On Optimal Number of Cognitive Radios Considering Co-site Electromagnetic Compatibility

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Research

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On Optimal Number of Cognitive Radios Considering Co-site Electromagnetic Compatibility

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***Abstract*—Cognitive radio is becoming one of the most important techniques for high utility of spectrum holes. If the holes available to cognitive users are abundant over a certain time, it is a worth consideration to increase network throughputs by orthogonal multiplexing as many as spectrum holes. A multi-transceiver configuration is one of the possible solutions for this purpose. With such a schema, all transceivers within a cognitive user work in a concurrent or parallel mode, by which the throughput of the network can be increased. However, co-site working cognitive radios may incur electromagnetic interference between each other. When more cognitive radios are equipped, much electromagnetic interference may be incurred. Based on an electromagnetic compatibility probability analysis, this paper proposes a novel method to decide how many cognitive radios can be installed for one cognitive user at most. We make a strict deduction on electromagnetic compatibility probability with various parameters of cognitive radios. Simulations are performed and the results show that the electromagnetic compatibility of the simulated cognitive radio system meet the deducted probability very well.**

Keywords—cognitive radio, cognitive radio network, electromagnetic compatibility, co-channel/adjacent channel interference, frequency difference

I. INTRODUCTION

With the development and wide applications of wireless communication technology, the limited spectrum resources and the fixed spectrum allocation policy could no longer satisfy the demand for wireless communication. The concept of cognitive radio (CR) was firstly proposed by Joseph Mitola [1] as a new solution to this problem. By 2005, Simon Haykin proposed a cognitive cycle model [2] as a guidance on the development of cognitive radio system.

Based on CR techniques, a CR network (CRN) has wits to detect spectrum holes without interference to the primary user and then to automatically configure the system according to the current electromagnetic environment [3, 4]. Sometimes the spectrum holes may be very abundant. In such cases, the secondary users have many spectrum candidates for communication. This provides a good chance for cognitive users to improve network throughputs. A simple but possible way is to integrate multiple transceivers into each cognitive user to transmit user data in a concurrent mode. These transceivers within one user work in a co-site mode. That is, they are located within short distance between each other and use different spectrum holes for communication simultaneously.

When multiple transceivers work simultaneously, there may produce various kinds of interference between each other, such as intermediate frequency interference, hermitian image interference, and co-channel/adjacent channel interference caused by transmitters. It may also produce harmonic interference, intermodulation interference, and cross-modulation interference caused by the non-linear mixing in either transmitters or transceivers. Generally, the more cognitive radios are equipped co-site by a cognitive user, the more possibility of electromagnetic interference may happen. For the system users, they expect that the possibility of electromagnetic interference should not exceed a threshold value. This implies that the number of transceivers installed for one cognitive user should not exceed a certain number. To decide such an optimum number of co-site transceivers, the implicit relation between the number of transceivers and the possibility of electromagnetic compatibility (EMC) should be clarified.

This paper deals with this problem in our cognitive radio network [5-8] which is master-slave self-organized. The secondary user in the network is equipped with multi-transceivers [9], allowing using multiple different channels to communicate. For the cognitive radios in our system, intermediate-frequency interference could be suppressed by the double conversion or increasing the quality factor of IF filter. Hermitian image interference can be suppressed by choosing high IF 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 is an amplitude modulated signal [10] which is not used in our system and thus such interference will not be discussed in this paper.

If the signal from a transmitter is near to the receiving frequency, the signal will reach the receiver and generate interference to the receiver. This is so-called co-channel/adjacent channel interference while adjacent channel interference is related to the transmit filter and the IF filter in a receiver [11], both of them need to be prevented because they cannot be avoided. From the results of the simulation for our system, we found that the co-channel/adjacent channel interference plays the most important role [12]. The possibility of co-channel/adjacent channel interference is much higher than that of harmonic interference and intermodulation interference, accounting for about 95% or more in all cases of interference. Therefore, this paper will focus on the analysis on the possibility of co-channel/adjacent channel interference to decide the optimum number of transceivers installed in a cognitive user. As far as we know, there have no such literatures to address this cognitive radio planning problem based on electromagnetic compatibility probability analysis.

Our contributions by this paper are summarized as follows: (1) We present a method to estimate EMC probability for a cognitive user working in a co-site multi-transceiver mode for the first time; (2) We conduct complete simulations to evaluate the performance of the proposed method. The results show that our method can achieve high accuracy; (3) Our method provides the system manager of a CRN with a new ability to determine the optimal number of cognitive radios installed within each cognitive user.

The main structure of this paper is as follows. Section II & III discuss the method and the model of our system respectively. Section IV gives the analysis on EMC in detail. Section V presents the simulations of EMC probability for our system in use. The conclusion is given in the Section VII.

II. METHODS/EXPERIMENTAL

We took a methematical method in this work to build a model for estimating EMC probability for a cognitive user working in a co-site multi-transceiver mode. Then we designed a simulation framework based on the parameters of radios we used. The detailed settings can be found in Section Simulations. By comparing the results of the mathematical model the one by simulations, we checked the validness of our mathematical model.

III. THE RELATED MODELS

A. The System Model

Our system takes a topology in which some cognitive users are the parent nodes of other cognitive users. Taking Fig. 1 as an example, there are three cognitive users where one user, PSU (Parent Secondary User), is the parent of two users, CSU-1 (Child Secondary User 1) and CSU-2. Each user has two transceivers each of which uses a different spectrum for communication. Those transceivers using the same spectrum make a structure called a cluster, such as C_1 (the polygon with solid lines) and C_2 (the dotted polygon) in Fig. 1.

If one transceiver can contribute certain network throughputs, then two transceivers may double the throughputs if they can work simultaneously without interference between each other. Therefore, the multi-transceiver model may increase the throughputs for the network.

The system user may expect a level of electromagnetic compatibility for the system to work normally. We denote this expected EMC level by P_{EMC} which is the probability of no electromagnetic interference among transceivers of one cognitive user. Therefore, the system model can be expressed by (1) where $EMC\left(\{TX_i\}\right)$ is the probability of no electromagnetic interference among all transceivers of one cognitive user, denoted by $\{TX_i\}$.

$$\Pr\left\{EMC\left(\{TX_i\}\right)\right\} \geq P_{EMC} \tag{1}$$

B. Model of Electromagnetic Compatibility

Generally, the electromagnetic compatibility of the system is related not only to the interference signal strength, but also the receiver's ability to suppress the interference.

Suppose the frequency of an interference signal is f_t. The receiver will produce a certain suppression on the interference signal after it reaches the receiver, denoted by R, a discrete random variable with the range $\{r_1, \cdots, r_k\}$. Generally, R is a step function of Δf, which is the difference between f_t and receiving frequency f_r, denoted by $R(\Delta f)$, as shown in (2) where the intervals $(\delta_i, \delta_{i+1}]$ and each r_i is determined by the receiver itself.

$$R(\Delta f) = \left\{r_i \mid \delta_i < \Delta f = |f_t - f_r| \leq \delta_{i+1}\right\} \tag{2}$$

The probability distribution of R can be written as (3).

$$\Pr\{R = r_i\} = \Pr\{\delta_i < \Delta f \leq \delta_{i+1}\} \tag{3}$$

Suppose the power of interference signal reaching the receiver is P_t, then the non-interference function is

$$\lambda(P_t, L, R) = \begin{cases} 1, & P_t - L - R \leq T_s \\ 0, & otherwise \end{cases} \tag{4}$$

where T_s is the anti-interference threshold of receiver determined by the receiver itself and L is the attenuation of the interference signal through the antenna-feeder system, which will be addressed in the next subsection. If the value of the function is zero, the signal will interfere with the receiver thus have an effect on its normal work. Conversely, the interference signal will not affect the normal work of the receiver.

C. Model of Attenuation of Antenna-feeder System

The attenuation L of an antenna-feeder system is denoted by

$$L = L_h + L_t + L_r \tag{5}$$

where L_h is the horizontal isolation between transmitter and receiver antennas. L_t and L_r are the feeder attenuations of transmitter and receiver respectively. We adopt a method in [13] to calculate L_h (dB) by

$$L_h{=}22{+}20\lg\left(\frac{fd_h}{C}\right) - \left(G_t{+}G_r\right) - \left(S_t{+}S_r\right) \tag{6}$$

where f (Hz) is the frequency of the interference signal, C (m/s) is the speed of light, the d_h (m) is the horizontal distance between antennas, G_t (dBi) and G_r (dBi) are the direction gain of maximum radiation of transmitter antenna and receiver antenna respectively, and S_t (dBp) and S_r (dBp) are the 90° to the direction of sidelobe level of transmitter antenna and receiver antenna respectively. In this paper, we suppose that omnidirectional antennas are used, so $S_t = 0$ and $S_r = 0$.

The antenna-feeder system and related parameters are sketched in Fig. 2.

IV. EMC Probability Analysis

A. Probability Calculation of EMC

Based on the non-interference model by (4) in Section III, we can calculate the probability of no co-channel/adjacent channel electromagnetic interference between q co-site transceivers $\{TX_l \,|1 \le l \le q\}$ using

$$\Pr\left\{EMC\left(\{TX_l\}\right)\right\} = \frac{1}{pn}\sum_{i=1}^{p}\sum_{j=1}^{n}\sum_{k=1}^{m}\left[\begin{matrix} P_{FD}\left(\delta_k, \delta_{k+1}, q\right)^* \\ \lambda\left(PT_i, L_j, r_k\right)\end{matrix}\right] \quad (7)$$

In (7), we suppose that the power of the interference signal is a uniform distributed discrete variable with the range $\{PT_1, PT_2, \cdots, PT_p\}$ where p is the number of possible transmitting powers used by a transceiver.

Because the antenna-feeder attenuation is closely related to the frequency of a transmitting signal, we use L_j to indicate such an attenuation of a signal with corresponding frequency f_j and the total number of all possible frequencies is n . We assume that each transceiver uses the same antenna and feeder thus L_j is independent of both the length of the feeder and the type of the antenna.

The most important item in (7) is P_{FD} which is a probability distribution function of frequency difference among q transceivers. This distribution function will be discussed in the next subsection.

B. Probability Analysis on Frequency Difference

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To define item $P_{FD}\left(\delta_k, \delta_{k+1}, q\right)$ in (7), we firstly introduce $P_{MFD}\left(d_k, q\right)$ as

$$P_{MFD}\left(d_k, q\right) = \Pr\left\{d_k = \frac{\min\{\Delta f\}}{f_n - f_1} \ge \frac{\delta_k}{f_n - f_1}\right\} \quad (8)$$

where d_k are normalized to a real number between 0 and 1, f_n is the maximal working frequency and f_1 is the minimal one and thus $[f_1, f_n]$ form the spectrum scope of transceivers.

The meaning of $P_{MFD}\left(d_k, q\right)$ can be explained by the meaning of its complementary form $\left(1 - P_{MFD}\left(d_k, q\right)\right)$ which is the volume of a defined *q-dimension* polyhedron. When $q = 2$, it becomes the area of a defined polygon which is shown by Fig. 3 below.

Based on (8), $P_{FD}\left(\delta_k, \delta_{k+1}, q\right)$ is defined as (9) which means what probability of the minimum difference among q random real numbers within [0, 1] falls into the range $\left[\frac{\delta_k}{f_n - f_1}, \frac{\delta_{k+1}}{f_n - f_1}\right]$.

$$P_{FD}\left(\delta_k, \delta_{k+1}, q\right) = P_{MFD}\left(d_k, q\right) - P_{MFD}\left(d_{k+1}, q\right) \quad (9)$$

C. Deduction on Minimum Difference Probability

Simply, we use $h(d,n)$ to denote $P_{MFD}\left(d_k, q\right)$ and thus as inspired by Fig. 3, $h(d,n)$ can be calculated by an integral expression:

$$h(d,n) = n!\int_d^1 \int_0^{x-d} \int_0^{x-d} \cdots \int_0^{x-d} \underbrace{dx \cdots dx dx}_{n} \quad (10)$$

To calculate $h(d,n)$, we firstly prove a lemma below.

Lemma 1

$$\begin{aligned} f(x,n) &= n!\int_0^{x-d}\int_0^{x-d}\cdots\int_0^{x-d}\underbrace{dx\cdots dxdx}_{n} \quad \text{for } n \in N, 0 \le d \le 1 . \\ &= (x-d)\left[x - d(n+1)\right]^{n-1} \end{aligned}$$

Proof. (with induction)

For the case of $n = 1$, we have

$$f(x,n) = n!\int_0^{x-d}\int_0^{x-d}\cdots\int_0^{x-d}\underbrace{dx\cdots dxdx}_{n} = \int_0^{x-d} dx = x - d \quad (11)$$

Suppose that the lemma holds for n , and then with the method of integration by parts we have the following equation for the case of $(n+1)$:

$$\begin{aligned} f(x,n+1) &= (n+1)!\int_0^{x-d}\int_0^{x-d}\int_0^{x-d}\cdots\int_0^{x-d}\underbrace{dx\cdots dxdxdx}_{n} \\ &= \frac{n+1}{n}\int_0^{x-d}(x-d)d\left[x-d(n+1)\right]^n \\ &= (x-d)\left[x-d(n+2)\right]^n \end{aligned}$$

Based on Lemma 1, we can prove a formula below to calculate $h(d,n)$.

$$\begin{aligned} &h(d,n) \\ &= n!\int_d^1\int_0^{x-d}\cdots\int_0^{x-d}\underbrace{dx\cdots dxdx}_{n} = (n-1)^{n-1}(-d)^n + \left(1-dn\right)^{n-1} \end{aligned} \quad (12)$$

Proof.

$$h(d,n) = n!\int_d^1 \int_0^{x-d} \cdots \int_0^{x-d} \underbrace{dx \cdots dxdxdx}_{n-1}$$
$$= n\int_d^1 (x-d)\left[x-dn\right]^{n-2} dx$$
$$= \frac{n}{n-1}\int_d^1 (x-d)d\left[x-dn\right]^{n-1}$$
$$= (n-1)^{n-1}(-d)^n + \left[1-dn\right]^{n-1}$$

V. SIMULATIONS

We performed two simulations, one for the minimum frequency difference probability and the other for the EMC probability. The parameters for simulations are introduced in Part A, and the details of both simulations are given in Part B, C respectively. Note that all the settings for simulation is specific for our system, and that all the settings can be changed whenever necessary. Nevertheless, the simulation process will be the same and the main conclusion based on simulations will be not changed.

A. Parameters for Simulation

The electromagnetic compatibility related parameters of the cognitive radio used for our system are listed in Table I.

As shown in Table I, the anti-interference threshold of the radio receiver T_s is -80dB. There are 5 candidates for the radio to select transmitting power, that is $p = 5$. The working frequency f_i will be set from 30MHz to 300MHz with a uniform spacing of 25 kHz, that is, the band of a channel is 25 kHz and there are 10,800 channels in total. This spectrum section is widely used in mountainous areas for radio networking [7]. The distance between radios is set to 10m. The gain factor of the antenna used is assumed to 5 dB. With frequency difference Δf varying from 25 kHz to 4 MHz, the receiver's restraint on the interference varies from 0dB to 160dB. Especially, the restraint value 0 implies that the receiver has no any restraint on signals very near to the receiving signal. Thus, the minimal Δf implies the minimal electromagnetic compatibility probability.

TABLE I. PARAMETERS AND SETTINGS FOR SIMULATION

Parameters	Settings
T_s	-80dB
PT_1~PT_p	{5,10,15,25,30}dBm
f_1~f_n	{30, 30.025,…, 300}MHz
d_h	10m
G_t, G_r	5dB
R	0 dB if $\Delta f < \delta_1 = 25kHz$ 30 dB if $25kHz = \delta_1 \le \Delta f < \delta_2 = 50kHz$ 50 dB if $50kHz = \delta_2 \le \Delta f < \delta_3 = 100kHz$ 90 dB if $100kHz = \delta_3 \le \Delta f < \delta_4 = 1MHz$ 100 dB if $1MHz = \delta_4 \le \Delta f < \delta_5 = 2MHz$ 120 dB if $2MHz = \delta_5 \le \Delta f < \delta_6 = 4MHz$ 160 dB if $\Delta f \ge \delta_6 = 4MHz$

B. Simulation for minimum frequency difference

We performed a simulation for frequency difference distribution. The process is described in detail below.

Step 1: **For** q=2..15 /*for different number of radios*/
Step 2: **For** k=1..6
P_s [k] ←0, p_t[k] ←0; /*initialization*/
EndFor
Step 3: **For** *pass*=1..100,000 /*repeat 100,000 times*/
Step 4: **For** i=1..q
generate radio i with random frequency fi
EndFor
Step 5: Calculate the minimum frequency difference d, s.t. $d \le \left|f_i - f_j\right|, i \ne j, 1 \le i, j \le q$
Step 6: select k, s.t. $d \le \frac{\delta_{k+1}}{f_n - f_1}$
p_s [k] ← delta[k]+1,
Step 7: **For** k=1..6
p_s [k] ←delta[k]/10000
EndFor
Step 8: **For** k=1..6
p_t [k] ← Calculate $h\left(d_k, q\right)$ with (12),
$d_k = \frac{\delta_k}{f_n - f_1}$
EndFor
Step 9: **For** k=1..6
Calculate error and output: | p_t [k]- p_s [k]|
EndFor
EndFor /*end of the program */

First, we generate q $\left(q \in \left[2..15\right]\right)$ cognitive radios each with a random frequency over the spectrum scope $f_1 \sim f_n \left(n = 10,800\right)$.

Then the minimum difference between frequencies of these radios is calculated and normalized. Repeat both steps for 100,000 times and make a statistic analysis to get how many times the normalized minimum difference falls into $\left[0, \frac{\delta_k}{f_n - f_1}\right]\left(\delta_k \in \left\{\delta_1, \delta_2, \delta_3, \delta_4, \delta_5, \delta_6\right\}\right)$.

TABLE II. PROBABILITY OF MINIMUM FREQUENCY DIFFERENCE

δ_i	0.025/270		0.05/270		0.1/270		1/270		2/270		4/270	
q	***T***	***S***	***T***	***S***	***T***	***S***	***T***	***S***	***T***	***S***	***T***	***S***
2	0.000185	0.00020	0.00037	0.00043	0.00074	0.00077	0.007393	0.00719	0.014759	0.01499	0.02941	0.02919
3	0.000555	0.00053	0.00111	0.00102	0.00222	0.00198	0.022098	0.02184	0.043952	0.04446	0.08692	0.08715
4	0.001117	0.00128	0.00222	0.00209	0.00443	0.00458	0.043789	0.04383	0.086281	0.08606	0.16744	0.16586
5	0.001850	0.00172	0.00369	0.00389	0.00738	0.00767	0.072041	0.07152	0.140119	0.13812	0.26497	0.26270
6	0.002774	0.00263	0.00554	0.00560	0.01106	0.01086	0.106281	0.10591	0.203327	0.20307	0.37214	0.37046
7	0.003882	0.00379	0.00775	0.00799	0.01545	0.01602	0.145815	0.14603	0.273463	0.27183	0.48154	0.47650
8	0.005173	0.00534	0.01032	0.01059	0.02055	0.02065	0.189855	0.18875	0.347936	0.34636	0.58648	0.58436

9	0.006647	0.00661	0.01325	0.01326	0.02635	0.02685	0.237545	0.23830	0.424171	0.42298	0.68171	0.67848
10	0.008302	0.00832	0.01654	0.01640	0.03284	0.03221	0.287989	0.28544	0.499751	0.49854	0.76380	0.76037
11	0.010138	0.01060	0.02018	0.01982	0.04000	0.03981	0.340279	0.33867	0.572556	0.56898	0.83117	0.82979
12	0.012154	0.01192	0.02417	0.02456	0.04781	0.04845	0.393521	0.39182	0.640842	0.63600	0.88388	0.88256
13	0.014342	0.01446	0.02850	0.02820	0.05627	0.05566	0.446863	0.44915	0.703303	0.70047	0.92324	0.92307
14	0.016721	0.01648	0.03318	0.03355	0.06534	0.06560	0.499515	0.50076	0.759081	0.75741	0.95128	0.94923
15	0.019269	0.01936	0.03819	0.03874	0.07503	0.07507	0.550768	0.54946	0.807750	0.80660	0.97035	0.97072

After simulation, we calculated theoretic values P_{MFD} with (12) to be compared with simulated results (Step 9). The simulated results are shown in columns marked "S" in Table II and the theoretic results are shown in adjacent "T" columns. Specially, we chose data with $\frac{\delta_k}{f_n - f_1}$ varying from 1/270, 2/270 to 4/270 to be demonstrated in Fig. 4 for absolute errors between theoretically calculated probabilities and the simulations.

From the results in Table II and the absolute errors shown in Fig. 4, we can see that the data exhibit sound consistency between simulated values and deduced ones by (12), and that the errors between theoretically calculated probabilities and the simulations are very little ($1‰ \sim 6‰$) for all cases of cognitive radio parameters and can nearly be negligible.

Note that the most frequently used values for q are from 2 to 8 in our actual cognitive radio networks.

C. Simulation of EMC Probability

This simulation is to examine what is the probability of no electromagnetic interference between q cognitive radios. The details are as follows.

Step 1: **For** q=2..15 /*for different number of radios*/
$pr \leftarrow 0$; /* Initialization for interference probability*/
Step 2: **For** *pass*=1..100,000 /*repeat 100,000 times*/
$emc \leftarrow 0$; /* Initialization for EMC counter*/
Step 3: **For** i=1..q /*construct a CRN system*/
generate radio i with random frequency f_i and random power $P_t(i)$
EndFor
Step 4: **For** i=1..q
For j=i+1..q
Calculate $\lambda\left(P_t(i), L(f_i), R\left(\left|f_i - f_j\right|\right)\right)$ with (4) where L is defined by (6), R is defined by (2).
If $\lambda = 1$ **Then** $emc \leftarrow emc + 1$; **break Step 5**;
EndFor
EndFor
Step 5: $emc \leftarrow emc$ / 100,000;
Step 6: **For** i=1..p /* for all p(=5) possible powers */
For j=1..n /* for all n possible frequencies */
For k=1..6 /* for all 6 possible receiver's restraints */
$$P_{FD}(\delta_k, \delta_{k+1}, q) \leftarrow P_{MFD}(d_k, q) - P_{MFD}(d_{k+1}, q)$$
$$d_k = \frac{\delta_k}{f_n - f_1}$$
$$pr \leftarrow pr + P_{FD}(\delta_k, \delta_{k+1}, q) * \lambda(P_t(i), L_j, R_k)$$
EndFor
EndFor
EndFor
$pr \leftarrow pr / p / n$
Step 7: Output *pr* and *emc* for different values of q
EndFor /* End of the program*/

In this simulation, we set parameters for each radio with random values listed in Table I and check whether they interfere with each other according to (4). After simulation we calculate such EMC probability defined by (7) with (12).

Both deduced and simulated results are shown in Table III below. From the data below, we see that the theoretic results are closely near to that of simulation. We make Fig. 4 to show how the consistency reaches. Therefore, if the system user expects a probability of no interference between co-site cognitive radios, the user can use the data in Table III to decide the optimal number of co-site radios. For example, if 0.96 is expected, then at most 8 radios can be used for concurrent communication.

TABLE III. CONTRAST BETWEEN THEORETICAL AND SIMULATED EMC RESULTS

Number of Cognitive Radios	Theoretical result	Simulated result
2	0.99883	0.99853
3	0.99606	0.99561
4	0.99212	0.99128
5	0.9864	0.98558
6	0.97953	0.97859
7	0.97193	0.97039
8	0.96398	0.96108
9	0.95273	0.95076
10	0.9422	0.93954
11	0.93115	0.92754
12	0.91767	0.91486
13	0.90357	0.90161
14	0.88902	0.88789
15	0.87581	0.87379

VI. RESULTS AND DISCUSSION

The simulatons in Section V provide us two good results. One is related to the probability of minimum frequency difference. From the results in Table II and the absolute errors shown in Fig. 4, we can see that the data exhibit sound consistency between simulated values and deduced ones by (12), and that the errors between theoretically calculated probabilities and the simulations are very little ($1‰ \sim 6‰$) for all cases of cognitive radio parameters. The other is related to the probability of no interference between q co-site cognitive radios. From the deduced and simulated results shown in Table III, we can see that the theoretic results are closely near to that of simulation. The errors between theoretically calculated probabilities and the simulations are still very little ($1‰ \sim 5‰$) for all cases of cognitive radio numbers.

We can discuss the results as below. First of all, if the system user expects a probability of no interference between co-site cognitive radios, the user can use the formula (7) with (12) to decide the optimal number of co-site radios. For example, if 0.96 is expected, then at most 8 radios can be used for concurrent communication in our scenario. However, in a real world, other than EMC, we have many factors should be considered for installing a multiple CRs in the same site, e.g., the power supply, the network management, and so on. Therefore, we suggest the method and simulation results related to EMC and optimal number of CRs be referred an important but sole guidence for CRN setup.

VII. Conclusions

A cognitive radio network can increase data throughputs by configuring multiple transceivers for each radio to utilize as many as spectrum holes simultaneously. Such co-site transceivers may incur electromagnetic interference between each other. The requirement is to decide how many transceivers can be installed according to the level of acceptable electromagnetic interference. Based on a mathematic analysis on frequency difference distribution, a method of electromagnetic probability estimation for q transceivers is presented in this paper, and corresponding simulations under the system parameters are performed. The theoretical results and simulation results achieve sound consistency. This indicates that the electromagnetic interference level among multiple transceivers can be pre-determined. Thus, the system user can decide how many co-site transceivers can be installed for one cognitive user radio at most before deploying a cognitive radio network. As far as we know, it is the first time to address such cognitive radio planning problems based on electromagnetic compatibility probability analysis. As for our future work, we will extend our work to other scenarios with different parameters such as smaller distance between antennas, various feeder attenuations, and other spectrum bands. Furthermore, we will extend our approaches to thread collision prediction in computer science and other similar applications.

VIII. List of Abbreviations

CR for cognitive radio; CRN for cogintive radio network; EMC for electromagnetic compatibility; PSU for parent secondary user; CSU for child secondary user.

IX. Declarations

A. Availability of Data and Materials

We use simulated data for this paper to make a deduction on what is the optimal number of cognitive radios to be installed on one site. Therefore data sharing is not applicable to this article.

B. Competing Interest

The authors have declared that no competing interests exist.

C. Funding

The authors have declared that no funding for this work.

D. Authors Contribution

Mingxue Liao carried out the the whole theory modelling and reduction, simulation and programming, the design of the study and performed the statistical analysis.

E. Authors Information

The authors carried out many experiments of cognitive radio networking for long years in mountainous areas in China. Through these experiments, we found that, though a multi-transceiver configuration could help increase the throughput of the network, co-site working cognitive radios may incur electromagnetic interference between each other. To clarify this problem, we built a mathematical model to figure out what is the optimal number of co-site wireless radios for our network. Then we designed the simulation framework based on the parameters of devices we used in experiments. We found that the simualted results supported the theory very well.

F. Acknowledgment

We thank professor Zhisong Bie for his useful EMC related guides.

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X. Figure Title and Legend Setion

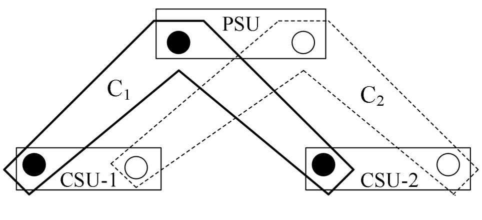

Fig. 1. The network structure of our system consisting of two subnets (clusters) C_1 and C_2. Our system takes a topology in which some cognitive users are the parent nodes of other cognitive users. The network here has three cognitive users where one user, PSU (Parent Secondary User), is the parent of two users, CSU-1 (Child Secondary User 1) and CSU-2. Each user has two transceivers each of which uses a different spectrum for communication. Those transceivers using the same spectrum make a structure called a cluster, such as C_1 (the polygon with solid lines) and C_2 (the dotted polygon).

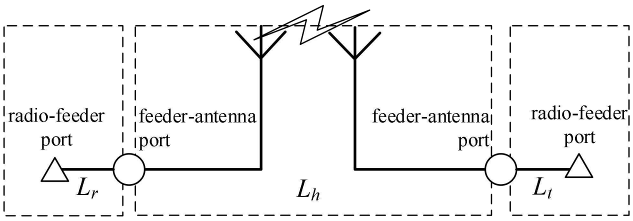

Fig. 2. The antenna-feeder system. The attenuation L of an antenna-feeder system consists of three parts: L_h is the horizontal isolation between transmitter and receiver antennas, L_t and L_r are the feeder attenuations of transmitter and receiver respectively.

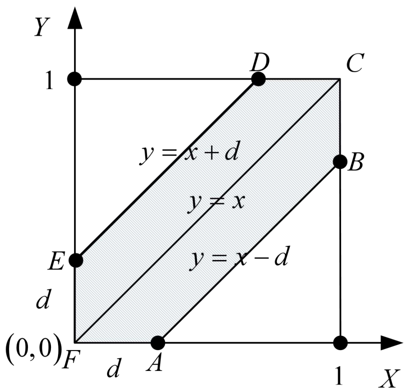

Fig. 3. The 2D form of $\left(1 - P_{MFD}\left(d_k, q\right)\right)$. The area of hexagon *ABCDEF* is $\left(1 - P_{MFD}\left(d_k, q\right)\right)$ where d_k is simplified as *d*, when $q = 2$.

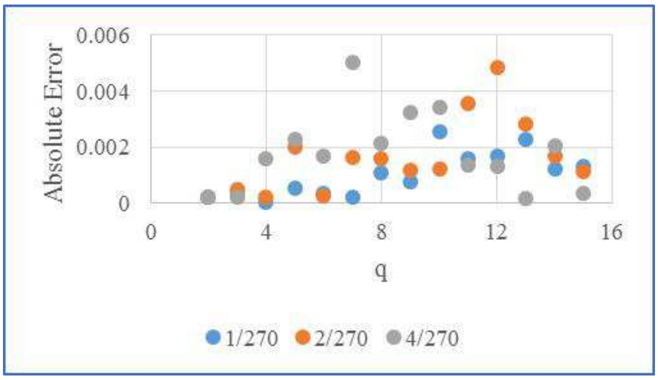

Fig. 4. The absolute errors between theoretically calculated minimum frequency difference probability and simulations. Specially, we chose data with $\frac{\delta_k}{f_n - f_1}$ varying from 1/270, 2/270 to 4/270 to be demonstrated for absolute errors between theoretically calculated probabilities and the simulations. Here q is the number of considered CRs.

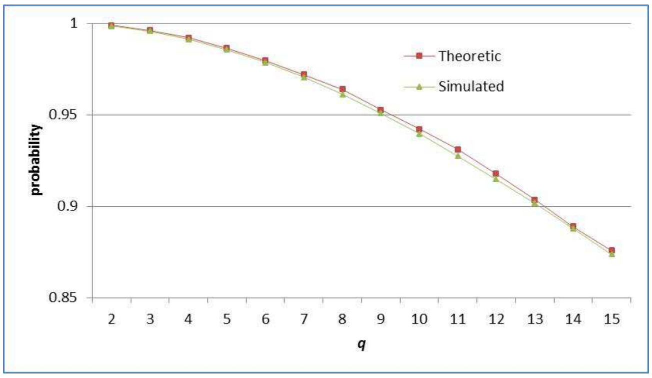

Fig. 5. The probability of no interference between q co-site cognitive radios. With q (the number of CRs installed) increase, the probability that the system meets EMC decreases. Therefore, if the system user expects a probability of no interference between co-site cognitive radios, the user can decide the optimal number of co-site radios. For example, if 0.96 is expected, then at most 8 radios can be used for concurrent communication.

Figures

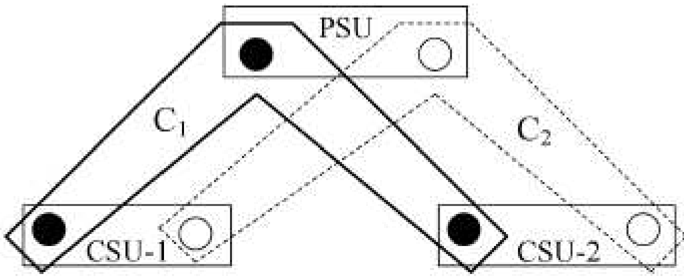

Figure 1

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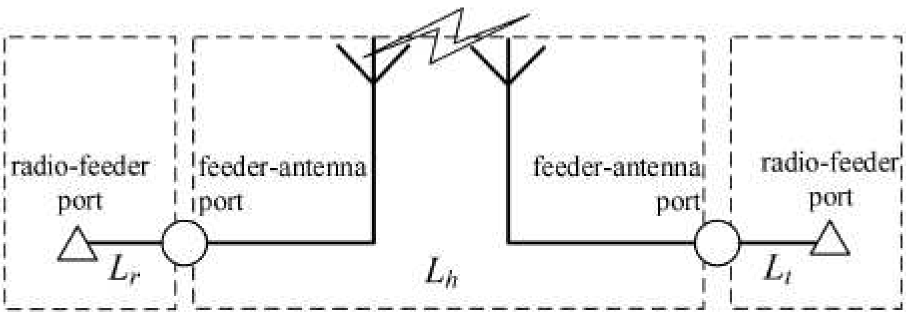

Figure 2

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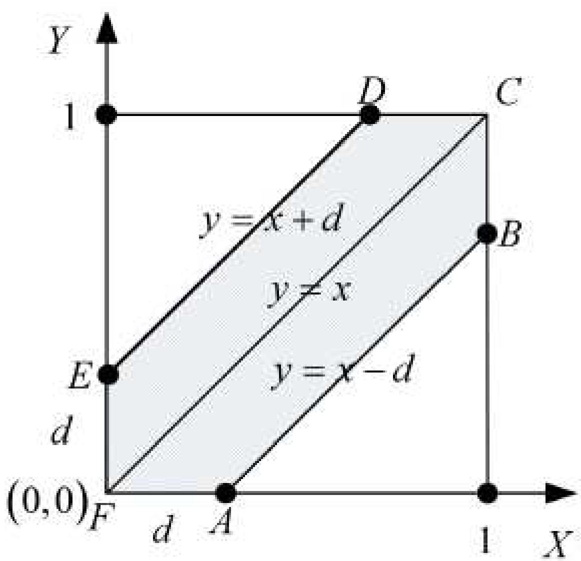

Figure 3

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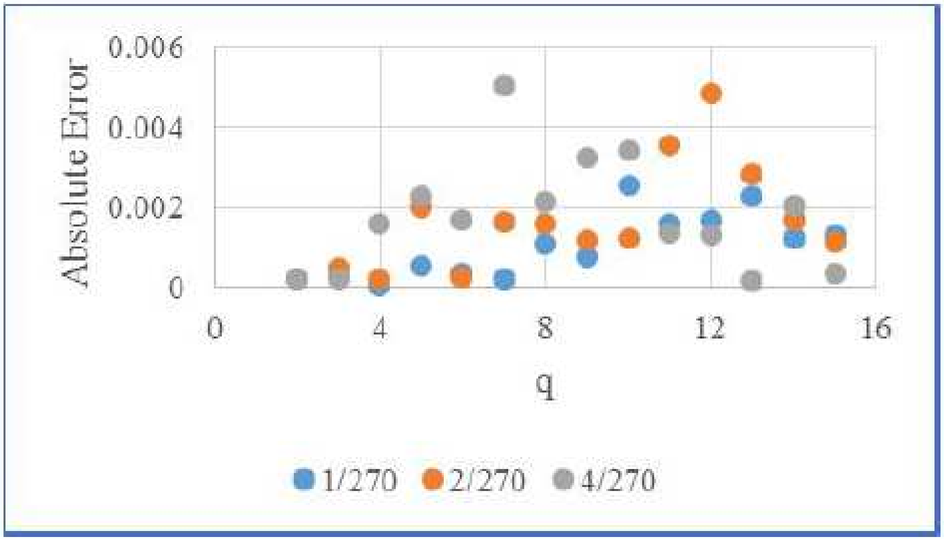

Figure 4

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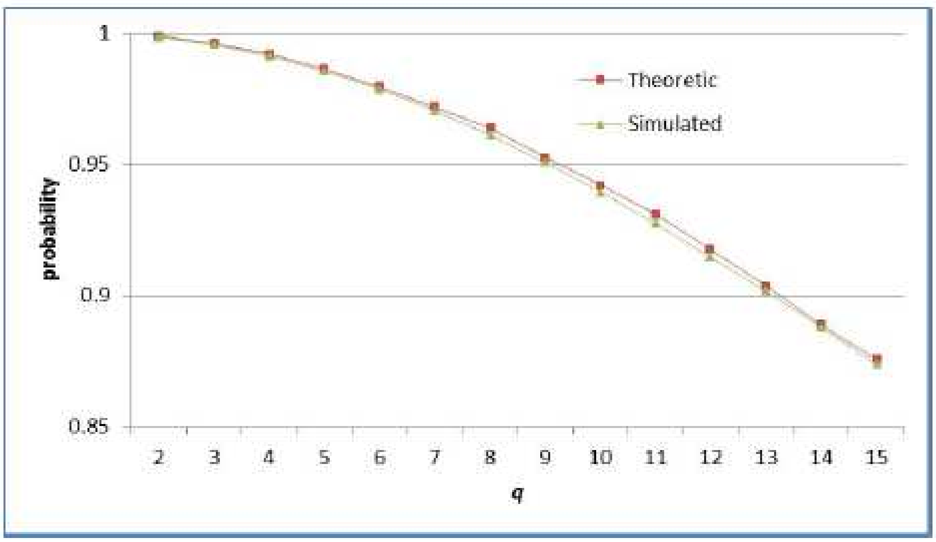

Figure 5

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