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Research Article

UAV-Relaying Cooperation for Internet of Everything with CRT-Based NOMA

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Due to the great potential of the combination of machine learning technology and unmanned aerial vehicle (UAV) enabled wireless communications, various optimization algorithms on resource allocation have been proposed for the Internet of Things. UAVs not only can perform the missions under the extreme conditions but also enhance the overall performance of the system as an aerial relay assisting transmission in the public and civil domains, which have been received extensive attentions. However, with the limited capacity and power constraints, they are difficult to support the transmission for the big data information users. In addition, the lack of spectrum resource poses challenges to satisfy the quality of service (QoS) of mobile users in wireless networks. To contribute to these urgent problems, this article first studies the potential and effective applications of UAVs, by introducing the Chinese remainder theorem (CRT) and nonorthogonal multiple access (NOMA) technologies into UAV relay networks. Two scenarios with/without direct transmissions between the source and destination nodes are investigated, following the decomposition and reconstruction mechanisms to satisfy the big data information transmission. Considering the user fairness, we further discuss the effect of the UAV numbers to the overall system capacity. To maximize the system capacity, the designs of transmission protocol and receiver are also discussed, in various channel conditions. Finally, a low complexity and efficient two-stage power allocation scheme is established for the perspective of users and UAV relays.

1. Introduction

The sixth generation (6G) communication requires supporting massive Internet of Things (IoT) devices and extremely differentiated IoT applications for the air-space-ground integrated network. Relying on the aerial superiority, unmanned aerial vehicle (UAV) is capable of acting as aerial base station (BS) and supporting IoT deployment in remote and disaster areas. Moreover, emerging techniques, i.e., machine learning (ML) and artificial intelligence (AI), are pushing the integration of UAVs into wireless communications, and thus millions of UAVs are estimated to be massively adopted in various real-life applications, from civilian (surveillance, transportation, environmental monitoring, industrial monitoring, agriculture services, and disaster relief) [1] to military services (air exploration, battlefield surveillance, target localization, tracking, damage assessment, and antiterrorism arrests) [2]. The popularity of multi-UAV is attributed to their vital features, such as mobility, adaptive altitude, effortless deployment, flexibility, and adjustable usage. For example, UAVs in [3] were employed to provide edge computing service for ground users. Specifically, compared to the traditional ground relays, UAVs served as mobile relays in wireless networks have been widely discussed [4, 5], since they are cost-effective and can easily and swiftly be deployed whenever needed making them very suitable for emergency and temporary events.

Due to the limitations of the small size, light weight, enduring energy, processing capability, and signal transmission range, UAVs are incapable of transmitting information with long packets. However, some actual scenarios, i.e., virtual reality, augment reality, and video surveillance, are demanding of long packet data, which poses the difficulty for UAV-assisted communications. Fortunately, Chinese

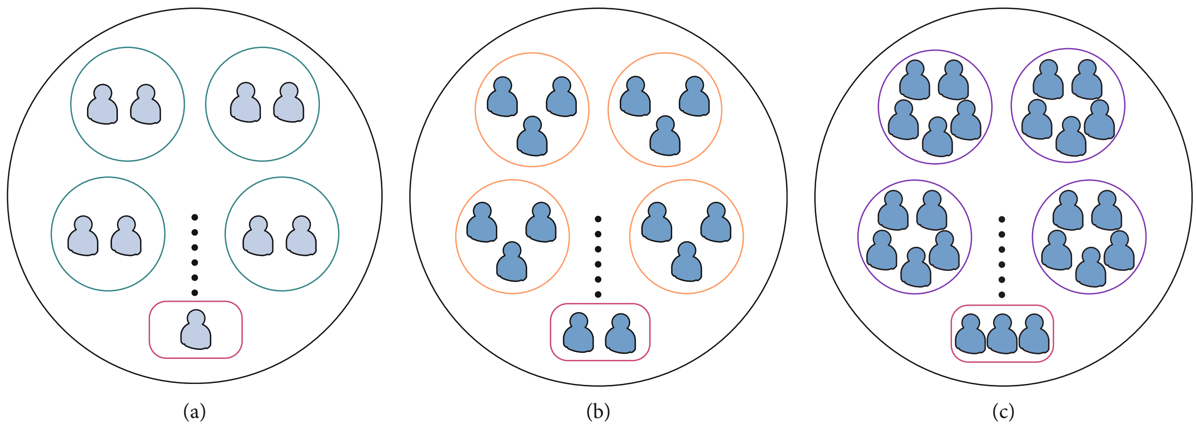

Figure 1: The graph of CRT: (a) an integer with divisor 2 and residue 1, (b) an integer with divisor 3 and residue 2, and (c) an integer with divisor 5 and residue 3.

remainder theorem (CRT) and nonorthogonal multiple access (NOMA) technology are emerging as the promising solutions to support that splitting the long packet data into the short packets using CRT, while performing superposition code (SC) for these short packets to simultaneously forward the spitted information via the UAVs. Finally, the receiver reconstructs the original long packet information, which shows the excellent spectral efficiency [6].

The Chinese remainder theorem (CRT) provides a meaningful mentality to reconstruct a single nonnegative integer from its residues modulo several smaller positive integers (called moduli) when the corresponding integer is less than the least common multiple of all the moduli (as shown in Figure 1). With this residue characteristic, the CRT has tremendous applications in many fields, i.e., the cryptograph, computing, and digital signal processing [7–9]. Different from traditional multidigit complex operations, CRT is characterized by multiple parallel and simple operation units (residue, moduli), that are a small number of digits. Besides, the parallel calculation form makes CRT enjoy more efficiency and lower complexity. Therefore, the CRT-based algorithm can be efficiently employed by wireless local area network [10], undersampling frequency estimation, and phase unwrapping [11]. With above observations, taking advantages of the residue system of CRT to decompose the long packet data into short packets, the capacity-limited UAVs will be with the ability that of assisting communications as a traditional relay between the source and destination nodes, whereas accompanied by the transmission of multiple short packets, the increase in routing complexity, and delay becomes a nonnegligible issue.

On the other hand, thanks to the superiority of spectrum efficiency, NOMA technology proposed by Saito et al. [12] has attracted a heat attention. Compared with the orthogonal multiple access (OMA), NOMA multiplexes nonorthogonal power domain at the transmitter to achieve multiple access. Meanwhile, at the receiver, multiple signals can be decoded via successive interference cancellation (SIC), which is easy to realize [13]. In a NOMA system, different transmit powers are allocated for signals with the same frequency according to the channel conditions. For example, greater power should be assigned to the signal transmitted to a UAV with better channel coefficient (i.e., weak UAV); on the contrast, smaller power will be allocated to the one transmitted to the UAV with worse channel coefficient (strong UAV). It is worth noting that the user fairness should be considered during the power allocation; in other words, the achievable rates of users in the system should not differ greatly.

Through multiplexing power domain, multiple short packets decomposed form long packets based on CRT are superposition coded at the transmitter, that will be decoded using SIC to reconstruct the original information. In this manner, the communications between users can be achieved or enhanced by this capacity-limited UAV relays. In addition, the key to realize the benefits of NOMA is that how to jointly allocate nonorthogonal resources (power, channel resources, etc.). The joint optimization of power and frequency in NOMA systems has been proved to be a mixed integer programming problem as well as a nondeterministic polynomial (NP) problem [14], which can be generally solved by the exhaustive search method. However, large number of short packets decomposed form long packets leads to a substantial increase in power allocation factors, resulting in an extremely complicated power allocation problem. Therefore, an efficient and low-complexity algorithm for power allocation is a standard to support the UAV-assisted relay networks.

To effectively enhance cooperative communications for UAV-assisted relay networks using CRT and NOMA technique, the following issues need to be investigated:

(i) Based on the CRT to establish a mathematical model for UAV-assisted relay networks, the mathematical model is the standard to effectively apply CRT to UAV relay networks. In the condition of a pair of users and a small number of UAV relays, how to design the decomposition and reconstruction schemes for long packets? In the scenario with multiple users and multiple UAV relays, how to decompose and reconstruct the long packets according to CRT in an effective way?

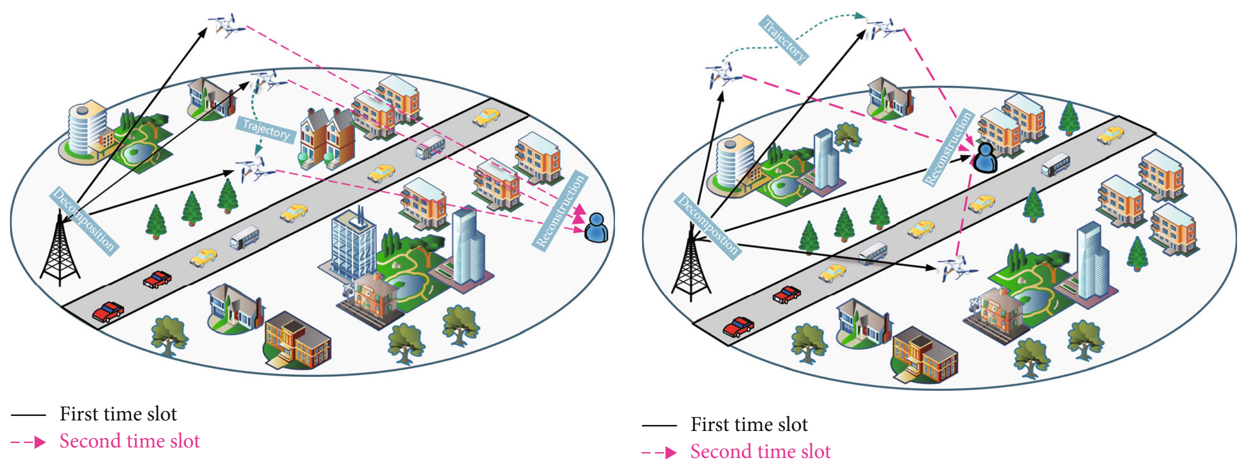

FIGURE 2: UAV-assisted relay networks: (a) without direct transmissions and (b) with direct transmissions.

(ii) Design a transmission protocol and receiver to maximize system capacity with user fairness constraints: how to ensure user fairness when designing the transmission and receiving protocols? How to calculate the effective system capacity? How does the scale of the system and various channel conditions affect user fairness and system capacity?

(iii) Develop an efficient two-stage power allocation schemes for the overall system: how to convert the power allocation problem into an optimization one? As the number of users and short packets increases, power allocation factors will increase accordingly, and hence how to investigate an efficient power allocation scheme?

The rest of this article is organized as follows. First, the decomposition and reconstruction schemes for long packets are proposed, based on the proposed mathematical model for UAV-assisted relay networks. The user fairness and system capacity are studied in NOMA enabled and UAV-assisted relay networks, providing theoretical basis for the design of capacity enhanced transmission protocol and receiver. Moreover, the power allocation schemes are developed in the perspective of users and UAV relays, in various channel conditions. Finally, we draw the main conclusions and future works.

2. Decomposition and Reconstruction of Long Packets Based on CRT

Establishing a mathematical model for long packets decomposition and reconstruction based on CRT is the basis for subsequent theoretical analysis and power allocation. In this section, under the model of a single user and a small number of UAV relays, coprime moduli will be selected as the entry point, following by the decomposition criteria and reconstruction scheme. Finally, we investigate multiuser and multirelay scenarios and preliminarily discuss the application of robust CRT (non-prime moduli) in the described system.

2.1. Mathematical Model for UAV-Assisted Relay Networks. Two types of mathematical model are summarized in this article.

(i) Without direct transmissions: the source node cannot to communicate with the destination node directly (as shown in Figure 2(a)). In this model, the source node first precodes the initial long packet data (i.e., calculate its moduli), assigns the index and allocates the transmit powers to the short packets decomposed from long packets, and then implements the SC for short packets. After receiving short packets performed by NOMA technique, UAV relay nodes decode them using SIC and then allocate transmit powers considering the channel conditions between the UAVs and destination node. In what follows, the receiver decodes the NOMA signal according to the index and signal-to-interference-plus-noise ratio (SINR). Finally, long packet information can be reconstructed using CRT

(ii) With direct transmissions: The source node is able to communicate with destination node directly (as shown in Figure 2(b)): The difference between this model and previous one is that the source node transmits short packets with SC to not only UAV relay nodes but also the receiver, during the same time slot. After receiving NOMA packets from the source node, the receiver can decode them immediately or jointly decode them after receiving the signals from the relay nodes

In above two models, the receiver distinguishes short packets according to their index and uses SIC to decode the NOMA signal. It is worth noting that in the first model, the cooperation is carried out among multiple UAV relays. The UAV relays need to coordinate demodulation schemes and forwarding schemes to maximize transmission rates of short packets on relay paths, while power allocation schemes for the source node and UAV relay nodes need should be considered simultaneously. On the other hand, in the second

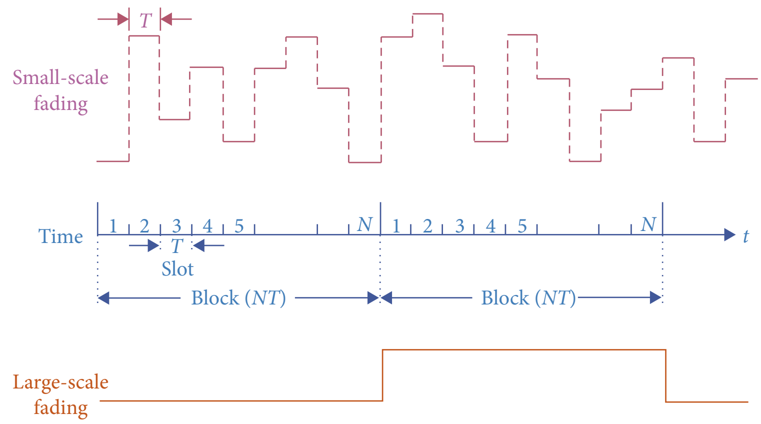

FIGURE 3: Channel variation for UAV relay nodes.

model, the destination node receives NOMA signal not only from the source node at the first time slot but also from UAV relays during the next time slot [15]. Therefore, to develop a cooperative demodulation scheme for the destination node and UAV relay nodes, thus to maximize achievable rates of short packets in the direct path and relay paths, the efficient power allocation for short packets from source node and UAV relay nodes is required.

The time domain model for the whole network is shown as in Figure 3. Time is divided into slots of length T, on the order of hundreds of microseconds, and L consecutive slots form a block, on the order of hundreds of milliseconds. Since the large scale fading of channels is typically determined by UAVs locations, which is less likely to change too much during one block, it is assumed invariant during one block but may change from one block to another. However, due to the mobility of UAVs, we assume independent and identically distributed small scale channel components for different slots, which remain constants during one slot. The users in the proposed system have the knowledge of the large scale fading information, which can be estimated or fed back from UAVs per block with a low signaling overhead. The small scale fast varying component can be assumed as an independent and identically distributed (i.i.d.) random variable for different slots but remains constant during one slot.

2.2. Decomposition and Reconstruction Scheme for Long Packets. Based on above models and CRT, long packets generated from the source node can be decomposed into multiple short packets and forwarded by UAV relay nodes and reconstructed by destination node. Though the higher latency will be introduced by signal decomposition at the source node, the small packets can be transmitted in parallel manner with the aid of NOMA, which is more efficient than the orthogonal transmission. Moreover, decomposing large packets into small ones will contribute the accuracy for decoding signals, especially for UAVs with limited communication capacity. For the reliable signal decomposition, the following cases should be considered when the decomposition happens:

(i) Case 1: two sets of index should be involved, i.e., one is for long packets, and the other is for short packets

(ii) Case 2: the elements for short packets are coprime integers, and their product should be larger than the original long packet information

To enable receiver nodes (including UAV relay nodes and destination node) to reconstruct original information effectively and accurately, receiver nodes need to acknowledge the index for long packets as well as short packets and the theory of CRT.

The following two mechanisms for moduli selection are introduced:

(i) The mechanism based on the capacity of UAV relay nodes: for the reason that the relatively prime elements (represent the volume of bits of short packets) obtained from long packets are not specific, this moduli selection scheme is based on the capacity of UAV relays. Assuming that each UAV relay is capable of process u bits, we have residue + moduli $< u$. Given the volume of bits of long packet M, each UAV in the system is capable of forwarding the obtained short packets on the condition of $(u/2)^N > M$

This scheme not only satisfies the requirement that the product of coprime elements which represent the volume of bits of short packets, is larger than that of the original long packet, but also ensures that each UAV relay node is able to forward the obtained short packets. However, the value of coprime moduli is limited by $u/2$, resulting in a poor efficiency of resource utilization, and the increase in the number of moduli will also pose pressure on the computational complexity for power allocations.

(ii) The mechanism based on the volume of bits of short packets: since the residue is generally much smaller than the value of moduli, this scheme intends to adopt the reverse thought; that is, the transmitter will try one by one ($N > 2$). After the decomposition

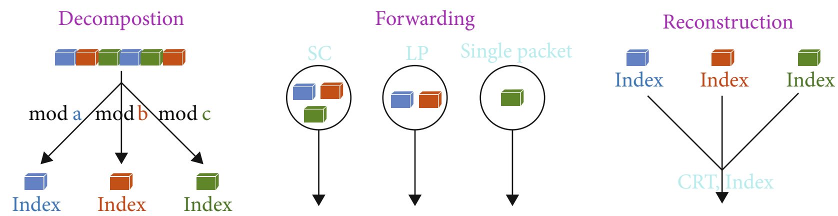

Figure 4: Three stages for data transmission.

is completed, the judgment happens: if the condition moduli + residue <, the minimum data bits of relays nodes is satisfied, and the process stops; otherwise $N = 3$, until the condition moduli + residue ≥ the minimum data bits of relays nodes holds

This scheme makes full use of the capacity of UAV relays and completes the decomposition of long packets with a small number of moduli. However, the disadvantage of this scheme lies in the large amount of calculation and high complexity. In practical scenarios, the moduli selection scheme can be determined according to not only the capacity of UAV relays but the size of data to be transmitted.

This article intends to divide the whole stage into three stages corresponding to the source node, UAV relay nodes, and receiver node (as shown in Figure 4).

(i) Decomposition stage: after completing the selection of moduli with coprime elements, a long packet is decomposed into multiple short packets in the form of moduli and residue, such that UAV relay nodes can forward short packet information successfully, and then the corresponding index is assigned to each short packet

(ii) Forwarding stage: UAV relays decode each short packet according to their data bits and SINR and forward them to the destination node after assigning new power allocation factors

(iii) Reconstruction stage: the destination node reconstructs original long packet using CRT and the index of short packets

3. Capacity Discussion for the NOMA Enabled and UAV-Assisted Relay Networks

The capacity of the described NOMA enabled and UAV-assisted relay networks is mainly discussed in this section.

3.1. Impact Factors of User Fairness and System Capacity. Since the achievable rate of each node in the system is a metric to quantify user fairness, we try to maximize the system capacity. To calculate the achievable rate, two signal input methods are considered: Gauss signal and phase-shift keying (PSK)/quadrature amplitude modulation (QAM) signal. For a Gaussian signal, the key is to find the optimal power allocation strategy that ensures the user fairness in NOMA enabled systems with low SNR. Because there is no degree of freedom (DoF) loss, the maximum achievable rate will inevitably break user fairness in the condition of high SNR (the larger power allocation coefficient approaches 1, and the smaller one approaches 0). For a finite set of input signals, it can be predicted that the achievable rate tends to spectral efficiency in the case of high SNR; however, in case of low-to-medium SNR, the achievable rate becomes complicated to predict. After all, the method of horizontal search followed by vertical search can be adopted to find the optimal power allocation scheme from a large number of time slot solutions. The horizontal search refers to developing power allocation scheme given the lower bound of each node's achievable rate. For example, for the optimization problem formulation, the system capacity is maximized under the QoS constraints, which are obtained from user fairness. The vertical search is to find the optimal scheme from horizontal search given various achievable rates.

3.2. Capacity Enhanced Transmission Protocol and Receiver Design. When a direct path exists, the source node decomposes long packet into multiple short packets in the first time slot and then performs superposition coding and allocates transmit power for short packets. In this process, the demodulation sequence at the destination node and UAV relay node will determine the achievable rates of short packets. In the second time slot, the UAV relay node forwards one or several short packets to the receiver. During the communication period, the system capacity is determined by the achievable rates of short packets in each transmission path. However, the achievable rates of short packets may be different, given different demodulation sequences in destination node and UAV relay nodes.

In the scenario without direct path, both the demodulation sequence and forwarded packets in UAVs have an impact on system capacity. Different demodulation and forwarding schemes should be analyzed given different channel conditions, to find the optimal one that can achieve the maximum system capacity. Some existing methods have provided instructions to help design effective transmission protocols and receiver schemes. In terms of the transmission protocol, there are detection-and-forward, SIC-and-forward, and amplify-and-forward, and so on, to choose from [16]. Moreover, the following two schemes can be considered for the receiver design:

(i) Scheme 1 In the first time slot, the packet with larger transmit power is firstly decoded by SIC.

(ii) Scheme 2 Using maximum ratio combining (MRC) or linear combining (LM) method, the receiver

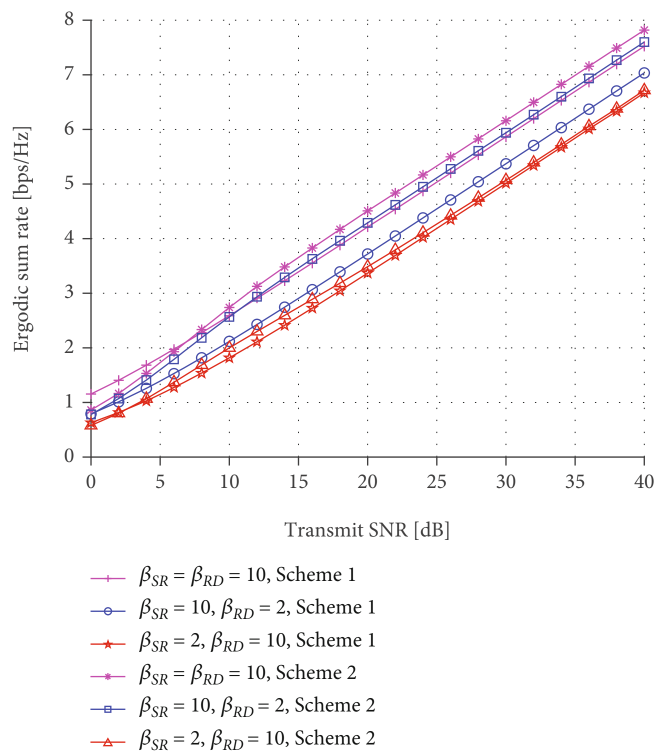

Figure 5: Performance comparison of the receiver design.

jointly decodes packets from source node and UAV relay nodes. For the model with direct transmissions, as shown in Figure 2(a), this scheme can be carried out in a similar way.

For different transmit SNRs, the performance of the considered two schemes is demonstrated in Figure 5, with the existence of the direct link.

3.3. Achievable Rates in Various Channel Conditions. When we analyze the achievable rate of each user, it is necessary to consider the impact of long/short transmission distance and perfect/imperfect channel information on the achievable rate. Based on the QoS threshold and channel information, and combining with NOMA decoding criterion (by giving larger power determined by the QoS threshold to the signal that will be transmitted to the UAV relay far away from source node, user fairness can be achieved.), all the received packets can be decoded using SIC. In the condition of imperfect channel information, the channel error can be expressed in the form of norm-bounded-error (NBE), and the achievable rate of each user can be obtained in the worst case. After all, the bounds of system capacity can be quantified in closed form expressions.

4. A Two-Stage Power Allocation Scheme

In the multiuser scenario, the source node will perform two-layer SC (i.e., two-layer NOMA signal): long packets from multiple source nodes and short packets decomposed from long packets. It can be found that there will be $N \times M$ short packets (N denotes the number of long packets, and M represents the number of short packets) in the system. The power allocation problem is a large scale NP-hard problem that should be solved within extremely large time complexity. Therefore, this article intends to develop an efficient and low-complexity two-stage power allocation scheme, which cannot only reduce the computational complexity but also reflect efficient performance gain in combination with user fairness.

4.1. Power Allocation for Source Nodes. The power allocation for source nodes is carried out among long packets, which needs to satisfy user fairness as well as the constraints of UAV relay nodes. For simplicity, we consider a system without direct transmissions between source node and destination node, and two UAV relay nodes decode then forward NOMA signals. To narrow the achievable rate gap between two relay paths, he power allocation factors for source node and relay node denoted by $\alpha \geq 0$ and $p \geq 0$, respectively, should satisfy $((2^{\mu} - 1)/2^{\mu}) \cdot ((P_T h_{1,R}^2 + 1)/P_T h_{1,R}^2) \leq \alpha \leq 1$ and $2^{\mu} - 1/P_R h_{1,R}^2 \leq p \leq 1$, where μ is the QoS requirement obtained according to Shannon's theorem, $h_{1,R}$ and $h_{R,1}$ are channel information, and P_T and P_R denote the transmit power of source node and relay node, respectively. Combining the QoS and relay node constraints, the power allocation at source node is formulated as a ergodic capacity maximization problem. For the system with multiple source nodes, a similar method can be applied to perform power allocation at source nodes.

4.2. Power Allocation for UAVs Relay Nodes. The power allocation for UAV relay nodes is a two-step process: power allocation for short packets and relay nodes. According to different forwarding strategies, the SINR of source nodes is theoretically analyzed and compared, so as to determine the optimal power allocation scheme. It is noted that when power allocation is performed at UAV relay nodes in the system without direct transmissions, the transmit power of each relay node should be consistent with that of source node; meanwhile, power constraints should also be satisfied. Through analyzing the relationship between secondary power allocation coefficients and system capacity, the optimal joint power allocation scheme can be obtained.

5. Conclusion

By introducing CRT and NOMA technologies into UAV-assisted relay networks, the implement of UAV relays can be achieved to assist communication between transmitter and receiver. In this article, a set of applications and challenges for realizing the vision of UAV relays is identified and discussed, following by the presentation for potential solutions of CRT and NOMA. We then present the mathematical model as well as long packets decomposition and reconstruction scheme for UAV-assisted relay networks, based on CRT. Meanwhile, important aspects of the NOMA enabled system capacity are carefully discussed, including user fairness, transmit protocol, and receiver design and channel quality. Finally, a two-stage power allocation scheme is given to further enhance system capacity. As a complex cyber physical system, the UAV enabled wireless systems integrate multidisciplinary techniques and heterogeneous resources. The coordination among communication, computation, and control is vital to the efficiency and performance of executing UAV enabled wireless communications.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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