Latency-Reliability Analysis for Multi-antenna System (Workshop)

Zhichao Xiu(✉), Hang Long, and Yixiao Li

Wireless Signal Processing and Network Lab, Key Laboratory of Universal Wireless Communication, Ministry of Education, Beijing University of Posts and Telecommunications, Beijing, China
xiuzhichao@bupt.edu.cn

Abstract. The relationship between the latency and reliability of multi-antenna diversity system is investigated in this paper. The system performance of diversity system is analysed with the outage probability chosen as the reliability metric. Two combining techniques are considered in the diversity system. It is proved that the latency-reliability trade-off degree (LRTD), i.e., the slope of the latency-outage curves with logarithmic scales, equals the number of the diversity order. In addition, the diversity system with considering system overhead is investigated. Golden section search algorithm and a simplified iterative method can be used to obtain the optimum diversity order of multiple-input and single-output (MISO) system adopted with maximal ratio combining and section combining techniques, respectively.

Keywords: Latency-reliability trade-off degree · Multi-antenna · Overhead

1 Introduction

In the emerging fifth wireless communication systems, there are several crucial performance requirements and targets including the data rate, the number of connected devices, device battery life, end-to-end latency, and reliability of communication [1]. The use case with low latency and high reliability is a very important application scenario [2]. For example, in vehicular network applications, data transmission latency below 5 ms and very high reliability of packet error rations $< 10^{-6}$ are expected [2]. Other application scenarios of low-latency and high-reliability communications include future factory applications, distributed utility grid protection, autonomous driving and so on [3].

Some solutions are proposed to meet the low latency target such as: employing shorter transmission time interval (TTI), cooperative communications, and massive multiple-input multiple-output (MIMO) [1]. Simultaneously, in-depth

Supported by China Unicom Network Technology Research Institute and project 61302088 which was supported by National Natural Science Foundation of China.

© ICST Institute for Computer Sciences, Social Informatics and Telecommunications Engineering 2020
Published by Springer Nature Switzerland AG 2020. All Rights Reserved
H. Gao et al. (Eds.): ChinaCom 2019, LNICST 313, pp. 364–377, 2020.
https://doi.org/10.1007/978-3-030-41117-6_30

theoretical analyses among the solutions for low-latency and high-reliability communications are necessary. In [4], the fundamental trade-off between the outage capacity, system bandwidth, and the latency requirement for ultra-reliable and low-latency systems is demonstrated by system-level simulations. In [5], the relationship among reliability, throughput, and given latency requirement is shown. Given the existing studies in the literature, a generalized analysis on the relationship among latency, reliability and other performance metrics is much needed.

The relay technique has been used to meet the reliability and latency requirements. Cooperative communication based relaying schemes are discussed in [6], which can provide ultra-high reliability while meeting the latency requirement at moderate SNR. The low-latency and high-reliability communications in multi-relay systems have been considered, and a new metric termed latency-reliability trade-off degree (LRTD) is proposed in [7], which can also be analysed in other communication systems.

At the same time, diversity technique can also be used for low-latency and high-reliability communications. The ultra-reliable and low-latency communication can be supported through high diversity, transmission with shared diversity resources is proposed in [8]. Diversity technique can result in significant increase in system performance. Simultaneously, more system elements are cost for system overhead [5], which is important and not ignorable in low-latency frame structures. The reliability constraints on control information are studied in [9], and some enhancement techniques are proposed. Reference [10] characterizes the trade-off between the training sequence length and data code length. It is important to consider the system overhead in the low-latency and high-reliability communications.

In this study, the relationship between latency and reliability in multi-antenna diversity systems is analysed. The relationship between latency and reliability has been investigated in [7]. For spatial diversity systems, the slope of the logarithmic scaled latency-reliability curve in diversity systems is proven to be equivalent to the number of diversity order. In addition, the system overhead is considered. In the multi-antenna diversity system with overhead, the reliability increases because of the diversity gain at first, and decreases at last because of the system overhead. With considering the system overhead, the optimum number of diversity number is investigated. Golden section search algorithm is used to find the optimum diversity order for the multiple-input and single-output (MISO) system adopted with maximal ratio combining. A simple iterative method is used for the MISO system adopted with selection combining.

The remainder of this paper is organized as follows. In Sect. 2, the relationship between latency and reliability of spatial diversity system is analysed. Section 3 investigates the optimum number of diversity order for MISO system, where the system overhead is considered. Section 4 concludes this study.

2 Latency-Reliability Analysis of Diversity System

To improve the performance of the communication systems, we consider the adoption of diversity technique. There are several diversity techniques can be applied to wireless communication systems. In time diversity, the same data is transmitted at different time slots, which is difficult to achieve in low latency scenario. The channel gain in frequency diversity is related to the bandwidth and transmitted signal. In this paper, we focus on spatial diversity when describing diversity systems and the different combing techniques.

Multiple antennas can be installed at the transmitter or/and at the receiver to achieve spatial diversity. In spatial diversity at the receive side, the receiver is employed with multiple antennas. Consider a single-input and multiple-output (SIMO) system, the multiple received signals can be combined by maximum ratio combining (MRC), selection combing (SC), or equal gain combing (EGC) [11].

For transmit diversity, consider a MISO system. Under the assumption that the channel state information (CSI) is available to both the transmitter and receiver, the transmit diversity design is quite similar to receive diversity with MRC. The detailed analysis of maximum ratio transmission (MRT) scheme has been presented in [12]. Similarly, the analysis for SC under transmit diversity is the same as under receiver diversity. That is to say, the system performance analyses of SIMO and MISO systems can be described by the same formulas.

In this section, latency-reliability analyses of diversity systems are investigated, while MRC and SC combining techniques are applied respectively. In diversity systems, the fading paths are assumed to be independent and identical distributed (i.i.d.) Rayleigh fading channels.

Similar to the system model described in [7], the system performance can be analysed as follows. Data packets of length of C bits are transmitted over a system bandwidth of B Hz. The required latency is L in the unit of seconds. The outage probability is chosen as the system reliability metric. The instantaneous received signal-to-noise ratio (SNR) is defined as ρ, which is considered as a variable due to channel fading. According to the Shannon capacity theorem, the system spectral efficiency can be shown as a function of ρ, i.e., $\log_2(1+\rho)$ bits/symbol. In the ideal system without any overhead, the number of time and frequency resource elements of the spatial diversity system is BL. In this section, we take a SIMO system as a reference, which consists of one antenna for transmission and N_R antennas for reception. The system outage probability can be shown as

$$P_{out} = \Pr\left[BL\log_2(1+\rho) < C\right] = \Pr\left[\rho < \rho_{\text{th}}\right], \tag{1}$$

where

$$\rho_{\text{th}} = 2^{\frac{C}{LB}} - 1 \tag{2}$$

is the SNR threshold.

Rayleigh fading is assumed for the multiple wireless channels. Each channel has the same average SNR. As such, the instantaneous SNR ρ_i of each channel is an exponentially distributed variable

$$p(\rho_i) = \frac{1}{\gamma}\mathrm{e}^{-\frac{\rho_i}{\gamma}}, \tag{3}$$

where $\gamma = E(\rho_i)$ is the average SNR. According to the probability density function (PDF) of the instantaneous SNR in (3), the system outage probability in (1) can be attained as

$$P_{out} = \int_0^{\rho_{\text{th}}} p(\rho)\mathrm{d}\rho. \tag{4}$$

The instantaneous received SNR ρ is a function of the multiple SNRs of the independent fading channels, which depends on the combining technique and the number of diversity channels.

2.1 Diversity System with MRC

Considering of combining the multiple receive signals by MRC technique, the received SNR is seen as the sum of the SNR of each antenna as follows [11]

$$\rho = \sum_{i=1}^{N_R} \rho_i, \tag{5}$$

where ρ_i is the received SNR of the i-th antenna. We can rewrite (4), the outage probability of diversity system adopted with MRC technique for any N_R can be obtained as

$$\begin{aligned} P_{out}(N_R) &= \int\limits_{\rho_1+\cdots+\rho_{N_R}<\rho_{\text{th}}} \int \cdots \int p(\rho_1)p(\rho_2)\cdots p(\rho_N)\mathrm{d}\rho_1\mathrm{d}\rho_2\cdots\mathrm{d}\rho_{N_R} \\ &= 1 - \mathrm{e}^{-\frac{\rho_{\text{th}}}{\gamma}} \sum_{i=0}^{N_R-1} \frac{{\rho_{\text{th}}}^i}{i!\gamma^i}. \end{aligned} \tag{6}$$

The outage probability in (6) can also be viewed as a function of latency L. The outage probability results with $N_R = 1, 2, 3$ are plotted against the latency in Fig. 1. The outage probability and the required latency are both plotted with the logarithmic scale. Obviously, the outage probability is a monotonically decreasing function of L. The latency and reliability of a system have their own constraints and cannot be improved simultaneously. Therefore, the latency-reliability trade-off should be analysed. As can be seen from Fig. 1, the curves with different average SNRs are nearly parallel.

As it is well known, the slope of the SNR-outage probability curve amounts to the diversity order, that is,

$$d = -\lim_{\gamma\to\infty} \frac{\log P_{out}}{\log \gamma} = N_R. \tag{7}$$

The relationship between latency and reliability can be derived by analyzing the latency-reliability trade-off degree defined in [7]. Similar to the diversity order, the LRTD can be derived as follows. First, we define

$$f = \frac{\rho_{\text{th}}}{\gamma} = \frac{a^{\frac{1}{L}} - 1}{\gamma}. \tag{8}$$

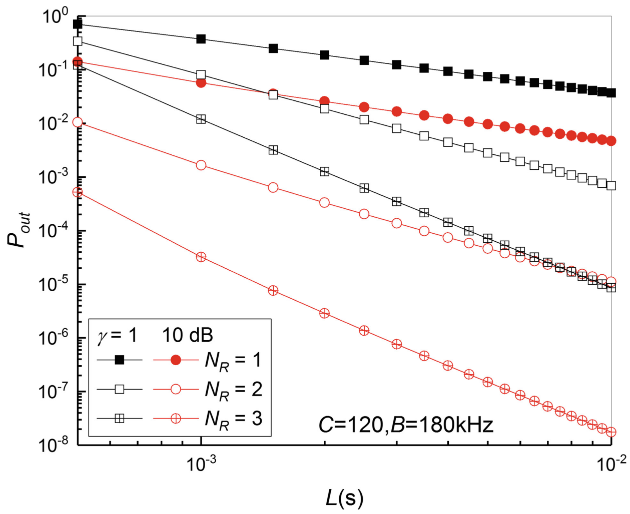


Fig. 1. Outage probability vs. latency with logarithmic scale in a diversity system with MRC

Then we have

$$\begin{aligned} d_{LR} = &\ -\lim_{L\to\infty}\frac{\log P_{out}(N_R)}{\log L} \\ = &\ \lim_{x\to 0}\frac{\log\left(1-\mathrm{e}^{-f}\sum_{i=0}^{N_R-1}\frac{f^i}{i!}\right)}{\log x} \\ = &\ \lim_{x\to 0}\frac{xf'\mathrm{e}^{-f}\frac{f^{N_R-1}}{(N_R-1)!}}{1-\mathrm{e}^{-f}\sum_{i=0}^{N_R-1}\frac{f^i}{i!}} \\ = &\ \lim_{x\to 0}\frac{f'}{(N_R-1)!}\frac{xf^{N_R-1}}{1-\mathrm{e}^{-f}\sum_{i=0}^{N_R-1}\frac{f^i}{i!}} \\ = &\ \lim_{x\to 0}\frac{f'}{(N_R-1)!}\frac{xf^{N_R-2}f'(N_R-1)+f^{N_R-1}}{\mathrm{e}^{-f}\frac{f^{N_R-1}}{(N_R-1)!}f'} \\ = &\ 1+\lim_{x\to 0}\frac{xf'(N_R-1)}{f}=1+N_R-1 \\ = &\ N_R. \end{aligned} \tag{9}$$

As can be seen from (9), the result does not depend on particular values of f. It only requires that

$$\lim_{x\to 0} f = 0, \tag{10}$$

the derivative of f,

$$f' = \frac{\partial f}{\partial x} \tag{11}$$

exits, and

$$\lim_{x \to 0} f' \neq 0. \tag{12}$$

As can be seen in (9), in a diversity system with MRC, the LRTD is the same as the system diversity order, which can also be seen from the slopes of the outage probability-latency curves in Fig. 1.

2.2 Diversity System with SC

Considering of combining the multiple receive signals by SC technique, the diversity antenna with the maximum SNR is chosen to receive the signal as follows

$$i_c = \underset{i \in [1,\, 2,\, ...,\, N_R]}{\arg\ \max} \quad \rho_i, \tag{13}$$

where ρ_i is the received SNR of the i-th antenna. Therefore, the outage probability of the diversity system adopted with SC technique for any N_R can be obtained as

$$\begin{aligned} P_{out}(N_R) &= \Pr\ [\ \max(\rho_i) < \rho_{\text{th}}] \\ &= \Pr\ [\rho_1 < \rho_{\text{th}}, \rho_2 < \rho_{\text{th}},\ \cdots,\ \rho_N < \rho_{\text{th}}]. \end{aligned} \tag{14}$$

For each diversity channel, the outage probability can be derived as

$$P_{out}(1) = \Pr[\rho_i < \rho_{th}] = \int_0^{\rho_{\text{th}}} p(\rho_i)\mathrm{d}\rho_i = 1 - \mathrm{e}^{-\frac{\rho_{\text{th}}}{\gamma}}. \tag{15}$$

The diversity antennas are independent and have the identical distributed channels. Then (14) can be rewritten as

$$P_{out}(N_R) = \prod_{i=1}^{N_R} \Pr\ [\rho_i < \rho_{th}] = [P_{out}(1)]^{N_R}. \tag{16}$$

The outage probability results with $N_R = 1, 2, 3$ are plotted against the latency in Fig. 2. As can be seen, similar to Fig. 1, the curves with different average SNRs are nearly parallel.

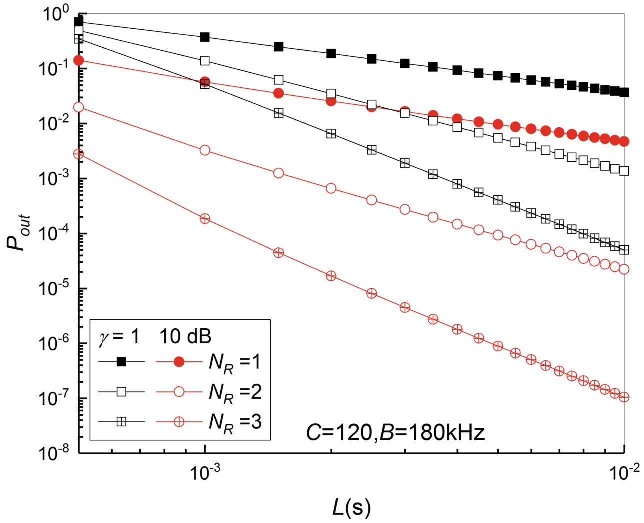


Fig. 2. Outage probability vs. latency with logarithmic scale in a diversity system with SC

Similar to the analysis in (9), we analysis the LRTD with any N_R. We have

$$\begin{aligned} d_{LR} &= -\lim_{L\to\infty}\frac{\log P_{out}(N_R)}{\log L} \\ &= \lim_{x\to 0}\frac{\log P_{out}(N_R)}{\log x} \\ &= \lim_{x\to 0}\frac{xP'_{out}(N_R)}{P_{out}(N_R)} \\ &= 1+\lim_{x\to 0}\frac{xP''_{out}(N_R)}{P'_{out}(N_R)} \\ &= 1+\lim_{x\to 0}(N_R-1)\frac{xP'_{out}(1)}{P_{out}(1)}+\lim_{x\to 0}\frac{xP''_{out}(1)}{P'_{out}(1)} \\ &= 1+N_R-1 \\ &= N_R. \end{aligned} \tag{17}$$

As can be seen in (17), in a diversity system with SC technique, the LRTD is the same as the system diversity order, which can also be seen from the slopes of the outage probability-latency curves in Fig. 2.

In this section, spatial diversity with multiple antennas is applied to the low-latency and high-reliability communications. The latency-reliability trade-off of the diversity system is analysed. The above analysis indicates that the slope of the P_{out}-L curve is the same as the diversity order. That is, the SNR scaling is similar to the latency scaling. The conclusion remains the same when the diversity system is applied with different combining techniques. Therefore, we can replace L with γ in (9) and (17) while the conclusion remains the same. In other words, the latency and reliability can be improved with diversity techniques.

3 System Overhead Analysis in Diversity System

In a diversity system, the SNR received from each diversity channel ρ_{i} should be known at receive or transmit side for the purpose of combining. We can assume that the system overhead ratio of all the resource elements for a reference signal is α. In a SIMO system with one transmitting antenna and N_R receiving antennas, one reference signal is required at the transmit side. Hence, the number of resource elements for overhead is constant. With the diversity antennas increase, the SIMO system performance gets better. However, in a MISO system with N_T transmitting antennas and one receiving antenna, the required reference signals have the linear relation with the number of diversity antennas N_T. That is, when the transmitter is equipped with N_T antennas, the number of resource elements for the overhead is $N_T \alpha BL$, and the number of resource elements left for data transmission is $BL(1 - N_T \alpha)$.

In consideration of the system overhead for reference signals, (2) can be rewritten as

$$\rho_{\mathrm{th}} = 2^{\frac{C}{LB(1-N_T\alpha)}} - 1. \tag{18}$$

As can be seen, ρ_{th} is a monotonically increasing function of N_T in consideration of the overhead, which affects the relationship between latency and reliability as we discuss in more detail as follows.

3.1 MISO System with MRC

Without considering the overhead, as shown in (6), the outage probability of the multi-antenna diversity system with MRC is a monotonically decreasing function of N_T. In the case of considering the overhead, integrating (18) into (6), we have the outage probability of the MISO system with MRC as a function of N_T.

In order to analysis the trend of outage probability with the growth of N_T, we can first analysis how the SNR threshold ρ_{th} affects the outage probability. Using the properties of incomplete gamma function [13], the outage probability in (6) can be written as

$$\begin{aligned} P_{out}(N_T) &= 1 - e^{-\frac{\rho_{\mathrm{th}}}{\gamma}} \sum_{i=0}^{N_T-1} \frac{\left(\frac{\rho_{\mathrm{th}}}{\gamma}\right)^i}{i!} \\ &= \frac{1}{(N_T-1)!} \int_0^{\frac{\rho_{\mathrm{th}}}{\gamma}} t^{N_T-1} e^{-t} dt. \end{aligned} \tag{19}$$

As can be seen from (19), the outage probability of the MISO system is a monotonically increasing function of ρ_{th}. In (18), ρ_{th} is a monotonically increasing function of N_T in consideration of the overhead. Therefore, in the multi-antenna diversity system with overhead, with the increase of N_T, the outage probability will initially decrease due to the diversity gains. Then, too many system resource elements are occupied due to the system overhead. The system outage probability will increase at last. There exists an optimum number of diversity order to achieve the lowest outage probability.

As plotted in Fig. 3 using the parameter $\alpha = 0.05$ [7], the outage probability is a discrete unimodal distribution function of the diversity order N_T, which is in accordance with the previous theoretical derivation. It can be seen from Fig. 3 that the optimum number is $N_T = 9$. We can use greedy search to find the optimum N_T, but the optimum number is very large when α is small.

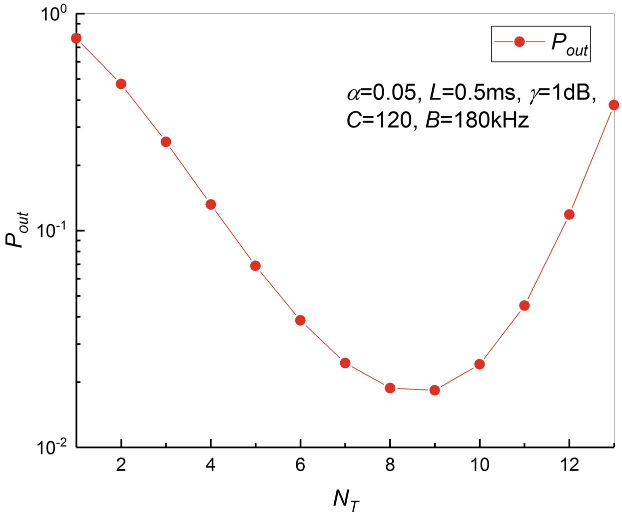


Fig. 3. Outage probability vs. diversity order in the system with MRC

In order to reduce the number of calculations, we propose to use the Golden Section Search (GSS) algorithm for finding the optimum diversity order N_T which leads to the minimum value of P_{out} [14]. Compared with the Binary Search algorithm, the benefit of GSS is that the function value is calculated additionally once more instead of two times at each iteration. GSS is usually adopted for finding the extremum of a unimodal continuous function, but in this problem, P_{out} is a discrete function. The initial search interval of N_T is $[1, \lfloor 1/\alpha \rfloor]$. In the algorithm, the search interval is narrowed down by the golden section ratio $r = 0.618$ after each iteration. The searching process using GSS algorithm is shown in Algorithm 1.

In the GSS algorithm described above, we have $1/r = r/1 - r$ as shown in Fig. 4. Therefore, one new point is selected and one more function value is calculated at each iteration. The number of diversity order N_T is discrete, so that the iteration of the golden section search can terminate when the size of search range is less than or equal to 2, i.e., $b - a \leq 2$. Then, the optimum number is $N_T = \lceil (a + b)/2 \rceil$.

Algorithm 1. GSS algorithm for finding the optimum diversity order N_T

Input: function value P_{out}, parameter α
Output: optimum diversity order N_T

initial $a = 1, b = floor(1/\alpha), r = 0.618, left = 1, right = 1$
repeat
    if $left$ **then**
        $x1 = floor(b - r(b - a)), f1 = P_{out}(x1)$
    end if
    if $right$ **then**
        $x2 = ceil(a + r(b - a)), f2 = P_{out}(x2)$
    end if
    if $f1 > f2$ **then**
        $a = x1, x1 = x2, f1 = f2, left = 0, right = 1$
    else
        $b = x2, x2 = x1, f2 = f1, right = 0, left = 1$
    end if
until $(b - a \leqq 2)$
return N_T= ceil((a + b)/2)

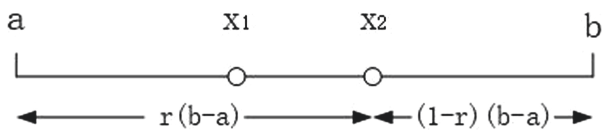
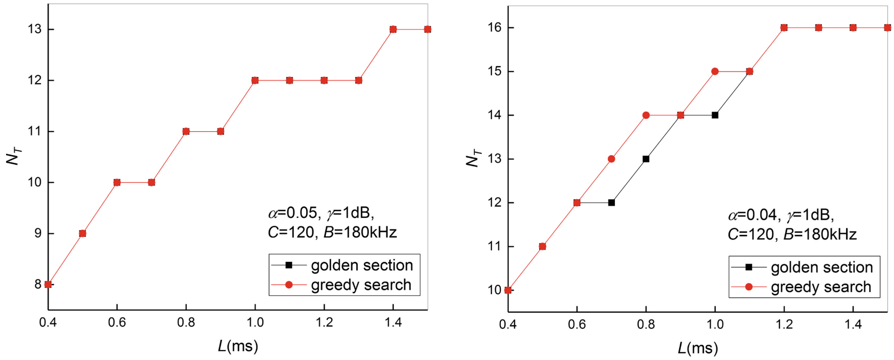


Fig. 4. Division of interval in GSS algorithm

As shown in Fig. 3, when the latency $L = 0.5$ ms, the optimum number of diversity order is $N_T = 9$. Using the GSS algorithm, when $\alpha = 0.05$, the initial search interval is $[1, 20]$, the result is also $N_T = 9$. As shown in Fig. 5(a), when $\alpha = 0.05$, the GSS algorithm gives the same results as greedy search algorithm. When $\alpha = 0.04$, more results are plotted in Fig. 5(b). The reason for calculation error of GSS algorithm is that the outage probability is a discrete unimodal distribution function of the diversity order N_T. At each iteration, the new point selected by golden ratio should be rounded up or down to the nearest integer. The search range cannot be narrowed down any more when $b-a = 1$ *or* 2. Therefore, there could be an error by using GSS algorithm. As shown in Fig. 5(a) and (b), with the increase of L, the optimum number of diversity order N_T increases. Comparing Fig. 5(a) with (b), it can be seen that, with the decrease of α, the optimum N_T increases.

The results of optimum number by using GSS algorithm and greedy search algorithm are compared in Fig. 5(a) and (b). The GSS algorithm gives smaller results of N_T than the greedy search algorithm. The error is less than or equal to 1. Moreover, the GSS algorithm needs less number of calculations than the greedy search algorithm, especially when α is small. Therefore, when the outage probability is a discrete unimodal distribution function of the diversity order, the GSS algorithm can be used to find the optimum diversity order N_T.



(a) with α=0.05 (b) with α=0.04

Fig. 5. Optimum number of diversity order with the GSS and greedy search algorithm

3.2 MISO System with SC

Without considering the overhead, as shown in (16), the outage probability of the multi-antenna diversity system with SC is a monotonically decreasing function of the diversity order. In the case of considering the overhead, integrating (18) into (16), we have the outage probability of the MISO system with SC as a function of N_T.

As can be seen from (15), the outage probability is a monotonically increasing function of ρ_{th}. In (18), ρ_{th} is a monotonically increasing function of N_T in consideration of the systems overhead. Therefore, in the MISO system with SC with overhead, with the increase of N_T, the outage probability of the diversity system will initially decrease due to the diversity gains. Then, because of the overhead, the system outage will increase at last. Therefore, there exist an optimum number of diversity order to achieve the lowest outage probability. The outage probability considered of system overhead with $L = 1\,\text{ms}$ and $\alpha = 0.05$ is plotted as a function of N_T in Fig. 6.

The outage probability of the MISO system with SC is similar to the outage probability of multi-relay system modeled in [7]. To obtain the optimum diversity order, we can use the simplified iterative method proposed in [7], which is much simpler than greedy search method. The optimum number of diversity order can be obtained taking the derivative of the outage probability in (16), then we have

$$P_1 \log P_1 + N \frac{\partial P_1}{\partial N_T} = 0, \tag{20}$$

where $P_1 = P_{out}(1)$. Because that the number of antenna N_T should be an integer, the result should round down to the nearest integer. According to the LRTD analysis in (17), when considering the system overhead, we have an approximate fitting function

$$P_1 \approx \frac{b}{L(1 - N_T \alpha)}, \tag{21}$$

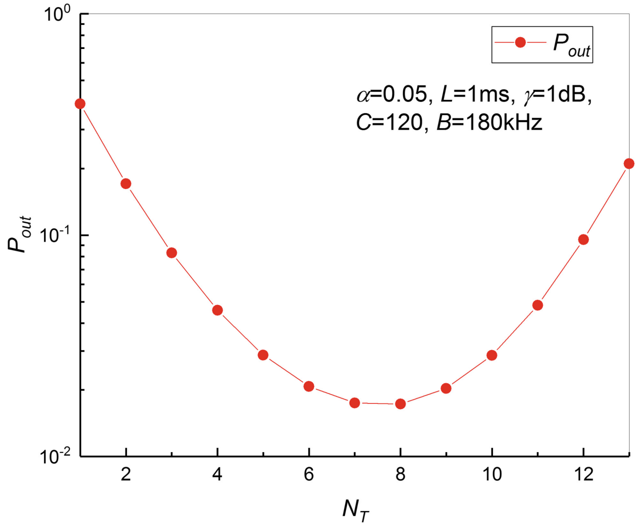


Fig. 6. Outage probability vs. diversity order in the system with SC

where b is a constant, which can be obtained by fitting the outage probability curve indicated by the black square symbol in Fig. 2, $b = 0.0003694$.

Integrating (21) into (20), we have

$$\frac{L}{b}x = e^{(1-x)/x}, \tag{22}$$

where

$$x = 1 - N_T \alpha. \tag{23}$$

Equation (22) can be rewritten as

$$x = \frac{1}{1 + \log\left(\frac{L}{b}x\right)}. \tag{24}$$

It can be proved that the two functions in (22) have a single intersection point in the interval of $x \in [0, 1]$. That is, there is an optimum diversity order.

Therefore, the sole root of (24) can be calculated by the iterative method. The iteration start from $x = 1$. The iteration process to obtain the optimum diversity order N_T is shown in Algorithm 2.

As shown in Fig. 6, the optimum number of diversity order is $N_T = 8$. The simplified iterative method in Algorithm 2 gives the result $N_T = 7$.

The results of optimum number by using simplified iterative method and greedy search method are compared in Fig. 7. The simplified iterative method gives smaller results of N_T than the greedy search method. The error is not large. Simultaneously, the error of the lower bound of the outage probability due to inaccurate N_T is small. The iterative method can be used to find the optimum diversity order N_T with simpler and less calculations.

Algorithm 2. A simplified iterative method for finding the optimum N_T

Input: function parameter α, the required latency L
Output: optimum diversity order N_T

```
initial b = 0.0003694, x = 1, n = 1
while n = 1 or |N − N0| > 0.1 do
    x0 = x
    x = 1/(1 + log(Lx/b))
    N = (1 − x)/α
    N0 = (1 − x0)/α
    n = n + 1
end while
return N_T = floor(N)
```

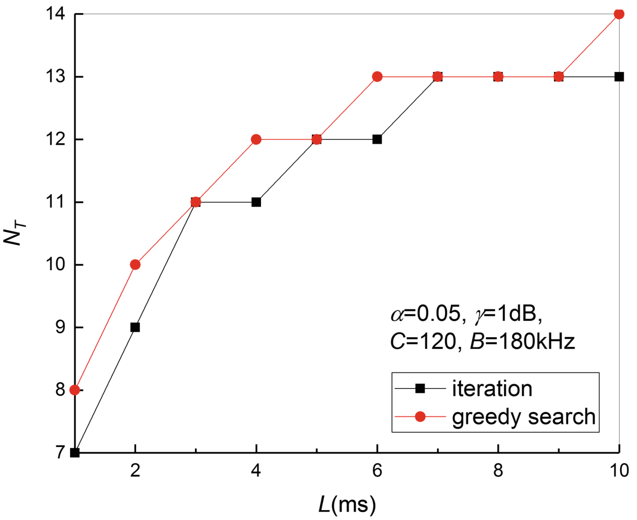


Fig. 7. Optimum number of diversity order with the iteration method and greedy search method with $\alpha = 0.05$

4 Conclusion

In this paper, the relationship between the latency and reliability of diversity system is investigated. Diversity systems adopted with maximal ratio combining and selection combining techniques are analysed respectively. The LRTD is proved to be the same as the number of the diversity order whichever combining technique is adopted. For the MISO system considered of system overhead, the trade-off between diversity gains and the system overhead is analysed. For system with MRC, golden section search algorithm for discrete function is proposed to obtain the optimum number of diversity order. For system with SC, the optimum diversity order is obtained with a simplified iterative method which is much simpler than greedy search method.

References

1. Osseiran, A., Boccardi, F., Braun, V., Kusume, K., Marsch, P., Maternia, M., et al.: Scenarios for 5G mobile and wireless communications: the vision of the metis project. IEEE Commun. Mag. **52**(5), 26–35 (2014)
2. METIS D1.5, Updated scenarios, requirements and KPIs for 5G mobile and wireless system with recommendations for future investigations. ICT-317669-METIS/D1.5, Deliverable D1.5 (2015)
3. Li, Z., Uusitalo, M.A., Shariatmadari, H., Singh, B.: 5G URLLC: design challenges and system concepts. In: 2018 15th International Symposium on Wireless Communication Systems (ISWCS), Lisbon, Portugal, pp. 1–6 (2018)
4. Li, C.-P., Jiang, J., Chen, W., Ji, T., Smee, J.: 5G ultra-reliable and low-latency systems design. In: 2017 European Conference on Networks and Communications (EuCNC), Oulu, Finland, pp. 1–5 (2017)
5. Soret, B., Mogensen, P., Pedersen, K.I., Aguayo-Torres, M.C.: Fundamental tradeoffs among reliability, latency and throughput in cellular networks. In: 2014 IEEE Globecom Workshops (GC Wkshps), Austin, TX, USA, pp. 1391–1396 (2014)
6. Swamy, V.N., Suri, S., Rigge, P., Weiner, M., Ranade, G., Sahai, A., et al.: Cooperative communication for high-reliability low-latency wireless control. In: 2015 IEEE International Conference on Communications (ICC), London, UK, pp. 4380–4386 (2015)
7. Long, H., Xiang, W., Sun, Y.: Low-latency and high-reliability performance analysis of relay systems. IET Commun. **12**(5), 627–633 (2018)
8. Kotaba, R., Navarro Manchón, C., Balercia, T., Popovski, P.: Uplink transmissions in URLLC systems with shared diversity resources. IEEE Wirel. Commun. Lett. **7**(4), 590–593 (2018)
9. Shariatmadari, H., Li, Z., Iraji, S., Uusitalo, M.A., Jäntti, R.: Control channel enhancements for ultra-reliable low-latency communications. In: 2017 IEEE International Conference on Communications Workshops (ICC Workshops), Paris, France, pp. 504–509 (2017)
10. Schiessl, S., Al-Zubaidy, H., Skoglund, M., Gross, J.: Delay performance of wireless communications with imperfect CSI and finite-length coding. IEEE Trans. Commun. **66**(12), 6527–6541 (2018)
11. Aloi, G.: Wireless Communications. Cambridge University Press, Cambridge (2007)
12. Lo, T.K.Y.: Maximum ratio transmission. IEEE Trans. Commun. **47**(10), 1458–1461 (1999)
13. Telatar, E.: Capacity of multi-antenna Gaussian channels. Eur. Trans. Telecommun. **10**(6), 585–595 (1999)
14. Cheney, W., Kincaid, D.: Numerical Mathematics and Computing. Cole Publishing Company, Pacific Grove (2007)