Optimal Relay Path Selection and Cooperative Communication Protocol for a Swarm of UAVs

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***Abstract* - In many applications based on the use of unmanned aerial vehicles (UAVs), it is possible to establish a cluster of UAVs in which each UAV knows the other vehicle's position. Assuming that the common channel condition between any two nodes of UAVs is line-of-sight (LOS), the time and energy consumption for data transmission on each path that connecting two nodes may be estimated by a node itself. In this paper[1], we use a modified Bellman-Ford algorithm to find the best selection of relay nodes in order to minimize the time and energy consumption for data transmission between any UAV node in the cluster and the UAV acting as the cluster head. This algorithm is applied with a proposed cooperative MAC protocol that is compatible with the IEEE 802.11 standard. The evaluations under data saturation conditions illustrate noticeable benefits in successful packet delivery ratio, average delay, and in particular the cost of time and energy.**

Index Terms - Cooperative UAVs, CSMA/CA 802.11, data relay network, cooperative MAC protocol.

I. INTRODUCTION AND RELATED WORK

UAVs have become popular in various fields of application such as radar localization [1], wildfire management, observing support [2], agricultural monitoring, border surveillance, environmental and meteorological monitoring, and aerial photography, as well as for search and rescue missions [3]. The most significant benefits of using UAVs include low cost and improved safety for humans when compared to the conventional manned vehicle missions. In addition, as a part of our research activities, UAVs have been proposed for use in oil spill recovery, ice monitoring, and ship traffic surveillance. These platforms are not only deployed in onshore or nearby areas, but are also complexly implemented in remote areas where are no adequate permanent communication infrastructures. These small UAVs, or a swarm of UAVs, are fully cooperative and autonomous with the assignments by a central station. The objective is to completely receive the sensing data for an area of interest. For instance, an area with high radiation levels that are extremely harmful to humans is great of interest; an area with serious flooding where an overall image is especially needed for aid and rescue missions and so forth. In these situations, each UAV would be in charge of monitoring and collecting information from a small/sub area. The sensing data would then be transmitted to a base station, for instance, a data processing center that then provides the analysis information to the action team. However, the communication distance between some UAVs and the base station could readily be larger than the communication range of the individual UAVs. Consequently, these UAVs would need to relay information to other UAVs that are closer and capable of communicating with the base station. Normally, one way to do so is to distribute the UAVs in an uninterrupted chain that connects the furthest one to the nearest one, and then to the station [4][5]. Another way is to let them self-organize in some clusters with a cluster head (CH) for each. These CHs will then in turn establish a chain to connect them with the base station. A main focus of this paper will be on the selection of optimal relay path within a cluster. There have been many studies on how to efficiently solve this issue in conventional mobile or static ad hoc networks [6]. In [7] clustering solutions for mobile aeronautical network in which the nodes are civil aircrafts are investigated. In their study they proposed how to establish a stable cluster among the airplanes during their flights. However, another main focus of our paper is data communication in a cluster of nodes. In many applications such as area monitoring, aerial photographing, et cetera, a high bit rate communication channel between each UAV and its CH is required in order to send the sensing data. The CH also needs to transmit this data as quickly as possible to the base station via other CHs. Without loss of generality, the common needed enhancement for these clusters is to improve the communication internally in a cluster, for instance, between the UAVs and its CH. In this paper, for clarity, we name the sensing UAVs as sUAV and the serving cluster head UAV as cUAV. It is seen that this study could be generalized for network of several cUAVs and the base station.

For data communication between a sUAV and its cluster head or between two cluster heads, point-to-point communication could be initialized using a direct or indirect path. This usually depends on the communication constraints such as the receiving signal strength or channel conditions. Moreover, in this paper, other factors such as the throughput, the node's mobility, and energy efficiency are added for selecting an optimal relaying path. In practice, the direct communication path is usually selected rather than the indirect one. Nevertheless, as it is shown in this paper, this is not always the best choice if all of the above mentioned factors are taken into consideration. In [8] P. Liu and co-authors developed a cooperative MAC protocol, which improves the transmission bit rate for packet communication from the source to its destination by using helper nodes located in their communication range. However, as with many other protocols, this protocol has a maximum of two relay paths. Otherwise there would be too much overhead due to the intensive information exchange necessary between the nodes on the relay

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paths. The energy consumption was calculated at the relay node in [8], but it was not ensured that the selected path was optimal (with respect to energy consumption) among all feasible paths. In addition, an efficient backup scheme for retransmitting data was not mentioned. A cooperative backup scheme was developed for efficient retransmission in [9]. However, the relay path was not optimized with respect to energy consumption, and only two relay paths were at most used at the time.

It is reasonable to assume that in a cluster of UAVs, line-of-sight (LOS) channels exist between any pair of nodes constituted by the source, the destination, and possibly other relay nodes. Our goal is to find the optimal relay path that concurrently minimize the transmission time (maximize the throughput) and energy consumption. This optimization algorithm is a modified Bellman-Ford algorithm. We also propose a cooperative relay MAC protocol that is completely compatible with the well-known IEEE 802.11 standard. Both the MAC protocol and the optimization algorithm will be explained in detail in Section II. The simulation-based performance evaluations at different network sizes and number of UAV nodes are presented in Section III. Section IV concludes the paper and contains suggestions for feasible future studies.

II. COOPERATIVE RELAY MAC PROTOCOL

A. Multirate of 802.11 in UAV network

In the IEEE 802.11 standard, the packets may be transmitted at different rates, which are closely related to the channel condition such as signal-to-noise ratio (*SNR*) and the bandwidth (*B*). Assuming that there is only one active node transmits data at a given time and no significant external inference source, the instantaneous SNR_{ij} between two nodes *i* and *j* in a LOS channel is [10]:

$$SNR_{ij} = \frac{P_t G_t G_r \lambda^2}{(4\pi d)^2 N} \quad (1)$$

where, $N = kTBN_f$, is the noise, with k=1.38e^{-23} J/K being the Boltzmann constant, T=300K is the ambient temperature, B is the bandwidth, N_f is the noise factor at receiver node, P_t is transmission power at the transmitter node, and G_t and G_r are the gains at the transmitter and receiver nodes, respectively. λ is the wavelength ($\lambda = c/f$, where c=3E+5 km/s and f is the carrier frequency), and d is the distance between two nodes. As a result, the SNR usually depends on the transmitting power and the distance d. Using Equation (1) and with standard conditions of operation for IEEE 802.11g, the feasible transmission rates vary from 54Mbps (R_{10}) to 1Mbps (R_1) depending on the distance between the two UAVs. These values are distributed in ten steps as shown in Table 2. Assuming the channel fading is unchanged during packet transmission and that the distance (d_{ij}) between two nodes is known, the respective transmission rate (R_{ij}) could be determined accordingly.

B. Metrics for relay routes optimization

By assuming that the distance between any pair of nodes located in the communication range of both transmitter and receiver is known, the respective transmission rate on that path between them can be calculated. This distance could be calculated by listening or sensing the broadcasted position message of each node in the cluster. It may require another radio channel used for broadcasting position, air speed, next trajectory, et cetera, for each individual UAV. It would be a requirement of integration of UAVs with the current air traffic management system [11]. We proposed a self broadcasting communication system for aeronautical communication which could be also efficiently applied for the UAV's integration [12]. In order to convert the transmission rate into a comparable metric, the required transmission time on a path is cited as t_{ij}; we have $t_{ij} \sim 1/R_{ij}$, where R_{ij} is the transmission rate. The formula for calculating the time required for the direct and indirect path will be presented in the MAC protocol description. In addition to transmission time, a new metric that describes the energy consumption for data transmission between the two nodes is introduced for evaluating, E_{ij}. Essentially, this energy is proportional to the product of transmission power and the required time, so that $E_{ij} \sim P_{ij}^t t_{ij}$. In a LOS channel and with an unchanged transmitting power (the value of P_0^t), the corresponding energy consumption on the path between nodes i and j is $E_{ij} \sim P_0^t t_{ij} \sim P_0^t / R_{ij}$. Depending upon the actual bit rate or the actual distance between the two nodes, E_{ij} is determined.

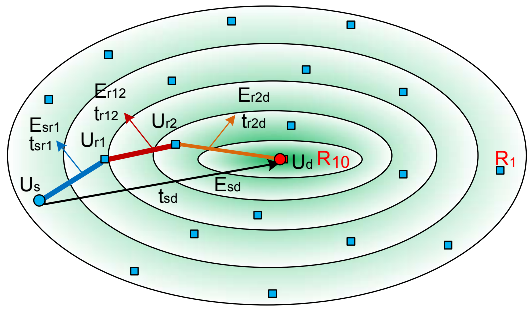

Fig. 1. Metrics for optimized cooperative relay
(U_s is source UAV and U_d is cluster head UAV)

Moreover, to overcome the problem of changing relative distance between the nodes (and therefore changing transmission rate and energy consumption) due to the fast movement of UAVs, we will incorporate the predicted position of the UAVs in the path selection. The next location of each UAV may, for instance, be estimated using a Kalman filter based on the knowledge of the previous and heading or course positions. For the sake of simplicity, we will in this paper assume that the future positions are known, and simulate the motion of the UAVs using random inputs. Assuming that the UAVs are distributed in a Cartesian coordinate's plane, the next location could be predicted by:

$$\begin{cases} x_{t+\Delta t} = x_t + \Delta t . v . \cos \psi \\ y_{t+\Delta t} = y_t + \Delta t . v . \sin \psi \end{cases}$$

where Δt is the maximal time interval over which the optimization scheme must be solved (for instance 1s or smaller), ψ is the heading (course) direction. With this prediction, the appropriate transmission rate is matched accordingly with the maximum of $(d_{ij,t}, d_{ij,t+\Delta t})$. Consequently, the respective metrics of time t and energy E can be calculated and indicated on each path as in Fig. 1.

C. Modified Bellman-Ford algorithm

A modified Bellman-Ford algorithm is used to solve the problem of finding the optimal relay route between each sUAV and the cUAV. The reason for using the modified version is to have the possibility of limiting the number of relay nodes used while still finding the optimal direct or indirect path. For a complete description of the modified Bellman-Ford algorithm, the interested reader is referred to [13]. Here, the cluster is modeled as a weighted directed graph. The weight associated with an edge representing the total cost in terms of both of time and energy used for data transmission on the channel between two nodes:

$$W_{ij} = \max\left(\frac{\alpha}{R_{ij}} + \frac{\beta P_0^{\mathrm{t}}}{R_{ij}}, \frac{\alpha}{R_{ij}^{\mathrm{p}}} + \frac{\beta P_0^{\mathrm{t}}}{R_{ij}^{\mathrm{p}}}\right)$$

where α, β are positive constants that stand for the priority of the system on time and energy, respectively. The higher value for α or β the higher priority will be for time or energy. For instance, with the equal priority for time and energy, α should have a similar value of βP_0^{t} (cf. Table 1). $R_{ij}, R_{ij}^{\mathrm{p}}$ are the current and predicted transmission rate according to actual and predicted distance between the two nodes i and j.

D. Cooperative relay MAC protocol for UAV network

This section describes the MAC protocol used for cooperatively relaying data from the source node (U_s) to its destination (U_d). As in the papers afore-mentioned, this MAC protocol follows the standard IEEE 802.11 and uses the distributed coordination function. When the source node has data to send, it senses the channel for a period of DIFS (distributed inter-frame space). If the channel is idle, it initializes a random backoff process for a period that is uniformly distributed between 0 and a contention window represented by $CW_i = 2^i CW_{min}$, $CW_i \in [CW_{min}\ CW_{max}]$, where i is an integer number and $i \geq 0$; CW_{min} and CW_{max} are the min and max of contention window sizes that are defined in the protocol. After this process the source node transmits a RTS packet to the destination node. The reception node then sends back a CTS packet after a SIFS (short inter-frame space) if it is not busy at the time. Through this handshake process, these two nodes can exchange more information about their transmission plan as well as inform surrounding neighbor nodes about the data transaction. These neighbors then need to update their network allocation vectors (NAV) for deferring a transmission until the end of the working cycle. The length of this cycle includes 3SIFS, RTS, CTS, DATA, and ACK packets durations. In case of a reception failure at the receiver, all steps of the cycle are repeated.

The aim of this paper is to find the best way to send data from the source to the destination. The route for sending data may be the direct path or the least costly relay paths in regards to both time and energy consumption. In this protocol, the following features are emphasized:

1) The transmission time and total energy consumption are simultaneously minimized.

2) The number of relay path is not limited to two; it is a result of the optimal relay path selection scheme.

3) Packet retransmission could be automatically executed at a transmitting node after a specific period of observing packet's relaying behavior at a receiving node. All the processes of are not repeated.

4) Completely compatible with the IEEE 802.11 standard.

There are two cases that need to be explained in detail:

a) Processes with the existence of relay nodes

The best relay paths are only found when the total weight on the respective relay paths is smaller than the weight required for transmission of the same data but on the direct path (between the source node and destination node). In other words, the overall data transmission time and node's energy consumption is minimized.

First of all, the source node (U_s) senses the channel to detect if it is idle, and sends a RTS directly to the destination node (U_d) at a basic transmission rate (i.e. 1Mpbs for IEEE 802.11g) and at the standard transmitting power. The purpose is to reserve a period of one full cycle for its data transmission. If U_{r1}, U_{r2},..., U_{rn-1} are relay nodes in the selected paths and there is no additional delay in packet receiving-forwarding at a relay node, the duration that needs to be reseerved is (cf. Fig. 2a):

$$T_c = nT_{SIFS} + T_{ACK} + 2T_{SIFS} + T_{CTS} + \sum_{k=1}^{n} \frac{8L}{R_k} \quad (2)$$

where L is the packet length in bytes and R_k is the bit rate on the respective k^{th} path connecting node k with its predecessor. At k=1, the path connects node number one and the source node; node n is the destination node.

Compared to the required time for transmission on the direct path and the energy metric, the condition of determining an indirect route contains n relay hops is:

$$nT_{SIFS} + \sum_{k=1}^{n}\left(\frac{8L}{R_k} + \mathrm{E_k}\right) < \frac{8L}{R_{sd}} + E_{sd} + T_{SIFS} \quad (3)$$

where E_{sd} is the energy usage for data transmission on the direct path connecting the source and destination node, and R_{sd} is transmission bit rate on this direct path.

Each relay node needs an additional period of T_{SIFS} plus the coressponding data transmission time of $8L/R_k$. In this protocol, an ACK packet is not needed on each relay path but it still enables us to establish a full backup scheme. The failed packet is only retransmitted between the respective transmitter and receiver. This process will be explained in detail in the case of packet failure in the later paragraph.

If idle, the destination node will return to the source node a CTS packet after a SIFS period. The NAV (network allocation vector) of its neighbors will be updated based on the information in this packet. This process helps to avoid hidden terminal issues. After receiving the CTS, the source node starts to transmit data on the first relay path after a SIFS period. In the address fields (address No. 3 of MAC header format [8]), it must indentify the final destination of the packet, U_d. At the same time, it needs to include the other two addresses (address No.1 and No.2) of the sender itself and the intermediate destination. Usually, as in the protocols mentioned in section I, the source node must inform this relay node that it needs to relay this packet to the next relay node U_{r2} by some method. In this protocol it is assumed that all the nodes are in the same mission and are willing to relay other node's data. The main advantage of the scheme is that the optimal route from the source to the final destination ($U_s \rightarrow$

U_d) is a type of global optimum route (cf. the algorithm in Section II.C). As a result, node U_{r1} can find out that the next node it needs to relay is U_{r2} because the route of $U_{r1} \rightarrow U_{r2} \rightarrow U_d$ is the best selection. It is noticeable that some new relay nodes may be located in the communciation range of the intermediate relay nodes but are out of the communication range of the source node. As a result these nodes will be not included in the relay route selection executed by the source node. However, as shown in Fig. 1, the selected relay node is usually close to both the source and destination nodes. Therefore, those hidden nodes are not potential nodes for the optimal route selection.

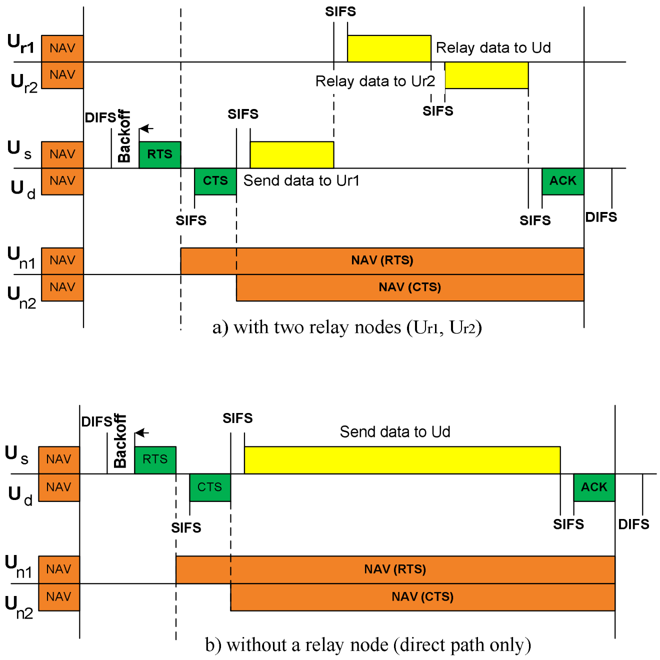

Fig. 2. Description of n-relay cooperative MAC protocol

After receiving the packet successfully, U_{r2} will wait for another SIFS before it continues to relay the packet to the destination node U_d. This step completes all relaying processes for this packet. Node U_d will send back an ACK packet to the source node U_s. Through this packet, all other relay nodes will acknowledge that the packet is received by the destination node, and thus complete a transmission cycle for this packet.

If the packet fails to be received at one receiver node, for example at U_{r1}, the respective transmitter, node U_s, will retransmit the same packet after sensing for a period during which U_{r1} should have sent the packet to U_{r2}. The sensing period is the sum of T_{SIFS} and $8L/R_{r12}$, where R_{r12} is the bit rate between U_{r1} and U_{r2}. Through this sensing or receiving this packet retransmission, the surrounding nodes of the receiver, including the source node, destination node, and other relay nodes, will update their NAVs with an extension due to this packet retransmission. This duration has the same length as the period normally required for a relay hop between two nodes. In this case the period is $T_{SIFS} + 8L/R_{sr1}$. Similarly, in the case of a failure occurred at node U_{r2}, node U_{r1} will retransmitting the packet after waiting and sensing for a period of $T_{SIFS} + 8L/R_{r2d}$, where R_{r2d} is the bit rate between relay node U_{r2} and the destination U_d.

In addition, in this protocol each node knows other neighbor node's position, as well as the distances and transmission bit rates from this neighbor to other nodes. Therefore, after deciding the source node and destination node through sensing the RTS/CTS packets, each individual relay node can calculate the time that the packet arrive at the node itself. This information is used as a timeout of the packet at each node. For instance, after receivng a CTS packet, if node U_{r1} and other relay nodes do not receive any packet after a period of $T_{SIFS} + 8L/R_{sr1}$, this packet is assumed to be aborted, and the nodes reset their NAV vectors. In the case that no CTS packet is transmitted from the destination node after a RTS packet, all the possible relay nodes will clear their NAV vectors, and the source node needs to start a regular backoff process that is similar to the case of a packet collision.

b) Processes without a relay node

In this case, the procedure is the same as the IEEE 802.11 standard and there is no additional overhead required. Only two address fields are used to define the source and destination nodes in the MAC header format (cf. [8]). After sensing the channel, the source node, if it is idle, will wait for a DIFS period and commence a RTS packet to the destination. If it is a successful reception, an ACK packet will be sent back to the source node. The duration of a packet transmission cycle should be $3T_{SIFS} + \frac{8L}{R_{sd}} + T_{RTS} + T_{CTS} + T_{ACK}$. The procedures in the cases of packet failure and packet collision are similar with the standard cases in the IEEE 802.11.

III. PERFORMANCE EVALUATION

In this section, system throughput, delay, and the cost improvement ratio are evaluated for the two cases of with and without the optimized relay route selection algorithm. The throughput is calculated as the ratio beetween the successful delivered packets and the number of transmitted packets. The average delay for a packet transmission is counted from the moment of sending the RTS packet until it successfully receives an ACK from the destination. The cost improvement describes the benefical rate of using the relay path selection scheme, compared with the case of not using it. This metric can be calculated as $1 - C_{wt}/C_{wo}$, where C_{wt}, C_{wo} are the total costs of time and energy in the two respective cases. In the case where only the direct path is used for sending data, this value becomes zero.

In this system, the destination node is assumed to be the cluster head UAV (cUAV), and any of the sensing UAVs (sUAV) could be the source node. The cUAV is assumed to be positioned at the centre of the area of interest while other sUAVs are randomly located in the same area. To evaluate system performance under the staturated packet transmission, each sUAV is assumed to always have a packet for transmitting. All the sUAVs and cUAV are on the same 2-D plane and characterized by their Cartesian coordinates. The area of interest varies from the small size of 1E+6 to the large size of 16E+6 square meters. The number of sUAVs varies from 10 to 40. Many of the parameters are the same with the IEEE 802.11g standard, as shown in Table 1.

A. Parameters

Without loss of generality, this paper surveys the data transmission bit rates measured in the IEEE 802.11g standard.

At these ranges, it would be suitable to apply for some of the sample applications with the UAVs as mentioned in Section I as well as for other scenarios. Regarding the transmission rates in Table 2, they are first obtained from the relation between the rate and operating distance applied in the IEEE 802.11g standards [14]. These standard rates are the results of applying an exponent path loss of 3 and a specific value for signal-to-noise ratio [15]. For a network of all the UAVs, free space path loss would be applied so a conversion in operating distance is needed. With the same SNR, the corresponding rates and new operating distances are shown in Table 2. Hence, if we apply the same signal-to-noise ratio, we have the same data bit rate. In the referenced environment, $SNR \sim 1/d_1^3$, but in our case, $SNR \sim 1/d_2^2$, where d_1, d_2 are the distances that the same SNR has been obtained in those two radio conditions.

TABLE 1. SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
Frequency	2.4 GHz	SIFS	10 µs
P_0^t	0.2 W	DIFS	50 µs
G_{et}, G_r	1 dB	Packet size	1023 bytes
B	20 MHz	CW_{min}	32
MAC header	272 bits	CW_{max}	1024
PHY header	192 bits	Retransmit times	3
MAC/PHY/RTS/ CTS/ACK rate	1 Mbps	Time weight (α)	1
		Energy weight (β)	5
RTS	160 bits		1000x1000 m^2
CTS, ACK	112 bits	Size of the area of	2000x2000 m^2
Slot duration	20 µs	interest	4000x4000 m^2
UAV avg. speed	25±3 m/s	No. of sUAVs	10, 20, 30, 40
Rec. sensitivity	-94 dBm		

TABLE 2. DATA BIT RATE FOR 802.11g STANDARD
(*With path loss exponent of 2, BER≤10^{-5}*)

Rate (Mbps)	Distance (m)	Rate (Mbps)	Distance (m)
54	89	12	397
48	118	9	430
36	207	6	524
24	272	2	676
18	364	1	d_{max}

B. Results

The simulation results are represented in Figs. 3-6. The common horizontal axis in these figures is the number of sUAV, which varies from 10 to 40. The vertical axes are the average successful packet delivery ratio, average delay, average number of relaying hops, and the average cost improvement ratio, respectively.

From Fig. 3, with an area of 1E+6m^2 and the optimal relay selection algorithm, all the packets are successfully delivered when the number of sUAV increases, even up to 40. At this largest number of sUAV, there is a reduction of about 35% in successful packet delivery if the relay selection scheme is not used. Figure 4 shows that the average delay increase as the number of sUAV rises due to an increase of packet retransmissions. This worsens in the case of not using the relaying scheme because many packets will fail even after multiple attempts of retransmissions. However, regarding to the cost improvement ratio in Fig. 6, it is still possible to save between 25% to 30% of total time and energy in data transmission if the optimization scheme is applied for selecting optimal relay paths. This cost benefit likely increases when the number of sUAV in the network rises. This is reasonable because of an increase in potential relay nodes. For the number of relay hops, Fig. 5 illustrates that it usually passes the packet through two relay paths but it rarely use more than this number of paths.

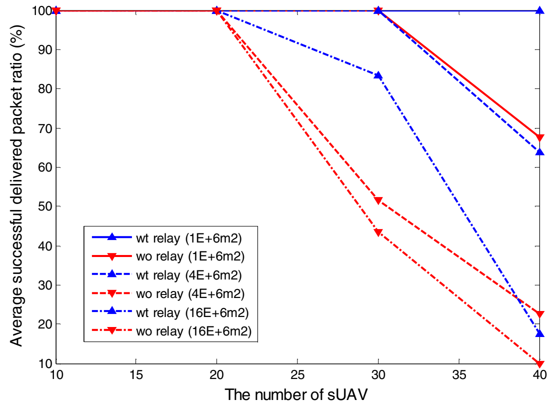

Fig. 3. Average success ratio of packet delivery

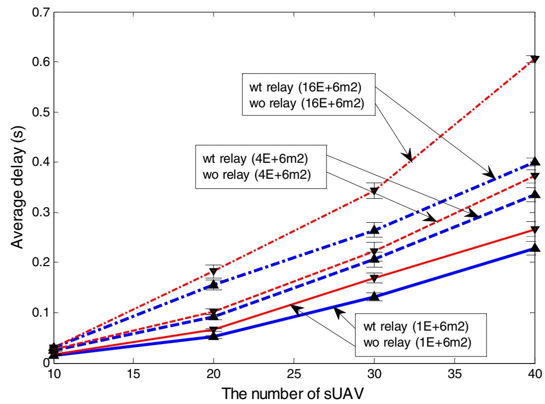

Fig. 4. Average delay of packet transmission

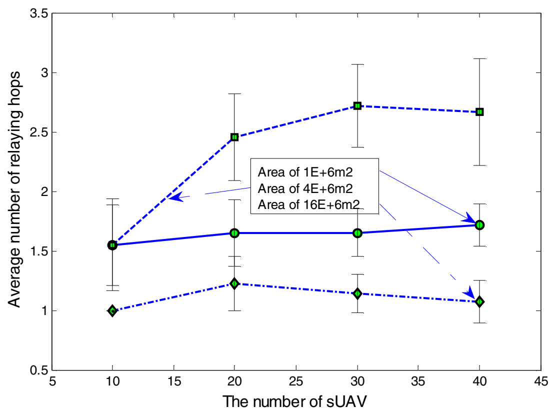

Fig. 5. The average number of hops used in relaying

For the results with the large area of 16E+6 m^2, there is not a significant improvement in successful packet delivery ratio between the two cases of using and not using the optimal relay selection algorithm. This ratio is quite low when the sUAVs rises to 40, compared to the case with a smaller area due to low bit rate between sUAV and cUAV. At this density of sUAV in the network, the average delay in the case of not using the optimal relay selection scheme is quite higher than that in the case of using the scheme. This is possibly because of a large number of retransmissions and a lack of potential relay nodes (cf. Fig. 5). This is also reasonable for a poor cost improvement ratio, which is only maximal at about 7% (cf. Fig. 6).

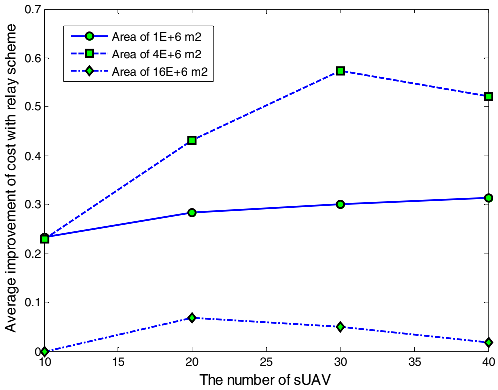

Fig. 6. The improved cost ratio in case of using relay

With the medium area of interest of 4E+6 m^2, in Fig. 3, the dashed-dotted blue line shows that all of the packets are delivered to the cUAV until the existence of 30 sUAVs in the network. It reduces to 65% when the number of sUAVs is 40. However, there is a consistent improvement of up to 45% for the average successful packet delivery ratios in the two cases of with and without using the optimal relay selection scheme when the number of sUAVs is between 30 and 40. This optimization scheme has only made the average delay slightly lower compared to the case where optimization is not used (cf. Fig. 4). The benefit in this scenario is the very high cost improvement ratio of between 45% and 55% when the number of sUAV is increasing from 20 to 40 (cf. Fig. 6). With this size of the area of interest, the average distance between source node and destination node is usually large, about a quarter of the length of the area (2000 meters), i.e. 500 meters. As a result, the actual transmission bit rate is usually low. But from Table 2, at lower rates, the ratio between the two consecutive bit rates increases due to the distribution of the transmission rates and operating distances. For instance, the ratio of 6/2 at the distances of 524m and 676m is much larger than the ratio of 54/48 at the distances of 89m and 118m. This explanation may also be applicable for the results in the large area size (16E+6 m^2) where the average distance is about 1km. At this average distance, the bit rate is low and it is difficult to find other relay node with good improvement in transmission time and energy. As a result of the medium area size, the ratio between the improvement cost ratio becomes more considerable. Consequently, the cost benefit becomes higher than that in the case with the small area of 1E+6 m^2 if they contain the same number of sUAV (cf. Fig. 6). However, at small number of sUAV (e.g. at 10), the cost benefit ratio in the small and medium area sizes is similar. This is possibly because of spatial sUAV distributions in the two cases, which leads to a difficulty in finding a potential relay node. Nevertheless, these improvement cost ratios are much better than its value in the case with the large area size because the average distance between sUAV and cUAV is quite large in that case. It is also important to point out that, at the medium size of the area of interest, the number of relaying hops is usually more than two when the number of UAVs increases from 10 (cf. Fig. 5). This means that even though the packet is relayed through several relay paths, the relay route optimization scheme shows a high benefit for both time and energy. This is the main innovation of this paper when comparing to other papers, which limits the number of a relay paths to two.

IV. Conclusion

The analyses of the numerical results illustrates the considerable gains of using this optimal relay selection algorithm. In the combination of this algorithm and the proposed protocol, the sum of transmission time and energy is consistently reduced. The benefit essentially depends on the size of the area and the number of source nodes located in the network. More generally, it increases when the average distance from the source node and the destination node increases, but not too large. It also increases when there are more nodes, but not too many, located in the area. In addition, both the successful packet delivery ratio and the average delay are consistently better than their values in the case of transmitting on the direct path. These results would be even improved if each UAV has fewer packets to send to the cluster head UAV. Furthermore, with the broadcasting feature of data communication on each relay path, other nearby nodes may naturally listen to this information. We plan to add a cooperative diversity scheme into this protocol in order to improve both throughput and delay with the help of these neighbor nodes.

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