Blind Cognitive MAC Protocols

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Abstract—We consider the design of cognitive Medium Access Control (MAC) protocols enabling an unlicensed (secondary) transmitter-receiver pair to communicate over the idle periods of a set of licensed channels, i.e., the primary network. The objective is to maximize data throughput while maintaining the synchronization between secondary users and avoiding interference with licensed (primary) users. No statistical information about the primary traffic is assumed to be available a-priori to the secondary user. We investigate two distinct sensing scenarios. In the first, the secondary transmitter is capable of sensing all the primary channels, whereas it senses one channel only in the second scenario. In both cases, we propose MAC protocols that essentially learn the primary service traffic on-line. Our simulation results demonstrate that the proposed blind MAC protocols asymptotically achieve the throughput obtained when prior knowledge of primary traffic statistics is available.

I. INTRODUCTION

Most of licensed spectrum resources are under-utilized. This observation has encouraged the emergence of dynamic and opportunistic spectrum access concepts, where unlicensed (secondary) users equipped with cognitive radios are allowed to opportunistically access the spectrum as long as they do not interfere with licensed (primary) users. To achieve this goal, secondary users must monitor the primary traffic in order to identify spectrum holes or opportunities which can be exploited to transfer data [1].

The main goal of a cognitive MAC protocol is to sense the radio spectrum, detect the occupancy state of different primary spectrum channels, and then opportunistically communicate over unused channels (spectrum holes) with minimal interference to the primary users. Specifically, the cognitive MAC protocol should continuously make efficient decisions on which channels to sense and access in order to obtain the most benefit from the available spectrum opportunities. Several cognitive MAC protocols have been proposed in previous studies. For example, in [2], MAC protocols were constructed assuming each secondary user is equipped with two transceivers, a control transceiver tuned to a dedicated control channel and a software defined radio SDR-based transceiver tuned to any available channels to sense, receive, and transmit signals/packets. On the other hand, [3] proposed a sensing-period optimization mechanism and an optimal channel-sequencing algorithm, as well as an environment adaptive channel-usage pattern estimation method.

The slotted Markovian structure for the primary network traffic, adopted here, was also considered in [5] where the optimal policy was characterized and a simple greedy policy for secondary users was constructed. The authors of [5], however, assumed that the primary traffic statistics (i.e., Markov chain transition probabilities) were available a-priori to the secondary users. Here, our focus is on the blind scenario where the cognitive MAC protocol must learn the transition probabilities on-line.

In this work, we differentiate between two scenarios. The first assumes that the secondary transmitter can sense all the available primary channels before making the decision on which one to access. The secondary receiver, however, does not participate in the sensing process and can wait to decode on only one channel. This is the model adopted in [4]. In the sequel, we propose an efficient algorithm that optimizes the on-line learning capabilities of the secondary transmitter and ensures perfect synchronization between the secondary pair. The proposed protocol does not assume a separate control channel, and hence, piggybacks the synchronization information on the same data packet. Our numerical results demonstrate the superiority of the proposed protocol over the one in [4] where the primary transmitter and receiver are assumed to access the channel in a predetermined sequence, which they agreed upon a-priori.

The second scenario assumes that both the secondary transmitter and receiver can sense only one primary channel in each time slot. This problem can be re-casted as a restless multi-armed bandit problem where the optimal algorithm must strike a balance between exploration and exploitation [8]. Unfortunately, finding the optimal solution for this problem remains an elusive task [10]. Inspired by the recent results of [8] and [9], an efficient MAC protocol is constructed which can be viewed as the Whittle index strategy of [8] augmented with a similar learning phase to the one proposed in [9] for the multi-armed bandit scenario. Our numerical results show that the performance of this protocol converges to the Whittle index strategy with known transition probabilities [8].

II. NETWORK MODEL

A. Primary Network

We consider a primary network consisting of \( N \) independent channels with its users communicating according to a synchronous slot structure. We use \( i \) to refer to the channel index \( i \in \{1, \cdots, N\} \), and \( j \) to refer to the time-slot index \( j \in \{1, \cdots, T\} \). The \( i \)th primary channel has a bandwidth...
of $B_i$. The traffic statistics of the primary network are such that the occupancy of each of the $N$ channels follows a discrete-time Markov process with two states. The state of the $i$th channel at time slot $j$, $S_i^{(j)}$, is equal to 1 if the channel is free, and to 0 if it is busy. The state diagram for a single Markov channel model is illustrated in Figure 1. The channel state transition matrix of the Markov chain is given by $P_i = \begin{bmatrix} P_{00}^i & P_{01}^i \\ P_{10}^i & P_{11}^i \end{bmatrix}$. We assume that $P_i^i$ remains fixed for a block of $T$ time slots and is unknown a-priori to the secondary user.

B. Secondary Pair

It is assumed that the secondary transmitter can sense $L_1$ channels ($L_1 \leq N$) and can access $L_2 = 1$ channel in each slot. The secondary transmitter can only transmit if the channel it chooses to access is sensed to be free. Here, we only report our results for the two special cases $L_1 = N$ and $L_1 = 1$. The more general case will be addressed in the journal version.

The secondary receiver does not participate in channel sensing and is assumed to be capable of accessing only one channel [4]. This assumption is intended to limit the decoding complexity needed by the secondary receiver. Another motivation behind restricting channel sensing to the transmitter is the potentially different sensing outcomes at the secondary transmitter and receiver due to the spatial diversity of the primary traffic which can lead to the breakdown of the secondary transmitter-receiver synchronization.

Conceptually, our proposed cognitive MAC protocol can be decomposed into the following stages:

- **Decision stage**: The secondary transmitter decides which $L_1$ channels to sense. Also, both transmitter and receiver decide which channel to access.
- **Sensing stage**: The transmitter senses the $L_1$ selected primary channels.
- **Learning stage**: The transmitter updates the estimated primary channels’ statistics, $\bar{P}_i$.
- **Access stage**: If the access channel is sensed to be free, a data packet is transmitted to the secondary receiver. This packet contains the information needed to sustain synchronization between secondary terminals and, hence, synchronization does not require a dedicated control channel. The length of the packet is assumed to be large enough such that the loss of throughput resulting from the synchronization overhead is marginal.
- **ACK stage**: The receiver sends an ACK to the transmitter upon successful reception of sent data.

The performance of the sensing stage is limited by two types of errors. If the secondary transmitter decides that an empty channel is busy, it will refrain from transmitting, and a spectrum opportunity is overlooked. This is the false alarm situation, which is characterized by probability of false alarm $P_{FA}$. On the other hand, if the detector fails to sense a busy channel as busy, a miss detection occurs resulting in interference with primary user. The probability of miss detection is denoted by $P_{MD}$. In the rest of the paper, $S_i^{(j)}$ denotes the state of channel $i$ at time slot $j$ as sensed by the transmitter, which might not be the actual channel state $S_i^{(j)}$. Overall, successful communication between the secondary transmitter and receiver occur only when: 1) they both decide to access the same channel, and 2) the channel is sensed to be free and is actually free from primary transmissions.

III. Full Sensing Capability: $L_1 = N$

In this section it is assumed that the secondary transmitter can sense all $N$ primary channels at the beginning of each time slot. The initial packet sent to the receiver includes estimates for the transition probabilities, and the belief vector $\hat{\Omega}_i$, where $\hat{\Omega}_i = [\hat{\omega}_1, \cdots, \hat{\omega}_N]$, and $\hat{\omega}_i$ is the common transmitter’s and receiver’s estimate of the prior probability that channel $i$ is free at the beginning of time slot $j$, on the basis of the sensing history of channel $i$. Once the initial communication is established, the secondary transmitter and receiver implement the same spectrum access strategy described below for $j \geq 1$.

1) **Decision**: At the beginning of time slot $j$, and using belief vector $\hat{\Omega}_i$, the secondary transmitter and receiver decide to access channel $i^* = \arg \max_{i=1,\cdots,N} \hat{\omega}_i B_i$.

2) **Sensing**: The secondary transmitter senses all channels and captures the sensing vector $\Phi_j = [\bar{S}_1^{(j)}, \cdots, \bar{S}_N^{(j)}]$, where $\bar{S}_i^{(j)} = 1$ if the $i$th channel is sensed to be free, and $\bar{S}_i^{(j)} = 0$ if it is found busy.

3) **Learning**: Based on the sensing results, the transmitter updates the estimates $\hat{P}_i^0$ and $\hat{P}_i^1$ for all primary channels as explained below.

4) **Access**: If $\bar{S}_i^{(j)} = 1$, the transmitter sends its data packet to the receiver. The packet includes $\Phi_j$, $\hat{P}_i^0$, and $\hat{P}_i^1$. In addition, if the transmission at slot $j - 1$ has failed, the transmitter sends $\Omega_j$, which is the belief vector computed at the transmitter based on its observations. If the receiver successfully receives the packet, it sends an ACK back to the transmitter. Parameter $R_i^{(j)}$ is equal to unity if an ACK is received by the transmitter, and zero otherwise. If the channel is free, the forward transmission and the feedback channel are assumed to be error-free.

5) Finally, the transmitter and receiver update the common belief vector $\hat{\Omega}^{(j+1)}$ such that:
An optimal learning algorithm for HMM is described in [7] where, the optimal HMM algorithm. The estimated probabilities by the optimal HMM algorithm. The expected throughput becomes \( \max_{i=1,\ldots,N} [P_{S_i=1} B_i] \) [9]. Assuming, however, that the transition probabilities are unknown but both nodes know that \( P_{l_1} = P_{01} \), one can estimate each channel’s free probability \( P_{S_i=1} = P_{S_i=1} N_i^1(j)/j \). In Section 4 we quantify the value of this side information by comparing the performance of this strategy with our universal algorithm that does not make any prior assumptions about the transition probabilities.

IV. THE RESTLESS BANDIT SCENARIO: \( L_1 = 1 \)

Assuming that the transition probabilities are known a-priori by the secondary users, the medium access scenario in this case can be formulated as a partially observable Markov decision process (POMDP) [5]. The optimal policy, in this

\[
\omega_{i}^{(j+1)} = \begin{cases} 
\tilde{P}_i, & \text{if } K_i^j = 1, i = 1 \ast (j) \\
A_i \: \tilde{P}_i + (1 - A_i) \: \tilde{P}_0, & \text{if } K_i^j = 1, i \neq 1 \ast (j), \bar{S}_i^j = 1 \\
C_i \: \tilde{P}_i + (1 - C_i) \: \tilde{P}_0, & \text{if } K_i^j = 1, i \neq 1 \ast (j), \bar{S}_i^j = 0 \\
D_i \: \tilde{P}_i + (1 - D_i) \: \tilde{P}_0, & \text{if } K_i^j = 0, i = 1 \ast (j) \\
\tilde{P}_i \: \tilde{P}_i + (1 - \tilde{P}_i) \: \tilde{P}_0, & \text{if } K_i^j = 0, i \neq 1 \ast (j)
\end{cases}
\]

where:

\[ \tilde{A}_i = P_{\tilde{R}(S_i^j) = 1} \tilde{S}_i^j = 1 = (1 - P_{FA}) \tilde{S}_i^j = 1 - P_{FA} \tilde{S}_i^j = 1 - P_{MD} \tilde{S}_i^j = 1 \]

\[ \tilde{C}_i = P_{\tilde{R}(S_i^j) = 1} \tilde{S}_i^j = 0 = P_{FA} \tilde{S}_i^j = 1 - P_{MD} \tilde{S}_i^j = 1 \]

\[ \tilde{D}_i = P_{\tilde{R}(S_i^j) = 1} K_i^j = 0 = P_{FA} \tilde{S}_i^j = 1 - P_{MD} \tilde{S}_i^j = 1 \]

\[ \tilde{P}_i \: \tilde{P}_i + (1 - \tilde{P}_i) \: \tilde{P}_0, \]

\[ \tilde{P}_i \: \tilde{P}_i + (1 - \tilde{P}_i) \: \tilde{P}_0, \]

In a nutshell, the proposed algorithm uses the full sensing capability of the secondary transmitter to decouple the exploration (i.e., learning) task from the exploitation task. After an ACK is received, both nodes use the common observation-based belief vector to make the optimal access decision. On the other hand, in the absence of the ACK, both nodes can not use the optimal belief vector in order to maintain synchronization. In this case, the proposed algorithm opts for a greedy strategy in order to minimize the time between two successive ACKs. At this point, we only conjecture the optimality of this strategy and continue to work on the proof for the journal version of this work.

As an analytical benchmark, we have the following upper-bound on the achievable throughput in this scenario. Assuming that the delayed side information of all the primary channels’ states \( S_i^{(j-1)} \) is given to the secondary transmitter and receiver, to decide on the channel to access at time \( j \), an upper bound expected throughput per slot is given by:

\[
R = \sum_{S_N=0}^{1} \cdots \sum_{S_2=0}^{1} \sum_{S_1=0}^{1} \left[ \prod_{i=1}^{N} P_{S_i} \right] \left( \max_{i=1,\ldots,N} [P_{S_i=1} B_i] \right)
\]

where, \( P_{S_i} \) denotes the state transition probability for channel \( i \) from state \( S_i = (0, 1) \) to the free state. \( P_{S_i} \) is the Markov steady state probability of channel \( i \) being free or busy. The first term in the summation corresponds to the probability that the \( N \) channels are in one of the \( 2^N \) states, and the second term represents the highest expected throughput given the current joint state for the \( N \) channels.

A final remark is now in order. Assuming that \( P_{l_1} = P_{01} \), a channel’s probability of being free, \( P_{S_i=1} \), becomes independent of the previous state, i.e., \( P_{S_i=1} = P_{l_1} = P_{01} \). In this case, the optimal strategy, assuming that the transition probabilities are known, is for the secondary transmitter to access the channel \( i^* = \arg \max_{i=1,\ldots,N} [P_{S_i=1} B_i] \) and the expected throughput becomes \( \max_{i=1,\ldots,N} [P_{S_i=1} B_i] \) [9]. Assuming, however, that the transition probabilities are unknown but both nodes know that \( P_{l_1} = P_{01} \), one can estimate each channel’s free probability \( P_{S_i=1} = P_{S_i=1} N_i^1(j)/j \). In Section 4 we quantify the value of this side information by comparing the performance of this strategy with our universal algorithm that does not make any prior assumptions about the transition probabilities.
The strategy works as follows. Choose which channel to access at each time slot. In summary, a period (LP) information on-line in order to make the appropriate access decision. A blind cognitive MAC protocol must now learn this statistical information. Adding another interesting dimension to the problem since the secondary transmitter/receiver assigns Whittle’s index to each channel. More recent work, the problem was recast as a restless bandit problem and the Whittle’s index approach was used to obtain the Whittle index strategy for the L1 = 1 case. Here, we relax the assumption of the a-priori known transition probabilities by the secondary transmitter/receiver. This adds another interesting dimension to the problem since the blind cognitive MAC protocol must now learn this statistical information on-line in order to make the appropriate access decisions. Inspired by previous results of Lai et al. in the multi-armed bandit setup, we propose the following simple strategy. At the beginning of the T slots, each of the N primary channels is continuously monitored for an initial learning period to get an estimate for P_{01} and P_{11}. Then, by assigning Whittle’s index T^{(j)} to each channel, we are able to choose which channel to access at each time slot. In summary, the strategy works as follows.

1) **Initial learning period**: Each channel is continuously sensed for LP time slots. At the end of the learning period, the transition probabilities are estimated as P_{01} = \frac{N_{01}}{N_{01}}, P_{11} = \frac{N_{11}}{N_{11}}, P_{00} = \frac{N_{00}}{N_{00}}, P_{10} = \frac{N_{10}}{N_{10}}.

2) **Decision**: At the beginning of any time slot (j > N \times LP), the secondary transmitter and receiver decide to access channel i^*(j) = \text{arg max}_{i=1,...,N} T^{(j)}_i B_i.

3) **Sensing**: The secondary transmitter senses channel i^*(j).

4) **Learning**: If i^*(j) = i^*(j-1), update N_{11}^i, N_{11}^i, N_{01}^i, N_{01}^i, \bar{P}_{11}^{i}, \bar{P}_{11}^{i}, and \bar{P}_{01}^{i}, \bar{P}_{01}^{i}.

5) **Access**: If \tilde{S}_{i^*}^{(j)} = 1, the transmitter sends its data packet to the receiver. If the receiver successfully receives a packet, it sends an ACK back to the transmitter.

6) The transmitter and receiver calculate \tilde{S}_{i^*}^{(j+1)} given that:

$$\bar{\omega}_{i^*}^{(j+1)} = \begin{cases} \bar{P}_{11}^{i^*} \\text{if } i^*(j) = i^*(j+1) \wedge \omega_i^{(j)} \neq 0, \omega_i^{(j)} \wedge \omega_i^{(j)} = 0 \\text{if } i^*(j) = i^*(j) \wedge \omega_i^{(j)} \neq 0 \end{cases}$$

where \bar{P}_{11}^{i^*} and \bar{P}_{01}^{i^*} are the latest successfully shared \bar{P}_{11}^{i^*} and \bar{P}_{01}^{i^*} between the secondary transmitter-receiver pair. Finally, \bar{\Omega}^{(j+1)} is used to update Whittle’s index T^{(j+1)} of each channel as detailed in [8].

In the case of time-independent channel states, i.e., \bar{P}_{11}^{i^*} = \bar{P}_{01}^{i^*}, the problem reduces to the a multi-armed bandit scenario considered in [9]. The difference, here, is the lack of the dedicated control channel, between the cognitive transmitter and receiver, as assumed in [9]. The following strategy, which is applied as soon as the initial synchronization is established, avoids this drawback by ensuring synchronization using the ACK feedback over the same data channel.

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**V. Numerical Results**

In this section, we present simulation results for the two scenarios discussed earlier. Throughout this section, we assume that the number of primary channels N = 5, each with bandwidth B_i = 1. The spectrum usage statistics of the primary network were assumed to remain unchanged for a block of T = 10^6 time slots for Figures 2 and 4, and for a block of T = 10^5 time slots for Figure 3. The transition probabilities for each channel \bar{P}_{11}^{i^*} and \bar{P}_{01}^{i^*}, were generated randomly between 0.1 and 0.9. The plotted results are the average over 1000 simulation runs. The discount factor used to obtain the Whittle index is 0.99999. In all reported simulations, perfect sensing is assumed, and the average throughput per time slot is plotted.

Figure 2 reports the throughput comparison between the different cognitive MAC strategies, all with prior knowledge about the channels transition probabilities. The loss in throughput between the upper bound and the proposed strategy for the L1 = N case is shown and the gain offered by the full sensing capability as compared with the L1 = 1 scenario is apparent. It is seen also that the strategies we proposed achieve higher throughput than the best offline bound described in [4], in

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![Fig. 2. Throughput comparison between: the upper bound from equation (1), the proposed blind strategy proposed for L1 = N, the Whittle index strategy for L1 = 1, the greedy strategy for L1 = 1, and the maximum achievable offline bound.](image-url)
which the channel with highest steady state probability of being free is always chosen. Figure 3 illustrates the convergence of the throughput of the proposed blind strategy for $L_1 = N$, with no prior information, to the case with prior knowledge of the transition probabilities as $T$ grows. In Figure 4, we assume that $P_{11}^i = P_{01}^i$ for all channels. It is shown that even if the secondary users are unaware of this fact, and apply the proposed strategy, the achievable throughput converges asymptotically to genie-aided upper bound (when the transition probabilities are known a-priori), albeit at the expense of a longer learning phase. Interestingly, both strategies are shown to converge asymptotically to genie-aided upper bound (when the transition probabilities are known). Finally, Figure 5 demonstrates the tradeoff between the learning time overhead in the blind strategy of Section IV and the final achievable throughput at the end of the $T$ slots. Clearly, this figure supports the intuitive conclusion that for large $T$ blocks, one can tolerate a longer learning phase in order to maximize the steady state achievable throughput.

VI. CONCLUSION

In this work, we propose blind cognitive MAC protocols that do not require any prior knowledge about the statistics of the primary traffic. We differentiate between two distinct scenarios, based on the complexity of the cognitive transmitter. In the first, the full sensing capability of the secondary transmitter is fully utilized to learn the statistics of the primary traffic while ensuring perfect synchronization between the secondary transmitter and receiver in the absence of a dedicated control channel. The second scenario focuses on low-complexity cognitive transmitter capable of sensing one channel only at the beginning of each time slot. For this case, we propose an augmented Whittle index MAC protocol that allows for an initial learning phase to estimate the transition probabilities of the primary traffic. Our numerical results demonstrate the convergence of the blind protocols performance to that of the genie-aided scenario where the primary traffic statistic are known a-priori by the secondary transmitter and receiver.

REFERENCES

[1] S. Haykin, “Cognitive radio: brain-empowered wireless communications,” IEEE JSAC, vol. 23, no. 2, pp. 201-220, Feb 2005.
[2] H. Su and X. Zhang, “Opportunistic MAC Protocols for Cognitive Radio,” Proc. 41st Conference on Information Sciences and Systems (CISS 2007), March 2007.
[3] H. Kim and K. Shin, “Efficient Discovery of Spectrum Opportunities with MAC-Layer Sensing in Cognitive Radio Networks,” IEEE Transactions on Mobile Computing, vol. 7, no. 5, pp. 533-545, May 2008.
[4] S. Srinivasa, S. Jafar and N. Jindal, “On the Capacity of the Cognitive Tracking Channel,” IEEE International Symposium on Information Theory, July 2006.
[5] Q. Zhao, L. Tong, A. Swami, and Y. Chen, “Decentralized Cognitive MAC for Opportunistic Spectrum Access in Ad Hoc Networks: A POMDP Framework,” IEEE JSAC, vol. 25, no. 3, pp. 589-600, April 2007.
[6] A. Sahai, N. Hoven, S. Mishra and R. Tandra, “Fundamental tradeoffs in robust spectrum sensing for opportunistic frequency reuse,” Tech. Rep., 2006. Available: www.eecs.berkeley.edu/~mm/CognitiveTechReport06.pdf
[7] L. Rabiner and H. Juang, “An introduction to hidden Markov models,” IEEE ASSP Magazine, vol. 3, no. 1, Jan. 1986.
[8] K. Liu and Q. Zhao, “A Restless Bandit Formulation of Opportunistic Access: Indexability and Index Policy,” 5th IEEE Annual Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks Workshops (SECON Workshops '08), June 2008.
[9] L. Lai, H. El-Gamal, H. Jiang and H. Poor, “Cognitive Medium Access: Exploration, Exploitation and Competition,” submitted to the IEEE Transactions on Networking, Oct. 2007.
[10] P. Whittle, “Restless Bandits: Activity Allocation in a Changing World,” Journal of Applied Probability, vol. 25, 1988.