Cognitive Communications by Sequential Scanning Scheme

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Abstract —
Nowadays, the FHSS systems have been widely used in civil and military communications, but somewhat their benefits would be potentially neutralized by a follow-on jamming (FOJ) with wideband scanning and responsive jamming capabilities covering the hopping period. The FOJ concept is actually implicitly analogous to a CR communication with spectrum and location awareness, listen-then-act, and adaptation characteristics. In this paper, a cognitive radio unit (CRU) model with a sequential scanning (S-scanning) technique and cognitive probability ratio (CPR) metric for cognitive communications will be proposed. In this model real-time spectrum sensing characteristics are coordinated together with system parameters in temporal and frequency domains, e.g., scanning rate and framing processing time, for evaluating the performance of the CR communications under a hyperbolic operation scenario. High CPR value means high spectrum awareness, but low coexistence. Moreover, many intriguing numerical results are also illustrated to examine their interrelationships.

I. INTRODUCTION

For the past years, traditional spectrum management approaches have been challenged by their actually inefficient use or low utilization of spectrums even with multiple allocations over many of the frequency bands [1]. Thus, within the current regulatory frameworks of communication, spectrum is a scarce resource [2]. Cognitive radio is the latest emphasized technology that enables the spectrums to be used in a dynamic manner to relieve these problems. The term "cognitive radio (CR)" was first introduced in 1999 by Mitola and Maguire and is recognized as an enhancement of software defined radio (SDR), which could enhance the flexibility of personal wireless services through a new language called the *radio knowledge representation language* (RKRL), and the cognition cycle to parse these stimuli from outside world and to extract the available contextual cues necessary for the performance of its assigned tasks [3-4]. Haykin therefore defines the cognitive radio as an intelligent wireless communication system that is aware of its surrounding environment, and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming *RF stimuli* by making corresponding changes in certain operating parameters in real-time [5]. In addition, some engineering views and advances for helping the implementation of cognitive radio properties into practical communications are described [6-7]. With these groundbreaking investigations and developments, international standardization organizations and industry alliances have already established standards and protocols for cognitive radio as well [8-10].

The frequency hopping spread spectrum (FHSS) systems are widely used in civil and military communications, but somewhat the benefits of FHSS systems could be potentially neutralized by a follow-on jamming (FOJ) with an effective jamming ratio covering the hopping period [11-13]. In spite of the active jamming measures taken, FOJ is implicitly analogous to a cognitive radio communication with spectrum and location awareness, listen-then-act, and adaptation characteristics. For transmission security concerns, concurrent anti-jamming and low probability detection were investigated to have a secure communication [14]. Therefore, the cognitive process cannot be simply realized by monitoring the power or signal-to-noise ratio in some frequency bands of interest in a FH radio environment. A novel technique to capture the spectrum holes with temporal, spatial and frequency variations still remains to be explored.

The remainder of this paper is organized as follows. In Section II, the basic concept, functionalities, and characteristics will be addressed respectively. In Section III, we will first build the architecture of a cognitive radio unit (CRU) with the ability to sense the effective dwell time of a FH communication system. Then the latency breakdown for all possible response delays and effective dwell time in CRU will be considered further for elaborated analysis. Based on this, a wideband sequential scanning (S-scanning) scheme will be taken as an example to scan the incoming signal bands of interest and to implant transmit CR signal if necessary. Moreover, an operation scenario with an elliptic geometry will be considered as well, which is dependent on their relative positions among CRU, FH transmitter, and FH receiver. A quantified metric of cognitive probability ratio (*CPR*) will be available for evaluations by taking this S-scanning scheme under a hyperbolic operation scenario for cognitive communication. In Section IV, many intriguing numerical results based on the proposed cognitive radio model will be illustrated and addressed. Conclusion is in final Section V.

II. COGNITIVE RADIO CONCEPT

The cognitive radio should be capable of capturing the spectrum holes with temporal, frequency or spatial variations in sophisticated radio environment and avoid interference to other users under current spectrum allocation framework dynamically. Moreover, it should be capable of adjusting parameters according to the environment to adapt to the demands of communications and improve its quality as well. Based on these, cognitive radio technology must provide the capability to use or share the spectrum in an opportunistic and dynamic manner to operate in the best available channel. More specifically, four functionalities should be required. *Spectrum sensing* is to determine which portion of the spectrum is available and detect the presence of licensed users when a user operates in a licensed band. *Spectrum management* is to select and capture the best available spectrum and meet user communication requirements. *Spectrum sharing* is to coordinate access to this channel with other users and provide the fair spectrum scheduling method. And *spectrum mobility* is to maintain seamless communication requirements during the transition to better spectrum and vacate the channel when a licensed user is detected. Moreover, two main characteristics of cognitive radio, i.e., cognitive capability and reconfigurability are addressed, respectively, as follows [4-5].

The basic process and task required for cognitive capability in an open spectrum is referred to as the *cognitive cycle* which is consisted of spectrum sensing, spectrum analysis, and spectrum decision. *Spectrum sensing* is to monitor the available spectrum bands (RF stimuli), capture their information, and then detect the spectrum holes from a radio environment. *Spectrum analysis* is to analyze and estimate the characteristics of the spectrum holes that are detected through spectrum sensing, and declare channel capacity to spectrum decision. Finally, *spectrum decision* is to receive spectrum hole and channel capacity information, and send the adapted transmitted signals back to the specific radio environment.

The cognitive capability provides spectrum awareness whereas re-configurability enables the radio to be dynamically programmed according to the radio environment. More specifically, the cognitive radio can be programmed to transmit and receive on a variety of frequencies and to use different access technologies supported by the hardware design. Since most of the spectrum has already been assigned, the most important challenge is to share the licensed spectrum without interfering with the transmission of other licensed users. Therefore, re-configurability is the capability of adjusting operating parameters for the transmission without any modifications on the hardware components. This capability enables the cognitive radio to adapt easily to the dynamic radio environment. Maybe there are several reconfigurable protocol parameters that can be incorporated into the cognitive radio more adaptive to the user requirements or channel conditions, e.g., operating frequency, modulation scheme, transmit power, and etc. For these transmit parameters a cognitive radio can be reconfigured not only at the beginning of a transmission but also during the transmission. According to the spectrum characteristics, the parameters can be reconfigured such that the cognitive radio is switched to a different spectrum band. Moreover, a cognitive radio can be used to provide interoperability among different communication systems as well.

III. COGNITIVE MODEL

In this section, a cognitive radio model with inherent direction finding (DF), emitter location (EL), and fast scanning receiving capabilities to counter frequency hopping communication system is introduced. Then the effective dwell time interval over hopping period, the sequential scanning scheme for searching signals of interest in frequency and temporal domains, and the Hyperbolic geometry scenario incorporated for location awareness are introduced for analyzing this model. Thereafter, the cognitive probability radio metric is introduced, which is a quantified parameter for evaluating the effectiveness of a cognitive communication.

Firstly, in order to beware the frequency hopping features, the architecture of a cognitive radio unit (CRU) with the ability to sense the effective frequency hopping dwell time of a FHSS communication system is shown in Fig. 1. The main components of CRU are DF & EL (direct-finding & emitter location) wideband scanning receiver, demodulator, frequency synthesizer, power amplifier, filter bank, and CRU processor. Each component can be reconfigured via CRU processor.

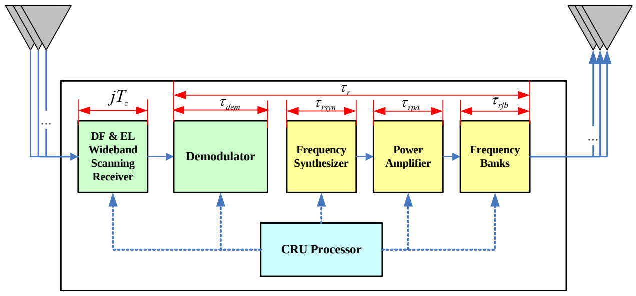

Fig. 1 Cognitive radio unit (CRU) architecture and latency time breakdown

Within the wideband scanning receiver (RF front-end), the received signal is amplified, mixed and A/D converted for demodulation processing (baseband rear-end). The novel characteristic of CRU is a wideband sensing capability in the RF front-end, which is mainly related to RF hardware technologies such as wideband antenna, low noise amplifier, adaptive filter, and etc. The RF hardware for the cognitive radio should be capable of tuning to any part of a large range of frequency spectrum and detecting weak signals in a large dynamic range, which requires a multi-GHz A/D converter with high resolution. Such spectrum sensing enables real-time measurement of spectrum information from radio environment.

As shown in Fig. 1, many time intervals allocated to acquire or process the incoming signals within CRU are listed as well, where jT_z is the total framing processing time needed to acquire the instant FH frequencies and τ_r is the total activation time needed to synthesize and amplify the intercepted signals of interest. The jT_z is related to the FH emitter locations and incoming signal directions, which can be shortened by collaboration with other cognitive radio users. The τ_r is composed of the latency time of rear-end baseband demodulator (τ_{dem}), frequency synthesizer (τ_{rsyn}), power amplifier (τ_{rpa}), and filter banks (τ_{rfb}). In addition, the propagation difference time ($\Delta\tau_d$) dependent on the relative positions among CRU, FH transmitter, and FH receiver should be included for effective cognitive capability analysis as well.

Secondly, in order to cover the hopping period of a FH communication system, the scanning rate of CRU should be fast enough to trace the hopping rate with more framing processing time (T_z) per scanning window. The CRU architecture, latency time breakdown, and window definitions in temporal and frequency domains will be addressed. Fig. 2 shows the CRU architecture and the latency time breakdown for effective dwell time, where T_r represents the total response time and propagation delay ($=\tau_r+\Delta\tau_d$), T_l represents the total latency time before effective dwell on FH hopping period ($=jT_z+T_r$), and T_J represents the effective dwell time ($=T_h-T_l$) on frequency hopping period T_h. Suppose that a FH communication system operate in the bandwidth W only and CRU know the FH communication system parameters. Therefore, exactly at this moments (t=0), CRU will initiate scanning of the actual channel. FH terminal will start to transmit signal in a specific window at the moment t_0. Let t_1 be the moment when the actual FH transmit channel be found by the wideband scanning receiver of CRU ($t_1 = jT_z$). Let t_2 be the moment when the CRU initiates transmission of the found channel if allowable. And let t_3 be the moment when the transmit signal of CRU reaches the receiver site of the found channel after passing through a propagation difference time $\Delta\tau_d$. Of course, under this circumstance, the CRU will not interfere with the existing primary FH communication system. Equation (1) and (2) show their interrelationships.

$$T_l = jT_z + (\tau_r + \Delta\tau_d) = jT_z + T_r, \quad (1)$$

$$T_J = T_h - (jT_z + T_r) = T_t - jT_z, \quad (2)$$

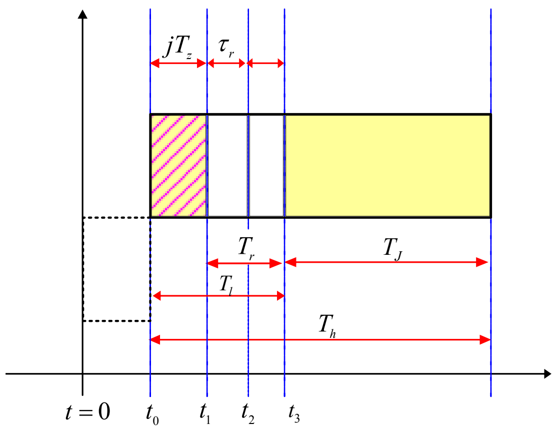

Fig. 2 Effective dwell time (T_J) and latency time breakdown for CRU operation

T_J must be smaller than T_h under any circumstance for any response time or propagation delays. The effective dwell ratio h is defined to be T_J over T_h. The framing window number available during each hopping period is defined to be m and represented as

$$m = \left\lfloor \frac{T_h - T_r}{T_z} \right\rfloor = \left\lfloor \frac{T_t}{T_z} \right\rfloor, \quad (3)$$

where T_z represents the framing processing time per scanning window W_s and the bracket symbol means the maximum integer equal to or smaller than the value inside is taken. It follows that CRU could analyze at most m windows during the dwell period, T_h. Furthermore, the scanning window number available in the FH system bandwidth W is defined to be n and represented as

$$n = \left\lceil \frac{W}{W_s} \right\rceil, \quad (4)$$

where W represents the hopping bandwidth of a FH system, W_s represents the scanning window set by the CRU, e.g., 1 or 5MHz, and the bracket symbol means the minimum integer equal to or larger than the value inside is taken. It follows that the CRU could analyze at most n windows during the whole hopping bandwidth W. The wider the scanning window W_s is, the smaller the window number n will be. This means that a faster scanning but rougher scanning condition is set. Let k be the window number of framing and scanning during each hopping period, it is evident that

$$k = \min\{m, n\}, \quad (5)$$

which means the smaller one of m or n is selected as the window number.

Thirdly, a sequential scanning (S-scanning) scheme will be taken as the scanning measure to scan the incoming frequency hopping signals fast enough to implant CRU transmit signal if it is allowable. Based on the basic definitions as aforementioned, if CRU analyzes all scanning windows randomly with sequential probability $p(T_J)=1/(n+1-j)$, then $p(T_J)=(n-k)/(n+1-j)$ will be the probability not analyzed in the scanning window. Therefore, the probability distribution of the effective dwell time can be given by

$$p(T_J) = \begin{cases} \dfrac{n-k}{n+1-j}, & j > k\,(T_J = 0) \\ \dfrac{1}{n+1-j}, & j = 1,2,\ldots,k \end{cases} \quad (6)$$

It is assumed that T_r is assumed not zero and $T_r=\tau_r+\Delta\tau_d=l\times T_h$, where l is the propagation time ratio between T_r and T_h. The average effective dwell time can therefore be derived and given by

$$\overline{T}_J = \sum_{j=1}^{k} T_J \cdot p(T_j) = \sum_{j=1}^{k} \left(\frac{(1-l)\cdot T_h - jT_z}{n+1-j} \right) \quad (7)$$

From the derived result of equation (7), the criterion of hopping rate (R_h) and framing processing time product (T_z) for effective dwell time can be available and given by

$$R_h \cdot T_z \le \frac{\sum_{j=1}^{k}\left(\frac{1-l}{n+1-j}\right)}{\sum_{j=1}^{k}\left(\frac{j}{n+1-j}\right)} \qquad (8)$$

which is the basic criterion whenever $T_r \neq 0$ for effective coverage of the hopping period. Therefore, the effective dwell time ratio and the scanning rate by sequential scanning scheme can be manipulated further and given by equation (9) and (10), respectively.

$$h_s = \frac{\bar{T}_J}{T_h} = \sum_{j=1}^{k}\left(\frac{1-l}{n+1-j}\right) - \frac{T_z}{T_h}\cdot\sum_{j=1}^{k}\left(\frac{j}{n+1-j}\right) \qquad (9)$$

$$R_s = \frac{W_s}{T_z} = W_s \cdot R_h \cdot \left(\frac{\sum_{j=1}^{k}\left(\frac{j}{n+1-j}\right)}{\sum_{j=1}^{k}\left(\frac{1-l}{n+1-j}\right) - h_s}\right) \qquad (10)$$

Fourthly, an operation scenario with a hyperbolic geometry for special domain analysis will be examined, which is dependent on their relative positions among CRU, FH transmitter, and FH receiver as shown in Fig. 3. FH receiver is moveable. If the range between FH transmitter and CRU position is fixed (i.e., $R_{tc}=a$) and FH receiver position is roaming around these two focuses, the following expression will be available by using the fact that the latency time (T_l) must be smaller than the hopping period (T_h) for effective hopping period coverage.

$$T_l = jT_z + \tau_r + \tau_d = jT_z + \tau_r + \frac{\left(a + R_{cr} - R_{tr}\right)}{c} \le T_h, \qquad (11)$$

where τ_r can be assumed to be zero for instant response, R_{cr} is the range between CRU and FH receiver, and R_{tr} is the range between FH transmitter and FH receiver. After a simple manipulation, a hyperbolic equation will be available and given by

$$\frac{x^2}{(D-a)^2} - \frac{y^2}{D(2a-D)} \ge \frac{1}{4}, \qquad (12)$$

where D is assumed to equal $(T_h - jT_z - \tau_r)\times c$ and is given by the following inequality

$$\left(a + R_{cr} - R_{tr}\right) \le \left(T_h - jT_z - \tau_r\right)\cdot c = D \qquad (13)$$

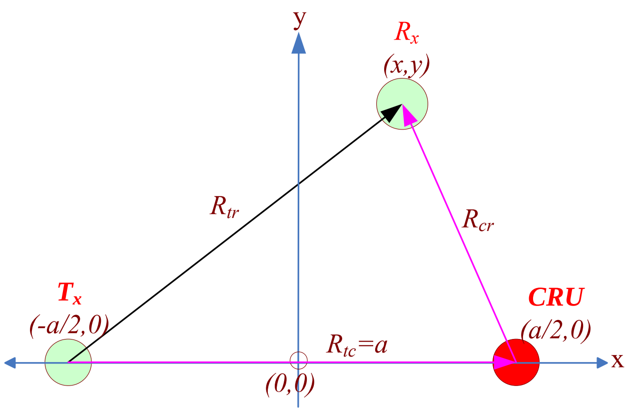

Fig. 3 Hyperbolic CRU operation scenario with movable R_x (FH receiver) and fixed R_{tc} (=a)

Finally, it is known that cardiopulmonary resuscitation (CPR) is, in reality, an emergency medical procedure for a victim of cardiac arrest or, in some circumstances, respiratory arrest. But in order to explore and "probe" the spectrum awareness further with geometry-dependent situation as described in Fig. 3 for cognitive communications, the propagation time ratio l can be replaced with geometry-dependent parameters and given by

$$l = R_h \cdot \left(a + R_{cr} - R_{tr}\right)\cdot c^{-1}, \qquad (14)$$

where all range parameters are defined the same as equation (11). Then the effective probability ratio (*CPR*) for CRU by taking S-scanning scheme under a hyperbolic operation scenario can be redefined from equation (9) and (10) and given by

$$CPR = \sum_{j=1}^{k}\left(\frac{1 - R_h \cdot \left(a_h + R_{cr} - R_{tr}\right)\cdot c^{-1}}{n+1-j}\right) - T_z \cdot R_h \cdot \sum_{j=1}^{k}\left(\frac{j}{n+1-j}\right) \qquad (15)$$

$$R_s = \frac{W_s}{T_z} = W_s \cdot R_h \cdot \left(\frac{\sum_{j=1}^{k}\left(\frac{j}{n+1-j}\right)}{\sum_{j=1}^{k}\left(\frac{1 - R_h \cdot \left(a_h + R_{cr} - R_{tr}\right)\cdot c^{-1}}{n+1-j}\right) - CPR}\right) \qquad (16)$$

where *CPR* is the quantified metric for cognitive communication in a FHSS system. And whenever CRU scanning rate R_s is concerned, equation (16) can be applied. If *CPR* value is high when in comparison with specific *CPR* level set by incorporating many system parameters (e.g., > 0.8), CRU will beware much more the existence of the FH communication and should rescan and shift to other frequency bands of interest for specific communication purpose in an opportunistic manner without affecting any existing FH communication system. Nevertheless, on the contrary, if *CPR* value is low (e.g., < 0.2), CRU will coexist well with the FH communication system and should prepare to acquire and utilize this spectrum resource for specific cognitive communication purpose.

IV. NUMERICAL RESULTS

In this section, many intriguing numerical results based on derivations from previous sections will be illustrated and addressed in more details. Fig. 4 shows the *CPR* vs. R_h curves for different framing processing time (T_z) with the assumption of W_s=1MHz and T_r =0.1T_h. Basically, *CPR* changes inversely with hopping rate with other parameters fixed, i.e., the higher R_h is, the smaller *CPR* will be. Moreover, for fixed R_h, the shorter T_z is, the higher *CPR* will be, i.e., CRU will beware more the existence of a primary FH communication system and should avoid interference to it.

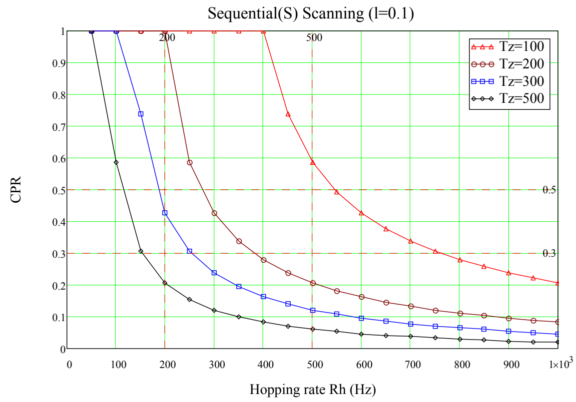

Fig. 4 *CPR* vs. hopping rate R_h with different T_z (l=0.1; W_s=1MHz; T_z=100, 200,300, and 500 *us*)

The scanning rate R_s and *CPR* are two important parameters of CRU and are closely related to each other. Fig. 5 shows the R_s vs. *CPR* curves with W=20MHz and with different R_h and W_s combinations when T_r=0.1T_h (i.e., l=0.1). When *CPR* is larger, the scanning rate R_s should be increasingly higher. For fixed *CPR*, the higher R_h is, the higher R_s will require accordingly. For fixed R_h and *CPR*, the wider W_s, i.e., 5MHz, the higher R_s will be required for CRU.

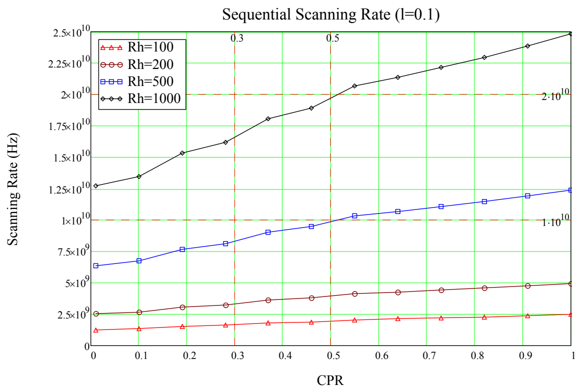

Fig. 5 Scanning rate (R_s) vs. *CPR* with different R_h and W_s combinations (l=0.1)

Furthermore, in order to examine the location awareness, the hyperbolic *CPR* contours are shown in Fig. 6 with S-scanning, T_z=100*us* and R_h=200Hz (y-axis vs. x-axis: ±250km×±250km) The red dashed cuves show the constant tilted angles formed by the varying CRU and the other two fixed FH transmitter and receiver; blue solid curves show the hyperbolic *CPR* trajectories and values. It is observed that when FH receiver changes its trajectory in a hyperbolic manner from left to right and approaches to CRU and FH transmitter located on the positions of (x, y)=(±50km, 0), the *CPR* values varied from about 0.5 to 0.9 are shown in Fig. 13. If location awareness through *CPR* is established, the cognitive probability can therefore be sensed and analyzed from where it is located. For example, when CRU is located on (x, y)=(100km, 100km), its analyzed *CPR* value is around 1.0.

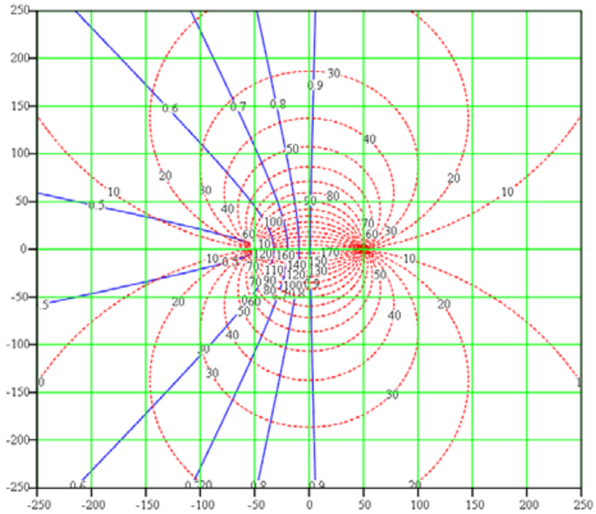

Fig. 6 Hyperbolic *CPR* contours with S-scanning (y-axis vs. x-axis: ±250km×±250km; R_h=400Hz; T_z=100*us*)

Fig. 7 shows the similar hyperbolic *CPR* contours with S-scanning and T_z=100*us*, but with higher hopping rate (i.e., R_h= 500Hz). It is observed that when CRU changes its trajectory in a hyperbolic manner from left to right and approaches to CRU and FH transmitter located on the positions of (x, y)=(±50km, 0), the *CPR* values varied from about 0.3 to 0.8 are shown in Fig. 7. If the primary receiver is located on (x, y)=(100km, 100km), then its analyzed *CPR* value is around 0.69. This *CPR* value with higher hopping rate is much smaller when in comparison with the *CPR* value (i.e., 1.0) in Fig. 6. It means that the coexistence between CRU and the FH communication system is much better due to lower hopping rate.

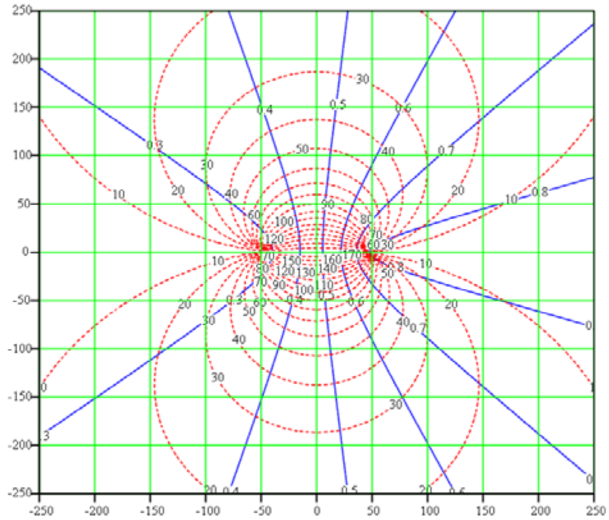

Fig. 7 Hyperbolic *CPR* contours with S-scanning (y-axis vs. x-axis: ±250km×±250km; R_h=500Hz; T_z=100*us*)

V. CONCLUSION

In this paper, the status of cognitive radio advances and basic concept, functionalities, and characteristics have first been surveyed. Because the active jamming measures taken by FOJ applied in conventional military communications is implicitly analogous to a cognitive radio communication. A CRU model with FH spectrum and location awareness characteristics is proposed and analyzed thoroughly. The proposed S-scanning scheme for CRU has also been coordinated successfully with a hyperbolic geometry-dependent scenario, which is the most crucial foundation for cognitive radio communications. A quantified metric of cognitive probability ratio (*CPR*) for cognitive communications is therefore available for evaluations of the coexistence with a specific FHSS system. Many interesting results have also been illustrated to examine the interrelationships between *CPR* and many other system parameters. In fact, the proposed model and metric have paved one practical way for the system evaluations of CR communications.

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