A Novel Composite Cognitive Capability Modeling with an Overlay Sensing Approach

Chien-Hsing Liao[a] and Tai-Kuo Woo[b]
[a]*Program of Information Technology, Fooyin University, Taiwan (ROC)*
[b]*Department of Information Management, National Defense University, Taiwan (ROC)*

***Abstract* —Cognitive radios are promising solutions to the problem of overcrowded spectrum. The cognitive capability is the key technology that enables the secondary users to use licensed spectrum in a dynamic manner that the spectrum of the primary users are as unaffected as possible. But the metrics for composite cognitive capability are required in time in order to capture the temporal, spectral, and spatial variations (“spectrum holes”) with cognitive signal strength under a sophisticated cognitive radio environment. In this paper, in order to evaluate the spectrum awareness effectively, a novel analytical modeling of composite cognitive radio capability with an overlay sensing approach is proposed. An elliptic cognitive scenario with spatial variations is assumed, which consists of traditional primary units (*PUs*) and cognitive radio units (*CRUs*) with concurrent temporal and spectral scanning schemes. In addition, in a cooperative overlay sensing approach, the *CRU* will also detect the primary transmission signals for spectrum holes and “assist” the primary receiving signal through a tone-assisted relaying signal to enhance system performance and reach lower symbol error probability with a specific tone-to-signal ratio (*TSR*) above *SNR* decision thresholds.**

I. INTRODUCTION

The cognitive radio is 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 [1]. Therefore, the ultimate objective of the cognitive radio is to obtain the best available spectrum with two main characteristics, i.e., cognitive capability and reconfigurability [2]. The former refers to the ability of the radio technology to capture or sense the information from its radio environments; the latter is the capability of adjusting operating parameters for the transmission on the fly without any modifications on the hardware components. In addition, some engineering views and advances for helping the implementation of cognitive radio properties into practical communications are described [3-4]. A relay selection is executed for cooperative spectrum sensing in cognitive radio networks to improve the performance of cooperative communication systems [5]. Not only focusing on geometrical or power aspects of jamming, a mathematical intercept model is analyzed and derived for computation of the jamming probability when a follower jammer with a wideband-scanning receiver jams a single FH system [6]. Different interpretations of cognitive radio that underlay, overlay, and interweave the transmissions of the cognitive user with those of licensed users are described [7]. In spite of the active jamming measures taken, follow-on jamming 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 [8]. Traditional radio would not change its objectives as radio scenarios vary, unless transmission security is concerned for a specific traditional radio. Unlike traditional radios, a cognitive radio may change its objectives as radio scenarios vary. Therefore, the performance evaluations of CR node or network through practical metrics for cognitive capability is the first fundamental problems but has received limited attention from the CR community. In addition, the metrics for cognitive capability cannot simply be realized by monitoring the power in some frequency band of interest, but more sophisticated techniques are required in order to capture the temporal, spectral, and spatial variations (“spectrum holes”) in cognitive radio environments and avoid interference to the other users. The concurrent anti-jamming and low probability of detection process has been investigated to have a secure radio communication, which is realized by monitoring the power and signal-to-noise ratio simultaneously in some frequency bands of interest in a FH radio environment [9-10]. A coexistence window inside which the primary user and secondary user share the radio channel in time division manner is proposed. Connectivity probability and link utility efficiency are defined to measure the performance of secondary user. Considering the practical noise channel, how the metrics change is studied and the data rate of the secondary user in this case is obtained [11]. An optimal power allocation scheme for a physical layer network coding relay based secondary user communication in cognitive radio networks is proposed. The secondary users are located on two different primary user coverage areas and one energy and spectrally efficient SU communication scheme is introduced [12]. Finally, a latest systematic overview on CR networking and communications by looking at the key functions of the physical (PHY), medium access control (MAC), and network layers involved in a CR design and how these layers are crossly related are proposed, which can help researchers and practitioners have a clear cross-layer view on designing CRNs [13]. In addition, the overview of various performance metrics at the node, network, and application level is discussed, which includes interrelationships among metrics, utility functions, cognitive engine algorithms, and achieved performance, as well as various testing scenarios [14].

In this paper, in order to evaluate the spectrum awareness effectively, an elliptic cognitive scenario with spatial variations is assumed, which consists of traditional primary users and cognitive radio units with concurrent temporal and spectral scanning schemes. The derived metrics of spectrum holes ratios are investigated and proposed for evaluating the composite cognitive capability in such an elliptic cognitive scenario [15]. Moreover, the performance characteristic of a specific overlay tone-assisted relay signal is investigated in order to reach the goal of accessing licensed spectrum without interfering with the existing primary users, but instead enhancing their performance [16]. In a cooperative spectrum sensing approach, the cognitive radio unit will detect the

Corresponding author:jasonarpon78@gmail.com

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primary transmission signals for spectrum holes and “assist” the primary receiving signal through this tone-assisted relay signal, i.e., enhance system performance to reach lower error probability with a specific tone-to-signal ratio (*TSR*) and *SNR* above decision thresholds.

The remainder of this paper is organized as follows. In Section two, the novel analytical modeling for cognitive capability through an overlay sensing approach is proposed. In Section three, the performance characteristic of a specific tone-assisted relaying signal with concurrent temporal, spectral, and spatial variations is investigated to reach this analytical goal of cognitive capability. Conclusion is in final Section four.

II. OVERLAY SENSING APPROACH: ANALYTICAL MODELING

Cognitive radio is an essential technology in future wireless communications since it promises more efficient spectrum utilization by means of accessing licensed spectrum band in an opportunistic manner without causing interference to the licensed users. Therefore, cognitive radios have to be aware of the communication signal signatures of licensed primary users in complicated electromagnetic environments as unaffected as possible. Under these circumstances, it is not straightforward to make wise and prudent evaluations and decisions for cognitive radio capabilities with concurrent *CRUs* and *PUs* communications. Therefore, flexible and convenient metrics for achieving these are expected. Moreover, how to get an analysis model and metrics of evaluating effectively a special type of *CRU* with real-time (or near concurrent) detection (passive scanning) and transmission capability (called overlay and relaying) for a sophisticated communication system is also expected. Finally, based on these, spectrum sensing technique like this with real-time detection and transmission capability, especially for a cognitive radio communication, is also expected to be available for communication resources sensing. In this section, the novel analytical modeling for composite cognitive capability through an overlay sensing approach is proposed. An elliptic cognitive scenario with spatial variations is assumed, which consists of two traditional primary units and one cognitive radio unit with concurrent temporal and spectral scanning schemes, i.e., uniform scanning (*U*-scanning) and sequential scanning (*S*-scanning), respectively. In addition, in a cooperative overlay sensing approach, the cognitive radio unit will also detect the primary transmission signals for spectrum holes and “assist” the primary receiving signal through this tone-assisted relaying signal to enhance system performance and reach lower symbol error probability with a specific tone-to-signal ratio (*TSR*) above *SNR* decision thresholds.

The cognitive capability of a cognitive radio enables real time interaction with its environment to determine appropriate radio parameters and adapt to the dynamic radio environment. A cognitive radio scenario (as shown in **Fig. 1**) with cooperative spectrum sensing approach will be examined firstly, which consists of two main primary users of transmitter (PU_T) and receiver (PU_R) located in the *x*-axis positions of ($\pm f/2$, 0), respectively, one mobile cognitive radio units (*CRU*) located in the position of (*x*, *y*), and several *CRUs* located in other positions of elliptic loci. Both *CRUs* will collaborate with each other for spectrum holes detection and relay. The relative distances among these three nodes (i.e., *CRU*, PU_T, and PU_R) are labeled as R_{tr} (=*f*), R_{tc} and R_{cr}, respectively. The antenna gains are labeled as G_{tr}, G_{rt}, G_{cr}, and $G_{rc}(\theta)$, respectively, which are function of the relative geometric pointing angles as shown in **Fig. 1.**

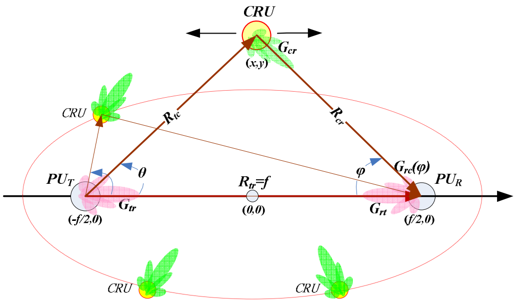

Fig. 1 Overlay cognitive radio spatial scenario with elliptically mobile *CRUs* and two fixed primary unit (*PU*) distance (R_{tr}= *f*)

In order to avoid interference with the receiver (PU_R), *CRU* with cognitive capability should first beware the existence of PU_T and utilize possible radio resources before PU_T reaches to PU_R. After a geometric manipulation, the elliptic equation dependent on ellipse’s focal distance and the minimum virtual distance *D* will be available and given by

$$\frac{x^2}{a^2}+\frac{y^2}{b^2}=\frac{x^2}{\left(\frac{D+f}{2}\right)^2}+\frac{y^2}{\left(\frac{\sqrt{D\cdot(D+2f)}}{2}\right)^2}\geq 1, \tag{1}$$

where *a*, *b* and *f* are one-half of the ellipse's major axe, one-half of the minor axe, and ellipse’s focal distance, respectively; *D* is the virtual distance defined to be R_{tc} + R_{cr} − *f*, which is mainly dependent on *CRU* scanning time, propagation delay ($\Delta\tau_d$), and *PU* symbol period as described later. Moreover, the encompassed elliptic surface area and R_{tc} are therefore given by

$$A_e=\frac{\pi}{4}(D+f)\sqrt{D\cdot(D+2f)} \tag{2}$$

$$R_{tc}=\frac{a\cdot(1-e^2)}{1\pm e\cos(\theta)}, \tag{3}$$

where *e* is eccentricity defined to be the ratio of *f* and *a*; θ is the tilted angle between R_{tc} and R_{tr}. In addition, R_{cr} is simply available by the law of cosine.

In order to explore the relaying characteristic in signal strength domain, the typical *CRU* system function block with wideband signal scanning processing and relaying signal generation capabilities is shown in [16]. If the relay waveform that enters S_t-channel is modeled as a tone that is undistorted by the receiver bandpass filter, then the error probability is derived and represented as

$$P_{t1T}=\frac{1}{2}\cdot e^{\left(-\frac{1}{2}\cdot SNR\cdot(1+TSR)\right)}\cdot I_0\left(SNR\cdot\sqrt{TSR}\right), \tag{4}$$

where $TSR=S_i/S_t$ and $SNR=S_t/N_t$. If S_c-channel is relayed by a tone, but S_t-channel is not, then a similar derivation will be available. As shown in Fig. 1, *CRU* will detect and relay, and the tone-to-signal ratio can be represented as system- and geometry-dependent parameters

$$TSR=\frac{P_c\cdot G_{cr}\cdot G_{rc}(\varphi)}{P_tG_{tr}G_{rt}}\left|\frac{R_{tr}}{R_{cr}}\right|^2, \tag{5}$$

where G_{tr} and G_{rt} are antenna gains for *PU* link; G_{cr} and $G_{rc}(\varphi)$ are antenna gains for *CRU* and PU_R link with relative geometric pointing angle (i.e., φ); P_c and P_t are power from *CRU* and PU_T, respectively; R_{tr} =*f*; and R_{cr} represents the distance between *CRU* and PU_R. In addition, the *CRU* should cover and detect the radio signal features by sweeping through the symbol period of the radio system to further explore the possible “spectrum holes” in temporal and spectral domains [15]. The effective spectrum holes ratios, (*SHR*), which is defined to be the expected cognitive dwell period over the symbol period. Moreover, the *CRU* scanning rate should be also fast enough to trace the symbol rate with less unit framing-processing time (T_z) per scanning window.

III. COMPOSITE COGNITIVE CAPABILITY EVALUATION

In order to evaluate the cognitive capability based on the proposed overlay sensing approach, various quantitative comparisons are made with varied signal strength, spatial position, temporal framing, and spectral bandwidth in this section. The metrics for cognitive capability cannot simply be realized by monitoring the power in some frequency bands of interest, but more sophisticated techniques are required in order to capture the spatial, temporal, and (or) spectral variations ("spectrum holes") concurrently in sophisticated cognitive radio environments and avoid interference to the primary users as unaffected as possible. The evaluation of composite cognitive capability by coordinating power, spatial, temporal, and spectral cognitive signals simultaneously is addressed as follows. **Table 1** shows the assumed system parameters for evaluating the overlay cognitive capabilities.

Table 1 Assumed system parameters for overlay sensing approach

Symbol rate (R_s)	1 MHz
Symbol period (T_s)	$1/R_s$
Operating frequency	300 MHz
Focal distance (*f*)	100 m
Antenna efficiencies (η)	0.55
PU_T power (P_t)	1 W
CRU power (P_c)	1 W
PU_T antenna gain (G_{tr})	0.5 m diameter
PU_R antenna gain (G_{rt})	0.5 m diameter
CRU antenna gain in PU_R (G_{cr})	1.0 m diameter
PU_R antenna gain in *CRU* (G_{rc})	0 dB (omni)
temporal windows analyzed (*m*)	50
spectral windows scanned (*n*)	10,20,30,50

In geometric point of view, the central concept of CR communications is trying to take covering, detection, and relaying measures to work within the primary user's prescribed region(s), i.e., physically allowed "green" zones, when in comparison with conventional communications. The effective spectrum holes ratios, *SHR*, is defined to be the expected cognitive dwell period over the symbol period. The virtual distance *D* is defined to be $R_{tc} + R_{cr} - f$, which is mainly dependent on *CRU* scanning time, propagation delay ($\Delta\tau_d$), and *PU* symbol period. **Fig. 2** shows the virtual distance *D* versus spectrum hole ratio (*SHR*) comparisons for *U*-scanning (solid red) and *S*-scanning (blue empty) schemes under the constraint of fixed temporal windows analyzed (*m*=50) and varied spectral windows analyzed, i.e., *n*=10, 20, and 50. *D* is inversely related to *SHR*. For specified *D*, the more is the spectral windows analyzed, the larger is the *SHR* value. **Fig. 3** shows the spatial elliptic distributions of spectrum hole ratios (*SHRs*) for *U*-scanning (solid red) and *S*-scanning (blue empty) schemes based on the cognitive radio scenario of **Fig 1**. Basically *S*-scanning scheme is a spectrum sensing method with "memory", nevertheless, the *U*-scanning scheme is a spectrum sensing method uniformly without "memory". Therefore, the scanning speed is for the former scheme is quicker than the latter one. Under the constraint of fixed focal distance of *f*=100 and *SHR* value, e.g., *SHR* =0.1, 0.2, and 0.5, *S*-scanning scheme shows a wider encompassed area than the *U*-scanning scheme for its quicker scanning speed. Moreover, for both schemes, the smaller is the *SHR* value, the wider is the encompassed area, and vice versa.

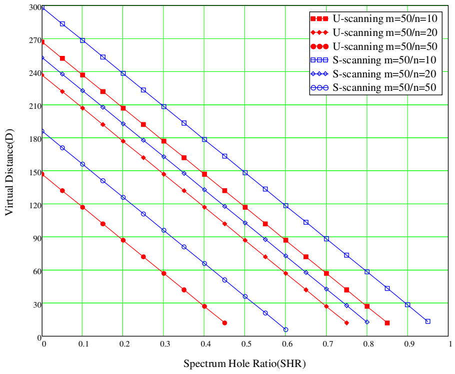

Fig. 2 Virtual distance versus spectrum hole ratio (*SHR*) comparisons for *U*-scanning (solid red) and *S*-scanning (blue empty) schemes in an elliptic cognitive radio scenario

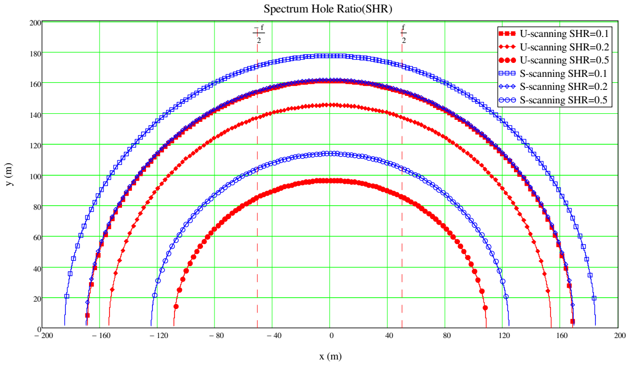

Fig. 3 Spatial spectrum hole ratio (*SHR*) distribution for *U*-scanning (solid red) and *S*-scanning (blue empty) schemes in an elliptic cognitive radio scenario

The *CRU*s with composite cognitive capability will cover, detect, and relay signal in time for cognitive radio communications, where the relayed tone-to-signal ratio (*TSR*) can be represented as system- and geometry-dependent parameters from (5). Given that the focal distance for the primary users (e.g., for two base stations) is fixed, a mobile *CRU* with specified virtual distance (i.e., *D*), which is functions of R_{tc} and R_{tr}=*f*, and R_{cr}, will form an elliptic locus with fixed *SHR* value as shown in **Fig. 3**. If θ is assumed to be the tilted angle between R_{tc} and R_{tr}=*f*, then R_{cr} is simply available by the law of cosine. Therefore, if θ is varied, R_{tc}, R_{cr}, and *TSR* with system-dependent parameters fixed will vary accordingly. Furthermore, from (4) the one-tone error probability represented as function of tone-to-signal ratio (*TSR*) and signal-to-noise ratio (*SNR*) parameters can be taken for system performance evaluation of composite cognitive capability.

Under the constraints of fixed temporal and spectral windows (i.e., *m*=50 and *n*=10) with specified *SHRs* and elliptic loci, Fig. 10 shows the *TSR* variations with the angle (θ) relative to PU_T and PU_R link line, where the solid red loci are for *U*-scanning scheme and the blue empty loci are for *S*-scanning scheme, respectively. *TSR* decreases as θ angle increases due to increased R_{cr} value. *TSR* increases with increased specified *SHR* due to shortened virtual distance. Moreover, for specified *SHR* (e.g., 0.1, 0.2, 0.5, and 0.7) the *TSR* value for *U*-scanning scheme is higher than *S*-scanning scheme, which is due to the fact that the former encompassed area is larger than the latter one. From (4) and **Fig. 5**, the error probability varied with angle θ increases with the *TSR* in **Fig. 4**, i.e., the higher is the *TSR* value, the lower (better) is the error probability under the same circumstances.

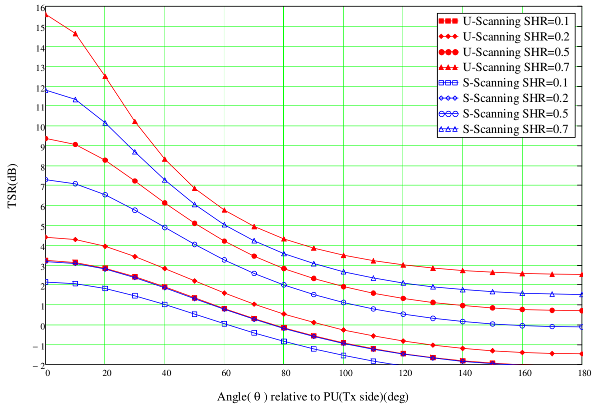

Fig. 4 *TSR* versus angle (*θ*) relative to PU_T and PU_R line with fixed *m*=50/ *n*=10 and specified *SHRs* for *U*-scanning (solid red) and *S*-scanning (blue empty) schemes

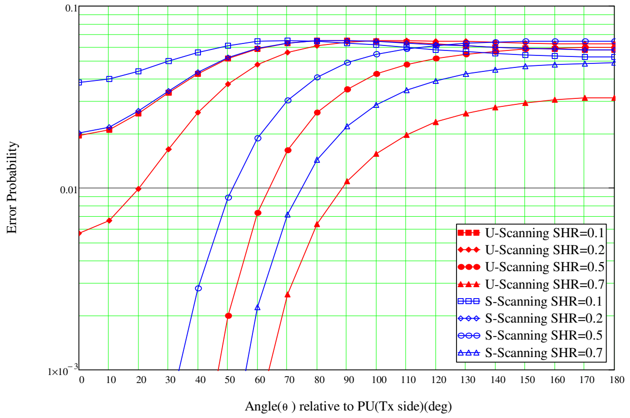

Fig. 5 Error probability versus angle (*θ*) relative to PU_T and PU_R line with fixed *m*=50/ *n*=10 and specified *SHRs* for *U*-scanning (solid red) and *S*-scanning (blue empty) schemes

IV. CONCLUSION

Cognitive radios are promising solutions to the problem of overcrowded spectrum and cognitive capability is the key technology that enables secondary users to use licensed spectrum in a dynamic manner that the spectrum of the primary users are as unaffected as possible. In order to evaluate the spectrum awareness effectively, a novel analytical modeling of composite cognitive capability with the overlay sensing approach is proposed. The composite cognitive capability will capture the temporal, spectral, spatial, and power signal variations concurrently under a sophisticated cognitive radio environment. The *CRU* parameters can be adjusted to enhance *TSR* and error probability performance correspondingly. The proposed modeling and approach have paved a very practical way for system evaluation of cognitive probability effectively.

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