Key MAC Layer Technologies of Cognitive Radio Network

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Abstract:
As a smart spectrum sharing technology, Cognitive Radio (CR) is becoming a hot topic in the field of wireless telecommunications. Besides providing traditional services, the cognitive radio network Media Access Control (MAC) layer is required to perform an entirely new set of functions for effective reusing spectrum opportunity, without causing any harmful interference to incumbents. Spectrum sensing management selects and optimizes sensing strategies and parameters by the selection of sensing mode, sensing period, sensing time, sensing channel, and sensing quiet period. Access control avoids collision with primary users mainly by cooperation access and transparent access. Dynamic spectrum allocation optimizes the allocation of uncertain spectrum for binary interference model and accumulative interference model. Security mechanism adds authentication and encryption mechanisms to MAC frame to defense MAC layer security attacks. Cross-layer design combines MAC layer information with physical layer or higher layers information, such as network layer, transmission layer, to achieve global optimization.

As Cognitive Radio (CR), a smart spectrum sharing technology, effectively alleviates the contradiction between the scarcity of spectrum resource and the increasing demand for wireless access by means of secondary utilization of licensed spectrums, it is drawing more and more attention.

To avoid harmful interference of CR users on licensed users when CR users make use of spectrum holes, the Media Access Control (MAC) layer of CR network is required not only to provide traditional services, such as media access control and robust data transmission, but also to support a series of new functions so as to achieve effective opportunistic spectrum utilization without interfering with licensed users. These new functions cover almost all aspects of the MAC layer, including spectrum sensing management, access control, dynamic spectrum allocation, security mechanism and cross-layer design.

This work was supported by the National Natural Science Foundation of China under Grant No. 60772110.

1 Spectrum Sensing Management

The spectrum sensing management function of the MAC layer is mainly used to control the execution of spectrum sensing algorithms at the physical layer, for instance, to decide which channels to be detected and when to detect them. Current research on spectrum sensing management at the MAC layer focuses on selection and optimization of sensing policies and parameters such as sensing mode, sensing period, sensing time, sensing channel and sensing quiet period.

By sensing times of CR users, the sensing modes can be divided into periodic and on-demand sensing. In the periodic sensing mode, a CR user performs channel sensing continuously at certain interval irrespective of whether it has a packet to transmit. With the status information of channels being periodically collected, this sensing mode helps to estimate channel conditions and quickly locate spectrum holes. In on-demand sensing, channel sensing is started only when a CR user has a packet to transmit. Compared with periodic sensing, the on-demand sensing mode reduces unnecessary sensing costs, but it takes a long time to discover spectrum holes. Reference [1] develops a pattern for adaptive selection of sensing mode by leveraging energy consumption and idle-channel discovery delay on the principle of energy efficiency.

In periodic sensing, a key point is proper setting of sensing period. If the period is too long, some idle spectrums can not be discovered, leading to loss of some access opportunities, and harmful interference on licensed users may occur due to their presence not being timely detected. If the period is too short, sensing will be performed frequently, resulting in unnecessary energy consumption. Periodic sensing is often performed with two mechanisms: synchronous and asynchronous. In the synchronous mechanism, start times and sensing periods of all channels are the same, so it is easy to implement, but not flexible enough. In contrast, the asynchronous mechanism is very flexible and thus attracts more attention.

Reference [1] proposes an adaptive asynchronous sensing-period optimization mechanism, aiming to minimize loss of access opportunities. This mechanism sets sensing period adaptively for each channel, which is helpful for reducing the delay in finding an available channel and maximizing access opportunities. But for each channel, the sensing period is fixed. In other words, the optimal sensing period cannot be changed once it is determined. Hence, it is still a sensing mechanism based on fixed sensing period. To improve the fixed period-based sensing mechanism, Reference [2] suggests a sensing mechanism based on Flexible Sensing Period (FSP) and introduces the "period control factor". By adjusting this factor to shorten the sensing period in the regions where channel conditions are likely to change, the mechanism enhances sensing efficiency, embodying its flexibility in a period change. To extend the sensing period to a general form as a random variable, Reference [3] introduces a Random Asynchronous Periodic Spectrum Sensing (RAPSS) scheme and presents a generalized Markov analytical model—Maximum Reward Model of Sensing Period Optimization (MRM-SPO). This model takes into account detection errors brought by the limitation of sensing algorithms at the physical layer as well as the impact of CR users delayed occupancy channel mechanism, which is used to avoid collision with licensed users on spectrum usage, on sensing period optimization.

Sensing time is another important parameter in periodic sensing. A proper sensing time is essentially a compromise between sensing quality and sensing speed. Shortening the time is likely to degrade sensing quality; while prolonging the time can improve sensing quality but it reduces the utilization of idle spectrums. Besides underlying hardware and sensing algorithms at physical layer, CR users' utilization of idle spectrums[4] and tradeoff between sensing speed and sensing performance[5] should be considered.

To quickly find spectrum access opportunities, sensing channel should be properly selected in addition to sensing time optimization. With regard to selection of sensing channel, current research mainly focuses on selecting the most possible idle channel for sensing[6] and optimizing channel sensing sequence[1].

The setting of sensing quiet period is also an important subject in the research of spectrum sensing management at the MAC layer. From the perspective of CR network, when a CR user detects a spectrum in the network, other users of the system that operate on the spectrum should keep quite for a certain period, making sure the CR user's communication will not interfere with its sensing of licensed users' signals. This period is called quiet period. By implementation method, quiet periods are divided into two kinds: synchronous and asynchronous[7]. In a synchronous quiet period, all CR users stop to transmit signals on all available channels in the system so that each CR user can sense all channels. This period is easy to set. In asynchronous period, one or several CR users stop to transmit signals on the channels they occupy. As a result, different quiet periods can be assigned for these channels and each CR user can detect the channels it occupies only. As the implementation of synchronous quiet period requires support from dynamic broadband filter, current research pays more attention to asynchronous quiet periods, including guard-interval based asynchronous quiet periods and asynchronous quiet periods that do not overlap each other[8].

2 Access Control

The access control function of MAC layer is used to decide whether a CR user can access the network and which access strategy should be used. It is a basic prerequisite for spectrum allocation optimization. Because licensed users take absolute priority in accessing the channels, CR users act as slaves in accessing the channel dynamically. This master-slave relation between them is depicted in this process: When licensed users do not occupy the channels, CR users take the opportunity to access and use them; but when licensed users re-appear, CR users have to timely exit the channels so as to avoid collision with licensed users. Often, all channels shared by licensed users and CR users form a spectrum sharing pool. Depending on the presence of CR users to be considered by licensed users or not, the access control schemes of CR users can be classified into two kinds: coordinated and transparent.

2.1 Coordinated Access Control

If the access control policy of a licensed user is adjustable for CR users, CR users can negotiate with the licensed user to access the spectrum pool. In this access scheme, the licensed user detects the presence of CR users and automatically selects an idle channel in the sharing pool to access. If there are idle channels in the sharing pool, CR users can continue to use the channels they are occupying; otherwise, their services may be forcedly interrupted by the licensed user. Because the licensed user considers the presence of CR users when it accesses the channel, CR users' services will be forcedly interrupted only when spectrum resources are insufficient or the licensed user's call requests are blocked. With spectrums being shared by licensed users and CR users, the overall utilization of spectrum resources is greatly improved. Simulation results show that this access scheme can increase the channel utilization η by up to 40%, and restrict the block probability P_b under 10% and a forced interruption probability P_f of about 0.1%[9], compared with schemes adopted in current communication systems where licensed users exclusively occupy the channels. However, this scheme requires some changes in the licensed user network, for example, adding a control channel, which are often difficult to implement in real networks.

2.2 Transparent Access Control

A more realistic situation is: The licensed user does not consider the presence of CR users when it accesses a spectrum. That is to say, whether CR users occupy spectrums is completely transparent for the licensed user. In this case, CR users should adopt flexible access control polices to enable licensed user's transparent access and minimize the impact of the re-presence of the licensed user on their services. If all licensed users always treat their access spectrums as idle spectrums and do not care if these spectrum are being used by CR users, any a CR user in the network may risk forced service interruption. In the same simulation environment as the coordinated access control scheme, the η and P_b of transparent access control are almost the same as those in coordinated scheme, but its P_f increases nearly by an order of magnitude. High P_f has great impact on CR services, especially real-time communication services. As a result, decreasing P_f has become an important issue. Currently, two main approaches have been worked out: Channel reservation and prediction.

(1) Channel Reservation Based Transparent Access

Channel reservation based transparent access is an effective strategy of reducing CR users, P_f. The channels can be reserved for either licensed users or CR users. In case the channels are reserved for licensed users, licensed users first select idle reserved channels for access. If all the reserved channels are occupied, non-reserved channels will be used. Supposing R channels are kept for licensed users, at most $M-R$ channels are available for CR users' access. This scheme reduces the possibility of CR user service interruption (i.e. P_f) by letting licensed users first access reserved channels. But meanwhile, it decreases the number of channels available for CR users, thus enlarging P_b. In case the channels are reserved for CR users, CR users will switch over to other reserved channels when the licensed user of the channel occupied appears again. This scheme does not control licensed users' access, leaving the licensed user network unchanged, but it also increases P_b. In short, the core idea of the channel reservation based access control approach is to reduce P_f by reserving certain spectrum resources for licensed users or CR users. It is a virtual method of improving P_f performance at the cost of degrading P_b performance. Often, a tradeoff between P_b and P_f is achieved by working out the optimal number of reserved channels.

(2) Prediction Based Transparent Access

Channel reservation based access schemes can reduce P_f to some extent, but CR users have to quit the channels passively when they collide with licensed users. This will not only bring harmful interference on licensed users, but also cause CR users' transmission to be frequently interrupted. In the case the channels are reserved for CR users, the switchover of CR users from one channel to another will inevitably cause some delay. In the prediction based transparent access, CR users actively select the best channel access opportunities by predicting the channels' characteristics, including channel occupancy rules of licensed users, locations of possible spectrum holes and their durations of being idle, thus reducing the probability of collision with licensed users. The prediction method can be simple estimation from historical information or some complicated intelligent algorithms.

Based on such historical information as dynamic change in the occupancy and idle status of channels, Reference [10] proposes a heuristic prediction based access algorithm, which estimates the availability of a channel from the perspective of available time. Reference [11] suggests a Hidden Markov Model (HMM) based channel prediction algorithm, which works out the time and duration of spectrum holes by predicting the spectrum occupancy of licensed users. CR users then decide which channels to use based on the probabilities of spectrum holes. In this way, a CR user can timely leave the channel that will be used by licensed users in the next time slot based on the prediction information rather than be forced out of that channel upon the sensing of the licensed user, thus greatly reducing the occasions of collision with licensed users.

3 Dynamic Spectrum Allocation

As idle spectrum resources are limited, CR users have to contend for these resources. Besides, the priorities and Quality of Service (QoS) requirements of CR users differ. As a result, CR network should not only guarantee that CR users with high priorities are served earlier than other users, but also prevent spectrum resources being exclusively occupied by some users, ensuring idle spectrum resources to be fairly and effectively managed. The main purpose of idle spectrum allocation is to fairly and effectively allocate the limited resources based on CR users' priorities and QoS classes, enabling network performance to be improved or optimized to an ultimate degree.

However, affected by licensed users' usage of spectrums, the number and locations of spectrums available for CR users vary with time. Optimizing allocation of these uncertain spectrum resources is actually a problem of allocating limited spectrums. The most important feature of spectrum allocation technologies of CR network is real time, which distinguishes them from other wireless spectrum allocation technologies. The real-time feature means the execution time of spectrum allocation algorithm should be as short as possible because the spectrum occupancy of licensed users is a random process and available spectrums keep changing. The improvement of real time performance is reflected in several aspects, such as decrease in algorithm complexity and reduction in signaling overhead.

In spectrum allocation algorithms, if only two cases are considered for the interference results between CR users and licensed users and between CR users: non-interference and interference, which can be denoted by 0 and 1 respectively, binary interference model is set up. If the interference of several users on a licensed of CR user is taken into account, which is often the case, accumulative interference model is established, where each CR terminal is required to measure the local interference temperatures of different bands. In binary interference model, if the interference result of a band is 1, CR users can not be assigned to this band; while in accumulative interference model, CR user cannot be assigned to a band only when the accumulative interference temperature of several CR users in the band exceeds the threshold. Corresponding to these two interference models, there are two types of spectrum allocation algorithms.

(1) Spectrum Allocation Based on Binary Interference Model

Most of existing binary interference model-based spectrum allocation algorithms are built on graph coloring theory. Depending on whether CR users cooperate with each other, these algorithms are further divided into two kinds: Cooperative and non-cooperative.

Cooperative spectrum allocation algorithms allow several CR users to exchange allocation information and negotiate spectrum allocation, so they have good performance. Reference [12], aiming at maximum channel utilization and fair allocation, proposes a Distributed Greedy Algorithm (DGA) and a Distributed Fair Algorithm (DFA) respectively. To reduce the complexity, it also presents a Randomized Distributed Algorithm (RDA), and points out that the algorithm with low complexity is preferred for CR network environment. The implementation time of DGA, DFA or RDA increases with the number of channels. To shorten such time, Reference [13] suggests a parallel algorithm, which breaks a complex graph into several simple subgraphs. This allocation algorithm is quite applicable to large systems. All the above algorithms assume network topology is fixed. For variable network topology, Reference [14] introduces a local bargaining approach where CR users affected by the mobility event self-organize into bargaining groups and only local optimization within the groups is required. Compared with DGA, this approach reduces the communication overhead by over 50%, but in terms of channel utilization, it does not perform as well as DGA. Besides, certain cooperative communication overhead is incurred within the group.

To share the cooperative information that is frequently exchanged among neighboring users, the above cooperative algorithms require common coordination protocols and control channels. This will inevitably complicate the system and incur extra overhead. Hence, these algorithms are not suitable for communication systems with constrained energy, such as Ad hoc network and wireless sensor network. To address this issue, Zheng et al[15] propose a rule-based approach, where users observe local interference patterns and independently adapt their spectrum usage using a set of rules preset for various scenarios, thus achieving tradeoff among system performance, implementation complexity and communication costs. Experiments show that this rule-based non-cooperative approach reduces communication costs by a factor of 3-4 while providing as good performance as cooperative approaches.

(2) Spectrum Allocation Based on Accumulative Interference Model

The majority of existing accumulative interference model-based spectrum allocation algorithms are built on game theory. By CR users' occupancy of spectrums, these algorithms can be divided into two kinds: shared and exclusive.

Shared spectrum allocation means spectrum resources are allocated among several CR users in a way of interference avoidance or time division multiplexing. As several CR users share the same spectrum band, co-channel interference is unavoidable. Hence, a big challenge of this kind of algorithms is how to reduce the co-channel interference and maximize CR users' gains. For various sharing scenarios, different models and algorithms have been worked out respectively in recent research. One scenario is that licensed users can only offer few spectrum resources for CR users, so several CR users have to contend for the limited spectrums. This scenario can be abstracted into a Cournot game model, which is an economic model used to analyze the oligopoly market where supply cannot meet demand. Taking into account only the interference between CR users rather than the interference of CR users on licensed users, Reference [16] proposes interference utility functions based on the potential game theoretic model. The potential game is applicable to utility functions for cooperative users, and its convergence speed is fast. It is not suitable for the case of selfish users, where no-regret learning algorithm can be applied. Simulation results show that no-regret learning algorithm converges to a mixed strategy Nash equilibrium. With the objective of maximizing overall transmission rate of several CR users on all channels, Reference [17] suggests a utility function from the perspective of avoiding collisions from spectrum contention among CR users. Several CR users avoid conflicts by adjusting their transmission probabilities on available channels, thus increasing the overall transmission rate. To achieve the correlated equilibrium, Reference [17] also proposes an adaptive algorithm based on no-regret learning that guarantees convergence, and proves that this algorithm converges to correlated equilibria at the probability of 1. According to simulation results, optimal correlated equilibria achieve 5-15% performance gain, compared to Nash equilibria.

In exclusive spectrum allocation, the co-channel interference will not occur because each user occupies a spectrum exclusively. The contention among CR users is purely for spectrums. Suppose there are several licensed users who rent spectrums and several CR users who buy spectrums in the system. The licensed users rent their unused spectrums by auction and the CR users get spectrums by way of bidding. This relationship can be modeled with double auction rules in the game theory. As there exist several licensed users and several CR users, not only the CR users but also the licensed users have to contend with each other. In the double auction model, a CR user has to select its bidding price based on other users' quotes, so frequent information exchange is involved among users. However, in actual systems, it is difficult to achieve any bilateral bargaining in the double auction because of the time-variance of spectrums and the selfishness of users. To solve this problem, Reference [18] improves the double auction model and proposes a belief-assisted dynamic pricing approach based on double auction rules for the scenario without central control but with selfish users. This approach predicts the belief of other user strategies with historical information, which can be used to guide user decisions, thus achieving efficient bargaining under the condition of incomplete information. It can also take advantage of the expansion and shrink rules in the double auction model to further quicken the convergence.

4 Security Mechanism

The introduction of CR technologies brings some new security vulnerabilities for CR networks in addition to security problems present in traditional wireless networks. At the MAC layer, CR networks are vulnerable due to their inherent problems such as synchronization of spectrum sensing and lack of common control channel. In sum, there are four new attacks against the MAC layer of CR network:

(1) Biased Utility Attack

In this attack, a selfish CR user modifies parameters of the utility function for MAC layer spectrum allocation to get more spectrums. If other CR users or the base station cannot detect such an abnormal behavior, the spectrum resources available for other CR users will be reduced.

(2) Asynchronous Sensing Attack

When other CR users conduct synchronous sensing in a quiet period, a malicious CR user sends signals in an asynchronous way. Consequently, the base station or other CR users erroneously think they are sent by the licensed user, thus missing the spectrum access opportunity.

(3) False Feedback Attack

In false feedback attack, a malicious user harms the fairness of allocation or triggers wrong behaviors of other nodes by returning false spectrum sensing or allocation information. This attack can be implemented in both centralized and distributed CR networks. In centralized CR networks, this attack often occurs when the malicious node returns false spectrum sensing information to the base station. As the base station makes decisions by way of information convergence, the implementation of this attack requires lots of malicious nodes to report the same false information. Consequently, the attack efficiency is quite low. In distributed CR networks, CR users coordinate channel allocation by means of information exchange. If one or a group of malicious users send false information about the licensed users' spectrum occupancy status or channel's availability, other users may make wrong decisions, thus interfering with licensed users or losing spectrum access opportunities.

(4) Control Channel Saturation Attack

In CR networks, the common control channel is both a bottleneck of network performance and a critical point in network security. The following two cases of common control channel decrease network performance, making it a bottleneck: First, traffic increase leads to frequent control information interaction, which may cause the control channel to be saturated; second, the collisions of control information packets reduce the effectiveness of control mechanism and affect the channel allocation negotiation process. The reason why common control channel is a critical security point is that attackers can send lots of false MAC control information to saturate the control channel, preventing legal CR users from using the control channel to negotiate channel allocation, thus leaving CR network unavailable.

The above attack behaviors are implemented mainly by means of modifying or forging MAC frames. In centralized networks, authentication mechanisms of MAC frames can be included. For example, in IEEE 802.22 Wireless Regional Area Network (WRAN), four special modularized security sublayers are created with Base Station/Customer Premises Equipment (BS/CPE) protocol reference model to protect data, authenticate spectrum sensing and location information and verify configuration information of spectrum management entities. In contrast, in distributed CR networks, as no trustable entity acts as a server to control the key distribution, which is designed to encrypt authentication and protect integrity, it is very difficult to apply security sublayers. Therefore, neighboring node monitoring mechanism is more suitable for them.

5 Cross-Layer Design

The design of the above MAC layer key technologies is often restricted by traditional layered protocol models. To meet the characteristics of CR network, i.e. adaptive to dynamic wireless environment, a key issue is how to design and implement globally optimized MAC layer technologies based on physical layer and upper layer information, which has now become one hot research topic.

In terms of cross-layer design between MAC and physical layers, Reference [19] proposes a spectrum sharing algorithm based on sensing contribution weighted proportional fairness, which combines spectrum allocation of MAC layer with spectrum sensing of physical layer and assigns the largest portion of spectrums to the CR user who contributes the most in the spectrum sensing. In this way, not only fair spectrum allocation is realized, but also the system throughput is maximized. Reference [20] suggests Bandwidth and Power Control Game (BPCG) algorithm, which integrates spectrum allocation of MAC layer with power control of physical layer. This algorithm exploits spectrum resources and increases network throughput by means of efficient spectrum allocation, and at the same time, reduces interference between users.

As to the cross-layer design between MAC layer and network layer, studies show that the combination of spectrum allocation of MAC layer with route selection of network layer can significantly increase both connection reliability and end–to–end throughput[21]. The basic idea of this design is to incorporate route selection and spectrum allocation tasks into a single task at the network layer, letting the network layer select the route and schedule conflict–free channel usage on the route. Based on this idea, Reference [22] suggests a collaborative route and spectrum allocation solution. The collaboration between MAC and network layers is achieved through a hierarchical route and channel selection process. This solution, i.e. selecting the route while scheduling the conflict–free channel usage on the route, improves route reliability as well as end–to–end throughput.

Between MAC and transport layers, the cross–layer design integrating spectrum allocation of MAC layer and Transmission Control Protocol (TCP) protocol at the transport layer can avoid the impact of dynamic spectrum change on TCP Retransmission Time–Out (RTO) mechanism. A possible solution should look like this: TCP protocol first learns the current band of a CR user based on spectrum allocation of MAC layer, works out Round Trip Time (RTT) of the band and sets RTO parameter accordingly. When spectrum allocation changes at the MAC layer, TCP protocol re–computes the RTT and then adaptively adjusts RTO parameter, enabling optimization of the protocol performance.

6 Conclusion

CR network is a hotspot in current research, and in particular, the key technologies of its MAC layer draw special attentions. At present, the studies on spectrum sensing management, access control, dynamic spectrum allocation, security mechanism and cross–layer design of MAC layer still stay at the theoretical level. With persistent efforts of researchers, it is expected that CR networks would be put into actual application in the near future.

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