FCM: Frequency Domain Cooperative Sensing and Multi-channel Contention for CRAHNs

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Abstract—**Radio spectrum resource is shown to be significantly underutilized with fixed spectrum assignment policy. As a promising solution, cognitive radio allows unlicensed users to opportunistically access the spectrum not used by the licensed users. Cooperative sensing is further exploited to improve the sensing performance of unlicensed users 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 becomes an 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). FCM moves cooperative sensing and multi-channel contention from time domain into frequency domain. Thus, the control overhead caused by cooperation and contention can be significantly reduced, without reducing the sensing and access performance. 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.**

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 [?]. Cognitive radio (CR) technology has recently been receiving significant research interest both from academia and industry, due to the poor spectrum utilization of fixed spectrum assignment policy enforced today. CR is envisaged to solve this critical spectrum inefficiency problem by enabling the access of the intermittent periods of vacant spectrum in the licensed band for the CR users, without affecting the licensed or primary users (PUs).

However, the design of CR networks 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 the PU is detected. This sensing accuracy is compromised with many factors, such as multi-path fading and shadowing [1]. 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. 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 problems in CR networks.

In order to solve the above-mentioned challenges and minimize the 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 information for data transmission. Recently, some works leverage OFDM (Orthogonal Frequency Division Multiplexing) modulation to move the contention from time domain into frequency domain, in order to improve the efficiency of 802.11 MAC [3]. Motivated by the researches using frequency domain for channel contention, we propose a novel MAC protocol for CR Ad Hoc Networks (CRAHNs), termed FCM (Frequency domain Cooperative sensing and Multi-channel contention). 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 contribution of this paper is: 1) A cost-effect 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; and 2) Extensive simulations, which verify the effectiveness of FCM, and indicate that FCM can achieve throughput gain of 220% over Traditional Cooperative MAC for CRAHNs.

II. FCM Design

In this section, we first present the basic idea and design challenges of FCM, Frequency domain Cooperative sensing

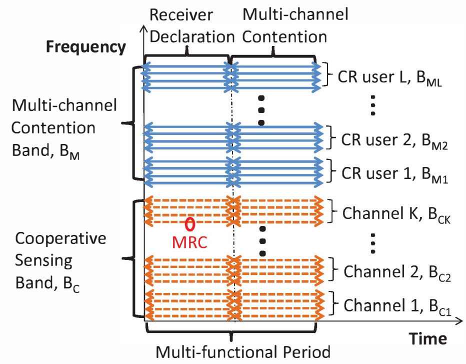

Fig. 1: Illustrations of Hierarchical Subcarrier Structure

and Multi-channel contention. Main strategies of FCM is then demonstrated to see how we address these 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 [1]; 2) an error-free common control channel ch_0 is available for CR users at any time, which can be predefined in unlicensed band. 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 [2] [3]; 4) each CR user is equipped with two half-duplex antennas, one is for listening and the other is for transmission.

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 [3], 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 [2] 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 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. 1, 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. 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. II-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 [2] [3].

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 obtaining their 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*

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

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

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. 1. 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 Algorithm 1, where V denotes all the CR users in the network and E represents the allocation conflict relationship among CR users.

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
```

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 $G(V, E)$. Each color represents one *MRC* in every sub-band. CR users operate in synchronous rounds, and in each round they execute Algorithm 2. 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.

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 can be considered as future work to improve cooperative gain.

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. Senders conduct contention in the second time slot. Each of them randomly picks up a number M from $[1, 2^{N_M}]$ as its contention number. "0" represents no contention at all. Meanwhile, every CR user use listening antenna to acquire others' contention numbers and construct a transmission order. The one with the smallest contention number has the highest priority to transmit, and vice versa. 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 obtaining 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.

III. Performance Evaluation

In this section, we evaluate the performance of FCM through extensive simulations using self-defined network simulator. 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.

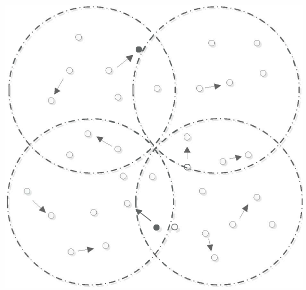

Fig. 2: Random topology with multiple collision domains, each domain with 5 to 15 CR users

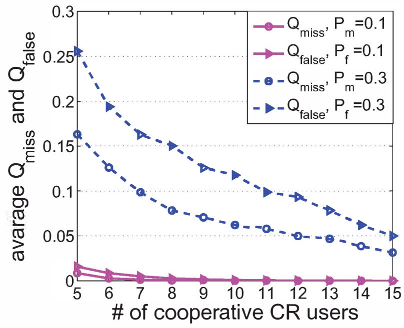

Fig. 3: Average miss detection rate and false alarm rate for cooperative sensing

A. 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. II-C. The total number of data channels is 10. For each run of a simulation, we choose one collision domain from Fig. 2. 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. 3 as functions of the number of cooperative CR users.

As shown in Fig. 3, 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 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.

B. 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. III-A. 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. 4 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.

C. 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. In particular, T-MAC 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. **??**. 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 $50sec$. 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. 2 to conduct contention and transmission in each run.

Fig. 5 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

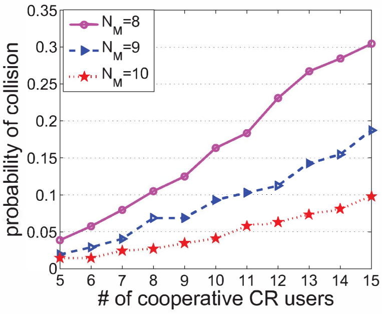

Fig. 4: Collision probability for CR users to choose the same contention number

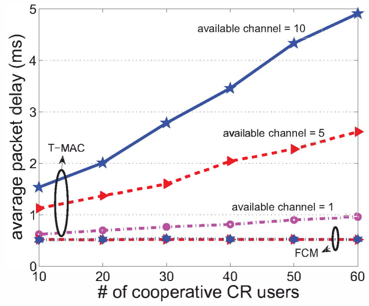

Fig. 5: Aggregate transmission delay with different number of CR users

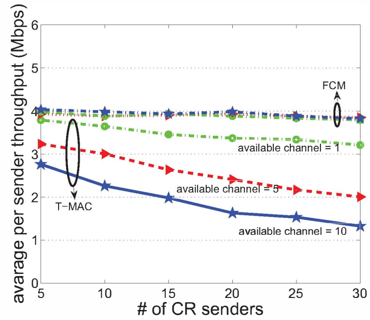

Fig. 6: Aggregate throughput with different number of CR users

TABLE I: Configuration Parameters

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

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. 6 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, resulting in a rather poor performance of around 1MBps. However, the performance of FCM remains satisfactory for all the conditions of around 4Mbps due to less control overhead.

IV. Related Work

Many researches have been presented by minimizing the coordination overhead in common control for cooperative sensing. In [4], a censoring method is proposed to solve the bandwidth constraint in control channel, where a decision can be reported only after local test. In [5], the authors design an efficient combination scheme that allows reporting data to be superposed at the FC side. However, none of the above approaches takes contention overhead together into consideration, and reduces the overhead in frequency domain. Recently, some works [3] [2] leverage OFDM modulation to improve the efficiency of 802.11 MAC by moving the contention into frequency domain, such as T2F [2] and EPICK [3]. They reduce the MAC layer overhead by representing control information in frequency domain. Another type of work, like Side channel [6], uses "interference pattern" to reduce the control overhead without interference cancellation. And our previous work, *ℏ*jam [7] and FAST [8] utilize interference cancellation to transmit both control information and data packets together. However, none of them utilizes frequency domain to reduce the cooperation and contention overhead in CR networks, which is the main target of FCM.

V. 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, 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.

Acknowledgment

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