# Performance of an Energy Detector with Generalized Selection Combining for Spectrum Sensing

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**Abstract.** Diversity reception schemes are well-known to have the ability to mitigate the adverse effects of multipath wireless channels. This paper analyzes the performance of an energy detector with generalized selection combining (GSC) over a Rayleigh fading channel and compares the results with those of the conventional diversity combining schemes such as, maximal-ratio combining (MRC) and the selection combining (SC). Novel closed-form expressions have been derived for the average detection probability over the independently, identically distributed (i.i.d) diversity paths. Receiver operating characteristics (ROCs) and average detection probability versus SNR curves have been presented for different scenarios of interest.

**Keywords:** Cognitive radio · Spectrum sensing · Energy detection · Diversity combining · Generalized selection combining

## 1 Introduction

Cognitive radio has been well-recognized to offer smart solutions to meet the increasing bandwidth demands of emerging wireless services and communication devices by utilizing the licensed / license-free radio spectrum. Spectrum sensing is the key technology for the realization of opportunistic spectrum access (OSA), as it enables the secondary users (SUs) to reliably detect the *white spaces* and ensures the effective use of the vacant bands without causing any deleterious effect to the primary incumbent [10]. Among different spectrum sensing methods including energy detection, matched filtering, cyclostationary detector etc., energy detection is the most popular approach owing to the non-coherent structure as well as low computation and implementation cost. However, the performance of energy detector is highly susceptible to the variation of the detection threshold due to noise uncertainty and interference level [5]. The performance of energy detector based spectrum sensing system degrades further in the multipath fading and shadowing scenario.


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Diversity combining schemes are known to have the distinct ability to mitigate the above harmful effects. A detailed analysis of the performance of energy detection based spectrum sensing for diversity reception has been presented in [3], for the composite shadow fading channel ($K$ and $K_G$ channels) where, the MRC based detector has been shown to outperform the SC based detector at the cost of increased system complexity. A moment generating function (MGF) based approach for the performance evaluation of energy detector with diversity reception in generalized fading channels (including $\eta$-$\mu$, $\kappa$-$\mu$, $\alpha$-$\mu$, $K$, $G$ and $K_G$ channels) has been presented in [1], where the authors have analyzed three different diversity combining schemes namely the MRC, the square law combining (SLC) and the square law selection (SLS) receivers, in which the MRC based receiver has been shown to provide the optimal detection.

One major deficiency of the MRC combining scheme is its sensitivity to channel estimation error which tends to be more vulnerable when the instantaneous SNR is low. In addition, the SC scheme makes the use of only one path out of $L$ resolvable multipaths and hence fails to exploit the full diversity offered by the wireless multipath channel. In order to bridge the gap between the two extreme schemes (SC and MRC), the generalized selection combining (GSC) has been suggested [2], which is an adaptive combining scheme that *selects* $L_c$ strongest resolvable paths (in terms of SNR) among the total $L$ available paths and then coherently *combines* these $L_c$ paths using the MRC scheme. The error probability analysis of GSC in different fading channels has received much research interest in the past years [6,7,9], and it has now been well-established as an alternative to both MRC and SC in terms of complexity and performance respectively. To the best of author's knowledge, the performance analysis of GSC in the context of spectrum sensing is still missing in the open literature.

In the present paper, we endeavor to analyze the performance of energy detection based spectrum sensing system using GSC in a Rayleigh fading channel. A closed-form expression for the average detection probability has been derived and the receiver operating characteristic (ROC) has been obtained by evaluating both the integral and the closed form expressions in order to verify the validity of the obtained results.

The rest of the paper is organized as follows: Sect. 2 briefly discusses the system model for energy detection with no diversity and with GSC and gives the tractable solution for the case of GSC. Numerical results have been presented in Sect. 3, followed by conclusions in Sect. 4. Appendix A, B and C are provided at the end of the paper in order to illustrate the derivation of the closed-form expression.

## 2 System Model

The received signal sample at a sensing node can be expressed as:

$$y[n] = \begin{cases} w[n], & H_0 \\ h[n]s[n] + w[n], & H_1 \end{cases} \tag{1}$$

where, $y[n]$, $h[n]$, $s[n]$ and $w[n]$ denote the $n^{\text{th}}$ sample of the signal received, channel fading coefficient, transmitted sample and the zero-mean additive white Gaussian noise (AWGN) with variance $\sigma_w^2$ respectively at the sensing node. $H_0$ and $H_1$ denote the null and the alternate hypotheses respectively, corresponding to the absence and the presence of the primary user (PU). At the sensing node the energy of the received signal is measured for a predefined bandwidth $\Omega$ over a period of time $\tau$, provided $N = \Omega\tau \in \mathbb{Z}^+$, with $\mathbb{Z}^+$ being the set of positive integers. The received energy per sensing event is given as:

$$\Lambda = \sum_{n=0}^{N-1} \left[ |y[n]|^2 \right] \tag{2}$$

The decision rule can be adopted as:

$$\begin{aligned} H_0 &: \Lambda < \lambda \\ H_1 &: \Lambda \geq \lambda \end{aligned} \tag{3}$$

$\Lambda$ is also termed as the *test statistic* for the energy detector and follows a central chi-square distribution with $2N$ degrees of freedom under $H_0$ hypothesis, or a non-central chi-square distribution with $2N$ degrees of freedom under hypothesis $H_1$. $\lambda$ in (3) is the predefined threshold. In order to analyze the performance of the sensing scheme, the probability of false alarm $P_{fa}$ and the probability of detection $P_d$ need to be evaluated. The parameters are defined as:

$$\begin{aligned} P_{fa} &= P\left[H_1|H_0\right] \\ P_d &= P\left[H_1|H_1\right] \end{aligned} \tag{4}$$

where, $P\left[\cdot|\cdot\right]$ denotes the conditional probability.

### 2.1 Energy Detection with No Diversity

For the case of energy detection without any diversity, $P_{fa}$ and $P_d$ are defined as [3]:

$$\begin{aligned} P_{fa} &= \frac{\Gamma\left(N, \lambda/2\right)}{\Gamma(N)} \\ P_d &= Q_N\left(\sqrt{2\gamma}, \sqrt{\lambda}\right) \end{aligned} \tag{5}$$

where, $\Gamma(\cdot)$ is the Gamma function, $\Gamma(s,x) = \int_x^\infty t^{s-1}\exp(-t)dt$ is the upper incomplete Gamma function, $Q_N(\cdot,\cdot)$ is the generalized Marcum-Q function and $\gamma$ is the received SNR for the target signal. The expression for $P_d$ in (5) represents the detection probability for the AWGN case. In the case of fading channel, where the fading coefficient varies, the average detection probability $\overline{P_d}$ is obtained by averaging $P_d(\gamma)$ over the statistics of the instantaneous channel SNR $\gamma$, i.e.,

$$\overline{P_d} = \int_0^\infty P_d(\gamma) f(\gamma) d\gamma \tag{6}$$

where, $f(\gamma)$ is the probability density function (PDF) of the channel SNR, with $\gamma = |h|^2 E_s/\sigma_w^2$ (SNR per received symbol) and $E_s$ being the transmission energy per received symbol.

### 2.2 Energy Detection with GSC

In the case of energy detector with GSC scheme, the energy detector compares the received energy after combining the signals from $L_c$ i.i.d. branches against a predefined threshold [3]. The nominal expressions for the instantaneous $P_{fa}$ and $P_d$ in this case remain the same at the output of GSC as for the AWGN channel as (5). The instantaneous SNR of the combiner output can be expressed as [2, (8)]:

$$\gamma_{\text{GSC}} = \sum_{i=1}^{L_c} \gamma_{i:L} \tag{7}$$

where, $\gamma_{i:L}$ is the instantaneous SNR of the $i^{\text{th}}$ received diversity path and $\gamma_{1:L} \geq \gamma_{2:L} \geq \ldots \geq \gamma_{L:L}$. The nominal expressions for the instantaneous false-alarm and detection probability in this case remain the same at the output of GSC as for the AWGN channel as (5) with $\gamma$ replaced by $\gamma_{\text{GSC}}$. To get the average detection probability for the case of fading channel, $P_d\left(\gamma_{\text{GSC}}\right)$ should be averaged over the statistics of the channel SNR, $\gamma_{\text{GSC}}$. Assuming that $\overline{\gamma}_{1:L} = \overline{\gamma}_{2:L} = \ldots = \overline{\gamma}_{L_c:L} = \overline{\gamma}$, where, $\overline{\gamma}_{i:L}$ is the average SNR of the $i^{\text{th}}$ received branch, the PDF of $\gamma_{\text{GSC}}$ considering the i.i.d. Rayleigh fading diversity channels can be given as [2]:

$$\begin{aligned} f(\gamma_{\text{GSC}}) =& \binom{L}{L_c}\left[\frac{\gamma_{\text{GSC}}^{L_c-1} e^{-\gamma_{\text{GSC}}/\overline{\gamma}}}{\overline{\gamma}^{L_c}(L_c-1)!} + \frac{1}{\overline{\gamma}} \sum_{l=1}^{L-L_c} (-1)^{L_c-l+1} \binom{L-L_c}{l} \left(\frac{L_c}{l}\right)^{L_c-1}\right. \\ & \left. \cdot\, e^{-(\gamma_{\text{GSC}}/\overline{\gamma})} \left( e^{(-l\gamma_{\text{GSC}}/L_c\overline{\gamma})} - \sum_{m=0}^{L_c-2} \frac{1}{m!} \left(\frac{-l\gamma_{\text{GSC}}}{L_c\overline{\gamma}}\right)^m \right)\right] \end{aligned} \tag{8}$$

The average detection probability for the energy detector based spectrum sensing with GSC in the fading case is obtained as:

$$\begin{aligned} \overline{P_d^{\text{GSC}}} =& \int_0^\infty P_d(\gamma_{\text{GSC}}) f(\gamma_{\text{GSC}}) d\gamma_{\text{GSC}} \\ =& A_1 + A_2 + A_3 \end{aligned} \tag{9}$$

where,

$$A_1 = \int_0^\infty Q_N\left(\sqrt{2\gamma_{\text{GSC}}}, \sqrt{\lambda}\right) \binom{L}{L_c} \frac{\gamma_{\text{GSC}}^{L_c-1} e^{-\gamma_{\text{GSC}}/\overline{\gamma}}}{\overline{\gamma}^{L_c}(L_c-1)!} d\gamma_{\text{GSC}} \tag{10}$$

$$\begin{aligned} A_2 = \int_0^\infty Q_N\left(\sqrt{2\gamma_{\text{GSC}}}, \sqrt{\lambda}\right) \binom{L}{L_c} \frac{1}{\overline{\gamma}} \sum_{l=1}^{L-L_c} (-1)^{L_c-l+1} \binom{L-L_c}{l} \left(\frac{L_c}{l}\right)^{L_c-1} \\ \cdot\, e^{-(\gamma_{\text{GSC}}/\overline{\gamma})} e^{(-l\gamma_{\text{GSC}}/L_c\overline{\gamma})} d\gamma_{\text{GSC}} \end{aligned} \tag{11}$$

$$\begin{aligned} A_3 = -\int_0^\infty Q_N\left(\sqrt{2\gamma_{\text{GSC}}}, \sqrt{\lambda}\right) \binom{L}{L_c} \frac{1}{\overline{\gamma}} \sum_{l=1}^{L-L_c} (-1)^{L_c-l+1} \binom{L-L_c}{l} \left(\frac{L_c}{l}\right)^{L_c-1} \\ \cdot\, e^{-(\gamma_{\text{GSC}}/\overline{\gamma})} \sum_{m=0}^{L_c-2} \frac{1}{m!} \left(\frac{-l\gamma_{\text{GSC}}}{L_c\overline{\gamma}}\right)^m d\gamma_{\text{GSC}} \end{aligned} \tag{12}$$

Exact infinite series for (10) was proposed in [4, (9)], which does not qualify the conditions for a tractable solution. In the present paper, we derive the closed form solutions for $A_1, A_2$ and $A_3$. With the aid of Appendix A, the solution for (10) can be derived as:

$$A_1 = 2\binom{L}{L_c}\frac{1}{\overline{\gamma}^{L_c}(L_c-1)!}\left[G_{N-1}+\frac{\Gamma(L_c)\left(\frac{\lambda}{2}\right)^{N-1}\exp\left(-\frac{\lambda}{2}\right)}{2(N-1)!\left(1+\frac{1}{\overline{\gamma}}\right)^{L_c}}\right. \\ \left. {}_1F_1\left(L_c; N; \frac{\lambda}{2}\frac{\overline{\gamma}}{1+\overline{\gamma}}\right)\right] \tag{13}$$

where, ${}_1F_1(\cdot)$ is the confluent hypergeometric function. The solution for (11) is obtained as [see Appendix B]:

$$A_2 = 2\binom{L}{L_c}\frac{1}{\overline{\gamma}}\sum_{l=1}^{L-L_c}(-1)^{L_c-l+1}\binom{L-L_c}{l}\left(\frac{L_c}{l}\right)^{L_c-1}\left[D_{N-1}+\right. \\ \left.\frac{(\lambda/2)^{N-1}\exp\left(-\frac{\lambda}{2}\right)}{2(N-1)!\left[\frac{1}{\overline{\gamma}}\left(1+\frac{l}{L_c}\right)+1\right]}\;{}_1F_1\left(1; N; \frac{\lambda}{2}\frac{\overline{\gamma}}{1+\frac{l}{L_c}+\overline{\gamma}}\right)\right] \tag{14}$$

In a similar fashion, the solution for (12) can be derived as [see Appendix C]:

$$A_3 = -2\binom{L}{L_c}\frac{1}{\overline{\gamma}}\sum_{l=1}^{L-L_c}(-1)^{L_c-l+1}\binom{L-L_c}{l}\left(\frac{L_c}{l}\right)^{L_c-1}\sum_{m=0}^{L_c-2}\frac{1}{m!}\left(\frac{-l}{L_c\overline{\gamma}}\right)^{m} \\ \cdot\left[J_{N-1}+\frac{\Gamma(m+1)\left(\frac{\lambda}{2}\right)^{N-1}}{2(N-1)!}\frac{e^{(-\lambda/2)}}{\left(1+\overline{\gamma}^{-1}\right)^{m+1}}\;{}_1F_1\left(m+1; N; \frac{\lambda\overline{\gamma}}{2(1+\overline{\gamma})}\right)\right] \tag{15}$$

## 3 Numerical Results

The performance behavior of the energy detection based spectrum sensing system with the generalized selection combining is presented for different scenarios of interest by depicting the receiver operating characteristics (ROC) and $\overline{P_d^{\mathrm{GSC}}}$ vs. $\overline{\gamma}$ curves.

Figure 1 shows the comparison of ROCs for $L = 4$, $L_c = 3$ and $N = 1$ with different values of $\overline{\gamma}$. For the verification of the derived closed-form expressions, the curves are drawn through integration as well as through the closed form expression. Furthermore, as expected, with the increase in average SNR per branch ($\overline{\gamma}$), the detection probability increases.

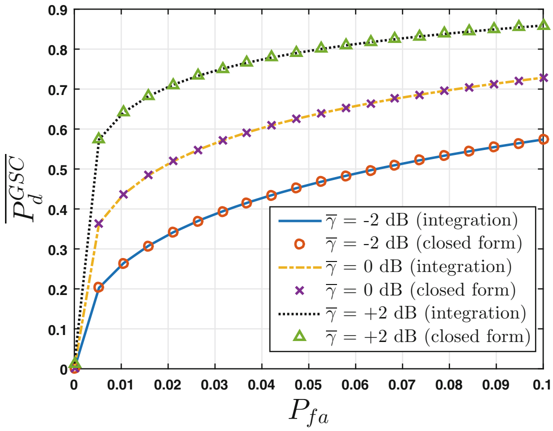


**Fig. 1.** ROCs for $N = 1$, $L = 4$, $L_c = 3$ and different values of $\overline{\gamma}$.

Figure 2 shows the effect of the chosen value of $L_c$ on the overall detection performance. The value of $L$ is taken as 6 and ROC plots have been shown for $L_c$ varying from 1 (i.e., SC) to 6 (i.e., MRC). It is interesting to note that although $L_c = 6$ provides the best detection performance, the degradation in the performance with $L_c = 5$ as compared to the case $L_c = 6$ is almost negligible.

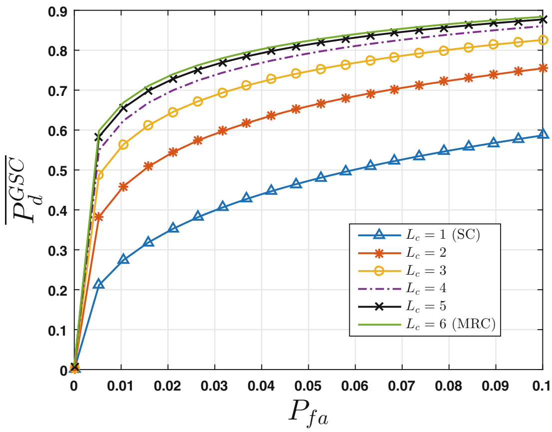


**Fig. 2.** ROCs for $N = 1$, $L = 6$, $\overline{\gamma} = 0$ dB and different values of $L_c$.

In Fig. 3, the variation of the detection probability versus the average SNR $\overline{\gamma}$ has been shown for three different values of target false alarm probability 0.01, 0.05 and 0.1.

Figure 4 shows the variation of the detection probability versus the average SNR for $L = 6$ and for different values of $L_c$ varying from 1 to 6. It is important

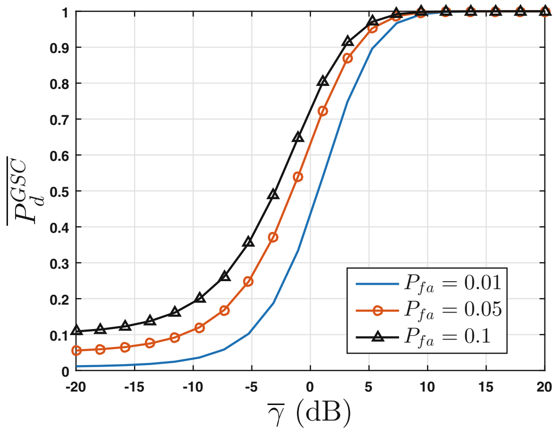


**Fig. 3.** Variation of detection probability versus $\overline{\gamma}$ with $N = 1$, $L = 4$ and $L_c = 3$.

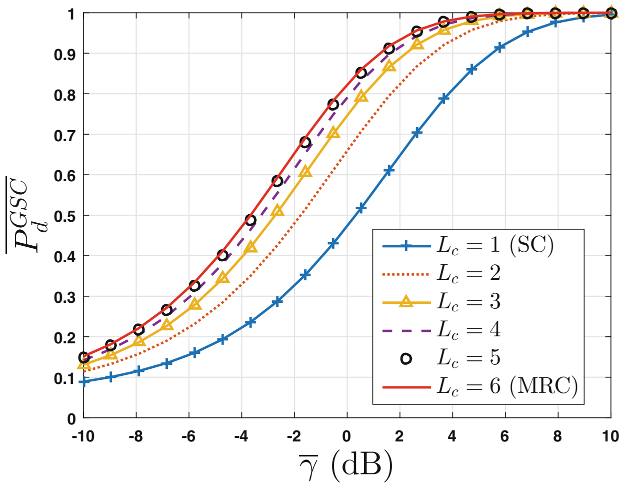


**Fig. 4.** Variation of detection probability versus $\overline{\gamma}$ with $N = 1$, $L = 6$ and $P_{fa} = 0.05$.

to note that for a lower value of the target $P_{fa}$ (0.05 for the case), the detection performance for $L_c = 5$ and 6 are almost identical.

## 4 Conclusions

We study the performance of energy detector with generalized selection combining under the Rayleigh fading channel. Novel closed-form expressions are derived for the average detection probability. Numerical evaluation both through integration and the closed-form expression have been provided to validate the expected accuracy of the expression and to illustrate the behavior of the energy detector with GSC. The results confirm that the GSC receivers perform very well as compared to the MRC receivers for spectrum sensing, with a reasonable value of $L_c$ and the associated reduction in system complexity.

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# A Appendix

### Evaluation of $A_1$ in (10)

Using [8, (5)], $A_1$ can be written as:

$$A_1 = \binom{L}{L_c} \frac{1}{\overline{\gamma}^{L_c}(L_c-1)!} \int_0^\infty \left[1 - \exp\left(-\frac{2\gamma_{\text{GSC}}+\lambda}{2}\right) \sum_{n=N}^{\infty} \left(\frac{\sqrt{\lambda}}{\sqrt{2\gamma_{\text{GSC}}}}\right)^n \cdot I_n\left(\sqrt{2\gamma_{\text{GSC}}\lambda}\right)\right] \gamma_{\text{GSC}}^{L_c-1} \exp\left(-\frac{\gamma_{\text{GSC}}}{\overline{\gamma}}\right) d\gamma_{\text{GSC}} \quad (16)$$

where, $I_n(\cdot)$ is the modified Bessel function of order $n$. Using transformation and change of variable, (16) can be written as:

$$\begin{aligned} A_1 =& 2\binom{L}{L_c} \frac{1}{\overline{\gamma}^{L_c}(L_c-1)!} \int_0^\infty Q_N\left(\sqrt{2}\gamma_{\text{GSC}}, \sqrt{\lambda}\right) \gamma_{\text{GSC}}^{(2L_c-1)} \exp\left(-\frac{\gamma_{\text{GSC}}^2}{\overline{\gamma}}\right) d\gamma_{\text{GSC}} \\ =& 2\binom{L}{L_c} \frac{1}{\overline{\gamma}^{L_c}(L_c-1)!} \cdot G_N \end{aligned} \quad (17)$$

From [8, (29)], the above equation becomes equal to (13) where, $G_1$ can be defined as [8, (25)]:

$$G_1 = \frac{2^{L_c-1}(L_c-1)!}{(2/\overline{\gamma})^{L_c}} \left(\frac{\overline{\gamma}}{1+\overline{\gamma}}\right) \exp\left(-\frac{\lambda}{2(1+\overline{\gamma})}\right) \sum_{k=0}^{L_c-1} \epsilon_k \left(\frac{1}{1+\overline{\gamma}}\right)^k \cdot L_k\left(-\frac{\lambda\overline{\gamma}}{2(1+\overline{\gamma})}\right) \quad (18)$$

where,

$$\epsilon_k \equiv \begin{cases} 1; & k < L_c - 1 \\ 1 + \frac{1}{\overline{\gamma}}; & k = L_c - 1 \end{cases} \quad (19)$$

and $L_k(\cdot)$ is the Laguerre polynomial of degree $k$.

# B Appendix

### Evaluation of $A_2$ in (11)

From (11), $A_2$ can be given as:

$$\begin{aligned}
A_2 =& \binom{L}{L_c}\frac{1}{\overline{\gamma}}\sum_{l=1}^{L-L_c}(-1)^{L_c-l+1}\binom{L-L_c}{l}\left(\frac{L_c}{l}\right)^{L_c-1}\int_0^\infty\left[1-\exp\left(-\frac{2\gamma_{\text{GSC}}+\lambda}{2}\right)\right.\\
&\left.\cdot\sum_{n=N}^{\infty}\left(\frac{\sqrt{\lambda}}{\sqrt{2\gamma}}\right)^n I_n\left(\sqrt{2\gamma_{\text{GSC}}\lambda}\right)\right]\exp\left[-\frac{\gamma_{\text{GSC}}}{\overline{\gamma}}\left(1+\frac{l}{L_c}\right)\right]d\gamma_{\text{GSC}}\\
=&2\binom{L}{L_c}\frac{1}{\overline{\gamma}}\sum_{l=1}^{L-L_c}(-1)^{L_c-l+1}\binom{L-L_c}{l}\left(\frac{L_c}{l}\right)^{L_c-1}\int_0^\infty Q_N\left(\sqrt{2}\gamma_{\text{GSC}},\sqrt{\lambda}\right)\\
&\cdot\exp\left[-\frac{\gamma_{\text{GSC}}^2}{\overline{\gamma}}\left(1+\frac{l}{L_c}\right)\right]\gamma_{\text{GSC}}d\gamma_{\text{GSC}}\\
=&2\binom{L}{L_c}\frac{1}{\overline{\gamma}}\sum_{l=1}^{L-L_c}(-1)^{L_c-l+1}\binom{L-L_c}{l}\left(\frac{L_c}{l}\right)^{L_c-1}\cdot D_N
\end{aligned}\tag{20}$$

From [8, (29)], the above equation becomes equal to (14) where, $D_1$ can be defined as [8, (25)]:

$$D_1 = \frac{(\overline{\gamma}L_c)^2}{2\,(l+Lc)\,(l+L_c+\overline{\gamma}L_c)}\exp\left(-\frac{\lambda\,(l+L_c)}{2\,(l+L_c+\overline{\gamma}L_c)}\right)\cdot\left[\left(1+\frac{l+L_c}{\overline{\gamma}L_c}\right)\right]\tag{21}$$

In the above equation, it is important to note that the value of Laguerre polynomial for order 0 becomes 1.

# C Appendix

### Evaluation of $A_3$ in (12)

Following the same analogy as in Appendix A, (12) can be written as:

$$\begin{aligned}
A_3 =& -2\binom{L}{L_c}\frac{1}{\overline{\gamma}}\sum_{l=1}^{L-L_c}(-1)^{L_c-l+1}\binom{L-L_c}{l}\left(\frac{L_c}{l}\right)^{L_c-1}\cdot\sum_{m=0}^{L_c-2}\frac{1}{m!}\left(\frac{-l}{L_c\overline{\gamma}}\right)^m\\
&\cdot\int_0^\infty Q_N\left(\sqrt{2}\gamma_{\text{GSC}},\sqrt{\lambda}\right)\exp\left(-\gamma_{\text{GSC}}^2/\overline{\gamma}\right)\gamma_{\text{GSC}}^{2m+1}d\gamma_{\text{GSC}}\\
=& -2\binom{L}{L_c}\frac{1}{\overline{\gamma}}\sum_{l=1}^{L-L_c}(-1)^{L_c-l+1}\binom{L-L_c}{l}\left(\frac{L_c}{l}\right)^{L_c-1}\cdot\sum_{m=0}^{L_c-2}\frac{1}{m!}\left(\frac{-l}{L_c\overline{\gamma}}\right)^m\cdot J_N
\end{aligned}\tag{22}$$

From [8, (29)], the above equation becomes equal to (15) where, $J_1$ can be defined as [8, (25)]:

$$J_1 = \frac{2^m m!}{(2/\overline{\gamma})^{(m+1)}} \frac{\overline{\gamma}}{1+\overline{\gamma}} \exp\left(-\frac{\lambda}{2(1+\overline{\gamma})}\right) \sum_{k=0}^{m} \phi_k \left(\frac{1}{1+\overline{\gamma}}\right)^k L_k \left(-\frac{\lambda\overline{\gamma}}{2(1+\overline{\gamma})}\right) \tag{23}$$

where,

$$\phi_k \equiv \begin{cases} 1; & k < m \\ 1 + \frac{1}{\overline{\gamma}}; & k = m \end{cases} \tag{24}$$

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