UNIFORM SCANNING MODEL FOR COGNITIVE COMMUNICATIONS

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ABSTRACT

In this paper, in order to capture the spectrum holes with temporal, spatial and frequency variations in sophisticated FHSS radio environments and avoid interference to the existing primary users, a cognitive radio unit (CRU) model with a uniform scanning (U-scanning) technique and cognitive probability ratio (*CPR*) metric for cognitive communications has been 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 cognitive radio communications under an elliptic operation scenario. The *CPR* value is inversely with hopping rate and high *CPR* value means high spectrum awareness but low coexistence. Moreover, many intriguing numerical results are also illustrated to examine their interrelationships.

Keywords: cognitive radio (CR), cognitive radio unit (CRU), uniform scanning (U-scanning), cognitive probability ratio (CPR), follow-on jamming (FOJ).

1. 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]. Nevertheless, Jondral made a historical and meaning review for this new intelligent radio technology based on SDR or the evolution of it [6]. Akyildiz et al. made a thorough survey for the next generation wireless networks with dynamic spectrum access and cognitive radio functionalities. Cognitive capability and re-configurability are two main characteristics of cognitive radio, which will provide spectrum awareness through the real time *cognitive cycle* of spectrum sensing, analysis, and decision, and enable the radio to be dynamically programmed with appropriate communication parameters according to the radio environment, respectively [7].

Therefore, a variety of investigations related to cognitive radio process have been made for this tempting technology by exploring the potential of relieving spectrum scarcity and promoting spectrum efficiency. For example, Srinivasa and Ja explored the throughput potential of cognitive radio communication and summarized that the optimal licensing is equal to the traffic duty cycle lying between fully licensing and fully opportunistic operation [8]. Based on a processing gain approach for ultra wideband (UWB), Sahin and Arslan presented a comprehensive system design for cognitive radio, which leads to an increased range for cognitive networks [9]. Hoven and Sahai explored the effect of transmit power on cognitive radio and proved that a cognitive radio can vary transmit power while maintaining guarantee of service to the primary users by using the received SNR as a proxy for distance and the fundamental constraint on transmit power is the minimum SNR it can detect [10]. A key issue in spectrum pooling concept is the reliable and efficient detection of spectrums that are accessed by the licensed users or spared for the non-licensed users. Hillendbrand et al. devised formulas for the calculation of the detection and false alarm probability for the general case of an arbitrary measurement covariance matrix in a spectrum pooling system [11]. Larsson and Skoglund presented an analysis of the carrier-to-noise-and-interference situation in a cellular wireless network, and analyzed the impact of cognitive users starting to transmit. Nevertheless, they concluded that it is still very challenging by introducing cognitive transmitters in a frequency-planned cellular network without causing substantial interference [12].

For CR engineering concerns, Jondral and Karlsruhe discussed some important and necessary engineering aspects of CR, e.g., location and spectrum awareness, transmission power control, and signal analysis [13]. Mody et al. described the advances in cognitive communications and combined the concepts of signal processing, communications, pattern classification, and machine learning to make dynamic use of the spectrum, such that the emanated signals do not interfere with the existing ones. They concluded that incremental learning and prediction would allow knowledge enhancement and result in improved decision as more snapshots of data are processed [14]. With these groundbreaking investigations and developments, international standardization organizations and industry alliances have already established standards and protocols for cognitive radio, which provide architecture, requirements, applications, and coexistence considerations. These not only form the basis for the definition of this air interface standard, but will also serve as foundation for future research in the promising area of CRs. [15-17].

Nowadays, frequency hopping (FH) technology is widely used in civil and military communication systems, but somewhat their benefits could be potentially neutralized by a follow-on jamming (FOJ) with an effective jamming ratio covering the hopping period. Torrieri devised fundamental limitations on the effectiveness of this FOJ, which arise because of the geometry and the need for frequency estimation and signal sorting [18]. Felstead presented FOJ design considerations on frequency hopping systems. For example, the minimum determination time and the probability of correct determination were derived as a function of the intercepted SNR and the "determinator" resolution. Geometrical considerations showed the spatial limit at which the FOJ becomes impossible to work. It is concluded that the vulnerability to FOJ can be reduced to tolerable levels by use of suitable hop rates [19]. Instead of focusing on power or geometry aspect of jamming only, Burder derived a mathematical intercept model for computation of the jamming probability when a FOJ with a wideband-scanning receiver jams a single frequency hopping system [20]. In spite of taking an active jamming measure, the FOJ concept is implicitly analogous to a cognitive radio communication with spectrum and location awareness, listen-then-act, and adaptation characteristics. For transmission security concerns, Liao et al. investigated concurrent anti-jamming and low probability detection to have a secure communication [21]. 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 as addressed in previous paragraphs. A novel technique to capture the spectrum holes with temporal, spatial and frequency variations still remains to be explored. In this paper, we will propose a practical CR model with location awareness, fast framing processing, and wideband scanning capabilities for evaluating the effectiveness of spectrum awareness for a FH communication system.

The remainder of this paper is organized as follows. In Section 2, the basic concept, functionalities, and characteristics will be addressed respectively. In Section 3, 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 uniform scanning (U-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 a U-scanning scheme under an elliptic operation scenario for cognitive communication. In Section 4, many intriguing numerical results based on the proposed cognitive radio model will be illustrated and addressed. Conclusion is in final Section 5.

2. COGNITIVE RADIO CONCEPT

The term, cognitive radio, can be formally defined as follows: *A Cognitive Radio is a radio that can change its transmitter parameters based on interaction with the environment in which it operates* [7]. Therefore, cognitive radio should capture 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 re-configurability are addressed, respectively, as follows [4-5, 7].

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 as shown in Fig. 1. *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.

3. COGNITIVE RADIO MODEL (CRU)

The use of two independent synthesizers in a FH system permits a non-constant relationship between each pair of frequency channels, i.e., transmission channel and complementary channel. For BPSK modulation each symbol is transmitted as one of two frequencies, the pair of possible frequencies changes with each hop. In general, frequency hopping may be classified as fast or slow frequency hopping. Fast frequency hopping implies that the hopping rate equals or exceeds the information-bit rate. Nevertheless, slow frequency hopping occurs if two or more symbols are transmitted in the time interval between frequency hops. In this section, a cognitive radio unit (CRU) model with inherent location awareness, i.e., direction finding (DF) and emitter location (EL), wideband scanning, and fast framing processing capabilities is introduced to coexist with this type of FH system. Based on the proposed model, four related subtopics will be investigated further, respectively, in this section, i.e., the effective dwell time breakdown over FH hopping period, the uniform scanning (U-scanning) scheme for searching frequency bands of interest, the elliptic geometry scenario incorporated for location awareness, and the cognitive probability radio (CPR) metric for evaluating the effectiveness of a cognitive communication.

A. CRU architecture

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. 2. 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.

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. 2, CRU architecture and 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.

For example, the τ_d propagation difference time will be around 100 *us* for a 30 km range difference, which is far longer than the activation time τ_r in CRU (several *ns* order). Therefore, τ_r can be assumed to be zero under this circumstance, but it will not if τ_d is comparatively small as well.

B. Effective FH dwell time

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. In this subsection, CRU architecture, latency time breakdown, and window definitions in temporal and frequency domains will be addressed. Fig. 3 shows the effective dwell time (T_J) and latency time breakdown for CRU operation, where T_r represents the sum of the activation time and the propagation difference time ($=\tau_r+\Delta\tau_d$), 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 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, CRU will not interfere with the existing primary FH communication system. Equation (1) and (2) show their interrelationships.

$$T_l = jT_z + \left(\tau_r + \Delta\tau_d\right) = jT_z + T_r \tag{1}$$

$$T_J = T_h - \left(jT_z + T_r\right) = T_t - jT_z \tag{2}$$

T_J should be smaller than T_h under any circumstance. The framing window number available during each hopping period is defined to be m and represented as

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

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

$$n = \left\lceil \frac{W}{W_s} \right\rceil, \tag{4}$$

where W represents the hopping bandwidth of a FH system, W_s represents the scanning window set by 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 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

$$k = \min\{m, n\}, \tag{5}$$

which means the smaller one of m or n is selected as the window number. The effective dwell ratio h_u is defined to be T_J over T_h

$$h_u = \frac{T_J}{T_h} \tag{6}$$

And whenever m equals n, the effective dwell ratio h_u^* under this circumstance can be derived as follows

$$h_u^* = (1 - l) \cdot \frac{n-1}{2n}, \tag{7}$$

where l is the propagation time ratio between T_r and T_h. Fig. 4 shows its characteristic when the values of m=n are varied from 1 to 20 if different propagation delay cases are assumed, e.g., l=0, 0.2, and 0.5. If l=0 (i.e., T_r=0), it will approach to around 0.5 if the window number (m or n) is increasing.

C. Elliptic operation scenario

In this section, an operation scenario with an elliptic geometry for spatial domain analysis will be examined, which is dependent on their relative positions among CRU, FH transmitter, and FH receiver as shown in Fig. 5 [18-19]. CRU is moveable. If the range between FH transmitter (T_x) and FH receiver (R_x) is fixed (i.e., $R_{tr}=a$) and CRU position is roaming around these two ellipse 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.

$$T_l = jT_z + \tau_r + \frac{\left(R_{tc} + R_{cr} - a\right)}{c} \leq T_h, \tag{8}$$

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

$$\frac{x^2}{\left(D+a\right)^2} + \frac{y^2}{D\left(D+2a\right)} \geq \frac{1}{4}, \tag{9}$$

where D is assumed to equal (T_h - jT_z - τ_r)×c and is given by the following inequality

$$\left(R_{tc} + R_{cr} - a\right) \leq \left(T_h - jT_z - \tau_r\right) \cdot c = D \tag{10}$$

Fig. 6 shows two different operation scenarios for an elliptic CRU model. Whenever the frequency hopping rate R_h of a FH communication system is assumed, e.g., 500Hz, the dashed elliptic curve shows the operation boundary for this system. As shown in Fig. 6(a), if CRU penetrates through this boundary, enters into the specified ellipse area, and sends the same signal features as this FH communication system, an even higher FH hopping rate is required for the FH communication system to operate normally. Or CRU should reconfigure its operation frequencies or other operation parameters to coexist with this existing FH communication system. On the contrary, If CRU is still roaming outside of the assumed boundary as shown in Fig. 6(b), then a normal 500Hz hopping rate within this constrained elliptic area would still remain fast enough for the FH communication system to operate normally.

Fig. 7 illustrates the typical hopping rate ($R_h=1/T_h$) contours (blue solid curves) based on Fig. 5 and Fig. 6 scenarios with movable CRU position varied within this area ±250km×±250km. The red dashed curves show the constant tilted angles formed by the varying CRU and the other two fixed FH transmitter and receiver. It is also assumed that the total framing processing time is 1*ms* (i.e., jT_z= 10×100 μs =1*ms*) and fixed R_{tr} range a=100km. For example, if the operating hopping rates R_h are the same initially among CRU and these two FH communicators located on T_x and R_x positions (e.g. R_h =500Hz), the operating hopping rates will be even higher (e.g. 600Hz) as CRU approaches their locations (i.e., (x, y)=(±50km, 0)) to coexist.

D. Uniform scanning scheme

In this section, a uniform scanning (U-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 [20]. Based on the basic definitions in previous subsections, if CRU analyzes all scanning windows randomly with uniform probability $1/n$, then the probability not analyzed in the scanning window will be $(n\text{-}k)/n$. Therefore, the probability distribution of the effective dwell time can be given by

$$p(T_J)=\begin{cases}\dfrac{(n-k)}{n}, & j>k\,(T_J=0)\\[2mm] \dfrac{1}{n} & ,T_J=T_t-jT_z,\ j=1,2,\dots k\end{cases}, \tag{11}$$

where k is defined to be the same as equation (5). It is assumed that $T_r=\tau_r+\Delta\tau_d=l\times T_h$, 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

$$\bar{T}_J=\sum_{T_J}T_J\cdot p(T_J)=\frac{k}{n}\left((1-l)T_h-T_z\frac{k+1}{2}\right) \tag{12}$$

From the derived result of equation (12), the criterion of hopping rate (R_h) and framing processing time product (T_z) for effective dwell time can be available and given by

$$R_h\cdot T_z\le(1-l)\cdot\frac{2}{(k+1)}, \tag{13}$$

which is the basic criterion whenever $T_r \neq 0$ for effective coverage of the hopping period.

But in this subsection, in order to explore and “probe” the spectrum awareness further with geometry-dependent situation as will be described in Fig. 5 and Fig. 6 for cognitive communications, the propagation time ratio l can be replaced with geometry-dependent parameters and given by

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

where all range parameters are defined the same as equation (8). Therefore, the effective dwell time ratio by uniform scanning scheme can be redefined to be cognitive probability ratio (*CPR*) and given by equation (15)

$$CPR = \frac{\overline{T}_J}{T_h} = \frac{k}{n} \cdot \left(\left(1 - l\right) - \frac{T_z}{T_h} \frac{k+1}{2} \right), \tag{15}$$

where *CPR* is a quantified metric for cognitive communication in a FHSS system. And whenever CRU scanning rate R_s is concerned, equation (16) can be applied.

$$R_s = \frac{W_s}{T_z} = W_s \cdot R_h \cdot \left(\frac{k\left(k+1\right)}{2 \cdot \left(\left(1-l\right) \cdot k - n \cdot CPR\right)} \right) \tag{16}$$

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.

4. NUMERICAL RESULTS

In this section, many intriguing numerical results based on derivations from previous sections will be illustrated and addressed in more details. Fig. 8 shows the *CPR* vs. R_h curves for different framing processing time (T_z) with the assumption of W=20MHz, 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.

The scanning rate R_s and *CPR* are two important parameters of CRU and are closely related to each other. Fig. 9 shows the R_s vs. *CPR* curves 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.

In order to explore the influence of external propagation delay on CRU system performance, Fig. 10 shows the R_s vs. *CPR* curves with different T_r for fixed W_s=1MHz and R_h=500Hz. The scanning capability of CRU (R_s) is basically in proportion to *CPR* value. With higher *CPR* values CRU is therefore more aware of the existence of a specific FH communication system and the spectrum holes can be found more promptly and efficiently. Nevertheless, for fixed R_s, the longer T_r is, the less *CPR* will be, i.e., CRU can prepare to utilize these spectrum resources.

Furthermore, in order to examine the location awareness, the elliptic *CPR* contours are shown in Fig. 11 with U-scanning, T_z=100μs and R_h=200Hz (y-axis vs. x-axis: ±250km×±250km) The red dashed lines show the constant tilted angles formed by the varying CRU and the other two fixed FH transmitter and receiver; blue solid lines show the elliptic *CPR* trajectories and values. It is observed that when CRU changes its trajectory in an elliptic manner and approaches to FH transmitter and receiver located on the positions of (x, y)=(±50km, 0), the *CPR* values varied from about 0.45 to 0.75 are shown in Fig. 11. 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 0.66.

Fig. 12 shows the similar elliptic *CPR* contours with U-scanning and T_z=100μs, but with higher hopping rate (i.e., R_h= 500Hz). It is observed that when CRU changes its trajectory in an elliptic manner and approaches to FH transmitter and receiver located on the positions of (x, y)=(±50km, 0), the *CPR* values varied from about 0 to 0.45 are shown in Fig. 12. If the primary receiver is located on (x, y)=(100km, 100km), then its analyzed *CPR* value is around 0.21. This *CPR* value with higher hopping rate is much smaller when in comparison with the *CPR* value (i.e., 0.66) in Fig. 11. It means that the coexistence between CRU and the FH communication system is much better due to lower hopping rate.

In this section, many different parameter combinations, e.g., *CPR*, R_h, R_s and T_z, and simultaneous timing/frequency/space conditions have been considered for investigating their interrelationships under the nearly "perfect" circumstances of exact direction finding (DF) and emitter location (EL) for wideband scanning only as shown in the first block of Fig. 2. Therefore, for example, if imperfect conditions of finding directions and locating emitters are met, other statistical models or even their coordinated considerations with the newly developed model in this paper are remained to be investigated further for future works.

5. CONCLUSION

In this paper, the status of cognitive radio advances and its basic concept, functionalities, and characteristics have first been surveyed. A CRU model with FH spectrum and location awareness characteristics is proposed and analyzed thoroughly. The proposed U-scanning scheme for CRU has also been coordinated successfully with an elliptic 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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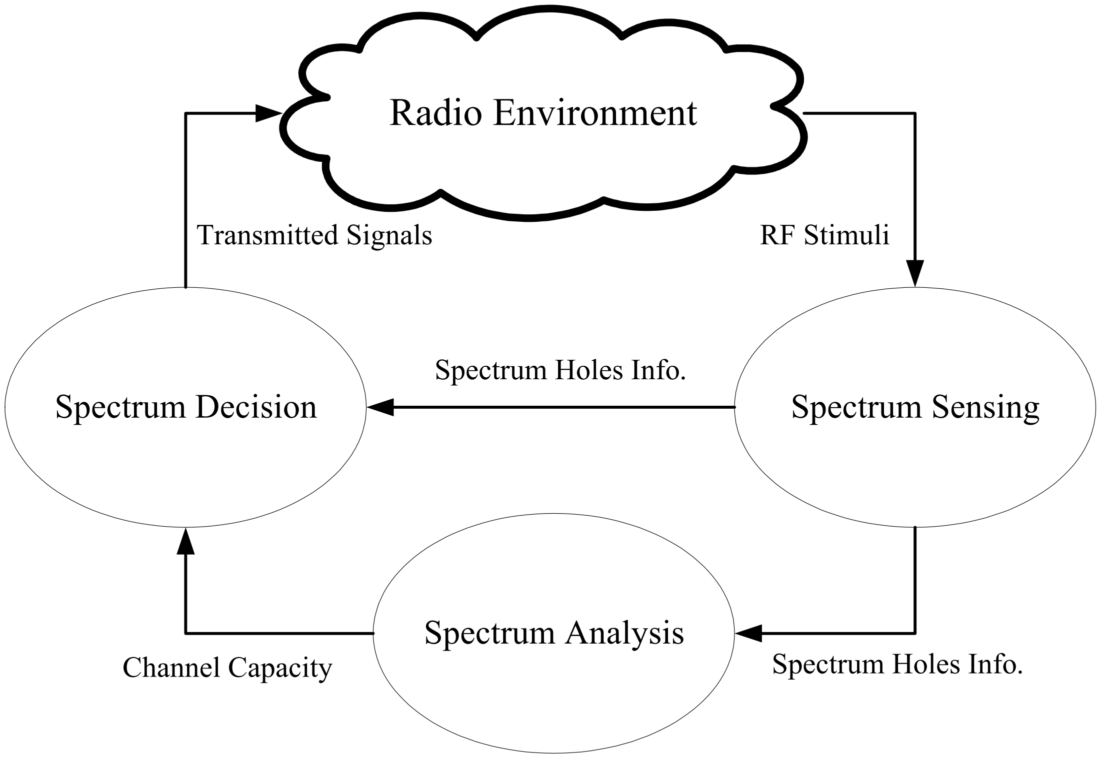


Fig. 1 *Cognitive cycle* concept

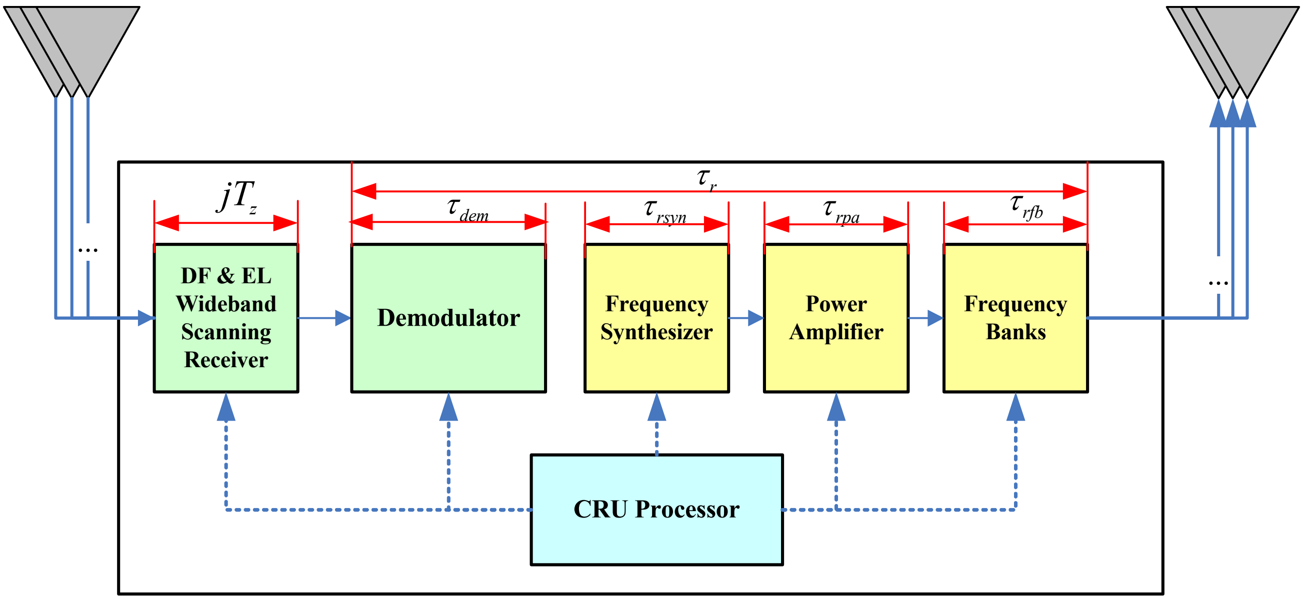


Fig. 2 Cognitive radio unit (CRU) architecture and latency time breakdown

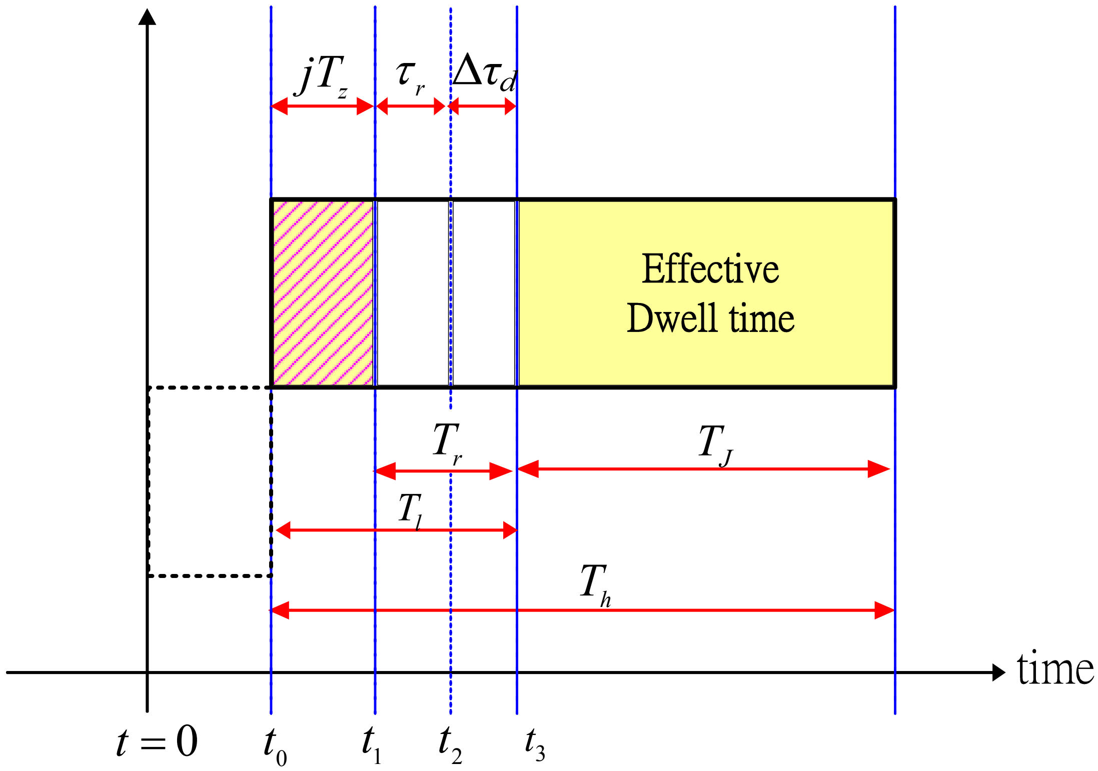


Fig. 3 Effective dwell time (T_J) and latency time breakdown for CRU operation

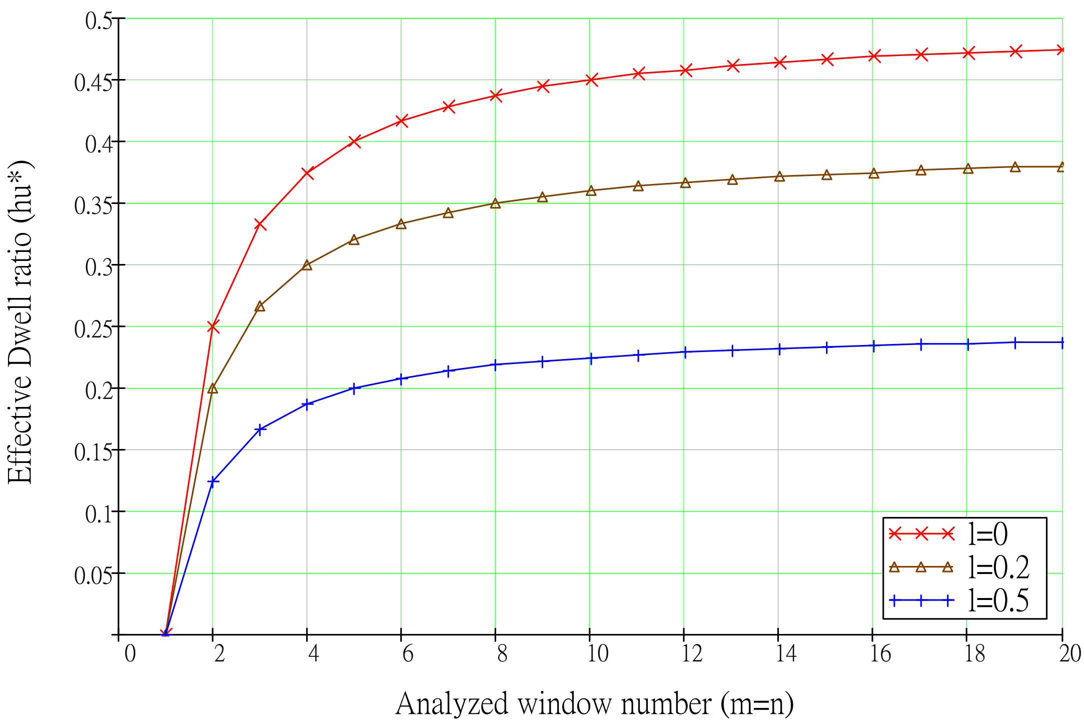


Fig. 4 Effective dwell ratio (h_u^*) vs. window number (m=n) (l=0, 0.2, and 0.5)

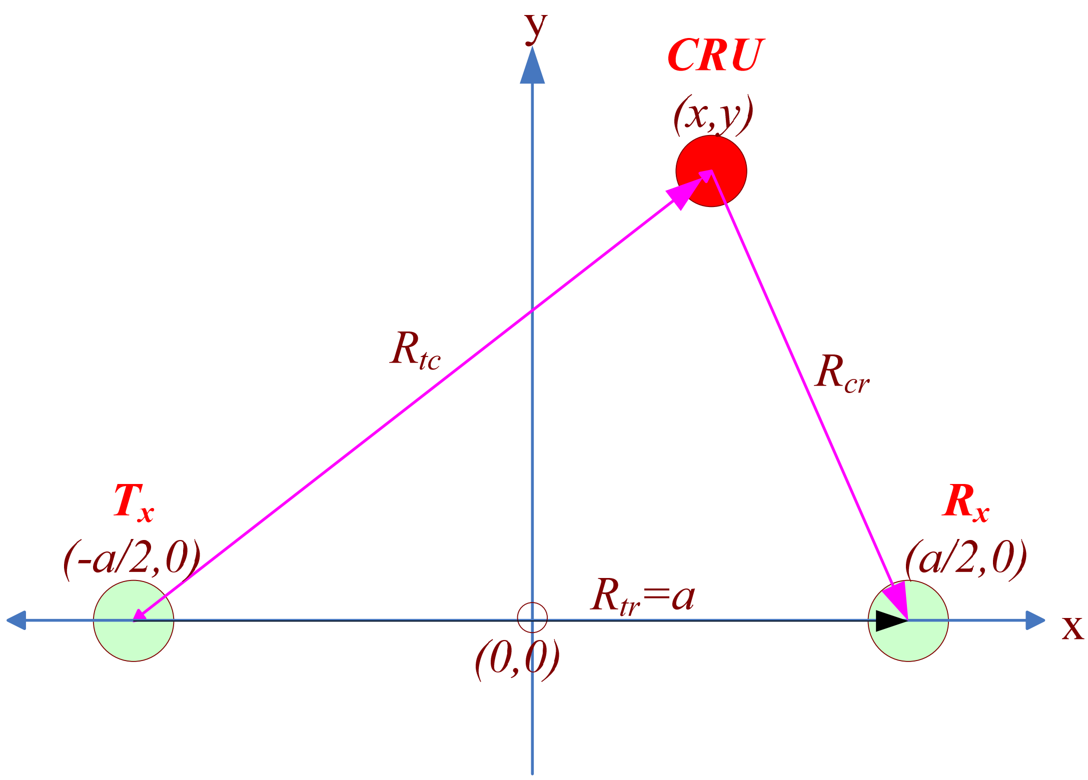
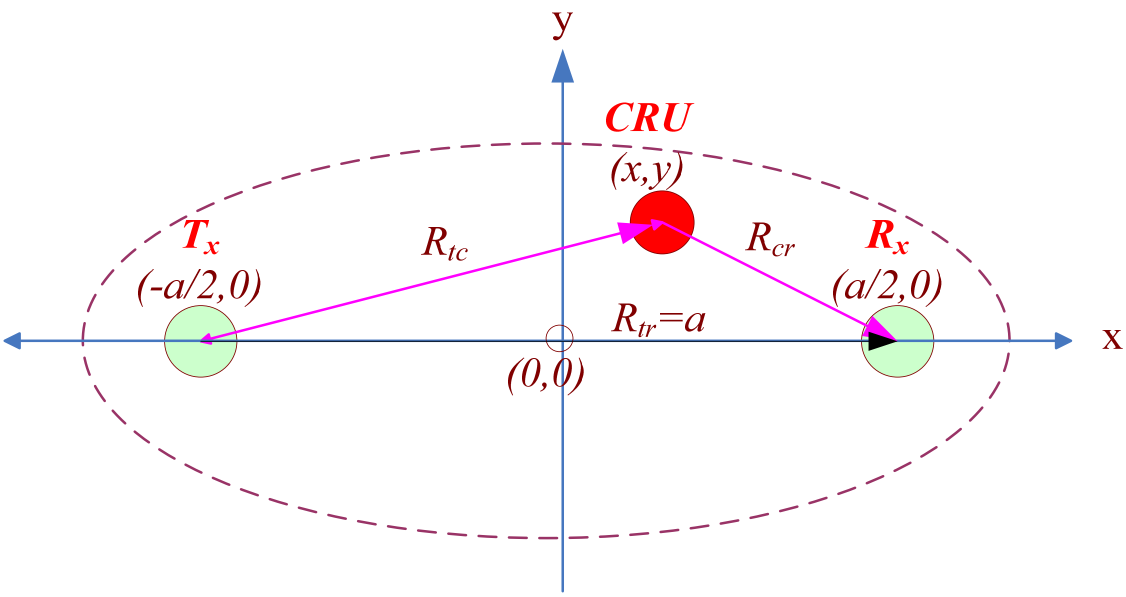
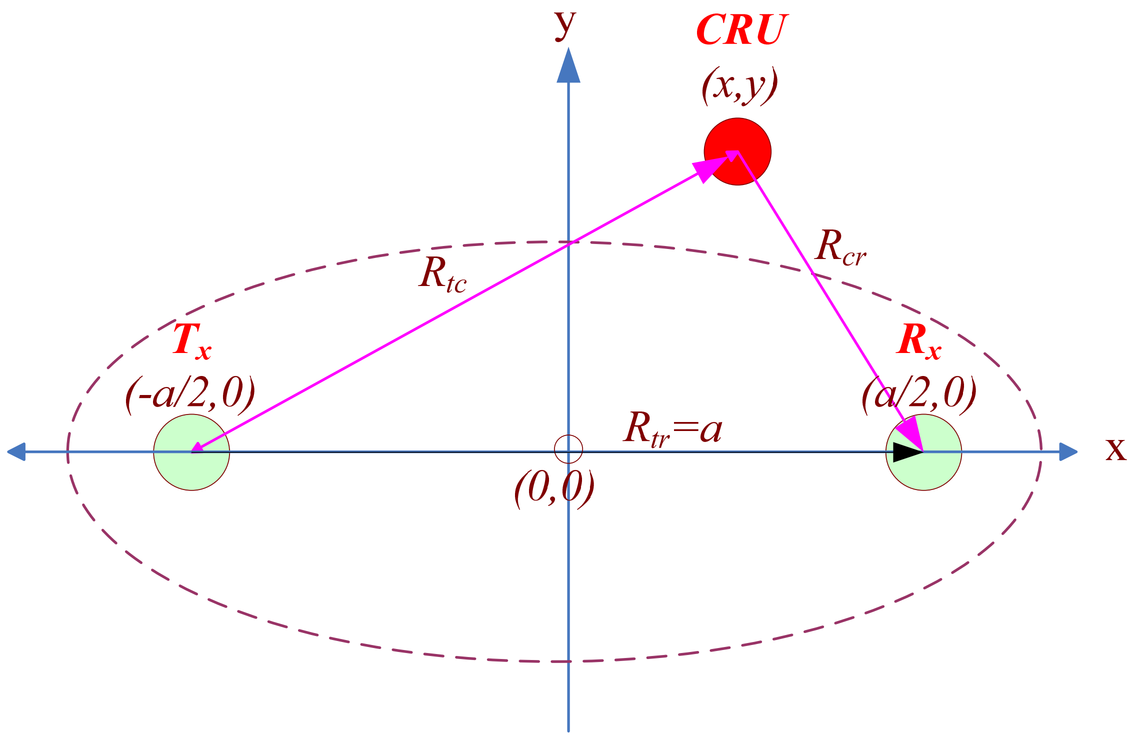


Fig. 5 Elliptic CRU operation scenario with movable CRU and fixed R_{tr} (=a)



(a)



(b)

Fig. 6 Elliptic operation scenarios with CRU (a) inside of (b) outside of a hopping rate R_h boundary (dashed)

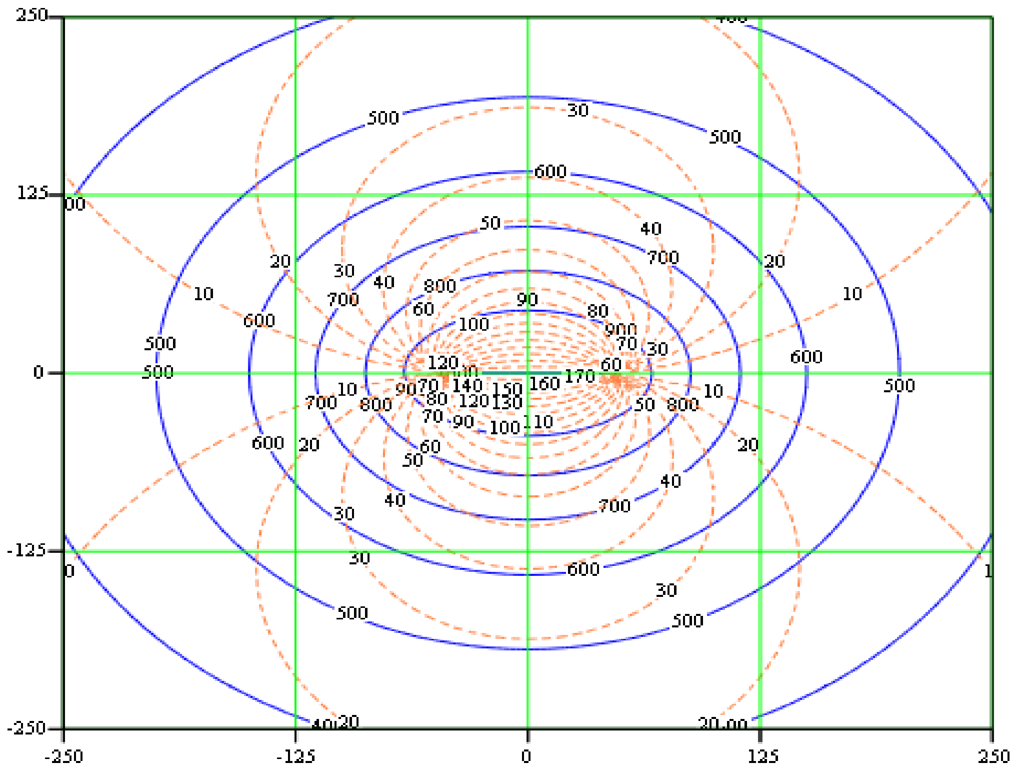


Fig. 7 Typical elliptic hopping rate R_h contours (y-axis vs. x-axis: ±250km×±250km; jT_z=1ms;

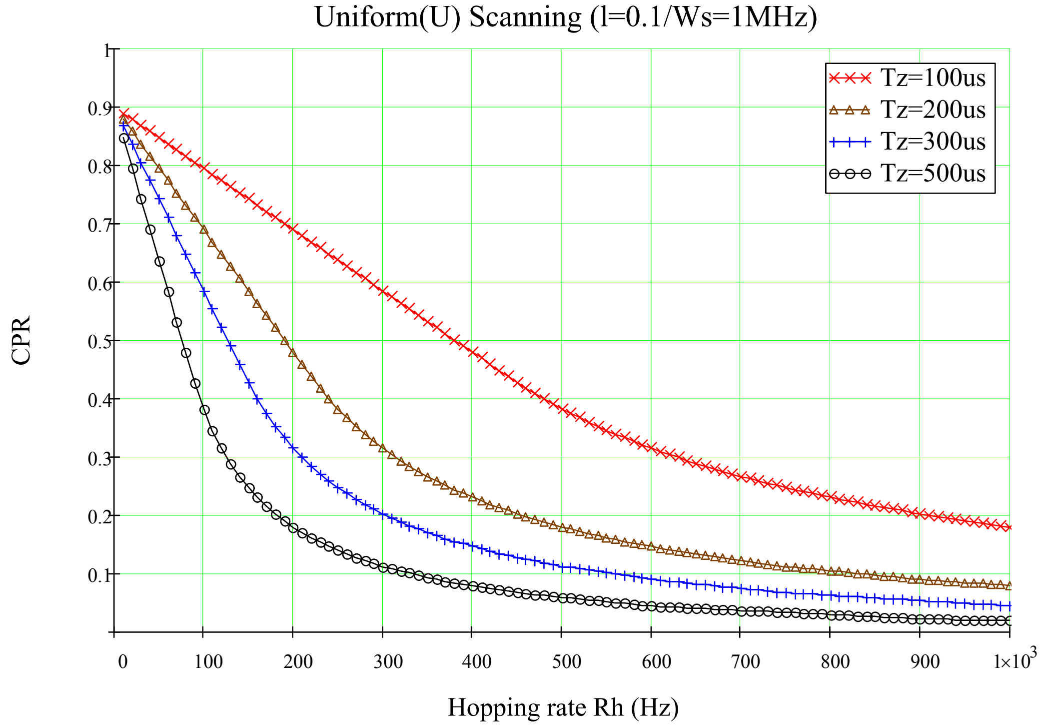


Fig. 8 *CPR* vs. hopping rate R_h with different T_z (l=0.1; W_s=1MHz; T_z=100, 200,300, and 500μs)

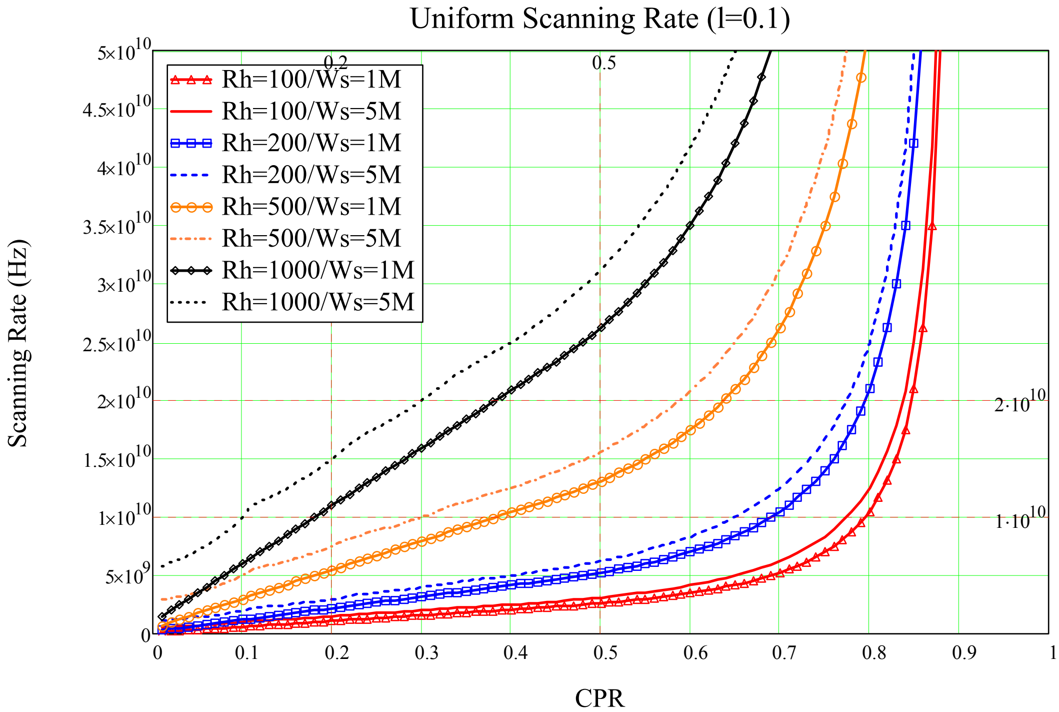


Fig.9 Scanning rate (R_s) vs. *CPR* with different R_h and W_s combinations (l=0.1)

a=100km)

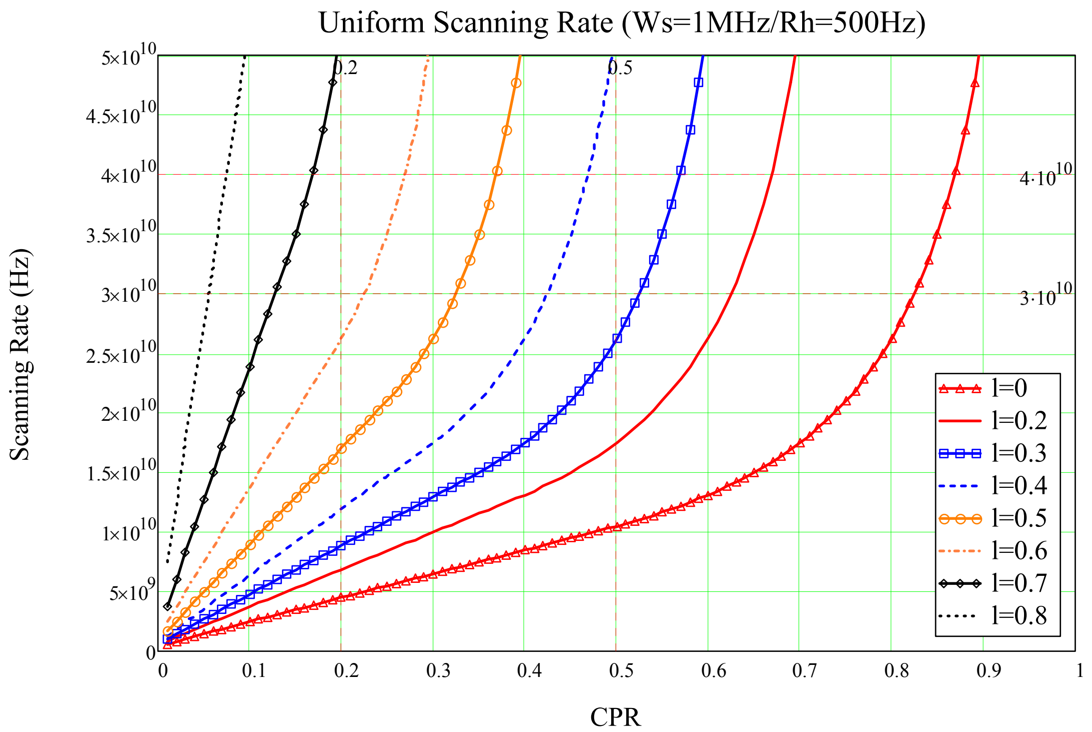


Fig. 10 Scanning rate (R_s) vs. *CPR* with different propagation ratio l (W_s=1MHz, R_h=500Hz)

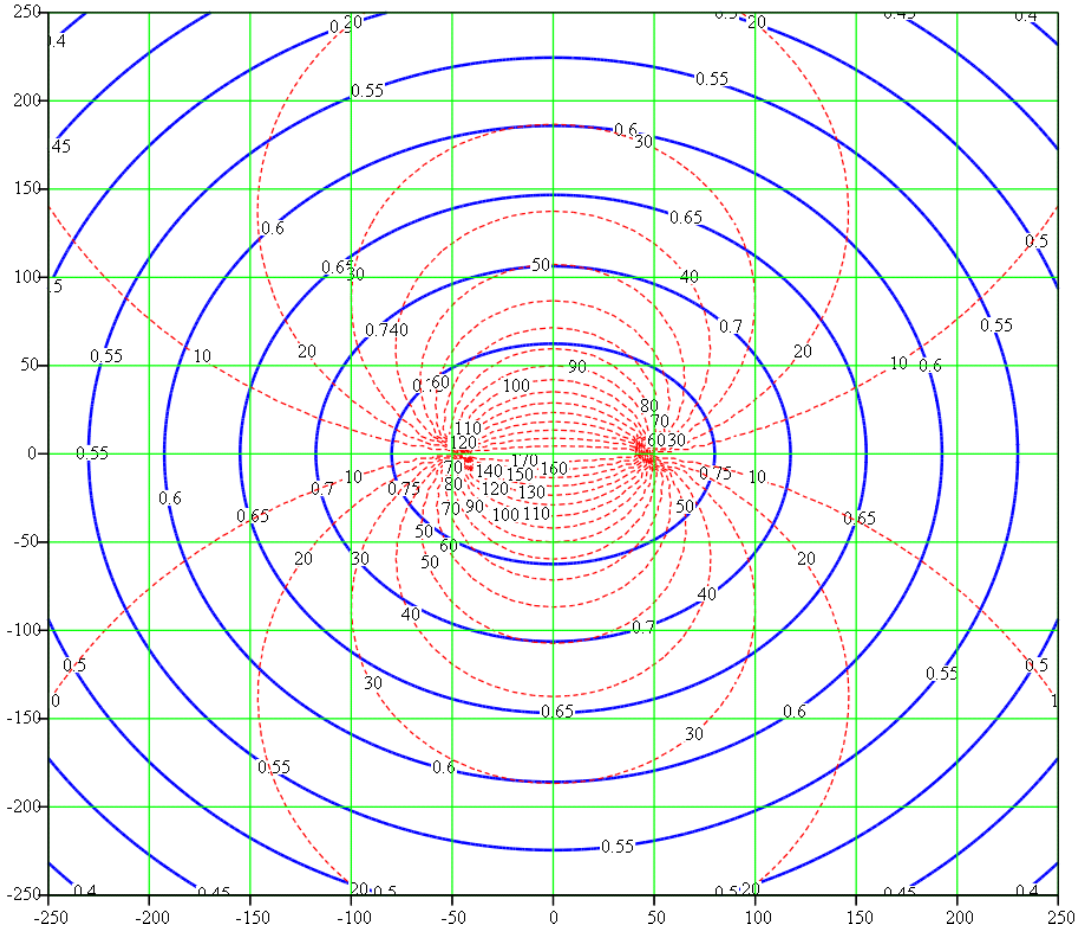


Fig. 11 Elliptic *CPR* contours with U-scanning (y-axis vs. x-axis: ±250km×±250km; R_h= 200Hz; T_z=100μs)

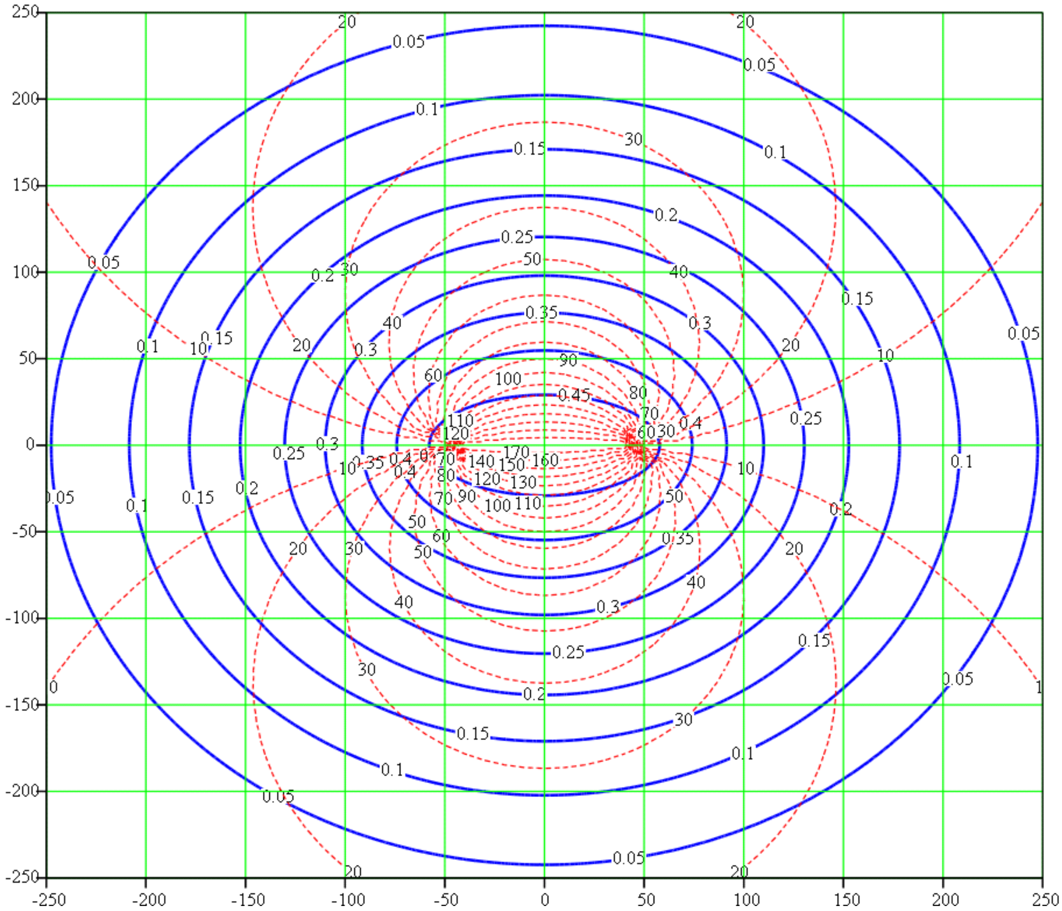


Fig. 12 Elliptic *CPR* contours with U-scanning (y-axis vs. x-axis: ±250km×±250km; R_h= 500Hz; T_z=100μs)