Abstract of Doctoral Dissertation

Studies on Spectrum Sensing and MAC layer Protocol for Wireless Mesh Networks

メッシュ型無線ネットワークにおけるスペクトラム検知と MAC 層プロトコルに関する研究

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The current spectrum regulatory rule, which exclusively allocates wireless spectrum to different specific applications and forbids violation from unlicensed users, has resulted in the unbalanced spectrum utilization. On one hand, some spectrum bands such as the ISM band are very crowded; on the other hand, most of the allocated spectrum bands are significantly underutilized in different locations and times. Such an unbalanced spectrum utilization problem can be alleviated by the emerging dynamic spectrum access techniques such as cognitive radio. As the fundamental component of dynamic spectrum access, implementing spectrum sensing is one of the most important goals in cognitive radio networks due to its key functions of protecting licensed primary users from harmful interference and identifying spectrum holes for the improvement of spectrum utilization. However, the performance of the local spectrum sensing, performed by a single cognitive radio, cannot work well when it is suffering from multi-path fading, shadowing, and receiver uncertainty. To overcome such challenges, cooperative spectrum sensing is usually employed. Since the typical architecture of cooperative spectrum sensing is similar to the wireless mesh networks, the cognitive wireless mesh networks have attracted more and more attentions in the recent years. Therefore, this dissertation focuses on the study of the cooperative spectrum sensing for cognitive wireless mesh networks, specially, two aspects of which are involved in this dissertation: the spectrum sensing to effectively find the white spaces in the primary spectrum bands, and the MAC protocol for data transmission in the cognitive secondary networks. Although various local spectrum sensing techniques can be utilized, energy detection is the most widely used technique in the cooperative spectrum sensing because of its simplicity and no requirement on the prior knowledge of the primary signals. Thus, it is utilized in the cooperative spectrum sensing investigated by this dissertation. In spectrum sensing, there exist several challenges that compromise its performance, i.e., the inter-channel interference, the threshold setting, and the reporting channel allocation. This dissertation tries to address such challenges.

In chapter 1, the wireless mesh network and the spectrum sensing for cognitive radio are briefly introduced. At first, the architecture, characteristics, and the application scenarios of wireless mesh networks are described. Then, two main characteristics, cognitive ability and reconfigurability, are presented. Cognitive ability enables the radio technology to capture or collect the information from its operating environment. It consists of four steps: the spectrum sensing, management, sharing, and mobility. The reconfigurability is the capability of adjusting the transmission parameters of the radio to adapt to the working environment without any modification of the hardware.

In chapter 2, the well known spectrum sensing techniques and MAC protocols of wireless mesh network are briefly overviewed. In the local sensing, the pros and cons of various sensing techniques are analyzed and compared. Such techniques include energy detection, covariance detection, eigenvalue detection, cyclostationary detection, and wavelet detection. In cooperative spectrum sensing, the implementation model and evaluation metrics are firstly introduced. Then, the implementation steps, pros, and cons of hard combining and soft combining are presented, respectively. In the review of MAC protocols of wireless mesh network, the typical single radio single channel MAC, single radio multi-channel MAC, and the multi-radio multi-channel MAC are briefly
introduced. The advantages and disadvantages of such MAC protocols are analyzed and compared.

In chapter 3, the performance improvement through interference cancellation is firstly analyzed. The analysis indicates that the performance of cooperative spectrum sensing can be improved by interference cancellation in terms of probability of detection and probability of false alarms. Then, the non-coherent power decomposition-based energy detection method for cooperative spectrum sensing is proposed to alleviate the impact of the inter-channel interference and improve the detection performance. Due to its use of power decomposition, the interference power, background noise power, and the target signal power can be individually separated from the superposed received power, and thus, interference cancellation can be applied in energy detection by subtracting it from the total received power. The proposed power decomposition does not require any prior knowledge of the primary signals. The power decomposition with its interference cancellation can be implemented indirectly by solving a non-homogeneous linear equation set with a coefficient matrix that involves only the distances between primary transmitters and cognitive secondary users (SUs). The optimal number of SUs for sensing a single channel and the number of channels that can be sensed simultaneously are also derived. The simulation results show that the proposed method is able to cope with the expected interference variation and achieve higher probability of detection and lower probability of false alarm than the conventional method in both hard combining and soft combining scenarios. Since the proposed power decomposition scheme depends on the distances between primary transmitters and cognitive SUs, the position accuracy of both primary transmitters and cognitive SUs has an impact on the performance of cooperative spectrum sensing. However, the analysis of position accuracy indicates that the impact is so weak that it can be ignored when the inaccuracy of both primary transmitters and cognitive SUs is very small compared to the distances between these two kinds of nodes.

In chapter 4, both the threshold setting problem and the reporting channel problem are addressed. In order to address the threshold setting problem, different from the conventional method, which cannot optimize both the probability of false alarm and the probability of detection since it sets the determination threshold to a target probability of false alarm, an optimal threshold setting method is proposed in this chapter. The optimal threshold is able to minimize the sum of the probabilities of false alarms and missed detection. It depends only on the means and variances of the power samples when the primary signals are absent and when they are present. The derivation process of optimal threshold setting indicates that it is more accurate when the number of samples of test statistic is large due to the application of central limit theorem, which corresponds to the cases that the SINR is low. Then, it is successfully applied in the power decomposition method described in chapter 3. In addition, the reporting channel will become the bottleneck when the number of cognitive radios need to be coordinated becomes large in the soft combing scenario. In order to address the bottleneck problem, multiple in-band orthogonal channels are designated as reporting channels. In this scheme, a multi-radio conflict graph is utilized to model the co-channel interference, and the vertex coloring algorithm is applied to the multi-radio conflict graph to figure out the reporting channel allocation results. By considering the traffic pattern of sensed data transmission, a Breadth First Search (BFS) in a bottom-up order is applied in the vertex coloring algorithm to decrease the complexity. Simulations verify the feasibility of the optimal threshold setting and
show that it can work well in the low SINR range and can achieve low sensing delay.

In chapter 5, the MAC protocol of secondary wireless mesh network is investigated. In this chapter, a two-stage coordination multi-radio multi-channel MAC (TSC-M2MAC) is proposed. It can be utilized to solve the bottleneck problem, resulted from the increasing number of concurrent traffic flows in the single common control channel. It designates all the available in-band orthogonal channels as both control channels and data channels in a time division manner through a two-stage coordination. On the first stage, similar to the reporting channel allocation in chapter 4, the multiple control channels allocation is performed. However, the vertex coloring algorithm is performed in a top-down order since the links with less hop counts should be given higher priority of allocating channels with less interference according to the traffic pattern of wireless mesh networks. On the second stage, a REQ/ACK/RES mechanism is proposed to dynamically channel allocation for data transmission. The control messages, i.e., REQ, ACK, RES, and periodically transmitted beacons and pilots, are exchanged in the pre-allocated control channels on the first stage. In this stage both the primary channel and the secondary channels can be allocated. The proposed TSC-M2MAC is able to alleviate the multi-channel hidden terminal problem when using multiple control channels and cope with the variation of the number of concurrent traffic flows. In addition, a power saving mechanism is designed for TSC-M2MAC to decrease its power consumption. Simulation results show that the TSC-M2MAC protocol is able to achieve higher throughput and lower end-to-end packet delay than conventional schemes. They also show that the TSC-M2MAC can achieve load balancing, save energy, and remain stable when the network becomes saturated.

In chapter 6, I conclude the dissertation and state the future works.
<table>
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<tr>
<th>Category (Subheadings)</th>
<th>Articles in refereed journals</th>
<th>Presentations at International conferences</th>
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