Optimal power allocation for a wireless cooperative network with UAV

Jing Yan [1,2], Xuefeng Deng [2], Jihua Liu [3], Liming Wang [1]

[1] National Key Laboratory of Electronic Test Technology, North University of China, Taiyuan, Shanxi, China

[2] School of Information Science and Engineering, Shanxi Agricultural University, Taigu, Shanxi, China

[3] Department of Computer Science, Luliang University, Lvliang, Shanxi, China

Corresponding Authors:
Jing Yan, Liming Wang
No.3 Xueyuan Road, Taiyuan City, Shanxi Province, 030051, China,
Email address: yanjing_sxau@163.com, wlm@nuc.edu.cn

Abstract

The main objective of this work is to investigate the optimal power allocation strategy in the UAV cooperative wireless Decode and Forward (DF) relay network. Firstly, the outage probability of the system with and without diversity gain is derived. Two optimization problems are studied for different application scenarios. One of the optimization problems aims to find an optimal power allocation strategy in certain total power constrain to minimize the system outage probability. Since the optimization problem we established is convex, the Lagrange multiplier method is adopted. For the system without diversity, the explicit expression of the optimal power allocation is derived. While for the diversity gain system, the relationship between UAV transmission power and source node transmit power is obtained and then the Newton iterative method is used to obtain the optimal power allocation method. The simulation results show that the optimal power allocation strategy can reduce the outage probability of the system under the same conditions, and the reliability of the system is improved meanwhile. Another optimization problem aims to use the lowest power to ensure that the outage probability within a certain specific threshold for saving energy resources. Because the optimization problem is non-convex, we propose an effective method to solve the optimal power allocation strategy. Similarly, we derive the closed-form solution of the power allocation strategy for the system without diversity. Finally, simulation results verify the correctness of the proposed algorithm.

Keyword

Outage probability; power allocation; relay network; UAV

Introduction

The direct link between communication nodes will become unreliable with increasing space distance among nodes due to the influence of the multipath effect and shadow fading of the environment in the wireless network communication. To improve the performance (coverage, throughput, outage probability, and bit error rate) of wireless communication networks (cellular network, WLAN, and WSN), relay cooperative transmission technology has attracted extensive attention(Alemayehu & Kim 2017; Egashira et al. 2017; Indrasen & Pratap 2018; Katla & Babu 2020; Liu et al. 2012; Tutuncuoglu et al. 2015).

With the development of technology and the gradual reduction of manufacturing cost, UAV has gradually developed from the initial military equipment to civil consumer products, resulting in a large number of new applications, including a meteorological monitoring system, forest fire-prevention technology, man-machine field, etc.(Chen 2020; Jiao et al. 2019; Ma et al. 2018) It is generally considered that the introduction of unmanned units to build a new wireless network architecture is the key technology to establish an integrated ubiquitous network in the future. UAVs can be deployed in various environments on a large scale according to the requirement, to reduce the cost of network deployment. In addition, its flexible mobility and reasonable flight path planning can effectively improve the performance of wireless networks. Wireless power supply communication network is considered as a promising future communication network architecture, which can satisfy the energy and communication needs of the nodes in the Internet of things at the same time. Wireless energy transmission technology is one of the research hotspots in wireless energy supply communication networks. The great idea of wireless energy transmission technology has been put forward by a famous electrical engineer Nikola Tesla for a long time. A large number of scientists have studied this subject for over a century, but there has been no major improvement. Notably, the research team of MIT finally made a great breakthrough in wireless energy transmission technology until 2007. They applied the principle of electromagnetic coupling resonance to wireless energy transmission and lit a 60-watt bulb with a power supply two meters away through wireless energy transmission(A et al. 2008; Kurs et al. 2007). The breakthrough of wireless energy transmission technology provides us with a new direction of energy balance strategy, which can realize energy balance through wireless transmission from the nodes with high-energy to low-energy nodes. Establishing UAV assisted wireless energy transmission system which uses UAV as an airmobile energy transmitter to supply power to ground nodes is considered to be an effective solution to improve energy transmission efficiency(Baek et al. 2020; Yuan et al. 2021). The team from Michigan State University has built a UAV wireless energy transmission system to provide wireless energy for sensor nodes successfully (Mittleider et al. 2016). The research shows that the near-field wireless energy transmission based on magnetic resonance coupling(Griffin & Detweiler 2012; Mittleider et al. 2016) and the far-field wireless energy transmission based on RF signal(Baek et al. 2020; Xu et al. 2018) can be used to provide wireless energy for low-power nodes such as sensors. These works further verify the feasibility of UAVs in the application of wireless energy transmission systems. Furthermore, the UAV flight trajectory optimization algorithms in different scenarios are proposed to improve energy transmission

80 efficiency for UAV wireless energy transmission systems (Feng et al. 2020; Yang et al. 2019). The
81 network of a UAV equipped with a directional antenna is studied where two ground nodes are
82 charged through wireless power transmission technology, and the balance between the received
83 energy intensity of the two ground nodes is revealed by optimizing the deployment position of the
84 UAV(Wu et al. 2018).

85   The network where the UAV acts as a relay node has also received wide attention, and the
86 relevant research work mainly on the following aspects: the optimal layout of UAV relay, flight
87 path planning, and network performance analysis(Baek & Lim 2019; Lhazmir et al. 2019; Nguyen
88 et al. 2020). The research on the performance of UAV relay communication systems mainly
89 focuses on the performances, such as bit error rate, receiver signal-to-noise ratio, outage
90 probability, capacity, and so on. Most researchers analyze the performance of relay transmission
91 systems from the perspective of the physical layer(Abualhaol & Matalgah 2011; Jiang &
92 Swindlehurst 2010; Zhan et al. 2011). The features of the link between relay UAV and ground
93 receiver under fading channel is analyzed, and then the analytical expression of performance is
94 deduced. Additionally, the optimization algorithm is proposed for relay UAVs based on a certain
95 performance optimization criterion. During the era of the increasing shortage of natural resources,
96 reducing communication energy consumption has become a key point of the communication
97 industry. In the wireless relay system, the research on power consumption is essential, as the
98 optimal allocation can significantly improve the energy efficiency of the system if the power of
99 each node is limited. A wide range of research work has been conducted on power allocation
100 algorithms to improve the energy efficiency of the wireless communication network. The joint
101 resource allocation problem is investigated in a multicast scenario with simultaneously information
102 decode and energy harvest, where the UAV sends information and wireless energy to multiple
103 users on the ground, and then the user decodes and collects energy based on the power split (PS)
104 receiver structure(Kang & Chun 2020). Zhang et al.(Zhang et al. 2017) considered the network
105 where the UAV is regarded as an AF relay node and optimized the trajectory, transmission power,
106 and mobile device power of the UAV node to minimize the outage probability of the system.

107   Song et al.(Song et al. 2019) studied a full-duplex DF relay system based on UAV and
108 maximizes the instantaneous data rate by jointly optimizing beamforming and power allocation
109 under the constraints of a single power and total power of the source node and the relay node. They
110 proposed an effective algorithm and obtained the suboptimal solution of the problem by
111 decomposing it into two sub-problems based on the block coordinate descent method: the
112 beamforming optimization sub-problem with given power allocation and the power allocation sub-
113 problem with fixed beamforming.

114   To sum up, the network where UAV is only used to supply for the relay with wireless energy
115 transmission technology is not considered in the existing literature aboutthe UAV-assisted relay
116 network. However, it is meaningful for the energy-limited relay network.

117   This paper attempts to optimize power allocation for energy-limited wireless relay networks,
118 in which UAV charges the relay nodes through wireless energy transmission technology. The
119 outage probability with/without diversity is derived. Furthermore, two optimization problems are

120   studied for different application scenarios. The first optimization problem tries to minimize the
121   relay probability of the system when the total power of UAV and source node is certain, to improve
122   the reliability of the system. The second optimization problem considers that on the premise that
123   the system meets a certain transmission rate, the total power consumption is minimized through
124   power optimization to prolong the lifetime of energy-constrained networks. Moreover, simulation
125   verifies the correctness of the theoretical analysis.
126   The structure of this paper is organized as following: Section II introduces the system model
127   of UAV-assisted wireless relay network and obtains the outage probabilities; Section III and
128   Section IV formulate the optimization problem of optimal power allocation to minimize the outage
129   probabilities under different conditions. The theoretical analysis is verified by compared with the
130   simulation results provided in section V; ; The conclusion of the paper is presented in section VI.
131

System Model

133   As shown in Fig. 1, the UAV-assisted energy-constrained wireless relay network is studied in this
134   paper, which consists of a UAV node U, a source node S, an energy-constrained relay node R, and
135   a destination node D. DF protocol is chosen by the relay node R as it outperforms AF protocol.
136   Both systems with and without diversity gain have been studied and the selection combining is
137   picked for the information received at the destination node. The transmit power of the UAV node
138   U, the source node S, and the energy-constrained relay node R are represented by P_U, P_S , and P_R,
139   respectively. The channels between nodes are statistically independent. The terrestrial channels
140   are all Rayleigh channels, subject to frequency flat-fading. The channel gains from the source node
141   to the relay node, between the source node and the destination node, and relay-to-destination are
142   denoted by h_{sr}, h_{sd}, and h_{rd}, respectively. The channel between the UAV node and the relay node
143   is assumed to be the line-of-sight channel.
144   As shown in Figure 2, the whole DF cooperation is divided into three phases. In the first
145   phase, the UAV transmits wireless signals to the relay node within the initial αT time, and the
146   energy-constrained relay node uses wireless energy transmission technology for energy harvesting
147   from the RF signals from UAV. Therefore, the energy collected by the relay node can be denoted
148   by [31]:

$$E_h = \frac{\beta_0}{d_U^2} P_U \eta \alpha T \tag{1}$$

150   where β_0 is the power attenuation factor of the line-of-sight channel; η is the efficiency of energy
151   collection; α is the time fraction of the charging process; d_U is the distance between the UAV
152   and the relay node.
153   In the second phase, the next $(1-\alpha)T/2$ time, the source node broadcasts the RF signal that is
154   needed to send, the relay node and the destination node receive the signal from the source node
155   at the same time, and the signal received at the destination node is:

$$y_{sd}(k) = \frac{1}{\sqrt{d_{SD}}} \sqrt{P_S} h_{sd} s(k) + n_a^{[sd]}(k) + n_c^{[sd]}(k) \tag{2}$$

157   where d_{SD} is the distance of the direct link from the source node to the destination node, n[sd] a(k)
158   is the Gaussian White Noise introduced by the receiving antenna at the destination node in the
159   direct channel, and the variance is $\sigma^2_{n_a^{[sd]}}$, n[sd] c(k) is the Gaussian white noise introduced by the

160   conversion circuit, and the variance is $\sigma^2_{n_c^{[sd]}}$, $s(k)$ is the signal sent by the source node and it is a

161   baseband signal after down-conversion.
162   Meanwhile, the signal received at the relay node is:

$$y_{sr}(k) = \frac{1}{\sqrt{d_{SR}}}\sqrt{P_S}h_{sr}s(k) + n_a^{[sr]}(k) + n_c^{[sr]}(k) \tag{3}$$

164   Where d_{SR} is the distance from the source node to the relay node, n[sr] a(k) is the Gaussian white
165   noise introduced by the receiving antenna at the relay node, and its variance is $\sigma^2_{n_a^{[sr]}}$, n[sr] c(k) is

166   the Gaussian white noise introduced by the conversion circuit at the relay node, and its variance is
167    $\sigma^2_{n_c^{[sr]}}$ 。

168   In the third phase, that is the last $(1-\alpha)T/2$ time, the relay node decodes the received signal
169   and then forwards the information to the destination node with the energy harvested at the first
170   phase. So, the signal received by the destination node can be described as

$$y_{rd}(k) = \frac{1}{\sqrt{d_{RD}}}\sqrt{P_R}h_{rd}s(k) + n_a^{[rd]}(k) + n_c^{[rd]}(k) \tag{4}$$

172   where n[rd] a(k) is the Gaussian White Noise introduced by the receiving antenna, and the variance
173   is $\sigma^2_{n_a^{[rd]}}$. n[rd] c(k) is the noise introduced by the conversion circuit, and the variance is $\sigma^2_{n_c^{[rd]}}$, d_{RD}

174   is the distance between relay node and the destination node.
175   According to formula (2), the instantaneous signal-to-noise ratio at the relay node can be
176   given as

$$\gamma_{SR} = \frac{|h_{sr}|^2 P_S}{d_{SR}\sigma^2_{SR}} \tag{5}$$

178   where $\sigma2$ SR is the total variance of Gaussian White Noise at the relay node and $\sigma^2_{SR} = \sigma^2_{n_a^{[sr]}} + \sigma^2_{n_c^{[sr]}}$.

179   In the direct link, the instantaneous signal-to-noise ratio at the destination node is:

$$\gamma_{SD} = \frac{|h_{sd}|^2 P_S}{d_{SD}\sigma^2_{SD}} \tag{6}$$

181   where, $\sigma2$ SD is the total variance of Gaussian white noise at the destination node in the direct link,
182   and $\sigma^2_{SD} = \sigma^2_{n_a^{[sd]}} + \sigma^2_{n_c^{[sd]}}$.

183   The instantaneous signal-to-noise ratio at the destination node in the two-hop link is:

$$\gamma_{RD} = \frac{2\eta P_U \beta_0 \alpha |h_{rd}|^2}{d_U^2 d_{RD}\sigma^2_{RD}(1-\alpha)} \tag{7}$$

185 where $\sigma 2$ RD is the total variance of Gaussian white noise at the destination node in the two-hop
186 link, $\sigma_{RD}^2 = \sigma_{n_a^{[rd]}}^2 + \sigma_{n_c^{[rd]}}^2$.

187   For the sake of simplicity, it is defined that, $G_0 = \dfrac{E\left[|h_{sd}|^2\right]}{d_{SD}\sigma_{SD}^2}$, $G_1 = \dfrac{E\left[|h_{sr}|^2\right]}{d_{SR}\sigma_{SR}^2}$,

188 $G_2 = \dfrac{2\eta\beta_0\alpha E\left[|h_{rd}|^2\right]}{d_{RD}d_U^2(1-\alpha)\sigma_{RD}^2}$. So $\overline{\gamma_{SD}} = G_0 P_S$, $\overline{\gamma_{SR}} = G_1 P_S$, $\overline{\gamma_{RD}} = G_2 P_U$.

189   In the delay-tolerance system, we have $R=\log_2(1+\gamma_0)$, where R is the fixed transmission rate
190 of the source node, γ_0 is the signal-to-noise ratio threshold for correct decoding at the destination
191 node. Therefore, the outage probability is the probability when the signal-to-noise ratio at the
192 destination node is less than threshold γ_0. The outage probability from S to D in the direct link can
193 be calculated as

$$P_{out1} = 1 - e^{-\frac{\gamma_0}{\gamma_{SD}}} \tag{8}$$

194

195   For a two-hop DF relay network, the outage probability of the system is limited to the one-
196 hop which is with the poor channel quality. If the direct channel is not considered, that is to say,
197 there is no diversity gain, the outage probability at the destination node is

$$P_{out}^{DF} = 1 - e^{-\frac{\gamma_0}{\gamma_{SR}}} e^{-\frac{\gamma_0}{\gamma_{RD}}} \tag{9}$$

198

199   Then, it is obvious that the outage probability of the two-hop relay network with a diversity
200 system can be derived as

$$P_{out2} = \left(1 - e^{-\frac{\gamma_0}{\gamma_{SR}}} e^{-\frac{\gamma_0}{\gamma_{RD}}}\right) \times \left(1 - e^{-\frac{\gamma_0}{\gamma_{SD}}}\right) \tag{10}$$

201

202   In particular, the network with diversity can achieve a smaller outage probability than the
203 system without diversity, that is to say,

$$\left(1 - e^{-\frac{\gamma_0}{\gamma_{SR}}} e^{-\frac{\gamma_0}{\gamma_{RD}}}\right) \times \left(1 - e^{-\frac{\gamma_0}{\gamma_{SD}}}\right) \le \left(1 - e^{-\frac{\gamma_0}{\gamma_{SR}}} e^{-\frac{\gamma_0}{\gamma_{RD}}}\right) \tag{11}$$

204

205

Power allocation to minimize the outage probability

207 This section studies the power allocation strategy based on the analysis of the outage probability.
208 The power allocation will be discussed for two situations when the system is both with diversity
209 and without diversity.

A. Problem Description
211 The goal of power allocation is to minimize the outage probability under a certain total transmit
212 power P_T. Assume that the maximum transmission power of the source node is P_{max1}, and the
213 maximum transmission power of the UAV is P_{max2}. The total transmit power P_T is generally
214 the maximum power allowed for a given data packet to be transmitted from the source node to the

215   destination node, while P_{max1} and P_{max2} correspond to the maximum power that the source node
216   and UAV can provide, respectively ($0.5P_T < P_{max1}$, $P_{max2} \le P_T$), then the constrained optimization
217   problem can be expressed as:

218
$$\min_{P_S, P_U} P_{out}$$
$$s.t. \begin{cases} P_S + P_U = P_T \\ P_S \le P_{max1}, \quad P_U \le P_{max2} \end{cases}$$
(12)

219   In the above formula, the objective function is the convex function of the variables P_S and P_U,
220   whether there is a diversity gain or no diversity gain. The constraint function is the linear function
221   of the optimization variables P_S and P_U. Therefore, this is a convex optimization problem. There
222   exists a globally optimal solution, which can be solved by Lagrange Multiplier Method.

223   **B.   Without diversity**
224   The system outage probability without diversity is shown in equation (9), then the optimization
225   problem can be expressed as:

226
$$\min_{P_S, P_U} P_{out}^{DF} = 1 - e^{-\frac{\gamma_0}{\gamma_{SR}}} e^{-\frac{\gamma_0}{\gamma_{RD}}}$$
$$s.t. \begin{cases} P_S + P_U = P_T \\ P_S \le P_{max1}, \quad P_U \le P_{max2} \end{cases}$$
(13)

227   In the formula above, minimizing the objective function is equivalent to maximizing the
228   expression $-\dfrac{\gamma_0}{\gamma_{SR}} - \dfrac{\gamma_0}{\gamma_{RD}}$, then the optimization problem is simplified to be

229
$$\max_{P_S, P_U} \left(-\frac{\gamma_0}{\gamma_{SR}} - \frac{\gamma_0}{\gamma_{RD}} \right)$$
$$s.t. \begin{cases} P_S + P_U = P_T \\ P_S \le P_{max1}, \quad P_U \le P_{max2} \end{cases}$$
(14)

230   To solve the problem, the Lagrange Multiplier Method is picked. If the second restriction is
231   neglected, the objective function is constructed as:

232
$$F_1(P_S, P_U, \eta) = -\frac{\gamma_0}{\gamma_{SR}} - \frac{\gamma_0}{\gamma_{RD}} + \eta(P_S + P_U - P_T)$$
(15)

233   According to the necessary for the existence of extreme values, it can be obtained

234
$$\begin{cases} P_S^* = \dfrac{\sqrt{G_2} P_T}{\sqrt{G_1} + \sqrt{G_2}} \\[3mm] P_U^* = \dfrac{\sqrt{G_1} P_T}{\sqrt{G_1} + \sqrt{G_2}} \end{cases}$$
(16)

235   As the value of the power given in equation (16) may be out of range, the second constraint
236   in equation (14) is combined to determine the optimal power. Moreover, if P^* S is out of bounds,
237   the optimal power allocation can be obtained as

238
$$\begin{cases} P_S^* = P_{\max 1} \\ P_U^* = P_T - P_{\max 1} \end{cases} \tag{17}$$

239 Conversely, if P^* U crosses the boundary, the optimal power can be derived by

240
$$\begin{cases} P_U^* = P_{\max 2} \\ P_S^* = P_T - P_{\max 2} \end{cases} \tag{18}$$

241 **C. With Diversity**
242 Since the system outage probability with diversity gain is given in equation (10), the optimization
243 problem, in this case, can be built as:

244
$$\min_{P_S, P_U} P_{out2} = \left(1 - e^{-\frac{\gamma_0}{\gamma_{SR}}} e^{-\frac{\gamma_0}{\gamma_{RD}}} \right) \times \left(1 - e^{-\frac{\gamma_0}{\gamma_{SD}}} \right) \tag{19}$$

$$s.t. \begin{cases} P_S + P_U = P_T \\ P_S \le P_{\max 1}, \quad P_U \le P_{\max 2} \end{cases}$$

245 Similarly, using Lagrange Method and ignoring the second constraint in (19), then the
246 simplified optimization function is:

247
$$F_2(P_S, P_U, \mu) = 1 - e^{-\frac{\gamma_0}{\gamma_{SD}}} - e^{-\frac{\gamma_0}{\gamma_{SR}}} e^{-\frac{\gamma_0}{\gamma_{RD}}} + e^{-\frac{\gamma_0}{\gamma_{SR}}} e^{-\frac{\gamma_0}{\gamma_{RD}}} e^{-\frac{\gamma_0}{\gamma_{SD}}} + \mu(P_S + P_U - P_T) \tag{20}$$

248 The equations that the extreme values should be satisfied are as follows,

249
$$\begin{cases} -\dfrac{\gamma_0}{G_0 P_S^2} e^{-\frac{\gamma_0}{G_0 P_S}} - \dfrac{\gamma_0}{G_1 P_S^2} e^{-\frac{\gamma_0}{G_1 P_S}} e^{-\frac{\gamma_0}{G_2 P_U}} + e^{-\frac{\gamma_0}{G_0 P_S}} e^{-\frac{\gamma_0}{G_1 P_S}} e^{-\frac{\gamma_0}{G_2 P_U}} \left(\dfrac{\gamma_0}{G_0 P_S^2} + \dfrac{\gamma_0}{G_1 P_S^2} \right) + \mu = 0 \\[2ex] -\dfrac{\gamma_0}{G_2 P_U^2} e^{-\frac{\gamma_0}{G_2 P_U}} e^{-\frac{\gamma_0}{G_1 P_S}} + \dfrac{\gamma_0}{G_2 P_U^2} e^{-\frac{\gamma_0}{G_2 P_U}} e^{-\frac{\gamma_0}{G_1 P_S}} e^{-\frac{\gamma_0}{G_0 P_S}} + \mu = 0 \\[2ex] P_S + P_U - P_T = 0 \end{cases} \tag{21}$$

250 The transmission power of the source node and the UAV can be obtained by solving the
251 formula above and the expression that the optimal values need to satisfy is

252
$$\begin{cases} P_S^* = \sqrt{\gamma_0 \left(\dfrac{1}{G_0} + \dfrac{1}{G_1} \right) \left(\dfrac{\gamma_0}{G_0 P_S^2} e^{\frac{\gamma_0}{G_1 P_S}} e^{\frac{\gamma_0}{G_2 P_U}} + \dfrac{\gamma_0}{G_1 P_S^2} e^{\frac{\gamma_0}{G_0 P_S}} - \dfrac{\gamma_0}{G_2 P_U^2} e^{\frac{\gamma_0}{G_0 P_S}} - \dfrac{\gamma_0}{G_2 P_U^2} \right)^{-1}} \\[2ex] P_U^* = P_T - P_S^* \end{cases} \tag{22}$$

253 where P_S^* and P_U^* is the optimal allocation power.

254 Although the Equation in (22) is not a closed-form solution about P^* S and P^* U, its optimal
255 solution can be obtained by successive approximation. It should be noted that, if P^* S$>P_{\max 1}$ during
256 the iteration process appears, the iteration is aborted to ensure the KKT conditions. Thus, the
257 optimal value of P^* S is $P_{\max 1}$, and the optimal power allocation is:

258
$$\begin{cases} P_S^* = P_{\max 1} \\ P_U^* = P_T - P_{\max 1} \end{cases} \tag{23}$$

259   Similarly, if the power value of the UAV exceeds P_{max2} in the iterative process, it is reduced
260   to P_{max2}, and the reduced power is allocated to the source node. Therefore, the optimal power
261   distribution is given by:

262
$$\begin{cases} P_U^* = P_{max\,2} \\ P_S^* = P_T - P_{max\,2} \end{cases}$$
(24)

263

264 Power distribution with a certain transmission rate

265   The section studies the power allocation strategy when the outage probability of the system meets
266   a certain threshold based on the analysis of system outage probability. The power will be allocated
267   for the cases with diversity and without diversity, respectively.

268 A.Problem description
269   The target of power allocation is to minimize the total power through power allocation under the
270   condition that the outage probability at the destination node guarantees a certain threshold
271   condition.

272   It is supposed that the threshold of outage probability is ρ_0, then the constrained optimization
273   problem can be expressed as:

274
$$\min_{P_S,P_U} P_S + P_U$$
$$s.t. P_{out} \leq \rho_0$$
(25)

275   Because the constraints are non-convex, the problem above is not a convex optimization. It
276   can be solved by the Lagrange multiplier method.

277 B.Without diversity
278   Substituting equation (9) into the expression above, the constrained minimization problem for a
279   system without diversity can be obtained as

280
$$\min_{P_S,P_U} P_S + P_U$$
$$s.t. 1 - e^{-\frac{\gamma_0}{\gamma_{SR}}} e^{-\frac{\gamma_0}{\gamma_{RD}}} - \rho_0 \leq 0$$
(26)

281   The Lagrange multiplier method is used for optimization, and the constructor is:

282
$$L(P_S, P_U, \theta) = P_S + P_U + \theta \left(1 - e^{-\frac{\gamma_0}{\gamma_{SR}}} e^{-\frac{\gamma_0}{\gamma_{RD}}} - \rho_0 \right)$$
(27)

283   The optimal value satisfies the equation as follows:

284

$$\begin{cases} \dfrac{\partial L(P_S,P_U,\theta)}{\partial P_S}=1+\mu\left(-\dfrac{\gamma_0}{G_1 P_S^2}e^{-\frac{\gamma_0}{G_2 P_U}}e^{-\frac{\gamma_0}{G_1 P_S}}\right)=0 \\[2ex] \dfrac{\partial L(P_S,P_U,\theta)}{\partial P_U}=1+\mu\left(-\dfrac{\gamma_0}{G_2 P_U^2}e^{-\frac{\gamma_0}{G_2 P_U}}e^{-\frac{\gamma_0}{G_1 P_S}}\right)=0 \\[2ex] \dfrac{\partial L(P_S,P_U,\theta)}{\partial\mu}=1-e^{-\frac{\gamma_0}{G_2 P_U}}e^{-\frac{\gamma_0}{G_1 P_S}}-\rho_0=0 \end{cases}$$

(28)

285 From the first two formulas of the equations above, the relationship between P_S and P_U can
286 be obtained as $P_S=(G_2/G_1)^{1/2}P_U$, and the optimal power can be expressed as

$$\begin{cases} P_S=-\dfrac{\gamma_0}{\ln(1-\rho_0)}\left(\dfrac{1}{\sqrt{G_1 G_2}}+\dfrac{1}{G_1}\right) \\[2ex] P_U=-\dfrac{\gamma_0}{\ln(1-\rho_0)}\left(\dfrac{1}{\sqrt{G_1 G_2}}+\dfrac{1}{G_2}\right) \end{cases}$$

(29)

C. With diversity
289 By substituting equation (10) into equation(25), the constrained minimization problem for a system
290 with diversity can be expressed as

$$\min_{P_S,P_U} P_S+P_U$$

291

$$s.t.\left(1-e^{-\frac{\gamma_0}{\gamma_{SR}}}e^{-\frac{\gamma_0}{\gamma_{RD}}}\right)\times\left(1-e^{-\frac{\gamma_0}{\gamma_{SD}}}\right)-\rho_0\le 0$$

(30)

292 Use Lagrange Multiplier Method to optimize, the constructor is:

$$L(P_S,P_U,\omega)=P_S+P_U+\omega\left[\left(1-e^{-\frac{\gamma_0}{\gamma_{SR}}}e^{-\frac{\gamma_0}{\gamma_{RD}}}\right)\times\left(1-e^{-\frac{\gamma_0}{\gamma_{SD}}}\right)-\rho_0\right]$$

(31)

294 According to the necessary existence conditions of extreme values:

$$\begin{cases} \dfrac{\partial L(P_S,P_U,\omega)}{\partial P_S}=1+\mu\dfrac{\partial}{\partial P_S}\left[\left(1-e^{-\frac{\gamma_0}{\gamma_{SR}}}e^{-\frac{\gamma_0}{\gamma_{RD}}}\right)\times\left(1-e^{-\frac{\gamma_0}{\gamma_{SD}}}\right)\right]=0 \\[2ex] \dfrac{\partial L(P_S,P_U,\omega)}{\partial P_U}=1+\mu\dfrac{\partial}{\partial P_U}\left[\left(1-e^{-\frac{\gamma_0}{\gamma_{SR}}}e^{-\frac{\gamma_0}{\gamma_{RD}}}\right)\times\left(1-e^{-\frac{\gamma_0}{\gamma_{SD}}}\right)\right]=0 \\[2ex] \left(1-e^{-\frac{\gamma_0}{\gamma_{SR}}}e^{-\frac{\gamma_0}{\gamma_{RD}}}\right)\times\left(1-e^{-\frac{\gamma_0}{\gamma_{SD}}}\right)-\rho_0=0 \end{cases}$$

(32)

296 From the first two constraints above, the relationship between P_S and P_U can be obtained as

$$\dfrac{1}{G_0 P_S^2}e^{-\frac{\gamma_0}{G_0 P_S}}\left(e^{-\frac{\gamma_0}{G_1 P_S}}e^{-\frac{\gamma_0}{G_2 P_U}}-1\right)=e^{-\frac{\gamma_0}{G_1 P_S}}e^{-\frac{\gamma_0}{G_2 P_U}}\left(\dfrac{1}{G_2 P_U^2}-\dfrac{1}{G_1 P_S^2}\right)\left(e^{-\frac{\gamma_0}{G_0 P_S}}-1\right)$$

(33)

298   By simultaneous the third formula in (32) and the formula in(33), we can obtain the optimal
299   power.
300   Considering the computation complexity is high, we tried to use the relationship between P_S
301   and P_U to give a relatively simple solution. First of all, as the constraint in equation (33) is valid,
302   we could take the equal sign. When the feasible region of P_S needs to meet certain conditions, P_U
303   can be expressed as a function of P_S as

304

$$P_U = \cfrac{-\gamma_0}{G_2\left[\cfrac{\gamma_0}{G_1 P_S} + \ln\left(1 - \cfrac{\rho_0}{1-e^{-\frac{\gamma_0}{G_0 P_S}}}\right)\right]} \tag{34}$$

305   On the one hand, as the entire cooperation process only works when the signal-to-noise ratio
306   of the direct channel is greater than the threshold ρ_0, there is

307

$$1 - e^{-\frac{\gamma_0}{\gamma_{SD}}} > \rho_0 \tag{35}$$

308   Solving the formula above, we can get $P_S < P_{th1}$, and $P_{th1} = -\gamma_0/\ln(1-\rho_0)G_0$. On the other hand,
309   the transmission power of the UAV is non-negative, then it can be derived according to the
310   equation (32), as

311

$$\left(1 - e^{-\gamma_0/G_1}\right)\left(1 - e^{-\gamma_0/G_0}\right) < \rho_0 \tag{36}$$

312   The values which satisfy $P_S < P_{th2}$ can be obtained by numerical methods according to the
313   equation (34). Thus, the two-dimensional problem in the equation (30) can be simplified to a one-
314   dimensional optimization problem according to equations (34), (35), and (36). The problem can
315   be remodeled as

316

$$\min_{P_S, P_U} \dot{f}(P_S) = P_S + \cfrac{-\gamma_0}{G_2\left[\cfrac{\gamma_0}{G_1 P_S} + \ln\left(1 - \cfrac{\rho_0}{1-e^{-\frac{\gamma_0}{G_0 P_S}}}\right)\right]} \tag{37}$$

$$s.t. P_{th1} < P_S < P_{th2}$$

317   To obtain the minimum total power when the system satisfies the transmission conditions,
318   the derivative of $\dot{f}(P_S)$ needs to be obtained, and the equation that optimal P^*_S needs to satisfy
319   can be expressed as

320

$$\left[\gamma_0 q_1\left(P^*_S\right)\right] / \left[G_2 q_2\left(P^*_S\right)\right] = -1 \tag{38}$$

321   where, $q_1\left(P^*_S\right) = \cfrac{-\gamma_0}{\left(P^*_S\right)^2}\left[\cfrac{\rho_0 e^{-\frac{\gamma_0}{G_0}}}{G_0\left(1-e^{-\frac{\gamma_0}{G_0}}\right)\left(1-e^{-\frac{\gamma_0}{G_0}}-\rho_0\right)} + \cfrac{1}{G_1}\right]$ and $q_2\left(P^*_S\right) = \left[\cfrac{\gamma_0}{G_1} + \ln\left(1 - \cfrac{\rho_0}{1-e^{-\frac{\gamma_0}{G_0}}}\right)\right]^2$.

322   It should be noted that P_U is a monotonically decreasing function of P_S within the feasible
323   range. Therefore, the optimal transmit power P^* S of the source node can be easily obtained by
324   numerical methods if an initial value of P_S is given. Then the optimal transmission power of the
325   UAV can be obtained by substituting P^* S into the equation (34).

326   **D.   Simulation**
327   The theoretical derivation in the previous is simulated in this section, and the correctness of the
328   theory is verified. Moreover, the influence of the signal-to-noise ratio threshold on the optimal
329   power allocation strategy is further discussed under different diversity reception modes. The
330   simulation parameters are set as follows: the corresponding average power gains are given as G_0
331   = 1, G_1 = 5, G_2 = 0.5, respectively and threshold of the signal-to-noise ratio is set as γ_0 = 5dB.

332   Fig. 3 shows the optimal power allocation strategy for a network with diversity when the
333   signal-to-noise ratio at the destination node is no less than the preset threshold.

334   We simulate the third equation in (32) and (33) (the curve and virtual real line in Figure 3
335   respectively) and find the intersection of the two lines which is the value of optimal power. To
336   reduce the computational complexity, the optimal power can also be obtained by simultaneous
337   equations (34) and (37), as shown by the black dot in the figure. We find that the same optimal
338   power can be obtained by the two methods, which verifies the correctness of the theoretical
339   derivation.

340   The optimal transmission power for both with/without diversity is depicted in Fig. 4 and Fig.
341   5, which vary with the outage probability threshold, respectively. The simulation value range of
342   the outage probability threshold is from 10^{-3} to 0.1. It can be seen that the optimal transmission
343   power required by the network is significantly reduced since the outage probability constraint is
344   relaxed. In addition, the optimal power with diversity is significantly less than it without diversity
345   for the same outage probability threshold. This is because there is an extra direct link from the
346   source node to the destination node in the diversity system, which strengthens the SNR at the
347   destination node.

348

349   **Simulation and discussion**
350   This section analyzes the performance of the system and verifies the correctness of the theoretical
351   analysis by simulation. Unless otherwise specified, the parameters of the system during the
352   simulation are set as follows: the distance from the source node to the destination node is 1.5, the
353   distance from the source node to the relay node and from the relay node to the destination node is
354   1, and the distance from the UAV node to the relay node is 0.2. The mean values of the channel
355   parameters h^2 sr, h^2 sd and h^2 rd are all units. For simplicity, it is assumed that the noise variables
356   at the relay node and the destination node are similar, σ^2 SR=σ^2 RD=σ^2 SD=0.3. The charging
357   time ratio is 0.3, the line-of-sight channel attenuation factor is 2, and the line-of-sight parameter is
358   -30dB. The charging efficiency is 1, and the threshold of the signal-to-noise ratio is 3.

359   Fig. 6 shows the outage probability performance curves of the optimal power allocation
360   algorithm proposed in this paper and the average power allocation algorithm when different relay
361   cooperation modes (with diversity and without diversity) are selected in the UAV-assisted wireless

362   network. It can be seen that the outage probability decreases with the increase of total power, and
363   the performance of the system outage probability is always more superior lower when the
364   cooperative mode with diversity gain is adopted, which means that it can obtain the same outage
365   requirements with less energy. This is because the increased direct channel from the source node
366   to the destination node increases the signal-to-noise ratio at the destination node, thus reducing the
367   outage probability of the system. The simulation results are consistent with the previous theoretical
368   analysis.
369   Fig. 7 compares the outage probability of the system when the diversity and without diversity
370   reception modes are adopted destination nodes respectively under different time ratios. Obviously,
371   the outage probability decreases as the energy collection time ratio continuously increases which
372   enables the available energy in the system to increase. It can be seen from the figure that the
373   optimal power allocation algorithm proposed in this paper can significantly reduce the outage
374   probability of the system compared with the average power allocation algorithm. In particular, the
375   outage probability of the system without diversity gain is 1 in the case that the time ratio of energy
376   collection is 0. The reason is that the energy available at the limited relay node to forward the
377   information from the source node to the destination, the signal-to-noise ratio at the destination
378   node is all less than the threshold. However, the outage probability of the system is not 1 where
379   the system is with diversity due to the existence of a direct link.
380   To investigate the throughput of the system, the throughput of the time split is described in
381   Fig. 8 both with/without diversity, respectively. It can be seen from figure 8 that the optimal power
382   allocation algorithm proposed in this paper is better than the average power allocation algorithm.
383   Moreover, the system with diversity can obtain greater throughput than the system without
384   diversity. For the system without diversity, the throughput increases from 0 to a maximum value
385   and then decreases to 0 with the increase of α. This is because the relay node collects very little
386   energy result in a very high outage probability of the system and then a small throughput when α
387   is very small. Nevertheless, with the continuous increase of α, the energy input to the system
388   increases, and the throughput of the system increases.
389   Then, the outage probability of the system decreases, and the time for information
390   transmission decreases, so the throughput of the system decreases as the α continues to increase.
391   Particularly, the throughput of the system is decreasing, and the outage probability is decreasing
392   meanwhile for the system with diversity as the energy collection time of relay nodes is continue
393   to increase. Therefore, an appropriate α should be chosen to make a compromise between the
394   outage probability and the throughput.
395   The outage probability of the system changes with the signal-to-noise ratio threshold at the
396   destination node with/without diversity is shown in Fig. 9, respectively. The outage probability
397   continues to increase together with the increase of the SNR threshold, as the SNR threshold at the
398   destination node is more and more difficult to reach. It can be seen from the figure that the optimal
399   power allocation algorithm proposed in this paper can reduce the system outage probability
400   compared with the average power allocation method, especially for the system with diversity.
401   Moreover, the outage probability remains to be 1 when the signal-to-noise ratio threshold is greater

402 than 15 in the system without diversity, which is mainly because the signal-to-noise ratio threshold
403 at the destination node is too large to achieve. Similarly, there also exists a certain range that the
404 outage probability of the system will all be 1 as the SNR threshold at the destination node continues
405 to increase in the system with diversity.
406   The system outage probability varies with the distance between the UAV and the relay node
407 is revealed in reveal Fig. 10 in the network with/without diversity, respectively. It can be observed
408 from the figure that the outage probability increases as the distance of the UAV to the relay node
409 is continuing to increase. The main reason is that the energy collected by the relay node from the
410 UAV's RF signal becomes less and the available energy of the system decreases. Obviously, the
411 outage probability in the system with diversity is significantly lower than that in the without
412 diversity reception. In addition, the optimal power allocation algorithm proposed in this paper can
413 reduce the outage probability of the system compared with the average power allocation algorithm.
414 Moreover, the outage probability remains to be 1 when the distance from the UAV to the relay is
415 greater than 0.6 in the system without diversity. This is because the energy collected by the relay
416 node is too small to support the signal-to-noise at the destination node to reach the threshold with
417 the increased charging distance.
418   Fig. 11 shows the change of the system outage probability with the line-of-sight channel
419 attenuation factor β_0 in the system with/without diversity, respectively. It can be seen that the relay
420 node could harvest more energy from the RF signal of the UAV with the continuous increase of
421 β_0. Thus, the outage probability decreases as the available energy of the system increases.
422 Obviously, the outage probability in the system with diversity is significantly lower than it is
423 without diversity. Similarly, the optimal power allocation algorithm proposed in this paper can
424 reduce the outage probability of the system compared with the average power allocation algorithm.
425 Moreover, the system outage probability decreases slowly with the continuous increase of β_0 when
426 β_0 is greater than a certain value since other parameters in the system are instead of the harvested
427 energy as the main factor to affect the outage probability.
428

Conclusions

430 This paper studies the optimal power allocation strategy in wireless networks where the energy-
431 constrained relay nodes through RF energy from the UAVs. Firstly, the system outage probability
432 with and without diversity gain is derived. Then, an optimal power allocation strategy for decoding
433 and forwarding cooperative systems with diversity under outage probability constraints is
434 proposed in detail. On the one hand, since the optimization problem with constraints is nonconvex
435 for the network with diversity, the conventional convex optimization method could not be adopted
436 to handle it. Therefore, an effective method is raised to reduce the computational complexity by
437 using the relationship between the power of the source node and the relay node. A closed-form
438 expression of the optimal power allocation strategy is acquired for the network without diversity.
439 On the other hand, this paper attempts to improve the network quality of service by minimizing
440 the outage probability under the total power constraint. As the optimization problems established
441 are convex for both situations that whether the network is with diversity or without diversity, the

442 Lagrange multiplier method is used to solve them. Newton iterative method is adopted to solve the
443 system with diversity, and the analytical formula of optimal power allocation can be directly
444 derived for the systems without diversity. Finally, simulation experiments verify the effectiveness
445 of the optimization method and the correctness of the theoretical analysis.
446
447 **Nomenclature**

α	time ratio of energy collection
η	the efficiency of energy collection
β_0	the power attenuation factor of the line-of-sight channel
P_U	the transmit power of UAV
d_U	the distance between the UAV and the relay node
d_{SD}	the distance from the source node to the destination node
$s(k)$	the signal sent by the source node
h_{sd}	the channel gain between the source and the destination
P_S	the transmit power of the source node
$n_a^{[sd]}(k)$	the noise introduced by the receiving antenna at destination in the direct link
$n_c^{[sd]}(k)$	the noise introduced by the conversion circuit at destination in the direct link
$n_a^{[sr]}(k)$	the noise introduced by the receiving antenna at the relay node
$n_c^{[sr]}(k)$	the noise introduced by the conversion circuit at the relay node
$n_a^{[rd]}(k)$	the noise introduced by the receiving antenna at the destination in the link from the relay node to the destination node
$n_c^{[rd]}(k)$	the noise introduced by the conversion circuit at destination in the link from the relay node to destination node
h_{sd}	the channel gains from the source node to the destination node
h_{sr}	the channel gains from the source node to the destination node
h_{rd}	the channel gains from the source node to the destination node

$y_{sd}(k)$	the signal received at the destination node in the direct link
$y_{sr}(k)$	the signal received at the relay node
$y_{rd}(k)$	the signal received at the destination node in the backward link
γ_{SR}	the signal-to-noise ratio at the relay node
γ_{SD}	the signal-to-noise ratio at the relay node in the direct link
γ_{RD}	the signal-to-noise ratio at the relay node in the two-hop link
σ_{SD}^2	the total variance of Gaussian white noise at the destination node in the direct link
σ_{RD}^2	the total variance of Gaussian white noise at the destination node in the two-hop link
G_0	$\dfrac{E\left[|h_{sd}|^2\right]}{d_{SD}\sigma_{SD}^2}$
G_1	$\dfrac{E\left[|h_{sr}|^2\right]}{d_{SR}\sigma_{SR}^2}$
G_2	$\dfrac{2\eta\beta_0\alpha E\left[|h_{rd}|^2\right]}{d_{RD}d_U^2(1-\alpha)\sigma_{RD}^2}$
γ_0	the signal-to-noise ratio threshold
P_{out1}	the outage probability from S to D in the direct link
P_{out2}	the outage probability with diversity
P_{out}^{DF}	the outage probability without diversity
P_{T}	the total transmit power
P_{max1}	the maximum transmission power of the source node
P_{max2}	the maximum transmission power of the UAV
P_S^*	the optimal transmission power of the source node
P_U^*	the optimal transmission power of the UAV

448

449 ## Acknowledgments

450 This research was supported by the National Natural Science Foundation of China under Grant
451 61842103, 61871351, and 61801437 and by the Science and Technology Foundation of State Key
452 Laboratory of electronic testing technology under Grant 6142001180410 and by the Technological
453 Innovation Foundation of the Higher Education Institutions of Shanxi Province, China under Grant
454 2020L0301 and 2020L0389 andi by the Poverty-relief Foundation of Shanxi Province under Grant
455 2020FP-11 and by Scientific and Technological Innovation Foundation of Higher Education
456 Institutions in Shanxi Province, China under Grant 18005520 and by Science Foundation of North
457 University of China under Grant XJJ201927. There was no additional external funding received
458 for this study.

459

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538

Figure 1

The illustration of UAV-assisted wireless powered relay network

The information is transmitted from the source to the node with the energy harvested from the UAV's RF signal in the down-link.
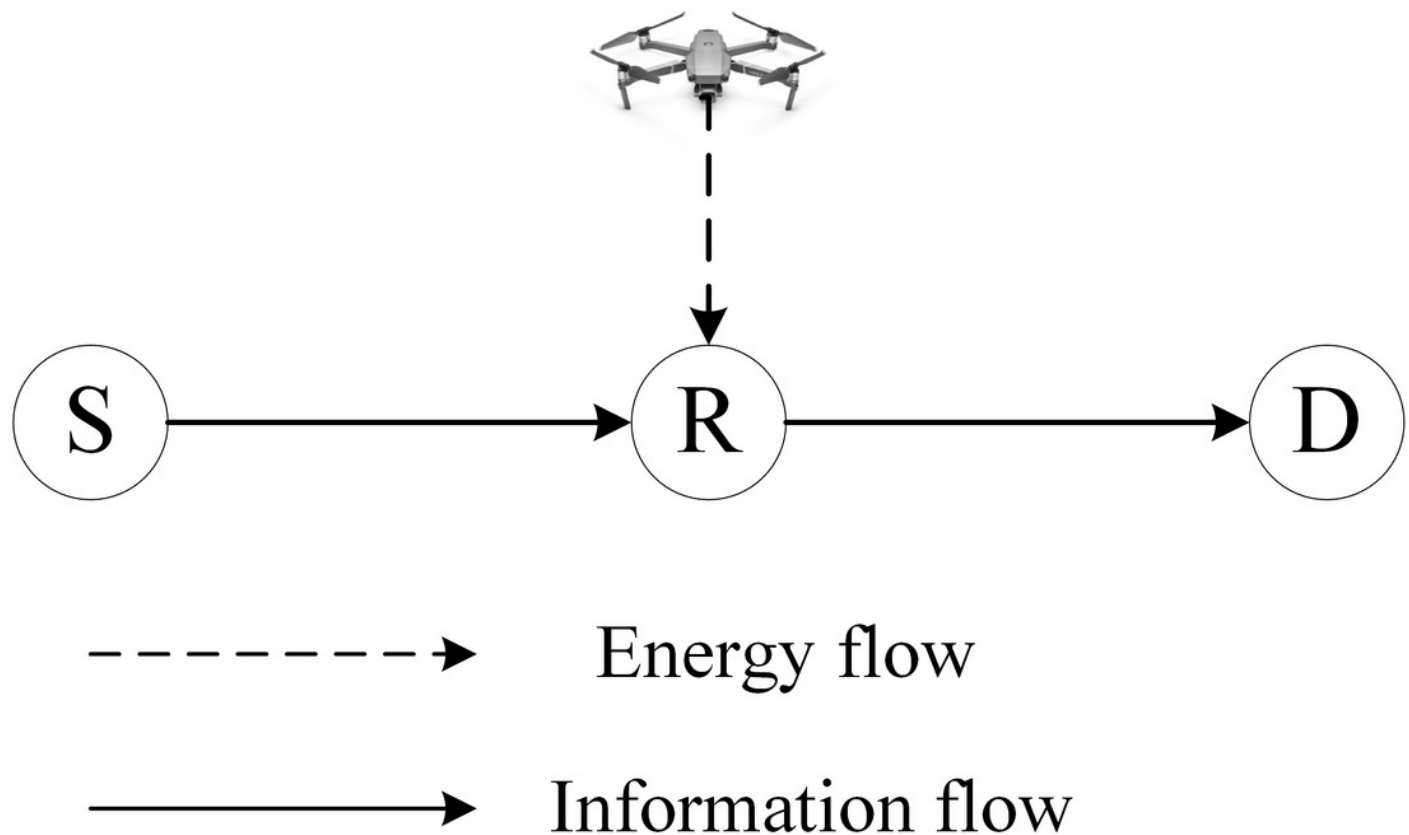
Figure 2

The schematic of the time allocation

The schematic of time allocation during a block time T. The block time T is divided into three phase. The first phase is for energy harvested. Then the second <!--[if !msEquation]--> <!--[endif]--> is used for information transmission from source node to relay node. And the information is transmitted form relay node to destination node with the remaining time <!--[if !msEquation]--> <!--[endif]-->.

$$T$$

UAV-to—Relay Wireless Power Transfer	Source-to—Relay Information Transmission	Relay-to—Destination Information Transmission
αT	$(1-\alpha)T/2$	$(1-\alpha)T/2$
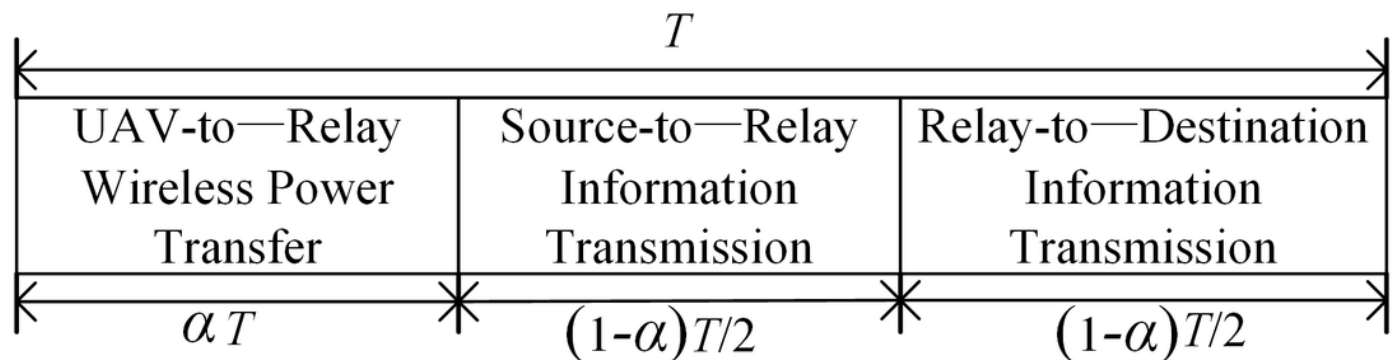
Figure 3

Calculation of the optimal power under the outage probability threshold

We simulate the third equation in (30) and (31) (the curve and virtual real line in Figure 3 respectively) and find the intersection of the two lines which is the value of optimal power. To reduce the computational complexity, the optimal power can also be obtained by simultaneous equations (34) and (37), as shown by the black dot in the figure.
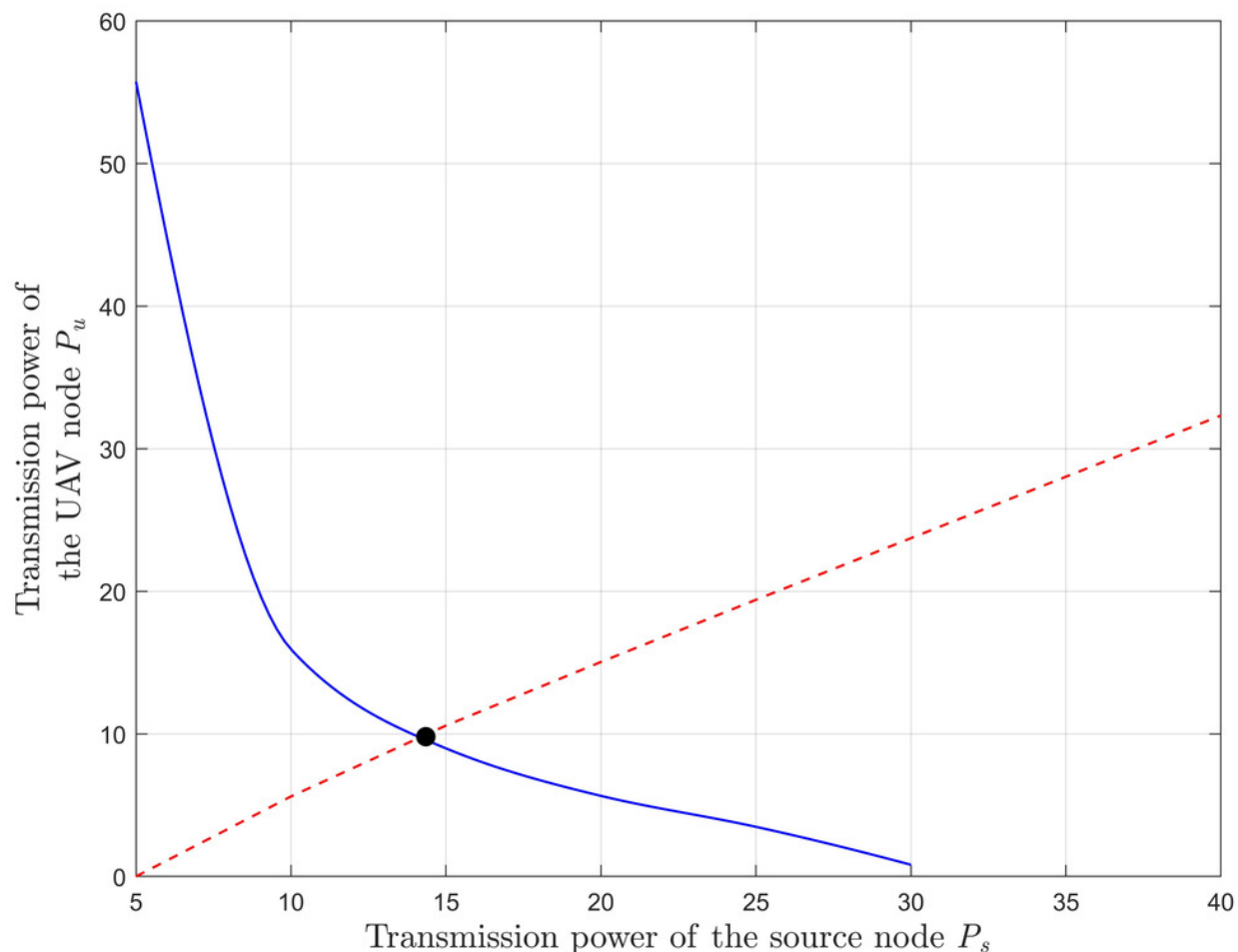
Figure 4

Optimal power versus the outage probability threshold for the system with diversity.

The optimal transmission power required by the network is significantly reduced since the outage probability constraint is relaxed.
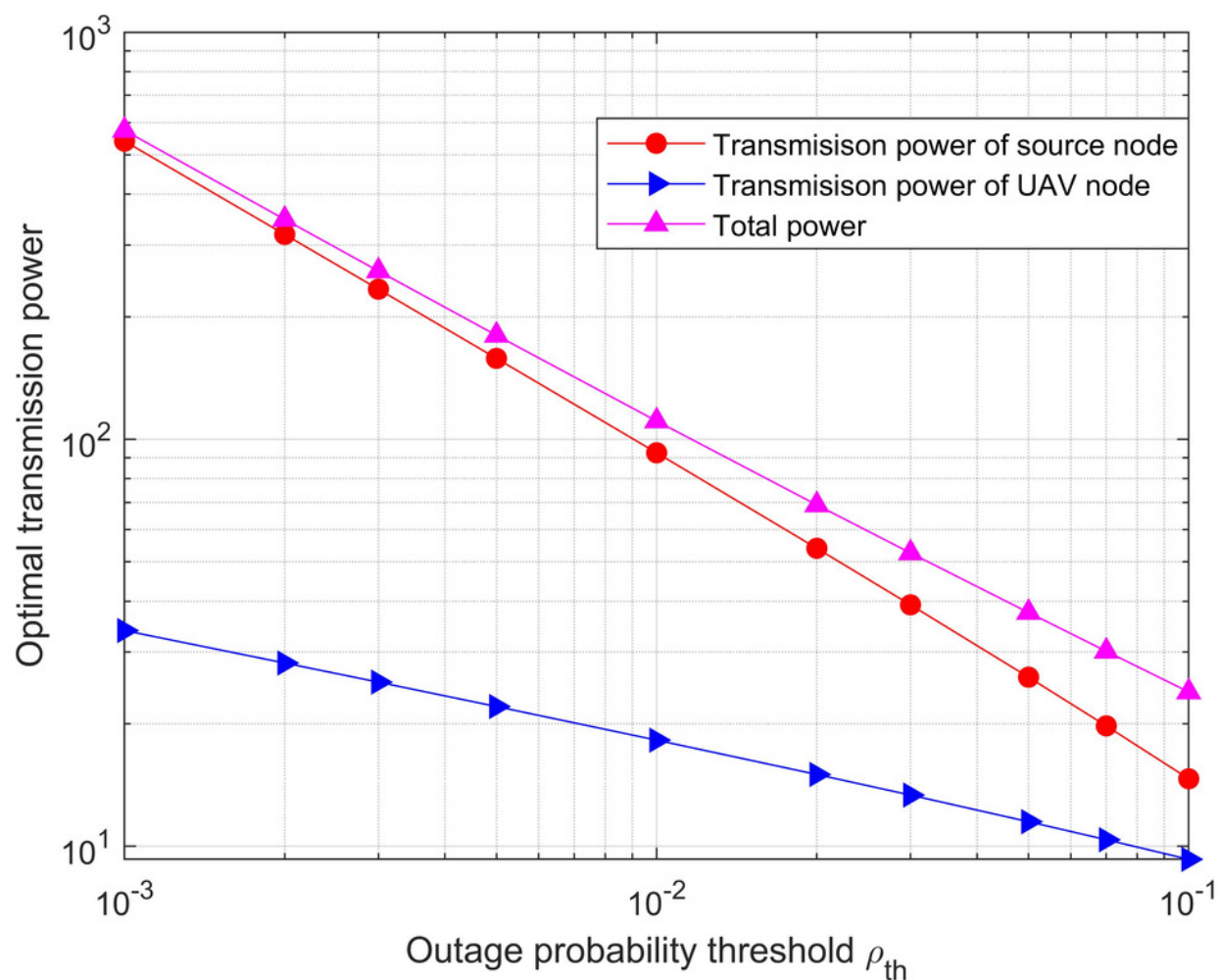
Figure 5

Optimal power versus the outage probability threshold for the system without diversity.

It can be seen that the optimal transmission power required by the network is significantly reduced since the outage probability constraint is relaxed. In addition, the optimal power with diversity is significantly less than it without diversity for the same outage probability threshold.
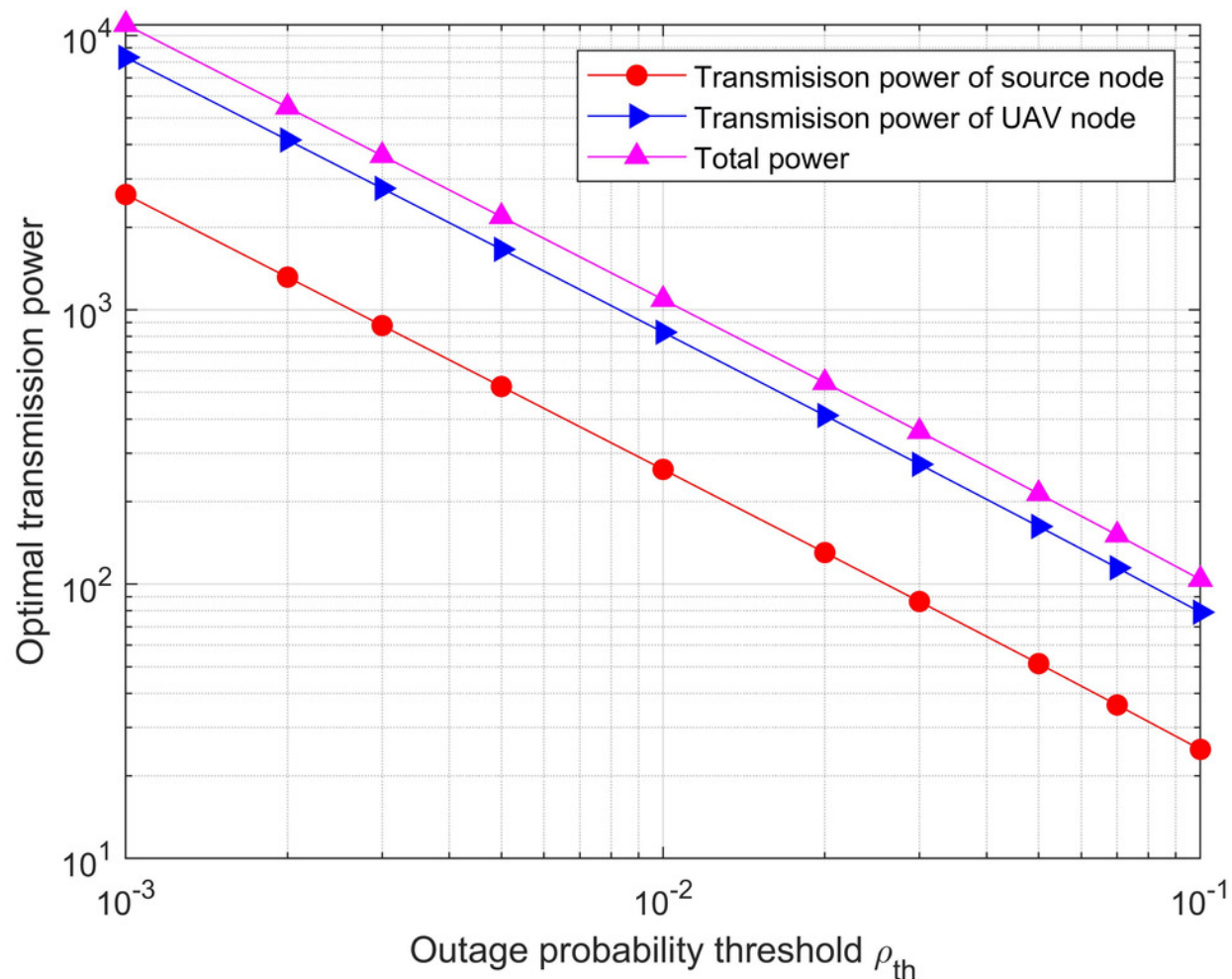
Figure 6

Minimization of the outage probability versus the total power threshold for the system with/without diversity.

The outage probability decreases with the increase of total power, and the performance of the system outage probability is always more superior lower when the cooperative mode with diversity gain is adopted, which means that it can obtain the same outage requirements with less energy.
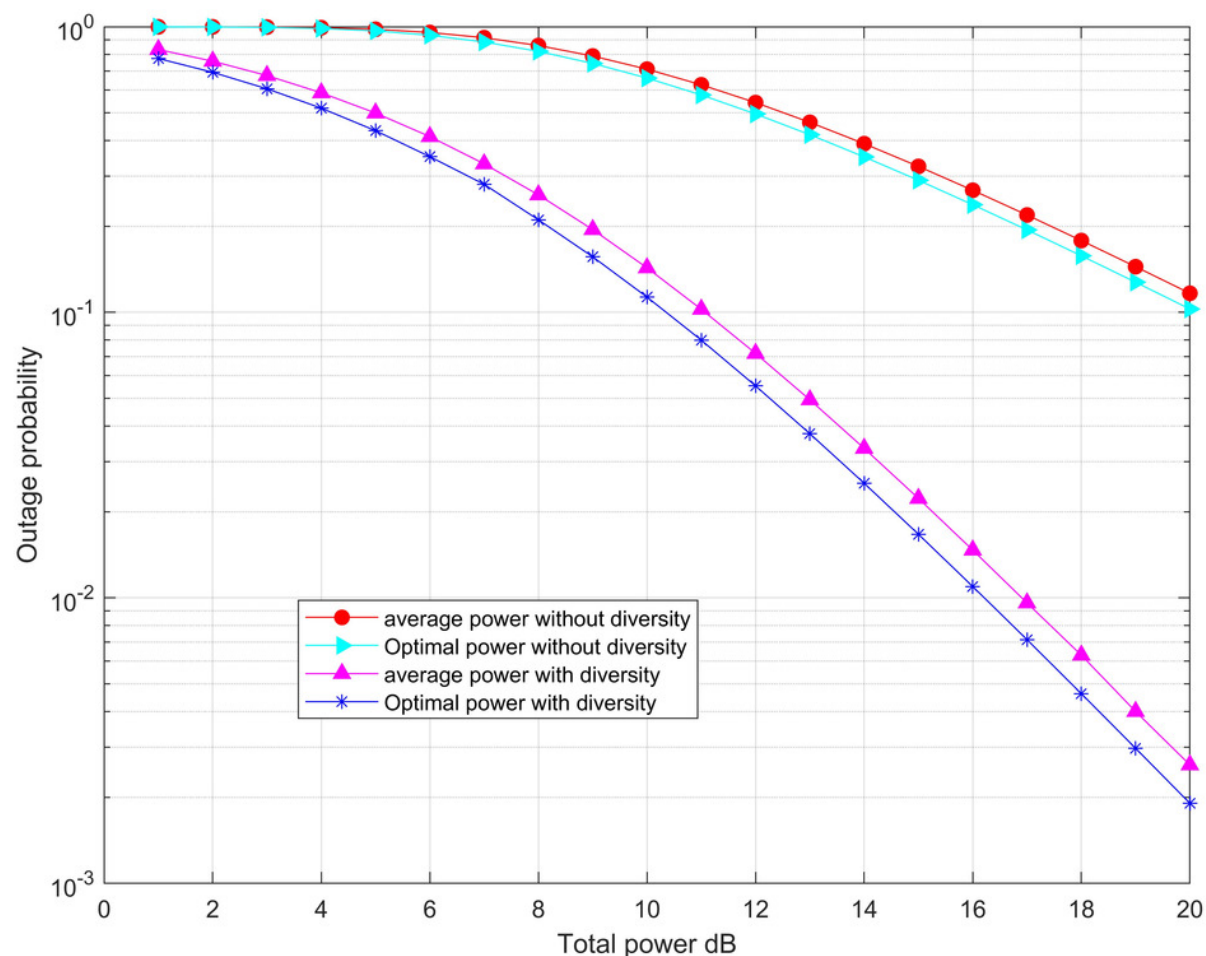
Figure 7

Minimization of the outage probability versus under the total power threshold.

The outage probability of the system is compared when the diversity and without diversity reception modes are adopted destination nodes respectively under different time ratios. Obviously, the outage probability decreases as the energy collection time ratio continuously increases which enables the available energy in the system to increase.
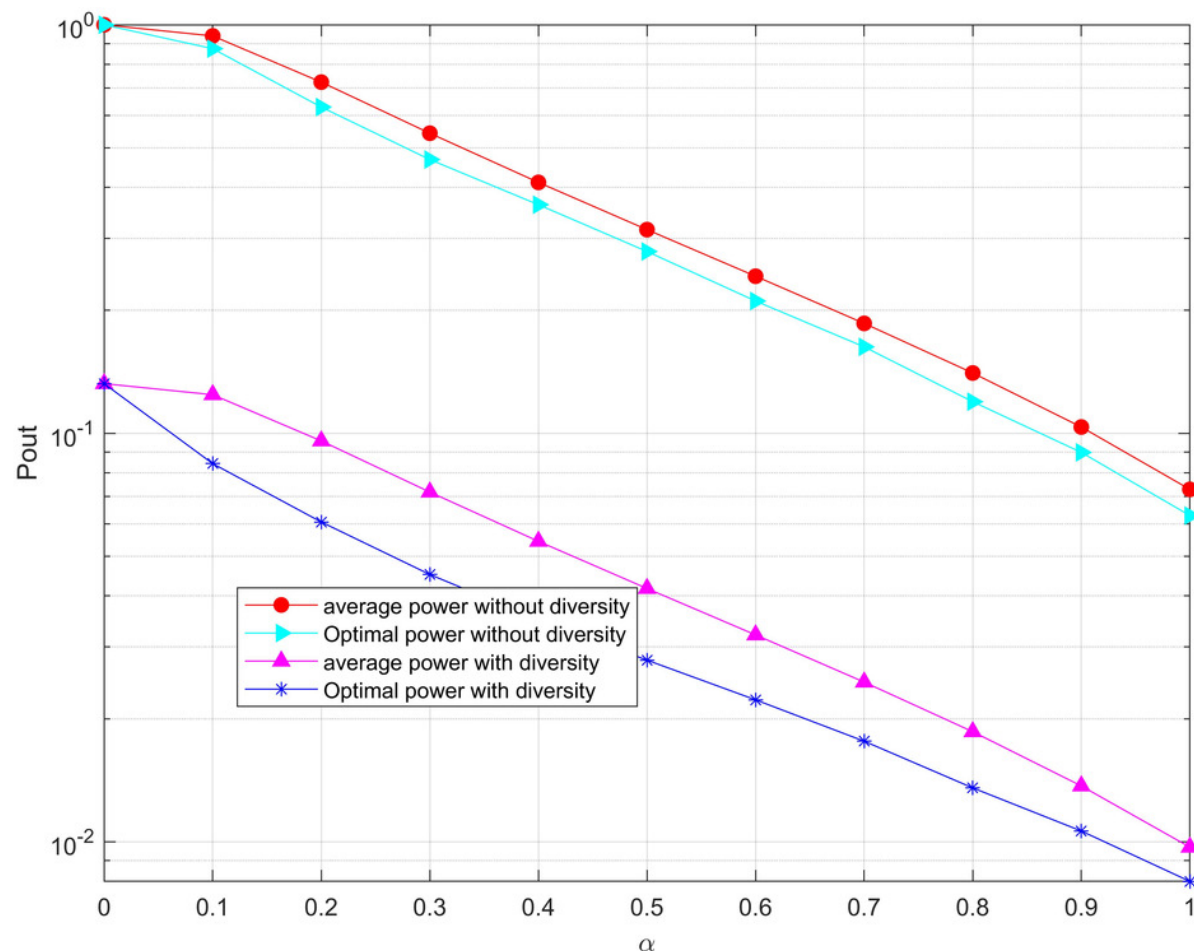
Figure 8

Maximization of the outage probability versus α under the total power threshold.

The optimal power allocation algorithm proposed in this paper is better than the average power allocation algorithm.
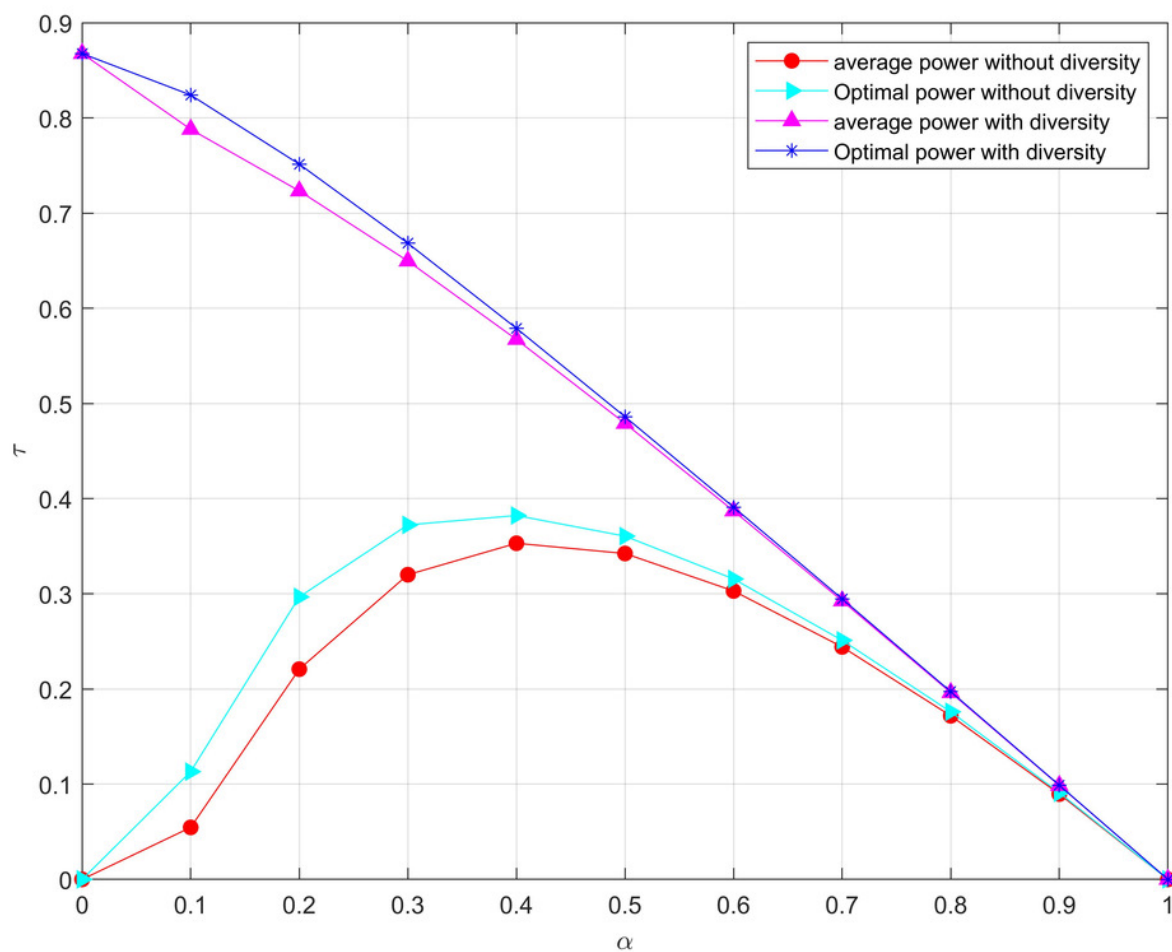
Figure 9

Minimization of the outage probability versus γ_0 under the total power threshold.

The outage probability continues to increase together with the increase of the SNR threshold, as the SNR threshold at the destination node is more and more difficult to reach.
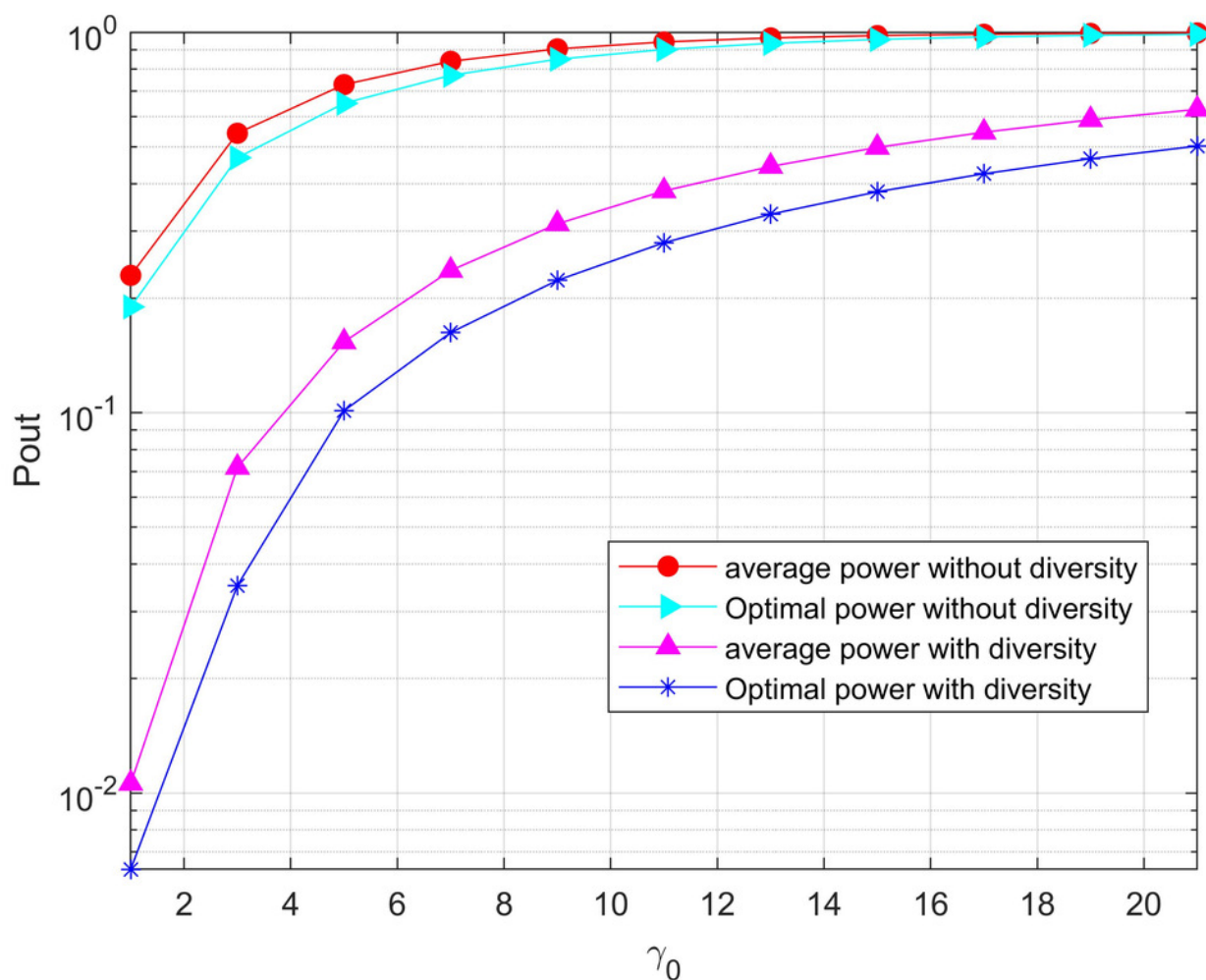
Figure 10

Minimization of the outage probability versus du under the total power threshold.

It can be observed from the figure that the outage probability increases as the distance of UAV to relay node is continuing to increase. The main reason is that the energy collected by the relay node from the UAV's RF signal becomes less and the available energy of the system decreases.
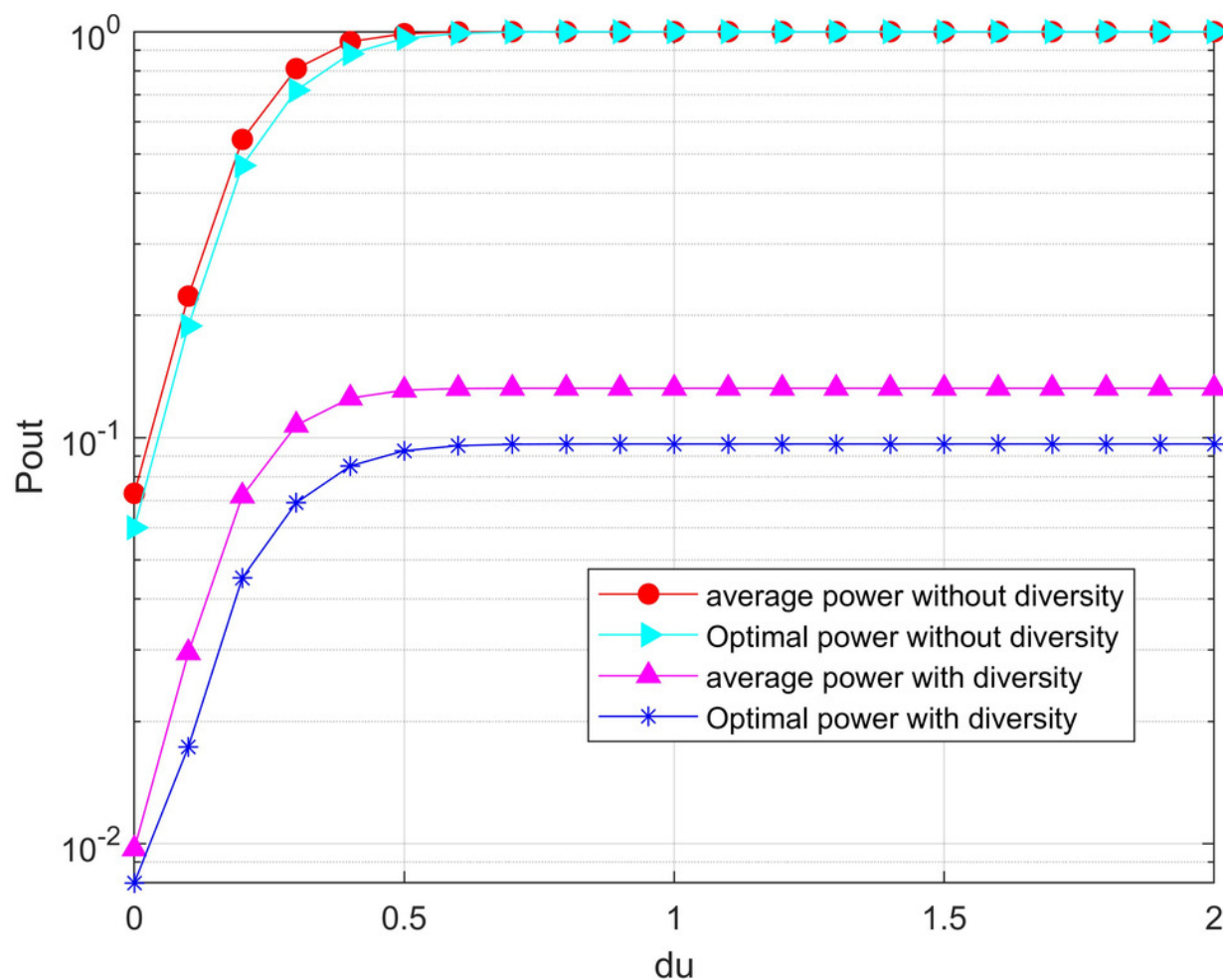
Figure 11

Figure 11 Minimization of the outage probability versus β_0 under the total power threshold.

The relay node could harvest more energy from the RF signal of the UAV with the continuous increase of β_0. Thus, the outage probability decreases as the available energy of the system increases.