Improvement of Underlay Cooperative Cognitive Networks Bandwidth Efficiency under Interference and Power Constraints

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Abstract

The definition of the bandwidth efficiency (BE) of cognitive cooperative network (CCN) is the ratio between a number of the licensed slot(s) or sub-channel(s) used by the unlicensed users to transmit a single data packet from the unlicensed transmitter to unlicensed destination, and from unlicensed relay(s) to unlicensed destination. This paper analyzes and improves the BE in the underlay CCN with a new reactive relay selection under interference and power constraints. In other words, this paper studies how unlicensed cooperative users use the licensed network slot(s) or sub-channel(s) efficiently. To this end, a reactive relay selection method named as Relay Automatic Repeat Request (RARQ) is proposed and utilized with a CCN under interference and power constraints. It is shown that the BE of CCN is higher than that of cooperative transmission (CT) due to the interference and power constraint. Furthermore, the BE of CCN is affected by the distance of the interference links which are between the unlicensed transmitter to the licensed destination and unlicensed relay to the licensed destination. In addition, the BE for multiple relays selection over a CCN under interference and power constraints is also analyzed and studied, and it is shown that the BE of CCN decreases as the number of relays increases.

Keywords: Bandwidth efficiency, reactive relay selection, cooperative transmission, cognitive cooperative network.

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1. Introduction

With the fast deployment of wireless services over the last decade, the radio spectrum has become a valued and scarce resource. Furthermore, the Federal Communications Commission has reported that most of the licensed spectrum is severely underutilized [1]. As a promising technique, a cognitive network (CN) is proposed to address the dilemma between spectrum scarcity and spectrum underutilization. CN allows unlicensed users to access licensed slots or sub-channels while taking into account the effect of interference on the licensed users, so it should not exceed the tolerable interference threshold [2]. Therefore, the underlying approach is utilized, where the unlicensed users are allowed to use the licensed slots or sub-channels with only a limited transmission power to prevent the interference of unlicensed users from exceeding the interference threshold that the licensed user can tolerate [3].

CT enables users to forward incoming data to each other, thus, and it creates a virtual multiple-input-multiple-output (MIMO) system for cooperative diversity [4, 5]. Although CT has some fundamental benefits compared to non-cooperative communication systems, it has undesirable features that affect communication. For example, when data is processed and transmitted using relays, some drawbacks occur, such as reduced BE [6], which increases the delay during communication [7].

In [8], analysis of BE for cooperative networks and the selection of the best relay node were investigated. That study relied on the harmonic mean of the links between source-relay and relay-destination to select the relay node based on the harmonic mean of these links. In addition to relay node selection, that author considered the incremental redundancy protocol that reduces the BE loss. In [9], the author proposed a joint next-hop node and a relay node selection (JNRS) protocol for wireless distributive multi-hop cooperative networks where the main goal of JNRS is to reduce loss in BE.

The CCN has recently inspected as a potential way to improve unlicensed users capacity using one of two approaches: cooperation between unlicensed users [10 - 11], and cooperation between the licensed user and unlicensed users [12]. In [13 - 22], the relay selection methods in underlay CCN are widely studied and the outage probability of decode-and-forward (DF) in CCN with both proactive and reactive relay selection in underlay approach was widely analyzed. More precisely in [23], the best multiple relay(s) selection method is proposed. Where a relay selection method with a good trade-off performance of gain for secondary users and loss for the primary user is proposed in [24]. In [25 - 26], the effects of both proactive and reactive relay selection performance on Bit Error Rate (BER) are analyzed and studied in underlay CCN. Recently in [27-30], the security performance with relay selection methods under one or both of realistic operation conditions such as maximum transmit power constraint for unlicensed user's, or interference power constraint for licensed users are considered. The performance analysis of optimal decode-and-forward (DF) relay selection for the full-duplex (FD) mode in underlay cognitive radio (CR) networks is studied in [31], with the impact of critical parameters such as the residual self-interference, the distributions of the received signal-to-noise ratio (SNR) and the outage probability. In [32] an opportunistic two-way full-duplex relay selection in underlay cognitive networks is inspected. A closed-form expressions for the distribution of end-to-end signal-to-noise ratio (SNR) is provided, and the theoretical closed-form expressions for various performance metrics, including the outage probability of each link, lower bounds of both the derived outage probability and the symbol error probability (SEP), and upper bound of the average/outage channel capacity, are derived.

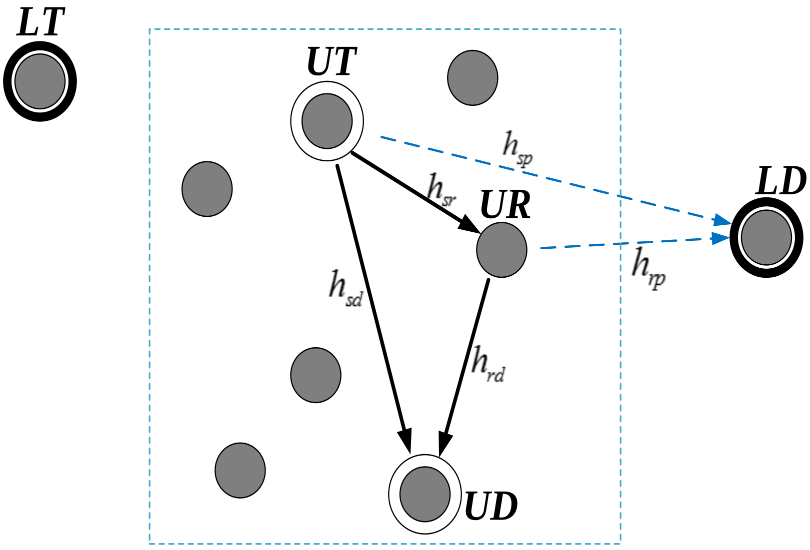
However, to the best of our knowledge, none of the previous works investigated and improved the BE of the CCN neither with reactive nor proactive relay selection. The contribution of this work is summarized as follow:

- A reactive relay(s) selection method based on ARQ principles is proposed, named as RARQ, and it is used with the CT and CCN for the first time.
- The BE is analyzed and improved in CT and CCN. Then, a formulation is provided to show the effects of interference and power constraints on relay selection and BE.
- The BE with the multiple relays selection based on RARQ for the CT and CCN are investigated, then we show the effect of the multiple relays selection under interference and power constraints on the overall system performance.
- The BE of CCN is affected by the distance of the interference links which are the links between the unlicensed transmitter to the licensed destination and unlicensed transmitter relay to the licensed destination.

The rest of the paper is organized as follows: In Section 2, the preliminaries and description of the CCN model are presented. In Section 3, the RARQ method is described for both cooperative and CCN. In Section 4, the BE of a cooperative network and a CCN are derived. In Section 5, the numerical analysis results are presented. Finally, the conclusions and recommendations for future work are presented in section 6.

2. System Model description

For the clarified CCN model in this section, an licnsed user (LU) coexists with the unlicensed user as shown in **Fig. 1**, where, LT, LD, UT, UR and UD represent a licensed transmitter, licensed destination, unlicensed transmitter, unlicensed relay and unlicensed destination, respectively, and we have M possible UR. In this paper, a cooperative decode-and-forward (DF) method is utilized, and it works in two phases. In the first phase, UT makes transmission to the M secondary relays and UD, then at the second phase, a relay(s) decodes the received data, re-encodes it and then forwards it to a UD.



Unlicensed Users

Fig. 1. System description of CCNs

For the considered slow fading (quasi-static) channels, let $h_{i,j}$ be a generic Rayleigh fading modeled channel for any link and it is represented with zero-mean complex Gaussian random variable and with variance $\sigma_{i,j}^2$. Therefore, the squared channel gains ($\left|h_{i,j}\right|^2$) are modeled with the parameter $\delta = 1/\sigma_{i,j}^2 = d_{ij}^{\rho}$ [33, 34], d_{ij} is the distance between node i and , and ρ is the path-loss exponent. In what follows, we denote the links $UT-UD$, $UT-UR$, $UR-UD$, $UT-LD$ and $UR-LD$ by $h_{sd}, h_{sr}, h_{rd}, h_{sp}$ and h_{rp} ,respectively.

3. Cognitive Cooperative Networks

The DF scheme under consideration is summarized as follows. In the first phase, the source broadcasts the data to all the relays including the destination. If a relay decodes the received data correctly, the data is re-encoded; otherwise, the relay remains silent. In the second phase, the relay retransmits the encoded data to the destination. Moreover, if more than one relay decodes the received data correctly; multiple signals of the data will be retransmitted to the destination. The relay selection method used in this work which is reactive relay selection, named as Relay Automatic Repeat Request (RARQ).

In this work, if the direct transmission (DT) fails to deliver the data packet to the destination correctly, the selected relay(s) forwards the data packet, which was transmitted from the source to the destination. The proposed RARQ method comprises of two cases:

Case1: If the link quality of h_{sd} is better than the qualities of the maximum of the minimum h_{sr} and h_{rd} links, then DT is used and destination sends a positive ACK to the relay(s) to keep them silent. This mode is expressed as:

$$\emptyset =: \ h_{max} < h_{sd} \ ; \ h_{max} = arg \underbrace{\max}_{m} \ min \{h_{sr}, h_{rd}\} \tag{1}$$

Cases2: If the link quality of h_{sd} is worse than the qualities of the maximum of the minimum h_{sr} and h_{rd} links, then the destination sends back a negative ACK to the relay(s), and the best relay forwards the received data to the destination. This mode is called CT mode, and it expressed as:

$$\ddot{\emptyset} =: h_{max} > h_{sd}; \ h_{max} = arg \underbrace{\max}_{m} \ min \{h_{sr}, h_{rd}\} \tag{2}$$

The selection criterion is (which is given as h_{max}) depends on the maximum of the minimum of the links quality of h_{sr} and h_{rd}, where $m = 1,2,3, \ldots, M$ is the relay number.

In this paper, the underlay approach is taken into consideration, in which the power of UT is not exceeded interference threshold, I_{thd} where I_{thd} is the maximum tolerable interference level on LD [3]. Thus, the transmission powers of UT and UR can be limited by considering the I_{thd}. Where, $I_{thd} = I_{sp} = \left|h_{sp}\right|^2 \cdot P_{UT}$ is interference power from UT to LD and $I_{thd} = I_{rp} = \left|h_{rp}\right|^2 \cdot P_{UR}$ is interference power from UR to LD. Therefore, the maximum power can be transmitted from UT is $P_{UT} \le I_{thd}/\left|h_{sp}\right|^2$, and the maximum power can be transmitted from UR is represented as $P_{UR} \le I_{thd}/\left|h_{rp}\right|^2$. Consequently, the maximum transmission powers are given as:

$$P_{UT} = I_{thd}/\left|h_{sp}\right|^2 \qquad for \qquad P_{max}^{UT} < I_{thd}, \tag{3}$$

And

$$P_{UR} = I_{thd} / \left|h_{rp}\right|^2 \qquad for \qquad P^{UR}_{max} < I_{thd}. \tag{4}$$

Where, P^{UT}_{max} and P^{UR}_{max} are the maximum transmission power from UT and UR. In this paper, the channel gains of h_{rp} and h_{sp} are assumed to be equal, so the P^{UT}_{max} is also equal to P^{UR}_{max}. To this end, the selection criterion should be redefined while considering both the interference and the maximum power constraints. Thus, the Case 1 of the RARQ method under power and interference constraints are defined as:

$$\emptyset =: h^{CC}_{max} < h_{sd} \tag{5}$$

Case 2 of the RARQ method under power and interference constraint modeled as:

$$\ddot{\emptyset} =: h^{CC}_{max} > h_{sd} \tag{6}$$

In which the h^{CC}_{max} is expressed as

$$h^{CC}_{max} = arg \underbrace{\max}_{m} min \left\{ (I_{thd}/h_{sp}) \cdot h_{sr} , (I_{thd}/h_{rp}) \cdot h_{rd} \right\} \tag{7}$$

Where, h^{CC}_{max} is the maximum of h_{sr} and h_{rd} under power and interference constraints for CCNs.

4. The Bandwidth Efficiencies

4.1 Bandwidth Efficiency of Cooperative Networks

In this subsection, the average BE of the CT with RARQ method has been derived. Laterally BE of the CCN is derived and formulated. The BE is a number of slots or sub-channels required to transmit single data packet over DT divided by the number of the of slots or sub-channels required to transmit single data packet over CT. Where, If M relays participated in cooperation, then $(M + 1)$ slots or sub-channels will be used to transmit single data packet from the source to the destination in the CT. Therefore, the BE of the CT, BE_{DT}, will be denoted by $1/(M + 1)$, then the BE of CT , BE_{CT}, is given as $BE_{DT}/(M + 1)$. The average BE with RARQ is expressed as [8].

$$BE^{av,CT}_{RARQ} = P_r(\emptyset) + 0.5\, P_r(\ddot{\emptyset}) \tag{8}$$

in which $\emptyset$ and $\ddot{\emptyset}$ are the events of DT and CT, respectively. $P_r(\emptyset)$ is the probability of DT, $0.5\, P_r\left(\ddot{\emptyset}\right) = 1 - P_r(\emptyset)$ is the probability of CT, the multiplication of $P_r\left(\ddot{\emptyset}\right)$ by 0.5 is due to the half-duplex mode. The probability of DT is expressed as

$$P_r(\emptyset) = P_r\ (h_{max} < h_{sd}) = P_{h_{max}}(h_{sd}) \tag{9}$$

where $P_r\ (h_{max} < h_{sd})$ is the cumulative distribution function of DT. Considering the RARQ method, the best relay selection bases on the max-min qualities of h_{sr} and h_{rd} links, and they are represented as exponential random variables with $\delta_{sr}\ and\ \delta_{rd}$ parameters. Hence,

$P_{h_{max}}(h_{sd})$ is expressed as [9]

$$P_{h_{max}}(h_{sd}) = 1 - \exp(\,-(\delta_{sr} + \delta_{rd}) \cdot h_{sd}), \tag{10}$$

$$P_{h_{max}}(h_{sd}) = 1 - \exp\left(-\left(\frac{1}{\sigma_{sr}^2} + \frac{1}{\sigma_{rd}^2}\right) \cdot h_{sd}\right) \tag{11}$$

The average cumulative distribution function is expressed as [8]

$$P_{h_{max}}^{av}(h_{sd}) = \int_0^\infty P_{h_{max}}(h_{sd}) \,.\, p_{h_{sd}}(h_{sd}) \;\; dh_{sd}, \tag{12}$$

$$P_{h_{max}}^{av}(h_{sd}) = 1 - \frac{1}{\sigma_{sd}^2}\left(\left(\frac{1}{\sigma_{sr}^2} + \frac{1}{\sigma_{rd}^2}\right) + \frac{1}{\sigma_{sd}^2}\right)^{-1} \tag{13}$$

Then, using eq.8, the average BE with RARQ method can be re-written as

$$BE_{RARQ}^{av,CT} = P_{h_{max}}^{av}(h_{sd}) + 0.5\left(1 - P_{h_{max}}^{av}(h_{sd})\right) = 0.5\left(1 + P_{h_{max}}^{av}(h_{sd})\right) \tag{14}$$

Then by inserting eq.13 into Eq.14, we directly obtain

$$BE_{RARQ}^{av,CT} = 1 - \frac{0.5}{\sigma_{sd}^2}\left(\left(\frac{1}{\sigma_{sr}^2} + \frac{1}{\sigma_{rd}^2}\right) + \frac{1}{\sigma_{sd}^2}\right)^{-1} \tag{15}$$

Here, eq.15 represents the expression of the average BE of a CT with the RARQ method. The RARQ method is improved the BE, by selecting the direct transmission if the channel gain of $UT - UD$ is better than the channel gain of max-min of the $UT - UR$ and $UR - UD$, and this makes $BE_{RARQ}^{av,CT}$ better than BE_{CT}.

It is obvious that, if the channel gain of the $UT - UD$ link is much better than the max-min channel gains of the $UT - UR$ and $UR - UD$ links, the BE approaches to"1", because the probability of the DT is increased. However, if the channel gain of the $UT - UD$ link is much worse than the channel gain of max-min channel gains of the $UT - UR$ and $UR - UD$ links, the BE approach to 0.5 that is because the probability of CT is high. The RARQ method in the CT for determining the best relay node is given in **Table 1**.

Table 1. RARQ Method Description in CT

```
Require: $(h_{sd}, h_{sr}, h_{rd}$ and $h_{max})$
begin
Collect the channel gains of $h_{sd}, h_{sr}, h_{rd}$ and evaluate $h_{max}$
for each relay node m in the secondary cooperative network
    $h_{sd}$ and $h_{max}$ are determined
```

```
    endfor
    if $h_{max} < h_{sd}$, then
        destination sends +ACK;
        Best relay node keeps silent and drops what received from the source;
    Else if $h_{max} > h_{sd}$, , then
        destination sends -ACK; then
        Best relay node sends to destination whatever it has received from the source ;
    endif
```

4.2 Bandwidth Efficiency of CCNs

In this subsection, the average BE of the CCN considering the power and interference constraint is derived. For our convenient, before driving $P_{h_{max}^{CC}}(h_{sd})$, let's redefine h_{max}^{CC} (7) as

$$h_{max}^{CC} = arg \underbrace{\max}_{m} \, min \left\{ \frac{I_{thd}}{x} y \, , \frac{I_{thd}}{w} z \right\} \tag{16}$$

where x and y are independent random variables. Then $P_{h_{max}^{CC}}(h_{max}^{CC} > h_{sd})$ is expressed as

$$P_{h_{max}^{CC}}(h_{max}^{CC} > h_{sd}) = P_{h_{max}^{CC}}\left(\frac{I_{thd}}{x} y > h_{sd}\right) . P_{h_{max}^{CC}}\left(\frac{I_{thd}}{w} z > h_{sd}\right) \tag{17}$$

for our convenient, h_{sd} is assumed to be equal to P_{max}. So, $P_{h_{max}^{CC}}\left(\frac{I_{thd}}{x} y < P_{max}\right)$ is expressed as

$$P_{h_{max}^{CC}}\left(\frac{I_{thd}}{x} y < P_{max}\right) = \int_{\frac{I_{thd}}{P_{max}} y}^{x=\infty} \int_{y=0}^{\frac{P_{max}}{I_{thd}} x} f_{X,Y}(x, y) \, dy \, dx, \tag{18}$$

$$P_{h_{max}^{CC}}\left(\frac{I_{thd}}{x} y < P_{max}\right) = \int_{\frac{I_{thd}}{P_{max}} y}^{x=\infty} \int_{y=0}^{\frac{P_{max}}{I_{thd}} x} \delta_x \, \delta_y \, \exp\left(-\left(x\delta_x + y\delta_y\right)\right) dy \, dx. \tag{19}$$

The average probability of DT is expressed as (see appendix I)

$$P_{h_{max}^{CC}}^{av}(P_{max}) = 1 - \left(\frac{\sigma_{sp}^2}{\sigma_{sr}^2} \, \frac{I_{thd}}{P_{max}} + 1\right)^{-1} \left(\frac{\sigma_{rp}^2}{\sigma_{rd}^2} \, \frac{I_{thd}}{P_{max}} + 1\right)^{-1} \tag{20}$$

Then the average BE under interference and power constraint is expressed as

$$BE_{RARQ}^{av,CC} = 1 - 0.5\left(\left(\frac{\sigma_{sp}^{2}}{\sigma_{sr}^{2}}\,\frac{I_{thd}}{P_{max}} + 1\right)^{-1}\left(\frac{\sigma_{rp}^{2}}{\sigma_{rd}^{2}}\,\frac{I_{thd}}{P_{max}} + 1\right)^{-1}\right) \tag{21}$$

The expression of the average BE under interference and power constraints given in eq.21 that is completely different from the expression given in eq.15. The average BE of CCN is governed by channel gains of the $UT - LD$, $UR - LD$ links and $I_{thd}/\,P_{max}$. $BE_{RARQ}^{av,CC}$ approaches to 1 as the I_{thd} approaches to ∞ and P_{max} approaches to 0. Furthermore, $BE_{RARQ}^{av,CC}$ approaches to 0.5 as the I_{thd} approaches to 0 and P_{max} approaches to ∞. **Table 2** gives the description of the RARQ method in underlay CCN under interference and power constraints. The $BE_{RARQ}^{av,CC}$ is summarized in two scenarios,

Scenario 1: it is a situation that the UT and UR are located close to LD. The transmission power of UT (P_{UT}) towards the UR and the transmission power of UR (P_{UR}) towards the UD should be less than I_{thd} that it results weak signal-to-noise ratios of the $UT - UR$ and $UR - UD$ links and it is increased the probability of DT and the $BE_{RARQ}^{av,CC}$ increased.

Scenario 2: it is a situation that the UT and UR are located faraway to LD. The transmission power of UT towards UR and the transmission power of UR towards the UD will not be limited by I_{th}, and this results a better signal-to-noise ratio of the $UT - UR$ and $UR - UD$ links, and it is reduced the probability of DT and the $BE_{RARQ}^{av,CC}$ minimized.

Table 2. RARQ Method Description for CCN

```
Require: $(h_{sr}, h_{rd}, h_{sp}, h_{rp}, I_{thd}, P_{max}\ and\ h_{max}^{CC})$
begin
Collect the channel gains of $h_{sp}$ , $h_{rp}$ and interference threshold $I_{thd}$
Evaluate maximum power such that $P_{max} < I_{thd}$
for each relay node of totally $m$ relays in the secondary cooperative network determine $((I_{thd}/h_{sp}) \times h_{sr})_{max}\ and\ ((I_{thd}/h_{rp}) \times h_{rd})_{max}$
    then
determine $h_{max}^{CC}$
endfor
if $h_{max}^{CC} < P_{max}$, then
    destination sends +ACK;
    ( Best relay node keeps silent and dropped what received from the source);
else if $h_{max}^{CC} > P_{max}$, then
    destination sends -ACK;
    (Best relay node sends what received from the source to destination);
endif
```

Proposition: Given the average BE_{RARQ}^{av} for a cooperative network under RARQ, the BE for multiple relay selection (BE_{RARQ}^{M}) for cooperative network can be re-defined as:

$$BE_{RARQ}^{av,M} = \mathbf{1} + \sum_{\boldsymbol{m}=\mathbf{1}}^{\boldsymbol{M}} \binom{\boldsymbol{M}}{\boldsymbol{m}} \frac{(-\mathbf{1})^{\boldsymbol{m}}}{2\,\sigma_{sd}^2} \left(\left(\frac{1}{\sigma_{sr}^2} + \frac{1}{\sigma_{rd}^2} \right) + \frac{1}{\sigma_{sd}^2} \right)^{-m} \tag{22}$$

<u>Proof:</u> where it is assumed for the convenient that all the links have equal gains such that, $h_{r_m d} = h_{rd}$, $h_{sr_m} = h_{sr}$, and $h_{r_m p} = h_{rp}$. By this assumption, the $BE_{RARQ}^{av,M}$ of multiple relays selection can also be defined as follows:

$$P_{h_{max}}^{av}(h_{sd}) = \prod_{\boldsymbol{m}=\mathbf{1}}^{\boldsymbol{M}} \left(1 - \frac{1}{\sigma_{sd}^2} \left(\left(\frac{1}{\sigma_{sr}^2} + \frac{1}{\sigma_{rd}^2} \right) + \frac{1}{\sigma_{sd}^2} \right)^{-1} \right) \tag{23}$$

$$P_{h_{max}}^{av}(h_{sd}) = \left(1 - \frac{1}{\sigma_{sd}^2} \left(\left(\frac{1}{\sigma_{sr}^2} + \frac{1}{\sigma_{rd}^2} \right) + \frac{1}{\sigma_{sd}^2} \right)^{-1} \right)^{\boldsymbol{M}} \tag{24}$$

Then, applying the binomial series $(1-x)^M = 1 + \sum_{m=1}^{M} \binom{M}{m} (-1)^m x^m$ [35, eq. (1.111), p. 25], we obtained eq.22. Now, the same steps can be applied on eq.21 to obtain the BE for multiple relays of CCN ($BE_{RARQ}^{av,CC,M}$) as:

$$BE_{RARQ}^{av,CC,M} = 1 + \frac{1}{2} \sum_{m=1}^{M} \binom{M}{m} (-1)^m \left(\left(\frac{\sigma_{sp}^2}{\sigma_{sr}^2} \frac{I_{thd}}{P_{max}} + 1 \right)^{-1} \left(\frac{\sigma_{rp}^2}{\sigma_{rd}^2} \frac{I_{thd}}{P_{max}} + 1 \right)^{-1} \right)^{m} \tag{25}$$

5. Numerical Results

In this section, we aimed to prove the evaluated analytical results (for the BE performance in underlay CCN under interference and power constraints) of RARQ method over slow Rayleigh fading channels. We used a common model for the path-loss (fading variances), where we set $\sigma_{ij}^2 \propto d_{ij}^{-\rho}$, the d_{ij} is the distance between node i and j , and ρ is the path-loss exponent and it is set to 3. In what follows, we denote the links $UT-UD$, $UT-UR$, $UR-UD$, $UT-LD$ and $UR-LD$ by $d_{sd}, d_{sr}, d_{rd}, d_{sp}$ and d_{rp} ,respectively.

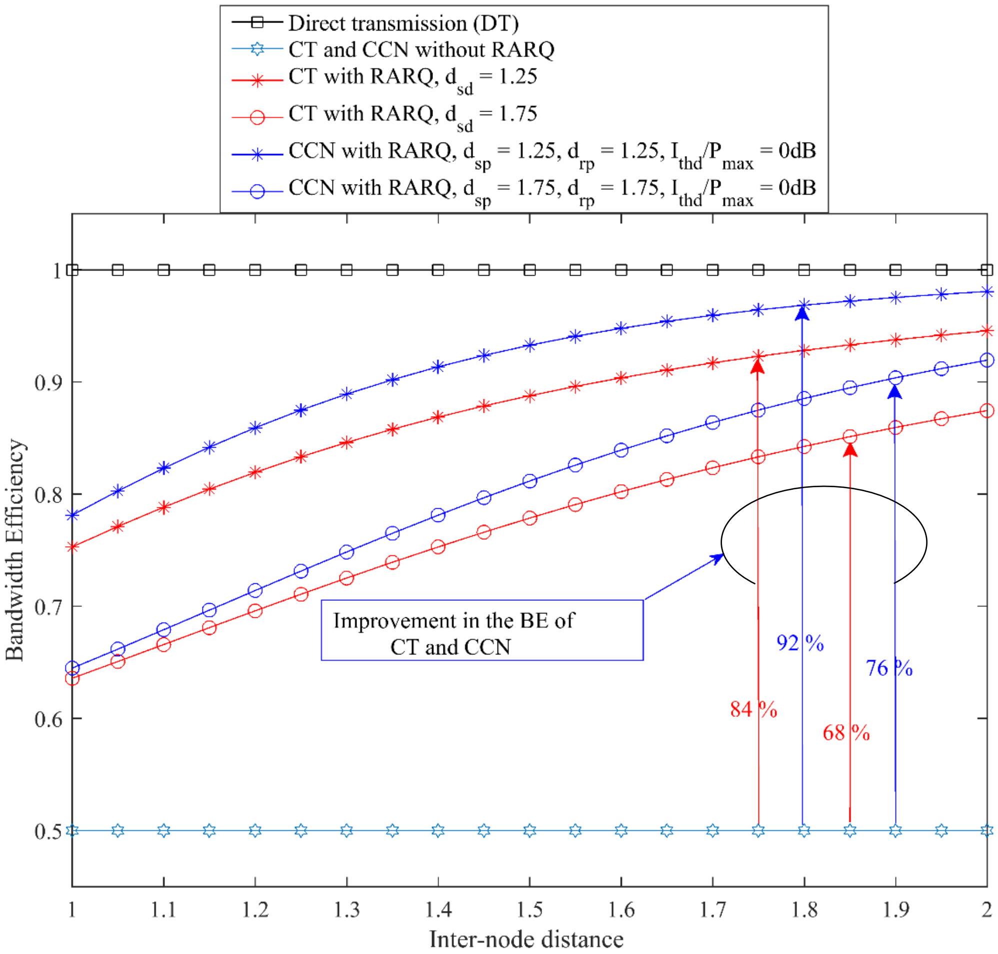


Fig. 2. Comparison of bandwidth efficiencies of CT (with and without RARQ), CCN, and direct transmission with inter-node distances.

Fig. 2 Shows the BE versus inter-node distance. In this figure, the x-axis denoted the distance of $UT-UR$ and $UR-UD$ links, and they are varied from 1 to 2. The important results appeared in the figure are summarized as follows:

1. The BE of the direct transmission is always one that it is because a single time slot or sub-channel required to transmit single data packet.
2. The BE of the CT and CCN is always 0.5, that it is because two time slots or sub-channels are required to transmit a single data packet.
3. The BE of CT with RARQ at small distance of the $UT-UD$ (d_{sd} = 1.25) is better than the BE for large distance of the $UT-UD$ (d_{sd} = 1.75), that is because as the distance of $UT-UD$ link decresed and distance of $UT-UR$ and $UR-UD$ links increased, the probability of direct transmission increased which improved the BE.
4. The BE of the CCN with RARQ is better when unlicensed cooperative network located near to licensed network for fix I_{thd}/P_{max} $(=0dB)$ and at distance of $UT-LD$ (d_{sp} = 1.25) and $UR-LD$ (d_{rp} = 1.25), that is because the direct transmission probability is

increased which consequently increased the BE. The direct transmission probability increased due to transmission power constraint from the UT to UR and from UR to UD.

5. The BEs of the CCN and CT with RARQ are increased as distance between $UT-UR$ and $UR-UD$ links increased.
6. The BE of the CCN and CT with RARQ are better than CT without RARQ.

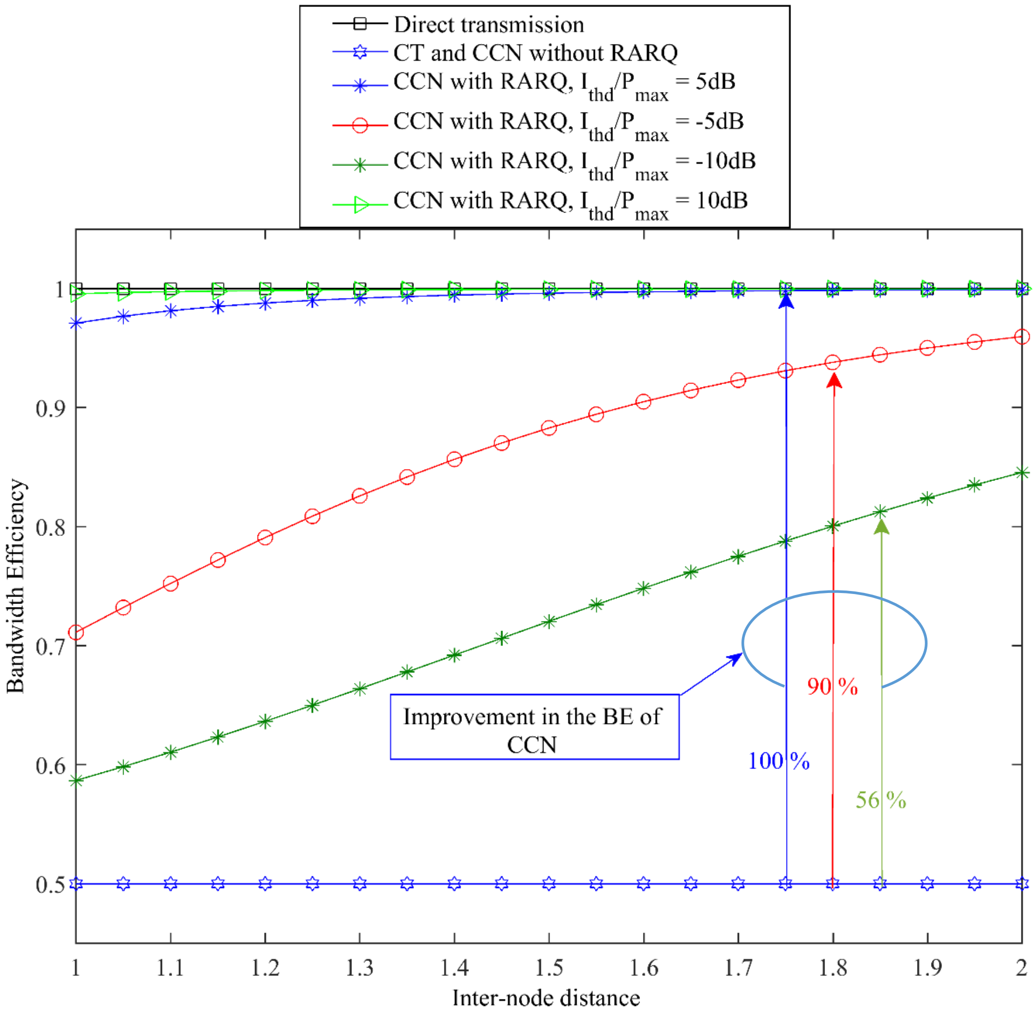


Fig. 3. Comparison of BE of CT (with and without RARQ), CCN, and direct transmission with inter-node distances

Fig. 3 shows the BE versus inter-node distance. In this figure, the x-axis denotes the distance of $UT-UR$ and $UR-UD$ links and they are varied from 1 to 2. Further, we set the $UT-LD$ ($d_{sp}=1$) and $UR-LD$ ($d_{rp}=1$) and they are fix. The important results appeared in the figure are summarized as follows:

1. The BE of direct transmission is one and CCN without RARQ is 0.5.
2. For the large I_{thd}/P_{max} $(=\ 10dB)$, the BE of CCN with RARQ is approached the BE of direct transmission.

3. For low I_{thd}/P_{max} $(= -10dB)$, the BE of cognitive cooperative with RARQ is less compared to low I_{thd}/P_{max} $(= -5dB, 0dB, 5dB$ and $10dB)$.
4. RARQ method achieved better performance compared to traditional CT.

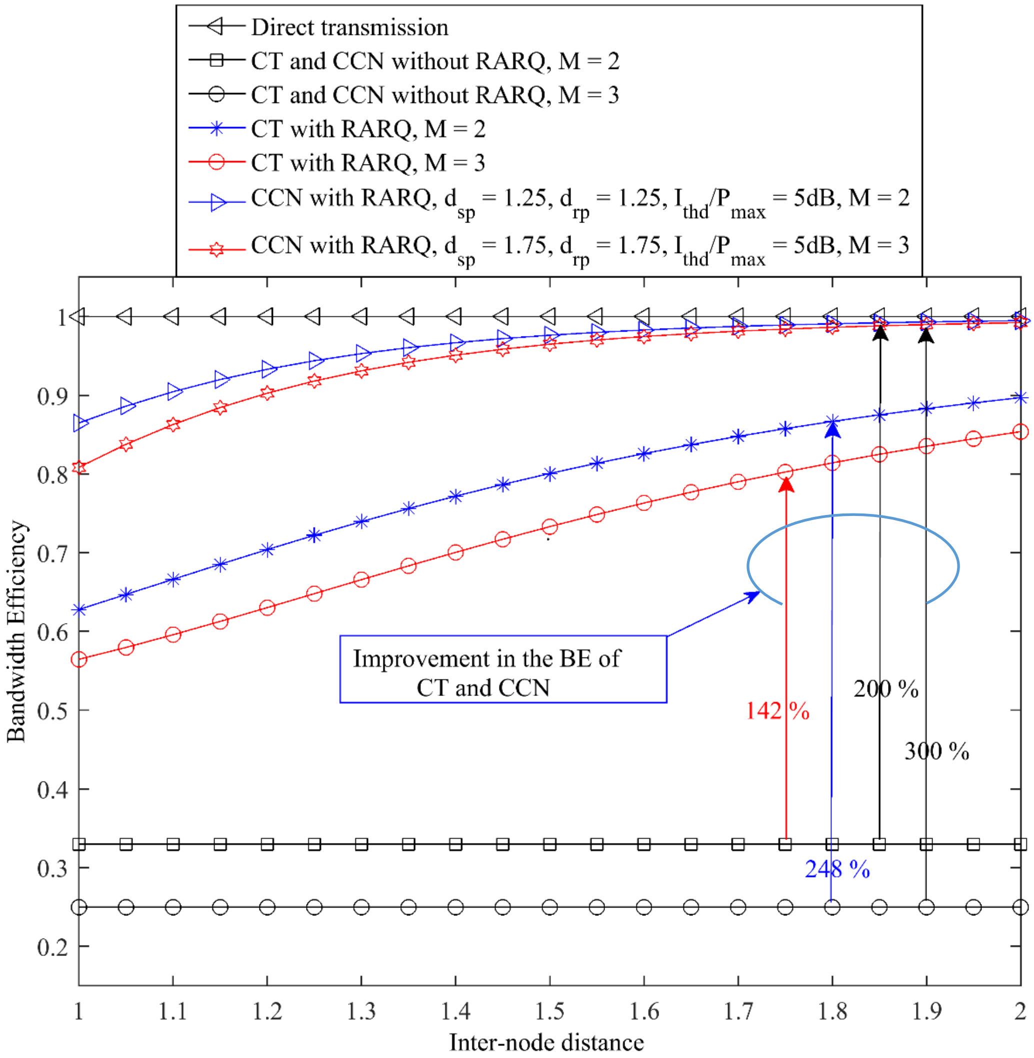


Fig. 4. Comparison of BE of CT (with and without RARQ), CCN, and direct transmission with inter-node distances.

Fig. 4 shows the BE versus inter-node distance. In this figure, the x-axis denoted distance of $UT - UR$ and $UR - UD$ links and they are varied from 1 to 2. Further, we used multiple relays to help UT. The important results appeared in the figure are summarized as follows:

1. The BE of the CT for $M = 2$ is 0.33, because we used two time slots or sub-channels for relaying the data packet pulse signal time slots or sub channels for direct transmission, thus the BE = $1/(1 + 2) = 0.33$.
2. BE for $M = 3$ is 0.25, that is because, we used three time slots or sub-channels for relaying the data packet pulse signal time slots or sub-channels for direct transmission, thus BE = $1/(1 + 3) = 0.25$.

3. For large M, the BE of CT and CCN with RARQ are low.
4. If the unlicensed network located near or far from licensed users and for large I_{thd}/P_{max} $(= 5dB)$, the BE of CCN with RARQ is better than BE of CT for $M = 2$ and $M = 3$.
5. RARQ method achieved better performance compared to traditional CT for multiple relays.

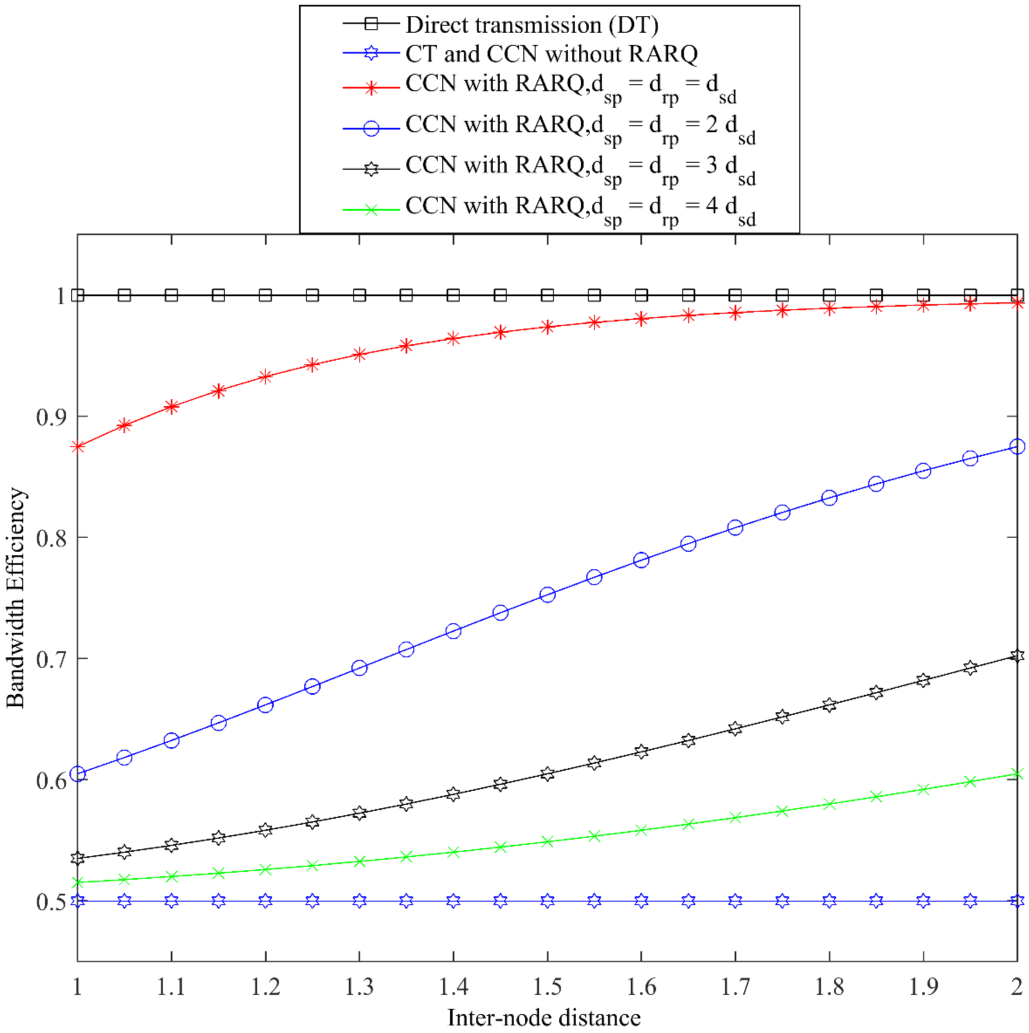


Fig. 5. Comparison of BE of CT without RARQ, CCN, and direct transmission with inter-node distances.

Fig. 5 shows the BE versus inter-node distance. In this figure, the x-axis denoted distance of $UT - UR$ and $UR - UD$ links and they are varied from 1 to 2. In this figure, the distance of the $UT - UD$ is set to 2 and $I_{thd}/P_{max} = 0dB$. For the CCN, we have increased the distance of the $UT - LD$ and $UR - LD$ links gradually from 1 times to four time. As we can see, the BE of the CCN is reduced as the distance of the interfere links, $UT - LD$ and $UR - LD$ links. That is because, as the distance of the $UT - LD$ and $UR - LD$ links increases, the probability of the cooperative increase as well which result reducation in the BE.

6. Conclusion

This work analyzed and improved the BE of underlay CCN under interference and power constraints using proposed reactive relay selection over slow Rayleigh fading. At first, BE expression for CT with RARQ method is presented. Then, the BE expression for the CCN is presented with RARQ method in the underlay approach. As a result of the work, it is shown that the BE of CCN is directly affected by the gain of $UT - LD$ and $UR - LD$ links. The result showed, as the unlicensed users located far away from the LD, the BE reduced and vice versa. In addition, the BE of CCN is directly affected by the interference threshold, where the result showed, as threshold increased, the BE of CCN increased as well. Furthermore, the BE is also examined under multiple relays scenario, and the results showed that the BE of CCN with RARQ method decreased as the number of relays increased.

In the future, the BE in underlay CCN under interference and power constraints with proposed RARQ and next hop selection can be studied and analyzed.

Conflict of Interests The author declares that there is no conflict of interests regarding the publication of this paper.

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Appendix

In this appendix the probability of direct tansmission of CCN under interference constraint is derived. Let assume $= \sigma_x$, $b = \sigma_y$, $h_{sr} = y$, $h_{sp} = x$, $R_1 = I_{thd}/P_{max}$ and $R_2 = P_{max}/I_{thd}$. Where, R_1 *and* R_2 are real non-negative number. Then, the probability is written as:

$$P_{h_{max}^{CC}}\left(\frac{I_{thd}}{x}y > P_{max}\right) = \int_{R_1 y}^{x=\infty} \int_{y=0}^{R_2 x} f_{X,Y}(x,y)\, dy\, dx \tag{27}$$

$$P_{h_{max}^{CC}}\left(\frac{I_{thd}}{x}y > P_{max}\right) = \int_{R_1 y}^{x=\infty} \int_{y=0}^{R_2 x} a\, b \exp(-(ax+by))\ dy\, dx. \tag{28}$$

Taking intergration with respect to y, we obtain

$$\int_{y=0}^{R_2 x} a\, b \exp\big(-(ax+by)\big)\ dy\ \rightarrow a \exp(-ax) \int_{0}^{R_2 x} b \exp(-by)\, dy \tag{29}$$

This yield to

$$a\exp(-ax)\int_{0}^{R_2x} b\exp(-by)\,dy = a\exp(-ax)\,(1-\exp(-bR_2x)), \tag{30}$$

Inserting the result in ( ), we obtain

$$P_{h_{max}^{CC}}\left(\frac{I_{thd}}{x}y > P_{max}\right) = \int_{R_1\,y}^{x=\infty} a\exp(-ax)\ dx - \int_{R_1\,y}^{x=\infty} \mathrm{a}\exp(-bR_2x-ax)\ dx. \tag{31}$$

We evaluate **<u>first term</u>** of the integral:

$$\int_{R_1\,y}^{x=\infty} a\exp(-ax)\ \ dx \ \ \rightarrow\ \ \exp(-aR_1\,y) \tag{32}$$

We evaluate **<u>2nd term</u>** of the integral :

$$\int_{R_1\,y}^{x=\infty} \mathrm{a}\exp(-x\,(bR_2+a))\ \ dx \tag{33}$$

Let assume $g = a + b\,R_2 \rightarrow a = g - \ b\,R_2$, we obtain

$$\int_{R_1\,y}^{x=\infty} (g-\ b\,R_2)\exp(-x\,g)\ \ dx\ \rightarrow\ \int_{R_1y}^{\infty} (g\exp(-xg\,)-\ b\,R_2\exp(-xg\,))\,dx \tag{34}$$

Then,

$$\int_{R_1y}^{\infty} (g\ exp(-xg\,)-\ b\,R_2\ exp(-xg\,))\ \ dx \rightarrow\ \exp(-gR_1y)\ \ -\ \frac{b\,R_2}{g}\exp(-gR_1y) \tag{35}$$

Hence, using first snd second term of integration, we obtain

$$P_{h_{max}^{CC}}\left(\frac{I_{thd}}{x}y > P_{max}\right) = \exp(-aR_1\,y) - \exp(-gR_1y)\ \ +\ \frac{b\,R_2}{g}\exp(-gR_1y),$$

$$P_{h_{max}^{CC}}\left(\frac{I_{thd}}{x}y > P_{max}\right) = \exp(-aR_1\,y) + \left(\frac{b\,R_2}{g} - 1\right)\exp(-gR_1y) \tag{36}$$

Taking the average with respect to random variable y, we obtain [32,9]

$$\int_{0}^{\infty} P_{h_{max}^{cc}}\left(\frac{I_{thd}}{x}y > P_{max}\right) p(y)dy \tag{37}$$

Where, $p(y)$ is the probability density function, and it is given as

$$p(y) = \frac{1}{\sigma_y}\exp\left(-\frac{1}{\sigma_y}\, y\right) \tag{38}$$

The average probability is given as:

$$P_{h_{max}^{cc}}\left(\frac{I_{thd}}{x}y > P_{max}\right) = \frac{1}{\left(aR_1\,\sigma_y + 1\right)} + \frac{\left(\frac{b\,R_2}{g} - 1\right)}{\left(gR_1\,\sigma_y + 1\right)} \tag{39}$$

Where $\sigma_y = 1/b$, hence

$$P_{h_{max}^{cc}}\left(\frac{I_{thd}}{x}y > P_{max}\right) = \frac{1}{\left(\frac{a\,R_1}{b} + 1\right)} + \frac{\left(\frac{b\,R_2}{g} - 1\right)}{\left(\frac{gR_1}{b} + 1\right)} \tag{40}$$

Let assume $= 1\,/\sigma_w$, $d = 1\,/\sigma_z$,$h_{rd} = z$, $h_{rp} = w$,

$$P_{h_{max}^{cc}}\left(\frac{I_{thd}}{w}z > P_{max}\right) = \frac{1}{\left(\frac{c\,R_1}{d} + 1\right)} + \frac{\left(\frac{d\,R_2}{g^*} - 1\right)}{\left(\frac{g^*R_1}{d} + 1\right)} \tag{41}$$

Where $g^* = c - dR_2$. Therefore,

$$P_{h_{max}^{cc}}^{av}(P_{max}) = 1 - \left(\frac{1}{\left(\frac{a\,R_1}{b} + 1\right)} + \frac{\left(\frac{b\,R_2}{g} - 1\right)}{\left(\frac{gR_1}{b} + 1\right)}\right)\left(\frac{1}{\left(\frac{c\,R_1}{d} + 1\right)} + \frac{\left(\frac{d\,R_2}{g^*} - 1\right)}{\left(\frac{g^*R_1}{d} + 1\right)}\right) \tag{42}$$

Where, for large R_1,

$$\frac{\left(\frac{b\,R_2}{g} - 1\right)}{\left(\frac{gR_1}{b} + 1\right)} \approx \frac{\left(\frac{d\,R_2}{g^*} - 1\right)}{\left(\frac{g^*R_1}{d} + 1\right)} \approx 0 \tag{43}$$

Hence,

$$P_{h_{max}^{cc}}^{av}(P_{max}) = 1 - \left(\frac{\sigma_{sp}^2}{\sigma_{sr}^2}\,\frac{I_{thd}}{P_{max}} + 1\right)^{-1}\left(\frac{\sigma_{rp}^2}{\sigma_{rd}^2}\,\frac{I_{thd}}{P_{max}} + 1\right)^{-1} \tag{44}$$

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