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COOPERATIVE ROUTING MEETS SWARM UAVS

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14. ABSTRACT

This project develops a novel and fundamental framework on which new enabling UAV swarm network communication technologies and routing protocols can be designed and analyzed:1) focuses on random network coding (RNC)-based routing protocols for UAV swarm networks where RNC is utilized to improve the efficiency of the flooding-based routing in swarm UAV networks without relying on network topology information and routing path discovery.; 2) optimizes the RNC-based routing protocol with the aim of minimizing the transmission cost in the first hop; and 3) demonstrates the effectiveness of the introduced strategies using Extendable Mobile Ad Hoc Network Emulator (EMANE)

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1.0 EXECUTIVE SUMMARY

1.1 Overview of the Project

Unmanned aerial vehicle (UAV) networks are a promising wireless communications infrastructure with wide-ranging applications in both commercial and military domains. To enable UAV networks to handle complicated missions, provide wireless coverage for a large range, and have a long lifetime, a UAV network may consist of a large amount of UAVs, which work cooperatively as a swarm, also referred to as a swarm UAV network. Although high mobility and numerous UAVs offer the potential of performance enhancement in swarm UAV networks, they also incur some technical challenges. One of the major challenges is the routing protocol design.

In light of the unique propagation characteristics as well as the new challenges of UAV swarm networks, the project "Cooperative Routing Meets Swarm UAVs" is funded by Air Force Research Laboratory (AFRL) under grant number FA8750-18-1-0175 to develop a novel and fundamental framework on which new enabling UAV swarm network communication technologies and routing protocols can be designed and analyzed. To be specific, the project 1) focuses on random network coding (RNC)-based routing protocols for UAV swarm networks where RNC is utilized to improve the efficiency of the flooding-based routing in swarm UAV networks without relying on network topology information and routing path discovery.; 2) optimizes the RNC-based routing protocol with the aim of minimizing the transmission cost in the first hop; and 3) demonstrates the effectiveness of the introduced strategies using Extendable Mobile Ad Hoc Network Emulator (EMANE) and Common Open Research Emulator (CORE). The emulation studies verify the effectiveness and superiority of the designed routing protocols, which have better performance on the average transmission delay and the delay violation probability than existing routing protocols. On the other hand, our demo results using EMANE/CORE confirm the analytical results.

1.2 List of People Involved

There is one faculty member, two Ph.D. students, and one Master student involved in the project, which is listed in the following:

- Lingjia Liu; Virginia Tech (VT); PI
- Hao (Antonio) Song; Virginia Tech (VT); Ph.D. student investigator
- Bodong Shang; Virginia Tech (VT); Ph.D. student investigator
- Bowen (Aaron) Xu; Virginia Tech (VT): M.S. student investigator

It is important to note that Hao defended his Ph.D. in February 2021 with help from the grant.

2.0 INTRODUCTION

Networks today are shifting to the paradigm, wherein many of their capabilities will be generated through, and dependent on, the integrated efforts of multiple components. In general, robust dynamic tactical networks can support 10,000 to 500,000 communicating devices. It goes beyond traditional tactical networks and ad-hoc networks. Furthermore, the network should provide robust data services to tens or hundreds of fixed and mobile users with different service levels. Some of the service challenges include guaranteed rates, communication over difficult channels, strict time-deadlines, reliable message delivery over unreliable networks, security, and policy-driven resource allocation.

Unmanned aerial vehicle (UAV) networks have recently been attractive to both military and commercial applications in wireless communications, due to their tremendous advantages, such as low cost, easy deployment, high mobility, and high flexibility [Zeng2016 Wireless], [Mozaffari2019 A]. For example, they are helpful in applications where human participation would be impossible. UAVs have been used for monitoring areas that are inaccessible [White2008 Contaminant], exploring locations/situations that are too dangerous for humans [Caltabiano2005 Architecture], or delivering information to and from areas with no infrastructure [Lee2009 Wireless]. UAVs are also useful to prevent the waste of human resources and enable efficient operations in some mechanical motions and routine missions, such as traffic monitoring [Puri 2007 Statistical], [Chen2007 Real-time], and agricultural surveillance [Herwitz2004 Imaging]. Military uses of UAV networks have been developed for a long time because of the benefit that they can execute missions securely and rapidly. These applications include border surveillance [Girard2004 Border] and reconnaissance [Bao2010 Path], [Kuiper2006 Mobility]. Owning to the flying platform and high-mobility nature, UAV networks have been widely studied to be employed in emergency communications. When communication networks and infrastructures, such as base stations (BSs) or power systems, get crippled by disasters, UAV networks are able to provide assistance in speeding up rescue and recovery operations by establishing temporary communication connections between the disaster survivors, rescue teams, and nearest available cellular infrastructure [Zhao2019 Uav-assisted], [Panda2019 Design], [Erdelj2016 Uav-assisted].

In some applications, UAV networks have to handle complicated missions, for example working as an aerial BS to provide the coverage for a small cell [Valavanis2015 Handbook], [Sekander2018 Multi-tier]. Due to the fact that some UAVs are simple devices with limited battery supply and low transmit power, the concept of swarm UAV networks has come up, where UAVs operate cooperatively as a swarm, enabling UAV networks to be effectively utilized in complicated missions [Zhong2020 Joint]. According to [Hayat2016 Survey], UAV networks would be more powerful with better communication quality, larger coverage range, and longer lifetime, if more UAVs are included in a swarm UAV network. Although the swarm feature could bring in significant benefits, it also incurs many technical challenges in practical use. The properties of a swarm UAV network are characterized as follows: 1) Lack of centralized control; 2) Dynamic network topology; 3) Limited capability; 4) Dense and a large amount of UAVs.

Routing, multicast, and data exchange are three fundamental and key technologies for swarm UAV networks. For routing, it is essential when a swarm UAV network works as a mobile ad hoc network, for example, used in device-to-device (D2D) networks. When a swarm UAV network is applied as a relay, some messages broadcasted by BSs are commonly required by all the UAVs, such as data and scheduling signaling, where multicast transmissions need to be carried out periodically. Efficient data exchange technologies are also critical. For example, UAVs could help each other retrieve their lost packets through data exchange between them. Unfortunately, the aforementioned characteristics of swarm UAV networks, especially dynamic network topology, the coordination of numerous UAVs, and the simple device nature of UAV devices, may become technical barriers for routing, multicast, and data exchange, compromising the performance or make existing technologies inapplicable.

Compared to retrieving lost packets through retransmissions of BSs, lost packets retrieved by requesting from their neighbor UAVs would be more efficient and reliable, especially when UAV networks are deployed far away from BSs where retransmissions of BSs experience long-distance propagation effects. However, a significant technical issue arises for retrieving lost packets through requesting other UAVs especially in a swarm UAV network where UAVs are widely and sparsely distributed to provide the coverage for a large area. In such a network, a UAV may fail to request its lost packets to UAVs relatively far away from it due to the low transmit power of UAVs. Thus, how to define "neighbor UAVs" that could help each other retrieve their lost packets should be studied. Instinctively, neighbor UAVs should be close to the UAV requesting its lost packets so that wireless transmissions between them are in a short-range with high success probabilities. On the other hand, the number of neighbor UAVs should be large enough to guarantee that at least one neighbor UAV could provide requested lost packets.

On the contrary, in a swarm UAV network where UAVs are closely distributed and all UAVs stay together, a long data exchange delay would be a significant technical challenge. Considerable delay will be caused by spectrum access competitions when a listen-before-talk spectrum access protocol is used, such as the carrier sense multiple access/collision avoidance (CSMA/CA). Since all UAVs are close and cause severe interference to each other, all UAVs will compete for spectrum access, incurring a long data exchange delay and large overhead. Hence, proper data exchange schemes should be designed for swarm UAV networks with closely distributed UAVs, enabling efficient data exchange between UAVs.

Two demos have been done. Specifically, the initial demo was performed in August 2020, and the final demo result was validated in March 2021. To be specific, random network coding-enabled routing for a five-node UAV swarm network has been demonstrated and the performance gain of the hardware demo is shown to match very well with the theoretical characterization.

The project was organized around three interconnected research thrusts:

1) Thrust 1: random network coding-enabled UAV swarm network routing protocols.
2) Thrust 2: optimization of the designed random network coding-enabled UAV swarm network routing protocols.
3) Thrust 3: EMANE/CORE demo for the designed UAV swarm network routing protocols.

In the following sections, we describe the Methods, Assumptions, Procedures, Results, and Discussions for each of the aforementioned contributions.

3.0 METHODS, ASSUMPTIONS, AND PROCEDURES

The project can be summarized into three interconnected research thrusts: Thrust 1: random network coding-enabled UAV swarm network routing protocols; Thrust 2: optimization of the designed random network coding-enabled UAV swarm network routing protocols; and Thrust 3: EMANE/CORE emulation for the designed UAV swarm network routing protocols.

The following technologies are adopted in the project to advance the objective in each thrust.

Random Network Coding (RNC)

Here, the encoding and decoding methods of RNC are described. Given M original packets, $x_1, x_2, \cdots, x_M$, a transmitter node creates encoded packets, also referred to as generations, by linearly combining original packets with randomly chosen encoding coefficients [Ho2006 A]. To be specific, the encoded packet/generation at the time slot t could be expressed as:

$$g_t = \alpha_{t1} \cdot x_1 + \alpha_{t2} \cdot x_2 + \cdots + \alpha_{tM} \cdot x_M = \sum_{i=1}^{M} \alpha_{ti} \cdot x_i \tag{1}$$

where α_{tm} denotes the multiplicative coefficient that corresponds to the original packet x_m at time slot t, $m = 1, 2, \cdots, M$, which is randomly drawn from a finite field F. This randomness could guarantee the linear independence of generations created at different time slots. In this way, any M different generations received by a receiver node could enable it to decode all M original packets. For example, when $M = 3$, if a receiver node successfully receives 3 different generations at any three different times, t_1, t_2, and t_3, respectively, it is able to obtain a coefficient matrix with full rank and decode all original packets as follows:

$$\begin{bmatrix} g_{t_1} \\ g_{t_2} \\ g_{t_3} \end{bmatrix} = \begin{bmatrix} \alpha_{t_1 1} & \alpha_{t_1 2} & \alpha_{t_1 3} \\ \alpha_{t_2 1} & \alpha_{t_2 2} & \alpha_{t_2 3} \\ \alpha_{t_3 1} & \alpha_{t_3 2} & \alpha_{t_3 3} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}. \tag{2}$$

Compared to the traditional method that assumes that original packets are delivered independently and separately, RNC has significant advantages, especially in multicast scenarios with multiple receiver nodes. First, when a receiver node fails to receive a packet, it does not have to wait for this packet to be transmitted again, as receiving a full set of any generations can lead to the successful decoding of the original packets. Second, the use of RNC can greatly reduce ACK feedback overhead, by which a receiver node is required to feed an ACK back to its transmitter UAV only when the receiver node receives a full set of generations [Esmaeilzadeh2017 Random]. However, when original packets are transmitted independently and separately, full feedback is needed for efficient transmissions. With full feedback, receiver UAVs need to feed ACKs back to the corresponding transmitters for each received packet, so that transmitters could be aware of the packets that have already been received by all receiver nodes to avoid redundant transmissions. To facilitate original packet decoding, the corresponding encoding coefficient information should be involved in encoded packets along with created generations [Gligoroski2015 Minimal]. The proper frame structure design of encoded packets will be discussed in the following section.

3.1 Flooding-based Routing Protocol Design Using Random Network Coding

The routing protocol design is critical and challenging in swarm UAV networks with dynamic network topologies and many UAVs. In this chapter, novel flooding-based routing protocols are designed in swarm UAV networks, enabling efficient flooding-based routing without relying on any network topology information and routing path discovery.

3.1.1 Routing Protocols for UAV Networks

In UAV networks, the dynamic topologies and a large number of potential destinations may result in frequent routing table updates and high overhead for routing path explorations. On the contrary, routing path explorations with reactive routing protocols are triggered based on the demand of packet arrivals [Biomo2014 Routing], [Oubbati2019 Uav-assisted]. As a result, although reactive routing protocols can effectively mitigate the overhead of routing path establishments, they may still be not suitable for UAV networks, as numerous UAVs with many potential routing paths will incur high routing path exploration delays and high end-to-end delays [Oubbati2019 Routing], [Jiang2018 Routing]. To shorten the delay, a reactive routing protocol, named energy-efficient connectivity-aware data delivery (ECaD), is introduced, in which the design of routing protocol considers both path failures and energy consumptions of UAVs [Oubbati2019 Ecad]. Although corresponding simulation study shows that this routing protocol could effectively reduce the end-to-end delay, a global vision of the connectedness degree of wireless links and the energy conditions of UAVs is needed. This would entail extra burden and high complexity. To overcome the disadvantages of proactive and reactive protocols, hybrid routing protocols have been introduced [Yang2009 Hybrid], [Wang2004 A], where the whole network is partitioned into different zones. Proactive routing is utilized inside each zone, while reactive routing is used in transmissions between zones. Despite the benefits of proactive and reactive routing protocols, new challenges arise, for example, how to reconstruct zones when current zones are not suitable anymore. In UAV networks, the repartioning of zones may be triggered frequently to adapt to the dynamic topology. Position-assisted routing protocols are shown to be able to effectively address the problems of routing path establishment overhead and end-to-end delay [Biomo2014 Routing], [Hyland2007 Simulation]. Unfortunately, the operation of position-assisted routing protocols depends on instantaneous and accurate geographic position information, the acquisition of which may need additional hardware, like GPS. The performance of GPS is dominated by many factors, such as environments and weather, which cannot always provide precise and instantaneous position information [Khelifi2018 Localization]. A novel position-assisted routing protocol is introduced in [Khelifi2018 Localization], where UAVs positions were acquired through localization techniques rather than GPS. However, the performance of this routing protocol heavily depends on the accuracy of the underlying localization technique. Even with an ideal condition that GPS is always functional and reliable, it is not easy to apply position information provided by GPS in routing protocol design. This is because powerful infrastructures, like control centers/base stations, are required to conduct a series of complicated operations, including collecting position information of UAVs, discovering a routing path, and feeding the discovered routing path back to UAVs. Considering the mobility and some special application scenarios of UAVs, it cannot be guaranteed that such a powerful infrastructure always exists for UAV networks. Apart from position information, other criteria are also leveraged to assist routing protocol design recently. For example, the probability of arriving and cost are taken into account in stochastic vehicle routing in [Cao2016 Improving], where mixed-integer linear programming (MILP) problems are formulated to find the optimal path. In [Mohan2018 Dynamic], the authors develop a dynamic attack resilient routing (ARR) approach, in which the optimal routing path is explored by an optimization formulation considering path reliability and load. The authors in [Zhang2018 An] design a QoS-aware routing algorithm, where the routing paths are arranged according to the priority of data and the reliability of links. Although these routing approaches have been proven capable of enhancing the performance of routing, they heavily depend on network topology information, path quality information, and centralized control, which may be unrealistic in swarm UAV networks.

3.1.2 System model for SBSS

As shown in Fig. 1, a swarm UAV network consisting of U UAVs is considered, where all the UAVs operate in a distributed way without centralized control. Furthermore, all UAVs are randomly distributed in the network and the position of each UAV will be changed over time. Let $\mathsf{U} = \{u | u = 1, 2, \cdots, U\}$, where UAV 1 and UAV U denote a source UAV and a destination UAV, respectively. Except for the source UAV and the destination UAV, all other UAVs are forwarding UAVs, which could serve as both receiver and transmitter UAVs.

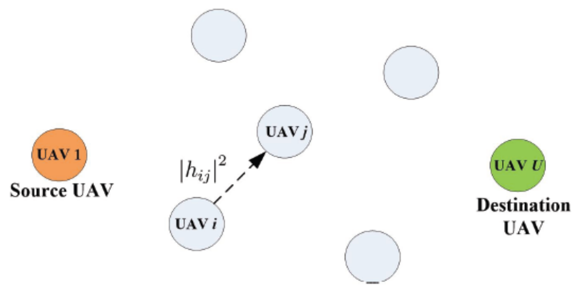


Figure 1: System Model

For simplicity, the only available wireless channel is shared by all the UAVs. Other UAVs are deemed as potential forwarding nodes to carry out routing processes. The wireless transmissions of encoded packets are time-slotted, and the time length of a slot corresponds to the length of the transmitted packet. Besides, it is assumed that the carrier sense multiple access with collision avoidance (CSMA/CA) MAC protocol is applied in UAVs to perform spectrum access and prevent collisions between UAVs. With CSMA/CA, a UAV can access a channel only if the channel is sensed to be idle.

In this paper, we adopted the Shannon approximation to determine the performance of the underlying wireless link between a transmitting UAV and a receiving UAV. Thus, the signal-to-noise ratio (SNR) of received signals is essential to calculate successful transmission probabilities between two different UAVs and the corresponding performance indicators.

The SNR of received signals at a receiver UAV j can be given by

$$r_{ij} = \frac{p_i \cdot |h_{ij}|^2}{B \cdot N_0} \tag{3}$$

where p and $|h_{ij}|^2$ are the transmit power of a transmitter UAV i, and the gain of the link from i to j, respectively. B and N_0 are channel bandwidth and noise spectral density, respectively.

3.1.3 Basic RNC-based routing protocol

It has been shown that RNC can effectively improve the transmission efficiency of multicast [Ho2006 A], [Li2016 Adaptive]. Therefore, RNC can naturally enhance the efficiency of a flooding-based routing process. In each hop, transmissions between a transmitter and multiple potential receivers can be viewed as a multicast system. Firstly, a basic RNC-based routing protocol is designed in swarm UAV networks, which is referred to as the proposed routing protocol 1 in the following.

In the first proposed routing protocol, operations of a UAV and the corresponding routing rules are very simple, which are shown in Fig. 2 followed with descriptions:

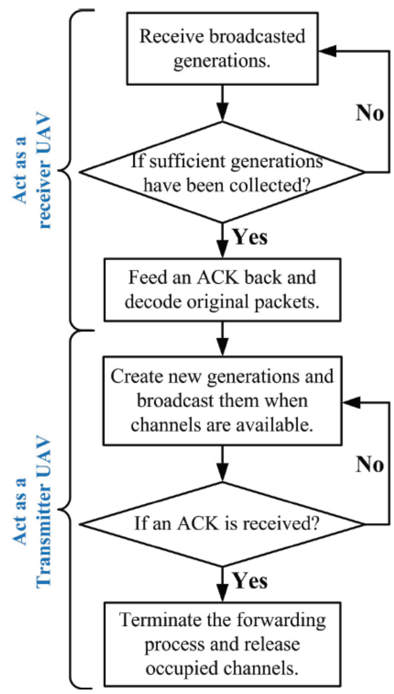


Figure 2: Operations with the Proposed Routing Protocol 1

Operations of a receiver UAV: After a receiver UAV collects sufficient linear independent generations, it feeds an ACK back to the current transmitter UAV and decodes original packets.

Operations of a transmitter UAV: A transmitter UAV is required to create new generations according to (2) and broadcast them when wireless channels are available. Then, once the transmitter UAV receives an ACK fed back from another UAV, it will terminate its forwarding process and release occupied wireless channels.

Termination rule 1: A forwarding UAV, that has already completed its forwarding processes, will not participate in forwarding processes related to the same set of original packets again, to move the routing process forward to the destination UAV.

Termination rule 2: The whole routing process is completed, when the destination UAV decodes original packets and feeds back an ACK. Thus, all the forwarding UAVs stop their forwarding processes immediately, once they receive an ACK from the destination UAV.

Routing recovery strategy: A transmitter UAV cannot receive any ACK feedback after broadcasting for a long time, meaning that its encoded packets cannot be successfully received by any UAVs, even for those nearby nodes. In this situation, the transmitter UAV will terminate its forwarding process and release its occupied channels. After a pre-defined period, the transmitter UAV will act as the source of original packets that encountered the routing failure and will start a new routing process. Notably, the time threshold of routing failure is varied according to the types of traffic, which should be determined based on the sensitivity to delay.

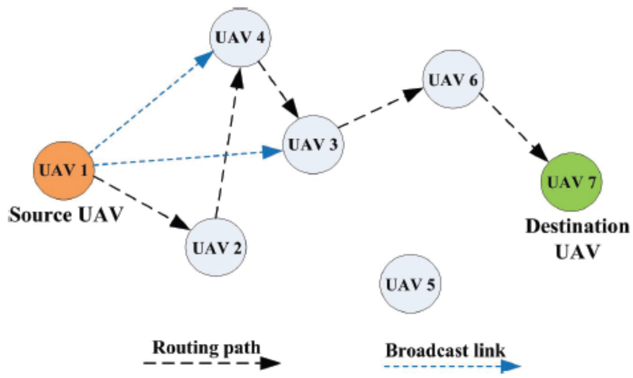


Figure 3: Routing with the Proposed Routing Protocol 1

Using RNC, generations received by a forwarding UAV may come from different transmitter UAVs in different hops. Therefore, routing processes can be significantly accelerated, as in some hops' receiver UAVs may only need to successfully receive fewer generations to decode original packets with a lower delay. Fig. 3 gives an example of the routing process with the proposed routing protocol 1, where a UAV network with 7 UAVs, 1 wireless channel, and M original packets is considered. In the first hop from the source UAV to UAV 2, UAV 2 will first accumulate M encoded packets to decode M original packets due to the shorter distance to the source UAV. UAV 3 and UAV 4 may also successfully receive $M1$ and $M2$ generations from UAV 1, respectively. However, the amounts of received generations are not sufficient to decode original packets since $M1 < M$ and $M2 < M$. In the following hops, UAV 3 and UAV 4 can accumulate a full set of generations quickly. This is because UAV 4 has already received $M2$ encoded packets from UAV 1 in the first hop. In the second hop from UAV 2 to UAV 4, UAV 4 merely needs to receive $M - M2$ generations from UAV 2 to decode original packets. Similarly, in the next-hop from UAV 4 to UAV 3, the forwarding process may be faster, as UAV 3 has accumulated some generations from UAV 1 and UAV 2 in previous hops. Less encoded packets are required to be delivered in the hop from UAV 4 to UAV 3.

3.1.4 Enhanced Routing Protocol with RNC

It is noticeable that in contrast to multicast scenarios, only one destination exists in swarm UAV networks, indicating that only the destination UAV must decode original packets. In other words, the goal of routing protocol design for swarm UAV networks is to let the destination UAV accumulate sufficient generations to decode original packets. It is unnecessary for forwarding UAVs to get original packets. Therefore, to further improve the efficiency of multi-hop transmissions, another enhanced routing protocol is designed based on RNC, also referred to as the proposed routing protocol 2. With the enhanced routing protocol, the multi-UAV diversity is exploited to efficiently create plentiful generations for the destination UAV, while each forwarding UAV merely needs to produce a new generation and broadcast it rather than decoding original packets, as shown in Fig. 4. The whole routing process could be divided into a first hop, middle hops, and the last hop, the details, and corresponding rules of which are described as follows.

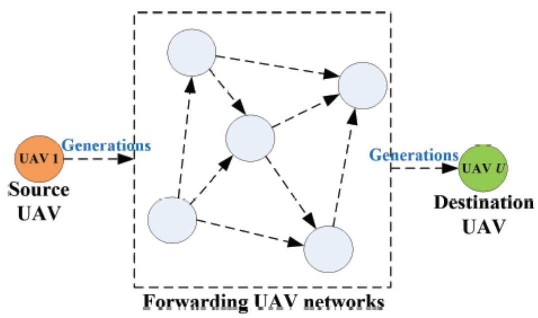


Figure 4: Routing with the Proposed Routing Protocol 2

First Hop: The first hop occurs when the transmitter UAV is a source UAV. The operations of a source UAV have been illustrated in Fig. 5.

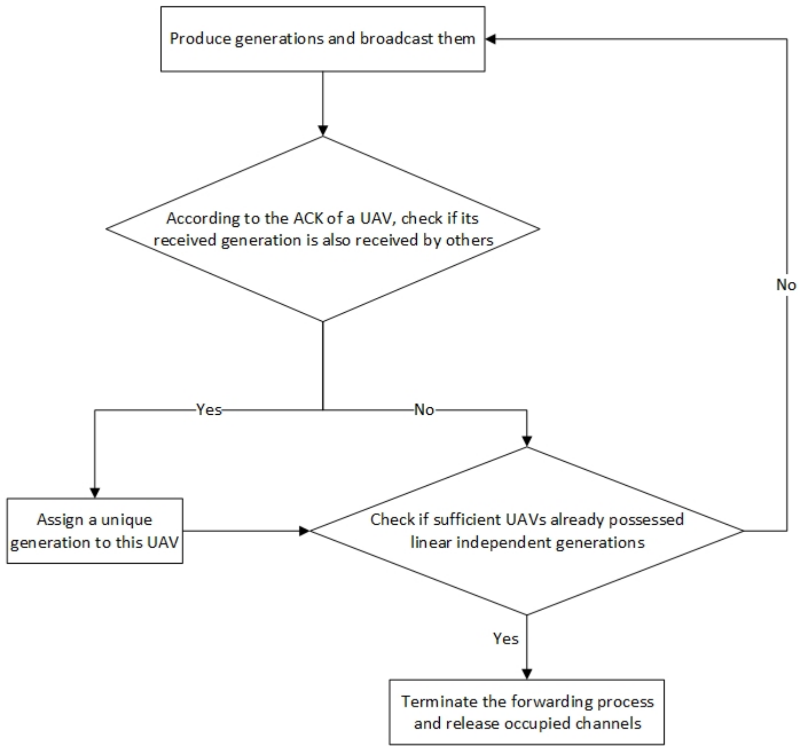


Figure 5: Operations of a Source UAV With The Proposed Routing Protocol 2

Operations of the source UAV: Generate linear independent generations according to (2) and keep broadcasting them.

Linear independence rule of the source UAV: After receiving an ACK from a forwarding UAV, the source UAV needs to check if the generation received by the forwarding UAV is also received by other forwarding UAVs that have already fed back ACKs. If yes, the source UAV will assign a particular generation, which can be only used by this forwarding UAV and should be discarded by others. The Identification (ID) of the desired forwarding UAV should be added in the encoded packet carrying its assigned generation to let the forwarding UAV recognize the generation assigned to it.

Termination rule of the source UAV: The source UAV terminates its transmissions and releases occupied channels when receiving enough ACKs from different UAVs, as well as the ACK regarding each assigned generation.

Operations of forwarding UAVs: Once receiving a generation or an assigned generation, a forwarding UAV feeds back an ACK to the source UAV. The ACK packet should include the information of received generations. If a forwarding UAV receives an assigned generation from the source UAV, its new generation will be created by

$$\begin{aligned} g' &= \beta_1 \cdot g_1 + \beta_2 \cdot g_2 \\ &= \beta_1 \cdot \sum_{i=1}^{M} \alpha_{1i} \cdot x_i + \beta_2 \cdot \underbrace{\sum_{i=1}^{M} \alpha_{2i} \cdot x_i}_{\substack{\text{the assigned} \\ \text{generation}}} \\ &= \sum_{j=1}^{2} \sum_{i=1}^{M} \beta_j \cdot \alpha_{ji} \cdot x_i \end{aligned} \tag{4}$$

where $g_j = \sum_{i=1}^{M} \alpha_{ji} \cdot x_i$ and β_j are j-th combined generation and the corresponding multiplicative coefficient, respectively. Otherwise, the forwarding UAV will treat g_1 as its generation, which will be broadcasted by the forwarding UAV when a wireless channel is available.

Theorem 1: If each forwarding UAV can have a unique generation to create its new generations, new generations created by them will be linearly independent.

Based on Theorem 1, the linear independence rule is designed to ensure that the first-hop generations created by different forwarding UAVs are linear independent.

Middle Hops: Middle hops indicate multi-hop transmissions among forwarding UAVs.

Operations of forwarding UAVs: After a forwarding UAV receives a generation from another forwarding UAV, it will feed an ACK back and linearly combine the generation with previously received generations. The forwarding UAV keeps performing the process until a wireless channel is detected to be idle. Then, the forwarding UAV will keep transmitting its created generation until receiving sufficient ACKs from different UAVs.

Last Hop: In the last hop, only the destination UAV will be deemed as the receiver UAV.

Operations of the destination UAV: Check the linear independence of each received generation and feed an ACK back when a linear independent generation is received. Keep carrying out the operations until accumulating sufficient generations to decode original packets.

General rules: Some general rules need to be followed by all the UAVs, including:

i) Termination rule 1 mentioned above.

ii) The required number of ACKs to terminate forwarding processes of a transmitter UAV should be at least equal to the number of original packets, guaranteeing that the destination UAV could accumulate sufficient linear independent generations for decoding.

iii) Some forwarding UAVs may receive ACKs fed back from the destination UAV before its forwarding processes. Let N represent the number of ACKs that have been received from the destination UAV before forwarding processes. As for a forwarding UAV, the number of ACKs required to terminate the forwarding process is $M - N$.

iv) If after a pre-defined period, a transmitter UAV still cannot receive sufficient ACKs from different UAVs, the transmitter UAV will terminate its forwarding process and release occupied wireless channels to let other UAVs continue the routing process.

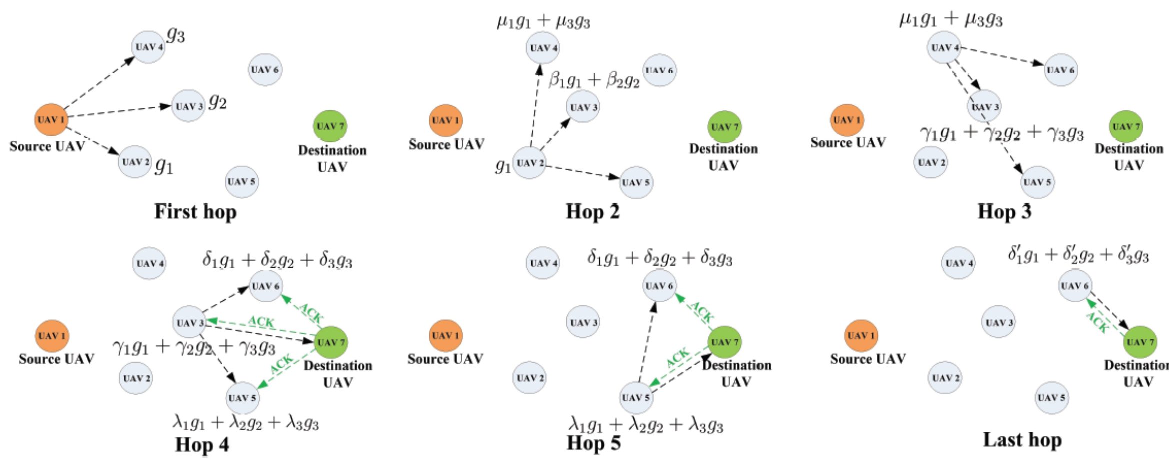


Figure 6: Routing Process of the Proposed Routing Protocol 2

To elaborate detailed routing processes of our proposed routing protocol, an example is given in a UAV network with 7 UAVs (1 source UAV, 1 destination UAV, and 5 forwarding UAVs), 3 original packets, 1 wireless channel, and 3 required ACKs, as shown in Fig. 6. The whole routing process consists of 6 hops, the details of which are described as follows.

First hop: The source UAV generates different generations in the form of linearly combining the source packets with randomly chosen coefficients and broadcast them using an idle channel. The source UAV will keep sending generations and occupying the unique channel until making sure that new generations created by 3 nearby UAVs according to (4), namely UAV 2, UAV 3, and UAV 4, are linearly independent with each other, which are denoted by g_1, g_2, and g_3.

Hop 2-Hop 3: Assume that UAV 2 wins the channel access opportunity from competitions with the other two UAVs under CSMA/CA protocol. Then, UAV 2 will keep sending its newly created generation until receiving 3 ACKs from the other three forwarding UAVs. To be specific, after receiving g_1 from UAV 2, UAV 3 and UAV 4 will linearly combine g_1 with their current generations, g_2 and g_3, respectively, while UAV 5 will store g_1 for future combination. When Hop 3 finishes, UAV 3 and UAV 5 will generate new generations, which are the linear combinations of $\beta_1 g_1 + \beta_2 g_2$ and $\mu_1 g_1 + \mu_3 g_3$, as well as g_1 and $\mu_1 g_1 + \mu_3 g_3$, respectively.

Hop 4-Last hop: Repeat the forwarding processes until the destination UAV collects sufficient different generations. It is noted that each UAV needs to check if a received generation is linearly independent with its current generation before combining them. For example, in Hop 5, if the generation $\lambda_1 g_1 + \lambda_2 g_2 + \lambda_3 g_3$ from UAV 5 is checked to be linearly independent with UAV 6's current generation $\delta_1 g_1 + \delta_2 g_2 + \delta_3 g_3$. If so, UAV 6 will linearly combine $\lambda_1 g_1 + \lambda_2 g_2 + \lambda_3 g_3$ and $\delta_1 g_1 + \delta_2 g_2 + \delta_3 g_3$ to produce a new generation $\delta'_1 g_1 + \delta'_2 g_2 + \delta'_3 g_3$, otherwise it will discard $\lambda_1 g_1 + \lambda_2 g_2 + \lambda_3 g_3$. Besides, some forwarding UAVs may receive ACKs from the destination UAV before its forwarding processes. According to the General rule iii), the number of ACKs required to terminate the forwarding process is $M - N$. For example, for UAV 5 and UAV 6, the required number of received ACKs is 2 and 1, respectively, since they have respectively received 1 ACK and 2 ACKs from the destination UAV before their forwarding processes. When the destination UAV sends $M = 3$ ACKs out, all UAVs terminate forwarding processes, and the whole routing process is completed.

Theorem 2: M original packets $\{x_1, x_2, \cdots, x_M\}$ could be successfully decoded when M generations with a full rank coefficient matrix are received, each of which is a combination of M linear independent generations. Linear independent generations are created.

3.1.5 Enabling Physical Layer Frame Structure

To enable the implementation of the proposed routing protocols, a physical frame structure is designed consisting of two main components, namely a packet header and transmitted data. The data part carries transmitted generations, while the packet header is placed in front of the data part to carry control information. As shown in Fig. 7, the packet header should be partitioned into multiple fields to carry different types of signaling, including:

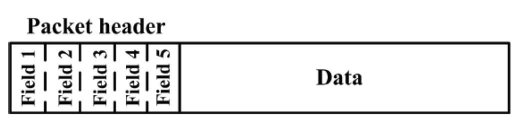


Figure 7: Frame Structure of an Encoded Packet

1) Frame Indicator: Indicate generations or ACK/NACK carried by the data part.

2) Transmitter UAV ID: Based on our proposed routing protocol using RNC, when a UAV receives a packet, it needs to know the ID of the transmitter for two purposes: 1) to avoid receiving the repeated generations from the same transmitter for energy efficiency; 2) to identify received ACKs from different UAVs.

3) Original packet ID: The original packet ID is utilized to indicate the original packets linearly combined in received generations, assisting receiver UAVs to judge whether adequate generations have been collected and avoid forwarding the generations containing the same original packets.

4) Destination UAV ID: Indicate the destination UAV that original packets attempt to reach.

5) Encoding coefficients: The information of encoding operations, like encoding coefficients, should be comprised in encoded packets to facilitate linear independence check and decoding.

3.2 Latency and Energy Optimization for Random Network Coding-Enabled Networks

RNC enables packets to transfer by linearly combining original packets with randomly chosen multiplicative coefficients [Ho2006 A]. RNC serves as a flexible routing protocol in dynamic networks without relying on information about the network topology or routing path. In RNC-enabled networks, a sufficient number of linearly independent encoded packets, i.e., generations needs to be guaranteed to ensure the decoding of the original packets [Song2020 Random]. A transmitter keeps generating and broadcasting linearly independent generations to receivers until it receives a required number of acknowledgments (ACKs) feedback. However, acquiring sufficient ACKs may incur a long latency and high energy consumption at the transmitter, especially when the channel condition is poor, and the required number of generations is large. Note that latency is a critical metric in the network performance which drives throughput and impacts the effectiveness of task completion [Zhang2021 Low-Latency]. On the other hand, energy is usually scarce for a mobile node which impacts its total operation time. Therefore, reducing both latency and energy consumption is significant in RNC-enabled networks.

3.2.1 System Model

In the encoding process of RNC, given M original packets, i.e., $x_1, x_2, \cdots, x_M$, the transmitter creates encoded packets, i.e., generations, by linearly combining original packets with randomly chosen coefficients. The created generation G_t at time slot t is given by $G_t = \sum_{i=1}^{M} a_{ti} x_i$, where a_{ti} denotes the multiplicative coefficient regarding the original packet x_i at the time slot t. In the decoding process of RNC, the destination node can successfully decode the original packets when it receives sufficient linearly independent generations. The transmitter keeps generating and broadcasting linearly independent generations. In a timeslot, a generation is generated with a unique set of multiplicative coefficients and transmitted to receivers, shown in Fig. 8. If receivers successfully receive the generation, one of the receivers will feed an ACK back after τ time slots, where τ is the feedback delay. The receivers compete for the channel and thus respond to the ACK at random. Once a receiver feeds an ACK back, the receiver will store the generation corresponding to the fed back ACK and discard other received generations to keep the uniqueness of generations.

Then, the receiver will not receive generations in future time slots. If there are K ACKs at the transmitter, it will terminate the generations' transmissions. Next, each receiver that has not fed an ACK back will combine its received generations transmitted in the last τ time slots. Note that in the traditional method, K equals to M to guarantee M linearly independent generations in the RNC-enabled network. In this letter, we introduce that K can be less than M while saving latency and energy.

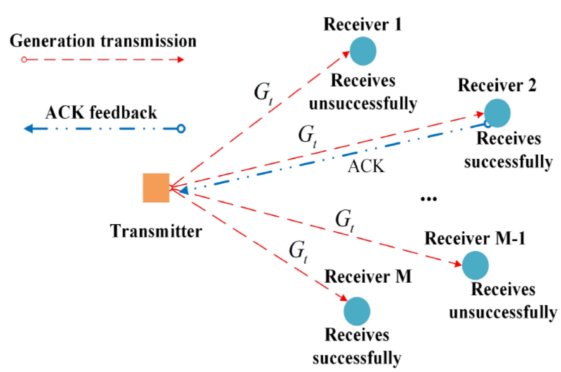


Figure 8: Generations' Transmissions in RNC-Enabled Networks

We consider that the required number of linearly independent generations in the network is M. The goal of generations' transmissions is that M receivers have M linearly independent generations. The signal-to-noise ratio (SNR) of receiver m at time slot t is given by $SNR_{tm} = P_T h_{tm} X_m^{-\alpha} / N_0$, where P_T denotes the transmit power at the transmitter, h_{tm} indicates the power channel gain of receiver m at time slot t, X_m is the distance between the transmitter and the receiver m, α represents the path loss exponent, and N_0 is the noise power. The SNR threshold for successfully receiving generations at the receivers is denoted by γ. The successful transmission probability P^{suc} is the probability that there are M linearly independent generations in the network when the transmitter receives K ACKs. In the following, we give an example of the successful transmission, where $\tau = 3$, $M = 6$, $K = 3$. Assume that when the transmitter receives three ACKs, the six receivers may have the generations as G_1, $G_4 + G_5$, G_2, G_3, $G_4 + G_5 + G_6$, $G_5 + G_6$, respectively. In this example, receiver 1 feeds back an ACK for G_1, receiver 3 feeds back an ACK for G_2, and receiver 4 feeds back ACK for G_3. It is observed that the six receivers have linearly independent generations after their generations' combinations. Since K is less than M, the latency and energy consumption in the generations' transmissions reduce accordingly. In addition, we define the threshold of successful transmission probability by ϖ, i.e., $\mathsf{P}^{suc} \ldots \varpi$.

The coverage probability of receiver m, i.e., $\mathsf{P}_m^{\text{cov}}$, is the probability that the SNR of receiver m is equal or greater than the SNR threshold γ. Denote the set of receivers as Φ. To maintain generality, we consider that the receiver's position $\boldsymbol{Z}_u \in \mathcal{R}^2$ with respect to a cluster center follows an arbitrary distribution with probability density function (PDF) $f_{\mathbf{Z}}(\mathbf{z})$. We specialize the case of interest where Φ is modeled as a Thomas cluster process [Haenggi2012 Stochastic]. Receivers are scattered according to a symmetric normal distribution with the variance of σ around a cluster center, where $f_{\mathbf{Z}}(\mathbf{z}) = \frac{1}{2\pi\sigma^2} \exp\left(-\frac{\|\mathbf{z}\|^2}{2\sigma^2} \right)$, where $\mathbf{z}$ is a realization of the random vector $\mathbf{Z}$. The distance between the transmitter and the cluster center is V.

The transmission cost in RNC-enabled networks is defined by $C = w_L T + w_E E$, where w_L and w_E are the weights for latency and energy consumption, respectively, T represents the latency depicted by the number of time slots for completing the generations' transmissions, and $E = TP_T$ is the energy consumption at the transmitter. Note that in C we omit the unit of a time slot which does not impact the optimal solution. To reduce the transmission cost, we minimize C while guaranteeing the successful transmission probability P^{suc} above a certain threshold of ϖ . The problem is formulated by

$$\min_{K,P_T} C = w_L T + w_E E \text{ s.t. } \mathsf{P}^{suc} \ldots \varpi \tag{5}$$

We jointly optimize the required number of ACKs K and the transmit power P_T to minimize C. It can be verified later by simulations that even if K is less than M , P^{suc} can be equal to one. However, in the traditional method, K is equal to M to guarantee M linearly independent generations in the RNC-enabled network. In our introduced method, the transmitter does not need to wait for M ACKs fed back from the receivers, which saves both latency and energy. It is worth noting that problem is challenging to solve since the analytical expressions of P^{suc} and T are unknown. In the next section, we develop an analytical framework to characterize the successful transmission probability and latency.

3.2.2 Modeling and Analysis

We introduce an analytical framework to minimize the transmission cost in RNC-enabled networks by deriving the coverage probabilities of receivers and the probability of having linearly independent generations.

Coverage Probability:

The coverage probability impacts the success of receiving a generation at a receiver. Considering that the coverage probability depends on the communication distance, we provide the distribution of the communication distance in the following.

Lemma1: Given the distance between the transmitter and the cluster center, i.e., V , the conditional PDF of the distance between the transmitter and an arbitrary receiver is given by $f_X\left(x|V\right) = \frac{x}{\sigma^2}\exp\left(-\frac{x^2+V^2}{2\sigma^2}\right)I_0\left(\frac{xV}{\sigma^2}\right)$, where $I_0\left(\cdot\right)$ is the modified Bessel function of the first kind with order zero.

The conditional cumulative distribution function (CDF) of X is given by $F_X\left(x|V\right) = 1 - Q_1\left(\frac{V}{\sigma},\frac{x}{\sigma}\right)$ where $Q_1\left(a,b\right) = \int_b^\infty te^{-\frac{t^2+a^2}{2}} I_0\left(at\right)dt$ is the Marcum Q-function [Afshang2018 Poisson].

Lemma2: Given the distance between the transmitter and the cluster center, i.e., V , the conditional PDF of the distance between the transmitter and the m -th nearest receiver, i.e., X_m , is given by [David2004 Order]

$$f_{X_m}\left(x|V\right)=\frac{\left(1-Q_1\left(\frac{V}{\sigma},\frac{x}{\sigma}\right)\right)^{m-1}}{B\left(m,M-m+1\right)}Q_1\left(\frac{V}{\sigma},\frac{x}{\sigma}\right)^{M-m}\frac{x}{\sigma^2}\exp\left(-\frac{x^2+V^2}{2\sigma^2}\right)I_0\left(\frac{xV}{\sigma^2}\right) \tag{6}$$

It is worth noting that receivers in different positions have various SNR statistics. Therefore, receivers' different coverage probabilities impact their receptions of the transmitted generations in the RNC-enabled network. In the sequel, we characterize the coverage probability of the m-th nearest receiver to the transmitter, which is given by

$$\begin{aligned} \mathsf{P}_m^{\text{cov}} &= \mathsf{E}_{X_m,t}\left\{\mathsf{P}\left\{SNR_{tm}..\gamma|X_m\right\}\right\} \\ &\overset{(a)}{=}\int_0^{\infty}\mathsf{P}\left\{\frac{P_T h_m X_m{}^{-\alpha}}{N_0}..\gamma\middle|x\right\}f_{X_m}\left(x|V\right)dx \\ &\overset{(b)}{=}\int_0^{\infty}\exp\left(-\frac{\gamma N_0}{P_T x^{-\alpha}}\right)f_{X_m}\left(x|V\right)dx \end{aligned} \tag{7}$$

wherein (a), h_m denotes the channel power gain of the m-th nearest receiver, $f_{X_m}\left(x|V\right)$ is the conditional PDF of X_m, (b) follows from the Rayleigh fading assumption, i.e., $h_m \sim \exp(1)$.

With $f_{X_m}\left(x|V\right)$, we obtain the coverage probability of the m-th nearest receiver, i.e., $\mathsf{P}_m^{\text{cov}}$.

Characterization of Different Generations:

We derive the probability that two receivers have different generations given Ω time slots.

Proposition 1: During Ω time slots, the probability that the i-th nearest receiver and the j-th nearest receiver have different generations is given by

$$\mathsf{P}_{i,j}^{Diff}\left(\Omega\right)=1-\left(1-\mathsf{P}_i^{\text{cov}}-\mathsf{P}_j^{\text{cov}}+2\mathsf{P}_i^{\text{cov}}\mathsf{P}_j^{\text{cov}}\right)^{\Omega} \tag{8}$$

Remark 1: In Proposition 1, it can be observed that the probability that two receivers have different generations increases with the total time slots.

Remark 2: In Proposition 1, when the absolute difference between $\mathsf{P}_i^{\text{cov}}$ and $\mathsf{P}_j^{\text{cov}}$ increases, $\mathsf{P}_{i,j}^{Diff}\left(\Omega\right)$ increases. This is because we have

$$\begin{aligned}\mathsf{P}_{i,j}^{Diff}(\Omega) &= 1-\left[1-\left(\mathsf{P}_i^{\text{cov}}+\mathsf{P}_j^{\text{cov}}-2\mathsf{P}_i^{\text{cov}}\mathsf{P}_j^{\text{cov}}\right)\right]^{\Omega} \\ &\geq 1-\left[1-\left(\mathsf{P}_i^{\text{cov}}+\mathsf{P}_j^{\text{cov}}-2\sqrt{\mathsf{P}_i^{\text{cov}}}\sqrt{\mathsf{P}_j^{\text{cov}}}\right)\right]^{\Omega} \\ &= 1-\left[1-\left(\sqrt{\mathsf{P}_i^{\text{cov}}}-\sqrt{\mathsf{P}_j^{\text{cov}}}\right)^2\right]^{\Omega}\end{aligned} \tag{9}$$

Therefore, the probability of two receivers having different generations increases $\left|\mathsf{P}_i^{\text{cov}}-\mathsf{P}_j^{\text{cov}}\right|$.

Based on Proposition 1, we can approximately obtain the probability that there are M linearly independent generations in the RNC-enabled network given in Theorem 1.

Theorem 1: Given the feedback delay τ, the required number of ACKs K, the successful transmission probability that there are M linearly independent generations in the RNC-enabled network is given by

$$\mathsf{P}_{suc} \approx \frac{1}{N_r}\sum_{u=1}^{N_r}\mathsf{P}(B_u)\mathsf{P}(C_u) \tag{10}$$

where

$$\begin{aligned}\mathsf{P}(B_u) &= \prod_{i\in\mathsf{S}_u}\left(1-\left(1-\mathsf{P}_i^{\text{cov}}\right)^{\tau}\right) \\ \mathsf{P}(C_u) &= \prod_{i,j\in\mathsf{S}_u, i\neq j}\mathsf{P}_{i,j}^{Diff}(\tau)\end{aligned} \tag{11}$$

$N_r = \begin{pmatrix} M \\ M-K \end{pmatrix}$, S_u denotes the u-th subset of $M-K$ receivers where $\left|\mathsf{S}_u\right| = M-K$, and $\mathsf{P}_{i,j}^{Diff}(\tau)$ is given in Proposition 1.

Latency Analysis:

We derive the average latency, i.e., the number of time slots.

Theorem 2: Given the feedback delay τ and the required number of ACKs K, the average latency $\mathsf{E}\{T\}$ is given by

$$\mathsf{E}\{T\} \approx \tau + \sum_{k=1}^{K}\frac{1}{\mathsf{P}^{ACK}(P_T, k-1)} \tag{12}$$

and

$$\mathsf{P}^{ACK}\left(P_T, k-1\right) = 1 - \prod_{m\in\Phi\backslash\{1,\cdots,k-1\}} \int_0^\infty \left(1 - e^{-\frac{\gamma N_0}{P_T x^{-\alpha}}}\right) f_{X_m}\left(x \middle| V\right) dx \tag{13}$$

Remark 3: Based on Remark 2, decreasing P_T may increase the absolute differences of receivers' coverage probabilities. However, in Theorem 2, decreasing P_T increases $\mathsf{E}\{T\}$. Thus, there is a trade-off between reliability and latency.

Based on the derived analytical framework, the transmitter or a virtual machine can solve the problem by exhaustive searching over K and P_T.

3.2.3 Deep Learning-Based Method

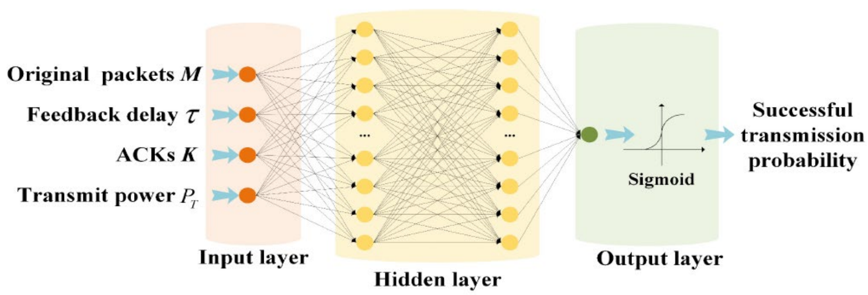


Figure 9: Deep Neural Network (DNN) for Obtaining Successful Transmission Probability

Compared to the analytical method, the deep learning method is more suitable when encountering model deficits and algorithm deficits. Specifically, it would be challenging to characterize the successful transmission probability with analytical expressions accurately, and thus we encounter a model deficit. Furthermore, the analytical derivations require a specific distribution of receivers. However, this distribution may not always be available in practice. On the other hand, calculating the successful transmission probability expressed in Theorem 1 consumes much time when M is very large, which leads to an algorithm deficit.

In Fig. 9, we present an architecture of a fully connected DNN. Specifically, there are four neurons in the input layer corresponding to M, τ, K, and P_T. There are two layers in the hidden layer, where each layer has 80 neurons. The activation function at each neuron in the hidden layer is the ReLU function. The biases are added to each neuron together with the weight sums before passing the activation functions. For obtaining the successful transmission probability which is within the range of $[0,1]$, we adopt a sigmoid function (i.e., $S(x) = \frac{1}{1+e^{-x}}$) in the output layer after the weighted sum at the output neuron. The cost function of the DNN is assumed to be the sum of the squared error, which is given by $J = \sum_{i=1}^{N_D} \frac{1}{2}(d_i - y_i)^2$, where N_D is the number of data pairs, y_i is the i-th output from the output neuron, and d_i is the i-th correct output from the training dataset. In the training process, the learning rate in the n-th epoch is given by $\lambda_n = \lambda_0 \lambda_d^{\frac{n}{N_{Epo}}}$, where λ_0 is the initial learning rate, λ_d is the decay rate, and N_{Epo} is the number of epochs. The hyperparameters are selected by evaluating various settings on the training loss of the test dataset. After the training process, we utilize the exhaustive search method to obtain K and P_T with the minimum transmission cost.

3.3 EMANE/CORE Emulation

In this task, we implemented the Random Network Coding Routing Protocol and the control protocol, fixed-path protocol, and we used EMANE/CORE to emulate and compare routing processes and results. The emulation results meet expectations. It is worth noting that the random network coding can significantly expedite routing processes for two reasons. First, with random network coding, a receiver node can successfully decode all M original packets, as long as it receives any M different encoded packets. For example, when M is 3, if a node successfully receives any three different generations, it can obtain a coefficient matrix with full rank and a constant matrix to decode all M original packets. Second, with random network coding, a receiver can decode original packets as long as it accumulates sufficient encoding packets that may be sent by different transmitters. We mainly utilized CORE 4.8 and EMANE 0.9.3 to set up the emulation environments for demonstrating RNC-enabled routing protocol.

3.3.1 EMANE Overview

EMANE is an open-source tool developed by Naval Research Laboratory (NRL). EMANE uses Network Emulation Module (NEM) to emulate Layers 1 and 2 with configurable MAC and PHY layers. EMANE framework can be used for modeling different radio interface types in the form of NEMs in real-time emulation. The supported standard RF models include RF-pipe, 802.11, TDMA, and LTE.

3.3.2 CORE Overview

CORE is an open-source emulator tool developed for building and emulating virtual networks on one or more machines. CORE provides a platform for executing real applications and protocols while utilizing the Linux operating system's features. It can be used to build a real-time emulation of a real-world computer network. CORE has a Graphical User Interface (GUI) for creating topologies and controlling emulated networks. It is commonly used for network and protocol research, demonstrations, application, and platform testing, networking scenario evaluation, etc. CORE connects directly to EMANE for scenario orchestration and individual node control.

3.3.3 Source UAV

For the source UAV, we use the following command to execute the code.

$ cat test.txt | python udp_broadcast_source_transmitter.py destination_uav_id(argv[1])

The argument1(argv[1]) after the python file name is the hostname of the destination UAV. It specifies the destination receiver's hostname and will be used for determining if packets are delivered to the destination. The source UAV splits the raw data from *test.txt*. After splitting the raw data, the source UAV encode split data based on Random Network Coding and broadcast. It will stop broadcasting when it receives a termination signal.

3.3.4 Relay UAV

For relay UAVs, we use the following command to execute the code.

$ python udp_broadcast_relay_transmitter.py

Relay UAVs receive packets from broadcasting. Once the number of packets is enough to solve the matrix, they send the termination signals to all senders that sent packets to the current UAV. The relay UAV will decode all packets to get the raw data. The last step is the same process as the source UAV, reencode and rebroadcast. It will stop broadcasting when it receives a termination signal.

3.3.5 Destination UAV

For destination UAVs, we use the following command to execute the code.

$ python udp_broadcast_relay_transmitter.py

To simplify code complexity, relay UAV code also runs on the destination UAV. The only difference is if the current UAV hostname is the same as the designated destination hostname, the destination will stop after it acquires and decodes the data.

3.3.6 Emulation

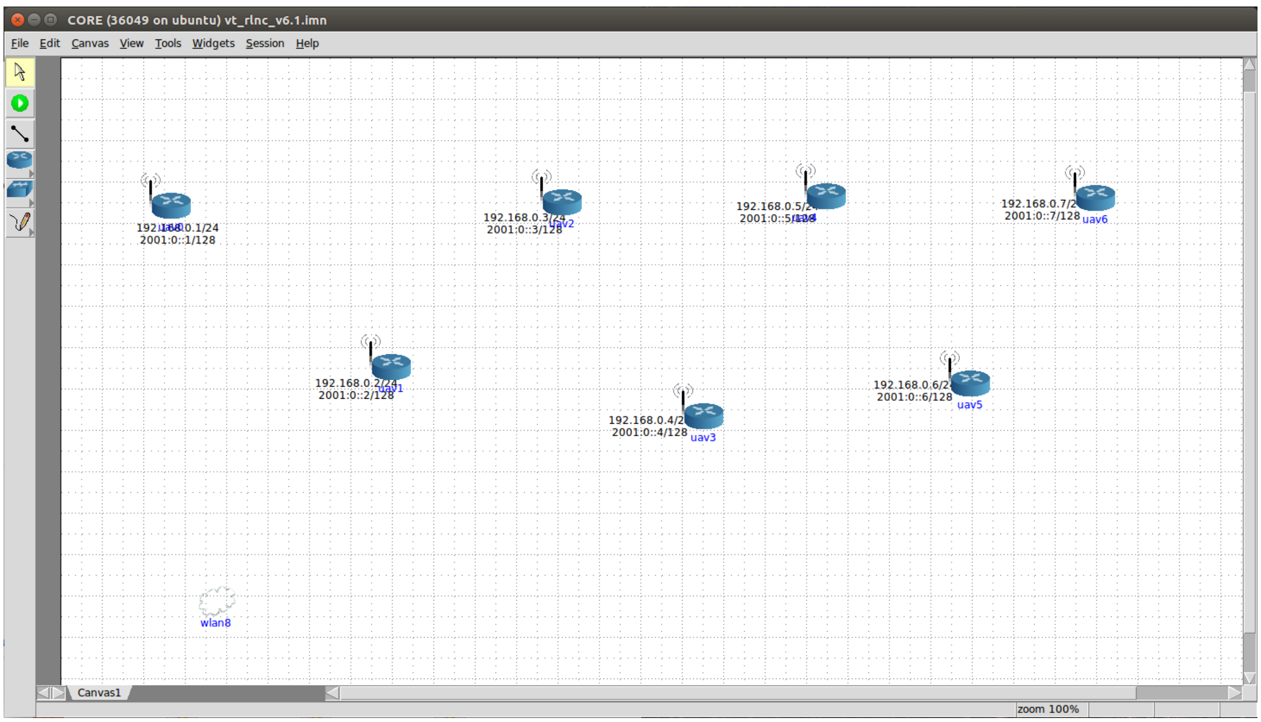


Figure 10: Network Topology for Emulation

- Data size: 65 bytes*60, 3,900 bytes
- Testbench:
    - OS: Ubuntu 16.04 LTS 64-bit in VMware Workstation 16 Pro
    - CPU: Intel® Core™ i7-7700K CPU @ 4.20 GHz × 8 (Providing 8 cores for VM)
    - VM RAM: 4,096 MB

The size of the data file we used is 3,900 bytes. The emulation was run on Ubuntu 16.04 LTS 64-bit in VMware Workstation 16 Pro. The CPU for the host machine is Intel® Core™ i7-7700K CPU @ 4.20 GHz × 8. We set it to providing 8 cores for the virtual machine. The RAM for the virtual machine is 4,096 MB.

In our emulation, node uav0 is the source node, and node uav6 is the destination node. Source UAV code runs on node uav0, and Relay UAV code runs on all other nodes.

4.0 RESULTS AND DISCUSSION

4.1 Flooding-based Routing Protocol Design Using Random Network Coding

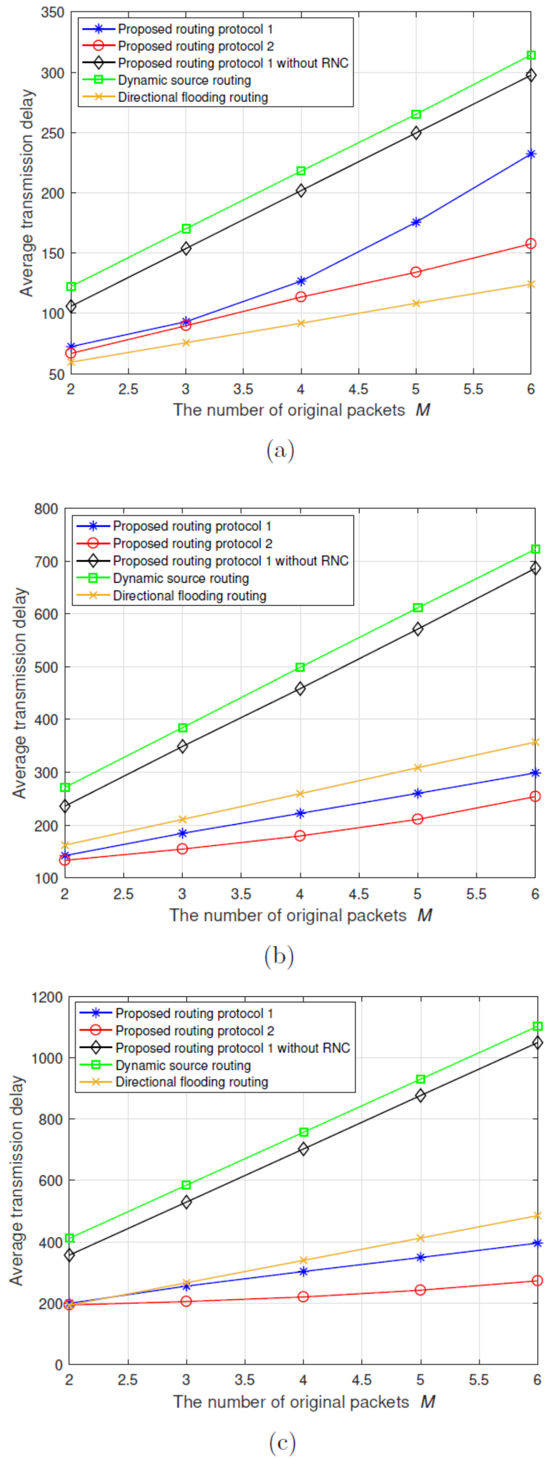
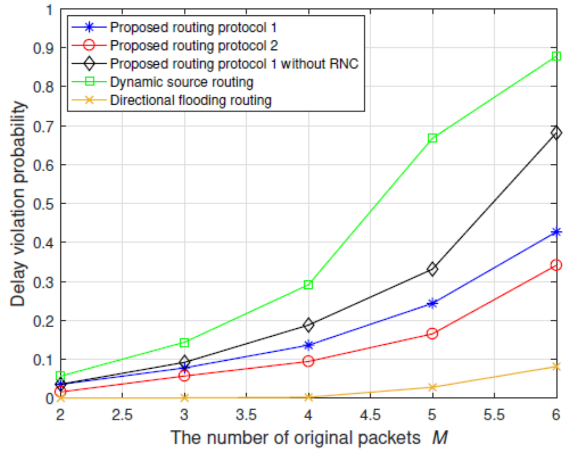


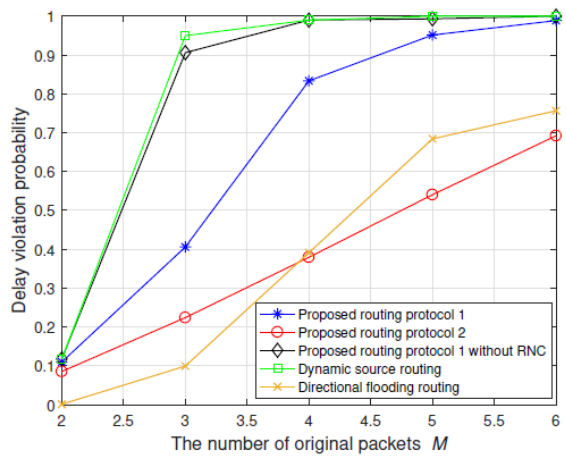
Figure 11: Average Transmission Delay Versus the Number of Original packets *M*

a) U = 7; b) U = 14; c) U = 20

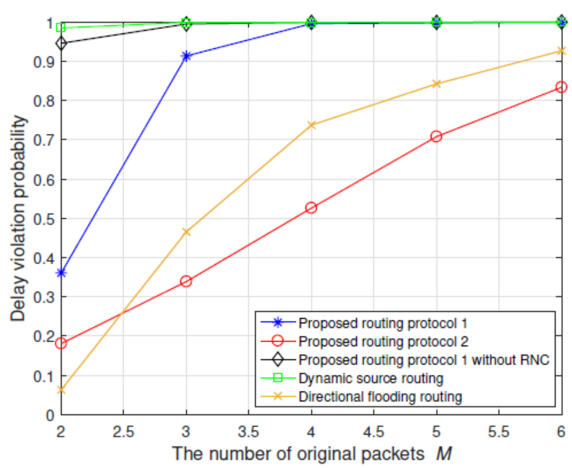
Fig. 11 shows the simulations of the average transmission delay versus the number of original packets under three different UAV densities, namely, $U = 7$, $U = 14$, and $U = 20$, respectively. It is obvious that the average transmission delay keeps rising with the growth of original packets M and UAVs U. When U becomes larger, for all the investigated routing protocols their routing processes would experience more hops, causing a more severe transmission delay. On the other hand, as for reference methods and the proposed routing protocol 1, a larger M results in more generations probably needed to deliver in each hop and prolongs transmission delay of each hop. While for the proposed routing protocol 2, with a larger M, it causes a forwarding UAV to terminate its forwarding process only if more ACKs received from different UAVs, bringing in a longer transmission delay in each hop, especially in the first hop. Another important observation is that the proposed RNC-based routing protocols always have a lower average transmission delay than the DSR routing protocol and the proposed routing protocol 1 without using RNC, while the proposed routing protocol 2 always outperforms the proposed routing protocol 1. This is because, with the help of RNC, a forwarding UAV could obtain the original packets as long as it collects sufficient generations no matter from its transmitter UAV or from overhearing in previous hops. Therefore, in the proposed routing protocol 1, the whole routing process could be significantly expedited, since most hops may only need to finish fewer generations transmissions. Additionally, the destination UAV may accumulate sufficient generations to decode original packets just by overhearing with fewer hops. The proposed routing protocol 2 is able to further accelerate routing processes compared to the proposed routing protocol 1. With the proposed routing protocol 2, transmitter UAVs directly create new generations by linearly combining generations received from other UAVs rather than decoding original packets first, while receiver UAVs only need one generation successfully received to trigger an ACK feedback, resulting in lower delay. Additionally, by comparing the simulation results between the proposed routing protocols and the directional flooding routing (DFR) routing protocol, it can be observed that the DFR has the lower transmission delay than the proposed routing protocols when the small number of UAVs exist in UAV networks, for example $U = 7$, while with a larger U, for example $U = 14$, and $U = 20$, our designed routing protocols have better performance on the average transmission delay. The reason behind this is that although FR is able to improve the efficiency of flooding-based routing by making the routing directional and limiting the nodes participating in the routing process, increasing the number of UAVs will harmfully degrade the improvement of the DFR on the flooding-based routing. Contrarily, our designed routing protocols expedite the flooding-based routing utilizing the RNC to reduce the number of packets transmitted in each hop, which are more adaptive to UAV networks with a large amount of UAVs.



(a)



(b)



(c)

Figure 12: Delay Violation Probability Versus the Number of Original Packets *M*

a) U = 7; b) U = 14; c) U = 20

Fig. 12 plots the delay violation probability as the function of M under different UAV densities. In the simulation, the maximum tolerable delay $\hat{D}_{tot}$ is set to be 300 ms. It is easy to see that a larger M and a larger U will make the routing process easier to violate delay requirements with higher delay violation probabilities. For the DSR and the proposed routing protocol 1, a large M and a large U may prolong the transmission delay of each hop and rise the number of hops in the whole routing process, respectively, both of which make the routing process encounter stricter delay constraints. In other words, each hop has to finish its forwarding process in a shorter time. However, the use of RNC can effectively mitigate the negative impacts brought by the increase of M and U. As analyzed above, with RNC the number of generations (encoded packets) required to be transmitted in most hops and the number of hops in a routing process would be less than those without using RNC. As a result, when M and U become relatively large, the proposed routing protocols using RNC have better performance on the delay violation probability compared to DSR and the proposed routing protocol 1 without using RNC. However, the proposed routing protocol 1 is still not capable to cope with larger M and U. For example, when M and U increase to 4 and 20, respectively, the proposed routing protocol 1 has very high delay violation probabilities. Obviously, the proposed routing protocol 2 could further improve the performance of delay violation probabilities, where a forwarding UAV uses a more efficient way to create new generations with a low routing delay. It is obvious that when a UAV network consists of a limited number of UAVs, for example $U = 7$, the DFR has lower delay violation probabilities compared to our proposed routing protocols owing to its directionality. Unfortunately, the DFR is not able to handle UAV networks with a large number of UAVs, while the proposed routing protocol 2 significantly outperforms the DFR when U and M become large.

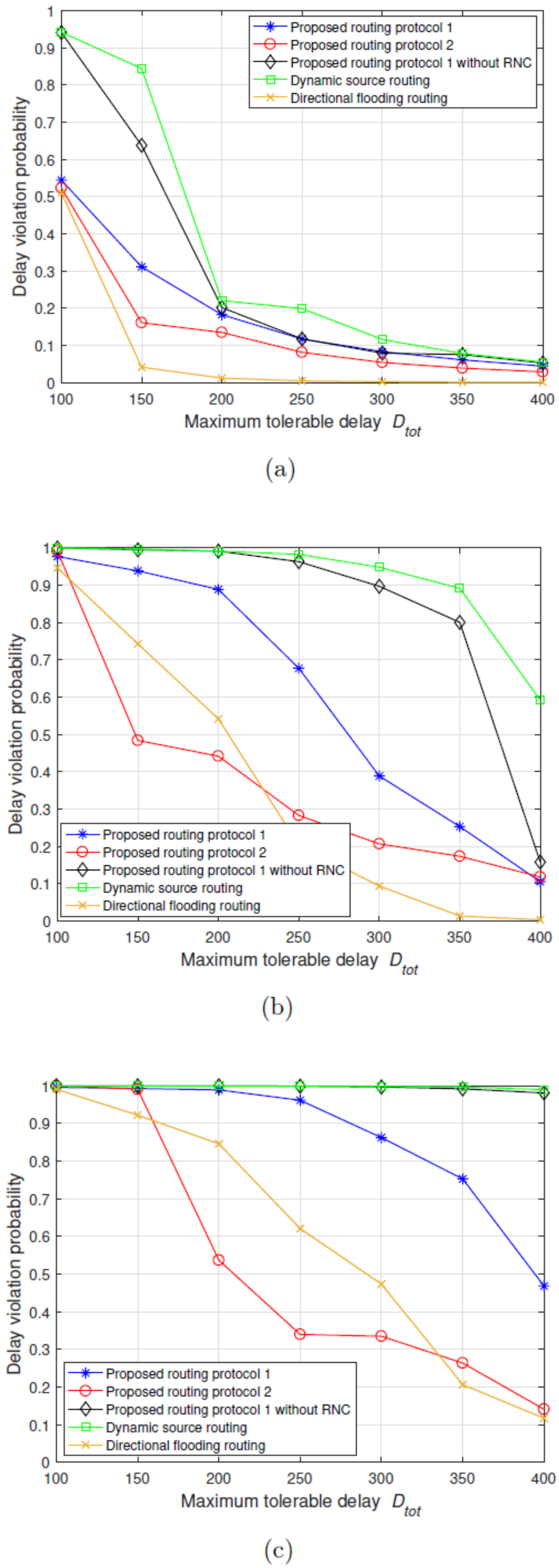


Figure 13: Delay Violation Probability Versus the Maximum Tolerable Delay D_{tot}
a) U = 7; b) U = 14; c) U = 20

In Fig. 13, the influence of the maximum tolerable delay $\hat{D}_{tot}$ on the delay violation probability is investigated with $M=3$. The general trend of the curves representing the delay violation probability is declining with the growth of $\hat{D}_{tot}$, since a smaller $\hat{D}_{tot}$ will make each hop have to meet a stricter delay constraint, incurring higher delay violation probabilities. Moreover, the same phenomenon with Fig. 12 can be observed in Fig. 13 that the performance of the delay violation probability is deteriorated with a larger U. Due to the attribute of RNC, a forwarding UAV can accumulate generations sequentially from any transmitter UAVs in any hops so that the routing process could be significantly expedited. However, it is apparent that the proposed routing protocol 1 cannot adapt to a small $\hat{D}_{tot}$, which has a bad performance on the delay violation probability when $\hat{D}_{tot}$ becomes small. Hence, the proposed routing protocol 2 is designed to tackle stricter delay constraints, which fully takes advantage of the whole UAV network to create new generations for the destination UAV, so that generations required to be delivered in most hops (except the first hop) could be as few as possible. As a result, the proposed routing protocol 2 always has smaller delay violation probabilities than the proposed routing protocol 1. Besides, the simulation results show that the proposed routing protocol 2 even can defeat the DFR when U is large, which depends on a strong assumption that the network topology is known to realize the directional flooding-based routing.

4.2 Latency and Energy Optimization for Random Network Coding-Enabled Networks

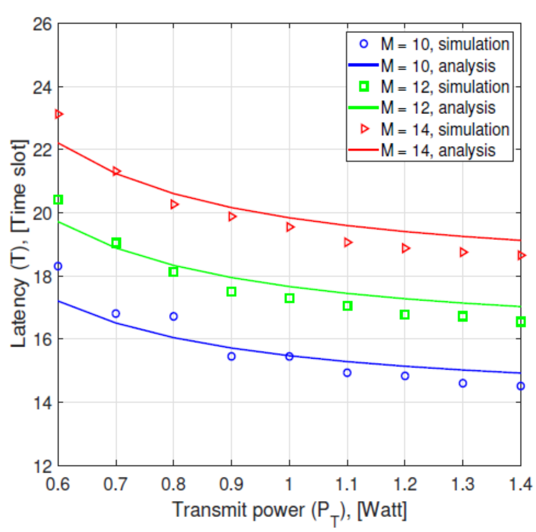


Figure 14: Latency Versus Transmit Power Under Different *M*

In Fig. 14, the latency T is examined versus the transmit power P_T under various numbers of original packets M . The simulation results are obtained by Monte Carlo simulations. In Fig. 14, we consider that the required number of ACKs K is equal to M . It is observed that given a P_T , when M increases, T increases. This is because an increased number of linearly independent generations should be guaranteed with more generations' transmissions. Furthermore, increasing P_T reduces the latency. This is because a higher P_T improves the coverage probability of receivers. As such, increasing P_T guarantees the reliability of generations' transmissions and avoids wasting additional time slots of unsuccessful transmissions. However, increasing P_T may consume more energy. Therefore, there is a trade-off between latency and energy consumption. Moreover, it is observed that the analytical results match the simulation results, which validates our theoretical analysis.

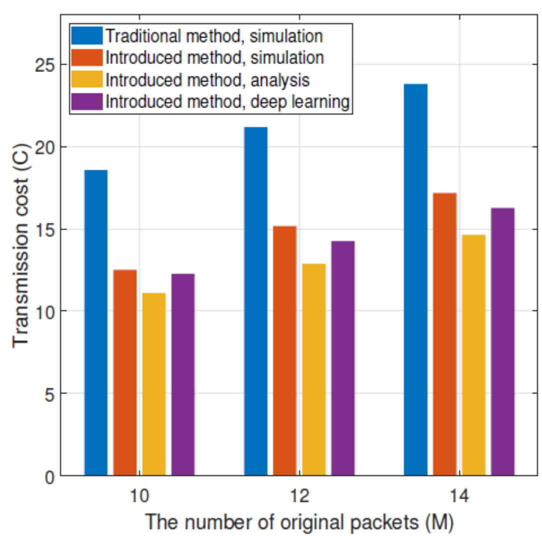


Figure 15: Transmission Cost Versus *M*

In Fig. 15, we compare the transmission cost C versus the number of original packets M . It is observed that C increases with M due to the higher energy consumption and latency for generations' transmissions. Furthermore, the deep learning-based results are closer to the simulation results than the analytical results. Note that there is a performance gap between the deep learning-based results and the simulation results. This is because the DNN model could not entirely capture the input-output data pairs' inherent relationships. In addition, compared to the traditional method where the transmitter has a constant transmit power and requires M ACKs for ensuring M linearly independent generations, our introduced method achieves a much lower transmission cost.

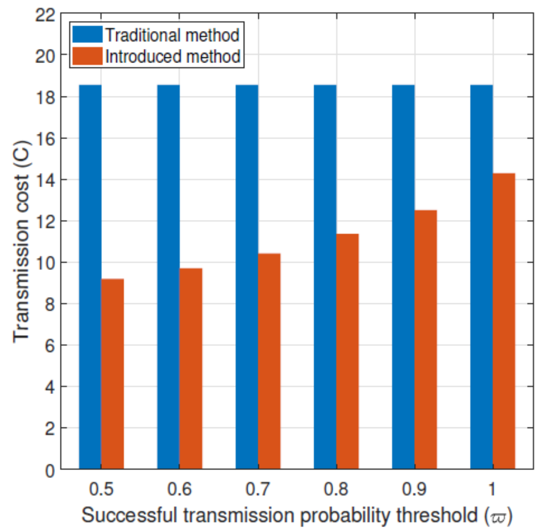


Figure 16: Transmission Cost Versus Successful Transmission Probability Threshold

In Fig. 16, we examine the transmission cost C versus the threshold of successful transmission probability ϖ. It is observed that the introduced method achieves a lower C than the traditional method even though ϖ equals one. Furthermore, in the introduced method when ϖ decreases, C reduces. This demonstrates the flexibility and advantages of our introduced method in reducing the latency and energy in RNC-enabled networks while balancing the generations' transmission reliability.

4.3 EMANE/CORE Emulation

4.3.1 Emulation Results

To compare RNC protocol and the control protocol, Fixed-path protocol. We emulated each protocol five times using the data size of 3,900 bytes and the network topology on Fig. 10. Tables 1 and 2 include total transmission time and bit rate for each emulation, and we take the average value from five emulations results.

In Table 1, one of the best results for the RNC protocol is emulation No. 4, which has a bit rate of 30,812 B/s. The longest transmission time is emulation No. 2, which has a bit rate of 22,178 B/s. The average bit rate is 25,790 B/s. The results for RNC protocol fluctuate more compared to Fixed-path protocol, because of a large number of calculations during transmission. The transmission time is highly dependent on the current remaining computer power of the host CPU. In Table 2, the result for the Fixed-path protocol is relatively stable. The average bit rate is 6,988 B/s. By comparing the average value, RNC protocol is around 3.7 times faster than Fixed-path protocol. It is also worth noting that a larger UAV swarm size and larger data size might cause the bit rate to be higher for RNC protocol.

Table 1: RNC Protocol Emulation Results

No.	Time(s)	Bit Rate (B/s)
1	0.151710	25,707
2	0.175853	22,178
3	0.148033	26,345
4	0.126575	30,812
5	0.153945	25,334
Avg.	0.151223	25,790

Table 2: Fixed-Path Protocol Emulation Results

No.	Time(s)	Bit Rate (B/s)
1	0.581212	6,710
2	0.560037	6,964
3	0.560682	6,956
4	0.562709	6,931
5	0.525994	7,415
Avg.	0.558127	6,988

4.3.2 Emulation Influencing Factors

4.3.2.1 Test Scenario Factors

- Packet Size: the most critical factor to our protocol is the packet size. Packet size is the size of the data we need to transmit. We have tried our best to optimize the packet size depending on the underlying communication scenario so that this protocol has good efficiency.
- UAV Swarm Size (The number of UAVs): if the UAV swarm size is large, the RNC protocol will have a greater advantage compared to the control protocol.
- Original Data Size: if the data size is bigger, the bit rate for the RNC protocol might be higher. It also depends on the number of messages and how many bytes in each message.

4.3.2.2 Testbench Factors

It is worth to note that there are also some factors of the testbench that could directly affect the emulation results:

- CPU: we tested all scenarios in a virtual machine; however, using a different number of CPU cores will have a big impact on the underlying performance of various protocols. The reason is that the RNC protocol requires computation of the coefficients. We assume that testing on a better CPU or a physical host machine will reduce the transmission time.
- Bandwidth: since our packet has a large amount of data, we found that by increasing the bandwidth in CORE WLAN Configuration, the transmission time will significantly reduce comparing to the control group; however, the EMANE version that we used has some problems by using a high bandwidth that is above 4 Mbps, so in our emulations, we must reduce the bandwidth to 4 Mbps unicast rate and multicast rate.

5.0 CONCLUSIONS

5.1 Flooding-based Routing Protocol Design Using Random Network Coding

Due to the inherent attributes, including dynamic network topology, lack of centralized control, and deficient capabilities of UAVs, existing routing protocols based on network topology information and routing path exploration are inapplicable in swarm UAV networks. Routing protocol design is a fundamental and major challenge that has to be addressed in swarm UAV networks. In this paper, two novel routing protocols using RNC are designed for swarm UAV networks, which do not require any network topology information and routing path explorations. In the first designed routing protocol, owing to RNC, UAVs are able to accumulate sufficient generations sequentially in any hops to decode original packets. As a result, the routing process could be significantly accelerated with fewer hops and fewer generations transmitted in some hops. To further hasten the routing process, the second routing protocol is introduced, which could fully take advantage of the whole UAV network to create and supply plentiful different generations to the destination UAV. Correspondingly, UAVs only need to receive one generation to trigger ACK feedbacks rather than receiving a full set of generations. The simulation studies verify the effectiveness and superiority of the designed routing protocols, which have better performance on the average transmission delay and the delay violation probability than the compared routing protocols. Additionally, the performance of the second designed routing protocol always surpasses the first one.

5.2 Latency and Energy Optimization for Random Network Coding-Enabled Networks

We aimed to reduce the weighted sum of latency and energy consumption in RNC-enabled networks under delayed feedback while guaranteeing the generations' transmissions reliability. We jointly optimized the required number of ACKs feedback and the transmit power to minimize the transmission cost and ensured the successful transmission probability above a certain threshold. Both the analytical and deep learning-based methods were introduced. Simulation results demonstrated the advantages of our introduced method.

5.3 EMANE/CORE Demo

Although implementing the RNC Routing Protocol from theory was challenging, we kept optimizing the implementation of RNC Routing Protocol. The emulation results met our expectations, and the bit rate of the RNC protocol is much higher than that of the fixed-path protocol. One of the key parts is how to segment the raw data, and this can significantly affect the bit rate. Since our solution relies on a large number of calculations, rather than just performing simple transmitting, we think the field test can show more advantages of the RNC Routine Protocol.

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APPENDIX – PUBLICATIONS AND PRESENTATIONS

PUBLICATIONS

- Hao Song, Lingjia Liu, Scott Pudlewski, and Elizabeth Serena Bentley, “Random Network Coding Enabled Routing Protocol in Unmanned Aerial Vehicle Networks,” IEEE Transactions on Wireless Communications, vol. 19, no. 12, pp. 8382-8395, Dec. 2020.
- Hao Song, Lingjia Liu, Bodong Shang, Scott Pudlewski, and Elizabeth Serena Bentley, “Enhanced Flooding-Based Routing Protocol Leveraging Random Network Coding and Clustering in Swarm UAV Networks,” IEEE International Conference on Computer Communications (INFOCOM), accepted for publication, 2020.
- Hao Song, Lingjia Liu, Scott Pudlewski, and Elizabeth Serena Bentley, “Random Network Coding Enabled Routing in Swarm Unmanned Aerial Vehicle Networks,” IEEE Global Communications Conference (GLOBECOM), Waikoloa, HI, USA, pp. 1-6, 2019.
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- Bodong Shang, Lingjia Liu, Hao Chen, Jianzhong Zhang, Scott Pudlewski, Elizabeth Serena Bentley, and Jonathan Ashdown, "Spatial Spectrum Sensing-Based D2D Communications in User-Centric Deployed HetNets," 2019 IEEE Global Communications Conference (GLOBECOM), 2019, pp. 1-6.
- Bodong Shang, Elizabeth Serena Bentley, and Lingjia Liu, “UAV Swarm-Enabled Aerial Reconfigurable Intelligent Surface: Performance Analysis and Design Insights”, submitted to IEEE Transactions on Communications, 2021.

PRESENTATIONS

Hao Song, Lingjia Liu, Bodong Shang, Scott Pudlewski, and Elizabeth Serena Bentley, “Enhanced Flooding-Based Routing Protocol Leveraging Random Network Coding and Clustering in Swarm UAV Networks,” IEEE International Conference on Computer Communications (INFOCOM), accepted for publication, 2020.

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LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

ARR	attack resilient routing
BS	base station
CORE	common open research emulator
CPU	Central Processing Unit
CSI	channel state information
CSMA/CA	carrier sense multiple access/collision avoidance
D2D	device-to-device
DSR	Dynamic Source Routing
EMANE	extendable mobile ad-hoc network emulator
GPS	global positioning system
LP	linear programming
LTE	Long Term Evolution
MAC	Medium Access Control
MILP	mixed-integer linear programming
NACK	Negative Acknowledgement
OS	Operating System
PCP	Poisson cluster Process
PHY	Physical Layer
QoS	quality of service
RAM	Random Access Memory
RF	Radio Frequency
RNC	random network coding
TDMA	Time Division Multiple Access
UAV	unmanned aerial vehicle
VM	Virtual Machine
WLAN	Wireless Local Area Network