IEEE Access
Multidisciplinary ⁝ Rapid Review ⁝ Open Access Journal

Received September 19, 2019, accepted October 6, 2019, date of publication October 11, 2019, date of current version November 4, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2947087

Is Hop-by-Hop Always Better Than Store-Carry-Forward for UAV Network?

FEI XIONG[1], LEI XIA[1], JIEJIE XIE[2], HAI WANG[1], AIJING LI[1], AND YU YU[3]
[1]College of Communication Engineering, Army Engineering University of PLA, Nanjing 210007, China
[2]Unit 31106 of PLA, Nanjing 210007, China
[3]Unit 31131 of PLA, Nanjing 210014, China

Corresponding author: Hai Wang (haiw.wang@gmail.com)

This work was supported by the National Science Foundation of China under Grant 61371124 and Grant 61702545.

ABSTRACT As energy supply on Unmanned Aerial Vehicle (UAV) is limited, energy efficient data transmission in UAV networks would be of great concern to the researchers. Nevertheless, UAV networks exhibit strong dynamic nature compared to ordinary Mobile Ad hoc Network (MANET), it is not rare that some nodes will be disjoint from other nodes from time to time. Under such circumstance, ordinary hop-by-hop routing schemes can not be used anymore, for there is no route existed from source to destination. Some solutions use store-carry-forward (SCF) routing to facilitate end to end data transmission. However, when should we use SCF routing, when we should use hop-by-hop routing if we taking energy into consideration? Is hop-by-hop routing always better than SCF? If it is good or not when the hop-by-hop routing is combined with the SCF routing? All these questions need to be answered. In this paper, we answered above questions by proposing three types of minimum energy consumption models of hop-by-hop routing, and two SCF routing models. We compared all these models and considered four tactics of combination modes for the transmissions in a rotary-wing UAV network. The researches show that two tactics have better performance than other modes in energy saving capabilities by reducing 70% at most with the hop-by-hop routing, and the transmission time of combination modes are in same scale compared with hop-by-hop routing. The two tactics are appropriate for different UAV networks respectively, in which the source UAV can or cannot get the GPS information of relay UAVs in the route. The research conclusion can also be used for the transmissions in a fixed-wing UAV network by modifying the energy consumption models of fixed wing UAV, which is different from rotary wing UAVs.

INDEX TERMS Hop-by-hop routing, store-carry-forward, UAV network, energy consumption.

I. INTRODUCTION

At present, some routing protocols have been proposed for Mobile Ad-hoc Networks (MANETs). Due to apparent similarity of Unmanned Aerial Vehicle (UAV) networks with MANETs, researchers have studied protocols used in MANETs for possible application in UAV networks. However, UAV networks may have different requirements, such as mobility patterns and node localization, frequent node removal and addition, intermittent link management, power constraints, application areas and their QoS requirements [1]. Due to many of these issues peculiar to UAV networks, while modifications have been proposed to MANET protocols, there is a need to develop new routing algorithms for UAV networks [3].

As energy supply on UAVs is limited, energy efficient data transmission in UAV networks would be of great concern so as to prolong the stability of UAV network [1]. The concerns regarding energy saving in the UAV networks are in some ways similar to that in MANET. There have been a few research efforts to adapt existing energy-aware protocols to UAV networks. These protocols are for hop-by-hop routing which is distributed in the next-hop, when node receives a packet to the destination, it forwards the packet to the nearest next hop corresponding to the destination node. The protocols determine the route from source to destination according to their evaluation criteria such as delay, energy consumption, or distance.

Nevertheless, UAV networks exhibit strong dynamic nature compared to ordinary MANET, it is not rare that some nodes will be disjoint from other nodes from time to time. Under such circumstance, ordinary hop-by-hop routing

The associate editor coordinating the review of this manuscript and approving it for publication was Theofanis P. Raptis.

schemes can not be used anymore, for there is no route existed from source to destination. Some solutions use store-carry-forward (SCF) routing to facilitate end to end data transmission. In SCF routing, the message is stored in a node (or some nodes) and moved from source to the destination one hop at a time [2].

However, when should we use SCF routing, when we should use ordinary routing if we taking energy into consideration? Is ordinary hop-by-hop routing always better than SCF? If it is good or not the hop-by-hop routing is combined with the SCF routing? All these questions need to be answered. To the best of our knowledge, there is no research to combine hop-by-hop routing and SCF routing in a protocol to improve the energy efficiently of transmission in UAV network. Therefore, in this article, we carry out researches for the energy consumption of the two techniques, and proposed our modification suggests for hop-by-hop routing protocols to save energy in rotary-wing UAV networks.

Our researches have made such contributions:

1) We proposed and researched the minimum energy consumption models of three hop-by-hop routing modes and two SCF routing modes for the transmissions in a rotary-wing UAV network.
2) Based on the minimum energy consumption models of hop-by-hop and SCF routing, we proposed four tactics of combination modes, and proved two tactics have better performance than others in energy saving that can reduce 70% energy consumption at most with hop-by-hop routing. The two tactics are appropriate for different UAV networks respectively, in which the source UAV can or cannot get the GPS information of relay UAVs in the route.
3) Simulation works validated our researches.

The remainder of this paper is organized as follows. Section II discusses important prior works about energy efficiency in UAV networks. Section III introduces the prior work about the flight energy consumption of rotary-wing UAV. Section IV introduces the transmission energy consumption model of hop-by-hop routing modes. Section V presents the transmission energy consumption model of SCF routing modes. In section VI, we propose and analyse the tactics of combination modes and validated their performances by numerical experiment in section VII. Finally, concludes the paper.

II. RELATED WORKS ABOUT ENERGY EFFICIENCY IN UAV NETWORK

Gupta *et al.* [1] has classified the energy-aware protocols for UAV network on the basis of the protocol layer they operate in and the energy saving strategy used. The energy conservation protocols in the data link layer, physical layer, and through cross-layer have nothing to do with our researches. We only focus on the protocols in the network layer which can be classified into the four categories: 1) Path selection based, 2) Node selection based, 3) Coordinator based, 4) Sleep based. The path selection based protocols aim to select paths that minimize total source to destination energy requirement. The node Selection based protocols aim to select nodes that preserve battery life of each node or exclude nodes with low energy. The coordinator based protocols is selection of a cluster head or a coordinator that will remain awake while the other nodes can sleep to conserve power. And the sleep based protocols conserve energy mainly by making as many nodes sleep for as long as possible. Our modification suggests are for the path selection based protocols such as follow.

1) EMM-DSR (Extended Max-Min Dynamic Source Routing) Protocol [4]: This protocol maximizes energy efficiency by finding the shortest path based on energy. It maintains a good end-to-end delay and throughput performance. It extends the Max-Min algorithm to maximize throughput, minimize delay and maximize energy efficiency. This extension has been applied to the existing on-demand dynamic source routing protocol (DSR) in the context of mobile ad hoc networks, and the resultant version takes the name of EMM-DSR. However, in [5], the performance based on end-to-end latency of DSR was worst for UAV networks as compared to AODV and directional OLSR.
2) FAR (Flow Augmentation Routing) [6]: FAR is a transmission power optimization protocol. It assumes a static network and finds the optimal routing path for a given source-destination pair that minimizes the sum of link costs along the path. The cost depends on cost of a unit flow transmission over the link, initial and residual energy at the transmitting node. The flow augmentation algorithm requires frequent route computations and transitions but it selects the shortest cost route each time. As pseudo-stability of the topology can only be assumed in a small subset of UAV network applications (e.g. communication coverage of a remote area), there will be heavy penalty in terms of computation of minimum cost link paths when the nodes change their relative positions frequently.
3) The Minimum-energy Routing: Minimum-energy routing saves power by choosing paths through a multi-hop ad hoc network that minimize the total transmit energy. Distributing energy consumption fairly maximizes the network lifetime. In this protocol, nodes adjust their transmission power levels and select routes to optimize performance. Topology may be selected by adjusting the power such that only immediate neighbors communicate. It is possible to set this up in UAV networks except that the neighbors may change more frequently. The work on multi-hop communication is a swarm of UAVs [7] has reported use of minimum-energy expenditure multi-hop routing similar to ExOR (Extremely Opportunistic Routing). High power hops are split into smaller low power hops. Edge weights represent attenuation in the network and Dijkstra's algorithm is used to calculate the shortest (lowest energy) path.

4) The Pulse protocol: A pulse, referred to as flood, is periodically sent at fixed interval originating from infrastructure access nodes and propagating through entire component of the network. This pulse updates each node about the nearest pulse source and each node tracks best route to the nearest pulse source based on some metric. The propagation of the flood forms a loop free routing tree rooted at the pulse source. If a node needs to send a packet it responds to the pulse with a reservation packet. This protocol could suffer from flood overlap delays and can result in significant consumption of energy [8].

All the researches above are hop-by-hop routing, and there is not any research concern the energy efficiency when hop-by-hop routing is combined with SCF routing. In this paper, we will present our researches on this matter.

III. RESEARCH BASIS

Zeng *et al.* [11] presented the calculation method of the flight energy consumption of rotary-wing UAV on the basis of paper [9] and [10], and studied the mathematical relationships among flight energy consumption, transmission energy consumption and transmission distance. In this paper, we set up the mathematical model of transmission energy consumption of hop-by-hop and SCF routing on the basis of Zeng's researches, then carry out further researches for combination modes.

In paper [11], we know the propulsion power consumption can be modeled as

$$P(V) = P_0(1 + \frac{3V^2}{U_{tip}^2}) + P_i(\sqrt{1 + \frac{V^4}{4v_0^4}} - \frac{V^2}{2v_0^2})^{1/2} + \frac{1}{2}d_0 \rho s A V^3 \qquad (1)$$

where V is the UAV flying speed, P_0 and P_i are two constants representing the blade profile power and induced power in hovering status respectively, U_{tip} denotes the tip speed of the rotor blade, v_0 is known as the mean rotor induced velocity in hover, d_0 and s are the fuselage drag ratio and rotor solidity respectively, ρ and A denote the air density and rotor disc area respectively.

By substituting $V = 0$ into formula (1), we obtain the power consumption for hovering status as $P_h = P_0 + P_i$.

When $V \gg v_0$, by applying the first-order Taylor approximation $(1 + x)^{1/2} \approx 1 + \frac{1}{2}x$ for $|x| \ll 1$, formula (1) can be approximated as

$$P(V) \approx P_0(1 + \frac{3V^2}{U_{tip}^2}) + P_i\frac{v_0}{V} + \frac{1}{2}d_0 \rho s A V^3 \qquad (2)$$

which is a convex function.

The transmission energy consumption includes the energies of all actions required to complete a transmission. The energy consumption of hop-by-hop routing mode includes the energies of communication and hovering. The energy consumption of SCF routing mode includes the energy of communication, hovering, and moving. Some additional energies may be consumed when UAV is accelerating or decelerating. If a transmission in SCF routing mode has accelerated and decelerated many times, it is hard to calculate the energy consumption and save energy. For the convenience of research, we assume the transmission in SCF routing mode has only one time acceleration and deceleration when the UAV leaves from the starting point and reaches the target point. The type of transmission task includes: Complete data task, which needs to receive all data before being used. Stream data task, which can be used while data is receiving.

TABLE 1. List of notation.

Notation	Interpretation
IECH	The ideal energy consumption model of hop-by-hop routing
RECH	The realistic energy consumption model of hop-by-hop routing
AECH	The approximate energy consumption model of hop-by-hop routing
FHC	The 'Fly-Hover-Communication' mode
FCC	The 'Fly-Continuous Communication' mode
STIF	The Switch Tactic base on the IECH and FHC
STAF	The Switch Tactic base on the AECH and FHC
STRF	The Switch Tactic base on the RECH and FHC

IV. THE MINIMUM TRANSMISSION ENERGY CONSUMPTION OF HOP-BY-HOP ROUTING

A. THE IDEAL ENERGY CONSUMPTION MODEL OF HOP-BY-HOP ROUTING (IECH)

Under the Ideal Energy Consumption model of Hop-by-hop routing (IECH), the UAVs are arranged in a straight line, as the green line in Fig.1 shows. We assume that, a message is transmitted between a pair of UAVs at a distance L, and the message would through $n - 1$ hops. Because the total transmission time of the complete data task is same as the stream data task, it is not need to analysis respectively.

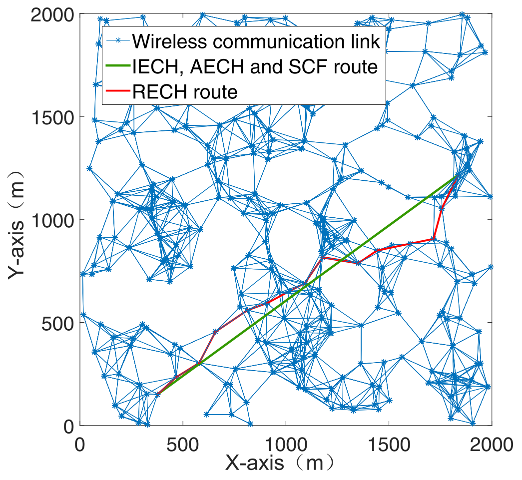


FIGURE 1. Routes in different modes.

We assume the traffic of message is $\tilde{Q}$, and the distance between neighbor UAVs is $d(n) = \frac{L}{n}$. Considering the need for safe flight, it is necessary to maintain a safe distance D_{sf} between neighbor UAVs, the distance between neighbor UAVs $d(n)$ must be greater than or equal to the safe distance D_{sf} and less than or equal to the distance between the source UAV and destination UAV L. The resulting constraint is $\frac{L}{D_{sf}} \geq n \geq 1$.

We assume that the wireless channels between UAVs are dominated by LoS links. Thus, the channel power gain between the UAVs can be modeled based on the free-space path loss model as $h(n) = \beta_0 d(n)^{-2}$, where β_0 represents the channel power gain at the reference distance of 1 meter. Furthermore, assuming a fixed transmission power P_c by the transmitter when it is scheduled for communication. According to the conclusion of paper [11], the achievable rate in bits per second (bps) is expressed as

$$R(n) = B\log_2(1 + \frac{P_c h(n)}{\sigma^2 \Gamma}) = B\log_2(1 + \frac{\gamma_0 n^2}{L^2}) \quad (3)$$

where B denotes the channel bandwidth in hertz (Hz), σ^2 is the noise power at the receiver, $\Gamma > 1$ accounts for the gap from the channel capacity due to the practical modulation and coding scheme employed, and $\gamma_0 \overset{\Delta}{=} P_c\beta_0/(\sigma^2\Gamma)$ is defined as the received signal-to-noise ratio (SNR) at the reference distance of 1 meter.

Therefore, the transmission time of one hop is

$$t_0(n) = \frac{\tilde{Q}}{R(n)} = \frac{\tilde{Q}}{B\log_2(1 + \frac{\gamma_0 n^2}{L^2})} \quad (4)$$

And the total transmission time of the route is

$$t_M(n) = nt_0(n) = \frac{n\tilde{Q}}{B\log_2(1 + \frac{\gamma_0 n^2}{L^2})} \quad (5)$$

The energy required to complete transmission is the sum of the communication energy consumption and the flight energy consumption that maintains the hovering state. The transmission energy consumption of one hop can be expressed as

$$E_0(n) = (P_c + P_h)t_0(n) = \frac{\tilde{Q}(P_c + P_h)}{B\log_2(1 + \frac{\gamma_0 n^2}{L^2})} \quad (6)$$

The total transmission energy consumption of the route can be expressed as

$$E_M(n) = nE_0(n) = \frac{n\tilde{Q}(P_c + P_h)}{B\log_2(1 + \frac{\gamma_0 n^2}{L^2})} \quad (7)$$

When $|x| \ll 1$, by applying the first-order Taylor approximation $\ln(1 + x) \approx x$, formula (7) can be approximated as

$$E_M(n) \approx \frac{\tilde{Q}(P_c + P_h)L^2 \ln 2}{B\gamma_0 n} \quad (8)$$

which is a convex function.

It can be seen that the total transmission energy consumption function is a monotonous decreasing function of n. When the maximum value n is taken as $\frac{L}{D_{sf}}$, we can achieve the minimum transmission energy consumption as

$$E_{M\_\min}(L, \tilde{Q}) = L\tilde{Q}\frac{D_{sf}(P_c + P_h)\ln 2}{B\gamma_0} \quad (9)$$

B. THE REALISTIC ENERGY CONSUMPTION MODEL OF HOP-BY-HOP ROUTING (RECH)

Under the Realistic Energy Consumption model of Hop-by-hop routing (RECH), the UAVs are randomly distributed, as the red line in Fig.1 shows. The message would goes through $n-1$ relay UAVs which are selected by the hop-by-hop routing algorithm, and finally reach the destination UAV. Since the UAVs are randomly distributed, the total transmission distance would not less than the straight-line distance L. The pathes set is $\{\tau_k\}(1 \leq k \leq n)$ and the total transmission distance can be expressed as $\sum_{k=1}^{n} \tau_k \geq L$.

The time to complete transmission of one hop is

$$t_0(\tau_k) = \frac{\tilde{Q}}{R(\tau_k)} = \frac{\tilde{Q}}{B\log_2(1 + \frac{\gamma_0}{\tau_k^2})} \quad (10)$$

The total energy consumption of route can be expressed as

$$\begin{aligned} E_M(\{\tau_k\}, \tilde{Q}) &= \sum_{k=1}^{n} \frac{\tilde{Q}(P_c + P_h)}{B\log_2(1 + \frac{\gamma_0}{\tau_k^2})} \\ &\approx \tilde{Q}\frac{(P_c + P_h)\ln 2}{B\gamma_0}\sum_{k=1}^{n}\tau_k^2 \end{aligned} \quad (11)$$

C. THE APPROXIMATE ENERGY CONSUMPTION MODEL OF HOP-BY-HOP ROUTING (AECH)

The distance of route between two UAVs are necessary for calculating the transmission energy consumption, but it is difficult to know them in practical applications. Moreover, the model of IECH cannot reflect the real situation. Therefore, we would like to propose an approximate expression of transmission energy consumption without the GPS information of relay UAVs in the route, as the green line in Fig.1 shows.

We assume that UAVs are evenly distributed in a $L_{\max} \times L_{\max}$ square plane space, and the average coverage area of a UAV is $\pi(\frac{D_\Delta}{2})^2$, where D_Δ is the cover diameter. The entire deployment space can fill up to $\frac{L_{\max}^2}{\pi(\frac{D_\Delta}{2})^2}$ circular planes. Therefore, the relationship between the number of UAVs N and D_Δ is $D_\Delta = 2\sqrt{\frac{L_{\max}^2}{\pi \mathrm{N}}}$. And we can deduce the transmission energy consumption model is

$$\begin{aligned} E_{M\_\min}(L, \tilde{Q}) &= \mu\tilde{Q}L\frac{D_\Delta(P_c + P_h)\ln 2}{B\gamma_0} \\ &= \mu\tilde{Q}LL_{\max}\frac{2(P_c + P_h)\ln 2}{B\gamma_0\sqrt{\pi \mathrm{N}}} \end{aligned} \quad (12)$$

where μ is an empirically chosen factor called area factor in this paper. For example, if the average effective coverage area of a UAV is calculated as a circular one, we have $\mu = 1$, and $\mu = \frac{(\frac{\pi r}{2})^2}{\pi r^2} = \frac{4}{\pi}$ when the average effective coverage area is calculated as a square one.

V. THE TRANSMISSION ENERGY CONSUMPTION OF SCF ROUTING

A. THE 'FLY-HOVER-COMMUNICATION' MODE (FHC)

In this mode, a message is transmitted between a pair of UAVs at a distance L. The source UAV would move to a suitable location according to the SCF routing, keeping hovering state, and then starts transmitting message to the destination UAV. We assume the distance that the source UAV keeps hovering from the destination UAV is D_c, which is not less than the safe distance D_{sf}.

When the source UAV keeps hovering at the distance D_c, the transmission rate is

$$R_{D\_0}(D_c) = B\log_2(1 + \frac{\gamma_0}{D_c^2}) \approx \frac{B\gamma_0}{D_c^2 \ln 2} \tag{13}$$

Therefore, the total transmission time for the entire task is

$$t_{D1\_0}(D_c, \tilde{Q}) = \frac{\tilde{Q}}{R_{D\_0}(D_c)} \approx \frac{\tilde{Q} D_c^2 \ln 2}{B\gamma_0} \tag{14}$$

Since the transmission power is constant, the total communication energy consumption is

$$E_{D1\_c}(D_c, \tilde{Q}) = P_c t_{D1\_0}(D_c, \tilde{Q}) \approx \frac{\tilde{Q} D_c^2 P_c \ln 2}{B\gamma_0} \tag{15}$$

The distance the source UAV needs to move is

$$D_{D1\_tr}(D_c, L) = L - D_c \tag{16}$$

where D_c is a variable, and $D_{sf} \leqslant D_c \leqslant L$. From [11], we can know that the most energy-efficient way is that the UAV keeps the maximum-range (MR) speed V_{mr} [11] to flight from the original location to the transmission location. Therefore, the time required for moving is

$$t_{D1\_tr}(D_c, L) = \frac{D_{D1\_tr}(D_c, L)}{V_{mr}} = \frac{L - D_c}{V_{mr}} \tag{17}$$

As we assume the UAV moves at a constant speed, it only involves one time acceleration and one deceleration. The energy consumption of acceleration and deceleration is small compared with the energy consumption of long-distance move. In order to simplify the calculation, the acceleration and deceleration problems involved in the move process are all ignored, so the energy consumption of move is

$$\begin{aligned} &E_{D1\_tr}(D_c, L) \\ &\quad = t_{D1\_tr}(D_c, L) P(V_{mr}) \\ &\quad \approx (L - D_c)(P_0(\frac{1}{V_{mr}} + \frac{3V_{mr}}{U_{tip}^2}) + \frac{P_i}{v_0} + \frac{1}{2} d_0 \rho s A V_{mr}^2) \end{aligned} \tag{18}$$

The energy consumption of keeping hovering is

$$E_{D1\_h}(D_c, \tilde{Q}) = P_h t_{D1\_0}(D_c, \tilde{Q}) \approx \frac{\tilde{Q} D_c^2 (P_0 + P_i) ln2}{B\gamma_0} \tag{19}$$

As the UAV keeps hovering during transmission, the total energy consumption of the hovering state is composed of the flight energy consumption that keeps hovering and the communication energy consumption. Therefore, the total energy consumption of transmission is the sum of the hovering stage and the moving stage.

$$\begin{aligned} E_{D1\_tot} &= E_{D1\_tr} + E_{D1\_h} + E_{D1\_c} \\ &\approx (L - D_c)(P_0(\frac{1}{V_{mr}} + \frac{3V_{mr}}{U_{tip}^2}) + \frac{P_i}{v_0} + \frac{1}{2} d_0 \rho s A V_{mr}^2) \\ &\quad + \frac{\tilde{Q}(P_0 + P_i + P_c) ln2}{B\gamma_0} D_c^2 \end{aligned} \tag{20}$$

where $D_{sf} \leqslant D_c \leqslant L$.

To simplify the expression formula (20), we set

$$\begin{aligned} \alpha_1 &= \frac{(P_0 + P_i + P_c) ln2}{B\gamma_0} \\ \alpha_2 &= P_0(\frac{1}{V_{mr}} + \frac{3V_{mr}}{U_{tip}^2}) + \frac{P_i}{v_0} + \frac{1}{2} d_0 \rho s A V_{mr}^2 \end{aligned} \tag{21}$$

The problem of minimizing energy consumption in this mode can be expressed as

$$\begin{aligned} &\min_{D_c, \tilde{Q}, L} \; E_{D1\_tot}(D_c, \tilde{Q}, L) = \alpha_1 \tilde{Q} D_c^2 + (L - D_c)\alpha_2 \\ &s.t. \; D_{sf} \leqslant D_c \leqslant L \\ &\qquad \alpha_1 = \frac{(P_0 + P_i + P_c) ln2}{B\gamma_0} \\ &\qquad \alpha_2 = P_0(\frac{1}{V_{mr}} + \frac{3V_{mr}}{U_{tip}^2}) + \frac{P_i}{v_0} + \frac{1}{2} d_0 \rho s A V_{mr}^2 \end{aligned} \tag{22}$$

The value of $\tilde{Q}$ and L are known in a transmission task. Therefore, the minimum energy consumption is determined by D_c. It is easy to know, the transmission energy consumption can achieve the minimum value when $D_c = \max\{D_{sf}, \frac{\alpha_2}{2\alpha_1(\tilde{Q})}\}$. Therefore, the expression of minimum energy consumption can be expressed as

$$\begin{aligned} &E_{D1\_tot\_\min}(L, \tilde{Q}) \\ &\quad = \begin{cases} L\alpha_2 - \frac{\alpha_2^2}{4\alpha_1(\tilde{Q})}, & \frac{\alpha_2}{2\alpha_1 \tilde{Q}} > D_{sf} \\ \alpha_1 \tilde{Q} D_{sf}^2 + (L - D_{sf})\alpha_2, & \frac{\alpha_2}{2\alpha_1 \tilde{Q}} \leqslant D_{sf} \end{cases} \end{aligned} \tag{23}$$

where

$$\begin{aligned} \alpha_1 &= \frac{(P_0 + P_i + P_c) ln2}{B\gamma_0} \\ \alpha_2 &= P_0(\frac{1}{V_{mr}} + \frac{3V_{mr}}{U_{tip}^2}) + \frac{P_i}{v_0} + \frac{1}{2} d_0 \rho s A V_{mr}^2 \end{aligned} \tag{24}$$

B. THE 'FLY-CONTINUOUS COMMUNICATION' MODE (FCC)

In this mode, a message is transmitted between a pair of UAVs at a distance L. The source UAV would move to the destination UAV and begin transmission once in the communication range, until the distance between the source UAV and the destination UAV is D_c. Then, the source UAV would keep hovering and transmitting. We use $D_x(t)$ to indicate the real-time distance between the source UAV and the destination UAV at time t, which $D_x(t) \geq D_{sf}$. $D_x(t)$ can be expressed as

$$D_x(t) = L - \int_0^t V(\tau)d\tau \tag{25}$$

where $V(\tau)$ is the instantaneous speed of the source UAV.

When the source UAV is located at $D_x(t)$, the transmission rate is

$$R_{D\_x}(D_x) = B\log_2(1 + \frac{\gamma_0}{D_x^2}) \approx \frac{B\gamma_0}{D_x^2 \ln 2} \tag{26}$$

We assume that the move maintains at a constant speed, and we use V_x to express the constant speed, which is an unknown variable. Therefore, D_x can be expressed as

$$D_x(t, V_x) = L - tV_x \tag{27}$$

When the source UAV is located at $D_x(t, V_x)$, the transmission rate is

$$R_{D\_x}(t, V_x) \approx \frac{B\gamma_0}{(L - tV_x)^2 \ln 2} \tag{28}$$

The total distance that the source UAV moves at speed V_x is

$$D_{D2\_tr}(D_c, L) = L - D_c \tag{29}$$

where D_c is an unknown variable and $D_{sf} \leqslant D_c \leqslant L$. The total time of move is

$$t_{D2\_tr}(D_c, L, V_x) = \frac{D_{D2\_tr}(D_c, L)}{V_x} = \frac{L - D_c}{V_x} \tag{30}$$

The source UAV start transmitting when moving to the maximum communication distance $D_{c\max}$ from the destination UAV. The move time before transmitting is

$$t_{D2\_tr\_0}(D_{c\max}, L, V_x) = \frac{L - D_{c\max}}{V_x} \tag{31}$$

The actual transmission time of the moving stage is

$$t_{D2\_tr} - t_{D2\_tr\_0} = \frac{D_{c\max} - D_c}{V_x} \tag{32}$$

Assuming the traffic is large enough, and the UAV would continue transmit during the hovering stage. The amount of traffic be transmitted during the moving stage is

$$\begin{aligned} Q_{D2\_tr}(D_c, L, V_x) &= \int_{t_{D2\_tr\_0}(D_{c\max}, L, V_x)}^{t_{D2\_tr}(D_c, L, V_x)} R_{D\_x}(t, V_x)dt \\ &\approx \frac{B\gamma_0}{V_x \ln 2}(\frac{1}{D_c} - \frac{1}{D_{c\max}}) \end{aligned} \tag{33}$$

The remained transmission traffic is

$$Q_{D2\_h}(D_c, L, V_x, \tilde{Q}) \approx \tilde{Q} - \frac{B\gamma_0}{V_x \ln 2}(\frac{1}{D_c} - \frac{1}{D_{c\max}}) \tag{34}$$

The required transmission time of the hovering stage is

$$\begin{aligned} t_{D2\_h}(D_c, L, V_x, \tilde{Q}) &= \frac{Q_{D2\_h}(D_c, L, V_x, \tilde{Q})}{R_{D\_0}(D_c)} \\ &\approx (\frac{\tilde{Q}\ln 2}{B\gamma_0} + \frac{1}{V_x D_{c\max}})D_c^2 - \frac{D_c}{V_x} \end{aligned} \tag{35}$$

The total energy consumption during the moving stage is composed of flight energy consumption and transmission energy consumption, which can be expressed as

$$\begin{aligned} &E_{D2\_tr}(D_c, L, V_x) \\ &= t_{D2\_tr}(D_c, L, V_x)P(V_x) + \frac{D_{c\max} - D_c}{V_x}P_c \\ &\approx (L - D_c)(\frac{P_0}{V_x} + \frac{3V_x P_0}{U_{tip}^2} + \frac{P_i}{v_0} + \frac{1}{2}d_0\rho sAV_x^2) \\ &\quad + \frac{D_{c\max} - D_c}{V_x}P_c \end{aligned} \tag{36}$$

While the total energy consumption during the hovering stage is the sum of hovering energy consumption and transmission energy consumption, it can be expressed as

$$\begin{aligned} &E_{D2\_h}(D_c, L, V_x, \tilde{Q}) \\ &= (P_h + P_c)t_{D2\_h}(D_c, L, V_x, \tilde{Q}) \\ &= (P_h + P_c)((\frac{\tilde{Q}\ln 2}{B\gamma_0} + \frac{1}{V_x D_{c\max}})D_c^2 - \frac{D_c}{V_x}) \end{aligned} \tag{37}$$

Therefore, we can achieve the total energy consumption, which is the sum of the energy consumption during the moving and hovering, as

$$\begin{aligned} &E_{D2\_tot}(D_c, L, V_x, \tilde{Q}) \\ &= E_{D2\_tr}(D_c, L, V_x) + E_{D2\_h}(D_c, L, V_x, \tilde{Q}) \\ &= \frac{1}{2}d_0\rho sALV_x^2 + \frac{3P_0 L}{U_{tip}^2}V_x + \frac{D_{c\max}P_c + P_0 L}{V_x} + \frac{P_i L}{v_0} \\ &\quad - \frac{1}{2}d_0\rho sAV_x^2 D_c - \frac{3P_0}{U_{tip}^2}V_x D_c - \frac{2P_c + P_h + P_0}{V_x}D_c \\ &\quad + \frac{P_h + P_c}{D_{c\max}V_x}D_c^2 + \frac{\tilde{Q}(P_h + P_c)\ln 2}{B\gamma_0}D_c^2 - \frac{P_i}{v_0}D_c \end{aligned} \tag{38}$$

where $0 \leqslant V_x \leqslant V_{\max}$ and $D_{sf} \leqslant D_c \leqslant L$.

Therefore, the problem of minimizing energy consumption in this mode can be expressed as

$$\begin{aligned} \min_{D_c, L, V_x, \tilde{Q}} \ & E_{D2\_tot}(D_c, L, V_x, \tilde{Q}) \\ s.t. \ & \leqslant V_x \leqslant V_{\max} \\ & D_{sf} \leqslant D_c \leqslant L \end{aligned} \tag{39}$$

The value of $\tilde{Q}$ and L are known in a task, therefore, the minimum energy consumption is determined by D_c and V_x. Since the concavity and convexity of the expression varies with the parameter, it cannot be directly solved by the convex optimization tool. As shown in the most value theorem, there must be a maximum and a minimum when the function is continuous over a closed interval. Therefore, we can gain the value of minimum energy consumption $E_{D2\_tot\_\min}(D_c, V_x)$

by comparing the size of the stationary point and the minimum value on the boundary.

1) STEP ONE

Search for all the stationary values of the expression.

we take the derivative of the objective function from D_c and V_x respectively, and solve the function $\frac{\partial E_{D\_tot}(D_c,V_x)}{\partial V_x} = \frac{\partial E_{D\_tot}(D_c,V_x)}{\partial D_c} = 0$, can obtain that

$$\begin{cases} \frac{3P_0L}{U_{tip}^2}V_x^2 - \frac{3P_0}{U_{tip}^2}D_cV_x^2 + d_0\rho sALV_x^3 - d_0\rho sAD_cV_x^3 \\ = D_{c\max}P_c + P_0L + \frac{P_h+P_c}{D_{c\max}}D_c^2 - (P_h+2P_c+P_0)D_c \\ D_c = \dfrac{\frac{P_h+2P_c+P_0}{V_x} + \frac{3P_0}{U_{tip}^2}V_x + \frac{P_i}{v_0} + \frac{1}{2}d_0\rho sAV_x^2}{2(P_h+P_c)(\frac{\tilde{Q}\ln 2}{B\gamma_0} + \frac{1}{D_{c\max}V_x})} \end{cases} \tag{40}$$

To facilitate further solution, we make

$$\begin{aligned} a_1 &= \frac{3P_0L}{U_{tip}^2} \\ a_2 &= \frac{3P_0}{U_{tip}^2} \\ a_3 &= d_0\rho sA \\ a_4 &= D_{c\max}P_c + P_0L \\ a_5 &= \frac{P_h+P_c}{D_{c\max}} \\ a_6 &= P_h + 2P_c + P_0 \\ a_7 &= \frac{P_i}{v_0} \\ a_8 &= \frac{2(P_h+P_c)\tilde{Q}\ln 2}{B\gamma_0}. \end{aligned} \tag{41}$$

The formula (40) can be simplified as

$$\begin{cases} a_1V_x^2 - a_2D_cV_x^2 + a_3LV_x^3 - a_3D_cV_x^3 \\ = a_4 + a_5D_c^2 - a_6D_c \\ D_c = \dfrac{a_6 + a_2V_x^2 + a_7V_x + \frac{a_3}{2}V_x^3}{a_8V_x + 2a_5} \end{cases} \tag{42}$$

Combining the two formulas of formula (42) and eliminating the variable D_c, we can get an expression about V_x as

$$\begin{aligned} &(\frac{{a_3}^2a_8}{2})V_x^7 + (\frac{5{a_3}^2a_5}{4} + \frac{3a_2a_3a_8}{2})V_x^6 \\ &+ ({a_2}^2a_8 + a_3a_7a_8 - \frac{5a_2a_3a_5}{2} - La_3{a_8}^2)V_x^5 \\ &+ (\frac{7a_3a_5a_7}{2} + 3{a_2}^2a_5 + a_2a_7a_8 + \frac{a_3a_6a_8}{2} \\ &- a_1{a_8}^2 - 4La_3a_5a_8)V_x^4 \\ &+ (4a_2a_5a_7 + 2a_3a_5a_6 - 4a_1a_5a_8 - 4La_3{a_5}^2)V_x^3 \\ &+ (a_4{a_8}^2 + 2a_2a_5a_6 + a_5{a_7}^2 - 4a_1{a_5}^2 - a_6a_7a_8)V_x^2 \\ &+ (4a_4a_5a_8 - {a_6}^2a_8)V_x + (4a_4{a_5}^2 - a_5{a_6}^2) = 0 \end{aligned} \tag{43}$$

For further simplification, we make

$$\begin{aligned} b_1 &= \frac{{a_3}^2a_8}{2} \\ b_2 &= \frac{5{a_3}^2a_5}{4} + \frac{3a_2a_3a_8}{2} \\ b_3 &= {a_2}^2a_8 + a_3a_7a_8 - \frac{5a_2a_3a_5}{2} - La_3{a_8}^2 \\ b_4 &= 3{a_2}^2a_5 + \frac{7a_3a_5a_7}{2} + a_2a_7a_8 + \frac{a_3a_6a_8}{2} \\ &\quad - a_1{a_8}^2 - 4La_3a_5a_8 \\ b_5 &= 4a_2a_5a_7 + 2a_3a_5a_6 - 4a_1a_5a_8 - 4La_3{a_5}^2 \\ b_6 &= a_4{a_8}^2 + 2a_2a_5a_6 + a_5{a_7}^2 - 4a_1{a_5}^2 - a_6a_7a_8 \\ b_7 &= 4a_4a_5a_8 - {a_6}^2a_8 \\ b_8 &= 4a_4{a_5}^2 - a_5{a_6}^2 \end{aligned} \tag{44}$$

Then, we can obtain

$$\begin{cases} b_1V_x^7 + b_2V_x^6 + b_3V_x^5 + b_4V_x^4 + b_5V_x^3 \\ +b_6V_x^2 + b_7V_x + b_8 = 0 \\ D_c = \dfrac{a_6 + a_2V_x^2 + a_7V_x + \frac{a_3}{2}V_x^3}{a_8V_x + 2a_5} \end{cases} \tag{45}$$

Using the Newton Iteration Toolkit to search the real solution of formula (45) in the interval of $0 \leqslant V_x \leqslant V_{\max}$. After that, we can substitute the real solution of V_x and D_c, then we can get the corresponding total energy consumption by using formula (38).

2) STEP TWO

Calculate the minimum value of the expression on the boundary of the defined domain.

(i)When $(D_c, V_x) = (L, 0)$ and $D_{c\max} \geqslant L$, the source UAV completes the transmission of all traffic without leaving the initial location. In such case, the transmission rate is

$$R_{D\_x}(t, V_x) = \frac{B\gamma_0}{L^2\ln 2} \tag{46}$$

So the transmission require time

$$t_{D2}(D_c, V_x) = \frac{\tilde{Q}L^2\ln 2}{B\gamma_0} \tag{47}$$

As the total energy consumption is the sum of the hovering and transmitting energy consumption, the value of total energy consumption is

$$\begin{aligned} E_{D2\_tot}(D_c, V_x) &= (P_h + P_c)t_{D2}(D_c, V_x) \\ &= \frac{\tilde{Q}L^2(P_h+P_c)\ln 2}{B\gamma_0} \end{aligned} \tag{48}$$

(ii)When $D_c = D_{sf}$, the source UAV would hover at the location which is D_{sf} from the destination UAV. In such case, the total energy consumption is

$$\begin{aligned} E_{D2\_tot}(V_x) = &\frac{D_{c\max}P_c + P_0L - (P_h+2P_c+P_0)D_{sf}}{V_x} \\ &+ \frac{(P_h+P_c)D_{sf}^2}{V_xD_{c\max}} \end{aligned}$$

$$+\frac{3P_0(L-D_{sf})}{U_{tip}^2}V_x+\frac{1}{2}d_0\rho sA(L-D_{sf})V_x^2$$
$$+\frac{\tilde{Q}(P_h+P_c)\ln 2}{B\gamma_0}D_{sf}^2+\frac{P_i(L-D_{sf})}{v_0} \qquad (49)$$

where $0 < V_x < V_{\max}$. To simplify the formula (49), we make

$$\begin{aligned} d_1 &= \frac{1}{2}d_0\rho sA(L-D_{sf}) \\ d_2 &= \frac{3P_0(L-D_{sf})}{U_{tip}^2} \\ d_3 &= D_{c\max}P_c+P_0L-(P_h+2P_c+P_0)D_{sf} \\ &\quad +\frac{(P_h+P_c)D_{sf}^2}{D_{c\max}} \\ d_4 &= \frac{\tilde{Q}(P_h+P_c)\ln 2}{B\gamma_0}D_{sf}^2+\frac{P_i(L-D_{sf})}{v_0} \end{aligned} \qquad (50)$$

Then, formula (49) can be simplified as

$$E_{D2\_tot}(V_x)=d_1V_x^2+d_2V_x+\frac{d_3}{V_x}+d_4 \qquad (51)$$

When $E_{D2\_tot}''(V_x)=2d_1+2\frac{d_3}{V_x^3}\geqslant 0$, $E_{D2\_tot}(V_x)$ can obtain the minimum value.

(iii)When $V_x = V_{\max}$, the source UAV moves at the maximum speed $V_{\max}$. In such case, the total energy consumption is

$$\begin{aligned} &E_{D2\_tot}(D_c) \\ &= (P_h+P_c)\left(\frac{1}{D_{c\max}V_{\max}}+\frac{\tilde{Q}\ln 2}{B\gamma_0}\right)D_c^2 \\ &\quad -\left(\frac{1}{2}d_0\rho sAV_{\max}^2+\frac{3P_0}{U_{tip}^2}V_{\max}+\frac{P_h+2P_c+P_0}{V_{\max}}+\frac{P_i}{v_0}\right)D_c \\ &\quad +\left(\frac{P_i}{v_0}+\frac{1}{2}d_0\rho sAV_{\max}^2+\frac{3P_0}{U_{tip}^2}V_{\max}+\frac{P_0}{V_{\max}}\right)L+\frac{D_{c\max}P_c}{V_{\max}} \end{aligned} \qquad (52)$$

where $D_{sf} < D_c < L$. We make

$$\begin{aligned} e_1 &= v\ (P_h+P_c)\left(\frac{1}{D_{c\max}V_{\max}}+\frac{\tilde{Q}\ln 2}{B\gamma_0}\right) \\ e_2 &= \frac{1}{2}d_0\rho sAV_{\max}^2+\frac{3P_0}{U_{tip}^2}V_{\max}+\frac{P_h+2P_c+P_0}{V_{\max}}+\frac{P_i}{v_0} \\ e_3 &= \left(\frac{P_i}{v_0}+\frac{1}{2}d_0\rho sAV_{\max}^2+\frac{3P_0}{U_{tip}^2}V_{\max}+\frac{P_0}{V_{\max}}\right)L+\frac{D_{c\max}P_c}{V_{\max}} \end{aligned} \qquad (53)$$

Formula (52) can be simplified as

$$E_{D2\_tot}(D_c)=e_1D_c^2-e_2D_c+e_3. \qquad (54)$$

When $D_c=\frac{e_2}{2e_1}$ and $D_{sf} < D_c < L$, the minimum total energy consumption is $E_{D2\_tot\_\min}=e_3-\frac{e_2^2}{4e_1}$.

3) STEP THREE

We can choose the solution with the minimum energy consumption by comparing the values of stationary points with the minimum value on the boundary of the defined domain.

TABLE 2. Simulation parameters.

Notation	Physical meaning	Simulation value
W	Aircraft weight	100 Newton
ρ	Air density	1.225 kg/m^3
R	Rotor radius in meter	0.5 m
Ω	Blade angular velocity	400 $radians/second$
U_{tip}	Tip speed of the rotor blade	200 m/s
b	Number of blades	4
c	Aerofoil chord length	0.0196
s	Rotor solidity	0.05
S_{FP}	Fuselage equivalent flat plate area	0.0118 m^2
d_0	Fuselage drag ratio	0.3
k	Incremental correction factor to induced power	0.1
v_0	Mean rotor induced velocity in hover	7.2 m/s
δ	Profile drag coefficient	0.012
P_c	Transmission power	50 w
γ_0	SNR	60 dB
V_{mr}	The MR speed	38 m/s
$V_{\max}$	Maximum speed	60 m/s
$D_{c\max}$	Maximum communication distance	200 m
B	Channel bandwidth	1 MHz

VI. THE COMPARISON AND COMBINATION BETWEEN HOP-BY-HOP AND SCF ROUTING

A. COMPARISON OF THE MINIMUM TRANSMISSION ENERGY CONSUMPTION OF HOP-BY-HOP AND SCF ROUTING

According to the parameters of Table 2, we do the simulations and compare the minimum transmission energy consumption of IECH, FHC, FCC. And we make the comparison in a scene which the traffic is set from 500 kbits to 50 Mbits, and the distance is set from 500 m to 1000 m. The performance is shown as Fig.2.

1) APPEARANCE 1

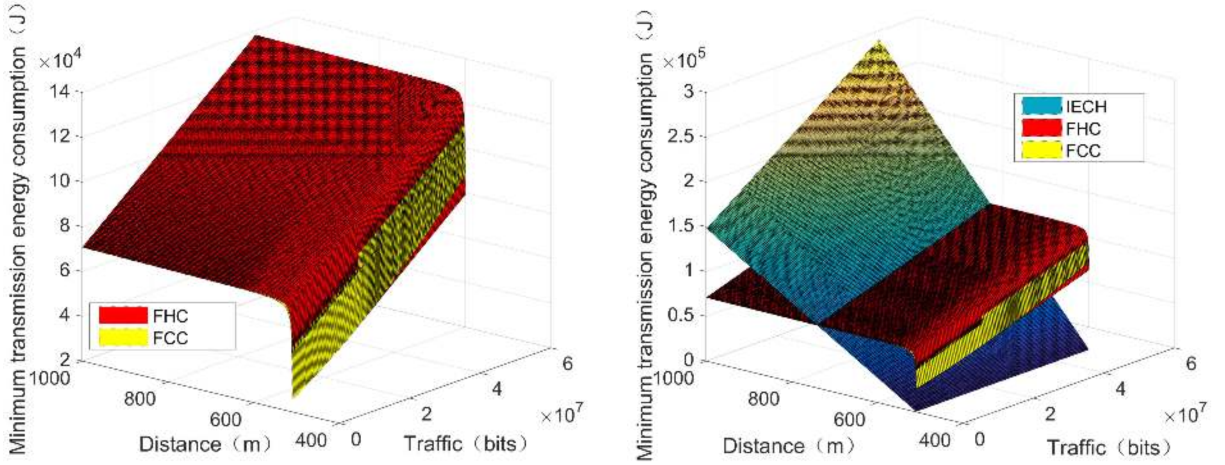
The minimum transmission energy consumption of FHC is higher than FCC.

As Fig.2(a) shows, the minimum transmission energy consumption of FHC and FCC almost overlapped, but the energy of FCC is almost lower than the FHC.

By comparing the experimental data of FHC and FCC, it can be seen that the different of energy consumption between two modes is small. The energy mean difference of the two modes is the 0.46% of FCC, the energy mean variance of the two modes is the 1.7% of FCC. As the FCC is more complicated, we recommend using the FHC in actual use.

2) APPEARANCE 2

As the traffic or distance increases, the SCF routing can save more energy compared to the hop-by-hop routing, and vice versa.



(a) Comparison of minimum transmission energy consumption of FHC and FCC

(b) Comparison of minimum transmission energy consumption of IECH, FHC and FCC

FIGURE 2. **Comparison of the minimum transmission energy consumption of hop-by-hop and SCF routing.**

As Fig.2(b) shows, the minimum transmission energy consumption of the SCF routing is significantly different from the hop-by-hop routing. As the traffic or distance increases, the minimum transmission energy consumption of the SCF routing rises slowly, while the minimum transmission energy consumption of the hop-by-hop routing rises sharply. When the traffic or distance decreases, the minimum transmission energy consumption of hop-by-hop routing decreases rapidly, and the minimum transmission energy consumption of SCF routing slowly decreases. Therefore, when the traffic or distance is large, the SCF routing can save more energy, and vice versa.

According to the appearances, the combination of hop-by-hop routing and SCF routing should save energy. In the next subsection, we will research the switch tactics of combination modes and prove the appearances.

B. THE SWITCH TACTICS OF COMBINATION MODES

According to above appearances, to accomplish transmission with minimum energy consumption, the source UAV should calculate the minimum transmission energy consumption of hop-by-hop and SCF routing before transmission, and select the lower one. We propose three switch tactics base on the three hop-by-hop routing modes and FHC as follows.

1) TACTIC 1

The Switch Tactic base on the IECH and FHC (STIF).

In the situation that the source UAV cannot get the GPS information of relay UAVs in the route, the source UAV should calculate the minimum transmission energy consumption of IECH and FHC before transmission, then select the lower mode to transmit. The decision-making process is as follows:

1) The source UAV gets the task information which include the $\tilde{Q}$ and L.
2) According to the minimum transmission energy consumption of IECH (formula (9)) and FHC (formula (23)), we can get their difference as:

$$\begin{aligned}
&\Delta E_{s1}(L,\tilde{Q})\\
&= E_{M\_\min}(L,\tilde{Q}) - E_{D1\_tot\_\min}(L,\tilde{Q})\\
&= \begin{cases} \alpha_1 D_{sf}\tilde{Q}L + \dfrac{\alpha_2^2}{4\alpha_1\tilde{Q}} - \alpha_2 L, & \dfrac{\alpha_2}{2\alpha_1 D_{sf}} > \tilde{Q} \\ (L - D_{sf})(\alpha_1 D_{sf}\tilde{Q} - \alpha_2), & \dfrac{\alpha_2}{2\alpha_1 D_{sf}} \le \tilde{Q} \end{cases}\\
\alpha_1 &= \frac{(P_0 + P_i + P_c)ln2}{B\gamma_0}\\
\alpha_2 &= P_0(\frac{1}{V_{mr}} + \frac{3V_{mr}}{U_{tip}^2}) + \frac{P_i}{v_0} + \frac{1}{2}d_0\rho s A V_{mr}^2
\end{aligned}$$

3) The source UAV selects the SCF routing to transmit the task when $\Delta E_{s1}(L,\tilde{Q}) \ge 0$, and selects hop-by-hop routing when $\Delta E_{s1}(L,\tilde{Q}) < 0$.

Further analysis showed that:

1) If $\tilde{Q} < \frac{\alpha_2}{2\alpha_1 L}$:
   Select SCF routing when
   $\Delta E_{s1}(L,\tilde{Q}) = (\alpha_1 D_{sf}\tilde{Q} - \alpha_2)L + \frac{\alpha_2^2}{4\alpha_1\tilde{Q}} \ge 0$
   Select hop-by-hop routing when
   $\Delta E_{s1}(L,\tilde{Q}) = (\alpha_1 D_{sf}\tilde{Q} - \alpha_2)L + \frac{\alpha_2^2}{4\alpha_1\tilde{Q}} < 0$
2) If $\frac{\alpha_2}{2\alpha_1 L} < \tilde{Q} \le \frac{\alpha_2}{\alpha_1 D_{sf}}$: Select hop-by-hop routing.
3) If $\frac{\alpha_2}{\alpha_1 D_{sf}} < \tilde{Q}$: Select SCF routing.

The flowchart of STIF is shown as Fig.3.

2) TACTIC 2

The Switch Tactic base on the AECH and FHC (STAF).

In the situation that the source UAV cannot get the GPS information of relay UAVs in the route, the source UAV should calculate the minimum transmission energy consumption of AECH and FHC before transmission, and select the

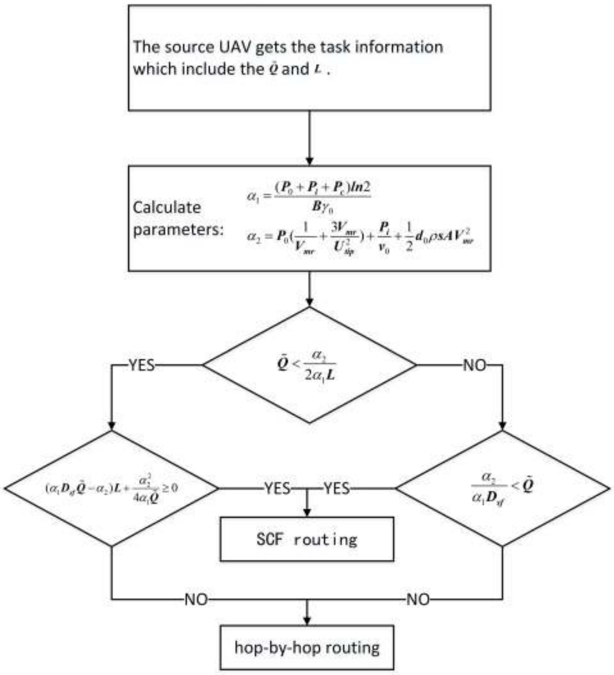


FIGURE 3. **The flowchart of STIF.**

lower mode to transmit. The decision-making process is as follows:

1) The source UAV gets the task information which include the $\tilde{Q}$ and L, and gets the UAV network information which include the N, $L_{\max}$ and μ.
2) According to the minimum transmission energy consumption of AECH (formula (12)) and FHC (formula (23)), we can get their difference as:

$$\Delta E_{s2}(L,\tilde{Q}) = E_{M\_\min}(L,\tilde{Q}) - E_{D1\_tot\_\min}(L,\tilde{Q}) = \begin{cases} (\alpha_1 \dfrac{2\mu L_{\max} L}{\sqrt{\pi N}}\tilde{Q} - \alpha_2)L + \dfrac{\alpha_2^2}{4\alpha_1 \tilde{Q}}, \\ \qquad \dfrac{\alpha_2}{2\alpha_1 D_{sf}} > \tilde{Q} \\ \alpha_1(\dfrac{2\mu L_{\max} L^2}{\sqrt{\pi N}} - D_{sf}^2)\tilde{Q} - (L - D_{sf})\alpha_2, \\ \qquad \dfrac{\alpha_2}{2\alpha_1 D_{sf}} \leq \tilde{Q} \end{cases}$$

3) The source UAV selects the SCF routing to transmit the task when $\Delta E_{s2}(L,\tilde{Q}) \geq 0$, and selects hop-by-hop routing when $\Delta E_{s2}(L,\tilde{Q}) < 0$.

Further analysis showed that:

1) If $\frac{\alpha_2}{2\alpha_1 D_{sf}} > \tilde{Q}$:
Select SCF routing when
$\Delta E_{s2}(L,\tilde{Q}) = (\alpha_1 \frac{2\mu L_{\max} L}{\sqrt{\pi N}}\tilde{Q} - \alpha_2)L + \frac{\alpha_2^2}{4\alpha_1\tilde{Q}} \geq 0.$
Select hop-by-hop routing when
$\Delta E_{s2}(L,\tilde{Q}) = (\alpha_1 \frac{2\mu L_{\max} L}{\sqrt{\pi N}}\tilde{Q} - \alpha_2)L + \frac{\alpha_2^2}{4\alpha_1\tilde{Q}} < 0.$
2) If $\frac{\alpha_2}{2\alpha_1 D_{sf}} \leq \tilde{Q}$:
Select SCF routing when
$\tilde{Q} \geq \frac{\alpha_2(L-D_{sf})}{\alpha_1(\frac{2\mu L_{\max}}{\sqrt{\pi N}}L^2 - D_{sf}^2)}.$

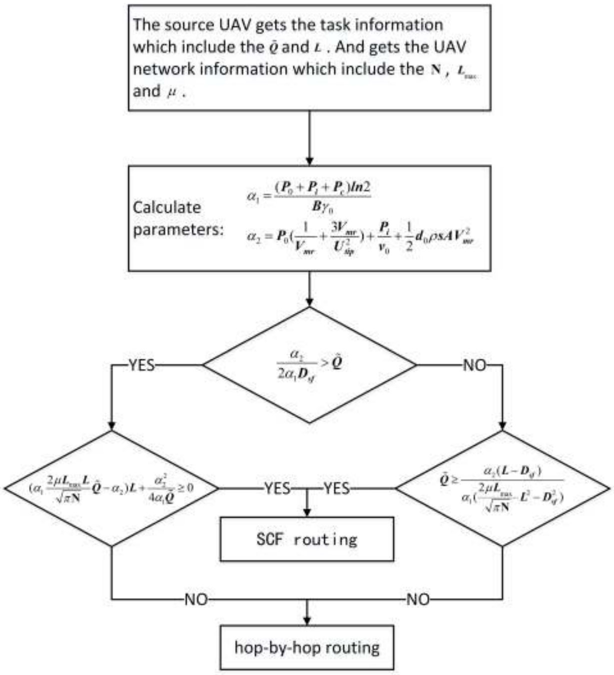


FIGURE 4. **The flowchart of STAF.**

Select hop-by-hop routing when
$\tilde{Q} < \frac{\alpha_2(L-D_{sf})}{\alpha_1(\frac{2\mu L_{\max}}{\sqrt{\pi N}}L^2 - D_{sf}^2)}.$

The flowchart of STAF is shown as Fig.4.

3) TACTIC 3

The Switch Tactic base on the RECH and FHC (STRF).

In the situation that the source UAV can get the GPS information of relay UAVs in the route, the source UAV should calculate the minimum transmission energy consumption of RECH and FHC before transmission, and select the lower mode to transmit. The decision-making process is as follows:

1) The source UAV gets the task information which include the $\tilde{Q}$, and gets the route information which include the $\{\tau_k\}$.
2) According to the minimum transmission energy consumption of RECH (formula (11)) and FHC (formula (23)), we can get their difference as:

$$\Delta E_{s3}(L,\tilde{Q}) = E_{M\_\min}(L,\tilde{Q}) - E_{D1\_tot\_\min}(L,\tilde{Q}) = \begin{cases} \alpha_1 \displaystyle\sum_{k=1}^{n} \tau_k^2 \tilde{Q} - \alpha_2 L + \dfrac{\alpha_2^2}{4\alpha_1\tilde{Q}}, \\ \qquad \dfrac{\alpha_2}{2\alpha_1 D_{sf}} > \tilde{Q} \\ \alpha_1(\displaystyle\sum_{k=1}^{n} \tau_k^2 - D_{sf}^2)\tilde{Q} - (L - D_{sf})\alpha_2, \\ \qquad \dfrac{\alpha_2}{2\alpha_1 D_{sf}} \leq \tilde{Q} \end{cases}$$

3) The source UAV selects the SCF routing to transmit the task when $\Delta E_{s3}(L, \tilde{Q}) \geq 0$, and selects hop-by-hop routing when $\Delta E_{s3}(L, \tilde{Q}) < 0$.

Further analysis showed that:

1) If $\frac{\alpha_2}{2\alpha_1 D_{sf}} > \tilde{Q}$:
   Select SCF routing when
   $$\Delta E_{s3}(L, \tilde{Q}) = \alpha_1 \sum_{k=1}^{n} \tau_k^2 \tilde{Q} - \alpha_2 L + \frac{\alpha_2^2}{4\alpha_1 \tilde{Q}} \geq 0.$$
   Select hop-by-hop routing when
   $$\Delta E_{s3}(L, \tilde{Q}) = \alpha_1 \sum_{k=1}^{n} \tau_k^2 \tilde{Q} - \alpha_2 L + \frac{\alpha_2^2}{4\alpha_1 \tilde{Q}} < 0.$$
2) If $\frac{\alpha_2}{2\alpha_1 D_{sf}} \leq \tilde{Q}$:
   Select SCF routing when
   $$\tilde{Q} \geq \frac{\alpha_2(L-D_{sf})}{\alpha_1(\sum_{k=1}^{n} \tau_k^2 - D_{sf}^2)}.$$
   Select hop-by-hop routing when
   $$\tilde{Q} < \frac{\alpha_2(L-D_{sf})}{\alpha_1(\sum_{k=1}^{n} \tau_k^2 - D_{sf}^2)}.$$

The flowchart of STRF is shown as Fig.5.

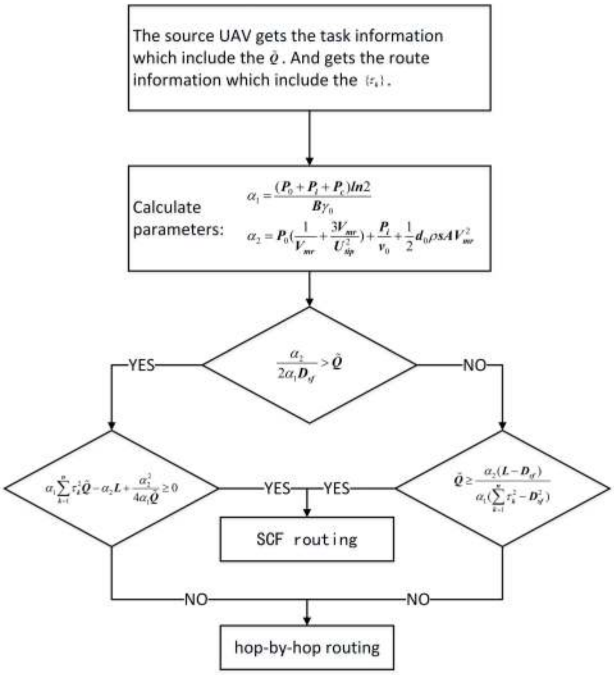


FIGURE 5. The flowchart of STRF.

C. THE HYBRID TACTICS OF COMBINATION MODE

The above switch tactics are two-choice modes. How about the performance when both hop-by-hop routing and SCF routing in a transmission? In this kind tactic, we assume parts of route use hop-by-hop routing, and parts of route use SCF routing. Considering that multiple accelerations and decelerations will lead to additional energy consumption, we assume only a part of route uses SCF routing, others use hop-by-hop routing. And more, the minimum transmission energy consumption of two transmission techniques are relative to distance, but independent of order, the hybrid tactics such as 'hop-by-hop+SCF', 'SCF+hop-by-hop', 'hop-by-hop+SCF+hop-by-hop' have same energy performance. We research the hybrid tactics according to the tactic of 'hop-by-hop+SCF'.

We assume the distance of route in hop-by-hop routing is L_c, and the distance of route in SCF routing is L_{tr}. It must be $L_c + L_{tr} + D_c \geq L$.

When the hop-by-hop routing is IECH, the transmission route is a straight line. Therefore, we have $L_c + L_{tr} + D_c = L$ and $L_{tr} + D_c = L_2$.

According to formula (9) and formula (23), the total transmission energy consumption of the 'hop-by-hop+SCF' tactic is

$$\begin{aligned} & E_{mix1\_2\_\min}(L_c, \tilde{Q}) \\ & = E_{M\_\min}(L_c, \tilde{Q}) + E_{D1\_tot\_\min}(L_2, \tilde{Q}) \\ & = \begin{cases} L_c(\tilde{Q}\frac{D_{sf}(P_c + P_h)\ln 2}{B\gamma_0} - \alpha_2) + L\alpha_2 \\ -\frac{\alpha_2^2}{4\alpha_1(\tilde{Q})}, & \frac{\alpha_2}{2\alpha_1(\tilde{Q})} > D_{sf} \\ L_c(\tilde{Q}\frac{D_{sf}(P_c + P_h)\ln 2}{B\gamma_0} - \alpha_2) + L\alpha_2 \\ -D_{sf}\alpha_2 + \alpha_1(\tilde{Q})D_{sf}^2, & \frac{\alpha_2}{2\alpha_1(\tilde{Q})} \leq D_{sf} \end{cases} \end{aligned} \tag{55}$$

We make

$$\begin{aligned} \alpha_3 &= \frac{{\alpha_2}^2 \tilde{Q}}{4\alpha_1(\tilde{Q})} = \frac{{\alpha_2}^2 B\gamma_0}{4(P_0 + P_i + P_c)ln2} \\ \alpha_4 &= \frac{\alpha_1(\tilde{Q})D_{sf}^2}{\tilde{Q}} = \frac{(P_0 + P_i + P_c)ln2}{B\gamma_0}D_{sf}^2 \\ \alpha_5 &= \frac{D_{sf}(P_c + P_h)\ln 2}{B\gamma_0} \end{aligned} \tag{56}$$

Formula (55) can be simplified as

$$\begin{aligned} & E_{mix1\_2\_\min}(L_c, \tilde{Q}) \\ & = \begin{cases} L_c(\alpha_5\tilde{Q} - \alpha_2) - \frac{\alpha_3}{\tilde{Q}} + L\alpha_2, \\ \quad \frac{\alpha_2}{2\alpha_1(\tilde{Q})} > D_{sf} \\ L_c(\alpha_5\tilde{Q} - \alpha_2) + \alpha_4\tilde{Q} + L\alpha_2 - D_{sf}\alpha_2, \\ \quad \frac{\alpha_2}{2\alpha_1(\tilde{Q})} \leq D_{sf} \end{cases} \end{aligned} \tag{57}$$

From formula (57), we know that:

When $\alpha_5\tilde{Q} - \alpha_2 > 0$, the total transmission energy consumption can achieve the minimum value at $L_c = 0$, meaning that the task consumes the minimum energy when using SCF routing only.

When $\alpha_5\tilde{Q} - \alpha_2 < 0$, the total transmission energy consumption can achieve the minimum value at $L_c = L$, meaning that the task consumes the minimum energy when using hop-by-hop routing only.

Therefore, the hybrid tactics of combination mode do not perform better than the switch tactics of combination mode.

VII. NUMERICAL EXPERIMENT

In our simulations, we set up a square plane space with side length $L_{\max}$ m in Matlab. There are N UAVs randomly distribute on the space and form a UAV network. UAVs are same and their parameters are listed in table 2. The Dijkstra's algorithm is used to calculate the shortest path for RECH in the UAV network. The experiments are introduced as follows.

We assume UAV updates its GPS information to its neighbors every 50 ms. The safe distance between UAVs should ensure the unexpected move within 50 ms does not lead to UAVs collision accident, so the maximum distance between neighbors within 50 ms is the safe distance D_{sf}, it is:

$$D_{sf} = 2V_{\max} \times 50 \times 10^{-3} = 6m.$$

A. THE ENERGY PERFORMANCE VALIDATION OF STIF

We assume that a message needs to be transmitted between a pair of UAVs in the UAV network. The message traffic $\tilde{Q}$ is set from 500 kbits to 50 Mbits. The distance L between the two UAVs is set from 600 m to 1100 m. The transmission energy consumption of IECH, FHC and STIF are shown as Fig.6, in which the performance of STIF is better than IECH and FHC.

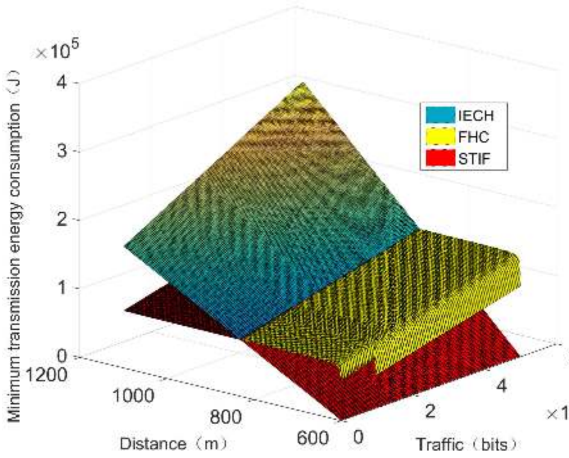


FIGURE 6. The transmission energy consumption of IECH, FHC and STIF.

B. THE ENERGY PERFORMANCE COMPARISON OF IECH, RECH AND AECH

We set N from 200 to 1200 to simulate random scenes respectively, and conduct 1000 simulations in which a source UAV and a destination UAV are randomly selected to transmit a message with $\tilde{Q} = 20$ Mbits. The following conclusions can be found by comparing the minimum transmission energy consumption of IECH, RECH and AECH.

As shown in Fig.7(a), with the increase of simulations times, the ratio of the mean difference between RECH and IECH to RECH gradually stabilize. The smaller N, the greater difference between the two modes. The ratio keeps from 96% to 97%, it is a big difference between RECH and IECH.

As shown in Fig.7(b), with the increase of simulation times, the ratio of the mean difference between RECH and AECH to RECH gradually stabilize. The bigger N, the greater difference between the two modes. The ratio keeps from -5% to 50%, it is a big difference between RECH and IECH.

Summarizing the above figures, we can see that:

Conclusion 1: **The minimum transmission energy consumption of IECH is too small from RECH. The minimum transmission energy consumption of AECH is close to RECH when the distribution density of UAV is small.**

C. THE ENERGY PERFORMANCE COMPARISON OF IECH, RECH, AECH, FHC AND SWITCH TACTICS

We set the $N = 300$ and $\tilde{Q}$ is from 5 kbits to 2 Mbits (10 kbits interval), and conduct 50 simulations in which a source UAV and a destination UAV are randomly selected to transmit a message with each $\tilde{Q}$. The following conclusions can be found by comparing the minimum transmission energy consumption of IECH, RECH, AECH, FHC, STIF, STAF and STRF.

As shown in Fig.8. With the $\tilde{Q}$ increasing, the minimum transmission energy consumptions of IECH and STIF increase slowly, the RECH and AECH increase rapidly, and the FHC barely change. The minimum transmission energy consumptions of IECH and STIF are far smaller than others, the RECH is same as AECH. When $\tilde{Q}$ is less than 0.8 Mbits, the performance of STRF and STAF are same as RECH and AECH. When $\tilde{Q}$ is greater than 0.8 Mbits, the performance of STRF and STAF are same as FHC.

Therefore, the performance of STRF is nearly same as STAF, the minimum transmission energy consumption of STIF is far smaller than STRF and STAF. Once the STIF is used for decision-making, the time to switch between hop-by-hop and SCF routing is very different with STRF or STAF, or the switch would never happen. The wrong decision of switch will lead the UAV uses a high energy consumption transmission mode.

Conclusion 2: **The STIF is not suitable for practical use.**

Conclusion 3: **The performance of STRF and STAF are better than IECH, RECH, AECH and FHC. The energy consumptions of STRF and STAF can reduce 70% energy consumption at most with RECH and AECH.**

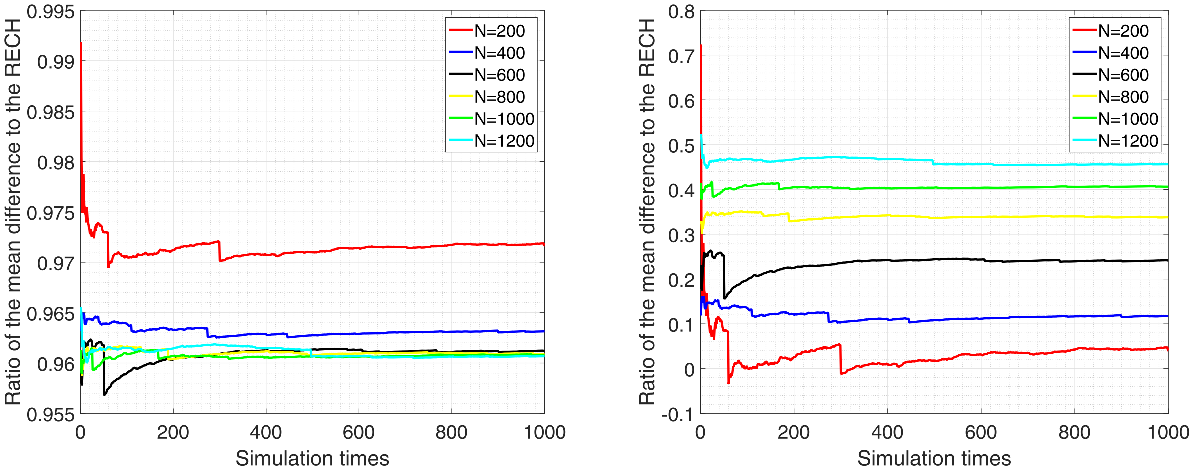
Conclusion 4: **The performance of STRF is nearly same as STAF.**

D. THE TRANSMISSION TIME COMPARISON OF RECH AND FHC

In the simulations, We set $N = 300$.

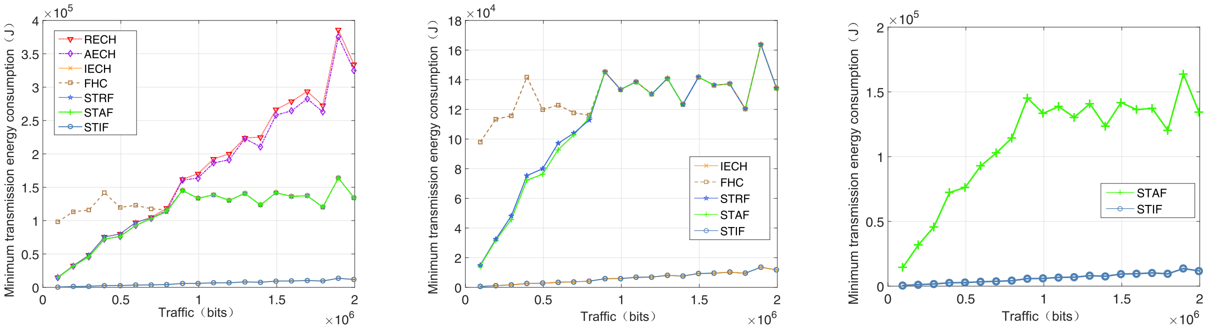
First, we set the $\tilde{Q}$ is from 5 kbits to 500 kbits (10 kbits interval), the distance between source UAV to destination UAV L is set 500 m, 1200 m and 1900 m respectively, and conduct 50 simulations in which a message is transmitted with the RECH and FHC respectively. The Fig.9 can be found by comparing the mean of minimum transmission time of RECH and FHC.

As shown in Fig.9(a), with L increasing, the transmission time of RECH and FHC increase. With the $\tilde{Q}$ increasing, the transmission time of RECH increases, but the transmission time of FHC changes from stable to reduce slowly after



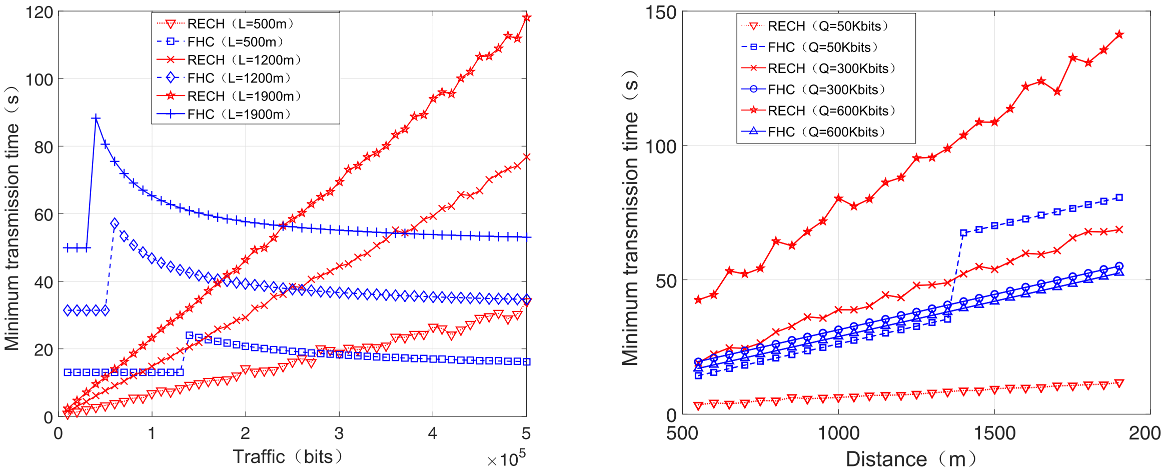
(a) The ratio of the mean difference between RECH and IECH to RECH (b) The ratio of the mean difference between RECH and AECH to RECH

FIGURE 7. **The energy performance comparison of IECH, RECH and AECH.**



(a) IECH, RECH, AECH, FHC, STIF, STAF and STRF (b) IECH, FHC, STIF, STAF and STRF (c) STIF and STRF

FIGURE 8. **The minimum transmission energy consumption of IECH, RECH, AECH, FHC, STIF, STAF and STRF.**



(a) The mean of minimum transmission time of RECH and FHC for different traffic (b) The mean of minimum transmission time of RECH and FHC for different distance

FIGURE 9. **The transmission time comparison of RECH and FHC.**

a leap. When the $\tilde{Q}$ or L is small, the transmission time of RECH is smaller, otherwise, the transmission time of FHC is smaller.

As shown in Fig.9(b), with L increasing, the transmission time of RECH increases. The transmission time of FHC increases in most cases, but may leap when L is great.

Based on Fig.9, some conclusions as follow:

Conclusion 5: **The transmission time of RECH and FHC are in same scale.**

Conclusion 6: **The transmission time of RECH is smaller when the traffic or distance is small. Otherwise, the transmission time of FHC is smaller.**

VIII. CONCLUSION AND FUTURE WORK

In this paper, we use the transmission energy consumption as metric to measure the combination performance of hop-by-hop and SCF routing in rotary-wing UAV network. We propose three hop-by-hop routing energy consumption models (IECM, RECM, AECM), two SCF routing energy consumption models (FHC and FCC), three switch tactics (STIF, STAF, STRF) and a hybrid tactic for combination mode in rotary-wing UAV network. According to the theoretical analysis and experimental verification, we find two switch tactics (STAF and STRF) can help UAV perform better in transmission energy consumption by reducing 70% at most with RECM and AECM, and the SCF routing have nearly same performance of transmission time with the hop-by-hop routing. In practical application, we recommend the STAF when the source UAV can not get the GPS information of relay UAVs in the route, and recommend the STRF when the source UAV can get the GPS information of relay UAVs in the route. Following these, we can modify hop-by-hop routing protocols to improve the energy efficiency of transmission in the rotary-wing UAV network in future works. The research conclusion can also be used for the transmissions in a fixed-wing UAV network by modifying the energy consumption models of fixed wing UAV, which is different from rotary wing UAVs.

Next, we will research more complex transmission scenarios which have more source and destination UAVs.

REFERENCES

[1] L. Gupta, R. Jain, and G. Vaszkun, "Survey of important issues in UAV communication networks," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 2, pp. 1123–1152, 2nd Quart., 2016.

[2] M. Y. Arafat and S. Moh, "Routing protocols for unmanned aerial vehicle networks: A survey," *IEEE Access*, vol. 7, pp. 99694–99720, 2019.

[3] O. K. Sahingoz, "Networking models in flying ad-hoc networks (fanets): Concepts and challenges," *J. Intell. Robot. Syst.*, vol. 74, nos. 1–2, pp. 513–527, 2014.

[4] B. Bouyedou, M. Feham, F. Didi, and H. Labiod, "Improvement of DSR performances in mobile ad hoc networks with trade-off between energy efficiency and path shortness," in *Proc. IEEE Int. Workshop ITS Ubiquitous Roads (UBIROADS)*, Jun. 2009.

[5] A. I. Alshabtat, L. Dong, J. Li, and F. Yang, "Low latency routing algorithm for unmanned aerial vehicles ad-hoc networks," *Int. J. Elect. Comput. Eng.*, vol. 6, no. 1, pp. 48–54, 2010.

[6] J.-H. Chang and L. Tassiulas, "Energy conserving routing in wireless adhoc networks," in *Proc. IEEE INFOCOM Conf. Comput. Commun., 19th Annu. Joint Conf. IEEE Comput. Commun. Societies*. vol. 1, Mar. 2000, pp. 22–31.

[7] R. Purta, S. Nagrecha, and G. Madey, "Multi-hop communications in a swarm of UAVs," in *Proc. Agent-Directed Simulation Symp.*, Apr. 2013, Art. no. 5.

[8] B. Awerbuch, D. Holmer, and H. Rubens, "The pulse protocol: Energy efficient infrastructure access," in *Proc. IEEE INFOCOM*, Hong Kong, vol. 2, Mar. 2004, pp. 1467–1478.

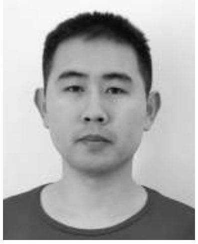
[9] A. R. S. Bramwell, G. Done, and D. Balmford, *Bramwell's Helicopter Dynamics*, Oxford, U.K.: Heinemann, 2001.

[10] A. Filippone, *Flight Performance of Fixed and Rotary Wing Aircraft*. Washington, DC, USA: AIAA, 2006.

[11] Y. Zeng, J. Xu, and R. Zhang, "Energy minimization for wireless communication with rotary-wing UAV," *IEEE Trans. Wireless Commun.*, vol. 18, no. 4, pp. 2329–2345, Apr. 2019.

FEI XIONG received the B.S. and M.S. degrees in computer science and technology from the PLA University of Science and Technology, Nanjing, China, in 2006 and 2009, respectively. He is currently pursuing the Ph.D. degree with the College of Communications Engineering, Army Engineering University of PLA. His current research interests include wireless networking and vehicular communications technologies.

LEI XIA received the B.S. degree in electronic and information engineering from Beihang University, in 2012, and the M.S. degree in communication and information systems from the PLA University of Science and Technology, in 2015. He is currently pursuing the Ph.D. degree with the College of Communications Engineering, Army Engineering University of PLA. His current research interests include routing protocols for mobile ad hoc networks, routing protocols for Delay Tolerant Networks, and mobile data offloading.



JIEJIE XIE received the B.S. degree in communication engineering from Hunan University, and the M.S. degree in communication and information engineering from Army Engineering University, in 2015 and 2017, respectively. His current research interests include drone small cell networks, topology control, and stochastic network optimization.

HAI WANG received the Ph.D. degree from the Nanjing Institute of Communications Engineering, China, in 1999. He is currently a Professor and a Doctoral Supervisor with the Army Engineering University of PLA. His current research interests include wireless networking, Ad hoc networking, and vehicular communications technologies.

AIJING LI received the Ph.D. degree in computer science and technology from the PLA University of Science and Technology, Nanjing, China. She joined the College of Communication Engineering, Army Engineering University of PLA, in 2015. Her current research interests include wireless communications, cognitive radio networking, and heterogeneous networking.

YU YU received the M.S. degree in communication and engineering from the PLA University of Science and Technology, Nanjing, China, in 2008. Her current research interests includes wireless communication and wire communication.