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doi:10.15199/48.2021.08.18

Analysis of Throughput in Narrowband Cognitive Radio Networks over Fading Channels: A Collaborative Spectrum Sensing Approach

***Abstract**. Spectrum is a valuable resource for wireless communication technologies. Recent studies show that the scarcity of spectrum generates dominant interest for research in wireless communications. As spectrum is a natural resource, the only alternative to meet up spectrum inefficiency is to exploit the unutilized or underutilized spectrum accurately using the concept of Cognitive Radios (CRs). Cooperation among the CR nodes provide the best sensing performance utilizing maximum accuracy compared to other sensing approaches. Hence, maximum throughput is guaranteed with reliable data transmission. In this research article, the sensing-throughput trade-off issues are analysed for both stand-alone and cooperative cases. We use an energy detection scheme to measure the detection performances due to its operational simplicity and low-cost in use. The attemptable throughput of the cooperative CR network (CRN) is maximized while the services to licensed users are not being hampered. The more the CR nodes are in cooperation, the higher the detection performance which consecutively enriches throughput. The achievements of attainable throughput are supported under Rayleigh and Rician fading channels.*

*Streszczenie. Widmo to cenne źródło technologii komunikacji bezprzewodowej. Ostatnie badania pokazują, że niedobór widma generuje dominujące zainteresowanie badaniami nad komunikacją bezprzewodową. Ponieważ widmo jest zasobem naturalnym, jedyną alternatywą dla zaradzenia nieefektywności widma jest dokładne wykorzystanie niewykorzystanego widma przy użyciu koncepcji radia kognitywnego (CR). Współpraca między węzłami CR zapewnia najlepszą wydajność wykrywania przy maksymalnej dokładności w porównaniu z innymi podejściami wykrywania. Dzięki temu maksymalna przepustowość jest gwarantowana przy niezawodnej transmisji danych. W tym artykule przeanalizowano kwestie kompromisu między czujnikami a przepustowością zarówno dla przypadków samodzielnych, jak i kooperacyjnych. Używamy schematu wykrywania energii do pomiaru wydajności wykrywania ze względu na jego prostotę operacyjną i niski koszt użytkowania. Przepustowość kooperacyjnej sieci CR (CRN) jest maksymalizowana, podczas gdy usługi dla licencjonowanych użytkowników nie są utrudnione. Im bardziej węzły CR współpracują, tym wyższa wydajność wykrywania, co sukcesywnie zwiększa przepustowość. Osiągnięcia osiągalnej przepustowości są obsługiwane przez kanały zanikania Rayleigh (**Analiza przepustowości w wąskopasmowych sieciach radiowych kognitywnych w kanałach zanikających: metoda oparta na współpracy wykrywania widma**)*

Keywords: Cognitive Radio, Decision Fusion, Fading Channels, Collaborative Spectrum Sensing, Throughput.
Słowa kluczowe: radio kognitywne, widmo, komunikacja bezprzewodowa

Introduction

Radio spectrum, a fixed resource of nature, is a prime requirement for wireless technologies. The interest of the radio spectrum is expanding day by day to cope up with the newly developed communications tools, protocols, and terrific mobile apps to make human life without problems around the world. Hence, the frequency spectrum is the most significant asset in terms of wireless technologies and sensor networks. CR is a contemporary approach of wireless communication that empowers the dynamic access of heavily underutilized spectrum possessed by PUs [1]. Usually, the PUs don't actively engage in operation always and the CRs utilize those spectrum opportunistically through periodically sensing its electromagnetic environment [2]. Every so often, the CR keeps an eye on the appearance of PU and as soon as it senses the existence of PU, it cancels the transmission of that band instantly without hampering the operation of PUs. Hence, CRs should have the capability to diagnose the existence of PUs with the highest accuracy as well as minimum sensing time.

Shadowing, multi-path fading, and time-varying components of the radio environment are considered as one of the challenging factors of spectrum utilization. Cooperation among CR nodes can overcome those challenges through exploiting various well-known fusion rules to obtain a global decision from individual CR decisions. Hence, sensing time increases for the procedure of collaborative spectrum sensing (CSS). To make the sensing procedure faster, it is recommended to use binary decision fusion rules [3]. Besides, the PUs are to be sensed with a minimum error rate as the decision is collected from multiple radios and thus attemptable throughput is maximized. For the overall operation, the sensing agenda should be designed such that the presence of PUs can be revealed with a specific tiny timeframe. A trade-off should be maintained between the spectrum sensing time and information transmission time to achieve optimum performance. It is desirable to enhance the throughput by providing maximum security to the PUs.

As radio frequency spectrum is the access medium for wireless communication therefore radio spectrum are currently on a high demand and applications of spectrum-sensing in cognitive radio can be useful for the deployment of emergency-network and to enhance WLAN throughput and transmission-distance extensions. Several sensing approaches i.e., energy detection (ED), cyclic feature-based detection, matched filter detection, radio identification-based sensing, waveform based sensing are available. Among them, the ED-based method is widely popular for its simplicity and low computational complexities [4]. However, it is a blind spectrum detection method where the sensing output of the detector is correlated with a threshold selected from noise floor analysis [5]. Performance can be affected by signal to noise ratio (SNR) as it is amenable to pessimism for multichannel fading effects. It can be less feasible whether it is possible to pre-determine the power of the random Gaussian noise.

Sudden variation of the amplitude and phase of a target signal through different fading channels for small-scale fading can be efficient to enhance the evaluation. However, large-scale fading illustrates signal energy attenuation through multipath fading and increases the complexity of evaluation because the ancestry of a closed-form interpretation for the standard detection probability regarding the hypothesized lognormal transportation provides terrain configuration. The ED-based sensing approach is exclusively dependent on the sensing of energy regardless of the other parameters of the radio frequency spectrum [6]. The unknown signal is determined in an unknown form as the probability of density function (PDF) estimation. Manifold investigations have been addressed for multipath fading in ED-based sensing to improve detection capacity with receiver diversity scheme [7]. Multiple sensor/ radio nodes sense the energy of the adjoining radio spectrum and measure with a certain threshold point to discover the existence of PU. These local decisions are then sent to the decision fusion centre (FC) to produce a global decision on the presence of PU. The global decision is utilized to find the value of throughput that could be obtained by the CR network. Finally, the value of throughput is varied with the variation of sensing time.

The main contributions of this paper are as follows:

a) To begin with, preliminaries for stand-alone as well as cooperative spectrum sensing are deliberated. To make the system more practical, various fading features are brought together.

b) We propose the system model for cooperative spectrum sensing enabling energy detection and cooperative spectrum sensing. Implementation simplicity and asking price are what make the energy detection scheme most popular.

c) We exploit various binary fusion rules to produce consistent decisions to find an opportunistic radio band for a CR under Rayleigh and Rician channel conditions. Moreover, it is figured out the attainable throughput for both stand-alone and cooperative occasions under practical fading conditions such as the Rayleigh channel and Rician channel. The optimal fusion rule shows the best result which is inclined with the research expectation.

d) We conclude that the attainable throughput is a function of the number of CR nodes and that is verified in this research work.

The research article has been organized into five sections. After this introductory section, spectrum sensing (stand-alone & cooperative) is depicted with relevant theoretical background in the section named ‘Sensing preliminaries’. In the section titled ‘System model,’ we would like to present the model along with binary decision fusion rules. Later, the receiver operating characteristics (ROC) curves for cooperative and non-cooperative approach is illustrated in section ‘Analysis of achievable throughput. Besides, the achievable rate (i.e. throughput) of a CR node under various fading channels has been investigated as a function of sensing time and the result has been summarized in the aforementioned section by way of proper justification. Finally, we draw some conclusions from the research work.

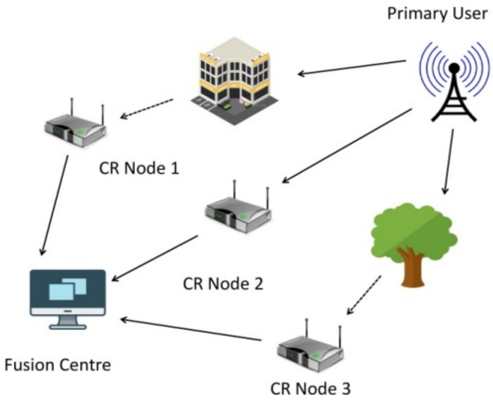

Fig. 1. Illustration of cooperative spectrum sensing scheme

Sensing preliminaries

Single transmitter spectrum sensing

The fundamental threat of CRs is to check, identify and notice radio spectrum features in the interest of identifying the existence of PUs. Hence, they should always arrange to vacant the PU band if any PU demands for it. In our research work, we have envisaged some probability criteria, i.e., the probability of detection (P_d), the probability of false alarm (P_{fa}), and the probability of miss detection (P_m) in order to observe the ROC curve implementation. ED approach gets space in the domain of frequency and a definite band in time by measuring the amount of sensing energy and comparing it with a predefine threshold value. In this accession, if the amount of energy of the determined signal is more than the threshold value, the system declares the PU as present in the sensing environment and in case of lower energy sensing compared to threshold, opportunity is available of the CRs to communicate among CRN. In this regard, we have considered two hypothetical parameters, H_0 and H_1 to decide the existence of PU accurately. H_0 represents the hypothesis of PU as inactive while H_1 declares opposite to it. Both the conditions are mathematically formulated in equation (1) and (2) where, $r(n)$ represents received signal of CR, $q(n)$ represents available noise of the environment, $s(n)$ represents transmitted signal by PU and n is sample index [8]. The received signal energy is calculated in eq. (3) where S represents the number of total samples and E is a random variable under H_0 with PDF [7-8]. In (4), probability of false alarm is determined where $P_0(x)$ a Chi-square distribution is, and Ψ is a pre-determined threshold value.

(1) $r(n) = q(n)$ i.e. {PU signal absent: H_0}

(2) $r(n) = s(n) + q(n)$ i.e. {PU signal present: H_1}

(3) $E = \frac{1}{s}\sum_{n=1}^{s}|r(n)|^2$

(4) $P_{fa} = P_r(E > \psi|H_0) = \int_{\psi}^{\infty} P_0(x)dx$

The amount of E is calculated applying (5) under the notion H_1 with PDF $P_1(x)$ [8].

(5) $P_d = P_r(E > \psi|H_1) = \int_{\psi}^{\infty} P_1(x)dx$

Cooperative spectrum sensing

Spectrum detection with cooperative concept is raised to solve the problem that creates because of noise uncertainty, multichannel-fading and shadowing during sensing of opportunistic spectrum. Moreover, CRs have no idea about the exact frequency band of PU or which is PU as many malevolent user can alter their surrounding environment to counterfeit a PU. Accordingly, the performance of spectrum detection is demoted in local CR for individual detection. As a group of CRs collaborates in spectrum sensing, the probability of false alarm and the probability of miss detection can be minimized as well as catastrophic interference to the PUs can be reduced. A situation of collaborative spectrum sensing is illustrated in Fig. 1. CR nodes 1, 2, and 3 sense their neighbouring radio environment and decide which frequency band is actively used by the PUs. As the fading effects exist, their individual decision may not be accurate. Hence, the individual outcome of each node is forwarded to one of the CR nodes which act as FC. Global decision is produced whether PU is present or absent by analysing the local decisions received in FC. Typical binary fusion rules such as *AND*, *OR*, *Majority* and *Optimal* fusion rules are applied to combine the local sensing decisions.

System model

ED based sensing is the most popular scheme for opportunistic spectrum sensing due to its easy design and computational cost. ED based sensing method has been applied by selecting a standard and logical threshold value as the reference for vacant bands or spectrum holes detection. Each CR node works as energy detector and the basic function of it is to measure the energy level that is received from adjacent radio environment. The amount of energy measured by each CR node has been contrasted with the logical threshold value on each event. No spectrum white spaces are identified if the level of signal energy received by CR node exceeds the threshold value. Hence, individual CR node declares the presence or absence of PU in the sensing environment based on hypothesis test presented in equation (1) and equation (2). The individual sensing result at each CR node has now been forwarded to FC to yield the global decision about the existence of PU through exploiting a number of binary fusion rules. The CR nodes work according to the global decision which is forwarded by the decision FC.

Several decision fusion schemes have been proposed including hard and soft decision fusion rules [9]. Binary decision fusion rules like *AND rule*, *OR rule*, *majority or* K *out of* N *rule*, and *optimal fusion rule* have been applied to achieve the maximum throughput of CR nodes. The separation between two CR nodes is considered mediocre compared to the separation between PU and CR. For the sake of simplicity two assumptions are essential in this case. *Firstly*, the total amount of fading effect experienced by each CR nodes for indistinguishable and distributed fading is considered equal. *Secondly*, the average value of SNR is considered identical. The FC combines the local sensing binary decisions according to equation (6) where, x is the number of CR node in which j is the number of CR nodes who announce H_1 as their individual result and Y_d is the probability of detection for spectrum sensing in cooperation [10]. A basic system model for collaborative spectrum sensing is exemplified in Fig. 2.

(6) $$Y_d = \sum_{i=j}^{x} \binom{x}{i} P_d^i (1 - P_d)^{x-i}$$

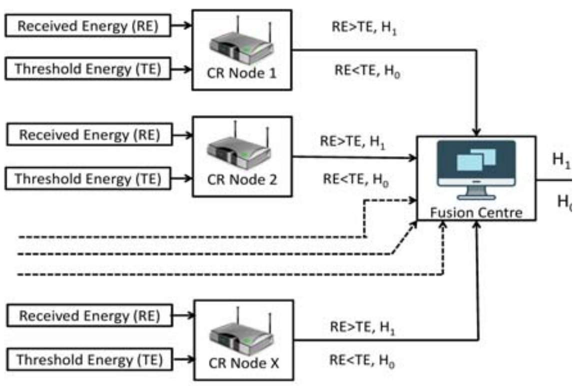

Fig.2. System Model for cooperative spectrum sensing

When applying AND rule, logical AND operation is implemented for decision making from the analysis of local sensing results. If all the local decisions in FC that are received from individual CRs are logic 1, the global decision will be high (+1) or else global decision will be low (0). The probability of detection in cooperative spectrum sensing for AND rule $j = x$ has been calculated using equation (7) [10].

(7) $$Y_d = P_d^x$$

In *OR* rule, FC takes its final decision as H_1 if any individual result of CR node is H_1 shown in equation (8) [10].

(8) $$Y_d = 1 - \sum(1 - P_d)^x$$

If at least half or more than half of the particular decision of CR nodes is 1, FC declares H_1 as per Majority or $K -$ out of $-N$ rule. The performance of cooperative sensing has been evaluated using equation (9) considering, $j = [x/2]$ [10].

(9) $$Y_d = \sum_{i=[x/2]}^{x} \binom{x}{i} P_d^i (1 - P_d)^{x-i}$$

According to optimum rule, a weighted value for each CR node is build up betting bottom dollar on the gap between CR and PU and environmental circumstances. The CR node faces less environmental obstacles and closer to the PU; the greater priority its outcome elicits [11]. Optimal fusion rule can be implemented from eq. (2) in [3]. The effective spectrum holes detection carries out throughput computation. To achieve the attainable throughput, T is considered as frame length from which t is preserved for sensing as shown in Fig. 3. Hence, CR transmission is highly possible along with the remaining length of time, $(T - t)$.

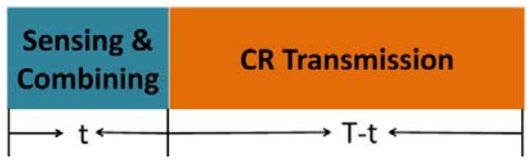

Fig.3. Frame structure of cooperative cognitive radio network

Depending on the sensing performance with cooperation, the achieved throughput of a CR is defined according to equation (10).

(10) $$R(t) = C_0 P(H_0)(1 - t/T)\left(1 - Q\left(\alpha + \sqrt{N\lambda}\right)\right)$$

where, $C_0 = log2(1 + SNRs), \alpha = \sqrt{(2\gamma + 1)}Q - 1(Pd)$ and $Q(x)$ is a monotonically declining function. For short sensing time *t*, information transmission time $(T - t)$ as well as throughput will large and vice versa. Therefore, a tradeoff between spectrum detection time and data transmission time is compulsory.

Analysis of achievable throughput

To create the simulation environment, it has chosen the Monte carlo value,$m = 10^5$, probability of false alarm, P_{fa}=10^{-4} and the SNR value is set 15dB. The attainable throughput performance of a non-cooperative (stand-alone CR) and cooperative (11 nodes) spectrum sensing under Rician channel condition is shown in Fig. 4. It is noted that for a stand-alone CR, the highest throughput has obtained 4.199 bits/sec/hz when the sensing time is minimum (initial condition). Attainable throughput decreases with the increase of the sensing time as higher time requirements in sensing shrinks the time for data transmission.

In Fig.4, attainable throughput is also explained for cooperative spectrum sensing where AND, OR, majority, and optimal fusion rules are implemented for Rician fading channels. The cooperative approach shows better performance in every case. Besides, the throughput performance in optimal fusion outperforms other fusion rules.

The simulated throughput vs. sensing time for the system with Rayleigh fading condition is shown in Fig. 5. Here, the obtained throughput is 4.463 bits/sec/hz which is

6.29% higher concerning the Rician fading channel (Fig. 4) while considering a single transmitter of CR node.

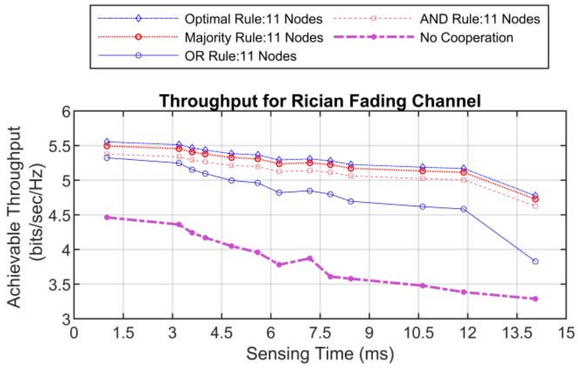

Figure 4. Attainable throughput for a stand-alone and collaborative CR under Rician channels.

To draw the analysis, numerical simulations have been implemented to observe the attainable throughput for cooperative cases. The analysis has started with calculating the probability of detection as well as the probability of false alarm under the Rayleigh channel and then the binary fusion rules named AND, OR, majority, and optimal rule applied. From Fig. 5, it is intuitive to observe that the highest attainable throughput is maximum for all the fusion rules when sensing time is minimum (initial condition). Attainable throughput is declining with the increase of sensing time.

Another interesting point to focus, if the number of CR nodes increased in a cooperative radio environment, then the probability of detection is increased which in turn grows the throughput at cooperation. This statement is justified in Fig.5 where the cooperative throughput of 7 CR nodes is higher than that of a single CR. Throughput is further enhanced when collaborating 11 CR nodes in the radio network. The attainable throughput deviates with the increasing sensing time for all the cases due to the utilization of more time to sense the spectrum hole. The optimum fusion rule draws the best performance as summarized in Fig. 5.

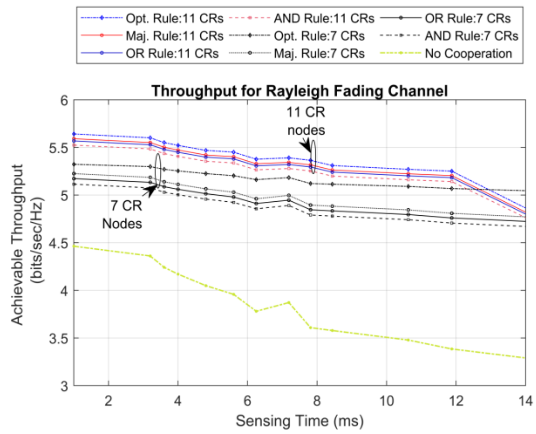

Fig. 5. Attainable throughput for a stand-alone and collaborative CR under Rayleigh channels

The maximum attainable throughput at the initial state for the non-cooperative method is 4.4630 bits/sec/hz under the Rayleigh channel. For cooperation with 7 nodes, it is obtained as 5.3226 bits/sec/hz for optimum fusion rule under Rayleigh channel which is 19.26% more than the non-cooperative scheme. When the CR nodes increase to 11, the attainable throughput is 5.6413 which is 26.40% more than the traditional non-cooperative scheme. Thus, overall throughput is appraised absolutely.

However, the performance of the Rician channel degrades compared to the Rayleigh channel (Fig. 5) due to the fading characteristics. While applying the optimal fusion rule, the Rician fading channel (Fig. 4) has provided the highest attainable throughput of 5.5532 bits/sec/hz while the Rayleigh channel (Fig. 5) has given throughput of 5.6413 bits/sec/hz. The overall throughput differs compared to the previous analysis due to the fading characteristics of Rayleigh and Rician.

Conclusion

Radio spectrum is one of the most important supporters for communication technologies and it is a must to develop and establish a specific cornerstone in the way of research and extension of CRNs. In our research work, we try to derive the efficient spectrum sensing approaches for stand-alone and cooperative scenarios spreading over typical fading channels. Achievable throughput is determined by exploiting several binary decision fusion rules. The result of optimal fusion rule outperforms among all the binary fusion rules which are confirmed in this paper. Furthermore, the number of CRs has been altered to observe the effect in throughput as well as detection performance of spectrum sensing. It has also analyzed the sensing-throughput tradeoff issues considering the probable factors for several fading channels. As the interests of PU and CR are antithetical, the spectrum sensing is done with the CSS approach for effective sensing with the lowest error rate. Thus, it is possible to maximize the attemptable throughput for effective CR transmission in the obedience that PUs are not hazarded as they are described with maximum precision.

Acknowledgment

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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