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Cache-aided multi-hop UAV-relaying networks ☆

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ABSTRACT

In this work, we study unmanned aerial vehicle (UAV) relaying networks with multi-hop, where one source communicates with one destination through the help of L relay hops. Cache is employed at the relay nodes nearby the destination. Then the destination can acquire the data directly through the cache instead of communicating with the source. For the multi-hop relaying networks with cache, we not only analyze the transmission performance of the considered system by deriving the analytical expressions for the outage probability as well as symbol error rate (SER), but also provide the asymptotic outage probability and SER, in the large region of transmit power. The proposed caching method is proved by simulation and numerical results, and validates that the usage of cache can provide ultra-reliable and low-latency communications for UAV systems.

1. Introduction

The fifth-generation (5G) wireless communication system has brought out the issue of wireless big data [1], and it should support many services such as Giga bits per second, massive connection, and very low latency [2,3]. To meet these requirements, many efficient transmission techniques have been devised for wireless communications in the literature. In particular, relaying technique can enhance the transmission quality, improve the coverage area and provide much flexibility to the wireless network without additional transmit power [4]. Two fundamental relaying protocols are proposed in the literature, such as the amplify-and-forward (AF) mode and decode-and-forward (DF) mode [5–8]. The interested performance metrics include capacity, outage probability, as well as symbol error rate (SER). The analytical expressions on outage probability and SER along with the asymptotic expressions in the high regime of transmit power have been studied in the literature. For the wireless communications over remote distances, multi-hop relaying has been used to enhance the transmission quality. In [9], the ergodic capacity of relaying systems with multi-hop was analyzed by providing the analytical expressions, where both the AF and DF relaying modes were used. Then the authors in [10] studied the opportunistic relay selection protocol for relaying networks with multiple hops, where the analytical expression of throughput was provided. The authors in [11] extended the multi-hop study to consider the Nakagami-m fading, and studied how the fading parameter affect the performance of multi-hop relaying networks.

The unmanned aerial vehicle (UAV) is an emerging technique in military, public and civil applications, having evolved into high-tech capable small vehicles, used by the armed forces worldwide, mostly for surveillance and data acquisition purposes. Moreover, UAV have gained much popularity for wireless communications due to their high mobility, flexible deployment and low operational costs. UAV has great potential to be applied for monitoring of harmful areas, aiding of rescue missions and so on. Each UAV monitors and collects information from a small area. This sensing information will then be delivered to a data center which provides comprehensive information to action team. However, the distance between some UAVs and the center station are beyond the transmission range of these UAVs. These UAVs therefore need other UAVs close to the center station to relay their data to the center station. One solution is to chain up the UAVs from the furthest one to the closest one, and then to the center station [12].

To achieve ultra-reliable and low-latency transmission for transmitting wireless big data, cache can prefetch the data from the remote base station [13,14], and then users can acquire the data from the nearby relay nodes [15,16], instead of having to communicate with the remote base station. In this way, cache can be beneficial to the communication quality significantly, and improve the quality of the user experience substantially [17]. The application of cache into relaying networks has drawn much attention recently. In [18], the authors studied the application of wireless caching at relays, in order to exploit the signal cooperation gain and content delivery diversity for improving the performance of collaborative relaying. In [19], in order to increase the experience quality in a relay network with two-hop, the authors studied how to optimize

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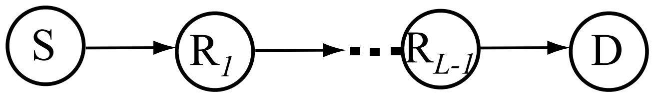


Fig. 1. System model of traditional multi-hop UAV relaying networks without cache.

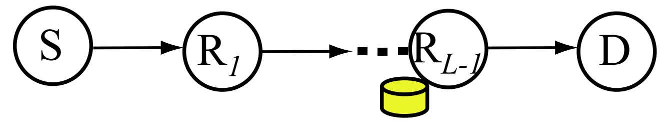


Fig. 2. System model of multi-hop UAV relaying networks with cache.

cache and fast video transmission from the cross-layer, where the base station could supply the service of the data of video to multi-users through the help of relays. The authors in [20] investigated the cache aided two-way relay networks, where the total degree of freedom (DoF) was studied. The authors in [21,22] studied how caching strategy affected the system transmission performance for dual-hop relaying networks. To the best of our knowledge, the application of cache into multi-hop relaying networks has not been considered in the existing works, which becomes the motivation of the work in this paper.

In this paper, we investigate multi-hop relaying networks, where one destination communicates with one source through the help of L hops. The data can be prefetched at the relay nodes nearby the destination, and in this way, the destination can directly communicate with the nearby relay nodes instead of communicating with the source. For the multi-hop relaying networks without and with cache, we not only study the transmission performance of the system by deducing the interruption probability and SER's analytical expressions, but also provide asymptotic interrupt probability and SER, when the transmit power is high. Numerical and simulation results are provided to verify the aforementioned performance analysis.

The rest of the paper is organized as follows. Section 2 briefly explains the experimental methods used in this paper, including that channel models configuration, computing tools, graphics tools, etc. Section 3 introduces the model of multi-hop UAV relying networks with and without cache. Section 4 analytically derives the interruption probability and SER performance, for the multi-hop relaying networks without and with cache, and also provides asymptotic analysis for interrupt probability and SER. Section 5 demonstrates some numerical and simulation results. Finally, Section 6 concludes this paper.

Notations. We utilize $\mathcal{CN}(0, \sigma^2)$ to denote a circularly symmetric complex Gaussian random variable (RV), the mean is zero and variance is σ^2. The probability density function (PDF) and cumulative density function (CDF) of the RV X are represented by $f_X(\cdot)$ and $F_X(\cdot)$, respectively. Furthermore, we use the expression $\Pr[\cdot]$ to obtain the probability result.

2. Methods/experimental

In this work, we design the study by incorporating the cache into relaying networks with multiple hops, in order to achieve ultra-reliable and super-low latency wireless transmission services. The setting of channel models are Rayleigh flat fading channels, and we set the additive noise at each node to white Gaussian distribution. The numerical calculation is based on C program, and we use GNUPlot to show the figures in this paper. The analytical results are presented to show the effectiveness of the proposed studies, as well as the asymptotic analysis.

3. System model

Fig. 1 describes the system model of traditional multi-hop UAV relaying networks without cache, where the source node S wants to send its data to the destination node D through $(L-1)$ UAV-based DF relays $\{R_1, \ldots, R_{L-1}\}$ $(L \geq 2)$. In contrast, Fig. 2 shows the system model of cache aided multi-hop relaying networks, where the data can be prefetched to the relay nodes around the destination D. In this UAV chain network, the node R_{L-1} sometimes represents a base station, which therefore has big buffer and can cache data information from the source node. Accordingly, the node D can acquire the required data from the near-by node R_{L-1}. Due to the size limitation, each node has a single antenna only [23], and each node works in the time-division half-duplex mode [24]. We will describe the signal transmission process in the following part.

For the traditional multi-hop relaying networks without cache, let P_S represent the transmit power of each node, and σ^2 be the additive noise variance at each node subject to white Gaussian distribution. We use $h_l \sim \mathcal{CN}(0, \alpha)$ to represent the instantaneous channel parameter of the lth hop relay link in Fig. 1. According to the DF protocol, the received SNR at the destination D from the end-to-end is written by

$$\mathsf{SNR}_D = \frac{P}{\sigma^2} \min(u_1, u_2, \ldots, u_L), \tag{1}$$

where $u_l = |h_l|^2$ is the instantaneous channel gain of the lth hop relay link. The transmission outage event happens when the instantaneous data rate of the multi-hop link becomes smaller than a target data rate R_t [25,26],

$$\frac{1}{L} \log_2(1 + \mathsf{SNR}_D) < R_t, \tag{2}$$

which is equivalent to

$$\mathsf{SNR}_D < \gamma_{1t}, \tag{3}$$

where $\gamma_{1t} = 2^{LR_t} - 1$ is the SNR threshold without cache.

For the cache-aided multi-hop relaying networks, the destination D can directly access the data from the nearest relay node R_{L-1} if the required data is prefetched at the cache of R_{L-1}. Under these circumstances, the received SNR at the destination D from end-to-end becomes,

$$\mathsf{SNR}_D = \frac{P}{\sigma^2} u_L. \tag{4}$$

The outage event happens when the instantaneous data rate is smaller than the given R_t,

$$\log_2(1 + \mathsf{SNR}_D) < R_t, \tag{5}$$

which is equivalent to

$$\mathsf{SNR}_D < \gamma_{2t}, \tag{6}$$

where $\gamma_{2t} = 2^{R_t} - 1$ is the SNR threshold with cache.

4. Outage probability and SER analysis

In this part, we study the system performance of outage probability as well as SER for the multi-hop relaying networks with or without cache. Let P_{out}^{w} and P_{out}^{wo} denote the outage probability of the muti-hop relaying networks with and without cache, respectively. We use P_e^{w} and P_e^{wo} to represent the SER of the muti-hop relaying networks with and without cache, respectively. From the performance comparison, we can find the advantages introduced by the cache technique.

4.1. Outage probability without cache

For the traditional muti-hop relaying networks without cache, the outage probability can be written as

$$P_{out}^{wo} = \Pr(\mathsf{SNR}_D < \gamma_{1t}) \tag{7}$$

$$= \Pr\left[\min\left(u_1, u_2, \ldots, u_L\right) < \frac{\gamma_{1t}\sigma^2}{P_S}\right] \tag{8}$$

$$= 1 - \Pr\left[\min\left(u_1, u_2, \ldots, u_L\right) \geq \frac{\gamma_{1t}\sigma^2}{P_S}\right]. \tag{9}$$

Since $\{u_l\}$ is independent of each other, we can further write P_{out}^{wo} as

$$P_{out}^{wo} = 1 - \Pr\left(u_1 \geq \frac{\gamma_{1t}\sigma^2}{P_S}\right)\Pr\left(u_2 \geq \frac{\gamma_{1t}\sigma^2}{P_S}\right) \cdots \times \Pr\left(u_L \geq \frac{\gamma_{1t}\sigma^2}{P_S}\right) \tag{10}$$

$$= 1 - e^{-\frac{L\gamma_{1t}\sigma^2}{\alpha P_S}}. \tag{11}$$

When the transmit power is high with $\frac{P_S}{\sigma^2} \gg 1$, we obtain an approximate outage probability of the muti-hop relaying networks without cache as

$$P_{out}^{wo} \simeq \frac{L\gamma_{1t}\sigma^2}{\alpha P_S}, \tag{12}$$

where we apply the approximation of $e^x \simeq 1 + x$ when $|x|$ is small [27]. From this asymptotic expression, we find that the network transmission performance becomes worse when there are increasing number of hop, as the weakest hop among multiple hops becomes the bottleneck of the whole transmission.

For the target outage probability level P_{out}^t, we consider the minimum transmit power which achieves the target outage probability. From the analytical expression of outage probability in (11), we can write the condition of transmit power as

$$1 - e^{-\frac{L\gamma_{1t}\sigma^2}{\alpha P_S}} \leq P_{out}^t, \tag{13}$$

which is equivalent to

$$P_S \geq \frac{L\gamma_{1t}\sigma^2}{-\alpha \ln(1 - P_{out}^t)} \tag{14}$$

where $\ln(\cdot)$ is the natural logarithm function. From the asymptotic expression of outage probability in (12), we obtain the minimum transmit power in an asymptotic form as

$$P_S \geq \frac{L\gamma_{1t}\sigma^2}{\alpha P_{out}^t}. \tag{15}$$

4.2. Outage probability with cache

For the cache-aided muti-hop relaying networks, we write the network transmission outage probability as

$$P_{out}^{w} = \Pr(\mathsf{SNR}_D < \gamma_{2t}) \tag{16}$$

$$= \Pr\left(u_L < \frac{\gamma_{2t}\sigma^2}{P_S}\right) \tag{17}$$

$$= 1 - e^{-\frac{\gamma_{2t}\sigma^2}{P_S\alpha}}, \tag{18}$$

where the PDF of $f_{u_L}(x) = \frac{1}{\alpha}e^{-\frac{x}{\alpha}}$ is used from (17) to (18).

When the transmit power regime is large with $\frac{P_S}{\sigma^2} \gg 1$, the outage probability of the cache-aided relaying networks with multiple hops is approximated by

$$P_{out}^{w} \simeq \frac{\gamma_{2t}\sigma^2}{P_S\alpha}, \tag{19}$$

where the approximation of $e^x \simeq 1 + x$ is used when $|x|$ is small [27]. By comparing the asymptotic outage probabilities with and without cache, we can find that cache can enhance the network transmission performance significantly, through prefetching data during non-peak traffic time.

With a given outage probability level P_{out}^t, the minimum transmit power can be written as

$$1 - e^{-\frac{\gamma_{2t}\sigma^2}{P_S\alpha}} \leq P_{out}^t, \tag{20}$$

which is equivalent to

$$P_S \geq \frac{\gamma_{2t}\sigma^2}{-\alpha \ln(1 - P_{out}^t)} \tag{21}$$

From the asymptotic outage probability in (19), one obtains the minimum transmit power in an asymptotic form as

$$P_S \geq \frac{\gamma_{2t}\sigma^2}{\alpha P_{out}^t}. \tag{22}$$

By comparing the minimum transmit power for the multi-hop relaying networks with and without cache in Eqs. (15) and (22), we can find that cache can save the transmit power significantly, at the cost of using cache. This indicates that cache and power can be exchanged with each other from the viewpoint of system resource management. Specifically, if the transmit power is not sufficient in the network, we can use the cache to storage the data in the relay nodes around the destination. In this way, the transmit power resource can be minimized at the cost of cache space. On the other hand, if the cache space is not enough, the transmit power should be increased to guarantee the network outage performance. In this way, the cache resource can be saved at the cost of more transmit power.

4.3. SER without cache

For the linear modulation scheme, the system detection error performance measured by the symbol error rate can be defined as

$$P_e^{wo} = \frac{1}{\sqrt{2\pi}}\int_0^\infty F_{\mathsf{SNR}_D}\left(\frac{x^2}{\lambda}\right)e^{-\frac{x^2}{2}}dx, \tag{23}$$

where λ is a constant which is related to the used modulation method, and F_{SNR_D} is the CDF of SNR_D. By applying the analytical expression in (11) and substituting γ_{1t} by $\frac{x^2}{\lambda}$, we can obtain the integral expression of P_e^w as

$$P_e^{wo} = \frac{1}{\sqrt{2\pi}}\int_0^\infty \left(1 - e^{-\frac{Lx^2\sigma^2}{\alpha P_S\lambda}}\right)e^{-\frac{x^2}{2}}dx. \tag{24}$$

We apply the result in [28, eq. (3.321.2)] to solve the required integral and then obtain the analytical SER expression for the traditional multi-hop relaying networks without cache as

$$P_e^{wo} = \frac{1}{2} - \frac{1}{2}\frac{1}{\sqrt{1 + \frac{2L\sigma^2}{\alpha P_S\lambda}}}. \tag{25}$$

For the large transmit power with $\frac{P_S}{\sigma^2} \gg 1$, we can approximate the SER of the traditional multi-hop relaying networks without cache as

$$P_e^{wo} \simeq \frac{L\sigma^2}{2\alpha P_S\lambda}, \tag{26}$$

where the approximation of $(1+x)^{-\frac{1}{2}} \simeq 1 - \frac{x}{2}$ is applied in the last equality [27].

For a target level of SER, P_e^t, we can write the requirement on the transmit power P_S from (25) as

$$\frac{1}{2} - \frac{1}{2}\frac{1}{\sqrt{1 + \frac{2L\sigma^2}{\alpha P_S\lambda}}} \leq P_e^t \tag{27}$$

which is equivalent to

$$\frac{2L\sigma^2}{\alpha P_S\lambda} \leq (1-2P_e^t)^{-2} - 1. \tag{28}$$

After some manipulation, we can write the minimum transmit power to achieve the target SER P_e^t for the traditional multi-hop relaying networks without cache as,

$$P_S \geq \frac{2L\sigma^2}{\alpha\lambda[(1-2P_e^t)^{-2}-1]}, \tag{29}$$

where the calculation can be efficiently computed by using some numerical methods. From the asymptotic SER expression in (26), we also find the minimum transmit power to achieve the target SER P_e^t in an asymptotic form as

$$\frac{L\sigma^2}{2\alpha P_S\lambda} \leq P_e^t, \tag{30}$$

which results in

$$P_S \geq \frac{L\sigma^2}{2\alpha\lambda P_e^t}. \tag{31}$$

From the above expression, we find that the minimum transmit power is linearly varying with hop number in the relaying networks, since more hops gives more constraint on the transmission, and the weakest hop among multiple hops is the bottleneck of the whole network transmission.

4.4. SER with cache

For the cache-aided multi-hop relaying networks, the received end-to-end SNR expression is given in Eq. (6). By referring to (18) and the derivation of (23)–(25), we can write the SER of the cache-aided multi-hop relaying networks as

$$P_e^w = \frac{1}{\sqrt{2\pi}}\int_0^\infty \left(1-e^{-\frac{x^2\sigma^2}{\alpha P_S\lambda}}\right)e^{-\frac{x^2}{2}}\,dx \tag{32}$$

$$= \frac{1}{2} - \frac{1}{2}\frac{1}{\sqrt{1+\frac{2\sigma^2}{\alpha P_S\lambda}}} \tag{33}$$

In a similar way, we apply the approximation of $(1+x)^{-\frac{1}{2}} \simeq 1-\frac{x}{2}$ as in (26), and then we can obtain the asymptotic SER of the cache-aided multi-hop relaying networks as

$$P_e^w \simeq \frac{\sigma^2}{2\alpha P_S\lambda}, \tag{34}$$

where the numerical computation can be referred to some existing works [29,30]. By comparing the asymptotic expressions of the multi-hop relaying networks with and without cache, we can find that cache can significantly improve the SER performance, by prefetching the data in the relay nodes around the destination D. This further validates the advantages of cache technique.

With a given target SER P_e^t, we can write the requirement on the transmit power P_S from (33) as

$$\frac{1}{2} - \frac{1}{2}\frac{1}{\sqrt{1+\frac{2\sigma^2}{\alpha P_S\lambda}}} \leq P_e^t \tag{35}$$

which results in

$$\frac{2\sigma^2}{\alpha P_S\lambda} \leq (1-2P_e^t)^{-2} - 1. \tag{36}$$

$$P_S \geq \frac{2\sigma^2}{\alpha\lambda[(1-2P_e^t)^{-2}-1]}. \tag{37}$$

From the asymptotic SER expression in (34), the minimum transmit power can be obtained to achieve the target SER P_e^t in an asymptotic form as

$$\frac{\sigma^2}{2\alpha P_S\lambda} \leq P_e^t, \tag{38}$$

which results in

$$P_S \geq \frac{\sigma^2}{2\alpha\lambda P_e^t}. \tag{39}$$

By comparing the minimum transmit power for the target SER of the relaying networks assisted by multiple hops with and without cache, we can find that by using the cache at the relay nodes, we can reduce the transmit power significantly. In other words, the transmit power and cache can be exchanged with each other from the view of system resource management.

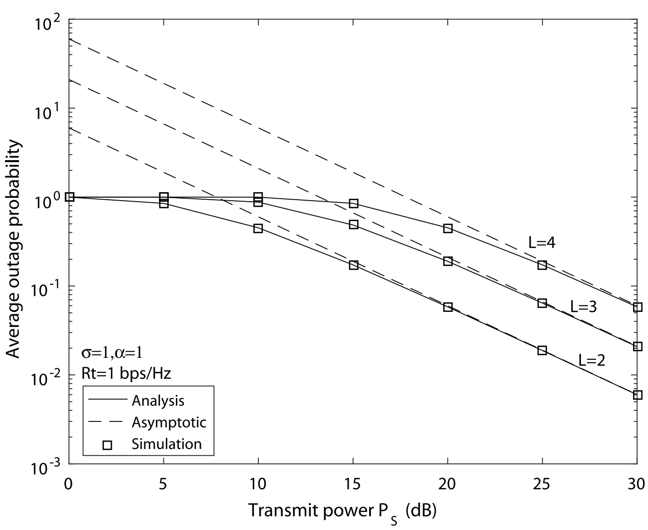
5. Numerical and simulation results

In this part, we validate the research presented earlier and show the advantages of caching technology, with some numerical and simulation results. All links in the system are experiencing Rayleigh fading, and we set the average channel gain of all links in the network to unity. In addition, the noise power is equal to 1, i.e., $\sigma^2 = 1$. So the transmit power P_s is equal to the signal to noise ratio P_s/σ^2, i.e., $P_s = P_s/\sigma^2$. Moreover, the target data rate R_t is equal to unity, so that the two associated SNR thresholds γ_{1t} and γ_{2t} are equal to 2^L-1 and 1, respectively. The linear modulation of BPSK scheme is used, so that λ is equal to 2.

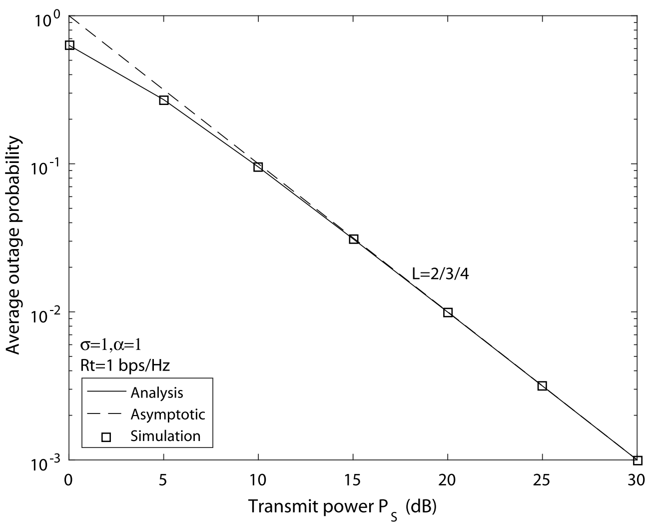
Fig. 3(a) illuminates the network outage probability varies with the transmit power P_S without cache, where $\alpha = 1$ and L varies from 2 to 4. From Fig. 3(a), we know that for various numbers of relay hops, the analysis of the outage probability and the simulation results are in good agreement, and the asymptotic outage probability fits well with the simulation one when the transmit power P_S is large. This shows the correctness and effectiveness of the analytical and asymptotic expressions for traditional multi-hop relays without caching. In addition, the network outage probability becomes larger with larger number of relay hops. This is because that the weakest hop is the bottleneck of the whole transmission, and more hops make the weakest hop even weaker.

Fig. 3(b) demonstrates how the network outage probability varies with the transmit power P_S with cache, where $\alpha = 1$ and L varies from 2 to 4. We can see from this figure that it is not only the outage probability is in good agreement with the simulation value, but also the asymptotic result is in good match with the exact one when the transmit power P_S is large. This depicts the correctness and effectiveness of the provided analytical and asymptotic expressions for the relaying networks with multiple hops. In addition, the system transmission performance does not depend on the number of relay hops, as the data has been prefetched to the relay nodes around the destination. The destination can directly acquire the data around the near-by relay node, instead of having to communicate with the source.

Fig. 4 clarifies how the minimum transmit power varies with the number of relay-hops L with and without cache, where $\alpha = 1$ and the target outage probability P_{out}^t is equal to 10^{-2}. Firstly we note that the performance derivation of Section 4 works for $L = 1$ as well. When $L = 1$ there has no relay node between the source node and the destination node, so the relaying network with cache reduces to the network without cache, resulting in the same minimum transmit power. Then we can find from Fig. 4 that by using cache, the minimum transmit power is about 23 dB, and it is not rely on the number of relay hops. On the contrary, in the traditional multi-hop relaying networks without cache, the minimum transmit power becomes larger with the number of

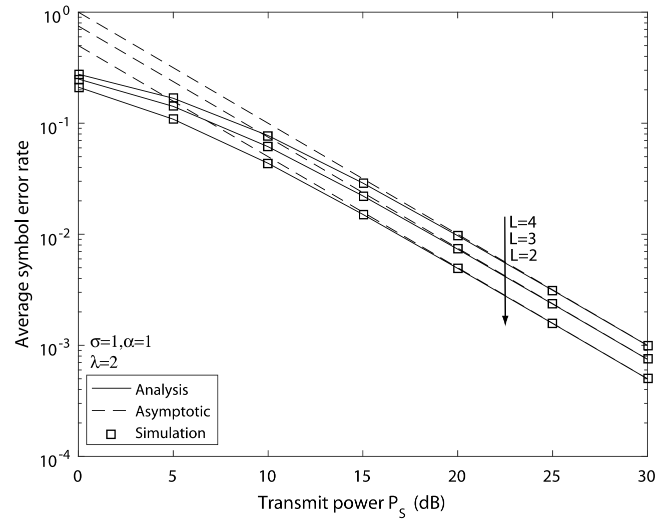


(a) Without cache

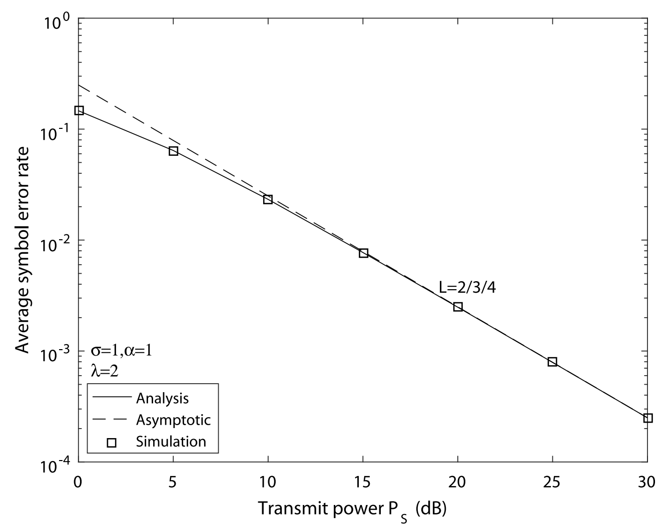


(b) With cache

Fig. 3. Outage probability versus the transmit power.



(a) Without cache



(b) With cache

Fig. 5. SER versus the transmit power.

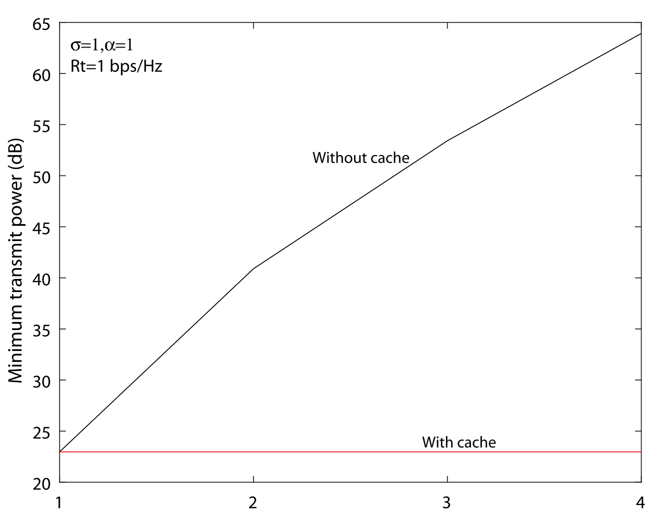


Fig. 4. Minimum transmit power for a target P_{out}^{t}.

relay-hops. In particular, the minimum transmit power reaches to 64 dB when $L = 4$. This indicates that by using cache, we can save the power resource about 41 dB, which validates that the cache and power exchange with each other in the multi-hop relaying networks.

Fig. 5(a) describes the SER versus the transmit power P_S for the traditional multi-hop relaying networks without cache, where $\lambda = 2$ and the number of relay hops L varies from 2 to 4. We can see from Fig. 5(a) that the analytical SER fits well with the simulated SER, and the asymptotic SER converges to the exact value in the high P_S region. This validates the correctness of the given analytical SER expression as well as the asymptotic SER. Moreover, the SER performance degrades with increasing number of relay hops, as more hops make the bottleneck of the whole transmission weaker. The performance curves have the same slope, showing that the number of relay-hops does not affect the network diversity.

Fig. 5(b) shows the impact of the transmit power P_S on the symbol error rate for the cache-aided multi-hop relaying networks, where $\lambda = 2$ and the number of hops L falls in $\{2, 3, 4\}$. As seen from Fig. 5(b), the analytical SER is in good agreement with the simulation SER, and the asymptotic SER becomes accurate with a

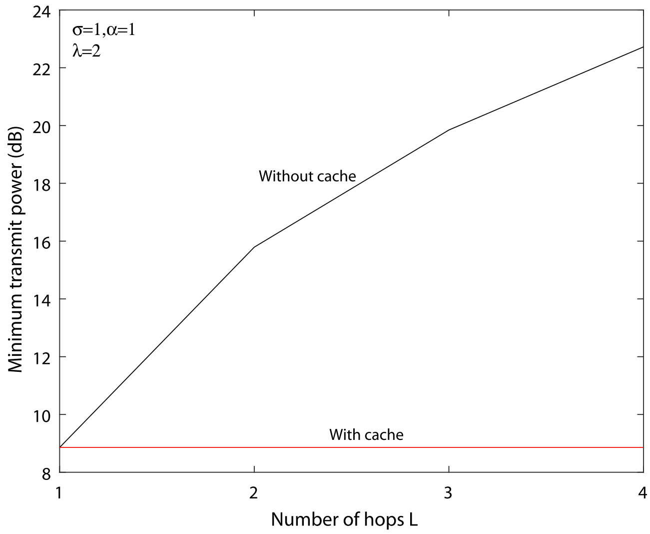


Fig. 6. Minimum transmit power for a target P_e^t.

large value of transmit power P_S, which further demonstrates the correctness of the given analytical and asymptotic SER expressions for the considered network with multiple hops. Moreover, the network SER result does not change with the number of relay-hops, as the destination can fetch the data from the near-by relay nodes, instead of communicating with the source which is possibly far from the destination.

Fig. 6 demonstrates the impact of number of relay hops L on the minimum transmit power P_S, where the target SER P_e^t is set to 10^{-2} and L is an integer between 1 and 4. We can see from Fig. 6 that the minimum transmit power of cache aided multi-hop relaying networks remains unchanged with the number of hops, as the destination acquire the data from the near-by relay nodes. In contrast, the minimum transmit power of the traditional multi-hop relaying networks increases with the number of relay-hops. The power gap between the cache-aided system and the system without cache enlarges with the value of L. In particular, when there are four hops in the network with $L = 4$, the minimum transmit power of the traditional relaying networks without cache is about 22.7 dB, while that of the cache aided relaying networks is only about 8.9 dB. In this way, the power resource about 13.8 dB can be saved at the cost of using cache. This also validates the resource exchange between cache and transmit power.

6. Conclusions

In this work, we investigated the cache-aided multi-hop UAV-relaying networks, where the destination could directly acquire the data from the cache at the nearby relay nodes instead of having to communicate with the source. For the multi-hop relaying networks with and without cache, we derived the analytical expressions for the system outage probability as well as SER. We also gave the asymptotic analysis for them. Simulation were provided to demonstrate the performance analysis, and illustrate that the usage of cache can provide ultra-reliable and low-latency communications for UAV multi-hop relaying systems. It has been concluded that cache and power resources can be exchanged with each other from the viewpoint of system resource management. In particular, for the target outage probability and SER of 10^{-2} with $L = 4$, the cache can save the transmit power of 41 dB and 13.8 dB, respectively. In the future works, we will incorporate some other wireless transmission techniques into the considered system [28,31], in order to further enhance the network reliability and security.

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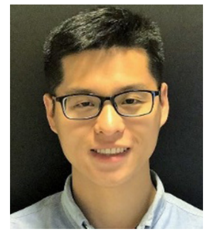

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