A Mini-Slot Sensing with Selective Coordinator in Cognitive Radio System

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***Abstract*—In this paper, a mini-slot sensing with selective coordinator in cognitive radio is investigated. In traditional sensing, a whole sensing duration is only used to sense one channel. In proposed mini-slot sensing, a sensing duration is divided into many mini-slots and each mini-slot can be used to sense one channel independently, then data from all slots are been sent to a coordinator for final decisions. A proof is put up to demonstrate that mini-slot sensing has a better performance than the traditional sensing. In this research, the ability of different secondary users sensing different channels are not equal. Based on this assumption, we prove that in mini-slot sensing, not all slots do benefits to CR system. Slots can be divided to two groups: contributor (slots which improve system performance) and destroyer (slots which decrease the performance). A selective coordinator is proposed to assist mini-slot sensing which receive data from all slots and reject the destroyers in making final decisions. Based on the analysis above, an optimization problem is formulated to find the optimal assignment for slots to channels. A Greedy based two stage assignment method is proposed as the sub-optimal solution. Simulation results show that our proposed method has a better performance than traditional methods.**

***Index Terms*—Cognitive Radio (CR); Spectrum Sensing; Coordinated Sensing.**

I. INTRODUCTION

In recent years, spectrum scarcity became a serious problem with the development of wireless communications. Cognitive radio systems are proposed to solve this problem [1]. In CR networks, the secondary users could dynamically access the licensed channels if the primary users don't exist. With a good performance in improving spectrum efficiency, CR technique has drew much attention and been a hot research topic. However, in dynamic spectrum access scenarios, primary users performance can be degraded because of the collision caused by secondary users' access. To avoid the collisions, spectrum sensing technique is proposed to detect whether primary users exist or not. Secondary users can only use licensed channels when no primary users are detected. Performance of spectrum sensing can be measured by two parameters: the detection probability and false alarm probability. So far, spectrum sensing strategy has been explored, such as energy detection, match filter detection, cyclostationary feature detection [2].

In local spectrum sensing, primary users may hardly be detected under the hidden terminal problem and that leads to a serious interference problem. On the other hand, cooperative spectrum sensing, in which two or more secondary users are assigned to sense one channel and send the sensing results to a center node for final decision, is proposed. Cooperative spectrum sensing proves to have a better performance in detection accuracy, but it is difficult to apply sensing into the wide-band detection because one secondary user may not be able to sense wide-band frequency spectrum under the limitation of sensing and computation time. Then coordinated spectrum sensing was proposed [3]], in which the wide-band is divided into several channels, and each secondary user is assigned to sense one channel while every channel should be detected by at least one secondary users. There is a coordinator to collect all the sensing results from secondary users and make a final decision.

The previous studies on coordinated spectrum sensing focus on assignment strategy. In [4], an iterative Hungarian algorithm based coordinated spectrum sensing strategy was proposed to solve the problem. In this study, a channel is usually sensed within full sensing duration. In [5] and [6], mini-slot sensing is discussed in the context of throughput optimization problem. But a specific slots assignment strategy is not provided and the advantage of mini-slot sensing is not discussed.

In this paper, a mini-slot sensing strategy is introduced and proved to have a better performance than traditional sensing. Considering that the detection performance of different secondary users which are sensing different channels are not equal, some slots will be beneficial to this CR system (contributor) while others decrease the system performance (destroyer). A selective coordinator is proposed to improve the performance of mini-slot sensing by accepting the contributors and rejecting the destroyers for final decisions. Based on analysis above, an optimization problem of slots assignment is formulated and Greedy based two stage assignment is proposed as a sub-optimal solution.

The rest of this paper is organized as follows: the system model is presented in Section II. The mini-slot sensing with selective coordinator is discussed in Section III. In Section IV, the simulation results are shown and Section V is the conclusion of this paper.

II. SYSTEM MODEL

In this Paper, we consider a centralized CR system with N secondary users and M channels to be sensed. Usually N and M are fixed values in a system and $N > M$. There is a fusion center with a coverage of all secondary users and channels to make final decision for this system. A frame of system consists two part: sensing duration and transmission duration. A secondary user can use sensing duration to sense channels and use transmission duration for communication if one channel is accessible. One sensing duration is proposed to be equally divided to K slots and each slot can be used to sense one channel. $K = 1$ means system uses full sensing duration to sense one channel (traditional sensing) and $K > 1$ represents the proposed mini-slot sensing. Fig 1 shows an example for the mini-slot sensing, where the index in each slot refers to the channel to be sensed.

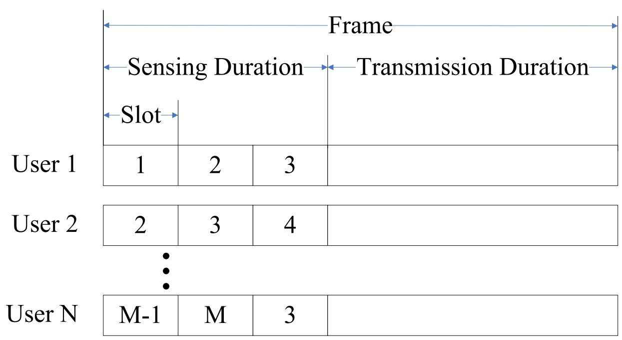

Fig. 1. Mini-Slot Sensing (K=3)

Denote $F(K) = [f_{n,k,m}]_{N*K*M}$ as the mini-slot assignment matrix. $f_{n,k,m} = 1$ means that secondary user n uses slot k to sense channel m and $f_{n,k,m} = 0$ means otherwise. For channel m, If $f_{n,k,m} = 1$, the binary hypothesis can be as follow

$$H_{m,0} : y_{n,k,m}(i) = w_m(i) \qquad i = 1, 2, \cdots, u\tau \tag{1}$$

$$H_{m,1} : y_{n,k,m}(i) = h_{n,m} s_m(i) + w_m(i) \qquad i = 1, 2, \cdots, u\tau \tag{2}$$

where $H_{m,0}$ and $H_{m,1}$ mean that the primary user in channel m is idle and busy respectively, i is the sample index, $y_{n,k,m}(\bullet)$ is the sampling data from channel m at slot k of secondary user n, $w_m(\bullet)$ is background noise with mean being $u_{noise} = 0$ and variance being $\sigma^2_{noise} = 1$. $s_m(\bullet)$ is the primary signal on channel m, and assumed to be complex PSK modulated with $u_p = 0$ mean and σ^2_m variance [5]. The received signal-to-noise ratio of the primary user (SNR_P) in channel m could be $\gamma_m = \sigma^2_m / \sigma^2_{noise}$ under the hypothesis $H_{m,1}$, and in this system SNR_P on all channels are assumed to be equal. u is the sampling rate, τ is the slot duration, $u\tau$ is the samples number ($u\tau$ is assumed to be an integer for notation simplicity), and sensing duration is T_s= Kτ. $H = [h_{n,m}]_{N*M}$ is the channel coefficient matrix, where $h_{n,m}$ is the channel coefficient the channel m from the primary user's transmitter to the secondary user n's receiver and is constant in one sensing duration. Since the ability of one secondary user sensing different channels are not equal, channel coefficients $h_{n,m}$ are different for all m and n.

The *test statistic* of signal energy in one slot sensing duration could be calculated as

$$T_{n,k,m}(y) = \frac{f_{n,k,m}}{u\tau} \sum_{i=1}^{u\tau} \left| y_{n,k,m}(i) \right|^2 \tag{3}$$

The secondary users send the test statistic of all slots to the coordinator, which uses soft decision rule to fuse all the data and make final decisions for all channels. The *overall test statistic* for channel m could be calculated as

$$T_{m,all} = \frac{\sum\limits_{n=1}^{N} \sum\limits_{k=1}^{K} T_{n,k,m}(y)}{\sum\limits_{n=1}^{N} \sum\limits_{k=1}^{K} f_{n,k,m}} \tag{4}$$

The overall test statistic is compared with a threshold ε_m for the final decisions. The primary user on channel m is estimated to be idle if $T_{m,all} \leq \varepsilon_m$, or busy otherwise. The detection probability and false alarm probability in this process are given as

$$P_{m,d} = \Pr(T_{m,all} > \varepsilon_m | H_{m,1}) = \tag{5}$$

$$Q\left(\sqrt{\frac{u\tau}{\sum\limits_{n=1}^{N} \sum\limits_{k}^{K} \left(\left(2h^2_{n,m}\gamma_m + 1 \right) f_{n,k,m} \right)}} \sum_{n=1}^{N} \sum_{k=1}^{K} \left(\left(\varepsilon_m - h^2_{n,m}\gamma_m - 1 \right) f_{n,k,m} \right) \right)$$

$$P_{m,fa} = \Pr(T_{m,all} > \varepsilon_m | H_{m,0}) = \tag{6}$$

$$Q\left((\varepsilon_m - 1) \sqrt{u\tau \sum_{n=1}^{N} \sum_{k=1}^{K} f_{n,k,m}} \right)$$

Where $Q(\bullet)$ is the Q function , defined as

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} \exp(-\frac{z^2}{2}) dz \tag{7}$$

There are two cases in which secondary users could access licensed channels. In first case, primary user exists on the channel but is not detected by the system. In this case, the average transmission rate of a secondary user on channel m is

$$R_{m,1} = \log_2 \left(1 + \frac{SNR_S}{SNR_P + 1} \right) \tag{8}$$

The throughput of CR system under $H_{m,1}$ could be

$$C_1(K, F(K)) = \left(1 - \frac{T_s}{T} \right) \sum_{m=1}^{M} \left(R_{m,1} P(H_{m,1}) (1 - P_{m,d}) \right) \tag{9}$$

Where SNR_S is the SNR of a secondary user on channel m, T is the frame duration, $P(H_{m,1})$ is the busy probability of channel m.

In second case, no primary user exists in channel m but CR system makes a false alarm. In this case, the average transmission rate on channel m is

$$R_{m,0} = \log_2(1 + SNR_S) \tag{10}$$

The throughput of CR system under $H_{m,0}$ could be

$$C_0(K, F(K)) = \left(1 - \frac{T_s}{T} \right) \sum_{m=1}^{M} \left(R_{m,0} P(H_{m,0}) \left(1 - P_{m,fa} \right) \right) \tag{11}$$

Here $P(H_{m,0})$ is the idle probability of channel m.

In CR system, there are $R_{m,0} \gg R_{m,1}$ and $P(H_{m,0}) > P(H_{m,1})$, so $C_0(K, F(K)) \gg C_1(K, F(K))$. The system throughput could be calculated

$$\begin{aligned} C(K, F(K)) &= C_0(K, F(K)) + C_1(K, F(K)) \\ &\approx \left(1 - \tfrac{T_s}{T}\right) \sum_{m=1}^{M} \left(R_{m,0} P(H_{m,0}) \left(1 - P_{m,fa}\right)\right) \end{aligned} \tag{12}$$

Let $R_{m,0} = 1$ and idle probability on all channels are equal, the system throughput could be simplified

$$C(K, F(K)) = \left(1 - \frac{T_s}{T}\right) P(H_{m,0}) \left(M - \sum_{m=1}^{M} P_{m,fa}\right) \tag{13}$$

Denote $P_{th} > 0.5$ as the threshold of detection for all channels and set $P_{m,d} = P_{th}$.

III. MINI-SLOT SENSING WITH SELECTIVE COORDINATOR

A. Mini-Slot Sensing

For both traditional sensing and mini-slot sensing, there are some restrictions: 1. All slots must be fully used; 2. Each slot can only be used by secondary user to sense one channel in a frame duration; 3. All channel must be sensed. So there are

$$\sum_{m=1}^{M} f_{n,k,m} = 1 \qquad n = 1, 2, \cdots, N \quad k = 1, 2, \cdots, K \tag{14}$$

$$\sum_{n=1}^{N} \sum_{k=1}^{K} f_{n,k,m} \geqslant 1 \qquad m = 1, 2, \cdots, M \tag{15}$$

In traditional sensing (K=1), for the limitation of the numeric region of assignment matrix, there must exist at least one optimal assignment matrix $F^o(1)$ that makes

$$\max\left[C(1, F(1))\right] = C(1, F^o(1)) \tag{16}$$

Here we can prove that mini-slot sensing has a better performance than traditional sensing

$$\max\left[C(K, F(K))\right] \geqslant \max\left[C(1, F(1))\right] \qquad K > 1 \tag{17}$$

Lemma 1: For all positive integer K and L, there is

$$\max\left[C(LK, F(LK))\right] \geqslant \max\left[C(K, F(K))\right] \tag{18}$$

Proof of Lemma 1:

Let $U(K, F(K)) = \sum_{m=1}^{M} P_{m,fa}$, for any specific integer K, there is

$$\begin{aligned} \max\left[C(K, F(K))\right] &= \left(1 - \frac{T_s}{T}\right) P(H_{m,0}) \left(M - \min\left(\sum_{m=1}^{M} P_{m,fa}\right)\right) \\ &= \left(1 - \tfrac{T_s}{T}\right) P(H_{m,0}) \left(M - U(K, F^o(K))\right) \end{aligned} \tag{19}$$

Here $F^o(K) = \left[f^o_{n,k,m}\right]_{N*K*M}$ is the optimal assignment matrix under specific K.

In the case of LK, define the corresponding assignment matrix $G(LK) = \left[g_{n,p,m}\right]_{N*LK*M}$, we can find a specific assignment matrix $G^*(LK) = \left[g^*_{n,p,m}\right]_{N*LK*M}$ with

$$g^*_{n,p,m} = f^o_{n,\lceil \frac{p}{L} \rceil,m} \qquad p = 1, 2, \cdots LK \tag{20}$$

Here $\lceil \bullet \rceil$ is the round up function and we can have

$$U(LK, G^*(LK)) = U(K, F^o(K)) \tag{21}$$

and

$$\begin{aligned} \max\left[C(K, F(K))\right] &= C(LK, G^*(LK)) \\ &\leqslant \max\left[C(LK, F(LK))\right] \end{aligned} \tag{22}$$

This completes the proof.

With the increase of K, system throughput has a trend to increase.

More slots could benefit this CR system, but the improvement of system throughput has a limitation

$$\begin{aligned} \lim_{K \to \infty} C(K, F(K)) &= \left(1 - \frac{T_s}{T}\right) P(H_{m,0}) \left(M - \lim_{K \to \infty} \sum_{m=1}^{M} P_{m,fa}\right) \\ &< \left(1 - \frac{T_s}{T}\right) P(H_{m,0}) M \end{aligned} \tag{23}$$

While improvement of system throughput has a limitation, the the complexity of system will increase as K increases. So there is a tradeoff between system throughput and complexity. In this paper, the problem of finding the optimal K is not discussed. In the following section IV, we will use a simple criteria to pick a proper K.

B. A Selective Coordinator

Although mini-slot sensing improves the system performance, but it may not achieve the optimal performance. Following is the proof.

Suppose channel m only be sensed by one slot with a channel coefficient $h_1 > 0$, and by equation (5) and (6), the false alarm probability of channel m under $P_{m,d} = P_{th}$ could be calculated

$$P^1_{m,fa} = Q\left(Q^{-1}(P_{th}) \sqrt{2|h_1|^2 \gamma_m + 1} + |h_1|^2 \gamma_m \sqrt{u\tau}\right) \tag{24}$$

Now anther slot with channel coefficient $h_2 \geqslant 0$ is assigned to sense channel m, and the corresponding false alarm probability of channel m could be

$$P^2_{m,fa} = Q\left(Q^{-1}(P_{th}) \sqrt{\left(|h_1|^2 + |h_2|^2\right)\gamma_m + 1} + \left(|h_1|^2 + |h_2|^2\right)\gamma_m \sqrt{\frac{u\tau}{2}}\right) \tag{25}$$

Suppose

$$Y(h_2) = Q^{-1}(P_{th}) \sqrt{\left(h_1^2 + h_2^2\right)\gamma_m + 1} + \left(h_1^2 + h_2^2\right)\gamma_m \sqrt{\frac{u\tau}{2}} \tag{26}$$

and

$$\frac{dY(h_2)}{dh_2} = h_2 \gamma_m \sqrt{2u\tau} + \frac{h_2 \gamma_m Q^{-1}(P_{th})}{\sqrt{\left(h_1^2 + h_2^2\right)\gamma_m + 1}} \tag{27}$$

The solution to $\frac{dY(h_2)}{dh_2} > 0$ is

$$h_2^2 > \frac{\left[Q^{-1}\left(P_{th}\right)\right]^2 - 2u\tau}{2u\tau\gamma_m} - h_1^2 \tag{28}$$

There are two cases, in the first case

$$\frac{\left[Q^{-1}\left(P_{th}\right)\right]^2 - 2u\tau}{2u\tau\gamma_m} - h_1^2 \leqslant 0 \tag{29}$$

Then $Y(h_2)$ is an increasing function within $h_2 \geqslant 0$.

In the second case

$$\frac{\left[Q^{-1}\left(P_{th}\right)\right]^2 - 2u\tau}{2u\tau\gamma_m} - h_1^2 > 0 \tag{30}$$

Then $Y(h_2)$ is an decreasing function within $0 \leqslant h_2 < \sqrt{\frac{\left[Q^{-1}(P_{th})\right]^2 - 2u\tau}{2u\tau\gamma_m} - h_1^2}$ or an increasing function within $h_2 \geqslant \sqrt{\frac{\left[Q^{-1}(P_{th})\right]^2 - 2u\tau}{2u\tau\gamma_m} - h_1^2}$.

We can also find that if $h_2 = h_1$, then

$$Y(h_2) > Q^{-1}\left(P_{th}\right)\sqrt{2h_1^2\gamma_m + 1} + h_1^2\gamma_m\sqrt{u\tau} \tag{31}$$

or if $h_2 = 0$, then

$$Y(h_2) < Q^{-1}\left(P_{th}\right)\sqrt{2h_1^2\gamma_m + 1} + h_1^2\gamma_m\sqrt{u\tau} \tag{32}$$

So there must exist h^o to make

$$Y(h^o) = Q^{-1}\left(P_{th}\right)\sqrt{2h_1^2\gamma_m + 1} + h_1^2\gamma_m\sqrt{u\tau} \tag{33}$$

When $h_2 \geqslant h^o$, there is $P_{fa}^1 \geqslant P_{fa}^2$, which means adding a slot improves the sensing performance. When $0 \leqslant h_2 < h^o$, there is $P_{fa}^1 < P_{fa}^2$, which means adding a slot decrease the sensing performance.

The statement above can be applied in this CR system, where there is $NK > M$ and some channels would be sensed by more than one slot. Since the channel coefficients between all secondary users and channels are not equal, some low channel coefficients slots may decrease the system performance. Based on this idea, a selective coordinator is proposed in mini-slot sensing. Unlike traditional coordinator, which accept data from all slots, the selective coordinator will divide all slots into two group: contributor and destroyer. some slots with high channel coefficient are viewed as contributors and accepted while others with low channel coefficient are viewed as destroyers and rejected. In this way, the performance of mini-slot sensing would be improved, although some slots may not be used because they are viewed as destroyers to all channels.

C. Greedy Based Two-Stage Assignment

Based on the analysis above, a mini-slot sensing with selective coordinator is applied to the CR system, and an optimization problem is formulated as follows

$$\max_{F(K)} C\left(K, F(K)\right) = \left(1 - \frac{T_s}{T}\right) P\left(H_{m,0}\right)\left(M - \sum_{m=1}^{M} P_{m,fa}\right) \qquad P1$$

$$s.t. \qquad P_{m,d} = P_{th}$$

$$\sum_{m=1}^{M} f_{n,k,m} \leqslant 1 \quad n = 1, 2, \cdots, N \quad k = 1, 2, \cdots, K$$

$$\sum_{n=1}^{N}\sum_{k=1}^{K} f_{n,k,m} \geqslant 1 \quad m = 1, 2, \cdots, M$$

$$K = K^o$$

Here K^o is a proper value considering system throughput and complexity. We have to find the optimal assignment matrix as the solution to problem P1. Since the numeric range of $F(K)$ is limited, optimal solution could be found though searching. But it is not practical for its high complexity. A Greedy based two-stage assignment is proposed as a sub-optimal solution to problem P1.

The Greedy based two-stage assignment has two stages: 1. Assign every channel with one slot ($\sum_{n=1}^{N}\sum_{k=1}^{K} f_{n,k,m} \geqslant 1$); 2. Selective coordinator assign the rest slots to channels with Greedy algorithm. Following is the detailed description.

STAGE 1

Step 1: There are NK slots and we define $X = \left[x_{p,m}\right]_{NK*M}$, in which $x_{p,m}$ is the system throughput after slot p is assign to channel m. If no slots are assigned to channel m, then set $P_{m,fa} = 1$. At first, no slots are assigned to any channels.

Step 2: Use every slot to test every channel and get $X = \left[x_{p,m}\right]_{NK*M}$. Find the max $x_{p,m}$, assign the corresponding slot p to channel m, then slot p quits the following assignment and channel m quit stage 1. If more than one slot achieve the max $x_{p,m}$, only assign one slot.

Step 3: Go to step 2 until every channel is assigned with one slot. Then go to step 4.

STAGE 2

Step 4: Use the rest slots to test all channels and get $X = \left[x_{p,m}\right]_{NK*M}$. Selective coordinator check if any $x_{p,m}$ is smaller than the former system throughput value, then set $x_{p,m} = 0$, which means slot p is a destroyer to channel m and is rejected . Find the max $x_{p,m}$, assign the corresponding slot p to channel m, then slot p quits the following assignment. If more than one slot achieve the max $x_{p,m}$, only assign one slot.

Step 5: Go to step 4 until all slots are used or the rest slots are destroyers to all channels. Then go to the end.

THE END

Using this assignment, the sub-optimal solution could be found.

IV. SIMULATION RESULTS

In this section, numerical results are presented to evaluate the mini-slot sensing with selective coordinator. The system set up is as follows: one frame duration is $T = 100ms$; sensing duration is $T_s = 5ms$; the sampling rate is $u = 6MHz$; SNR_P is $\gamma_m = -15dB$ for all channels; the threshold of detection probability is $P_{th} = 0.9$; idle probability of every channel is $P(H_{m,0}) = 0.9$; channel coefficient $h_{n,m}$ is a random value within $0 < h_{n,m} < 1$ for all n and m; Greedy based two-stage assignment is used to assign slots to channels.

A. Analysis

In this part, There are $N = 15$ secondary users and $M = 10$ channels. Greedy algorithm is used in mini-slot sensing. Fig 2 shows that system throughput has a trend to improve but reaches a limitation as slot number K increases. some points in Fig 2 are not perfectly reflect Lemma 1, because the slots assignments don't provide the optimal solutions. It proves that mini-slot sensing ($K > 1$) achieves higher throughput than traditional sensing ($K = 1$) and selective coordinator improve the performance of mini-slot sensing. Fig 3 shows that system complexity increases sharply as slot number K increases. So there is a tradeoff between system throughput and complexity. We choose $K = 3$ as a proper value for the following simulation because the improvement is significant when $K \leqslant 3$ and the complexity is small.

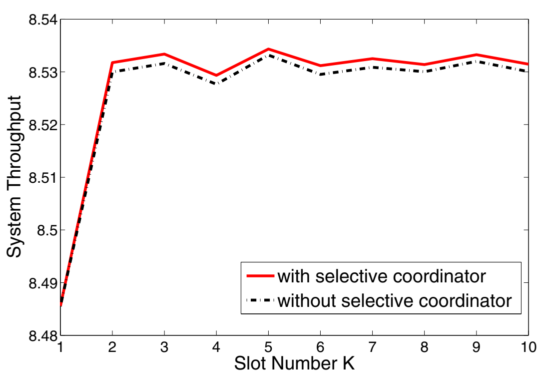

Fig. 2. System Throughput vs. Slot Number K

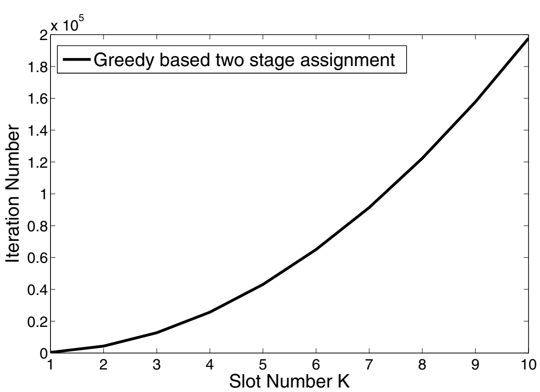

Fig. 3. Iteration Number vs. Slot Number K

B. Comparison

In this part, we choose $K = 3$ as a proper value. There are $N = 15$ sensing users in CR system. Fig 4 shows that mini-slot sensing with selective coordinator achieves better performance than traditional sensing. This advantage is very small when $M = 8$, but becomes bigger when channel number M increases. It indicates that our proposed method is more applicable for CR system with small N/M value.

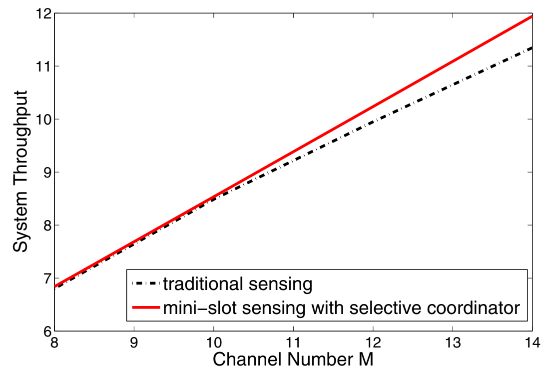

Fig. 4. System Throughput vs. Channel Number M

V. CONCLUSION

In this paper, a mini-slot sensing with selective coordinator is proposed. Mini-slot sensing is proved to have a better performance than traditional sensing in system throughput. Considering the ability of different secondary users sensing different channels are not equal, a selective coordinator is proposed to improve the performance of mini-slot sensing by accepting slots which benefit the system performance and rejecting those decreasing the system performance. A Greedy based two stage assignment is proposed to solve the optimization problem of slots assignment. Simulation demonstrates our proposed method has a better performance.

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