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Opportunistic Routing with Available Bandwidth Assurance for High Dynamic UAV Swarms

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Abstract. The reconstruction of routing schemes constitutes an important quality of service (QoS) support for UAV swarms to keep their applications and services stable and active. In this paper, we develop a forwarding distance and available bandwidth (AB) estimation based opportunistic routing (FD-ABOR) protocol for high dynamic UAV swarms. We first improve the AB estimation algorithm for multi-hop UAV ad hoc networks by taking full account of the disparity between the sending and receiving ability and reconsidering the bandwidth consumption induced by hidden nodes. Secondly, we propose the scheme that the sender broadcast the RTS frame piggybacked with available bandwidth information for route request. Based on available bandwidth and forwarding distance, neighbour node decides it to be the candidate forwarder and computes the forwarding priority, then competes with each other to forward data packets. The simulation results show that our method outperforms AODV and DSR in terms of throughput and packet delivery ratio.

1. Introduction
Recently, the great advances made in electronic, sensor and communication technologies enable the development of Unmanned Aerial Vehicles (UAVs) worldwide [1]. The UAV swarms, which is formed by a large number of mini-UAVs, is actually a function distributed and intelligent combat system. The UAV swarms have some advantages over single-UAV systems in cost, scalability, survivability and speed-up. It has been investigated increasingly due to their promising applications in warfare, such as cooperative reconnaissance, wide area surveillance, and saturation attack, etc.

Communication and networking are crucial technologies for UAV swarms to exchange information with each other and with the control station in an autonomous and collaborative manner [2]. Flying Ad Hoc Networks (FANETs) make it possible for UAV swarms to interconnect UAVs dynamically by multi-hop ad hoc networks [1]. However, several networking challenges, such as the high mobility, uneven UAVs distributions, and the fast changing topology, have made the implementation of communication for UAV swarms quite difficult [3]. One of the most prominent design problems lies on medium access control (MAC). In contrast to synchronized time division multiple access (STDMA) based MAC protocols, utilizing the carrier sense multiple access with collision avoidance (CSMA/CA) based MAC protocols in UAV swarms can obtain a satisfactory performance by taking advantage of their flexibility, robustness and reliability. Nevertheless, quality of service (QoS) provisioning is still an essential issue in CSMA/CA ad hoc networks. Available bandwidth (AB), that the maximum MAC
throughput that can be obtained between two adjacent nodes without disrupting the existing flows, has been regarded as the fundamental information which can contribute to the design of QoS solutions [4].

On the other hand, the reconstruction of routing schemes constitutes an important QoS support for UAV swarms. Many factors make opportunistic routing (OR) the best routing decision for UAV swarms in FANETs. During the past few years, an important number of opportunistic routing protocols with various strategies are proposed to exploit its benefits [5]. The available bandwidth is regarded as a routing metric because it approximates the residual data relaying capacity of a wireless channel, and it implicitly considers the wireless channel condition [6].

In this paper, we propose a forwarding distance and available bandwidth estimation based opportunistic routing protocol (FD-ABOR) for high dynamic UAV swarms. Specifically, an available bandwidth estimation algorithm for multi-hop UAV ad hoc networks is presented firstly. In contrast to previous efforts, we take full account of the difference between the node sending and receiving capacity and reconsider the bandwidth consumption induced by hidden nodes. In our design, the sender broadcast the RTS (Request-To-Send) frame piggybacked with the available bandwidth information to its neighbors for route request. Based on available bandwidth and forwarding distance, the neighbor decides it to be the candidate forwarder and computes the forwarding priority, then competes with each other to forward data packets. Finally, we evaluate the performance of our scheme and compare it with AODV and DSR.

2. Available bandwidth estimation for FD-ABOR
We first briefly introduce the available bandwidth estimation algorithm and then give the detailed account of FD-ABOR, which aims to discover a real-time transmission path with better link quality and fewer transmission hops. A similar available bandwidth estimation algorithm can be found in our previous work [7]. We also divide the estimation algorithm into three parts: maximum available bandwidth, preliminary estimation and refined estimation.

2.1. Maximum available bandwidth
The maximum available bandwidth denoted by \( AB_{\text{max}} \) is the maximum MAC throughput a link can achieve regardless of interfering traffic. We define a transmission cycle \( t \) to be the time taken for a successful packet transmission. Based on the specification of MAC protocol, we derive \( AB_{\text{max}} \) as

\[
AB_{\text{max}} = \frac{L_{\text{DATA}}}{t}. \tag{1}
\]

Here \( L_{\text{DATA}} \) is the size of a DATA frame. Note that the time duration for RTS/CTS handshaking includes the maximum wait time \( t_{\text{wmax}} \) for forwarders to reply with CTS.

2.2. Preliminary estimation of available bandwidth
To calculate the available time of a link \( (T_t) \), the node employs its carrier sensing capability to measure the local available transmission/reception duration in an estimation period of \( T \).

Considering the disparity between sender and recipient, the basis for identifying the available transmission time is whether the sensed signal power is less than the carrier sensing threshold and the idle interval is longer than the length of a distributed interframe space \( t_{\text{DIFS}} \). While the sensed signal power is less than the collision threshold for available reception time. Lastly, we obtain the total available transmission time of sender \( S \) as \( T_s(S) \), and the total available reception time of recipient \( R \) as \( T_r(R) \).

We define CES as the combination event that node \( S \) can serve as the sender but node \( R \) cannot be the recipient, while CER represents that node \( R \) can serve as the recipient but node \( S \) cannot be the sender. The probabilities of the above two combination events are estimated as \( P_{\text{CES}}(S,R) \) and \( P_{\text{CER}}(S,R) \) in [7]. Consequently, the total available time of link \( (S,R) \) can be calculated as

\[
T_t(S,R) = \min \left\{ \left[ 1 - P_{\text{CES}}(S,R) \right] \cdot T_s(S), \left[ 1 - P_{\text{CER}}(S,R) \right] \cdot T_r(R) \right\}. \tag{2}
\]
The recipient of the link locally computes the available time, thus derives the preliminary estimation of the AB by
\[
AB_{\text{pre}}(S, R) = \frac{T_i(S, R)}{T} \cdot AB_{\text{max}}.
\] (3)

2.3. Refined estimation of available bandwidth

We next reconsider the transmission failures induced by hidden nodes and improve the accuracy of the preliminary estimation. To elaborate the transmission failures, we introduce a representative scenario with related situations to refine the preliminary estimation in figure 1. The scenario is divided into 9 zones by the carrier sensing range \((R_{cs})\), the transmission range \((R_{tx})\) and the collision range \((R_{co})\) of node \(S\) and node \(R\).

Similarly, we deduce the probability of RTS collisions and DATA collisions due to interference from hidden nodes that locate in \(A_7\)-zone area as \(p_{\text{RTS}}\) and \(p_{\text{DATA}}\) respectively. Besides, we evaluate the probability of the inability to respond with CTS due to interference from the hidden nodes within \(A_8\)-zone area as \(p_{\text{C}}\). Ultimately, by deducting the bandwidth consumption induced by the above situations, the final refined estimation of the AB of a link can be expressed as
\[
AB_{\text{ref}}(S, R) = AB_{\text{pre}}(S, R) \cdot (1 - p_{\text{RTS}}) \cdot (1 - p_{\text{DATA}}) \cdot (1 - p_{\text{C}}).
\] (4)

3. Forwarding distance and available bandwidth estimation based opportunistic routing protocol

3.1. Route discovery

During the operation of the network, each node executes the available bandwidth estimation algorithm and then acquires and stores the time duration continuously for the calculation of available bandwidth. When sending the data packet, the sender does not specify the next hop forwarder in advance and broadcast the RTS frame piggybacked with available bandwidth information to its neighbours for route request.

The RTS frame has the function of route discovery like the RREQ packet in AODV so that the necessary routing information contained in RREQ is added to RTS frame.

3.2. Candidates selection and prioritization

3.2.1. Forwarding distance

The neighbor node of the sender receives RTS frame successfully then calculates the forwarding distance according to the geographic location between itself and the destination. We denote by \(N_S\) the sender (may be the source or relay node), \(N_D\) the destination, and by \(N_i\) a forwarding node. The distance between the source and the destination is denoted by \(\text{Dist}(N_S, N_D)\). Thus the forwarding distance of node \(N_i\) (denoted by \(DF(N_i, N_D)\)) is computed by
\[
DF(N_i, N_D) = \text{Dist}(N_S, N_D) - \text{Dist}(N_i, N_D).
\] (5)

It is the Euclidian distance between the sender and the destination minus the Euclidian distance between the neighbor and the destination. We state that \(DF(N_i, N_D) \in (0, R_{\text{tx}}]\), where \(R_{\text{tx}}\) is the transmission range. The primary candidate node satisfies the following three conditions: The candidate node must be the neighbor of its sender; the next hop forwarder is located between the source and the destination; the current candidate is not the neighbor of the last hop forwarder.

We define \(DF_{\text{min}}\) \((0 < DF_{\text{min}} < R_{\text{tx}})\) the minimum value of forwarding distance, hence \(\text{DF}(N_i, N_D) \in [DF_{\text{min}}, R_{\text{tx}}]\). Therefore, we compute the forward progress of node \(N_i\) as \(f_f(N_i, N_D)\) by
\[
f_f(N_i, N_D) = \frac{DF(N_i, N_D) - DF_{\text{min}}}{R_{\text{tx}} - DF_{\text{min}}}.
\] (6)
From (6), we know $f_f(N_s,N_d) \in [0,1]$. If the forward progress is greater than or equal to zero, the neighbor node can be selected as the primary candidate and added to the primary candidate relay set $\{C_i\}$.

3.2.2. Link available bandwidth

The primary candidate nodes analyse the available transmission duration of the sender ($T_s(N_S)$) from the received RTS frame. Then these nodes calculate their available bandwidth of the link consist of the sender and the candidate node as $AB(N_S,N_i)$, according to the available bandwidth estimation algorithm introduced formerly. Considering the required bandwidth of flow (RBF) in actual communication, the admission of traffic flow is controlled and the $RBF$ is set to the lower limit of available bandwidth. The primary candidate can act as a qualified candidate forwarder only if it meets the minimum bandwidth requirement, i.e., $AB(N_S,N_i) \in [RBF, AB_{max}]$. We define $f_{AB}(N_s,N_i)$ the bandwidth factor and calculate it as

$$f_{AB}(N_s,N_i) = \frac{AB(N_s,N_i) - RBF}{AB_{max} - RBF}.$$ (7)

The bandwidth factor $f_{AB}(N_s,N_i)$ is chosen as $[0,1]$. On the premise of satisfying the requirement of forwarding distance, the candidate relay set $\{F_i\}$ can be obtained by screening the primary candidate node under the condition that the bandwidth factor is greater than zero.

3.2.3. Forwarding priority

Based on forwarding distance and available bandwidth, the forwarding priority of candidate forwarder denoted by $pri(N_s,N_i)$ can be calculated as

$$pri(N_s,N_i) = \begin{cases} \alpha \cdot f_{AB}(N_s,N_i) + (1 - \alpha) \cdot f_f(N_i,N_d), & N_i \neq N_d \\ 1, & N_i = N_d \end{cases}.$$ (8)

Here $\alpha$ is a weight coefficient, and $\alpha \in (0,1)$, $pri(N_S,N_i) \in [0,1]$. The specific value of $\alpha$ should be decided on the network performance requirements. The priority of the destination is directly set to 1 if the candidate relay set contains the destination.

3.3. Back-off and compete to forward

The candidate forwarders set back-off time on basis of forwarding priority and compete to respond with CTS frame constructed by RTS frame. The back-off time denoted by $t_{BFCTS}$ is set to

$$t_{BFCTS} = t_{SIFS} + \frac{N_{en}}{N_{en}} \cdot t_{WFCTS}.$$ (9)

Among that $t_{wmax}$ is the maximum waiting time and it can be valued as a time slot length ($t_{slot}$). The candidate nodes must wait for SIFS earlier and continues to wait for a certain time related to priority. The time duration of the sender to wait for CTS is

$$t_{WFCTS} = t_{SIFS} + t_{wmax} + N_{en} \cdot t_{CTS}.$$ (10)

Here $N_{en}$ is the number of nodes enabled to reply with CTS. Meanwhile, $t_{WFCTS}$ is considered as the maximum waiting time in the back-off process. After waiting for the long time of $t_{WFCTS}$, the candidate forwarder will give up the response if it has not reply with CTS.

3.4. Packet forwarding and acknowledgment

If the sender has received CTS successfully, it transmits DATA to the responding node. Otherwise it will employ the retransmission mechanism to attempt to broadcast RTS again.

If the forwarder received the desired data packet within the waiting time, it replies with ACK and prepares to forward the data packet. When other candidate forwarders receive the data frame in the process of back-off to reply with CTS, they will cancel the back-off and exit the competitive forward.
4. Performance evaluation

4.1. Methodology and parameters
We have implemented the FD-ABOR protocol in Exata3.0 simulator and evaluate the performance through simulations. The global routing algorithm, AODV and DSR, are also used in the comparison. The main typical simulation parameters are listed in table 1.

Table 1. Simulation parameters.

| Parameters         | Value | Parameters         | Value |
|--------------------|-------|--------------------|-------|
| Transmission power | 15dbm | Traffic model      | CBR flow |
| $SINR_{th}$        | 10dB  | Packet size        | 1000bytes |
| Transmission range | 250m  | RTS size           | 52bytes |
| Carrier sensing range | 550m  | CTS size           | 30bytes |
| Transmission rate  | 2Mbps | ACK size           | 30bytes |
| Synchronization time | 192μs | Slot time          | 20μs |
| DIFS               | 50μs  | SIFS               | 10μs  |

To ensure the rationality of the number of candidates in candidate relay set, we design a network topology composed of 73 UAV nodes in figure 2. The entire topology consists of adjacent regular triangles and the UAVs are placed at the intersections with 200m distance. We assign four traffic flows ($f_1$, $f_2$, $f_3$ and $f_4$) with different required bandwidth (500K, 400K, 300K, and 100K) and establish time (0s, 5s, 10s, and 15s). The estimation period is set to 0.1s, and the routing lifetime of AODV and DSR is 5s. The simulation time is 20 seconds. We compare our FD-ABOR with AODV and DSR protocols in terms of throughput, packet delivery ratio and average end-to-end delay. The three performance metrics are counted up to the computing time.

4.2. Simulation results
The results of throughput and packet delivery ratio of $f_1$ over simulation time are shown in figure 3(a) and figure 3(b).

Figure 1. Scenario for refined AB.

Figure 2. Simulation topology.

Figure 3. Simulation results. (a) Throughput of $f_1$. (b) Packet delivery ratio of $f_1$. (c) Average end-to-end delay of $f_1$. (d) Total throughput.
Compared with the other two protocols, our approach has the best performance of throughput because it relies on the candidate relay set to forward data packets. The candidate forwarder is endowed a priority with larger available bandwidth thus can achieve higher throughput. Owing to initiating the route discovery process, AODV and DSR have lower throughput in the initialization phase. Yet FD-ABOR discovers the route by broadcasting RTS frame every time. However, the throughput declines sharply because of the significant interfere induced by flow 3, and it is aggravated due to the impact of flow 4. Predictably, the trend of packet delivery ratio is consistent with that of throughput.

The simulation results in figure 3(c) depict how average end-to-end delay of fl varies over time. The admission of other flows aggravates competition and leads to data collisions, which makes the end-to-end delay of fl increase gradually. Although AODV has the least delay, the throughput and delivery ratio are worse than FD-ABOR. Our method selects the relay node by considering not only forwarding distance, but also link available bandwidth. Nevertheless, it also determines that FD-ABOR does not always select the shortest path. Our scheme increases the end-to-end delay appropriately, but guarantees the QoS more importantly.

Afterwards, the four flows access the channel at the same time while the traffic load of each flow increases from 100Kbps to 600Kbps. The simulation results of total throughput shown in figure 3(d) further demonstrate the superiority of our scheme.

5. Conclusions
The design of routing schemes becomes essential and mandatory to better assist the transmission of packets for UAV swarms. In this work, we develop a forwarding distance and available bandwidth estimation based opportunistic routing protocol for high dynamic UAV swarms. We first improve the AB estimation algorithm for multi-hop UAV ad hoc networks. Based on available bandwidth and forwarding distance, the neighbor node that received the broadcast RTS decides it to be the candidate forwarder and competes to forward data packets. The simulation results show that our scheme outperforms AODV and DSR in throughput and packet delivery ratio.

In the future, combining available bandwidth and geographic location with other QoS metrics, such as delay and energy, is also an interesting attempt.

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