Channel Selection for Secondary Users in Decentralized Network of Unknown Size

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***Abstract*— In this letter, the challenge of optimal channel selection among the non-cooperative and unknown number of secondary (i.e., unlicensed) users (SUs) in the decentralized network is addressed. The proposed scheme consists of two phases: estimation and ranking (ER) phase and high throughput (HT) phase. In the ER phase, each SU chooses the channel randomly. Based on the sensing and collision outcomes, the proposed mathematical expression allows the SUs to independently estimate the channel ranking and the number of active SUs, U. In the HT phase, the SUs follow collision-free hopping to exploit top U channels. An upper bound on the time required for the SU orthogonalization in the HT phase, loss in throughput, and number of channel switchings are derived. Theoretical analysis and simulation results validate the superiority of the proposed scheme over existing state-of-the-art schemes.**

***Index Terms*— Decentralized network, dynamic spectrum access, multi-armed bandit.**

I. Introduction

AMONG various envisioned paradigms such as device-to-device communications and LTE-unlicensed networks, dynamic spectrum access (DSA) in the licensed spectrum seems to be a promising solution to improve the spectrum utilization [1]. DARPA's spectrum collaboration challenge 2016 was a significant step to bring the DSA to life [2]. For an efficient DSA in the decentralized network of unknown size and non-cooperative users, secondary users (SUs) need to: 1) Estimate the number of SUs, U, 2) Exploit top U channels, and 3) Minimize the number of collisions among SUs. Various schemes have been proposed to address these challenges. Please refer to [3]–[9] for more details.

The ρ^{rand} scheme [3] employs multi-armed bandit (MAB) algorithm to identify optimal channels and random rank selection approach for orthogonalization of the SUs. The scheme in [4] uses ρ^{rand} with advanced MAB algorithm to improve the throughput. References [5] and [6] employ MAB algorithm for channel selection as well as rank selection. The scheme in [7] proposes orthogonal channel allocation in each time slot at the cost of communications among SUs. Though the schemes in [3]–[7] offer higher throughput and fewer collisions than random channel selection scheme, they may not be suitable for battery operated SUs in the decentralized networks due to the need of prior knowledge of U and computationally intensive MAB algorithms. Furthermore, their performance degrades significantly as U increases through empirical observations.

The DSA scheme in [8] overcomes the drawbacks using the two-stage channel access scheme with common hopping sequence. However, its throughput is lower than [3]–[7] since SUs hop through channels with equal probability which results in the higher number of channel switchings. The multi-user $\epsilon-$greedy collision avoiding (MEGA) scheme in [9] and musical chair (MC) scheme in [10] are the only state-of-the-art schemes that do not need the knowledge of U. The drawbacks of [9] are that its average throughput is lower than the schemes in [3]–[6] and high computational complexity. Furthermore, [9] and [10] are designed for the DSA in the unlicensed spectrum where primary users (PUs) are absent while the focus of this paper is on the DSA in the licensed spectrum.

The proposed scheme presented in this paper allows each SU to independently estimate the channel ranking and number of SUs, U, without any co-operation among SUs. This is achieved by following the random channel selection approach for a fixed duration in the beginning of the horizon and utilizing the information of the number of SU collisions to estimate U. Then, the SUs follow collision-free hopping to exploit top U channels for the rest of horizon. A mathematical expression for estimation of U along with respective upper bounds on the time required for the SU orthogonalization in the top U channels after U estimation, the loss in throughput and the number of channel switching are derived. Theoretical analysis and simulation results validate the superiority of the proposed scheme over existing state-of-the-art schemes.

II. Proposed Work

In this section, the design details of the proposed scheme are presented. To begin with, the network model is discussed.

A. Network Model

Consider the decentralized network consisting of U non-cooperative SUs competing for $N(\geq U)$ uniform bandwidth channels in the licensed spectrum. We assume time slotted communication where the horizon is divided into T time slots, i.e., $t \in \{1, 2, .., T\}$ and SUs are aware when new horizon begins. Each slot is divided into two sub-slots. In the first sub-slot, the SU senses the channel for active PUs. In the second sub-slot, the SU transmits if channel is vacant, otherwise remains idle. When two or more SUs transmit on the same vacant channel, collision occurs. In case of no collision, data transmission is assumed to be successful. The channel statistics i.e. the probability of the i^{th}channel being vacant is governed by mean $\mu_i \in$ [0,1]. The channel statistics are stationary and unknown to SUs. For the ease of analysis, we assume $\mu_1 > \mu_2 > .. > \mu_N$. The aim of the DSA is to

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improve the throughput, S_T, and hence, minimize the loss, U_T, given by,

$$U_T = T\sum_{i=1}^{U}\mu_i - S_T = T\sum_{i=1}^{U}\mu_i - \sum_{u=1}^{U}\sum_{i=1}^{N} Y_{u,i} \quad (1)$$

where $Y_{u,i}$ is the number of times the u^{th} SU is the sole user of the vacant channel i. In addition, the DSA scheme should incur fewer number of channel switchings and guarantee fair channel allocation among SUs.

B. Estimation and Ranking (ER) Phase

In the proposed scheme, the horizon, T, is divided into two phases: 1) ER phase ($t \leq T_{ER}$), and 2) High Throughput (HT) phase ($T_{ER} < t \leq T$). The objective of the ER phase is to estimate $\hat{U}$ and channel ranking and is given in Algorithm 1. In ER phase, each SU chooses the channel randomly and based on the sensing and collision outcomes, the parameters are updated as shown in Algorithm 1. These parameters are: 1) $X_{u,i}$: Number of times the channel i is sensed vacant by the u^{th} SU, 2) $T_{u,i}$: Number of times the channel i is chosen by the u^{th} SU, 3) C_u: Number of collisions faced by the u^{th} SU and 4) $Y_{u,i}$. The duration of ER phase is T_{ER} during which every SU must sense each channel at least O_{min} number of times to guarantee ϵ-correct channel ranking ($\forall\epsilon > 0$) with probability 1 - δ ($0 < \delta < 1$). The ϵ-correct channel ranking means the absolute difference between ideal and estimated channel statistics is less than $\epsilon/2\ \forall i$. For O_{min}, we borrow the results in [10] obtained using Hoeffding's Inequality and given by,

$$O_{min} > \frac{2}{\epsilon^2}\cdot\ln\left(\frac{2\cdot N\cdot U}{\delta}\right) \quad (2)$$

Since each SU senses single channel in each time slot, the minimum number of time slots required to obtain O_{min} observations of all the channels i.e. T_{ER} is given by

$$T_{ER} \geq \frac{2\cdot N}{\epsilon^2}\cdot\ln\left(\frac{2\cdot N\cdot U}{\delta}\right) \quad (3)$$

Since U is unknown and $U \leq N$, substituting $U = N$ in Eq. (3), we get

$$T_{ER} \geq \frac{2\cdot N}{\epsilon^2}\cdot\ln\left(\frac{2\cdot N^2}{\delta}\right) \quad (4)$$

At the end of the ER phase ($t = T_{ER}$), the estimated channel statistics, $\hat{\mu}_i$ are calculated as shown in Step 16 which are then used to rank the channels as shown in Step 17. Next, each SU estimates the number of active SUs in the network, $\hat{U}$, using the expression derived in the next Section II-C.

C. Estimation of Number of SUs, U

The proposed scheme utilizes the number of collisions experienced by SUs to estimate $\hat{U}$. The probability of collision in each time slot of the ER phase is given by

$$P(C_u) = 1 - \overline{P(C_u)} = \frac{C_u}{T_{ER}} \quad (5)$$

The probability that the u^{th} SU may not experience the collision over the channel i is given by

$$\overline{P(C_u^i)} = P(A_u^i)\cdot P(B_u^i)\cdot[P(D^i) + P(E^i)] + P(F_u^i) \quad (6)$$

where

1) $P(A_u^i)$ denotes the probability that the u^{th} SU selects the channel i and it is equal to $\left(\frac{1}{N}\right)$.

Algorithm 1 Proposed Scheme for u^{th} SU: ER Phase

1: **Input** T_{ER}, T, N
2: **Output** $Z, \hat{U}$
3: **Init.** $C_u = 0, X_{u,i} = 0, T_{u,i} = 0, Y_{u,i} = 0 \forall i \in \{1, .., N\}$
4: **while** ($t \leq T_{ER}$) **do**
5: Randomly choose channel, $N_u = i \sim U(1, ..., N)$
6: Increment T_{u,N_u} by 1
7: **if** (N_u is vacant) **then**
8: Increment X_{u,N_u} by 1 and transmit over N_u
9: **if** (collision) **then**
10: Increment C_u by 1
11: **else**
12: Increment Y_{u,N_u} by 1
13: **end if**
14: **end if**
15: **end while**
16: $\forall i \in 1, .., N$, Estimate the channel statistics, $\hat{\mu}_i = \frac{X_{u,i}}{T_{u,i}}$
17: Sort indices in $[N]$, according to $\hat{\mu}_i$, in an array, Z.
18: Estimate the number of SUs, $\hat{U}$ using the Eq. (16) (Section II-C).

2) $P(B_u^i)$ denotes that the selected channel i is sensed as vacant by the u^{th} SU and it is equal to $\left(\hat{\mu}_i\right)$.
3) $P(D^i)$ denotes the probability that no other SU selects the channel i and it is given by

$$P(D^i) = \left(1 - \frac{1}{N}\right)^{\hat{U}-1} \quad (7)$$

4) $P(E^i)$ denotes the probability that at least one other SU selects the channel i and sense it occupied. It consists of two possibilities i.e. either all SUs select channel i and sense it occupied or some SUs select the channel i and sense it occupied while other SUs do not select the channel i. It is given by

$$P(E^i) = \left(\frac{1-\hat{\mu}_i}{N}\right)^{\hat{U}-1} + (\hat{U}-1)\sum_{\substack{i=1\\ \hat{U}\geq 2}}^{\hat{U}-2}\left\{\left(\frac{1-\hat{\mu}_i}{N}\right)^{i}\cdot\left(1-\frac{1}{N}\right)^{(\hat{U}-1-i)}\right\} \quad (8)$$

For example, when $U = 2$, $P(E^i)$ indicates that other SU selects the channel i and sense it occupied. It is given by

$$P(E^i)_{U=2} = \left(\frac{1-\hat{\mu}_i}{N}\right) \quad (9)$$

Similarly, when $U = 3$, $P(E^i)$ indicates that either both SUs select the channel i and sense it occupied or one of the SU selects the channel i and sense it occupied while other SUs select different channel and vice-versa. It is given by

$$P(E^i)_{U=3} = \left(\frac{1-\hat{\mu}_i}{N}\right)^2 + 2\cdot\left[\left(\frac{1-\hat{\mu}_i}{N}\right)\cdot\left(1-\frac{1}{N}\right)\right] \quad (10)$$

5) $P(F_u^i)$ denotes the probability that the u^{th} SU selects the channel i and sense it occupied. It is given by

$$P(F^i) = \frac{1}{N}(1-\hat{\mu}_i) \quad (11)$$

Then, modified Eq. (6) is given by

$$\overline{P(C_u^i)} = \frac{\hat{\mu}_i}{N} \cdot \Bigg[\left(1 - \frac{1}{N}\right)^{\hat{U}-1} + \left(\frac{1-\hat{\mu}_i}{N}\right)^{\hat{U}-1} + (\hat{U}-1)\sum_{\substack{i=1\\ \hat{U}\geq 2}}^{\hat{U}-2}\left\{\left(\frac{1-\hat{\mu}_i}{N}\right)^{i} \cdot \left(1-\frac{1}{N}\right)^{(\hat{U}-1-i)}\right\}\Bigg] + \frac{1}{N}(1-\hat{\mu}_i) \quad (12)$$

The probability that the u^{th} SU may not experience the collision over all channels is given by

$$\overline{P(C_u)} = \sum_{i=1}^{N} \overline{P(C_u^i)} \quad (13)$$

After substituting Eq. (13) into Eq. (12) followed by algebraic simplifications, we get

$$\overline{P(C_u)} = \sum_{i=1}^{N} \frac{1}{N} \cdot \hat{\mu}_i \left\{\left(1-\frac{1}{N}\right) + \left(\frac{1-\hat{\mu}_i}{N}\right)\right\}^{(\hat{U}-1)} + \frac{1}{N}\sum_{i=1}^{N}(1-\hat{\mu}_i)$$

i.e.

$$\overline{P(C_u)} = \sum_{i=1}^{N} \frac{\hat{\mu}_i}{N}\left\{1 - \frac{\hat{\mu}_i}{N}\right\}^{(\hat{U}-1)} + \frac{1}{N} \cdot \sum_{i=1}^{N}(1-\hat{\mu}_i) \quad (14)$$

Substituting Eq. (14) into Eq. (5), we get

$$P(C_u) = \frac{C_u}{T_{ER}} = 1 - \sum_{i=1}^{N}\frac{\hat{\mu}_i}{N}\left\{1-\frac{\hat{\mu}_i}{N}\right\}^{(\hat{U}-1)} + \frac{1}{N}\cdot\sum_{i=1}^{N}(1-\hat{\mu}_i) \quad (15)$$

After further simplifications, the generalized expression for the probability of collision is given by

$$P(C_u) = \frac{C_u}{T_{ER}} = \sum_{i=1}^{N}\frac{\hat{\mu}_i}{N} - \sum_{i=1}^{N}\frac{\hat{\mu}_i}{N}\left\{1 - \frac{\hat{\mu}_i}{N}\right\}^{\hat{U}-1} \quad (16)$$

When the channel sensing is assumed to be error-free, i.e., the status of channel is observed same by all SUs, the $P(C_u)$ can be simplified further and given by

$$P(C_u) = \frac{C_u}{T_{ER}} = \sum_{i=1}^{N}\frac{\hat{\mu}_i}{N}\left\{1 - \left(1 - \frac{1}{N}\right)^{\hat{U}-1}\right\} \quad (17)$$

By solving Eq. (16) or Eq. (17), each SU can independently estimate the number of SUs, $\hat{U}$, since other parameters are known to each SU at the end of the ER phase.

Algorithm 2 Proposed Scheme for u^{th} SU: HT Phase

Input $T, T_{ER}, Z, \hat{U}$
Init. $\eta_u = 0$
while ($T_{ER} < t \leq T$) **do**
  if $\eta_u == 0$ **then**
    Randomly choose any of the top $\hat{u}$ channel, $N_u = i \sim U(Z[1], .., Z[\hat{U}])$
  else
    Choose channel, N_u, using Eq. (18).
  end if
  if (N_u is vacant) **then**
    Transmit over the channel N_u
    if (No collision) **then**
      Increment Y_{u,N_u} by 1 and set $\eta_u = 1$
    end if
  end if
end while

D. High Throughput (HT) Phase

After estimating $\hat{U}$ and channel ranking, next task is to orthogonalize SUs into top $\hat{U}$ channels to guarantee no loss in throughput. In HT phase, given in Algorithm 2, the SU chooses any one of the top $\hat{U}$ channel randomly. If the channel is vacant, SU transmits over it. If collision occurs, SU remains idle and follow same process in the next time slot. Otherwise, the SU is said to have identified its orthogonal channel, i.e. $\eta_u = 1$. The SU with $\eta_u = 1$ chooses a channel in the subsequent time slots using the proposed block hopping scheme given by,

$$N_u = \begin{cases} (N_u + 1) \mod \hat{U} & t = \left\lfloor \dfrac{(T - T_{ER} - T_{OR})}{\hat{U}} \right\rfloor \\ N_u & \text{Otherwise} \end{cases} \quad (18)$$

where T_{OR} is the time required for orthogonalization of SUs. To obtain T_{OR}, consider $P(OR_u)$ be the probability that u^{th} SU orthogonalizes into one of the top $\hat{U}$ channel. Then,

$$P(OR_u) \geq \sum_{i=1}^{\hat{U}} \frac{\hat{\mu}_i}{\hat{U}} \cdot \left\{1 - \frac{\hat{\mu}_i}{\hat{U}}\right\}^{\hat{U}-1} \quad (19)$$

where the first term is the probability that the u^{th} SU chooses channel i and the second term gives the lower bound on the probability that the SUs who have not yet orthogonalized do not choose the channel i. Simplifying Eq. (19) further, we get

$$P(OR_u) \geq \sum_{i=1}^{\hat{U}} \frac{\hat{\mu}_i}{\hat{U} \cdot \exp(\mu_i)} \geq \sum_{i=1}^{\hat{U}} \frac{1}{\hat{U} \cdot \exp(1)} = \frac{1}{\exp(1)} \quad (20)$$

Then, T_{OR} is at most the expected number of times flipping a biased coin with probability $P(OR_u)$, i.e. $T_{OR} \leq \hat{U} \cdot \exp(1)$. The block hopping approach guarantees fairness among the SUs by allowing them an equal access to top $\hat{U}$ channels without compromising on the number of channel switchings which are fixed and equal to U.

E. Upper Bounds

In this section, the upper bounds on the loss of throughput and the number of channel switchings are derived. The throughput loss, U_T, is less than or equal to the sum of losses, U_{ER} and U_{OR}, incurred during ER phase and OR duration ($T_{ER} < t \leq T_{OR}$) of the HT phase, respectively. For $t > T_{OR}$, the loss is zero since all SUs are orthogonalized to the top U channels. Thus, $U_T \leq U_{ER} + U_{OR}$. An upper bound on the U_{ER} is based on the worse case where all SUs choose the same vacant channel leading to the collision. It is given by

$$U_{ER} \leq T_{ER} \cdot \sum_{i=1}^{N}\left(\frac{\mu_i}{N}\right)^{U} \quad (21)$$

The total loss of each player in OR duration is bounded by two times orthogonalization duration since every collision results in loss for at least two colliding SUs. Then, we have

$$U_{OR} \leq \sum_{u=1}^{U} 2 \cdot T_{OR} = \sum_{u=1}^{U} 2 \cdot U \cdot \exp(1) = 2 \cdot U^2 \cdot \exp(1) \quad (22)$$

Similarly, the upper bound on the number of channel switchings, W_T is given by

$$W_T \leq U \cdot (T_{ER} + T_{OR} + U) \quad (23)$$

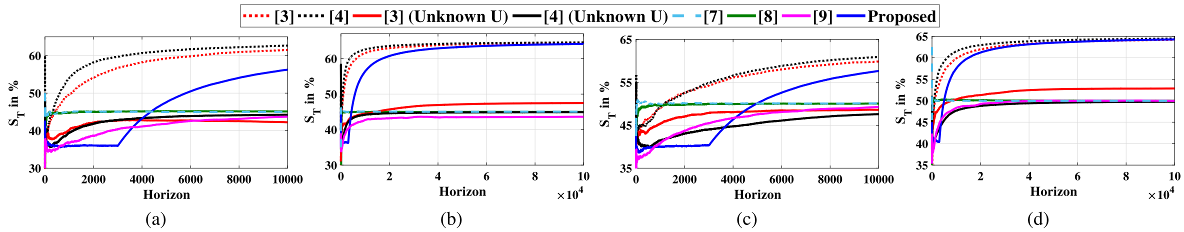

Fig. 1. The number of successful transmissions, S_T in % at different instants of the horizon for 1) Case 1 and $T = 10000$, 2) Case 1 and $T = 100000$, 3) Case 2 and $T = 10000$, and 4) Case 2 and $T = 100000$.

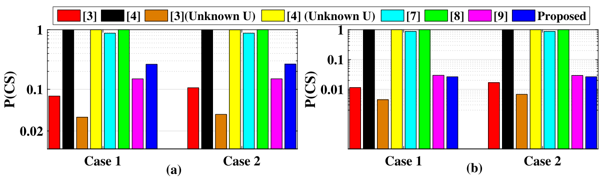

Fig. 2. $P(CS)$ comparison for (a) $T = 10000$, (b) $T = 100000$.

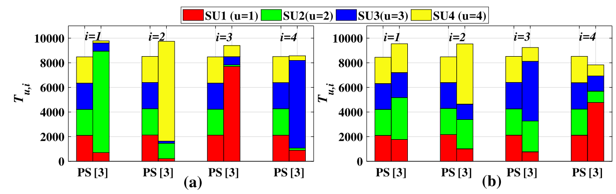

Fig. 3. Channel allocation fairness comparison for (a) Case 1, (b) Case 2.

Using Eq. (4) and Eq. (20), we have

$$W_T \leq U \cdot \left(\left\lceil \frac{2.N}{\epsilon^2} \cdot \ln \left(\frac{2.N^2}{\delta} \right) \right\rceil + U \cdot \exp(1) + U \right) \quad (24)$$

III. Simulation Results and Analysis

In this section, we present simulation results to compare the proposed scheme with the schemes in [3], [4], and [7]–[9] in terms of S_T and $P(CS)$ i.e. the probability of channel switching in each time slot. Each numerical result shown in the analysis is the average of the values obtained over 10 independent experiments and simulations consider a time horizon of 10000 and 100000 iterations. The value of T_{ER} for the proposed scheme is 3000. For illustration, we consider $N = 8$ and $U = 4$ with two different sets of channel statistics, μ.

1) Case 1:- μ:- [0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80]
2) Case 2:- μ:- [0.45 0.25 0.55 0.70 0.30 0.60 0.40 0.75]

For Case 1, the value of S_T in % with respect to genie-aided scheme at different instants of horizon are shown in Fig. 1a and Fig. 1b for $T = 10000$ and $T = 100000$, respectively. We consider two variations of the schemes in [3] and [4], with and without prior knowledge of U. It can be observed that the proposed scheme offers better performance over other schemes with unknown U. Also, for long horizon in Fig. 1b, the performance of the proposed scheme approaches to that of [3] and [4] with known U. Similar trend has been observed for Case 2 as shown in Fig. 1c and Fig. 1d.

Next, we compare the probability of channel switching in each time slot, $P(CS)$. The plots in Fig. 2(a) and (b), for $T = 10000$ and 100000, respectively, indicate that the $P(CS)$ for the proposed scheme is significantly lower in spite of using the random selection in ER phase and hopping in HT phase. Note that the y-axis is shown in the logarithmic scale. Though the schemes in [3] and [9] offers lower $P(CS)$ than the proposed scheme, the difference decreases as T increases and $P(CS)$ is close to 0.01 for $T = 100000$. Also, the schemes in [3] and [9] offer poor performance in terms of S_T. The scheme in [3] does not guarantee fairness in channel allocations as shown in Fig. 3 where we compare the number of times the top channels are accessed by each SU in the proposed scheme (denoted as PS) and [3]. The plots show that the proposed scheme allows all SUs to have an equal access to the top channels while in [3], some SUs get higher priority than others.

IV. Conclusions and Future Works

In this paper, a novel channel selection scheme for secondary users (SUs) in the decentralized network with unknown number of active SUs is proposed. Detailed theoretical analysis and extensive simulation results validate the superiority of the proposed scheme over existing state-of-the-art schemes. Future works include the extension of the proposed scheme for dynamic case where the channel statistics are quasi-stationary.

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