Towards Efficient Spectrum Sensing for Cognitive Radio Through Knowledge-Based Reasoning

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Abstract— **In this paper, an efficient approach to Medium Access Control layer spectrum sensing algorithm is introduced for the purpose of peer-to-peer communications with cognitive radio. The proposed algorithm is designed specifically for the application scenario of information gathering in a full-loaded legacy voice and data band, where the cognitive radio tries to utilize other available licensed bands through spectrum sensing. Efficiency is achieved in the proposed algorithm through the use of a knowledge-based reasoning approach to fine sensing, where the optimal range of channels to finely sense is determined using proactive fast sensing and channel quality information as priors. Simulation results demonstrate that the proposed spectrum sensing algorithm is capable of achieving improved performance over existing techniques by drawing a good balance between performance and operational complexity.**

I. INTRODUCTION

Recently, a dramatic increase in demand for ubiquitous wireless services has been straining the already limited and scarce radio spectrum, especially on those standardized for legacy voice and data transmission. This leads to awkward situations where outgoing calls fail despite of having full signal power in the handset as well as the inability to access WLAN (Wireless Local Area Network) services despite of sufficiently strong wireless connections. The main reason for these situations lies in the shortage of spectrum resources associated with the corresponding devices. On the other hand, a large portion of licensed spectrum has not been explored and utilized, which causes a significant number of spectrum holes [2]. According to statistics provided by the Federal Communication Commission (FCC), up to 85% of the licensed spectrum is not used in certain geographical areas, such as rural areas and thin population areas. Even in the areas with high population densities, there is still 15% of the licensed spectrum being underutilized. Therefore, FCC decided to deregulate the spectrum for increasing broadband usage rates. This deregulation opens a door for the unlicensed use of licensed spectrum and consequently opens the door for research in the area. As such, it has attracted extensive extensions from both industry and academia on how to utilize the temporarily released spectrum in an efficient and opportunistic manner.

Cognitive radio (CR) [1], [2] has been consequently proposed to solve the inefficiency in spectrum assignments of legacy static radio. Various definitions for CR have appeared in different circumstances. According to [3], cognitive radio is an intelligent radio with the capability of access radio spectrum resources by exploiting the radio environment for user-centric communications. Therefore, in a radio communication system, the nodes equipped with the CR can opportunistically gain access to an already-licensed spectrum band, such as any television (TV) bands within 30MHz-3GHz, to fill in the spectrum holes. In this sense, these nodes act as ”secondary” users relative to the licensed (or ”primary”) users. Since CR can efficiently increase the spectrum utilization, it has attracted lot of attention and has become a promising solution to the spectrum shortage problem.

Research on CR faces challenges from the broad range of available spectrum. Radio frequency (RF) hardware for CR should be capable of tuning to any part of multigigahertz-wide bandwidth. Therefore, such hardware devices require an extremely high-speed analog-to-digital (A/D) converter to detect a weak signal, which might be infeasible. The Physical (PHY) layer design issues related to this have been addressed by Cabric *et al.* [4]. In addition, reliable detection on the presence of primary users is also a crucial problem in a fading environment, where figuring out whether a channel is free or in deep fading is hard. A commonly used energy detection method can be adopted to detect the presence of an unknown signal in noise. However, it is often not sufficient for determining whether the primary user is indeed present. Therefore, a number of feature detection techniques have been proposed to differentiate noise energy from modulated signal energy. The main disadvantage of feature detection methods is that they require a much longer observation time than that taken by the energy detection method, as well as being computationally complex in comparison [5].

Since the major research problem on PHY layer dealing with how to correctly and quickly detect the existence of primary users and spectrum opportunities have not been solved, it is important to design an efficient spectrum sensing algorithm so that the CR can improve the sensing performance by control the detection timing while taking the aforementioned PHY layer issues as design constraints. There are several issues associated with the design of spectrum sensing algorithms on the Medium Access Control (MAC) layer. They are enumerated as follows:

1) **Timing**: An important design issue to consider is the timing of spectrum sensing. Proactive sensing can ob-

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tain spectrum information before the CR needs an idle channel at the expense of higher overhead than that by on-demand sensing [11]. On the other hand, with on-demand sensing, the CR senses the spectrum when it has a chunk of data that needs to be transmitted. Since the chunk of data cannot be launched until the CR finds one or multiple idle channels, it may introduce spectrum sensing delay.

2) **Efficiency**: Another important spectrum sensing design issue involves determining how many channels to go through in each sensing. Since each channel across the whole spectrum may or may not be accessible at a moment, the more channels the CR senses, the better chance the CR can obtain the spectrum access with desired quality. Conversely, given the size of data to be sent as well as a given bound on the latency of both sensing and transmission, a lengthy sensing process reduces the time left for transmission, which subsequently reduces the chance of successfully delivering the whole chunk of data. Furthermore, a lengthy sensing process will certainly consume more energy at the station. Therefore, a spectrum sensing algorithm that determines the lenghth of a sensing process in the presence of time and/or energy constraints is highly desired.
3) **Reliability**: Reliability of CR spectrum sensing refers to the ability of the CR on minimizing interferences in the spectrum access, where spectrum sensing serves this purpose in gaining channel status before accessing the channel. Since reliable spectrum detection is still an open issue in the PHY layer design, spectrum sensing and control signaling is expected to take an important role in reliability enhancement.
4) **Computational complexity**: The issue of computational complexity determines the feasibility of a CR spectrum sensing algorithm. In general, solving complicated optimization problems which leads to significant delay and energy consumption may not be feasible in the CR design.

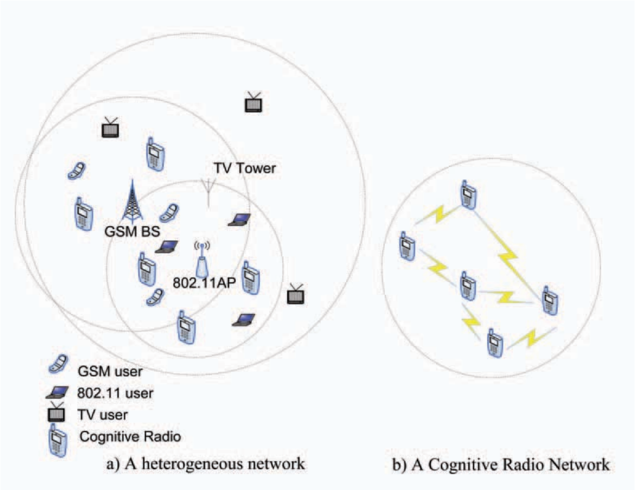
In this work, we consider the application scenario of information gathering in a full-loaded licensed GSM band and unlicensed ISM band, where the CR tries to access other available licensed bands, such as TV bands, to exchange information with neighbor peers. By assuming no central controller standby, secondary users equipped with CR form an ad-hoc network. Thus, the problem tackled in this paper is on CR spectrum sensing without perfect knowledge of PHY layer. We aim to undergo a detailed design and develop a CR spectrum sensing algorithm which is adaptive to the dynamic change of spectrum opportunities. The proposed solution answer some of the critical questions, such as when to start and stop the spectrum sensing and what strategy to take in the data transmission and rate selection so that an individual CR can get the channels that optimally fit its desired performance requirements. More specifically, the proposed spectrum sensing algorithm can minimize the sensing and transmission time through a knowledge-based reasoning approach, in which an optimization problem is formulated based on proactive fast sensing and channel quality information. Simulation is conducted to demonstrate the effectiveness and efficiency of the proposed algorithm. In this paper, we focus on the area of non-cooperative, stand alone MAC spectrum sensing. The reason is that it is often not possible for different CRs with different underlying technologies to cooperate with each other in many application scenarios.

The remainder of this paper is organized as follows. First, related work is discussed in Section II. The system model is presented in Section III. The proposed spectrum sensing algorithm is described in Section IV. Simulation results are provided in Section V. Finally, conclusions are drawn in Section VI.

II. RELATED WORK

There have been several algorithms designed for the purpose of non-cooperative CR spectrum sensing. In [11], two modes of MAC-layer spectrum sensing, reactive and proactive, and the corresponding tradeoff between these two modes were introduced. An energy-efficient mechanism was developed to determine the mode of sensing, while a sensing-period adaptation mechanism was further proposed to find the optimal sensing period. In [6], a framework of Partially Observable Markov Decision Process (POMDP) with unknown transition probabilities was proposed to determine which channels to sense. In the state-of-the-art algorithm proposed by Jia et al. [10], the hardware limitations, namely, the constraints on sensing and transmission, were taken into consideration in the design of the CR spectrum sensing algorithm. The sensing constraint used in the proposed algorithm stipulates that the sensing capacity is limited although the spectrum opportunity is all over the spectrum range. The transmission constraint used in the proposed algorithm defines the limitation of bandwidth and fragmentation. Therefore, the tradeoff between spectrum accessing opportunities and spectrum sensing overhead is formulated as a stopping problem, which decides whether or not the sensing process should continue.

The underlying concept behind the proposed spectrum sensing algorithm is similar to that by proposed in [10] but with a number of important improvements. First, the CR identifies the portion of the spectrum to finely sense based on fast sensing results, which are based on the busy channel index responded by the intended receivers. Second, based on the prior information obtained from the proactive fast sensing scheme, an optimal number of fine sensing is estimated subject to time constraints. It is different from the algorithm proposed in [10], where the CR obtains the optimal number by going through all the sensing stages without knowing the prior optimal number or time limitations. Third, instead of artificially truncating the sensing process to K stages, the estimated number determined by the proposed algorithm may be more reasonably closer to the global optimum. Fourth, we classify up to seven quality classes of available channels to further help the CR determine whether to continue the



a) A heterogeneous network

b) A Cognitive Radio Network

Fig. 1. Cognitive Radio Network Architecture

fine sensing process by comparing the expected throughput upper bound gained in the next move with present throughput. As such, the optimal range of channels to finely sense is determined using a combination of proactive fast sensing and channel quality information as priors. The simulation results show that the proposed algorithm can be easily implemented with minimized overall latency and outperforms this state-of-art algorithm.

III. SYSTEM MODEL

Prior to describing the proposed spectrum sensing algorithm, it is important to first provide a general overview on the system architecture, the channel access model, and assumptions in the study.

A. Network Architecture

In a heterogeneous network shown in Fig. 1. a), many different wireless access technologies, e.g., IEEE 802.11, GSM, and TV broadcast, may coexist. Users of these technologies form primary user networks, and the infrastructure corresponding to each primary user network are not required to allow for spectrum sharing with other networks. Users equipped with cognitive radios are considered as the secondary users to these networks. In general, a secondary user (with CR capability) needs to look for network resources in other networks (a user in its own network is primary) when it cannot obtain service in its own network. For example, the secondary users attempt to detect free spectrum on 400-800MHz Ultra High Frequency (UHF) TV bands, (the possible frequency bands for the CRs in a near future [4]). These secondary users form a network in an ad-hoc manner in situations where emergency and time-sensitive information gathering is required, such as during rescue operations after nature disasters or operation in an unknown adversary field. In our network model, this wireless ad-hoc network is denoted as the secondary user network, as shown in Fig. 1. b).

B. Channel Model

In the ad-hoc network, there is no central controller and each secondary user senses the spectrum before transmission. We assume that a common channel is reserved by manufacturers for control message exchanging which occurs after spectrum sensing. Therefore, the channel initiation and the transmission of control messages are performed on the common channel, named as common control channel. Data transmissions occur on detected available data channels. Since multiple free channels can be used in data transmission, an Orthogonal Frequency Division Multiple Access (OFDMA) system is taken as the underlying multiple access approach. In this study, a channel is a subcarrier in OFDMA system, and is categorized into seven different modulation schemes with the corresponding transmission rates, respectively, according to the perceived Signal to Noise plus Interference Ratio (SINR) of the channel. Since the performance of spectrum sensing is the main focus in this study, the data transmission rate is defined as the information bits carried by a set of sub-carriers in OFDMA system per second, and the expected throughput of interest in the study is the upper bound of the throughput that can be achieved immediately after spectrum sensing without considering the delay of processing MAC protocols.

C. MAC Layer Spectrum Sensing

In our MAC layer spectrum sensing model, we assume that both sensing and data transmission can not be processed simultaneously. Each secondary users detect the presence of primary users independently of each other by performing spectrum sensing. Nodes equipped with cognitive radios have two stages of spectrum sensing. According to the IEEE 802.22 specifications, the first stage of spectrum sensing is to perform fast sensing using energy detection over the entire spectrum scale. Such sensing is also known as fast sensing with relatively a high speed and little cost.

The second stage of sensing is in place when a transmission demand arrives, which is also known as fine sensing. With the knowledge of which portion of spectrum to scan obtained from the fast sensing, the CR MAC performs fine sensing on each channel one after the other to identify the corresponding channel conditions and applicable modulation schemes for the transmission request. It is seen that the fine sensing process is performed on-line after the arrival of the transmission request. Thus, it is critical to determine when to start and terminate the fine sensing, as well as how to select the transmission rate, which will be addressed in the proposed algorithm presented in the following section.

IV. PROPOSED SPECTRUM SENSING ALGORITHM

The proposed algorithm for CR spectrum sensing using knowledge-based reasoning can be described as follows. When performing the fine sensing process, the CR scans over the set of channels to determine channel conditions and availability. Since the fine sensing process is performed one channel after the other, the CR terminates the sensing process when it feels satisfied with the already found channels for the transmission.

In other words, the more channels the CR senses, the more likely the CR can obtain better channels, which leads to a better transmission rate and consequently a higher throughput. However, if the CR scans too many channels during the fine sensing stage, the overall transmission time will be significantly increased, which impairs the overall throughput. Even for transmissions with a loose delay constraint, undergoing a long fine sensing process will certainly increase the probability of unsuccessful transmission due to the time sensitivity of the spectrum sensing results. Therefore, the optimal number of channels to sense should be such that the total transmission time T (i.e., fine spectrum sensing time T_s plus data transmission time T_{tran}) is minimized. Mathematically, the problem can be formulated as follows:

$$Min\{T|T = T_s + T_{tran}\} \tag{1}$$

subject to:

$$T \leq T_{\max} \tag{2}$$

The total time consumed on spectrum sensing in the second stage, i.e., fine sensing, is given by the following expression:

$$T_s = nt \tag{3}$$

where n is the number of channels to be finely sensed and t is the time consumed by doing fine sensing to each channel. Since BPSK (Binary Phase Shift Keying) is the slowest modulation, the upper bound of the expected data transmission time can be expressed as follows:

$$T_{tran} \leq \frac{D}{R_{bpsk}} \tag{4}$$

where D denotes the data length which is known by the source, and R_{bpsk} is the data transmission rate of BPSK. The data transmission rate in the OFDMA system can be determined by the number of modulation symbols N_s, number of available sub-carriers k, and sample time τ. Therefore, the data transmission rate of BPSK in terms of information bits per second can be expressed as follows [13]:

$$R_k = \frac{N_s k}{\tau} \tag{5}$$

Notice that k is the number of available sub-carriers obtained by the cognitive radio after t times fine sensing. Assume that each sub-carrier is independently available with prob q; therefore, k has a binomial distribution with parameter q and the expected value nq:

$$P(X = k) = \left(\begin{array}{c} n \\ k \end{array} \right) q^k (1-q)^{n-k} \tag{6}$$

The available sub-carriers are the channels that are both available at transmitter and receiver. Therefore, the available channel can be used by a transmission pair if the following two independent conditions are satisfied:

1) **C1**: A specific channel is free at the transmitter side.
2) **C2**: There is no hidden terminal for a specific channel.

Therefore, the parameter q can be expressed as follows:

$$q = \mathrm{Prob(C1)Prob(C2)} \tag{7}$$

The probability of a channel to be free can be expressed as follows:

$$\mathrm{Prob(C1)} = \theta \tag{8}$$

where $\theta = P(noise < threshold)$. The probability of the second condition is hard to estimate because the transmitter has no knowledge of the channel condition at the receiver side, while the estimation can be performed at the transmitter. As mentioned earlier, in the first stage of fasting sensing, the CR nodes gains the knowledge on which channels may be currently occupied by their neighbors. Therefore, this proactive fast sensing information can be used as a prior to limit the range within which the optimal number of channels is determined, thus significantly reducing sensing overhead. Whenever the transmitter sends a transmission request (CH_REQ) to the receiver on a control channel, the receiver responds with a CH_RSP packet through the same channel with attached channel information of its neighbors. The channel information of neighbors is a list of of channels $\{CH_i^{Rx}\}$ that have been detected occupied on the first stage of spectrum sensing. At the same time, the transmitter has its own results of fast sensing. By comparing with received index of channels, the transmitter determines which portion of the spectrum can be chosen. We denote the value β as the element number of $\{CH_i^{Rx}\}$, and β' is element number of $\{CH_i^{Rx}\}$ in the range of the spectrum to be finely sensed. This information can therefore be used by the transmitter to approximate the probability of hidden terminals for a specific channel as:

$$\varepsilon = \beta'/n \tag{9}$$

Therefore, the probability of the second condition can be expressed as follows:

$$\mathrm{Prob(C2)} = 1 - \varepsilon \tag{10}$$

Substituting Eqn. (10) and Eqn. (8) into Eqn. (7), we get the following:

$$q = \theta(1 - \varepsilon) \tag{11}$$

Since the transmission rate is a linear function of k , according to the Eqn. (5), we can conclude that the probability of the transmission rate also has a binomial distribution with parameter q and the expected value nq.

$$P_{R_k} = Prob\{R = R_k\} = \left(\begin{array}{c} n \\ k \end{array} \right) q^k (1-q)^{n-k} \tag{12}$$

Therefore the average transmission rate of BPSK is given by:

$$\begin{aligned}\bar{R} &= \sum_{k=0}^{n} R_k P_{R_k} \\ &= \sum_{k=0}^{n} \frac{N_s k}{\tau} \left(\begin{array}{c} n \\ k \end{array} \right) q^k (1-q)^{n-k} \\ &= \frac{N_s}{\tau} n q \\ &= F(n)\end{aligned} \tag{13}$$

Substituting Eqn. (3), (5), and (13) into Eqn. (1), we get the complete formulation as follows:

$$\begin{aligned} &n = \arg\min_{n} \{nt + \tfrac{D}{F(n)}\} \\ &T \leq T_{\max}\end{aligned} \tag{14}$$

The CR transmitter applies Eqn. (14) to determine the estimated number of channels to be finely sensed by the cognitive radio, where the most conservative modulation scheme (i.e., BPSK) is assumed in the transmission.

So far, we have presented how a CR estimates the optimal number of channels for being finely sensed based on the limited information received from the PHY layer through proactive fast sensing. Based on the obtained n, one approach to the fine sensing process is to perform the fine sensing process n times with respect to the fast sensing prior information. However, this approach can still be costly due to accuracy issues associated with the fast sensing process. To further improve efficiency, we alternatively propose a knowledge-based reasoning approach that takes advantage of both fast sensing and channel quality information as priors. With the proposed knowledge-based reasoning approach, the CR MAC is equipped with intelligence and knowledge to determine whether to commit to sensing the next sub-carrier one after the other.

The proposed knowledge-based reasoning approach can be explained by an analog of "seashell collection" on a beach: Whenever a person encounters a seashell, the person can either collect it or not, and for any seashell that is not collected, it can never be considered again. In the scenario, the person has little knowledge on what kind of seashell will be encountered next, and does not know how far he should walk to encounter the next seashell because the tide may wash seashells ashore or take them away any time. Therefore, the person needs to make a decision on whether an encountered seashell should be collected or not based on limit information and observation after each move. In our case, the person is the CR, the seashells are spectrum resources, and the ocean tide represents the dynamic status of the sub-carrier availability. To determine whether to proceed the next sensing, the CR evaluates possible outcomes before taking the next move. Every spectrum sensing move may yields to possible results: an available channel is obtained or nothing at all. Either result sets up a chain of reactions on the subsequent movement. If an available channel is obtained, the CR has a chance to improve its transmission rate according to Eqn. (5) at the cost of the spent sensing time. If the sensed sub-carrier is not available, the CR simply wasted the time spent on the sensing, where the probability of failure in the data packet transmission within T_{max} is increased.

Mathematically, a spectrum offer X_j is obtained in the jth time of sensing, where X_j is a set of identical and independent random variable with cumulative distribution function F, which is also known as the *profile function* of the spectrum. The spectrum offer from the jth sensing is given by the following expression:

$$Y_j = \sum_{j=1}^{k} X_j - jC \tag{15}$$

where C is cost function of each spectrum sensing and is a function of time:

$$C \sim g(t) \tag{16}$$

The expected return of the next move is given by the following:

$$\bar{Y}_{j+1} = p[\sum_{j=1}^{k+1} X_j - (j+1)C] + (1-p)[\sum_{j=1}^{k} X_j - (j+1)C] \tag{17}$$

which can be calculated at the transmitter, and $p = \theta$. Therefore, as long as the expected return of the next move satisfies the following condition the CR can continue sensing the channel:

$$\bar{Y}_{j+1} > Y_j \tag{18}$$

Eqn. (18) is equivalent to:

$$pX_{j+1} - C \geq 0 \tag{19}$$

This equation can be simply interpreted as that one more sensing should have an expected marginal return. Otherwise, the fine sensing process should be stopped. In term of time, Eqn. (19) can be rewritten as follows:

$$\frac{D}{R_j} \geq \frac{D}{R_j(1+p)} + t \tag{20}$$

We can interpret Eqn. (20) as that the CR proceeds if one more sensing can make up the cost of time spending t through the increased transmission rate. Eqn. (20) serves as the 'reasoning' process, by which the transmitter makes decision on its next move to achieve satisfactory throughput. To take channel quality information into account, sub-carriers are classified into seven classes with a corresponding spectrum sensing threshold. By assuming any transmission will be at the maximum possible power, we can get the seven SNR levels. This prior information can further help the CR determine whether to continue the fine sensing process by comparing the expected throughput upper bound gained in the next move with present throughput.

With the proposed knowledge-based reasoning approach, we expect the sensing cost can be further reduced compared with that when just the optimal number of fine sensing is determined off-line as the proposed algorithm adapts with the changing environment. We will empirically verify the effectiveness of the proposed knowledge-based reasoning approach through simulation shown in the next section.

TABLE I

RELATIONSHIP BETWEEN SNR AND NUMBER OF MODULATION SYMBOLS OF DIFFERENT MODULATION SCHEMES

SNR (dB)	Number of modulation symbols of different modulation Scheme, N_s , (bits/sub-carrier)
<0	0[1]
0-5	0.5
5-8	1
8-12	1.5
12-15	2
15-18	3
18-23	4
>23	4.5

[1] this channel cannot be used to carry data signals

V. SIMULATION RESULTS

In the simulation, we first compare the performance of the proposed spectrum sensing algorithm with knowledge-based reasoning and that without knowledge-based reasoning. The case with knowledge-based reasoning applies Eqn. (20) and may stop the fine sensing when the condition is not met, while the case without knowledge-based reasoning finely senses all the n channels. Next, we compare the performance of our proposed spectrum sensing algorithm with the stopping algorithm proposed in [10].

The experimental parameters used in the simulation can be summarized as follows. We adopt 0.31ms [14] as the symbol size τ of the OFDMA system, and 92.5ms [15] as the fine sensing time. We assume that the length of data is uniformly distributed from 0 to 2048 bytes according to IEEE 802.16-2001 and IEEE 802.11 specifications. Sub-carriers are classified into seven classes with a corresponding spectrum sensing threshold. By assuming any transmission will be at the maximum possible power, we can get the seven SNR levels. The cognitive radio adjusts its modulation schemes according to these levels. In our simulation, the actual modulation scheme does not have an impact on the results, as we are only interested in the number of symbols N_s taken by each modulation scheme. Therefore, we list the relationship between SNR levels and the number of symbols in Table I [13] (where the relationship can be varied with different specifications or modulation technologies), which is taken in our quantitative analysis.

The whole processing time consists of algorithm processing time $T_{algorithm}$, fine sensing time T_s , and data transmission time T_{tran} , i.e., $T = T_{algorithm} + T_s + T_{tran}$. The throughput upper bound is thus given by $\rho = \frac{D}{T}(bits/\sec)$. Moreover, we are interested in the processing overhead introduced by the fine sensing, which is used to initiate a compromise between how fast the data is transmitted and how much cost it is spent. For the compromise, the overhead weight is defined as $\zeta = \frac{T - T_{tran}}{T_{tran}}$.

The simulation results of data rate on the proposed spectrum sensing algorithm with knowledge-based reasoning and that without reasoning are shown in Fig. 2 with associated optimal value of fine sensing n and actual number of fine sensing j are shown in Fig. 3. Although the data rate of the case without reasoning is almost twice as high as that with reasoning, the throughput upper bound in the former is about 40% lower, which is further shown in Fig. 2. In other words, scanning through all the n sub-carriers takes more than double the time in the fine sensing process in order to increase the data transmission rate at the expense of a significant decrease of the throughput upper bound. Therefore, adopting the proposed knowledge-based reasoning approach can greatly help improve system efficiency.

The processing overhead introduced by the fine sensing process is used as a measure for investigating the tradeoff between data transmission rate and overhead. In Fig. 4, we compare the overhead weight between the cases with knowledge-based reasoning and without. It is seen that the overhead weight of non-reasoning is much larger than that of knowledge-based reasoning. In Fig. 5, the simulation result of estimated times of fine sensing is plotted with different channel conditions, which is determined by Eq. (7). It is observed that the estimated times of fine sensing is reduced as the channel condition improves. In other words, when there is less interferences amongst neighbors, the CR only needs to sense a small number channels to meet its transmission requirement, which can help the CR to save time and energy. In the same figure, we have seen that the longer the data for transmission is, the larger number of channels the CR needs to finely sense, in order to increase the probability of successful transmission by getting better and more channels.

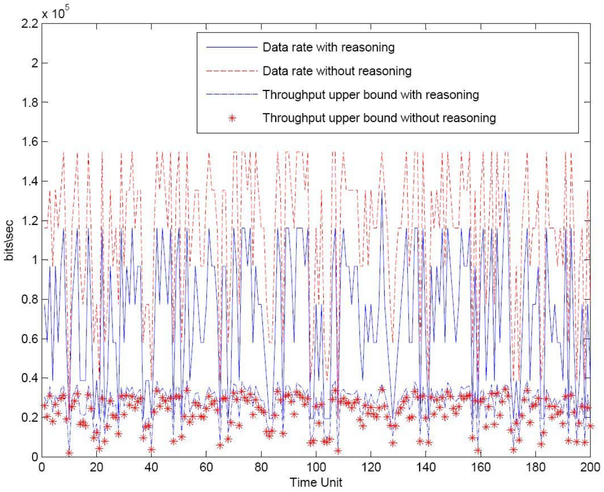


Fig. 2. Throughput upper bound vs data rate with reasoning and without reasoning

The simulation results of data rate of our proposed knowledge-based reasoning approach and the stopping algorithm proposed in [10] are shown in Fig. 6. It is seen that the average data of our proposed reasoning approach is close to those of stopping algorithm. It is because that our proposed algorithm relies on proactive fast sensing and

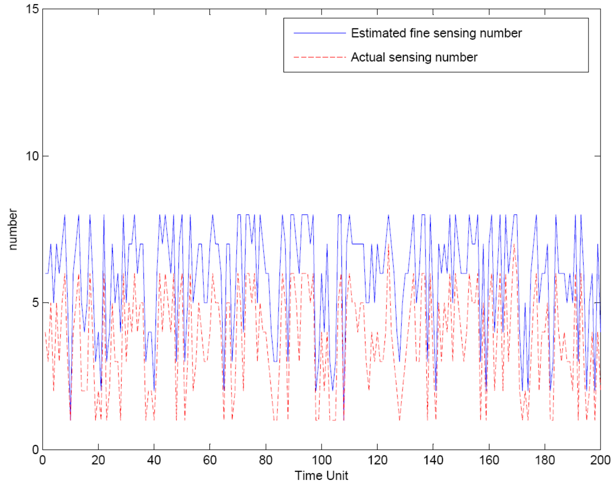


Fig. 3. Optimal value of fine sensing n vs actual number of fine sensing j

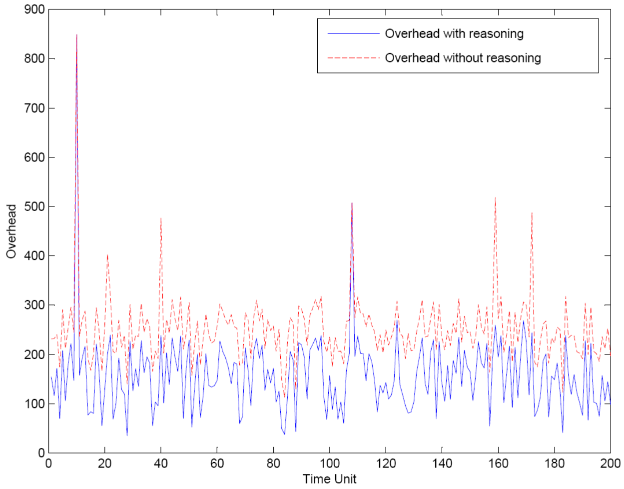


Fig. 4. Overhead weight comparison between reasoning and non-reasoning

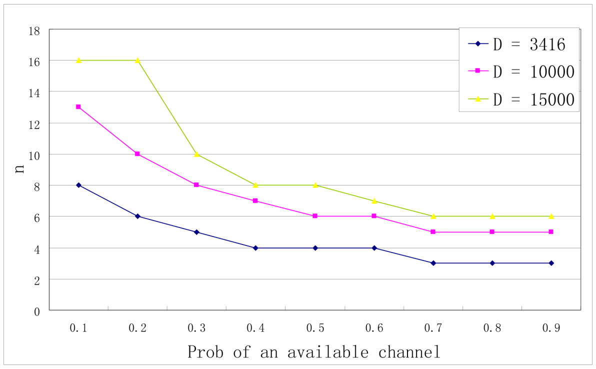


Fig. 5. Relationship between estimated fine sensing number and the channel condition

channel quality information as priors to determine a better range of spectrum for further fine sensing, and the estimated number n of spectrum sensing within the time constraint. These two factors make our results close to those with lengthy spectrum sensing which relies on the fixed truncated number. However, the higher data rate may not be achievable in real situation due to the lengthy sensing at a high risk of losing spectrum opportunities caused by channel fluctuation. For a further comparison, the simulation results of throughput of our proposed reasoning approach and the stopping algorithm described in [10] are shown in Fig. 7. It is seen the overall throughput of our proposed knowledge-based reasoning algorithm is higher due to the selection of a better range of spectrum and the reduction of sensing overhead.

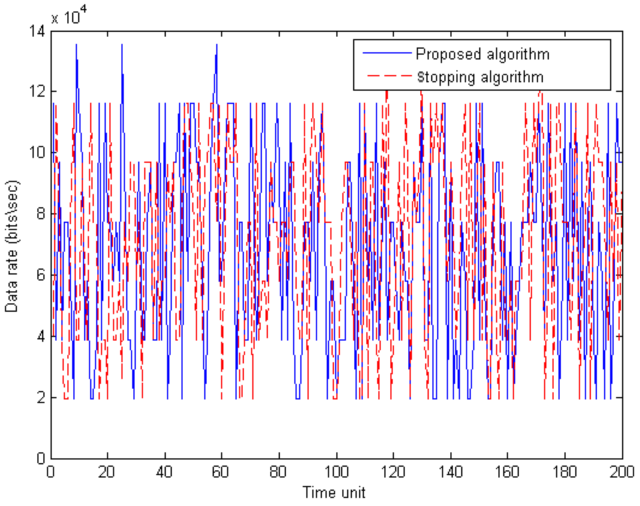


Fig. 6. Simulation results of data rate in comparison

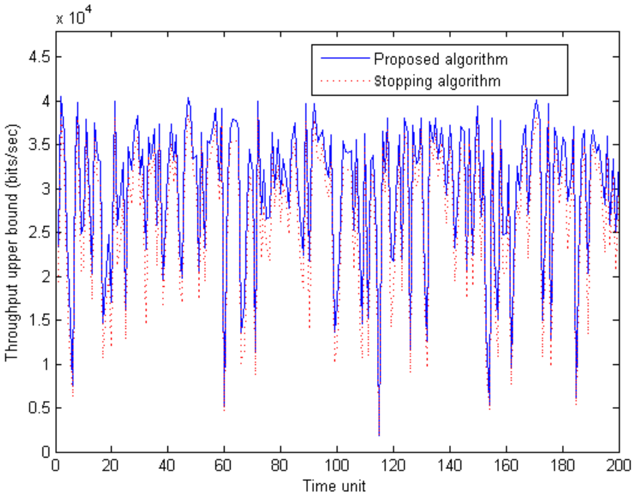


Fig. 7. Simulation results of throughput upper bound in comparison

VI. CONCLUSION

In this paper, we introduced an efficient MAC layer spectrum sensing algorithm based on a knowledge-based reasoning approach. The proposed sensing algorithm with knowledge-based reasoning can effectively realize the spectrum fine sensing, where the optimal throughput can be achieved by finding a balance between the transmission time and required sensing cost through the utilization of proactive fast sensing and channel quality information priors. Simulation was conducted to verify the proposed spectrum sensing algorithm and compare it with existing state-of-the-art algorithms. The simulation results demonstrated the effectiveness of the proposed algorithm, where the resulting throughput by sensing with knowledge-based reasoning is almost two times higher than the case without reasoning as well as higher than existing state-of-the-art sensing algorithms.

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