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

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Abstract—Radio spectrum resource is shown to be significantly under-utilized with fix spectrum assignment policy. Cognitive radio emerges as a promising solution to this problem, which allows unlicensed users to opportunistically access the spectrum not used by the licensed users. To ensure that unlicensed users can identify vacate spectrum fast and accurate without interfere licensed users, cooperative sensing is devised 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 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 to frequency domain. Therefore, it can significantly reduce the control overhead by cooperation and contention with ensured sensing performance. Extensive simulation results show that FCM can effective reduce the control overhead, and improve an average throughput to 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, such as TV broadcast frequencies below 700MHz, are extremely under-utilized [2]. Cognitive radio (CR) technology has recently been receiving significant research interest both from academia and industry, in no small part due to the poor spectrum utilization of fixed spectrum assignment policy enforced today. CR is envisaged to solve the 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 band once the PU is detected. The performance of spectrum sensing is compromised with many factors, such as multi-path fading and shadowing [4], which results in a low accuracy of identifying available spectrum. Recently, cooperative spectrum sensing has shown its superiority to improve the detection accuracy by exploiting spatial diversity. After exchanging sensing information among spatially located CR users, each of them can make a combined decision, which can be more accurate than individual ones. However, cooperation overheads increase dramatically and comprise the sensing performance, especially in distrusted 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 significant performance degradation. These challenges necessitate efficient designs that can simultaneously address extensive communication 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 [5] [8] [7]. 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), to combine both cooperative sensing and multi-channel contention in frequency domain. As shown in Fig. 1.
the overhead of cooperative sensing and multi-channel contention can be dramatically reduced. Specifically, we allow CR users to exchange and share their sensing information in a portion of OFDM subcarriers, and compute sensing decisions in a distributed manner. In the meanwhile, CR users contend for spectrum access in the other portion of the 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 according to the transmission order. Since decision sharing and multi-channel contention can be finished in the same short period, the coordination overhead and transmission delay is significantly reduced. To summarize, the contribution of this paper is listed below: 1) we propose a cost-effect MAC protocol termed FCM. FCM 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 CR networks; 2) we conduct extensive simulations to verify the effectiveness of FCM, which shows that FCM can achieve throughput gain of 220% over Traditional Cooperative MAC for CRAHNs.

II. PRELIMINARY

In cognitive radio, cooperative sensing plays a key role to improve the sensing performance by exploring spatial diversity. Owing to multi-path fading and shadowing, a CR user sometimes is not able to receive signal strong enough from the PU. This weak capacity of sensing requires complex implementation to increase the sensing sensitivity. However, cooperative sensing can relax this sensitivity requirement since a CR user can take sensing decisions from others for reference. Also, sensing time can be reduced due to cooperation. Therefore, a well-designed cooperative sensing scheme can contributes to a significant cooperation gain.

Fig. 2 illustrates two types of cooperative sensing. In centralized networks, there exists a central identity called Fusion Center (e.g. Access Point or 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. In particular, each CR user sends its own sensing data to others, combines its data with received sensing data, and makes cooperative decision on the presents of PUs. We can see that cooperative sensing can incur extensive cooperation overhead, such as coordination among CR users and Fusion Centers. The cooperation gain is compromised a lot by cooperation overhead. One way to reduce cooperation overhead is to use hard combing in data fusion. After individual sensing, each CR user makes a local decision and transmits the one-bit decision for combing. On the other hand, soft combing requires CR users to transmit the entire local sensing samples or the complete local test statistics for combining. Clearly, hard combining consumes much less control channel bandwidth, while soft combing can achieve better detection performance.

Therefore, there exists a tradeoff between detection accuracy and cooperation overhead. There are a number of decision fusion rules designed for hard combing, such as AND, OR, and majority rules. The AND rule confirms the presence of a PU only if every CR users reports its presence. Conversely, the OR rule only requires one CR user to report the presence of the PU. Similarly, the majority rule requires at least half of the CR users to report the presence of the PU. 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 in cooperative sensing, while Game theoretical model is also utilized to increase the detection accuracy.

III. FCM DESIGN

In this section, we present the design of FCM (Frequency domain Cooperative sensing and Multi-channel contention). First, the basic idea of FCM is introduced along with design challenges. Major components of FCM are then described to see how we address these challenges.

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. That is, CR users can sense all the channels at a short period of time, either using energy detection with multiple RF frontends, or using compress sensing [4]; 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 15 CR users in one collision domain. CR users get implicit synchronized as in [6] [7]; 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 [5], we can obtain 256 or more subcarriers within a 20MHz.
channel. Therefore, 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 decision among different CR users consumes a considerable amount of time in CRAHNs, how can we accomplish this process with minimum overhead without degrading the sensing performance? Third, in multi-channel scenario, sender-receiver negotiation and channel allocation are also critical problems. If we simply apply frequency contention as in [6], receiver has no idea which channel should be tuned to. Therefore, 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 to integrated cooperative sensing and multi-channel together, full-duplex Meta Reporting Channel to conduct 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**

![](image)

Figure 3: Illustrations of 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. 3, in the first layer, 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 subcarriers ($N_T + 1$) 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 layer, subcarriers are further divided into subbands and assigned to data channels and CR users respectively. Specifically, in cooperative sensing band, every $N_C$ subcarriers are grouped into sub-band $B_{C_l}$ and assigned to one of the channels for its decision sharing. According to the FCC regulation, about 10 channels are available for portable device in TV white space [2]. Therefore, $K \leq 10$. Similarly, in multi-channel contention band, every $N_M$ subcarriers are grouped into sub-band $B_{M_l}$ and assigned to one of the users for multi-channel contention. As we assumed before, the maximum number of CR users within one collision domain $L \leq 15$. The sub-band distribution algorithm for data channels and CR users will be present in Sec. III-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 relative 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 using transmission antenna at the same time. The effectiveness of self-cancellation technique has already been verified by several systems such as [6] [7]. This technique is essential to our design. We will see how FCM utilize it to undertake cost-effective cooperation and contention in following subsections.

**C. Full-duplex Meta Reporting Channel**

Full-duplex Meta Reporting Channel makes full utilize of the cooperative sensing band to undertake cost-effective decision sharing among different CR users. Here 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 the cooperative sensing band. According to our hierarchical subcarrier structure, we assign each data channel a unique sub-band $B_{C_l}$. CR users can fuse their sensing decisions for every 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 $B_{C_l}$ is assigned to the $i_{th}$ channel, e.g., $B_{C_0}$ is assigned to $c_{0}$. In cooperative sensing band, a subcarrier in one BAM time slot is treated as a basic unit termed Meta Reporting Channel (MRC), as shown in Fig. 4. 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 capacity is just enough since the sensing decision for each data channel is a binary number. We formulize MRC allocation as a vertex-coloring problem. First, we construct an un-directional graph $G(V, E)$ using Alg. 1 to represent the allocation conflict relationship among CR users,
where \( V \) denotes all the CR users in the network.

Algorithm 1 Construct G.

1: for each two CR users \( i, j \in V \) do
2: if \( i, j \) are within transmission range of each other then
3: add an edge \( e(i, j) \in E_1 \)
4: end if
5: end for
6: for each edge pair \( e(i, j), e(j, k) \in E \) do
7: add an edge \( e(i, k) \in E_2 \)
8: end for
9: \( E = E_1 \cup E_2 \)

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: \( e = (v, w) \in E \Rightarrow c_v \neq c_w \).

Algorithm 2 Vertex coloring in G.

1: Each node \( v \) executes the following code
2: \( v \) sends its ID to all neighbors
3: \( v \) receives IDs of neighbors
4: while \( v \) has an uncolored neighbor with higher ID do
5: \( v \) sends "undecided" to all neighbors
6: end while
7: \( v \) chooses the smallest color not used by any neighbor
8: \( v \) informs all its neighbors about its choice

We use a Synchronous Distributed Algorithm with a total of \( N_C \ast 2 \) colors to do vertex coloring in \( G \) [10]. Each color represents one MRC in every sub-band. Each CR user operates in synchronous rounds, and in each round it executes Alg. 2. This algorithm ensures that the neighboring CR users will not choose the same MRC, even in multiple collision domains. After running the algorithm, we assign one MRC to each CR user in each sub-band according to the coloring result. The above algorithm needs \( (L+1) \times N_M \) subcarriers. In Multi-function Period, the first time slot in \( B_{M_i} \) is used for receiver declaration. We utilize hash value of the MAC address to represent a receiver due to limited subcarriers. A sender will hash its receiver's ID into a value between 1 to \( 2^{N_M} \) and transmit this value in its own \( B_{M_i} \). Upon listening to this value, other CR users conduct the same hash function on its own ID to see if they are matched. This receiver declaration can also avoid busy sender problem, where one sender intends to transmit to another sender. 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. Meanwhile, every CR user use listening antenna to acquire others’ contention numbers and construct a transmission order. The CR user with the smallest contention number has the highest priority to transmit, while the one with the largest contention number has the lowest priority. To ensure the contention number 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 \( B_{M_i} \) is around \((15 + 1) \ast 10 = 160\) subcarriers.

To decide which sender-receiver pair should transmit on which data channel, each CR user has to sort 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 channel with the lowest index. The allocation continues until there is no available data channel for transmission. The procedure of FCM is shown in Fig. 4. There are totally 4 nodes and 2 data channels. S1 and S2 first declare their receivers as R1 and R2. Then they choose 12 and 7 as their contention numbers, which indicates the transmission order should be [S1, S2]. Meanwhile, all the CR users reports the sensing decision in \( B_{C_1} \) and \( B_{C_2} \). Using majority rule, the available channel list is [CH1, CH2]. Then, with order-matched multi-channel allocation, S1 and R2 will transmit in CH1.

The sender-receiver pair must have the highest priority to transmit, while the one with the largest contention number has the lowest priority. To ensure the contention number 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 \( B_{M_i} \) is around \((15 + 1) \ast 10 = 160\) subcarriers.

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The simulation conducts subcarrier allocation with different domain has in a 50 × 50 area, as shown in Fig. 5. Each contention domain has 5 ≤ L0 ≤ 15 CR users distributed randomly. For both 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 subcarrier allocation with different L_M, and is repeated 10 times to calculate the average number of rounds and subcarriers needed.

The solid lines in Fig. 6 depict the average number of MRCs needed using Synchronous Distributed Algorithm. We can see that this value remains 3 as the number of CR users increases. This result is reasonable since each CR user only needs to pick up the subcarrier different from its two neighbors. In random topology, the number of subcarriers increases as the number of CR users increases. However, it can be controlled around 15 even with the maximum number of CR users is 15 in one collision domain. This is because the maximum number of subcarriers needed is \((L + 1)\) using Synchronous Distributed Algorithm. The dash lines in Fig. 6 represent the average number of rounds needed to finish allocation. For line topology, it only takes around 5 to 10 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

In this subsection, we conduct simulations to evaluate the performance of majority fusion for cooperative sensing. Without loss of generality, we only consider cooperation in single collision domain, e.g., we choose one collision domain from Fig. 5. 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. III-C. The total number of data channel is 10. For each run of a simulation, all the CR users report their decisions for 10 data channels in \(B_C\), and meanwhile receive decisions from others to do decision fusion. We compute the miss detection rate \(Q_{\text{miss}}\) and false alarm rate \(Q_{\text{false}}\) of cooperative sensing at each CR user for each data channel, and plot the mean of \(Q_{\text{miss}}\) and \(Q_{\text{false}}\) in Fig. 7 as functions of the number of cooperative CR users.

As shown in Fig. 7, cooperative sensing improves the performance of individual sensing under all the conditions. As the number of CR users increases, \(Q_{\text{miss}}\) and \(Q_{\text{false}}\) decreases, indicating that after cooperation, each CR user get a better understanding about whether the PU presents 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 users has a relatively high sensing accuracy, say, \(P_m = P_f = 0.1\), the cooperative sensing performance, \(Q_{\text{miss}}\) and \(Q_{\text{false}}\) are mainly below 0.05, which is nearly 100% cooperative gain. However, if each CR users has a relatively low sensing accuracy, say, \(P_m = P_f = 0.1\), higher cooperative gain can be achieved only if the number of cooperative CR users is relative larger. 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 setting in...
Subsec. IV-B except that the bandwidth of sub-band $B_M$ is set to be 160 subcarriers. Since CR users contend in their own $B_M$ bands, each of them knows exactly what contention numbers others have chosen. Therefore, collision on contention number will not result in collision on data transmission. However, it does affect the transmission performance to some extent, 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 PC under different bandwidth of $B_M$ and different number of CR users.

Fig. 8 shows the contention probability in function of the number of CR users. Not surprisingly, as the number of CR users increases, PC increases, since more CR users is prone to result in more same choices. This probability can be reduced by increase the contention space, say, the value of NM. When NM = 8, the contention space is $2^8 - 1 = 255$, which results in a collision probability of 30% with the largest number of CR users, which is, however, acceptable for common settings. After we increase NM 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 multichannel contention band is $N_M \times (L + 1) = 160$. And the maximum number of subcarriers needed for FCM $N_S$ is $80 + 160 = 240$, which requires 256-point FFT OFDM modulation.

1) Performance of FCM: In this subsection, we quantify the performance of FCM in ad hoc networks, comparing with the Traditional Cooperative MAC (T-MAC) in CRAHNs that 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. Then CR uses adopts 802.11 CSMA/CA to contend for each available data channel. This procedure is also shown in Fig. 1. We use the parameters in Tab. II 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 has a regular on-off pattern. The on and off durations are exponentially distributed with mean 50 sec. 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. to conduct contention and transmission in each run.

Fig. 9 depicts the average packet transmission delay in terms of the number of CR users. The packet transmission delay is the time that a packet has waited for transmission. As for T-MAC, the packets delay increases as the number of CR users increases, PC increases, since more CR users is prone to result in more same choices. This probability can be reduced by increase the contention space, say, the value of NM. When NM = 8, the contention space is $2^8 - 1 = 255$, which results in a collision probability of 30% with the largest number of CR users, which is, however, acceptable for common settings. After we increase NM 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 multichannel contention band is $N_M \times (L + 1) = 160$. And the maximum number of subcarriers needed for FCM $N_S$ is $80 + 160 = 240$, which requires 256-point FFT OFDM modulation.
users increases. This is because with more CR users, the time for contention and resolution 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. This is because there are more data channels needed to be contended and negotiated. Control overhead becomes much larger. Meanwhile, the packet delay of FCM remains stable under all conditions. That is because FCM only consumes two BAM symbols on control transmission. Therefore, it has very little packet delay, even with a large number of CR users and available data channels. Fig. 10 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. However, the performance of FCM remains satisfactory for all the conditions, 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. 30. That is because collision may happen on contention numbers, which will result in transmission retreat for some CR senders. Fig. 11 shows the throughput gain of FCM over T-MAC with different PHY layer data rate. With higher data rate, FCM achieves higher gain. That is because FCM reduces the overhead for control transmission, which contributes a large portion of time in T-MAC with higher data rate.

V. RELATED WORK

Many researches have been presented by minimizing the coordination overhead in common control for cooperative sensing. In [11], a censoring method is proposed to solve the bandwidth constraint in control channel, where a decision can be reported only after local test. In [12], the authors design a 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 work [5] [7] [6] leverage OFDM modulation to improve the efficiency of 802.11 MAC by moving the contention into frequency domain. FICA [5] and T2F [6] reduce the back off overhead by counting contention in frequency domain. REPICK [7] extends the usage of subcarrier to represent ACK in frequency domain, in the meantime addresses most of the overhead in 802.11 DCF. Side channel [13] uses “interference pattern to reduce the control overhead without interference cancellation, and our previous work, hjam [14] and FAST [15] utiliz interference cancellation to transmit both control information and data packets together. However, none of them consider applying OFDM to reduce the cooperation and contention overhead in CR, which is main target of FCM.

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 to frequency domain. With hierarchical subcarrier structure, FCM is able to undertake decision sharing and multi-channel contention in the same short period, which significantly reduce 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.

REFERENCES