Spatial Spectrum-Sharing Strategy in Cognitive Radio Networks

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Abstract—This paper presents a new spectrum-sharing strategy based on spatial information about mutual interference constraints, temporal spectrum usages and positions of devices. This strategy can solve the coexistence problem of Cognitive Radio (CR) networks and simplify the design of CR devices. In fact, it is a cross-layer design strategy that integrates useful information obtained from the physical, MAC and network layers, in order to fully explore available spectrum resources without introducing interference to existing licensed incumbents.

1. Introduction

In recent years, the Cognitive Radio (CR) technique has developed rapidly. CR originates from the concept of software-defined radio and provides an adaptive solution for flexible usage of stringent radio spectrum resources. Especially, the IEEE 802.22 Wireless Regional Area Network (WRAN) Working Group is developing a standard of CR network intended to operate world wide in the unused segments of the terrestrial TV broadcast bands [1]. The main problem of a CR network is the coexistence with the Licensed Incumbent Users (LIU), which are the owners of licensed spectrum and have higher priorities. A practical CR device, or in other words, Customer Premise Equipment (CPE), shall not interfere with the existing LIUs. Although there are many literatures discussing the spectrum sensing function of the CPE, it is still difficult for the CPE to learn or estimate the spectrum occupation and usage of LIUs, as well as the interference level to LIUs nearby, because LIUs usually are receiving purpose only devices like TV sets and thus “hidden” out of the scope of the CPE. Therefore, it would be beneficial to the CPE that the CR network can provide some aids.

From the viewpoint of networking, the relevant spatial information can be spread in a centrally controlled way such as beacon transmitter or in some ad hoc distributed method. Necessary control functions are also defined. All useful information, such as spectrum usage, interference level, radio parameters, node position, network status, and so on, should be gathered to help the decision making of spectrum sharing and channel allocation. For example, the CR device can utilize the basic spectrum sensing function in physical layer to know available empty bands. Then, beacon signals identifying incumbent users can be enhanced to carry information about spatial-temporal spectrum usages. A kind of location-aided scheme can be applied to estimate and mitigate the mutual interference.

We derive a distributed networking solution to realize the negotiation procedure of spectrum allocation among CR devices. The CR network in a whole will have consistent knowledge of spectrum occupation and usage of its surroundings, and thus it can realize the optimal spectrum sharing throughout the network.

The author of [2] gives the theoretical results of capacity under spatial spectrum-sharing constraints; however those results are a little impractical and can not be directly applied in the CR network discussed in this paper. We try to develop own evaluation tools to learn the performance of real network. The simulation results show that the capacity of the CR network can be improved and at the same time the mutual interference between the CR network and existing licensed wireless networks can be controlled.

This paper is organized as follows. Section 2 discusses the mutual interference between LIUs and CPEs, while the aid of geo-location information is introduced. Section 3 proposes a cross-layer dynamic channel allocation DCA strategy, in which spectrum sensing, interference mitigation, location-aided control, and distributed computing etc. are combined to fully exploit available bands. Section 4 gives some preliminary evaluation results. Finally, our conclusions are given in Section 5.

2. Mutual Interference and Geolocation

In this section, we will discuss the problem of mutual interference between LIUs and CPEs. For the convenience, it is assumed that positions of all devices are known and devices have circular communication ranges with sharp boundaries. Therefore, the coverage distance of a TV transmitter is defined as $R_{TV}$. The radius of protection for LIU is $R_P$ and the beacon distance is $R_B$ if a kind of local beacon is used to identify LIU. The transmission (reception) ranges of CPEs are all the same as $R_C$. Generally, we have $R_{TV} >> R_B > R_P > R_C$, because the CPE should not interfere with the LIU under any conditions. It would be suitable for CR networks to be deployed in the rural or suburban areas near the coverage margin of TV signals, since LIUs are sparse there and potentially available bands are not too stringent. Fig. 1 and Fig. 2 below show simple but typical enough scenarios of CR networks.

2.1. CPE is outside the Protection Range of LIU
In Fig. 1, there are two CPEs, CPE$_1$ and CPE$_2$, which are within the communication range of each other and are all outside the protection range of the LIU. Also, CPE$_1$ and CPE$_2$ are far away from the TV Transmitter. It is obvious that the transmission between CPE$_1$ and CPE$_2$ introduce no interference to the LIU, so it is reasonable for these CPEs to utilize all TV bands to accelerate the data speed whether or not these bands are used for ongoing TV signals.

It should be noticed that CPE$_1$ is shadowed by signals from the TV Transmitter. When CPE$_2$ is receiving data packets from CPE$_1$ using the same bands as TV signals, CPE$_1$ suffers interference from the TV Transmitter. One possible solution is that CPE$_1$ performs spectrum sensing in order to find empty bands and then informs CPE$_2$ to transmit only on those bands. However, if we adopt some interference mitigation technique, the ongoing TV bands that are currently on-the-air could be reused by CPEs. On the other hand, the transmission from CPE$_1$ to CPE$_2$ does not encounter such problem, so the maximal amount of frequency bands could be exploited in this case.

### 2.2. CPE is within the Protection Range of LIU

Fig. 2 is similar with Fig. 1, except that CPE$_2$ is within the protection range of the LIU, so CPE$_2$ may interfere with the LIU. If the LIU can only passively receive one or several TV channels at the same time, it is possible for the CPE to reuse the rest frequency bands of on-the-air TV signals under some conditions. For example, in addition to using the empty bands by applying spectrum sensing technique, CPE$_2$ still has chances to exploits other ongoing TV channels without interfering with the LIU, given that CPE$_2$ knows which TV channel is being received by the LIU and the interference can be controlled.

Such an example is illustrated in Fig. 3, in which spectrum graphs viewed by different devices are shown. Without the loss of generality, assume the investigated TV band has $N$ channels in total, while in this example $N = 8$. The TV transmitter broadcasts TV programs on 4 channels (Channel #3, #4, #5, #6). At this time, the LIU is, for instance, tuned on Channel #5 and receiving the corresponding program. Therefore, these 4 on-the-air TV channels can be detected by both CPE$_1$ and CPE$_2$ using spectrum sensing technique, and consequently the rest empty channels can be allocated to CPEs. In addition, by considering positions of CPEs and estimating interference to and from the LIU and TV transmission, CPE$_1$ could take Channel #3~6 as potential candidates if the interference can be controlled lower than a desirable threshold. Similarly, CPE$_2$ could regard Channel #3, #4 and #6 as its potential channels, since they are orthogonal with Channel #5 being received by the LIU in the frequency domain and thus there is no inter-channel interference. Meanwhile, it is possible for CPE$_2$ to use Channel #5 as a reception channel, if the interference from the TV transmitter is low. Of course, CPE$_2$ must not transmit on Channel #5.

### 3. Dynamic Channel Allocation: A Cross-Layer Design

It is a challenge to construct an efficient channel allocation scheme, which can dynamically manage radio resources in a real-time pattern according the environment. The channel allocation scheme should at least satisfy two basic requirements: 1) it can exploit as many as possible available frequency bands; 2) it must NOT produce more interference to LIUs than before. However, there are some tradeoffs between these two requirements.

Based on the discussion of the previous section, beyond the traditional spectrum sensing method, there would be
chances for CPEs to exploit more frequency bands, if more information concerned with spectrum usage of LIU, interference level, positions etc. can be obtained. It is also implied that in the CR network asymmetric links among CPEs could be set up, depending on their specific surroundings. Therefore, the channel allocation scheme should take into account various factors of different layers in order to satisfy the requirements of CPEs.

### 3.1. Physical Layer

The physical layer can perform basic frequency detection and spectrum sensing tasks in order to find available empty frequency bands. There are many proposals concerned with spectrum sensing, such as matched filter detection, energy detection, fine/feature detection and so on [3]. The CPE could implement the spectrum sensing function, but inevitably the complexity and cost of the CPE would increase. On the other hand, in order to simplify the CPE, the WRAN base station (BS) could centralize the spectrum sensing function and broadcast the results in its cell. Because the WRAN base station is more powerful, it can get more accurate results and all CPEs controlled by it can have the consistent knowledge of spare spectra.

Especially, the frequency bands occupied by devices having transmitting and receiving capabilities, for example, Land Mobile Radio Cellphones and Part 74 devices, shall always be detected and excluded from the list of candidate bands for CPEs. TV receivers usually only have reception functions and can not transmit their own signals actively, therefore more potential channels could be exploited with the aid from upper layers.

### 3.2. MAC Layer

1) Beacon Enhancement

As discussed before, if the CPE has the knowledge of which channel the neighboring LIU (typically, TV receiver) is currently being tuned on, it could have chance to use the bandwidth of the rest on-the-air TV channels at the same time. The local beacon is a good method of identifying the LIU, that is, the LIU itself or a special beacon transmitter periodically broadcasts signals in order to actively announce the existence of the LIU to the surroundings. It becomes easier for the CPE to find neighboring LIUs and act correspondingly. For example, the CPE can estimate the distance from the LIU according to the received beacon signal strength. In a beacon frame, more specific IEs can be added, such as the “LIU Position (optional)”, the “Beacon Transmit Power (to calculate the path loss and estimate the interference reversely)”. 

2) Positioning

The location information of neighboring nodes is important for CPEs to estimate interference to and from the existing LIU devices. Also, the location information can help the CPE decide if a link can be set up with the other CPE. The Global Position System is a mature positioning method suitable for CR networks, since the distance between nodes would be relative large. If the CPE uses some specific radio techniques, such as impulse-radio ultra wideband, the CPE can measure distances and positions by itself.

The position of the LIU could be obtained by reading the beacon frames. Then the location information could be exchanged among CPEs with an ad hoc manner. In the central-controlled structure, the base station of the CR network could broadcast the position information to all CPEs. In this case, the feedback mechanism from the CPE to the base station should be defined.

3) Interference Estimation

The purpose of interference estimation is to tell if the potential channels of a CPE can be really used or not. At first, based on the position information, the path loss model, its maximum transmit power etc., the CPE could estimate its interference to the LIUs nearby if its potential channels were deployed. For example, if the estimated interference level does not exceed a predefined threshold, the corresponding potential channel for transmission can be regarded as “available”. More precisely, this kind of estimated interference can be expressed on a per-LIU-and-channel basis as

\[ \sum_{m \in S} d_{m,w} P_{txch} \leq Q_I, \]  

where \( d_{m,w} \) denotes the path loss from CPE \( m \) to the location \( w \) of the LIU, \( P_{txch} \) the maximum average power that the CPE can output on one channel, \( Q_I \) the predefined constraint of the undesired interference, and \( S \) the set of all active CPEs having the same potential channel on which the LIU is being tuned. If (1) is not satisfied, the CPEs close to the LIU tend not to use the potential channel (according to the path loss) until the accumulated interference does not exceed the predefined constraint.

The interference estimation is also necessary for a receiving CPE that is shadowed by the TV transmitter. Besides some possible interference mitigation technique, the shadowed CPE can estimate its signal-to-interference-and-noise ratio (SINR), according to the interference level from TV signals, the distance to the transmitting CPE and the transmit power of CPE etc., as shown below

\[ \frac{d_{m,l} P_{txch}}{d_{m,TV} P_{TVch} + N} \geq Q_{SINR}, \]  

where \( d_{m,l} \) denotes the path loss from CPE \( l \) to CPE \( m \), \( d_{m,TV} \) the path loss from TV Transmitter to CPE \( m \), \( P_{TVch} \) the maximum average power of TV signals on one channel, \( N \) the power of the additive white Gaussian noise (AWGN), and \( Q_{SINR} \) the predefined SINR threshold. If the estimated SINR exceeds the predefined threshold, the corresponding potential channel for reception can be regarded as “available”.

### 3.3. Network Layer

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1) Update and Exchange Band Information
Each CPE in the CR network shall be continuously sensing and measuring its surroundings, determining its available transmission and reception channels, and sending relevant information to other CPEs. If there are some events occurred, for example, a neighboring LIU is powered on or off, a LIU is tuning its working channels, or the position of a LIU is changed, the CPE should be able to detect these changes quickly, adjust its available channels, update its frequency usage database and let other CPEs know about it.

In the CR network, all CPEs shall have the consistent consensus about the common set of empty channels (not occupied by TV transmitters or other transceivers), which should be a minimal intersection of all spectrum sensing results from CPEs. This common set of empty channels can be adopted to realize some network control functions and provide seamless data delivery throughout the network. On the other hand, the potential channels of a CPE can in addition be utilized to increase the frequency usage factor and improve the data throughput locally.

2) Channel Allocation Negotiation
Because CPEs at different locations would have different perspectives of their own “available” channels, a channel allocation negotiation procedure should be needed before a data link can be set up between two adjacent CPEs. Such a negotiation procedure can be categorized as one of functions in the control plane of the CR network. A dedicated control channel can be set up by utilizing a common frequency band that is not occupied by any TV channel throughout the CR network. The control packets can be exchanged in an ad hoc manner, or a base station controls the channel allocation among CPEs while CPEs should send some feedback about their “available” channels to the base station.

One channel allocation negotiation procedure for unidirectional transmission is shown in Fig. 4. If one CPE has data to transmit, it should at first send the “Allocation Request” control packet that contains a list of its available transmission channels to the intended receiver. After having received this “Allocation Request”, the receiver should check its own available reception channels to decide which channels can be allowed for receiving data. Then the receiver sends back “Allocation Confirm” that indicates allowed transmission channels to the transmitter. If this negotiation is completed successfully, both transmitting CPE and receiving CPE will tune on the same frequency bands and start data transmission. Similarly, the bi-directional link can be set up by exchanging available transmission channel sets and reception channel sets between two communicating CPEs.

4. Performance Evaluation
We use the MATLAB to run our simulation. Parameter settings [4] are listed in Table 1. For simplicity, there are several assumptions: the positions of all nodes are known; the spectrum sensing is perfect; the CPE can detect the working channel of the LIU and act correspondingly when the LIU is changing its receiving channel. In our simulation, only AWGN channel is considered.

The results show that the performance heavily depends on the network topology and positions of nodes. By utilizing the interference estimation and avoidance methods, more channels can be shared by CPEs, and thus the WRAN capacity can be improved.

TABLE I. Parameter Settings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DTV station transmit power</td>
<td>90 dBm, ERP</td>
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<tr>
<td>DTV operating frequency</td>
<td>615 MHz, UHF band</td>
</tr>
<tr>
<td>channel bandwidth</td>
<td>6 MHz</td>
</tr>
<tr>
<td>CPE transmit power</td>
<td>36 dBm, EIRP</td>
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<td>Propagation curve</td>
<td>f(50,10) for Interfering Contours</td>
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<td>Undesired interference</td>
<td>32 dBu</td>
</tr>
<tr>
<td>SINR threshold</td>
<td>10 dB</td>
</tr>
</tbody>
</table>

Fig. 4. Channel allocation negotiation procedure

Fig. 5 shows the average SINR levels estimated by the CPE at different positions in the TV-signal coverage area. The CPE communicates with the WRAN BS, while the WRAN BS is located at some distance from the TV transmitter.
transmitter. We see that the CPE can still get good signal reception within the BS keep-out region of 150.3 km [4] from the TV transmitter if the co-channel interference to the LIU can be avoided according to the Equation (1). For example, if the distance between the WRAN BS and the TV transmitter is 140 km, the area where the SINR level is larger than the threshold of 10 dB is about 85 km², that means an effective increase of the WRAN coverage. In other words, this spatial spectrum sharing method can shorten the keep-out region as compared with the traditional spectrum-sensing method.

![Fig. 6. Capacity increase of the simple CR network](image)

Fig. 6 shows the increase of average capacity of the simple CR network as shown in Fig. 2, where the channel #5 could be reused by the CPE₁ for the transmission purpose. It is assumed that the CPE₁ can control its transmit power in order not to produce excess interference to the LIU. For simplicity, the capacity is defined by the famous capacity-cost function \( C(P) = \log(1 + P/N) \), where \( P \) denotes the signal power and \( N \) the sum of power of the AWGN and interference. The capacity of the simple CR network is calculated and average in the coverage area of the WRAN. In Fig. 6, three curves of capacity are shown respectively, corresponding to different distance (\( D = 140, 130 \) or \( 120 \) km) between the CPE₁ and the TV transmitter. We see that if the distance from the LIU to the CPE₁ is larger than about 16 km, the capacity tends to be saturated, because the CPE₁ is just out side of the keep-out region [4]. More importantly, by using spatial spectrum sharing, even though the CPE is close to the LIU, that is, the distance from the LIU is less than 16 km, the CR network can still have a certain capacity, which will not be allowed by traditional spectrum-sensing technique. We also notice that, if the \( D \) is larger, the capacity is higher, because the interference resulted from the TV transmitter is lower. Again, the keep-out region of 150.3 km can be broken through without deteriorating the performance of the existing TV broadcasting.

5. Conclusions

This paper presents a frame work of spatial spectrum-sharing strategy in the CR network. In order to fully exploit available spectrum resources without introducing interference to existing LIUs, we propose a cross-layer design strategy that tries to integrate useful information obtained from the physical, MAC and network layers. It is expected that this cross-layer design can improve the cognitive processing in the CR network, because CPEs can learn a comprehensive knowledge of spectrum usage and make suitable decisions.

References