# Analysis on the Probability of Electromagnetic Compatibility in Cognitive Radio

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*Abstract*—**How to determine an optimal topology is extremely important during the spectrum decision procedure for a cognitive radio network. In a multi-transceiver cognitive radio network, transceivers of a cognitive user will work in a parallel mode, by which the throughput of the network can be increased. Each cognitive user working in such mode should keep electromagnetic compatible (EMC), which will increase the time-complexity of spectrum decision dramatically. In order to solve this problem, an approximate decision model with lower time complexity is given. To evaluate the reliability of the approximate model, a method for EMC probability analysis is presented, which covers co-channel/adjacent channel interference, harmonic interference and intermodulation interference. With a network scene under development, both a theoretic EMC probability and a simulated estimation value are obtained and the good consistency between both results shows that the method is practicable in engineering.**

***Keywords-cognitive radio; spectrum decision; electromagnetic compatibility; co-channel/adjacent channel interference; harmonic interference; intermodulation interference***

## I. INTRODUCTION

With the development and wide application of wireless communication technology, the limited spectrum and inefficient fixed spectrum allocation policy could no longer satisfy the demand for wireless communication. This has been the key issues restricting the development of wireless communication. In 1999, the concept of cognitive radio (CR) was firstly proposed by Joseph Mitola [1], which provided a new solution to the problem of the lack of spectrum resources. In 2005, Simon Haykin proposed the cognitive cycle model covering spectrum decision, an important phase in the cognitive process [2].

Based on CR techniques, a CR network is an intelligent wireless system, able to sense the outside environments automatically and then to change communication parameters for cognitive users according to the current network conditions.

Spectrum decision [3,4], the process of selecting the optimal spectrums from those obtained by spectrum sensing [5] for secondary users (SU) in a network according to the QoS requirements of applications, is extremely important to cognitive radio. Spectrum decision problem studied in this paper is based on tree-based cognitive radio networks (TCRN) [6,7]. TCRN is a master-slave self-organized network where a secondary user in TCRN is equipped with multiple transceivers [8] so that it can access the parent secondary user (PSU) and can accommodate the child secondary user (CSU) at the same time.

When multiple transceivers work simultaneously within one site, there may have electromagnetic interference such as intermediate frequency interference, hermitian image interference and co-channel/adjacent channel interference caused by transmitter, and also may have harmonic interference, intermodulation interference and cross-modulation interference caused by the non-linear mixing in transmitter or transceiver. Therefore, in the procedure of determining the optimal topology, we need also consider the electromagnetic compatibility [9] besides the QoS requirements.

In practical applications, intermediate-frequency (IF) interference could be suppressed by the double conversion or increasing the quality factor of the IF filter of a transceiver. Hermitian image interference can be suppressed by choosing high intermediate frequency or increasing the quality factor of transceiver-amplifier [10]. Therefore, both kinds of interference are not taken into consideration in analysis of electromagnetic compatibility. Cross-modulation interference only occurs when the interference signal is an amplitude modulation one [10]. Based on the requirements of our TCRN system, the signals studied in this paper are not amplitude modulation ones, thus they will not be considered.

If the frequency of a signal from transmitter is near the receiving frequency, the signal will reach the receiver and generate interference with the receiver. This is the so-called co-channel/adjacent channel interference, which needs to be prevented. Owing to the influence of non-linear devices, the output signals from a transceiver contain not only the input signal itself but also the second-order or higher-order signals. These signals lead to the output waveform distortion, which is the harmonic interference. Usually fourth-order and higher order harmonic interference can be negligible, so we just consider the second-order and third-order harmonic interference.

In general, signals with different frequencies may produce intermodulation components in nonlinear circuits. In these produced signals, the even-order intermodulation signals have no need to be taken into consideration because they are usually far from the receiving frequency. Among the odd-order ones, the higher order signal is weaker than the lower one; therefore, the interference of three-order intermodulation is the most important among all kinds of intermodulation interference.

As the EMC judgment is very complex, the time complexity of spectrum decision considering EMC will be increased further. Other than a precise decision model with EMC consideration, we also present an approximate spectrum decision model based on the precise one, which reduces the time complexity. In order to evaluate the approximate model's reliability, we analyze the EMC probability in detail. In addition, a calculation and a simulation of the EMC probability for a real TCRN system are given.

The structure of this paper is as follows. Section II discusses the consideration and the model of EMC analysis in spectrum decision. Section III gives the analysis on EMC in detail. According to the discussion above, we only analyze co-channel/adjacent channel interference, the second-order and third-order harmonic interference and the third-order intermodulation interference in this section. Section IV presents a calculation and a simulation of EMC probability for a real TCRN system. The conclusion is given in section V.

## II. THE CONSIDERATION AND MODEL OF EMC ANANLYSIS

### A. *EMC consideration in spectrum decision*

Suppose that there are $n$ transceivers included in a PSU and each transceiver will make a so-called cluster with a subset of CSUs of the PSU, denoted by $C$. As shown in Fig. 1, both $C_1$ and $C_2$ are clusters.

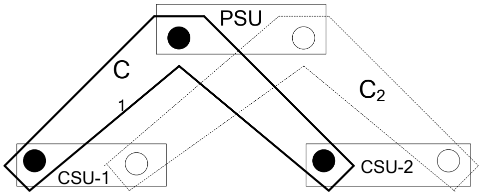

Figure 1. Topology of a subnet

The structure of cluster must satisfy two conditions. One condition is that a transceiver in a CSU belongs to one cluster at most. The other one is that a cluster accepts one transceiver from a CSU mostly at the same time. The set of the clusters is called the topology of the subnet, denoted by $T$. In Fig. 1, $T = \{C_1, C_2\}$.

Suppose the transceiver configuration of PSU and CSU is the same, both with $n$ transceivers. Moreover, suppose the subset has $m$ cognitive users, thus there exist $2^{mn}$ possible topologies in one subset. Thus, finding the optimal topology will be a great challenge during the procedure of spectrum decision.

#### 1) *Precise spectrum decision model*

After the procedure of spectrum sensing, the spectrums by which PSU may communicate with each CSU can be obtained. Given a certain topology, $T = \{C_1, C_2, \ldots, C_n\}$, the spectrums available for each cluster is also determined, denoted by $F_i$. When the subnet starts working, each cluster selects one spectrum from $F_i$ for data communication. All the selected communication spectrums constitute a working spectrum group for the subnet. Once the subnet senses that a primary user (PU) will use certain spectrums in the group, the CR subnet must switch its spectrum [3] for some of its transceivers. For a given topology $T$, the total amount of all possible working spectrum groups is denoted by $N_T$, then

$$N_T = \prod_{i=1}^{n} |F_i| . \tag{1}$$

$N_T$ can be used as a consideration factor of spectrum decision model. The topology with a larger number of working spectrum groups will be considered better than that with fewer groups.

Since all clusters of a subnet will work at the same time within a CR user, the working spectrum group must keep electromagnetic compatible. After discovering the activity of primary user, the subnet should change its working spectrum group to the next one electromagnetic compatible. Thus the number of working spectrum groups satisfying electromagnetic compatibility is also a crucial factor in spectrum decision, denoted by $C_T$.

Considering the two factors above, we can give a precise spectrum decision model

$$T \succ T' \Leftrightarrow \begin{pmatrix} C_T\left(\{F_i\}\right) > C_T\left(\{F_i'\}\right) \vee \\ \begin{pmatrix} C_T\left(\{F_i\}\right) = C_T\left(\{F_i'\}\right) \wedge \\ N_T\left(\{F_i\}\right) \le N_T\left(\{F_i'\}\right) \end{pmatrix} \end{pmatrix} . \tag{2}$$

In this model, when the factors $C_T$ of two topologies are the same, we consider the one with less $N_T$ is better. This is because selecting the next spectrum group electromagnetic compatible from a larger set of groups is more difficult than from a smaller one with the same number of spectrum groups satisfying electromagnetic compatibility.

This precise model requires traversing all possible working spectrum groups of each possible topologies of a subnet. Suppose each cluster has *k* spectrums available, then it need traverse $k^m$ times to get the number of working spectrum groups which keep electromagnetic compatible. In each traversal, it is necessary to evaluate the electromagnetic compatibility. The time complexity of this procedure is about $O(n^2)$. Therefore, the total time complexity will reach $O(2^{mn}k^m n^2)$. By this reason, we need consider an approximate spectrum decision model.

*2) Approximate spectrum decision model*

Since the EMC judgment is greatly complex, it can not meet the real-time requirement when a subnet becomes larger. So an approximate spectrum decision model is presented as (3) shows.

$$T \succ T' \Leftrightarrow N_T\left(\{F_i\}\right) > N_T\left(\{F_i'\}\right) \tag{3}$$

In order to assess the reliability of the approximate model, a detailed analysis on the EMC probability of the arbitrary *n* spectrums is necessary. In this paper, we give the theoretical calculation of EMC probability based on real TCRN system parameters. In addition, a simulation experiment is carried out with the same parameters. Using these results, we can determine the reliability of the approximate model by (3).

### *B. Model of EMC probability analysis*

The electromagnetic compatibility of the system is not only related to the strength of an interference signal, but also the receiver's ability in imposing restraint on the interference signal.

Suppose that the frequency of an interference signal is $f_d$. The receiver will produce a certain restraint, denoted by $R$, on the interference signals after they reach the receiver. It can be considered a discrete random variable with the range $U = \{r_1, \cdots, r_k\}$. Generally, $R$ is a step function of $\Delta f$, which represents the difference between $f_d$ and receiving frequency $f_r$, denoted by $R(\Delta f)$, as shown in (4) where the variable interval $(\delta_i, \delta_{i+1}]$ and the function values $r_i$ is determined by the receiver itself.

$$R(\Delta f) = \{r_i \mid \delta_i < \Delta f = \left| f_d - f_r \right| \le \delta_{i+1}\} \tag{4}$$

Note that functions $R(\Delta f)$ are different for different working frequencies of a receiver, denoted by $R$ simply. We write the probability distribution of $R$ as (5).

$$\Pr(R = r_i) = \Pr(\delta_i < \Delta f \le \delta_{i+1}) \tag{5}$$

Suppose that the power of an interference signal reaching the receiver is $P_{f_d}$, and then the interference function, which is used to determine if the interference signal will actually interfere with the receiver, can be written as (6).

$$Intf\,(f_r, f_d) = \begin{cases} 1, & P_{f_d} - R > T_s \\ 0, & P_{f_d} - R \le T_s \end{cases} \tag{6}$$

$T_s$ is the anti-interference threshold of a receiver determined by the receiver itself. If the function value is 1, the signal will interfere with the receiver. Conversely, the interference signal will not affect the normal work of the receiver.

## III. ANALYSIS ON EMC PROBABILITY

### *A. Co-channel/ Adjacent Channel Interference*

Suppose that the signal from transceiver A, working on spectrum $f_t$ and power $P$, reaches receiver B through antenna-feeder network. We denote the attenuation by antenna-feeder network is $L_{AB}$, so the frequency and power of the signal received by B respectively are

$$f_d = f_t,\ P_{f_d} = P - L_{AB}. \tag{7}$$

$P$ is a uniform distributed discrete variable, and its probability distribution is

$$\Pr(P = p_i) = 1/m. \tag{8}$$

The antenna-feeder attenuation $L_{AB}$ contains antenna isolation, transmitting feeder attenuation and receiving feeder attenuation. The antenna isolation can be calculated by the method in [11], and the others should be ascertained by corresponding engineering measurements. Thus the probability that transmitting signal has no interference with the receiver $\Pr_{en}(f_r, f_t)$ can be derived as follows according to (6) ~ (8).

$$
\begin{aligned}
&\mathrm{Pr}_{en}(f_r, f_t) \\
&= \mathrm{Pr}(Intf(f_r, f_d) = 0) \\
&= \sum_{i=1}^{m} \mathrm{Pr}(P = p_i)\,\mathrm{Pr}(p_i - L_{AB} - R \le T_s) \\
&= \sum_{i=1}^{m} \frac{1}{m} \sum_{j=1}^{k} \mathrm{Pr}(R = r_j)\,\mathrm{Pr}(L_{AB} \ge p_i - r_j - T_s)
\end{aligned}
\tag{9}
$$

### *B. Harmonic Interference*

Suppose that transceiver A works on spectrum $f_t$ and transmitting power $P$, thus its output signal will contain both the secondary-order harmonic signal and the third-order harmonic signal besides $f_t$. Their antenna-feeder attenuations are $L_{2h}$ and $L_{3h}$, respectively. The restraint on harmonic signal from A is denoted by $r_T$, so the frequency and power of harmonic signals reaching a receiver are

$$f_{2h} = 2f_t,\ P_{f_{2h}} = P - r_T - L_{2h} \tag{10}$$

$$f_{3h} = 3f_t,\ P_{f_{3h}} = P - r_T - L_{3h} \tag{11}$$

The differences between the harmonic frequency $f_{2h}$, $f_{3h}$ and receiving frequency $f_r$ are denoted by $\Delta f_{2h}$ and $\Delta f_{3h}$. By experiments, if $\Delta f_{2h}$ and $\Delta f_{3h}$ are more than a certain threshold $T_c$, the harmonic signal will not produce interference with the receiver. Therefore, according to (6)(10)(11), the probabilities that signals from A generates no second and third harmonic interference with a receiver, denoted by $\mathrm{Pr}_{2h}(f_r, f_t)$ and $\mathrm{Pr}_{3h}(f_r, f_t)$ respectively, are written as follows.

$$
\begin{aligned}
&\mathrm{Pr}_{2h}(f_r, f_t) \\
&= 1 - \mathrm{Pr}(\Delta f_{2h} \le T_c, Intf(f_r, f_{2h}) = 1) \\
&= 1 - \sum_{i=1}^{m} \frac{1}{m} \sum_{j=1}^{k} \mathrm{Pr}(R_{2h} = r_j, \Delta f_{2h} \le T_c, \\
&\quad L_{2h} < p_i - r_T - r_j - T_s)
\end{aligned}
\tag{12}
$$

$$
\begin{aligned}
&\mathrm{Pr}_{3h}(f_r, f_t) \\
&= 1 - \mathrm{Pr}(\Delta f_{3h} \le T_c, Intf(f_r, f_{3h}) = 1) \\
&= 1 - \sum_{i=1}^{m} \frac{1}{m} \sum_{j=1}^{k} \mathrm{Pr}(R_{3h} = r_j, \Delta f_{3h} \le T_c, \\
&\quad L_{3h} < p_i - r_T - r_j - T_s)
\end{aligned}
\tag{13}
$$

The probability that a transmitting signal generates no harmonic interference with a receiver is

$$\mathrm{Pr}_{har}(f_r, f_t) = \mathrm{Pr}_{2h}(f_r, f_t) \times \mathrm{Pr}_{3h}(f_r, f_t). \tag{14}$$

### *C. Intermodulation Interference*

Intermodulation interference contains transmitter intermodulation interference and receiver intermodulation interference. According to the engineering practice, we only consider one kind third-order transmitting intermodulation interference: the signal from transmitter A enters receiver B, generating third-order intermodulation signals.

Suppose that the frequency of signal from transmitter A is $f_{ta}$ with power $P$. The signal flees into another transmitter B through antenna feeder network. Let the transmitting frequency of B be $f_{tb}$. Signals from both A and B may generate the three-order intermodulation signals $2f_{ta} \pm f_{tb}$ and $2f_{tb} \pm f_{ta}$. If $f_{ta}$ and $f_{tb}$ are in different spectrum bands, the filter in B will filter out the signal from A, producing no third-order intermodulation interference signals. So we just consider the case that both $f_{ta}$ and $f_{tb}$ are in the same spectrum band. The signals $2f_{ta} \pm f_{tb}$ and $2f_{tb} \pm f_{ta}$ generate the same effect on a receiver.

Signals $2f_{ta} \pm f_{tb}$ enter a receiver C after the antenna-feeder network BC, their frequency and power respectively are

$$f_{d1} = 2f_{ta} + f_{tb},\ P_{f_{d1}} = P - L_{AB} - L_{ic} - L_{BC}^{f_{d1}} \tag{15}$$

$$f_{d2} = 2f_{ta} - f_{tb},\ P_{f_{d2}} = P - L_{AB} - L_{ic} - L_{BC}^{f_{d2}}. \tag{16}$$

$L_{ic}$ is the intermodulation conversion loss, the ratio of power of a unwanted signal to an intermodulation signal, and it is a step function of $|f_{ta} - f_{tb}|$. Let $L_{ic} \in \{l_1, \cdots, l_s\}$ which is a uniform distributed variable. Similar to harmonic interference analysis above, the probability that the three-order intermodulation signals $f_{d1}$

and $f_{d2}$ generate no interference with receiver can be written as (17) and (18) respectively according to (6), (15) and (16).

$$\begin{aligned}&\Pr_{tim_{f_{d1}}}(f_r, f_{ta}, f_{tb})\\ &=1-\Pr(\Delta f_1 = \left| f_{d1} - f_r \right| \le T_c, Intf(f_r, f_{d1}) = 1)\\ &=1-\sum_{i=1}^{m}\frac{1}{m}\sum_{q=1}^{s}\frac{1}{s}\sum_{j=1}^{k}\Pr(R(\Delta f_1) = r_j, \Delta f_1 \le T_c,\\ &\quad L_{AB} + L_{BC}^{f_{d1}} < p_i - l_q - r_j - T_s)\end{aligned} \tag{17}$$

$$\begin{aligned}&\Pr_{tim_{f_{d2}}}(f_r, f_{ta}, f_{tb})\\ &=1-\Pr(\Delta f_2 = \left| f_{d2} - f_r \right| \le T_c, Intf(f_r, f_{d2}) = 1)\\ &=1-\sum_{i=1}^{m}\frac{1}{m}\sum_{q=1}^{s}\frac{1}{s}\sum_{j=1}^{k}\Pr(R(\Delta f_2) = r_j, \Delta f_2 \le T_c,\\ &\quad L_{AB} + L_{BC}^{f_{d2}} < p_i - l_q - r_j - T_s)\end{aligned} \tag{18}$$

In total, the probability that signal $f_{ta}$ and $f_{tb}$ produce no transmitter intermodulation interference with receiver can be written as follows.

$$\begin{aligned}&\Pr_{tim}(f_r, f_{ta}, f_{tb})\\ &=\Pr^2_{tim_{f_{d1}}}(f_r, f_{ta}, f_{tb}) \times \Pr^2_{tim_{f_{d2}}}(f_r, f_{ta}, f_{tb})\end{aligned} \tag{19}$$

### D. EMC Probability of Communication System

In each SU in a TCRN, there exist a lot of transceivers working together. Only all the transceivers have no interference with each other could the system be viewed as electromagnetic compatible. The probabilities that there exists no co-channel/adjacent channel interference, harmonic interference and intermodulation interference are denoted by $\Pr_{en}$ , $\Pr_{har}$ and $\Pr_{tim}$ respectively, which can be obtained with methods above. Therefore, the EMC probability $\Pr_{EMC}$ can be written as

$$\Pr_{EMC} = \Pr_{en} \times \Pr_{har} \times \Pr_{tim}. \tag{20}$$

## IV. CALCULATION AND SIMULAION OF EMC PROBABILITY

### A. A Real TCRN System

In TCRN, each cognitive user needs a Common Control Channel (CCC) [12] to transmit control information between each other. The service channels are used to transmit user data.

In the real TCRN system studied in this paper, the subnet capacity is $(1+n)$ which means 1 PSU and $n$ CSUs. Each user has $m$ service transceivers and 1 CCC transceiver. The CCC transceiver uses $c_{\max}$ spectrums at most and one at least. CCC frequency $f_c$ is a uniform distributed random variable.

Spectrums for service channels include UHF spectrum $f_u$ , VHF spectrum $f_v$ and HF spectrum $f_h$ . Their numbers are also uniform distributed random variables. The number of UV spectrums $N_{uv}$ is one at least and $uv_{\max}$ at most. The number of HF spectrum is either one or zero.

### B. Calculaion of EMC Probability

According to the EMC analysis in section III, we can get the theoretical result of EMC probability is 58.9% on the basis of a real TCRN system. Among the three kinds of interference, the co-channel/adjacent channel interference is the strongest, with a non-interference probability only about 66.2%. The effect of transmitter intermodulation interference is weaker, and its non-interference probability is about 90.3%. Harmonic signal generates least interference with receivers with non-interference probability reaching about 98.5%.

### C. Simulation of EMC Probability

The simulation is completed with Microsoft Visual Studio 2005. It takes the same parameters used in the process of theoretic EMC probability deduction above.

In this simulation, frequencies are selected randomly over a discrete spectrum space with the size of 8060. The simulation procedure is as follows.

```
1:  Initialize system parameters
2:  for 1..loop1
3:      Generate the number of CCC channel randomly
4:      Set the central working frequency, transmitting
        power and the length of antenna-feeder system for
        each CCC spectrum randomly
5:      for 1..loop2
6:          Specify the number of service channels randomly
7:          Set the central working frequency, transmitting
            power and the length of antenna-feeder system
            for each service channel randomly
8:          if channels are not electromagnetic compatible
            then cnt ← cnt+1
9:  $P_{EMC}$ ← (1 - cnt / (loop1*loop2))
10: return $P_{EMC}$
```

The simulation above is executed in Windows XP platform equipped with 3.2GHz CPU. In the step 1, the system parameters are setup as follows. For a spectrum in VHF/HF, the frequency difference is 25 kHz at least, and 50 kHz for UHF. We set both $c_{\max}$ and $uv_{\max}$ to be 5 in this step. In the step 2 and 7, we will select one power from three possible kinds of power for each CCC spectrum and each service channel. Note that the length of antenna-feeder system is different for the CCC channel and the service channel. The former is fixed to 10 meters and the latter is only 5.

The simulated results are shown in Table 1. According to Table 1, we know the time of one EMC judgment is about 6.86*us*. Thus it will take almost 400 days to finish EMC judgment in a 5-users subnet with the sensed spectrum space with the size of 1500.

TABLE I. SIMULATION RESULTS

| $loop_1$ | $loop_2$ | *cnt* | time(*s*) |
|---|---|---|---|
| 1000 | 1000 | 379852 | 7 |
| 1000 | 1000 | 379102 | 7 |
| 1000 | 1000 | 376130 | 7 |
| 10000 | 10000 | 37771785 | 687 |
| 10000 | 10000 | 37765125 | 686 |
| 10000 | 10000 | 37794096 | 686 |

By a simple calculation with the simulation results the probability of electromagnetic compatibility in such system is about 62.2%. As shown in Table 2, this result is very close to the theoretical one.

TABLE II. CONTRAST BETWEEN THEORETICAL AND SIMULATION RESULTS

| **EMC** | **Simulation result** | **Theoretical result** |
|---|---|---|
| Co-channel/adjacent channel interference | 68.49% | 66.2% |
| Harmonic interference | 99.25% | 98.5% |
| Intermodulation interference | 91.53% | 90.3% |
| Total | 62.2% | 58.9% |

However, both results are not exactly the same. There are two possible causes for the difference. One is that we deal with some details approximately to simplify the procedure of EMC probability theoretical calculation, so there is a little error between theoretical results and the simulation one. Another cause of the error may be the independency hypothesis of each interference type on others. This is an ideal condition that may not the necessary case in simulations.

## V. CONCLUSION

In multi-transceiver cognitive radio network, multiple transceivers of the same cognitive user improve network throughput by a parallel working mode. But it will produce electromagnetic compatibility issues among multiple transceivers, which affects spectrum decision greatly. A method of EMC probability analysis is presented in this paper, and a simulation under the real system parameters is given. The theoretical result and simulation result are almost the same. This indicates that the EMC probability of multi-transceiver cognitive radio can be pre-determined. Therefore, the approximate method presented to determine the optimal topology which reduces the time complexity of spectrum decision can be used in practice

Although the EMC analysis in this paper is specified for a kind of real cognitive radio network system, this method can be generalized to the other real systems by changing related parameters to satisfy the requirements of EMC analysis and spectrum decision.

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