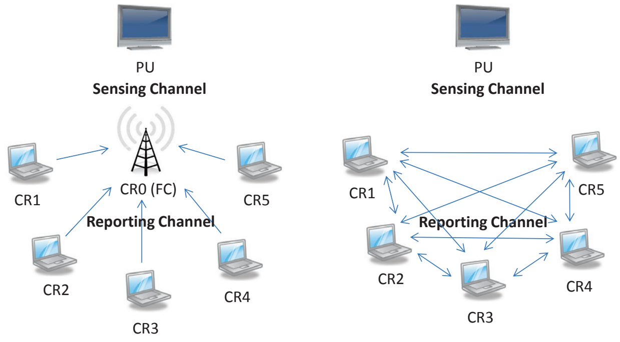

(a) Centralized (b) Distributed

Fig. 2: Illustrations of Cooperative Sensing

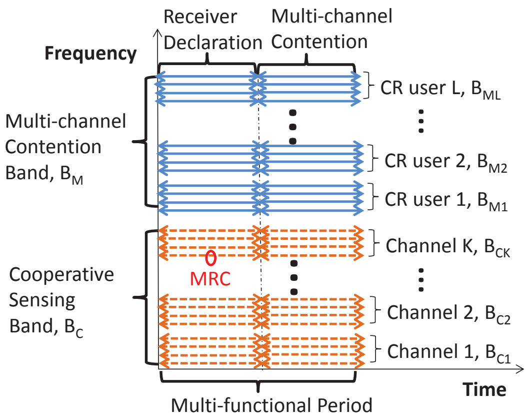

Fig. 3: Illustrations of Hierarchical Subcarrier Structure

cooperation gain. One way to reduce cooperation overhead is to use hard combining in data fusion. After individual sensing, each CR user makes a local decision, and transmits the one-bit decision instead of the entire local sensing samples for combing. There are a number of decision fusion rules designed for hard combing, among which *AND*, *OR*, and majority rules are the representatives. The *AND* rule confirms the presence of a PU only if every CR user reports its presence. Conversely, the *OR* rule only requires one CR user to report the presence of a PU. Similarly, the majority rule can be generalized as k out of the N rule. To be specific, if k out of n users reports the presence of a PU, then majority rule will confirm it. If we set the $k \geq N/2$ in the k out of N rule, we can obtain the majority rule.It is shown that when the number of cooperating CR users is large, the *OR* rule works best. Conversely, when the number of cooperating users is small, the *AND* rule works well. Besides linear fusion rules, advanced fusion techniques are also devised, which utilize the statistical knowledge for decision fusion. Linear-quadratic (LQ) fusion rule considers the correlation between CR users, and game theoretical model helps increase the detection accuracy for hard combing.

IV. FCM DESIGN

In this section, we describe the overall architecture of FCM, Frequency domain Cooperative sensing and Multi-channel contention. First, the basic idea along with the design challenges of FCM is presented. Main strategies of FCM is then demonstrated, including *hierarchical subcarrier structure*, *full-duplex Meta Reporting Channel* and *receiver declared contention*. We see how these strategies address the design challenges. Finally, we talk about some issues related to the design of FCM.

A. Overall of FCM

First, some necessary assumptions are summarized as following: 1) there are totally K adjacent data channels of interest $\{ch_i\}_k$. We assume full spectrum sensing ability for wide spectrum band, where CR users can sense all the channels at a short period of time [10]; 2) an error-free common control channel ch_0 is available for CR users at any time, which can be predefined in unlicensed band [27]. All the cooperation and contention are undertaken in this channel; 3) we only focus on sparse to medium networks, with maximum $L = 15$ CR users in one collision domain. CR users get implicit synchronized as in [12] [13]; 4) each CR user is equipped with two half-duplex antennas, one is for listening and the other is for transmission. It is noted that full-duplex wireless transceivers can also be utilized [14]. However, since it is in the start-up stage, we only consider the off-the-shell radios. 5) In the current stage, we do not take channel switching time into consideration. That is, the switching time between the common control channel and data channels.

With these assumptions in mind, we propose FCM to reduce the cooperation and contention overhead in CRAHNs. FCM utilizes OFDM as the PHY layer modulation scheme for common control channel ch_0. Taking advantage of OFDM subcarriers, more information can be encoded into one OFDM symbol. As stated in [11], we can obtain 256 or more subcarriers within a 20MHz channel. Thus the fundamental idea of FCM is: *to conduct decision sharing and multi-channel contention concurrently in frequency domain through OFDM subcarriers*.

The basic idea of FCM is simple and efficient, yet there remain several challenges for implementation. First, cooperative sensing and multi-channel contention are two individual processes, how to combine them together into a same period remains concern. Second, exchanging and sharing sensing decisions among different CR users consumes a considerable amount of time in CRAHNs, how can we accomplish this process with minimum time without degrading the sensing performance? Third, we can not simply apply frequency contention as in [12] in multi-channel scenario, since receiver has no idea which channel should be tuned to. Thus we should figure out how to conduct channel contention while notifying corresponding receiver in a cost-efficient way.

FCM has three strategies to address the above challenges: *hierarchical subcarrier structure* that integrates cooperative sensing and multi-channel together, *full-duplex Meta Reporting Channel* that conducts decision sharing, and *receiver declared contention* with order-matched multi-channel allocation. In the following subsections, we will present the design and functionality of these strategies.

B. Hierarchical Subcarrier Structure

In order to combine cooperative sensing and multi-channel contention together and move them into frequency domain, we propose a *hierarchical subcarrier structure* to conduct both

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of these two processes concurrently. Assuming there are N_S subcarriers in total for common control channel, which are numbered in ascending order starting with index 0 for the subcarrier at the lowest frequency. As shown in Fig. 3, in the first hierarchy, subcarriers are divided into two bands, termed cooperative sensing band B_C from subcarrier 0 to N_T and multi-channel contention band B_M from subcarrier $(N_T + 1)$ to N_S. Cooperative sensing band is used to exchange sensing information among CR users, and multi-channel contention band is used for contention and sender-receiver negotiation. In the second hierarchy, subcarriers are further divided into sub-bands and assigned to data channels and CR users respectively. Specifically, in cooperative sensing band, every N_C subcarriers are grouped into sub-band B_{Ci} and assigned to one data channel for its decision sharing. According to the FCC regulation, about 10 channels are available for portable device in TV white space [1]. Therefore, $K \leq 10$. Similarly, in multi-channel contention band, every N_M subcarriers are grouped into sub-band B_{Mi} and assigned to one CR user for multi-channel contention. As we assume, $L \leq 15$. The sub-band distribution algorithm for data channels and CR users will be presented in Sec. IV-C.

Instead of transmitting packets on these subcarriers, we use PHY layer signaling with Binary Amplitude Modulation (BAM) to transmit cooperation and contention messages. BAM modulates binary numbers “0” and “1” using on-off keying. Thus it is quite easy for CR users to demodulate BAM symbols using energy detection. As a tradeoff, the information contained in one BAM symbol is relatively small. To ensure the performance of both cooperation and contention, FCM utilizes two consecutive BAM time slots called *Multi-functional Period* for control transmission. Recall that each CR user has two antennas. Utilizing self-cancellation technique, a CR user can detect and decode BAM symbols from neighboring CR users with listening antenna, even it transmits its own BAM symbols with transmission antenna at the same time [12] [13].

C. Full-duplex Meta Reporting Channel

FCM leverages cooperative sensing band to undertake cost-effective decision sharing among cooperative CR users. In this paper, we focus on the process after each CR user obtains its individual sensing results. That is, how they exchange and share their sensing decisions to achieve cooperation gain. In FCM, CR users adopt hard combing as the data fusion rule, where binary local decisions are transmitted in cooperative sensing band. According to our *hierarchical subcarrier structure*, we assign each data channel a unique sub-band B_{Ci}. CR users fuse their sensing decisions for each data channel in the corresponding sub-band. The sub-band distribution is conducted as following: we number the data channels in ascending order starting with index 0 for the channel at the lowest center frequency. Then each sub-band B_{Ci} is assigned to the i^{th} data channel, e.g., B_{C0} is assigned to ch_0.

In cooperative sensing band, a subcarrier in one BAM time slot is treated as a basic unit termed *Meta Reporting Channel (MRC)*, as stated in Fig. 3. Each CR user is assigned one *MRC* in each sub-band to transmit its decision for the corresponding data channel. Although *MRC* only has the capacity of 1 bit, this is just enough since the sensing decision for each data channel is a binary number. We formulize *MRC* allocation as a vertex-coloring problem, and construct an un-directional graph $G(V, E)$ using Alg. 1, where V denotes all the CR users in the network and E represents the allocation conflict relationship among CR users.

Algorithm 1 Construct $G(V, E)$.

```
for each two CR users $i, j \in V$ do
    if $i, j$ are within transmission range of each other then
        add an edge $e(i, j) \in E_1$
    end if
end for
for each edge pair $e(i, j), e(j, k) \in E$ do
    add an edge $e(i, k) \in E_2$
end for
$E = E_1 \cup E_2$
```

Problem definition: Given an undirected graph $G = (V, E)$, assign a color c_u to each vertex $u \in V$ such that the following holds: $e = (v, w) \in E \Rightarrow c_v \neq c_w$.

We adopts a Synchronous Distributed Algorithm with a total of $N_C * 2$ colors to do vertex coloring in $G(V, E)$ [3]. Each color represents one *MRC* in every sub-band. During the network initialization, CR users operate in synchronous rounds, and in each round they execute Alg. 2 to get its own *MRC*. This algorithm ensures that the neighboring CR users will not choose the same *MRC*, even in multiple collision domains. According to the coloring results, we assign one *MRC* to each CR user in each sub-band. The above algorithm needs (L+1) colors, which requires $N_C * 2 \geq (L + 1)$. Since $L \leq 15$ and $K \leq 10$, the bandwidth of B_{Ci}, $N_C \approx 8$ subcarriers, and the bandwidth of $B_C \approx 80$ subcarriers.

Algorithm 2 Vertex coloring in $G(V, E)$.

```
Each node v executes the following code
v sends its ID to all neighbors
v receives IDs of neighbors
while v has an uncolored neighbor with higher ID do
    v sends "undecided" to all neighbors
end while
v chooses the smallest color not used by any neighbor
v informs all its neighbors about its choice
```

During the individual sensing period, each CR user makes local decision for all the data channels. When Multi-functional Period begins, each of them uses transmission antenna to transmit binary decision “1” or “0” on its own *MRCs* across all $B_{Ci}s$, where “1” represents the presence of a PU (H_1), and “0” represents the absence of a PU (H_0). Meanwhile, it uses listening antenna to acquire all the sensing results from others. Then each CR user applies a distributed fusion rule to obtain the cooperative decision. Here we adopt majority rule as the decision fusion rule. Advanced fusion techniques, such as some learning algorithms [25] [26] can be considered as future work to improve cooperative gain.

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D. Receiver Declared Contention

CR users undertake contention in multi-channel contention band B_M during Multi-functional Period. Each of them is assigned one unique sub-band B_{Mi}. Here we directly apply the coloring results of *MRC* allocation in cooperative sensing band to B_{Mi} allocation. As the algorithm needs (L+1) colors, the bandwidth of B_M should be $(L+1) \times N_M$ subcarriers. In Multi-function Period, the first time slot in B_{Mi} is used for receiver declaration. We utilize hash value of the MAC address to represent a receiver. A sender will hash its receiver's ID into a value between $[1, 2^{N_M}]$ and transmit this value in its own B_{Mi}. "0" represents that a CR user does not have a receiver. Upon listening to this value, other CR users conduct the same hash function on its own ID to see if they are matched.

In the next time slot, the senders keep silent, and the corresponding receivers will conduct contention. Each of them randomly picks up a number M from $[1, 2^{N_M}]$ as its contention number. "0" represents that there is no transmission requirement at all. Meanwhile, every CR user uses listening antenna to acquire others' contention numbers. Afterwards, a transmission order is constructed according to the values of the contention numbers. The one with the smallest contention number has the highest priority to transmit, and vice versa. This is called receiver based contention, since the contention is raised up at the receiver side. In this way, the sender can also confirm that its corresponding receiver has received the transmission request, which can avoids the hidden terminal problem to some extend. To ensure the contention space is large enough, we set $N_M = 10$ subcarriers. Then the contention space and hash space are both $(2^{10} - 1)$, which is sufficient for sparse to medium networks. The total bandwidth of B_M is around $(15+1) * 10 = 160$ subcarriers.

To decide which sender-receiver pair should transmit on which data channel, each CR user sorts the available data channels after it obtains the final cooperative sensing decisions. The sorted available data channels have an ascending order in terms of channel index. Then we conduct order-matched multi-channel allocation for CR sender-receiver pairs. The sender-receiver pair with the smallest contention number (highest priority) will transmit on the available data channel with the lowest index. This allocation continues until there is no available data channel for transmission. We illustrate the procedure of FCM in Fig. 4. There are totally 4 nodes and 2 data channels. In the first time slot, $S1$ and $S2$ first declare their receivers as $R1$ and $R2$. Afterwards, the corresponding receiver, $R1$ and $R2$ choose 12 and 7 as their contention numbers. These numbers indicate that the transmission order should be $[S2, S1]$. Meanwhile, all the CR users report their sensing decisions in B_{C1} and B_{C2}. Using majority rule, the sorted available data channel is $[CH1]$. Then, with order-matched multi-channel allocation, S2 and R2 will transmit in $CH1$.

E. Analysis of MAC efficiency

After presenting the idea of FCM, we analyze the efficiency of FCM compared with traditional cooperative MAC (T-MAC). As seen in Fig. 1 (a), T-MAC conducts cooperative sensing and multichannel channel contention in time domain. Each CR user reports its sensing decision one after another. Afterwards, a basic channel contention method, carrier sensing multiple access with collision avoidance (CSMA/CA) is adopted to contend for each available channel in parallel. When collision happens, each node will backoff b slots, where b is randomly chosen from a contention window $[0, CW)$. We can build a simple analytical model to compute the efficiency ratio for traditional MAC (T-MAC). We assume that each CR user needs one OFDM symbol to transmit its sensing decision, then the duration of reporting is $L * t_{OFDM}$, where L is the total number of CR users within a collision domain. As for the contention period, since a CR user chooses a random number uniformly from the contention window $[0, CW)$, the expected number of backoff slots is $W = CW/2$. Then the duration of contention for K available channels in parallel is $CW/2 * t_{slot}$. Equation 1 describes the efficiency ratio for T-MAC.

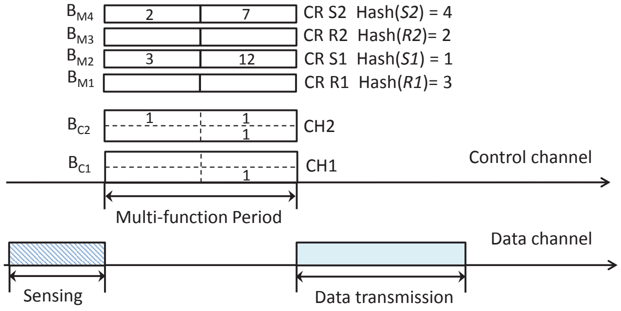

Fig. 4: Illustrations of FCM access method

$$\eta_{T_{MAC}} = \frac{t_{data}}{L * t_{OFDM} + \frac{CW}{2} * t_{slot} + t_{data}} \tag{1}$$

where t_{data} is the time used to transmit data on all the available channels. Here we ignore the individual sensing time, since it highly depends on the sensing mechanism adopted. From equation 1 we can observe that, cooperative sensing and multichannel contention becomes great overhead and constrained the efficiency of data transmission.

On the contrary, FCM conducts cooperative sensing and multi-channel contention in frequency domain through subcarriers, and it only occupies two OFDM symbols to convey the control message. Therefore, the efficiency ratio for FCM is,

$$\eta_{FCM} = \frac{t_{data}}{2 * t_{OFDM} + t_{data}} \tag{2}$$

We use the parameters in Table 1 compute the efficiency of both T-MAC and FCM. With 10 CR users, a CW size of 64, FFT size of 256 points and packet length of 1500 bytes $\eta_(T - MAC)$ is only 50%, and it drops to 30% with 30 CR users and a CW size of 128. As for FCM, since its efficiency is not affected by the number of CR users, η_{FCM} remains 95%, which is $1.9\times$ compared with T-MAC.

F. Points of Discussion

We finish the description of FCM with a few discussions.

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1) Accuracy of Decision Fusion: The accuracy of data fusion is an essential factor to the performance of FCM. We first analyze the accuracy of majority fusion rule. According to majority rule, a CR user declares $H_1(H_1)$ for a channel if $[L_0/2]$ out of L_0 CR users report "1". There are two aspects that will influence detection accuracy: miss detection rate (Q_{miss}) and false alarm rate Q_{false}. Q_{miss} is the probability of missing a PU when one is present and (Q_{false}) is the probability of falsely detecting a PU when one is absent. A lot of models have been proposed to analyze the probabilities of miss detection and false alarm . According to [4], Q_{miss} for majority fusion can be expressed as:

$$\begin{aligned} Q_{miss}(majority) &= Prob\{H_0|H_1\} \\ &= 1 - \sum_{l=[\frac{L_0}{2}]}^{L_0} \binom{L_0}{l} (1-P_m)^l P_m^{L_0-l} \end{aligned} \tag{3}$$

Similarly, Q_{false} for majority fusion is expressed by,

$$\begin{aligned} Q_{false}(majority) &= Prob\{H_1|H_0\} \\ &= \sum_{l=[\frac{L_0}{2}]}^{L_0} \binom{L_0}{l} P_f^l (1-P_f)^{L_0-l} \end{aligned} \tag{4}$$

where P_m and P_f are the miss detection probability and false alarm probability of an individual CR user during individual sensing.

As mentioned above, ***OR*** fusion rule can achieve satisfied performance when the number of CR users is relatively large. Therefore, we also analyze its miss detection rate Q_{miss} and false alarm rate Q_{false}. As for ***OR*** fusion rule, a CR user declares $H_1(H_1)$ for a channel if any CR users report "1". Therefore, according to [4], we can deduce that miss detection rate Q_{miss} and false alarm rate Q_{false} have similar forms,

$$\begin{aligned} Q_{miss}(OR) &= Prob\{H_0|H_1\} \\ &= 1 - \sum_{l=1}^{L_0} \binom{L_0}{l} (1-P_m)^l P_m^{L_0-l} \end{aligned} \tag{5}$$

$$\begin{aligned} Q_{false}(OR) &= Prob\{H_1|H_0\} \\ &= \sum_{l=1}^{L_0} \binom{L_0}{l} P_f^l (1-P_f)^{L_0-l} \end{aligned} \tag{6}$$

In practice, if the combined decision is not unified among different CR users due to listening or computational error, order-matched allocation may cause collision and degrade the overall throughput. To illustrate this problem, we conduct several simulations to evaluate the performance of FCM under chaotic decision fusion. Here we adopt the environmental settings in Sec. 5.3.1. The available channel is 1, 5 and 10. There are totally 10 pairs of CR sender-receivers. We vary the portion of CR senders without unified sensing decisions. Each circumstance runs 50 times. To ensure fairness, in each run we randomly choose the chaotic CR senders, and compute the aggregate overall throughput under each circumstance. The simulation results are shown in Fig. 5. As the portion of chaotic CR senders increases, the aggregate throughput of FCM decreases accordingly. This implies that more chaotic CR senders introduce more collisions, thus the aggregate throughout has been degraded. However, when the number of available channel K is relatively sufficient, e.g., $K \geq L/2$, where L is the total number of CR senders, the chaotic decision fusion only has little impact on the overall performance. That is because with more number of available channels, there is a lower probability that the order-match allocation introduces collisions. On the contrary, when the number of available channel is deficient, e.g., $K < L$, the aggregate throughput experiences certain degradation due to collision. To mitigate this problem, we can repeat the reporting slot one or more times. During each iterated reporting slot, CR users transmit their fusion decisions obtained from the previous reporting slot, and in the meanwhile receive othersąŕ decisions for further fusion. After each iteration, they apply fusion rules (e.g., majority rule) again to modify their decisions. The iteration stops until all the CR users reach an agreement. In this way, we ensure them to converge to a unified decision on each data channel. However, iterations will definitely consume more cooperation overhead. We leave it as future work to design an optimal solution with ensured accuracy and acceptable overhead.

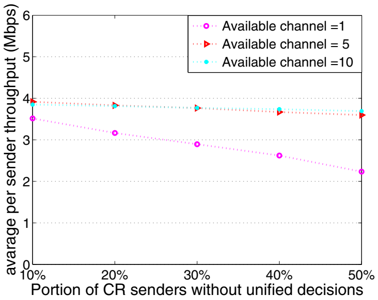

Fig. 5: Performance of FCM under chaotic decision fusion. The total number of CR senders L is 10. Each time we randomly choose a number of CR senders as those without unified decision, and each of them only has one chaotic channel.

2) Collision Probability of Contention: In multi-channel contention band, it is possible that two or more senders choose the same contention number. In this case, confusion may happen, and none of them are able to transmit with the desired receiver. The collision probability that two or more senders choose the same contention number in a collision domain with L_0 CR users, $P_{collision}$, can be expressed as:

$$P_{collision} = 1 - \frac{L_0!\binom{2^{N_M}-1}{L_0}}{(2^{N_M}-1)^{L_0}} \tag{7}$$

With listening antenna, the collided sender-receiver pairs are able to know that contention number has conflicted with each other. So they just give up contention in this round. Other pairs without collision will construct the transmission order and conduct transmission. According to our assumption, with $L_0 \leq 15$ and $N_M = 2^{10}$, $P_{collision} \leq 10\%$. This probability can ensure only a few senders cannot transmit due to collided contention number.

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3) Synchronization of CR Users: Another main concern is whether FCM is feasible in practice in terms of synchronization. It is known that OFDM modulation requires a strict synchronization between each node, and this synchronization issue is not easy to achieve in CRAHNs. We adopt a similar approach in [12], where the CR users get implicitly synchronized through the listening antenna when the channel becomes idle to enable concurrent subcarrier transmissions. Furthermore, to achieve symbol level synchronization, we extent the length of Cyclic Prefix (CP) for each OFDM symbol during the multi-functional period. CP is a build-in mechanism in 802.11 to fight against symbol misalignment. It is the copy of the OFDM symbolaŕs tailing samples, and is added as a prefix of that symbol. Therefore, as long as the misalignment is within a CP length, the receiver can still find a proper FFT window and demodulate the OFDM symbol. However, longer CP incurs more overhead. How to handle the tradeoff between robustness to symbol misalignment and CP control overhead leaves as our future research.

4) Protection for PU and Recovery of CR user: To provide protection for PUs, the CR users who are not on communication will continue perform sensing. Whenever a PU is detected, they will transmit the sensing decision on cooperative sensing band. In the meanwhile, the CR users who are on communication will always listen to the common control channel through listening antenna. Once they receive the reporting decision from others, they vacate the corresponding channel for PUs. To ensure the performance of CR users after vacation, we could select one or more data channels as backup channels from the available channel list each round. These channels are used to restore the communication of CR users in case that a PU suddenly appears. When a sender-receive pair vacates the data channel for PUs, it will search the list of backup channels and select the available one to resume transmission. This method guarantees the performance of CR users under the uncertainty of PUs.

V. PERFORMANCE EVALUATION

In this section, we evaluate the performance of FCM through extensive simulations. Since most of the prevailing network simulators like NS2 is difficult to simulate PHY layer, we hereby use a self-defined network simulator written by matlab and C++. The simulations are divided into two parts. We first quantify the components of FCM, including Distributed Allocation Algorithm, cooperative sensing and multi-channel contention. Afterwards, the performance of FCM is evaluated comparing with Traditional Cooperative MAC for CRAHNs.

A. Performance of Distributed Allocation Algorithm

First, we study the performance of Synchronous Distributed Algorithm for *MRC* allocation. The goal is to find out how many *MRCs* are needed for all the CR users within the network, and how many rounds does it take to finish this allocation. In fact, this is highly associated with the network topology. We start the evaluation with a simple line topology, where each CR user only has two neighbors. Then we use a much practical random topology with multiple contention domains in a 50×50 area, as shown in Fig. 6. Each contention domain has $5 \leq L_0 \leq 15$ CR users distributed randomly. For the above two topologies, the total number of CR users in the network L_M is set from 10 to 60. Each run of a simulation conducts *MRC* allocation with different L_M, and is repeated 10 times to calculate the average number of *MRCs* and rounds needed for allocation.

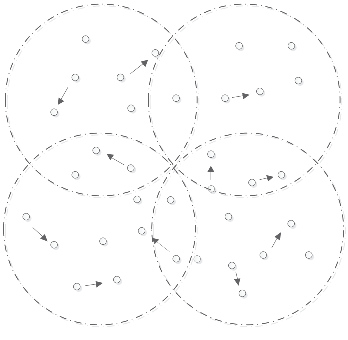

Fig. 6: Random topology with multiple collision domains, each domain with 5 to 15 CR users

The solid lines in Fig. 7 depict the average number of *MRCs* needed using Synchronous Distributed Algorithm. The value remains 3 as the number of CR users increases. This is reasonable since each CR user only needs to pick up the *MRC* different from its two neighbors'. In random topology, the number of *MRCs* increases as the number of CR users increases. But it can be controlled within 15 when the maximum number of CR users is 15 in one collision domain. This indicates that the maximum number of *MRCs* needed is $(L+1)$ using Synchronous Distributed Algorithm. The dash lines in Fig. 7 represent the average number of rounds needed to finish allocation. For line topology, it only takes around 5 to 15 rounds. While for random topology, it may take over 30 rounds with 60 CR users. However, this value is acceptable for network initialization, and thereby verifies the effectiveness of Synchronous Distributed Algorithm.

B. Performance of Cooperative Sensing

Now we evaluate the performance of majority fusion rule for cooperative sensing. Each CR user has an average probability of miss detection P_m and false alarm P_f for each data channel. We set the bandwidth of B_C to 80 subcarriers as discussed in Sec. IV-C. The total number of data channels is 10. For each run of a simulation, we choose one collision domain from Fig. 6. All the CR users report their decisions for 10 data channels in B_C, and meanwhile receive decisions from others to conduct decision fusion. We compute the miss detection rate Q_{miss} and false alarm rate Q_{false} of cooperative sensing at each CR user for each data channel, and plot the mean of Q_{miss} and Q_{false} in Fig. 8 as functions of the number of cooperative CR users.

As shown in Fig. 8, cooperative sensing improves the performance of individual sensing under all the conditions. As the number of CR users increases, Q_{miss} and Q_{false} decreases, indicating that after cooperation, each CR user get a better understanding about whether the PU is present or not. Besides, the detection performance of individual CR user, P_m and P_f, has certain impact on the performance

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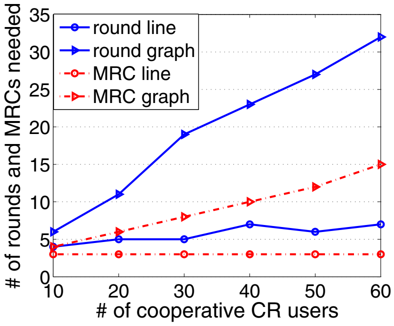

Fig. 7: number of *MRCs* and rounds needed for Synchronized Distributed Algorithm

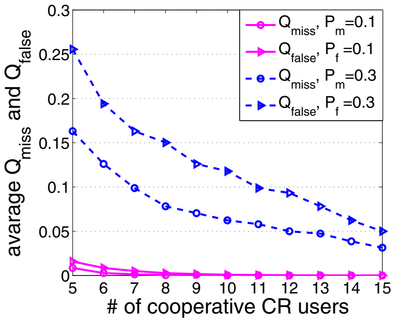

Fig. 8: Average miss detection rate and false alarm rate for cooperative sensing

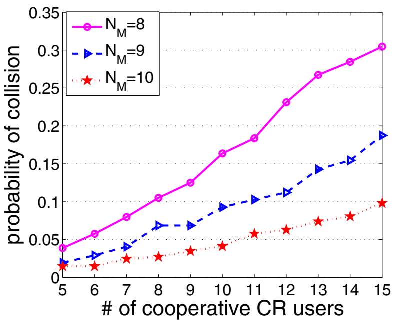

Fig. 9: Collision probability for CR users to choose the same contention number

of cooperative sensing. When each CR user has a relatively high sensing accuracy, say $P_m = P_f = 0.1$, the cooperative sensing performance, Q_{miss} and Q_{false} are mainly below 0.025, which is nearly 400% cooperative gain. However, if each CR users has a relatively low sensing accuracy, say $P_m = P_f = 0.3$, higher cooperative gain can be achieved only if the number of cooperative CR users is relatively large. Therefore, to design a fusion rule with higher cooperative gain will be our future work.

C. Performance of Receiver Declared Contention

In this subsection, the performance of multi-channel contention is evaluated using the same topology and similar setting in Subsec. V-B. We set the bandwidth of sub-band $B_M = 160$ subcarriers. Since CR users contend in their own B_M bands, each of them knows exactly what contention numbers others have chosen. Thus collision on contention number will not result in collision on data transmission. But it does affect the transmission performance to same extant, as CR users with the same contention number will retreat transmission from this round. If this happens frequently, none of them is able to transmit. For each run of a simulation, we let CR users conduct contention. We compute the probability that two or more CR users choose the same contention number P_C under different bandwidth of B_M and different number of CR users.

Fig. 9 shows the contention probability in function of the number of CR users. Not surprisingly, as the number of CR users increases, P_C increases, since more CR users are prone to have more same choices. This probability can be reduced by increase the contention space, say, the value of N_M. When N_M = 8, the contention space is $2^8 - 1 = 255$, which results in a collision probability of 30% with the largest number of CR users. After we increase N_M to 10, this probability drops to only 10%, showing that each CR user has a larger chance to choose different contention number from each other. With this setting, the maximum number of subcarriers needed in multi-channel contention band is $N_M \times (L + 1) = 160$. And the maximum number of subcarriers needed for FCM, N_S is $80 + 160 = 240$, requiring a 256-point FFT OFDM modulation.

1) Performance of FCM: In this subsection, we quantify the performance of FCM comparing with the Traditional Cooperative MAC (T-MAC) in CRAHNs, which undertakes cooperative sensing and multi-channel contention in time domain. To ensure the fairness, each CR user in T-MAC is equipped with two half-duplex antennas for control as well as data transmission. Moreover, T-MAC also has one particular channel as the common control channel. It assigns one time slot for each CR user in common control channel to report individual decision in sequential, and adopts 802.11 CSMA/CA for CR users to contend for each available data channel. This procedure is also shown in Fig. 1. We use the parameters in Tab. I for T-MAC and FCM. There are total 11 channels with channel bandwidth of 20MHz. One channel is for common control, and the others are for data transmission. The PUs have a regular on-off pattern. The on and off durations are exponentially distributed with mean $50sec$[20]. Each run of a simulation lasts $100sec$. Every CR user performs cooperative sensing, and we randomly pick up CR users from all the four contention domains in Fig. 6 to conduct contention and transmission in each run.

TABLE I: Configuration Parameters

Parameters	**Values**	**Parameters**	**Values**
SIFS	$16\mu s$	Sensing time	$500\mu s$
DIFS	$34\mu s$	Packet length	1500bytes
Slot time	$9\mu s$	N_{FFT}	256 points
CW_{min}	16	N_C	80 subcarriers
CW_{max}	1024	N_M	160 subcarriers

Fig. 10 depicts the average packet transmission delay with different number of CR users. The packet transmission delay is the time that a packet has waited for transmission. As for T-MAC, the packet delay increases as the number of CR users increases. This is because with more CR users, the time for reporting and contention becomes much longer. CR users need to go through a certain number of rounds before they win a data channel for transmission. Also, as the number of available data channel increases, delay also increases, since there are more data channels needed to be contended and negotiated. Meanwhile, the packet delay in FCM remains stable under all conditions, verifying the effectiveness that FCM only consumes two BAM symbols on control transmission. Thus it has very little packet delay, even with a large number of CR users and available data channels. Fig. 11 depicts the per sender throughput for both T-MAC and FCM. With T-MAC, throughput drops a lot as the number of CR users increases,

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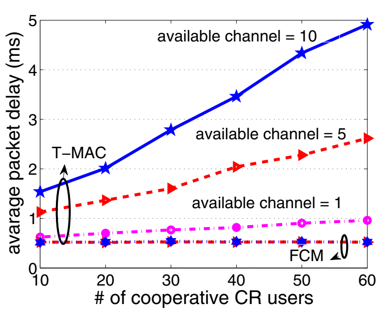

Fig. 10: Aggregate transmission delay with different number of CR users

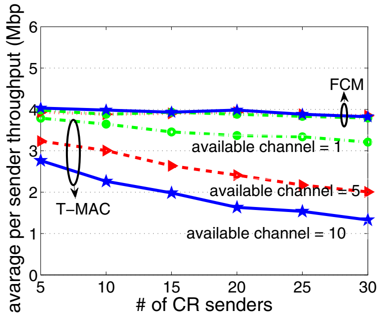

Fig. 11: Aggregate throughput with different number of CR users

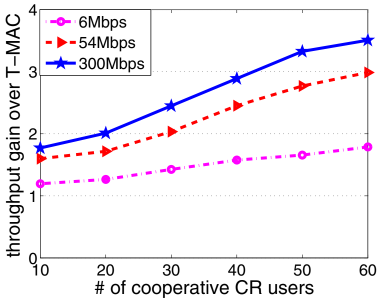

Fig. 12: Throughput gain with different data rate and different number of CR users

resulting in a rather poor performance of around 1MBps. However, the performance of FCM remains satisfactory for all the conditions of around 4Mbps, since FCM consumes less time on control overhead. It is noted that the throughput has a little degradation when the number of CR senders is large, e.g. 25. This is because collision may happen on contention numbers, which will result in transmission retreat for some CR senders.

We also quantify the throughput gain of FCM over T-MAC with different PHY layer data rates. As shown in Fig. 12, FCM archives an average throughput gain over T-MAC of 150% with 6Mbps, 220% with 54Mbps, and even 270% with 300Mbps. These performance gains stem from the fact that FCM reduces the overhead for control transmission, which constitutes a larger portion of time in T-MAC with higher data rate.

VI. CONCLUSION

In this paper, we propose a novel MAC design FCM, Frequency domain Cooperative sensing and Multi-channel contention, to reduce the cooperation and contention overhead in CRAHNs. FCM leverages OFDM modulation to move both cooperative sensing and multi-channel contention from time domain into frequency domain. With hierarchical subcarrier structure, FCM is able to undertake decision sharing and multi-channel contention in the same short period, which significantly reduces the control overhead on cooperation and contention. Extensive simulation results show that compared with Traditional Cooperative MAC, FCM can achieve 220% throughput improvement, verifying the effectiveness of frequency domain cooperative sensing and multichannel contention. Next, we propose to validate FCM on SDR platform, and exploit it to benefit more communication systems.

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