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Enhancing Transmission Capacity of a Cognitive Radio Network by Joint Spatial-Temporal Sensing with Cooperative Communication Strategy

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ENHANCING TRANSMISSION CAPACITY OF A COGNITIVE RADIO NETWORK BY JOINT SPATIAL-TEMPORAL SENSING WITH COOPERATIVE COMMUNICATION STRATEGY

Strictly as per the compliance and regulations of:

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I. Introduction

The radio spectrum is among the most heavily regulated and expensive natural resources around the world. In Europe, the 3G spectrum auction yielded 35 billion dollars in England and 46 billion in Germany. The question is whether spectrum is really this scarce. Although almost all spectrums suitable for wireless communications has been allocated, preliminary studies and general observations indicate that much of the radio spectrum is not in use for a significant amount of time, and at a large number of locations.

According to the statistics of the Federal Communications Commission (FCC), temporal and geographical variations in the utilization of the assigned spectrum range from 15% to 85% [1].

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The limited available radio spectrum and the inefficiency in spectrum usage necessitate a new communication paradigm to exploit the existing spectrum dynamically. The FCC has realized that overcrowding of unlicensed bands is only going to worsen and is considering opening up licensed bands for opportunistic use by secondary radios/users. One of the most efficient paradigms is the cognitive radio network (CRN), first introduced by J. Mitola [2], which is built upon software-defined radio (SDR) technology. S. Haykin defines a cognitive radio (CR) as "an intelligent wireless communication system that is aware of its environment and uses the methodology of understanding-by-building to learn from the environment and adapt to statistical variations in the input stimuli" [3,4] with the overarching aim of providing reliable communication whenever and wherever needed while efficiently using the resources available to it.

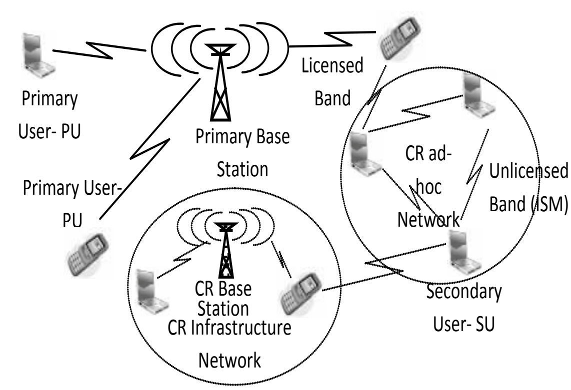

Figure 1 : CRN architecture. The CR users coexist with the primary users. The CR users can use both unlicensed bands and licensed bands that are free from primary users' activities

A CRN is built on the following principle: a network of secondary users (SU) (users without license) continuously senses the use of a spectrum band by primary users (PU) and opportunistically utilizes the band when PUs are absent. Any SU in a CRN performs two main functions: (1) sensing spectrum usage to identify absence or presence of a PU, and (2)

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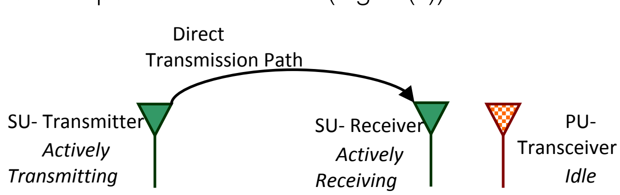
transmitting at appropriate power if the PU is absent. Thus, the design principle for CRN regards the CR users as visitors in the spectrum they occupy (Fig. 1). The successful operation of these principles relies on the CRN users' ability to be aware of their surroundings, which is accomplished through spectrum sensing solutions.

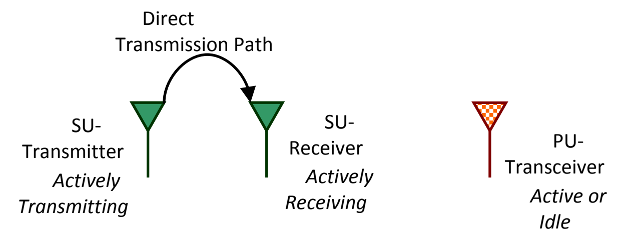
Spectrum sensing (the optimization of sensing parameters in a single spectrum band, spectrum selection and scheduling, and an adaptive and cooperative sensing method) enables CR users to adapt to the radio environment by determining currently unused spectrum portions, so-called spectrum holes or spectrum white spaces, without causing interference to the primary network. Generally, spectrum sensing techniques can be classified into four groups: (1) primary transmitter detection (matched filter detection, energy detection, and feature detection), (2) cooperative detection, (3) primary receiver detection, and (4) interference temperature management [1]. The SUs periodically sense the spectrum in order to identify and use the spectrum holes. When a SU senses that the PU is accessing the spectrum or determines that the PU is going to access the spectrum, it then vacates the spectrum and moves to the another spectrum or lowers its transmitting power. If there is another SU instead of the PU, then the first SU shares the spectrum with the new SU.

Spectrum holes exist both in time and in space. A spectrum hole in time may arise when a PU of the spectrum is idle, i.e., not transmitting. In this case, temporal spectrum hole is the duration for which the primary user-transmitter (PU_t) is in the idle state (Fig. 2 (a)). A spectrum hole in space with respect to a given frequency channel may occur if a given SU is sufficiently far from a PU that is actively transmitting (Fig. 2 (b)). In this case, the SU may transmit up to a certain level, which we called the maximum interference-free transmit power (MIFTP), without causing harmful interference to PUs who are receiving the transmissions. This results a useful spectrum sharing.

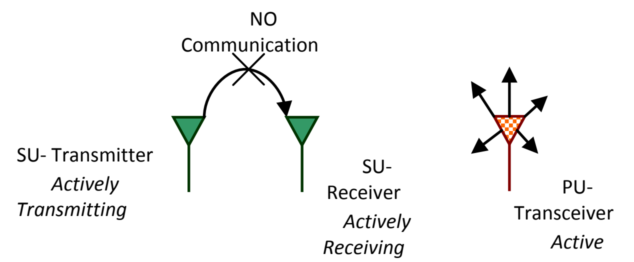
However, in the typical scenarios of static CRN where SU observe the activity of the PU in a fixed spectrum band and access the entire spectrum band if a spectrum opportunity is detected (based on IEEE 802.11 and IEEE 802.15.3 technologies), a SU transmitter communicates directly with SU receiver only when the PU is idle. A SU has to stop its transmission when no spectrum holes exist (Fig. 2 (c)).



(a)



(b)



(c)

Figure 2 : Typical spectrum sharing scenarios in CNR: The SU transmitter communicates directly with the SU receiver, due to the existence of a (a) temporal spectrum hole or a (b) spatial spectrum hole with respect to PU_t. Typical CRN transmission limitation due to lack of spectral holes in shown in (c)

To improve the transmission capacity of CRN, here we approach to combine CRN with cooperative communication strategy employing joint spatial-temporal sensing to maximize the transmission capacity of SUs in a CRN. In these scenarios, when PU transmitter is active, SU transmits to another SU receiver via a relay channel. By enabling the use of both the direct and relay channels, the transmission performance of the secondary system (CRN) can be improved significantly. Our proposed approach is depicted in Fig. 3.

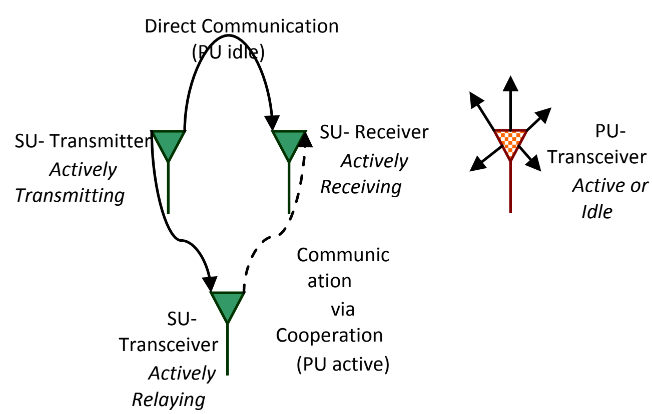


Figure 3 : Joint spatial-temporal spectrum sensing in a typical CRN for improving the transmission limitation due to lack of spectral holes by utilizing cooperative communication

Cooperative communications is a new paradigm that draws from the ideas of using the broadcast nature of the wireless channel to make communicating nodes help each other, of implementing the communication process in a distribution fashion and of gaining the same advantages as those found in MIMO systems [5]. The end result is a set of new tools that improve communication capacity, speed, and performance; reduce battery consumption and extend network lifetime; increase the throughput and stability region for multiple access schemes; expand the transmission coverage area; and provide cooperation tradeoff beyond source–channel coding for multimedia communications. This idea is true for wide varieties of wireless networks such as mobile ad hoc networks, sensor networks, or cellular networks. In this paper, we consider the decode-and-forward (DF) cooperative strategy focusing on the case of a single-hop relay channel.

II. System Model

a) Transmission frames and PU_t behavior

Time on the wireless channel is divided into frames consisting of N_s symbols. We shall assume perfect symbol level timing synchronization between the nodes of the secondary system. The primary user-transmitter (PU_t) alternates between active and idle states on a per-frame basis according to the active-idle Markov model of Fig. 4.

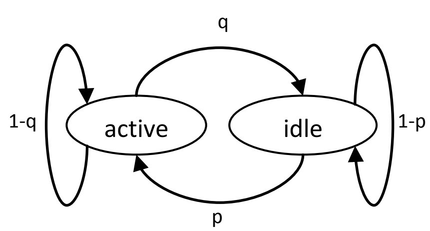


Figure 4 : 2-state Markov chain model for PU_t active/idle process

The active and idle durations can be modeled by geometric random variables with parameters q and p, respectively [6]. We focus on scenarios in which $q > p$; i.e., on average, PU_t is more often in the active state than the idle state (which is more practical to assume). Let us suppose that $q = kp$, where k is an integer with $k > 1$. Hence, if PU_t is idle for one time frame on average, it will be active for K time frames, on average. A similar approach can be used when $p > q$.

b) Cooperative transmission protocol

Suppose a secondary user-transmitter (SU_t) desires to transmit N_S symbols; i.e., it requires one full frame in which PU_t is idle. The cooperative protocol works as follows (Fig. 3): When PU_t is active, SU_t sends information to secondary user-receiver SU_r via the relay nodes SU_{relay}. When PU_t is idle, SU_t sends information directly to SU_r. In order to achieve this, the secondary nodes (SU_t, SU_{relay} and SU_r) perform joint spatial-temporal sensing [7]. In particular, all secondary users estimate their MIFTPs based on signal strength measurements, which they exchange with one another. They also decide whether the PU_t is active or idle, by transmitting their local decisions to a fusion center, which then makes the final decision.

We shall assume that there exists a communications path from SUt to SUr through SUrelay. This path would be established by a routing protocol. A repetition code [8] is used to repeat the transmission of the signal over K_0 and K_1 frames, where $K_0 + K_1 = K$. At each relay, the transmitted signal is amplified and forwarded to the next relay node until it reaches the destination. When PUt is idle, SUt can communicate N_S symbols over one time frame directly to SUr. Due to broadcast wireless channel, SUrelay also received a copy of signal from SUt but ignores it. When SUr receives a signal from the relay path, it stores the received signal and waits until it receives the same signal directly from SUt and vice versa. The received signals at SUr are then combined using MRC. Finally, maximum likelihood (ML) detection is used to detect the signals.

c) Cooperative Relaying

The received signal of a simple wireless channel model with flat fading and no shadowing is given by [9]

$$y = \delta\sqrt{\left(d_r/d\right)^{\alpha}}\, h\sqrt{\varepsilon}s + n = \sqrt{P}hs + n \qquad (1)$$

Where δ^2 is the free space signal-power attenuation factor between the source and a reference distance d_r, d is the distance between the source and destination, α is the propagation exponent, $h \sim CN\left(0,\sigma_h^2\right)$ is a complex Gaussian random variable with variance σ_h^2, $n \sim CN\left(0,N_0\right)$, and s is the transmitted signal. In Eq. (1), $P = \delta^2\left(d_r/d\right)^{\alpha}\varepsilon$ denotes the equivalent transmitted power after taking into account the effect of path loss. We also define $P_0 = \delta^2\left(d_r/d_0\right)^{\alpha}\varepsilon_0$, $P_1 = \delta^2\left(d_r/d_1\right)^{\alpha}\varepsilon_1$ and $P_t = \delta^2\left(d_r/d_t\right)^{\alpha}\varepsilon_t$ as the equivalent transmitted powers from SU_t to SU_{relay}, from SU_{relay} to SU_r, and from SU_t to SU_r, respectively. Here, d_0, d_1 and d_t denote the distances between the node pairs (SU_t, SU_{relay}), (SU_{relay}, SU_r), and (SU_t, SU_r), respectively. Also ε_0 and ε_1 denote the MIFTPs of SU_t and SU_{relay}, respectively when PU_t is

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active and ε_t denotes the maximum transmit power of SU$_t$. When $\varepsilon_0 << \varepsilon_t$, SU$_t$ may not communicate directly with SU$_r$ when PU$_t$ is active because the power level P_0 is too low. Hence, when PU$_t$ is active, SU$_t$ communicates with SU$_r$ through relay node SU$_{relay}$, which is closer to SU$_t$. The received signal at a relay is the MRC sum of a repetition code over K_0 time frames [8] as

$$y_1 = \sum_{i=1}^{K_0} g_i^*\left(g_i\sqrt{P_0}s + n_i\right) = \tilde{g}\sqrt{P_0}s + \tilde{n}\,, \qquad (2)$$

Where $\tilde{g} = \sum_{i=1}^{K_0}|g_i|^2$ and $\tilde{n} = \sum_{i=1}^{K_0} g_i^* n_i$, s is the transmitted symbol, $|s|^2 = 1$ and g_i is the channel gain between SU$_t$ and SU$_{relay}$ during time frame i. The received signal at SU$_r$ due to relay SU$_{relay}$ is

$$y_R = \sum_{j=1}^{K_1} h_j^*\left(\sqrt{P_1}h_j A\left(\tilde{g}\sqrt{P_0}s + \tilde{n}\right) + n_j\right) = \sqrt{P_0P_1}\tilde{h}A\tilde{g}s + n_R\,, \qquad (3)$$

Where $h = \sum_{j=1}^{K_1}|h_j|^2$, $n_R = \sum_{j=1}^{K_1}\left(|h_j|^2 A\sqrt{P_1}\tilde{n} + h_j^* n_j\right)$, h_j is the channel gain between SU$_{relay}$ and SU$_r$ during time frame j. Here, A is the amplification factor which is chosen to maintain average constant power output at SU$_{relay}$, $A^2 = 1/\left(P_0\tilde{g}^2 + N_0\tilde{g}\right)$. The noise variance of y_R is $\sigma_R^2 = A^2P_1\tilde{g}\tilde{h}^2N_0 + \tilde{h}N_0$ where $\tilde{h} = \sum_{j=1}^{K_1}|h_j|^2$. The direct transmission (SU$_t$ → SU$_r$) channel model is

$$y_T = f\sqrt{P_t}s + n_T\,, \qquad (4)$$

Where f is the channel gain between SU$_t$ and SU$_r$. f, h_j and g_i are constant over one time frame duration and independently identical distributed from one frame to another. At SU$_r$, MRC is used to combine y_R and y_T. The noise variables n_R and n_T have different powers because n_R includes a noise contribution at the relay. For this reason, noise normalization is necessary for MRC of y_T and y_R as in [10]. The resulting SNR is

$$\gamma_w = |f|^2\left(P_t/N_0\right) + \left|A\tilde{g}\tilde{h}\right|^2\left(P_0P_1/\sigma_R^2\right) = \gamma_t + \gamma_r\,, \qquad (5)$$

Where $\gamma_t = |f|^2\left(P_t/N_0\right)$ and

$$\gamma_r = \left|A\tilde{g}\tilde{h}\right|^2\left(P_0P_1/\sigma_R^2\right) = \left(\gamma_0\gamma_1/\left(\gamma_0 + \gamma_1 + 1\right)\right), \qquad (6)$$

with $\gamma_0 = \tilde{g}\left(P_0/N_0\right)$ and $\gamma_1 = \tilde{h}\left(P_1/N_0\right)$. We assume that f, g_i, h_j are known at receiving end. The symbol error probability (SEP) conditioned on the instantaneous SNR γ_w is given by $P_e = Q\left(\sqrt{k\gamma_w}\right)$ [10] where k is a constant that depends on the type of modulation and $Q(x) = \left(1/\sqrt{2\pi}\right)\int_x^\infty e^{-t^2/2}dt$ is the standard Q-function.

III. Performance Analysis

In this section, we derive a lower bound on the average SEP. We show that the SEP lower bound is minimized when $K_0 = K_1$ for K even and $K_0 = K_1 + 1$ for K odd. From Eq. (6), we can upper-bound γ_r as follows:

$$\gamma_r \le \left(\gamma_0\gamma_1/\left(\gamma_0 + \gamma_1\right)\right) \le \sqrt{\gamma_0\gamma_1}/2 = \left(\sqrt{P_0P_1}/2N_0\right)\sqrt{\tilde{g}\tilde{h}}\,, \qquad (7)$$

Taking expectations on both sides, we have

$$E[\gamma_r] \le \left(\sqrt{P_0P_1}/2N_0\right)E\left[\sqrt{\tilde{g}\tilde{h}}\right], \qquad (8)$$

Note that $g_i, h_j \sim CN(0,1)$ then $2\tilde{g}$ and $2\tilde{h}$ are independent χ^2-distributed random variables with $2K_0$ and $2K_1$ degrees of freedom, respectively. Applying Jensen's inequality,

$$E\left[\sqrt{\tilde{g}\tilde{h}}\right] \le \sqrt{E\left[\tilde{g}\tilde{h}\right]} = \frac{1}{2}\sqrt{E[2\tilde{g}]E[2\tilde{h}]} = \sqrt{K_0K_1}\,, \qquad (9)$$

From Eq. (8) and Eq. (9), we have

$$E[\gamma_r] \le \left(\sqrt{P_0P_1}/2N_0\right)\sqrt{K_0K_1}\,, \qquad (10)$$

Assuming M-PSK modulation, the average SEP can be expressed as follows [11]:

$$SEP = \frac{1}{\pi}\int_0^{\frac{(M-1)\pi}{M}} M_{\gamma_t}(-\kappa)M_{\gamma_r}(-\kappa)d\theta\,, \qquad (11)$$

Where $M_{\gamma_t}(u) \cong E\left[e^{u\gamma_t}\right]$ and $M_{\gamma_r}(u) \cong E\left[e^{u\gamma_r}\right]$ are the moment generating functions of γ_t and γ_r, respectively, and $\kappa \cong \left(k/\sin^2\theta\right) \ge 0$. Applying Jensen's inequality and Eq. (10), we have

$$M_{\gamma_r}(-\kappa) = E\left[e^{-\kappa\gamma_r}\right] = e^{-\kappa E[\gamma_r]} \geq e^{-\beta\sqrt{K_0 K_1}}, \qquad (12)$$

Where $\beta \cong \kappa\sqrt{P_0 P_1}/(2N_0) \geq 0$. The lower bound for the SEP is then obtained by substituting the right hand side of Eq. (12) into Eq. (11). If K is even, i.e., $K = 2m$ where m is an integer, $2\sqrt{K_0 K_1} \leq K_0 + K_1 = 2m$, with equality holding when $K_0 = K_1 = m$. In this case, Eq. (12) implies that the choice of $K_0 = K_1$ maximizes the performance of our proposed scheme. If K is odd, i.e., $K = 2m+1$, information-theoretic results in [12] suggest the choice $K_0 > K_1$, in order to maximize the SNR at the first hop. Let $K_0 = K_1 + n$, where $n \geq 1$ is an integer. We have $2K_1 = 2m + 1\text{-}n$,

$$4K_0 K_1 = 4m^2 + 4m + 1\text{-}n^2 \leq 4m^2 + 4m \qquad (13)$$

The equality in (13) holds for $K_0 = K_1 + 1$, which also suggests that choosing $K_0 = K_1 + 1$ minimizes $M_{\gamma_r}(-\kappa)$ and hence the SEP. Our analysis is confirmed by the simulation results presented in Section 4.

IV. Numerical Results

In this section, we present the simulated result of our proposed scheme in CRN. In the performance curves, the 95% confidence intervals are omitted for clarity. BPSK modulation is used and $f, g_i, h_j \sim CN(0,1)$ The frame length is 100 symbols. MRC and ML detection are used at the receiver.

In the first phase, we have assumed that the three channels have equal average SNRs, i.e. the distances between source, relay and destination are assumed to be equal. So it is logical to think the same MIFTPs for this case.

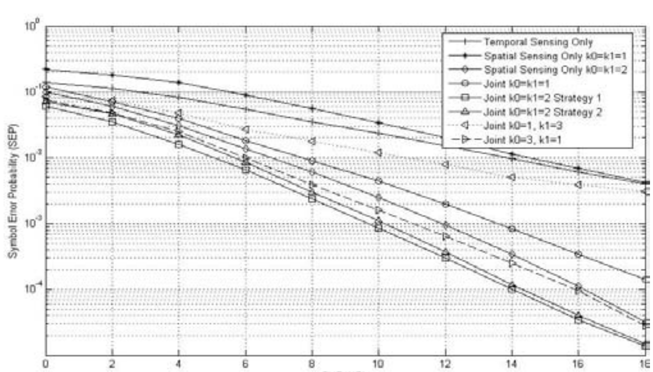

Figure 5 : Decode-and-Forward (DF) with one relay and K = 4

When $K = 2m$, the transmission strategy follows the scheme described in Section 2, which we call (strategy 1). The traditional cooperative communication scheme, which we call strategy 2, transmits m times on the path SU_t → SU_{relay} → SU_r over m branches.

Fig. 5 shows the SEP performance of our scheme with one relay and $K = 4$ in comparison to pure temporal sensing, pure spatial sensing, and traditional cooperative communications with $K_0 = K_1 = 1$. The pure temporal sensing scheme corresponds to direct communication from SU_t to SU_r, whereas the pure spatial sensing scheme corresponds to communication over the relay path. The simulation results confirm our analytical conclusion that the best performance is achieved with our proposed scheme with $K_0 = K_1 = 2$. Similar performance trends can be seen in Fig. 6, for which $K = 5$, $K_0 = 3$ and $K_1 = 2$.

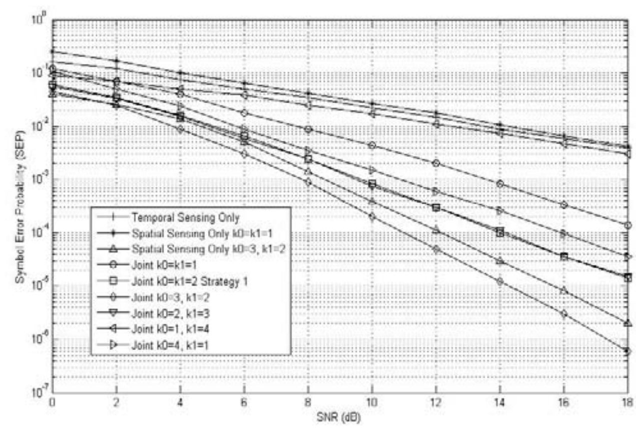

Figure 6 : DF with one relay and K = 5

In practice, the situation in the CRN becomes so much complex that it leads us to think different distances among the SU_t, SU_{relay} and SU_r (instead of assuming equal distances among them having the same average SNRs) which results different fading characteristics of these three channels. Hence these three channels will have different average SNRs. The simulated result of this condition is presented in Fig. 7 when the MIFTPs and the average SNRs (P_t/N_0), (P_0/N_0) and (P_1/N_0) are different. We found that a higher SNR at the link from SU_t to SU_{relay} results the best performance. The valuable insight from this is that we should choose the relay node that maximizes the average SNR (P_0/N_0) from the subset of relay nodes having the same total average SNR $((P_0 + P_1)/N_0)$. This also confirms the results in [12] in which the maximum transmission capacity is achieved when the relay is situated slightly near the source terminal or in the middle between the source and the destination.

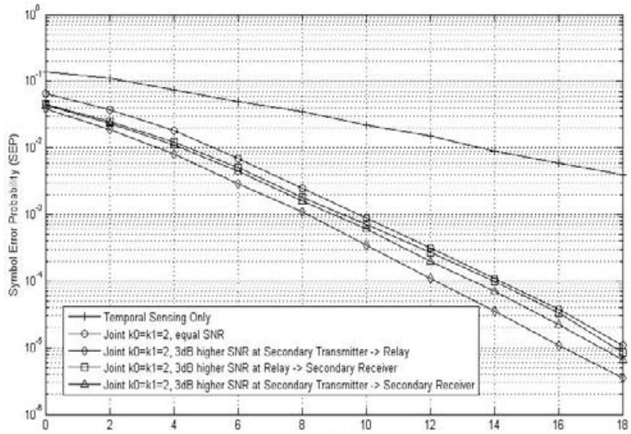

Figure 7 : DF with one relay, asymmetric SNR, and K = 4

V. Conclusion

We proposed a scheme works with the cooperative communication strategy in cognitive radio networks so that the secondary users can get all time transmission connectivity by using both spatial spectrum white space sensing and temporal spectrum white space sensing. This results maximum possible spectrum utilization. The proposed scheme improves the transmission capacity of static cognitive radio network to a great extent.

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