Outage analysis of cognitive communication system using opportunistic relay selection and secondary users as relays

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ABSTRACT
Efficient bandwidth utilisation is significant in new communication systems where secondary users can be used besides primary users considering interference issues and idle state of primary users. Using secondary users as relays to transmit their own signals in addition to the primary signals can be applied for more reliability of the system where opportunistic relay selection can significantly enhance the performance of the system. The best-condition secondary user is selected as the optimum relay for retransmission of primary/secondary signal. Outage probability is analysed in this paper based on decode and forward technique in secondary users while the closed-form statement for outage probability is provided and verified by numerical evaluations.

1. Introduction

Nowadays, higher demand of different wireless technologies with high bandwidth requirement causes the focus on the efficient exploitation of spectrum in communication systems. Cognitive communication approach is a promising solution for better bandwidth usage. Unused spectrum of primary users (PUs) can be exploited by secondary users (SUs) to transmit their data in the spectrum when PU is idle. On the other hand, to improve the capacity and data rate of the communication system, relay-based strategy can be applied for more reliable data delivery and throughput. In these cooperative systems, multiple relays play the interface role in delivering the data from sender node to the destination one. However, using multiple relays can affect the spectral efficiency requiring more time slots to prevent the interference between relay signals and transmitter/receiver signals. For $M$ assumed relays, $M+1$ time slots must be used where the direct link is assumed in the system. Thus, selecting the best relay increases the spectral efficiency in which this relay is selected based on signal-to-noise ratio (SNR) for relaying the signal from source node. Therefor two time slots, one for direct link and another for best-relay node are required for the signal transmission in this system, which is called opportunistic relay approach.

Combining the cognitive strategy and cooperative approach, multiple SUs can be assumed as multiple relays in which in the first time slot, they receive the signal of PU
and in the second time slot, they relay the PU signal in addition to the transmission of their own signal. Also for more spectral efficiency, the best relay is selected to relay the PU signal and its own signal. The strategy of signal relaying is considered Decode-and-Forward (DF). The main purpose of this structure is selecting the best relay based on SNR criterion to improve the reliability of the communication system and the spectral efficiency. Also, the outage probability is the main criterion for evaluating the efficiency of the proposed system where in different conditions, the outage must be lower than the predefined threshold for the reliability and satisfaction of communication systems.

2. Literature review

The outage probability analysis of cognitive transmissions by considering two phases, one for spectrum hole detection and the second for data transmission is discussed in Zou et al., (2010). In Subhash et al., (2020), the optimum SU power allocation to improve the ergodic rate of point-to-multipoint communication in a cognitive radio network is presented. Improper Gaussian signalling effect is applied in Amin et al., (2016) which is compared to the conventional Gaussian signalling to enhance the achievable rate of systems. Physical layer security based on existence of multiple eavesdroppers in 5 G network is considered in Lingwei et al., (2020) where outage and capacity analysis is performed. Non-Orthogonal Multiple Access (NOMA) system in cognitive radio is assumed in TRAN & a Miroslav Vozňák, (2018) to enhance the capacity and outage probability. Security analysis considering outage probability in existence of eavesdroppers is discussed in Ata and Erdogan, (2020). Performance analysis based on throughput analysis is realised in Filippou et al., (2015) for two cognitive systems as interweaved and underlay multiple-input-single-output (MISO) systems. In Paul & Maity, (2020), outage probability is presented in cognitive relay networks, in which the best relay is selected based on channel state information and energy harvesting technique. Device-to-device (D2D) transmission together with traditional communication is presented in Do et al., (2019) to form a new system model in NOMA. In Toan et al., (2018), the imperfect information of channel of SU to PU is assumed where outage probability is considered as the main quality parameter. Presence of PU interference in cognitive system and interference analysis is done in Xu et al., (2012) to discuss the outage probability in decode and forward (DF) strategy. Relay-based communication with opportunistic relay selection strategy in existence of direct link is also discussed in Ikki & Ahmed, (2010) for the analysis of outage probability. Relay selection strategy with optimal approach to maximise capacity in existence of interference and channel state information is discussed in Krikidis et al., (2012). Secondary rate maximisation with considering the constraint of primary rate is presented in (Blasco-Serrano et al., 2013) subjected to the power constraint as the main condition of optimisation. Outage probability and effective capacity in overlay and underlay strategy are discussed for maximisation of effective capacity and minimisation of outage in Zahedi, (2019), Zahedi et al., (2020). Spectrum sharing in cognitive system considering multiple antennas in PU/SU transmitters is assumed in Vashistha et al., (2015).

Considering above, opportunistic relay selection in cognitive cooperative system based on outage analysis is the main purpose of this paper. Selecting the best relay based on SNR improves the performance of the communication system in term of spectral efficiency and outage probability. Accurate analysis of outage probability in numerical
evaluation and simulation result is presented to propose a new efficient scheme in cognitive system where both results verify each other. The main novelties of the paper can be summarised as follows:

- Opportunistic relay selection based on SNR criterion
- Outage probability analysis in cooperative cognitive system using DF relaying strategy
- SU role assumption as relay nodes for PU/SU data delivery to the destination
- Assumption of communication channels as independent non-identical (dissimilar) channels
- Numerical evaluation of outage probability and verification by simulation result

In the sequel of the paper, in section 3, the model of communication system is presented where in section 4, quality of service (QoS) analysis is stated focusing on outage probability. Numerical results are provided in section 5 where some conclusions are mentioned in the last section, section 6.

3. System model

In Figure 1, system model is shown where SUs play the relay role in the system and transmit their own signals in addition to the PU signal. The source and destination nodes of PU and SU are shown in this figure where $h$ is used for the channel of PU to SUs and $g$ is used for relay-destination channel.

Figure 1. Proposed cognitive-based cooperative communication system.
The strategy of relaying is based on DF where from the multiple SUs in the model, best-condition SU node is selected as the optimum relay to deliver the signal of PU to its destination. The index of SU is used for SU nodes and pu is used for PU elements. The index b is denoted for the best secondary node selected for signal relaying. $S_{su}$ is the secondary sender node where $S_{pu}$ is the sender of PU. The similar notation is used for destinations of SU and PU ($D_{su}, D_{pu}$). $h_i$ is the channel between $S_{pu}$ and $S_{su,i}$ where $H_p$ is the direct link between $S_{pu}$ and $D_{pu}$. $H_S$ is also the direct link between $S_{pu}$ and $D_{su}$ using which, the interference cancellation (PU signal) can be done in the secondary destination. $g_{i,p}$ is the channel gain between $S_{su,i}$ and $D_{pu}$ where $g_{i,s}$ is the channel gain between $S_{su,i}$ and $D_{su}$. Rayleigh fading channel is assumed for all channels of the proposed communication system in Figure 1.

The strategy of signal transmission from sender to the destination is that in the first phase, $S_{pu}$ can send its signal to the $D_{pu}$ and $D_{su}$ (direct links) and to the multiple SU relays. If the channel in direct link is broken, the best relay of SUs can cooperate to bring the PU sender signal to its destination. The SU sender transmits both PU and SU signal. The channels in this model are independent but not identical (dissimilar). From M relay nodes as SUs, several SUs can optimally receive and decode the PU signal which make the decode set as C. From this set, one relay with maximum SNR is selected for relaying the PU signal in the second phase.

In the first phase, the received signal of relays from PU is as:

$$y_{su,i} = \sqrt{P_p} x_p h_i + n_i \quad (1)$$

where $P_p$ is the power in PU source, $x_p$ is assumed as the data of PU and $n_i$ is the Gaussian noise. $y$ is used as the receiver signal in each step where $y_{su,i}$ is the received signal of SU $i$-th relay. For the PU destination in direct link, it can be written as:

$$y_{D_{pu}} = \sqrt{P_p} x_p H_p + n_p \quad (2)$$

and in the SU destination, we have:

$$y_{D_{su}} = \sqrt{P_p} x_p H_s + n_s \quad (3)$$

The SNR due to (1) is calculated as:

$$\gamma_{hi} = \frac{P_p |h_i|^2}{N_0} \quad (4)$$

where $N_0$ is the Gaussian noise in relays and $\gamma_{hi}$ is the SNR of $h_i$ channel. The SNR of direct link from PU to its destination is (due to (2)):

$$\gamma_1 = \frac{P_p |H_p|^2}{N_0} \quad (5)$$

and also for another direct link, we have (due to (3)):

$$\gamma_2 = \frac{P_p |H_s|^2}{N_0} \quad (6)$$

It is worth mentioning that general assumption of Gaussian noise, $N_0$ is assumed in each destination. In the second phase, the best secondary node is selected in which a part of
power is allocated for PU signal transmission and another part is devoted for the secondary signal. The signal of relay in PU destination is presented as:

$$y_{D_{pu,2}} = \sqrt{\alpha P_s} x_p g_{b,p} + \sqrt{(1-\alpha)P_s} x_s g_{b,s} + n$$  \hspace{1cm} (7)

where $\alpha$ is the factor of power division, $P_s$ is the maximum transmitted power of secondary user in source (the best relay); $g_{b,p}$ is the channel between the best relay and receiver of primary user as mentioned above (Figure 1) and $n$ is additive white noise. Also in SU destination, we have:

$$y_{D_{su,2}} = \sqrt{\alpha P_s} x_p g_{b,s} + \sqrt{(1-\alpha)P_s} x_s g_{b,s} + n$$  \hspace{1cm} (8)

For the SNR calculation in $D_{pu}$, due to (7), we have:

$$Y_{D_{pu,2}} = \frac{aP_s \left| g_{b,p} \right|^2}{(1-a)P_s \left| g_{b,p} \right|^2 + N_0}$$  \hspace{1cm} (9)

The first term in denominator in (9) is denoted for the maximum tolerable interference from SU on PU signal in destination node which can be stated as:

$$(1-a)P_s \left| g_{b,p} \right|^2 = I_{NT}$$  \hspace{1cm} (10)

Thus, (9) can be rewritten as:

$$Y_{D_{pu,2}} = \frac{aP_s \left| g_{b,p} \right|^2}{I_{NT} + N_0}$$  \hspace{1cm} (11)

The interference threshold must be chosen as the outage happening is prevented and the acceptable data rate is achieved as:

$$\frac{1}{2} \log_2 (1 + \frac{aP_s \left| g_{b,p} \right|^2}{I_{NT} + N_0}) \geq R$$  \hspace{1cm} (12)

where $R$ is the minimum required data rate. Thus, the interference can be presented as below:

$$I_{NT} = \frac{aP_s \left| g_{b,p} \right|^2}{2^R - 1} - N_0$$  \hspace{1cm} (13)

Moreover, the SNR in secondary destination due to (8) can be written as:

$$Y_{D_{su,2}} = \frac{(1-a)P_s \left| g_{b,s} \right|^2}{aP_s \left| g_{b,s} \right|^2 + N_0}$$  \hspace{1cm} (14)

Since the PU sends its signal for destination of secondary in the first phase, the interference of PU on SU can be suppressed and the SNR can be stated as:

$$Y_{D_{su,2}} = \frac{(1-a)P_s \left| g_{b,s} \right|^2}{N_0}$$  \hspace{1cm} (15)
4. QoS analysis

The probability of not qualifying of SU relay to be as a relay node can be described as:

\[ A_i = Pr(y_{hi} \leq \frac{2^R}{\gamma_{hi}} - 1) = 1 - \exp\left(-\frac{2^R - 1}{\gamma_{hi}}\right) \]  \hspace{1cm} (16)

\( R \) is the data rate threshold lower which the connection is blocked and \( \gamma_{hi} \) is the expectation value of \( y_{hi} \). The probability density function of \( y_i \) (final PU received signal in the link from PU sender to its destination through the SU relay nodes) can be described as below (Ikki & Ahmed, 2010):

\[ f_{y_i}(x) = f_{y_i}(x|R_i \text{ is down})pr(R_i \text{ is down}) + f_{y_i}(x|R_i \text{ is active})pr(R_i \text{ is active}) \]  \hspace{1cm} (17)

where \( pr \) is used for probability statement and \( R_i \) is the i-th relay node. Thus, we can write:

\[ pr(R_i \text{ is active}) = (1 - A_i) \]

\[ pr(R_i \text{ is down}) = A_i \]  \hspace{1cm} (18)

where \( A_i \) shows non-suitable condition of the relay for retransmission of PU signal. Thus, the probability density function (pdf) of dropped link is presented as:

\[ f_{y_i|R_i \text{ is down}}(x) = \delta(x) \]  \hspace{1cm} (19)

and considering the Rayleigh fading channel, the pdf of active link from PU to SU nodes and then to the destination can be presented as:

\[ f_{y_i|R_i \text{ is active}}(x) = \frac{1}{\gamma_{gi}} \exp\left(-\frac{x^2}{\gamma_{gi}}\right) \]  \hspace{1cm} (20)

where \( \gamma_{gi} \) presents the average SNR of channel \( g \). Thus, combining these two links, we have:

\[ f_{y_i}(x) = A_i \delta(x) + (1 - A_i) \frac{1}{\gamma_{gi}} \exp\left(-\frac{x^2}{\gamma_{gi}}\right) i = 1, 2, \ldots, M \]  \hspace{1cm} (21)

4.1 PU outage analysis

Using maximum ratio combining (MRC) in PU destination, we have combined SNR of first and second phases as (due to (5) and (9)):

\[ IDF = \frac{1}{2} \log\left(1 + y_1 + \max\left(y_{Dpu,2}\right)\right) \]  \hspace{1cm} (22 – a)

where IDF is used for the information capacity of decode-and-forward (DF) relay strategy. IDF is applied in the PU destination where for analysis of PU outage probability, we have:

\[ p_{\text{out, } pu} = p(IDF < R) = p\left(y_1 + \max\left(y_{Dpu}\right) < 2^R - 1\right) \]  \hspace{1cm} (22 – b)

where \( p_{\text{out, } pu} \) is the outage probability of PU. The Eq. (22-b) leads to the convolution of each PDF of direct and indirect link as (Ikki & Ahmed, 2010; Vashistha et al., 2015):
resulting in (Bithas et al., 2005):

\[
p_{\text{out,pu}} = p(y_1 < 2^{2R} - 1) \times p\left(\max\left(y_{D_{\text{pu}2}}\right) < 2^{2R} - 1\right)
\] (23)

\[
p_{\text{out,pu}} = \left(\prod_{i=1}^{M} A_i\right)\left(1 - \exp\left(-\frac{x}{y_1}\right)\right) + \sum_{k=1}^{M} \left(-1\right)^{k+1} \sum_{\lambda_1=\lambda_1+1}^{M-k+1} \cdots \sum_{\lambda_k=\lambda_{k-1}+1}^{M-k+2} \prod_{i=1}^{k} \left(1 - A_{\lambda_i}\right) \times \left[1 + \frac{1}{\hat{y}_1 - \frac{1}{\sum_{i=1}^{k} \frac{1}{\hat{y}_{D_{\text{pu}2},\lambda_i}}}} \left(\prod_{i=1}^{k} \exp\left(-\frac{x}{\hat{y}_{D_{\text{pu}2},\lambda_i}}\right) - \hat{y}_1 \exp\left(-\frac{x}{y_1}\right)\right)\right]
\] (24)

**4.2 SU outage analysis**

Using MRC in SU destination, to prevent outage happening for SU, SU destination must receive the SU sender signal in addition to the PU signal in the first phase. Thus, the outage probability can be stated as:

\[
p_{\text{out,pu}} = 1 - Pr\left(\max\left(y_{D_{\text{su}2}}\right) < 2^{2R} - 1\right) \times Pr\left(\frac{1}{2}R_2 > R\right)
\] (25)

where \(p_{\text{out,pu}}\) is the SU outage probability and \(R_2\) is the data rate between primary transmitter and secondary receiver in the first phase described as \(R_2 = \frac{1}{2} \log_2(1 + y_2)\).

The reason of applying the factor of \(\frac{1}{2}\) is that the PU signal is transmitted in the first time slot to the destination of SU (the whole transmission needs two time slots). Then each term of (25) can be presented to calculate the total outage probability. For the first term, we have:

\[
p\left(\max\left(y_{D_{\text{su}2}}\right) > 2^{2R} - 1\right) = 1 - p\left(\max\left(y_{D_{\text{su}2}}\right) < 2^{2R} - 1\right)
\] (26)

where we have:

\[
p\left(\max\left(y_{D_{\text{su}2}}\right) < 2^{2R} - 1\right) = \int f_{y_{D_{\text{su}2}}}(x)dx
\] (27)

In other hand, we have the pdf of \(y_{D_{\text{su}2}}\) \((f_{y_{D_{\text{su}2}}}(x))\) as (Bithas et al., 2005; Ikki & Ahmed, 2010; Vashistha et al., 2015):

\[
f_{y_{D_{\text{su}2}}}(x) = \left(\prod_{i=1}^{M} A_i\right)\delta(x) + \sum_{k=1}^{M} \left(-1\right)^{k+1} \sum_{\lambda_1=\lambda_1+1}^{M-k+1} \cdots \sum_{\lambda_k=\lambda_{k-1}+1}^{M-k+2} \prod_{i=1}^{k} \left(1 - A_{\lambda_i}\right) \times \exp\left(-\frac{x}{\hat{y}_{D_{\text{su}2},\lambda_i}}\right) \sum_{i=1}^{k} \frac{1}{\hat{y}_{D_{\text{su}2}},\lambda_i}
\] (28)

Therefore, due to (27) and (28), the result can be stated as:

\[
Pr\left(\max\left(y_{D_{\text{su}2}}\right) < 2^{2R} - 1\right) = \left(\prod_{i=1}^{M} A_i\right) + \sum_{k=1}^{M} \left(-1\right)^{k+1} \sum_{\lambda_1=\lambda_1+1}^{M-k+1} \cdots \sum_{\lambda_k=\lambda_{k-1}+1}^{M-k+2} \prod_{i=1}^{k} \left(1 - A_{\lambda_i}\right)
\]
\[ x \left( 1 - \exp \left( \frac{-x}{\hat{y}_{D,w,2,\lambda}} \right) \right) \]  \hspace{1cm} (29)\\

And for the second term of (25), we can write as:

\[ p \left( \frac{1}{2} R_2 > R \right) = Pr \left( \frac{1}{2} \log_2 (1 + y_2) > R \right) = Pr \left( y_2 > \frac{2^R - 1}{\hat{y}_2} \right) = \exp \left( - \frac{2^R - 1}{\hat{y}_2} \right) \]  \hspace{1cm} (30)\\

Therefore, the outage probability of SU can be written as:

\[ p_{out, su} = \left( 1 - \prod_{i=1}^{M} A_i \right) + \sum_{k=1}^{M} \left( -1 \right)^{k-1} \sum_{\lambda_i = \lambda_{k+1}}^{\lambda_i = \lambda_{k+1}} \ldots \sum_{\lambda_i = \lambda_{M+1}}^{\lambda_i = \lambda_{M+1}} \prod_{i=1}^{k} \left( 1 - A_i \right) \times \left( 1 - \exp \left( \frac{-x}{\hat{y}_{D,w,2,\lambda}} \right) \right) \times \exp \left( - \frac{2^R - 1}{\hat{y}_2} \right) \]  \hspace{1cm} (31)\\

5. Numerical results

In this section, the numerical evaluation of above discussion is provided to verify the theoretical analysis of outage probability. In the first analysis, the outage probability in different number of secondary users is presented versus change of SNR. As depicted in Figure 2, the outage probability is reduced with increasing the number of relays which is predictable in the proposed cognitive system. In addition, without any secondary user, the outage probability depends only on primary channel which is constant versus SNR.

In the sequel, the analysis of outage probability versus different outage thresholds for outage happening is described where the results are shown in Figure 3. As depicted in this figure, increasing the threshold causes more outage in the proposed system while

![Figure 2. Outage probability of PU versus the SNR in different numbers of relays.](image-url)
Figure 3. Outage probability of PU versus the SNR in different outage thresholds.

Figure 4. Outage probability of SU versus the SNR in different numbers of relays and outage thresholds.
reducing the threshold leads to outage probability reduction. This result shows the effect of the threshold of channel condition on the outage probability.

In the third test case, the secondary user outage probability is discussed and its result is depicted in Figure 4. As described in this figure, using multiple relays and selection of lower threshold causes less outage probability in the proposed system. It is obvious that increasing the number of secondary users as relays improves the outage probability.

6. Conclusion

In this paper, the outage analysis of cognitive cooperative communication system based on multiple secondary users as relays and using opportunistic relay selection for retransmission is provided. Selection of the best relay from M assumed relays causes more spectral efficiency which can improve the reliability and reduce the outage probability. Theoretical analysis is discussed and evaluated using simulation results where both outcomes verify each other. Increasing multiple relays and reducing threshold of selection of best relay cause significant outage probability reduction and thus, the performance of the proposed cognitive system is notably improved.

As the future work, the power division factor (α) between PU and SU signal transmission can be optimised to minimise the outage probability in PU and SU destinations. This optimisation can improve the performance of the proposed system in power saving and outage probability reduction.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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