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Adaptive Hello Interval in FANET Routing Protocols for Green UAVs

IMTIAZ MAHMUD AND YOU-ZE CHO, (Senior Member, IEEE)
School of Electronics Engineering, Kyungpook National University, Daegu 41566, South Korea

Corresponding author: You-Ze Cho (yzcho@ee.knu.ac.kr)

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ABSTRACT With the recent advances in unmanned aerial vehicles (UAVs), the development of energy-efficient networking technology for mission-oriented multiple cooperative UAVs has become crucial. Routing in flying ad-hoc networks (FANETs) with UAVs is a challenging issue because of the high speed and sudden changes in direction of UAVs. Traditional routing protocols in FANETs periodically send hello messages for the establishment and maintenance of the routes. However, sending hello messages periodically after a fixed interval increases bandwidth wastage when the hello interval is excessively short or causes long delays in neighbour discovery when the hello interval is overly long. Moreover, several disconnected UAV groups have been observed in which the group members are connected among themselves but detached from the main network. By exchanging excessive hello messages inside the group, the UAVs maintain an unnecessary neighbourhood, causing wastage of energy. However, FANETs have certain advantages, such as knowledge about mission-related information. To solve the problem of unnecessary energy drain, we propose a novel adaptive hello interval scheme—energy efficient hello (EE-Hello)—based on available mission-related information, such as the volume of the allowed airspace, number of UAVs, UAV transmission range, and UAV speed. We present a method to decide the distance that a UAV needs to travel before sending a hello message. We also specify a technique to determine the number of UAVs necessary to achieve specific network requirements, such as packet delivery ratio or throughput, with the expenditure of minimum energy. We show that the proposed EE-Hello can save about 25% of the energy currently used, by suppressing unnecessary hello messages without degrading the overall network throughput.

INDEX TERMS FANETs, UAV networks, green UAV networks, energy efficient routing, adaptive hello interval.

I. INTRODUCTION

Recently, Unmanned Aerial Vehicles (UAVs) have become very popular because of their wide range of applications for which they can be used [1], [2]. In particular, their capability to work as a group with minimum human intervention has led to a productive area of research. However, energy efficiency is a major concern in today's UAVs [3]. Generally, small UAVs can fly for a maximum of 30 minutes depending upon available energy. Therefore, research has focused on producing energy-efficient green UAVs that can fly for longer. In addition, in a multi-UAV system, UAVs need to maintain communication links between themselves in order to accomplish their mission cooperatively. However, owing to the rapid movements of UAVs, network connectivity has become a critical issue, generating a new field of research, namely Flying Ad-Hoc Networks (FANETs) [4]–[8]. In FANETs, if the communication protocol generates excessive overhead, it can consume more energy than necessary. Repeated attempts to discover neighbour UAVs in ad-hoc mode can cause a large energy drain. To the best of our knowledge, research targeting this energy drain problem for traditional routing protocols considering FANET scenarios has not yet been carried out.

In FANETs, any UAV can move away, come forward, or change direction or speed, actions which negatively affect route maintenance and throughput, leading to delays in data dissemination. When UAVs move freely in the sky in 3D space, their antennas behave differently than they do in 2D space, a phenomenon which directly affects the physical layer [4]. Therefore, we need to consider a 3D topology in

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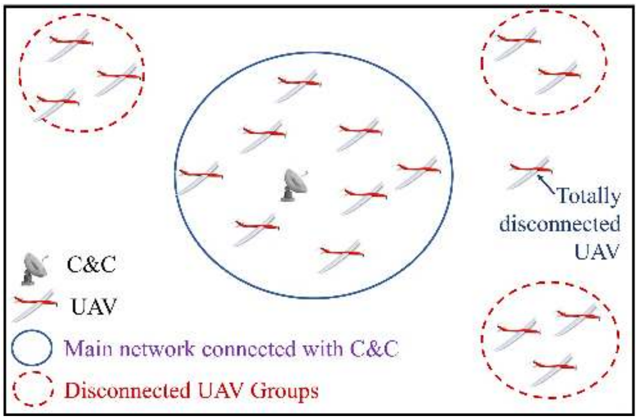


FIGURE 1. Typical FANET scenario.

order to better understand the network behaviour. To further complicate matters, UAVs move freely in 3D space at rapid speeds, causing fast topological changes. Typically, not all UAVs in a group are involved in communication. For example, if we consider a reconnaissance mission, only a UAV which finds a target sends information to its command and control (C&C) station. Amongst the other UAVs, some may act as relays, whilst others remain engaged in their own missions. In addition, UAVs try to move away from each other to cover larger areas. In such situations, they may create Disconnected UAV Groups (DUGs): small networks of groups of UAVs that are disconnected from the main network (Fig. 1), and some UAVs may be totally disconnected. Moreover, when a small number of UAVs attempts to explore a comparatively large area, the possibility of their meeting each other is reduced. Therefore, to establish a route, it is vitally important for a UAV to discover neighbour UAVs through hello messaging or a link layer feedback mechanism.

For neighbour detection and maintenance, soft state signalling—periodic exchange of hello messages by the routing protocol—is preferred over link layer feedback, as the former does not limit usage and implementation to any specific link layer technology (for instance, ACK packets) [9]. Previously in Mobile Ad-Hoc Networks (MANETs), several hello messaging schemes have been developed, which are concentrated on determining the dynamic network topology or updating live neighbours, using an energy-saving scheme which involves all UAVs in periodically exchanging hello messages or beacons while they are awake [10]. In such traditional hello messaging schemes, no start/end or adaptive interval conditions are defined [11]. This situation can cause unnecessary bandwidth usage and energy consumption in FANETs. The DUGs in particular can cause extensive energy drain. Moreover, the hello interval always leads to a trade-off, whereby a shorter interval facilitates quick detection of new neighbours or link breaks, but produces higher overhead and consumes more energy, whereas a longer interval reduces overhead and energy consumption but limits neighbour discovery and link break detection capability. Therefore, an optimized hello interval that can dynamically adapt to diverse circumstances is essential for FANETs. In spite of the difficulties, in most missions, UAVs have the advantage of the ready availability of mission-related information. If utilized properly, these data can be used to produce an optimal network solution.

In this paper, we propose an adaptive hello interval algorithm, Energy Efficient Hello (EE-Hello), consisting of four mechanisms for traditional FANET routing protocols, with the aim of producing energy-efficient green UAVs. First, we propose a novel method for calculating network density, which can affect network performance metrics such as packet delivery ratio or throughput. We also establish a mechanism to calculate the necessary number of UAVs which can satisfy the performance requirements of the network with minimal energy consumption. Second, we propose a method for determining the hello interval based on available mission-related information, such as the volume of permitted airspace, the number of performing UAVs, their transmission range, speed range and current speed. Third, given the value of the hello interval, we propose to set the timeout timer to an appropriate value. Fourth, in the case of an insufficient number of UAVs, we propose an additional immediate hello message feedback mechanism for better network throughput. Using simulations, we considered a 3D space scenario reflecting a practical situation. The simulation results show that the EE-Hello can reduce energy consumption by up to 25% by suppressing unnecessary overheads, without any significant degradation in network throughput.

The remainder of this paper is organized as follows. We describe related work and associated problems in Section II. Section III illustrates the proposed EE-Hello scheme and associated equations. Section IV evaluates the performance of the EE-Hello scheme based on simulation results using the metrics of network overhead, network throughput, network trade-offs and energy consumption. Finally, Section V summarises our conclusions.

II. RELATED WORK

Several researchers have proposed schemes to determine the hello interval for traditional MANET routing protocols. In this section, we discuss some of the key ideas which have focused on different parameters, and which directed us towards the new proposal.

Han *et al.* proposed an adaptive hello messaging scheme for traditional routing protocols to save energy by suppressing unnecessary hello messages without losing link detectability in MANETs [12]. These authors considered sending, forwarding, or receiving a message as an event, and monitored the intervals between consecutive events. If a node does not participate in any event for a given period, it does not need to maintain the status of the link and can suppress hello messages. Thus, the hello interval increases with an increase in event intervals. Whenever an event occurs, the hello interval is reset to the default value. However, in FANETs, many UAVs do not actively participate in communication and try to move away from each other, although they remain important to communication. Because of the highly dynamic nature of FANETs, whenever a UAV needs to send information, it requires knowledge of the network to route packets to the destination. If two non-communicating UAVs remain silent for a long period, and they come across each other during that silent time, they will not recognize each other as neighbours. Due to their high speed, they may lose the communication window in the silent time when they could communicate otherwise. Thus, this technique can cause a significant number of false link disconnections in FANETs. Moreover, because of the DUG problem, the UAVs involved in DUGs will keep trying to maintain unnecessary neighbourhoods, although they are disconnected from the main network. As a result, they will generate a significant amount of unnecessary overhead, a situation which is undesirable for energy-efficient green UAVs.

Hernandez-Cons *et al.* proposed an adaptive hello interval for traditional MANETs based on the link change rate, defined as the total number of added or deleted links per elapsed time [13]. If a node has a link change rate close to zero, its neighbourhood remains unchanged, and conversely, if a node has a high link change rate, its neighbourhood changes. As the link change rate increases, the hello interval decreases, and vice versa. Although this scheme significantly reduced overhead, the focus of this research was mainly on stable networks with few topology changes. In a typical FANET scenario, when the UAVs try to move away from each other, the possibility of a high link change rate decreases. As a result, UAVs will have a longer hello interval resulting in loss of link detectability. Moreover, due to the different speeds of UAVs, link changes can occur frequently in DUGs, resulting in increased overhead. As a result, it fails to satisfy the goal of an energy-efficient UAV network.

Giruka and Singhal proposed another solution for MANETs, in which the nodes transmit hello messages after a specific distance [14]. As the nodes have different speeds, high-speed nodes are assigned a short hello interval whereas low-speed nodes have a long hello interval. Though they achieved promising results, they did not define the method to determine the specific distance. In diverse FANET scenarios, the use of an identical specific distance will result in severe performance degradation. Thus, a method to determine the most appropriate specific distance is yet to be established.

Park *et al.* investigated the impact of node speed and transmission range on the hello interval for MANETs, and proposed a scheme to determine the hello interval based on those two factors [15]. However, in FANETs, allowed airspace, the number of operating UAVs, and the range of speeds involved play significant roles, as observed for MANETs by Hernandez-Cons *et al.* [13]. As a result, this approach is not completely suitable for FANETs. The issue of identifying a definitive scheme for determining an adaptive hello interval for traditional routing protocols in FANETs that performs energy efficiently without reducing network throughput therefore remains unsolved.

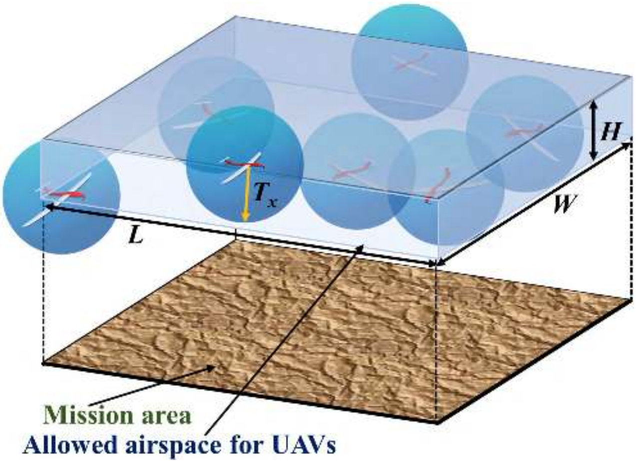


FIGURE 2. Schematic of a mission environment. Here, each sphere indicates a UAV's transmission area.

III. PROPOSED SCHEME (EE-HELLO)

In this section, we present the details of our proposed EE-Hello scheme to minimize energy consumption in traditional FANET routing protocols by reducing unnecessary hello messages. We based our study on the continuous measurement of UAV speed and knowledge of mission-related parameters. Therefore, our study is well suited to missions such as surveillance, search and rescue, and reconnaissance. However, we do not consider missions where UAVs are allowed to fly in an unbounded airspace. In the following discussion, we consider two UAVs to be neighbours only when they are within transmission range of each other. The terms "network performance" and "network requirements" are used interchangeably to refer to the packet delivery ratio and throughput of the network, unless stated otherwise.

The goal of the scheme is to dynamically adjust the hello interval and timeout timer according to the conditions of individual UAVs and the network. For example, for a high-speed UAV, it is desirable to use small values for the hello interval to quickly reflect changes in the network topology. For a low-speed UAV, a large value for the hello interval is more effective in reducing overheads. In an adequately-dense network, link changes occur frequently, and a shorter interval is therefore required. In contrast, in a low-density network, link changes are infrequent, so a longer interval is desirable.

In the following discussion, we first define a method for determining network density and its implications, and then explain the remaining three mechanisms in detail.

A. COMPUTATION OF NETWORK DENSITY

To decide whether a network is of low or adequate density to fulfil specific network requirements, we first determine the number of UAVs (U_{req}) required to connect the entire mission area. For FANET, we need to establish a network amongst the UAVs in a 3D space. Fig. 2 shows a typical UAV operation, in which the UAVs are allowed to fly within a given airspace over the mission area. The airspace has a specified length (L), width (W), and height (H). We assume that the UAVs are equipped with omnidirectional antennas for communication purposes. We consider the transmission area of a UAV to be a sphere centred around the UAV. As our goal is to create a connected network in the allowed airspace, we start by considering stationary UAVs. Because we are not considering the exact volume of each UAV's transmission range, we determine the number of UAVs that can be accommodated inside the airspace by dividing the volume of allowed airspace (V_M) by the volume of a sphere (V_{Tx}). For simplicity, suppose that all the UAVs have the same transmission range (T_x). We can then calculate the number of UAVs that can be accommodated in V_M as:

$$U_{accom} = \frac{V_M}{V_{Tx}} = \frac{3 \times L \times W \times H}{4 \times \pi \times T_x^3} \tag{1}$$

Because the UAVs need to be within the transmission range of each other to create a connected network, at least $2 \times U_{accom}$ UAVs are required. In practice the transmission volume is not perfectly spherical. Considering this factor, we define the minimum number of UAVs required to connect the allowed airspace as:

$$U_{req} = 3 \times U_{accom} = \frac{9 \times L \times W \times H}{4 \times \pi \times T_x^3} \tag{2}$$

The floating-point values of U_{req} and U_{accom} are rounded up to integer values. Because U_{req} can be calculated from the C&C station, in the case of UAVs having unequal T_x, the C&C station can simply take an average of all the UAVs transmission ranges ($T_{x,avg}$) and use it instead of T_x in Eq. (2).

For a dynamic network with moving UAVs, suppose the number of available UAVs involved in the mission is U_M. We then define the network density (N_D) using the following equation:

$$N_D = \frac{U_M}{U_{req}} = \frac{4 \times \pi \times T_x^3 \times U_M}{9 \times L \times W \times H} \tag{3}$$

N_D plays a significant role in determining the network performance. We define a parameter φ that determines a relationship between the above-mentioned physical parameters and the network requirements. When $N_D < \varphi$, we consider the network to be a low-density network; that is, there are not enough UAVs to compose the network. When $N_D \geq \varphi$, we consider the network to be an adequately dense network; the value of U_M is acceptable for the construction of a network with reasonable performance. In other words, when $U_M \geq \varphi \times U_{req}$, we consider that an acceptable number of UAVs can form a network that can achieve specific network requirements such as packet delivery ratio or throughput. As a result, the C&C station can save energy by deploying only the required number of UAVs for a mission. The value of φ can be determined by simulation experiments and is discussed in detail in Section IV-B.

B. ADAPTIVE HELLO INTERVAL ALGORITHM

As discussed earlier, FANETs have some unique characteristics, such as high speed, rapid changes in speed and direction, and DUGs. Thus, we must consider a UAV's speed when determining the hello interval. Moreover, dependence on event intervals or link changes can result in increased overhead for DUGs. If we totally suppress the hello messages in DUGs, the UAVs involved in DUGs will be unable to discover the main network. As a result, to solve the energy wastage problem in DUGs, either a fixed interval or fixed distance approach can be taken for determining the hello interval. However, the fixed interval approach is not suitable for FANET because speed cannot be properly taken into consideration. Therefore, we propose an algorithm that sends hello messages after UAVs travel a specific distance (γ). We calculate γ based on mission-related information: transmission range; allowed airspace; number of UAVs; and their speed ranges. The hello interval can then be determined by calculating the time required to travel that distance based on a UAV's speed.

The current hello interval ($T_H(n)$) is represented by the following equation:

$$T_H(n) = \gamma \times \frac{1}{v_{avg}(n)} \tag{4}$$

where γ is the distance after which a UAV has to send a hello message, and $v_{avg}(n)$ is the current average speed of the UAV. Instead of using an instant speed $v(n)$, we calculate an average speed by using an Exponential Weighted Moving Average (EWMA) [16] as follows:

$$v_{avg}(n) = (1 - \theta_{EWMA}) \times v_{avg}(n-1) + \theta_{EWMA} \times v(n) \tag{5}$$

where $v_{avg}(n-1)$ is the previously estimated average speed and θ_{EWMA} is a constant parameter for the EWMA.

In a previous study [15] we observed that a UAV with longer transmission range can maintain network throughput with a longer hello interval. Hence, we define γ as proportional to T_x:

$$\gamma = \alpha \times T_x \tag{6}$$

where α is a variable whose value depends on the mission-related information. To calculate α we assume that a UAV's highest and lowest speeds are limited to values between $v_{\max}$ and $v_{\min}$, respectively. Now, we determine α using the following equation:

$$\alpha = \frac{1}{N_D} \times \beta \times \frac{v_{\max}}{v_{\min}} \tag{7}$$

When other parameters are constant, α is inversely proportional to N_D. According to Hernandez-Cons *et al.* [13], increases in link changes can be observed with increases in U_M, and so ultimately with increases in N_D. Therefore, $T_H(n)$ needs to be decreased to identify link changes successfully. With this phenomenon, α decreases as N_D increases. On the other hand, $v_{\max}/v_{\min}$ represents the speed range, the possible extent of differences in speeds, where a high value indicates that UAVs with high velocity can travel much further during each time interval than UAVs with low velocity. Because we do not want to lose link detectability or expend energy unnecessarily, we place a limit on $T_H(n)$, so that $T_{\min} \leq T_H(n) \leq T_{\max}$, where $T_{\min}$ and $T_{\max}$ are the lowest and highest possible hello intervals, respectively. The $T_H(n)$ of UAVs with $v_{\max}$ should be greater than or equal to $T_{\min}$, and the $T_H(n)$ of UAVs with $v_{\min}$ should be less than or equal to $T_{\max}$. Thus, $T_H(n)$ for $v_{\min} < v(n) < v_{\max}$ should be distributed proportionally between $T_{\min} \leq T_H(n) \leq T_{\max}$. To ensure this characteristics, $v_{\max}/v_{\min}$ is incorporated in Eq. (7). Finally, a tuning constant β is multiplied with $v_{\max}/v_{\min}$.

From Eqs. (3), (6) and (7), we can derive an equation for γ:

$$\gamma = \frac{9 \times \beta \times L \times W \times H \times v_{\max}}{4 \times \pi \times U_M \times T_x^2 \times v_{\min}} \tag{8}$$

We can determine $T_H(n)$ by substituting the value of γ in Eq. (4) so that:

$$T_H(n) = \frac{9 \times \beta \times L \times W \times H \times v_{\max}}{4 \times \pi \times U_M \times T_x^2 \times v_{\min}} \times \frac{1}{v_{avg}(n)} \tag{9}$$

During the mission, if any parameter changes, the C&C station can transmit the information to the UAVs so that they can recalculate γ.

C. ADAPTIVE TIMEOUT TIMER

In traditional routing protocols, the timeout timer determines the amount of time during which a link to a neighbour is considered valid. In the case of the Ad-hoc On-Demand Distance Vector (AODV) routing protocol, the timeout timer for each neighbour is calculated as follows:

Neighbour Lifetime = *Allowed Hello Loss* × *Hello Interval*

By default, *Allowed Hello Loss* has a constant value of 2 and the *Hello Interval*is fixed at one second [17]. The Optimized Link State Routing (OLSR) protocol defines the timeout timer as:

Neighbour Hold-Time = 3 × *Refresh Interval*

By default, *Refresh Interval* is set (similar to the hello interval) to two seconds [18]. The timeout timer has a close relationship to the hello interval. Each protocol includes the lifetime/hold-time information in their hello message so that the receiving node can determine the lifetime of the link. Therefore, we propose to instantaneously update the timeout timer based on updates to $T_H(n)$. The receiving UAV sets the lifetime of a link to a neighbour based on the received lifetime/hold-time.

D. INSTANT HELLO MESSAGE FEEDBACK MECHANISM

We have mentioned that a network is considered to be a low-density network when $N_D < \varphi$. In such a network, insufficient numbers of UAVs are available to carry out a mission; that is, few numbers of UAVs are available to cover a comparatively large area. To complete the mission, the UAVs will try to cover the entire area as quickly as possible, so they will move away from each other. As a consequence, this behaviour reduces their possibility of coming across each other. In the worst-case scenario, this gives the UAVs a very short time window in which to discover neighbours. Because of the aim of minimizing the number of hello messages, this situation increases the possibility of missing that short time window, and thus decreasing link detectability. To handle such situations, we propose an immediate hello message feedback mechanism. Whenever a UAV receives a hello message from a new neighbour, it will immediately broadcast a hello message in reply, to confirm its presence. Before sending the hello message, the UAV will reset the hello interval and set the lifetime of the hello message according to the updated interval.

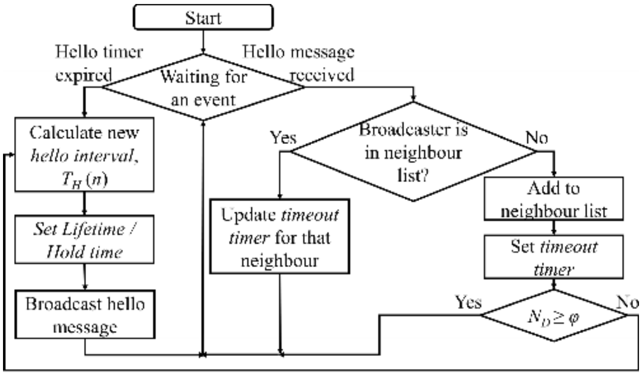


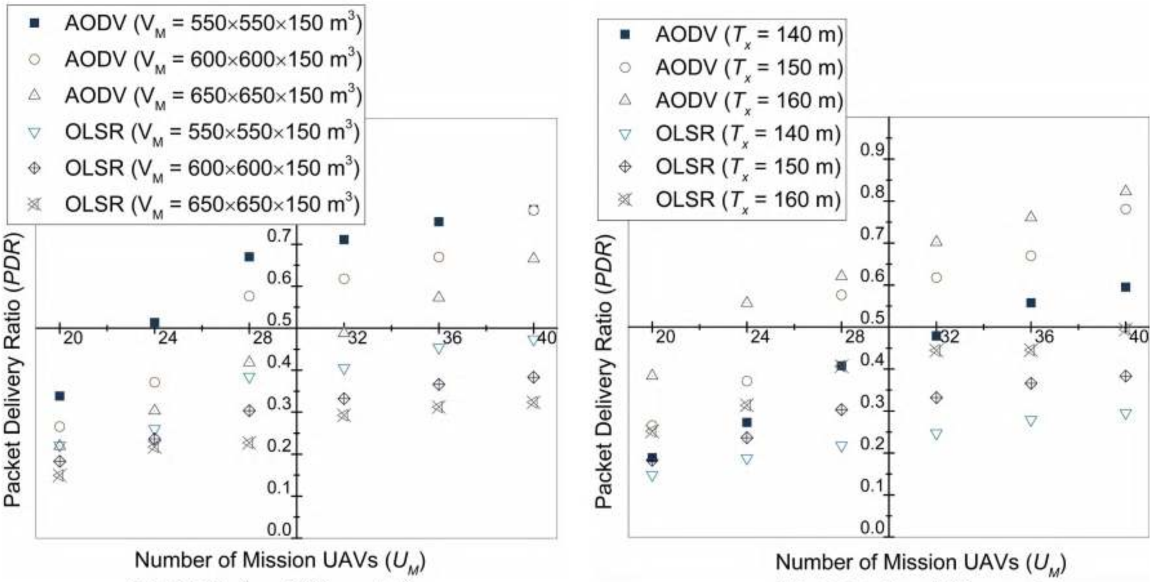
FIGURE 3. Flowchart of the proposed EE-Hello scheme.

The computational complexity of the entire EE-Hello algorithm is $O\left(n^2\right)$, where n is the input size in bits. The flowchart in Fig. 3 summarizes the EE-Hello algorithm.

IV. PERFORMANCE EVALUATION

In this section, we evaluate the performance of the EE-Hello scheme in terms of energy consumption, overhead requirements, network throughput, and network trade-offs. We simulated the scheme using two routing protocols: AODV as a reactive protocol, and OLSR as a proactive protocol. We considered five representative adaptive hello schemes for performance comparison: the default hello scheme [17], [18], Han's adaptive hello scheme [12], Hernandez-Cons's adaptive hello scheme [13], Park's adaptive hello scheme [15], and our proposed EE-Hello scheme. For simulation, we used as a network simulator NS-3 version 3.27 [19]. For the EE-Hello scheme, we used parameter values of $\varphi = 2.5$, $\theta_{EWMA} = 0.85$, $T_{\min}$ = default interval of the related protocol, $(v_{\max}/v_{\min}) \leq 10$ and $\beta = 0.1$.

For the simulations, we considered a mission area of 600 m × 600 m. The UAVs were free to fly through the permitted airspace over the mission area (600 m × 600 m × 150 m). We considered fixed-wing UAVs with minimum and maximum air speed constraints. In each time step (0.5 s), a UAV could change speed with a maximum acceleration of 5 $\mathrm{m/s^2}$ and a maximum deceleration of 7 $\mathrm{m/s^2}$, change in the horizontal direction by a maximum 6.3° and in the vertical direction by a maximum 3.15°. The UAVs were assumed to



(a) (b)

FIGURE 4. Impact of V_M and T_x on packet delivery ratio according to U_M. In the case of (a), T_x = 150 m and (b), V_M = 600 m × 600 m × 150 m. In all cases, speed range was [5–30] m/s. The other simulation parameters were same as in Table 2.

TABLE 1. Simulation considerations.

Parameter	Consideration
Mission area size	600 m × 600 m
Allowed airspace size	600 m × 600 m × 150 m
UAV type	Fixed wing UAV
UAV's intelligence	Avoid collisions by themselves
UAV's speed	[5 – {10, 15, 20, 25, 30, 35, 40, 45, 50}] m/s
Transmission range of a UAV	150 m
Mobility model	Gauss-Markov 3D mobility model
Maximum acceleration	5 m/s^2
Maximum deceleration	7 m/s^2
Maximum change in horizontal angle	6.3°
Maximum change in vertical angle	3.15°
Available information to each UAV	Size of allowed airspace, Number of participating UAVs in a mission, UAVs speed, UAVs transmission range

be intelligent enough to avoid collisions. Following previous research into UAVs [20]–[22], we modelled the movement of the UAVs using a Gauss-Markov 3D mobility model. We assumed that the UAVs move with random speeds in a range $[5 - s]$ m/s, where s can take values from the set $\{10, 15, 20, 25, 30, 35, 40, 45, 50\}$. For example, when the range is $[5-30]$ m/s, it implies that a UAV can randomly choose a speed between 5 and 30 m/s at any time depending on maximum acceleration and deceleration. The take-off and landing conditions were not considered, because we believe that they have a minor impact on the network. We assumed that each UAV has complete knowledge about the allowed airspace, the number of involved UAVs, its speed, and transmission range. Table 1 outlines the considerations for the simulation experiments.

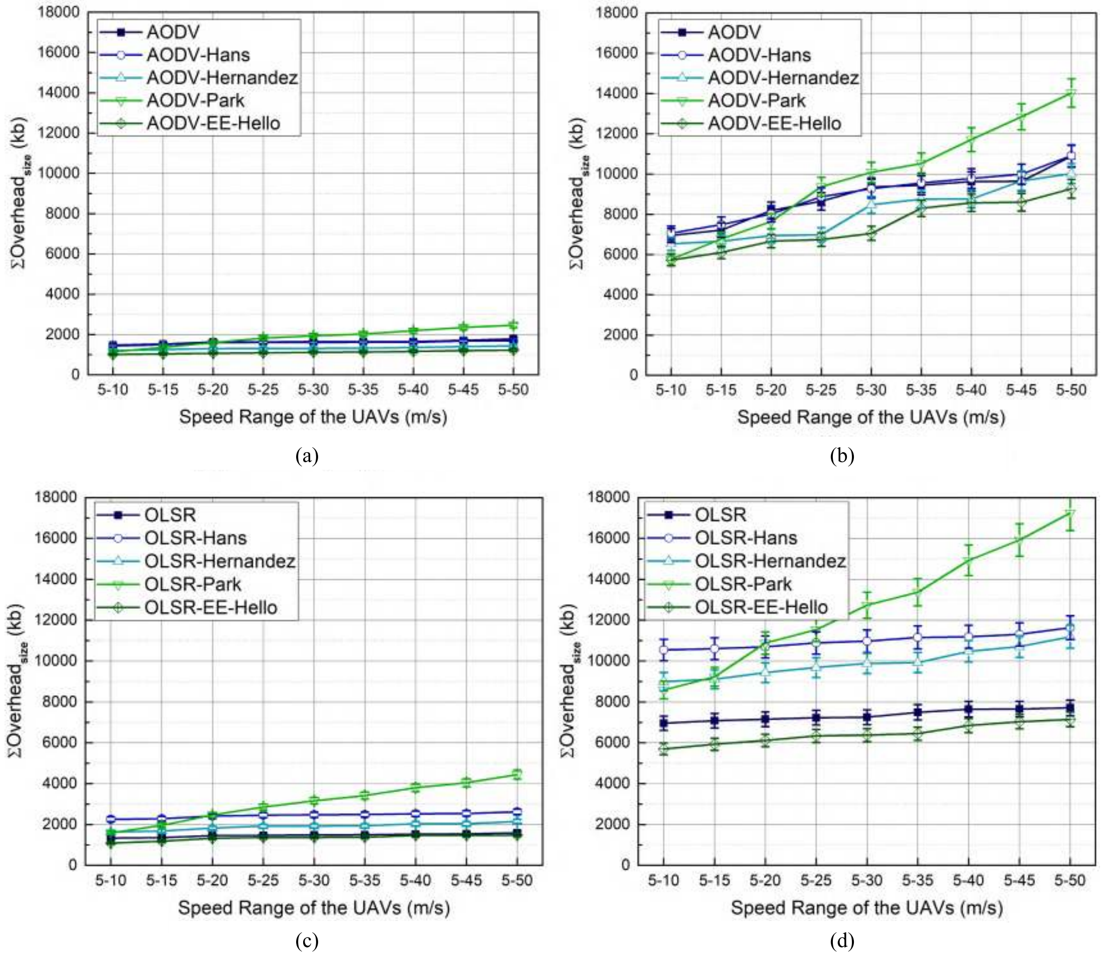
We evaluated the performance of the schemas using two different populations of UAVs: $U_M = 20$ and $U_M = 40$ with the aim of comparing the effects of network density, N_D. To evaluate the network performance, five or ten UAVs sent packets of 512 bytes using a Constant Bit Rate (CBR) of 16 kbps for $U_M = 20$ and $U_M = 40$, respectively. The CBR sources and destinations were unique and randomly chosen amongst all of the UAVs, so that all of the UAVs could become potential traffic sources or destinations. In order to have an equal load on the network, $U_M/2$ UAVs were engaged in packet exchanges in every simulation.

To evaluate the algorithm, we ran the five types of adaptive hello schemes. During the simulations, the random variables set for a scenario were the same for each scheme. For each scenario, we ran 30 independent simulations. We stored the resultant data of each simulation run in separate files. All of the graphs show average values with the 95% confidence interval. Table 2 shows the details of the parameters used in our simulations with NS-3, as used for Fig. 5 to Fig. 8. The NS-3 implementation of the EE-Hello scheme can be accessed from the GitHub repository detailed in [23].

A. PERFORMANCE METRICS

To determine N_D and its effect on network performance, we measured the Packet Delivery Ratio (PDR). We defined PDR as:

$$PDR = \frac{\sum Rec\_Data\_Packets}{\sum Sent\_Data\_Packets}$$



(a) (b)

(c) (d)

FIGURE 5. Comparison of total overhead according to the speed range of the UAVs. (a) AODV, $U_M = 20$. (b) AODV, $U_M = 40$. (c) OLSR, $U_M = 20$. (d) OLSR, $U_M = 40$.

TABLE 2. Simulation parameters.

Parameter	Value
Number of UAVs	20, 40
Mobility model – degree of randomness (alpha)	0.5
Mobility model – update interval	0.5 s
Source/destination pairs	5, 10
Packet size	512 bytes
Source packet rate	4 packets/s
Traffic model	Constant bit rate model
Loss model	Friss propagation loss model
Channel capacity	1 Mbps
Antenna type	Omnidirectional
Routing protocol	AODV, OLSR
PHY/MAC protocol	802.11b
Simulation time	300 s

In order to better understand the network performance, we varied the number of CBR flows (CBR_N) in accordance with U_M, so instead of conventional network throughput, we measured the throughput per CBR flow ($N_{T/CBR}$) by dividing the total network throughput (N_T) by CBR_N according to:

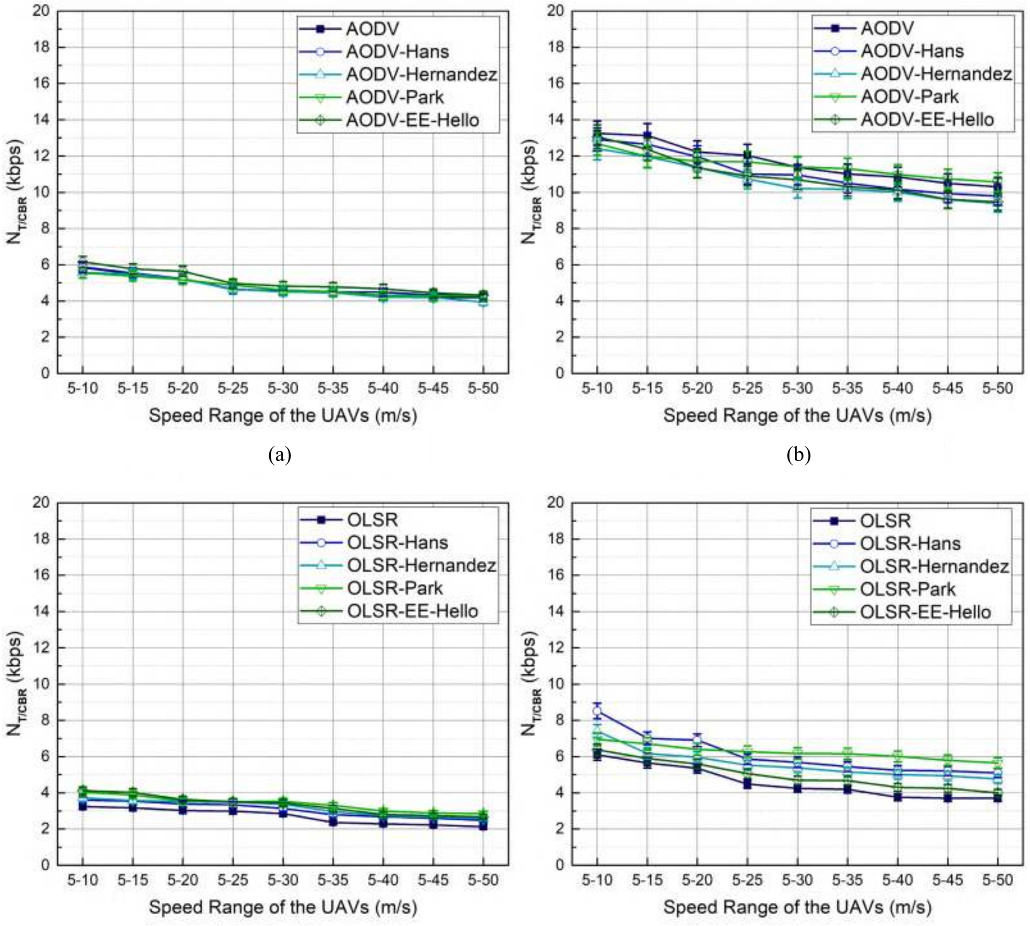
$$N_{T/CBR} = \frac{N_T}{CBR_N}$$

As discussed in Section I, the hello interval always involves a trade-off between link detection capability and overhead, so we defined a parameter, the Overhead Efficiency (OE), with which to investigate the nature of this trade-off. The reception of more data packets generally indicates that the links are well maintained, and the link detectability is sufficient. Therefore, we measured the size of all the data packets received ($\sum Rec\_Data\_Pkt_{size}$) and considered it to be the outcome of the network. We counted the size of all the control packets sent ($\sum Overhead_{size}$) and considered this metric to be the cost of the network. Thus, we defined OE using the following equation:

$$OE = \frac{\sum Rec\_Data\_Pkt_{size}}{\sum Overhead_{size}}$$

A higher OE implies a better network, because it can generate better throughput with a comparatively lower overhead cost.

To compare energy consumption, we measured the total amount of energy consumed by all the UAVs for the transmission and reception of control overheads each second. Following the energy consumption model of Han and Lee [12], we assumed the energy consumption for each byte (B) of



(a) (b) (c) (d)

FIGURE 6. Comparison of throughput per CBR flow according to the speed range of the UAVs. (a) AODV, $U_M = 20$. (b) AODV, $U_M = 40$. (c) OLSR, $U_M = 20$. (d) OLSR, $U_M = 40$.

TABLE 3. Determining φ for AODV.

V_M (m^3)	T_x m	Req. U_M to satisfy $PDR \geq 0.5$	U_{req}	N_D
550×550×150	150	24	10	2.40
600×600×150	150	27	12	2.25
650×650×150	150	33	14	2.36
600×600×150	140	34	15	2.27
600×600×150	160	23	10	2.30

overhead transmission and reception to be 200 and 150 μW, respectively.

B. IMPACT OF NETWORK DENSITY

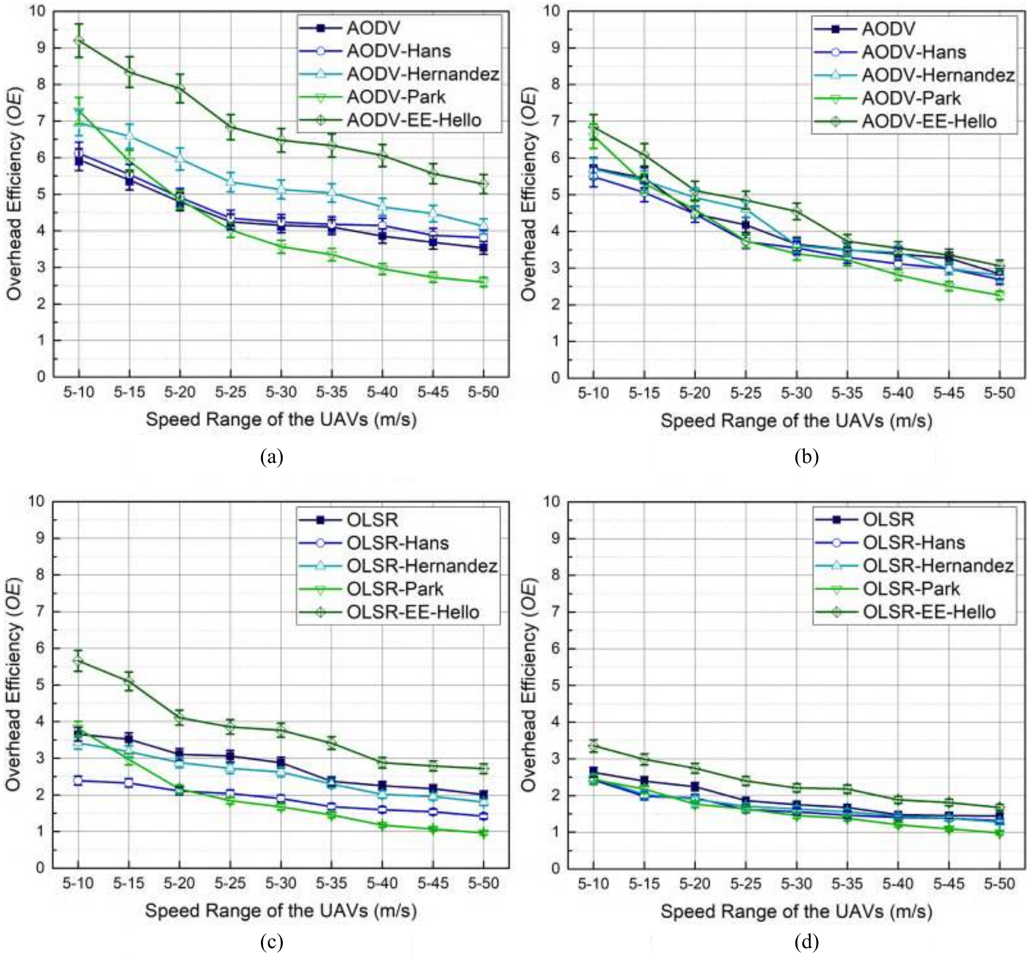
As discussed in Section III-A, N_D helps to determine whether U_M can fulfil any specific network requirement. In this work, we specified the compulsory network requirement as the network having a $PDR \geq 0.5$. Fig. 4 shows the impact of V_M and T_x on PDR for AODV and OLSR, and Table 3 lists the values of N_D required to satisfy $PDR \geq 0.5$ for AODV. According to Table 3, a $PDR \geq 0.5$ is achieved when the value of $N_D \geq 2.5$. Therefore, we can conclude that $\varphi = 2.5$. However, in the case of OLSR, we could not achieve a $PDR \geq 0.5$ in any case (Fig. 4(a) and (b)). As a proactive routing protocol, OLSR tries to maintain a record of the route of prior data transmissions. However, owing to the highly dynamic nature of FANETs, it fails to keep track of the topology changes. As a result, a large number of dropped packets are observed. However, we can still obtain a $PDR \geq 0.5$ by setting a higher value for φ. This result implies that the value of φ can change for different routing protocols, a hypothesis which can easily be tested using simulation experiments.

Given the available mission information and the value of φ, the C&C station can calculate the required number of UAVs for a mission according to network requirements and can save energy by deploying UAVs accordingly.

C. NETWORK OVERHEAD

From Fig. 5, we can observe the decrease in overhead traffic for different schemes. The greatest decrease is achieved by the EE-Hello scheme proposed in this paper.

In Hans's scheme, the hello message transmission is paused until the UAV receives any message. However, the DUG problem is very common in FANETs. In such a



(a) (b)

(c) (d)

FIGURE 7. Comparison of the overhead efficiency according to the speed range of the UAVs. (a) AODV, $U_M = 20$. (b) AODV, $U_M = 40$. (c) OLSR, $U_M = 20$. (d) OLSR, $U_M = 40$.

situation, in Hans's scheme, the UAVs participating in a DUG remain highly active as they try to maintain neighbourhoods. As a result, the scheme can save a small amount of overhead in comparison to AODV. For OLSR, Hans' approach experiences the same consequences, but it produces increased overhead because by default OLSR sends hello messages at two second intervals, whereas Han's scheme uses a shorter interval and generates higher overhead.

Hernandez's scheme, in comparison, shows a relatively promising result for AODV. Most of the time the UAVs experience only a small number of link changes. As a consequence, Hernandez's scheme can extend the hello interval to reduce overhead. However, it produces higher overhead than the EE-Hello scheme, a phenomenon which can be attributed to its failure to handle DUGs. In case of OLSR, Hernandez's scheme fails to consistently maintain the hello interval below two seconds, thus producing higher overhead. When the UAVs' speed range increases, overhead consumption increases significantly, owing to larger numbers of link changes caused by the extra speed. Although during their simulation they reported comparatively better results, we believe the relatively poor performance of our simulation is because we are comparing a relatively low-density network with high-speed UAVs.

Park's scheme produces fairly low overhead for low-speed ranges in both AODV and OLSR. However, when the speed range increases, this scheme results in the greatest overhead of all the schemes. This result is easily explained; the scheme is based on UAV speed and transmission range only. The higher a UAV's speed, the shorter the hello interval. Therefore, high overhead consumption occurs for high-speed ranges.

The EE-Hello scheme proposed in this paper follows a different approach. Firstly, we calculate N_D, which defines the network characteristics. Secondly, we determine an appropriate distance at which to periodically transmit hello messages, based on available mission-related information. We control the distance in such a manner that even the fastest UAV can have a sufficiently wide interval. We bound the lower interval to the default interval of the corresponding protocol. After calculating the distance, we allow the UAVs to send hello messages periodically after traveling that distance. Thirdly, we set the timeout timer to be consistent with the hello interval. As a result, we successfully reduced overhead to the maximum extent. We eradicated

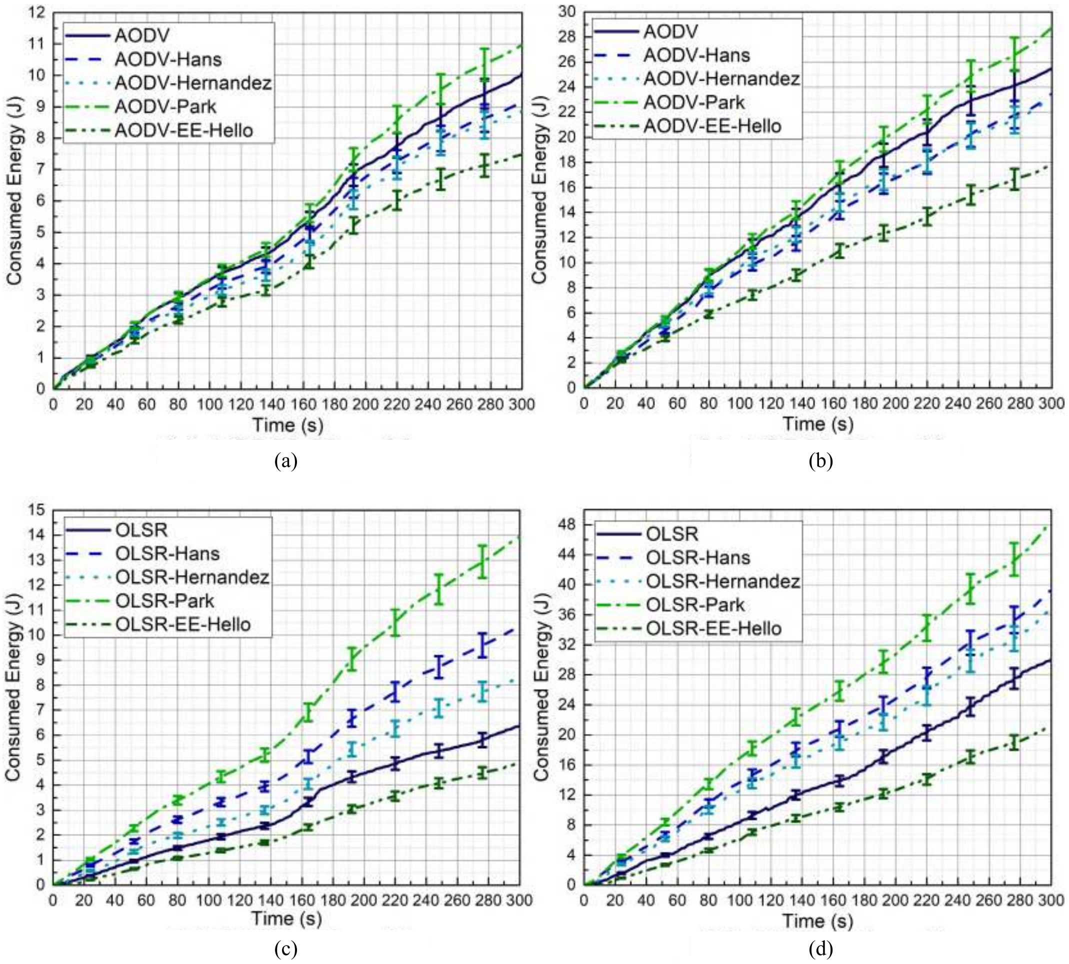


FIGURE 8. **Comparison of energy consumption by simulation time. Here, V_{max} and V_{min} were 5 and 30 m/s, respectively. (a) AODV, $U_M = 20$. (b) AODV, $U_M = 40$. (c) OLSR, $U_M = 20$. (d) OLSR, $U_M = 40$.**

the extra overhead caused by DUGs because the method is independent of link changes or event intervals. We eliminated the high-speed problem observed in Park's scheme because we consider not only the speed but also other related factors.

D. THROUGHPUT PER CBR FLOW

We can observe from Fig. 6 that all of the schemes show similar tendencies with respect to $N_{T/CBR}$ for AODV. In the low-density network, the EE-Hello scheme shows a higher $N_{T/CBR}$. This result can be attributed to the immediate hello message feedback mechanism introduced in the EE-Hello scheme. In the high-density case, Park's scheme shows a slightly higher $N_{T/CBR}$ for high speed ranges. In the high-speed ranges, Park's scheme sends hello messages with the lowest hello intervals. Consequently, this algorithm can identify link changes more quickly than the other schemes and hence attain relatively good $N_{T/CBR}$. In case of OLSR, a similar result is observed for the same reason in the low-density network case. However, in a high-density network, the other schemes reach a higher $N_{T/CBR}$ compared to the EE-Hello and default OLSR. This increase can be attributed to their relatively shorter hello interval compared with the EE-Hello and default OLSR.

E. OVERHEAD EFFICIENCY

We can compare network performance in terms of *OE* using Fig. 7. The EE-Hello scheme outperforms all other schemes for all instances. *OE* is the ratio between the total size of the received data packets and the total overhead. In the preceding sections, we observed that the EE-Hello scheme generates comparatively low overhead with reasonably better $N_{T/CBR}$. Therefore, in the case of *OE*, we see better performance from the EE-Hello scheme in all network scenarios. As discussed in Section I, the hello interval incurs a trade-off between overhead and link disruptions, and the more optimal the trade-off, the better the network performance. Because we can obtain a sensible throughput, link disruptions are usually low. Therefore, it is clear that the EE-Hello scheme provides a better trade-off for hello intervals.

F. ENERGY CONSUMPTION

We calculated the total amount of energy consumed by all the UAVs per second for transmission and reception overhead.

TABLE 4. **Percentage of performance changes for different schemes in comparison with default scheme in terms of energy consumption and throughput. Here, (+) and (−) indicate increase and decrease, respectively.**

	Percentage of change for energy consumption				*Percentage of change for* $N_{T/CBR}$			
	Hans	*Hernandez*	*Park*	*EE-Hello*	*Hans*	*Hernandez*	*Park*	*EE-Hello*
AODV, $U_M = 20$	(−) 7.26%	(−) 11.77%	(+) 8.72%	(−) 25.83%	(−) 0.43%	(−) 1.21%	(+) 1.01%	(+) 5.71%
AODV, $U_M = 40$	(−) 7.96%	(−) 9.31%	(+) 12.85%	(−) 30.23%	(−) 3.72%	(−) 10.32%	(+) 0.21%	(−) 6.12%
OLSR, $U_M = 20$	(+) 62.22%	(+) 30.01%	(+) 118.84%	(−) 23.57%	(+) 10.13%	(+) 18.44%	(+) 23.9%	(+) 20.6%
OLSR, $U_M = 40$	(+) 30.78%	(+) 21.7%	(+) 60.19%	(−) 29.02%	(+) 33.97%	(+) 26.77%	(+) 45.38%	(+) 10.55%

From Fig. 8, we can see that the EE-Hello scheme consumes a significantly smaller amount of energy then the other schemes. The amount of energy consumed is directly proportional to the overhead expended. The cause of the lower overhead consumption of the EE-Hello scheme, explained previously, also applies to the relatively lower energy consumption observed here. Most importantly, during the five minutes simulation time, in the case of AODV, we saved 2.6 J and 7.7 J of energy for low-density and high-density networks, respectively. If we consider the same rate of energy consumption for 30 minutes, we could save 15.6 J and 46.2 J of energy, respectively. This is an excellent start towards energy savings for energy efficient green UAVs. The same trend was also observed for OLSR.

Finally, Table 4 summarizes the percentage of amount of energy that different adaptive hello schemes require in comparison with the default scheme. It also shows the percentage of changes in $N_{T/CBR}$ for different schemes with respect to $N_{T/CBR}$ of the default scheme. In all cases, the EE-Hello scheme consumes significantly less energy than other schemes. Still, the performance is significantly high except for the case of AODV with high-density network. Even in such a case, when we compare with other schemes, the small decrease in $N_{T/CBR}$ becomes insignificant in comparison with the high decrease in energy consumption. This clearly indicates that the EE-Hello scheme can save a substantial amount of energy without degrading network performance.

V. CONCLUSION

In this work, we addressed the problem of high energy consumption in FANETs. To tackle this issue, we proposed EE-Hello, a novel scheme that can considerably reduce energy consumption, and validated the effectiveness of the scheme through extensive simulations. The proposed EE-Hello scheme can be implemented inside existing protocols without changing their architecture or the messages they exchange, or it can be added as an independent module.

In simulation experiments, we considered a practical 3D scenario for FANETs and measured the performance of the EE-Hello scheme with the default protocols AODV and OLSR, and three other schemes proposed by Hans, Hernandez, and Park, using different metrics. EE-Hello could reduce overhead significantly with a minimal difference in network throughput. From these results, we conclude that the EE-Hello scheme achieves an excellent trade-off, and that existing protocols could become more balanced by the addition of the EE-Hello scheme. In terms of energy efficiency, we saved an average of 25% and 23% energy with respect to AODV and OLSR. We also developed a method to determine the required number of UAVs to satisfy mission specific network characteristics, such as packet delivery ratio or throughput expending minimum energy.

In future work, this approach can be extended to various mobile ad-hoc network scenarios where similar mission-related parameters are available. Moreover, network discovery is highly crucial for delay-tolerant network based FANETs, because the UAVs barely come across each other. They also have limited energy sources and require an optimized adaptive hello interval algorithm for energy saving. The EE-Hello scheme could be implemented in such cases to achieve better network performance with low energy consumption.

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IMTIAZ MAHMUD received the B.Sc. degree in telecommunication and electronic engineering from Hajee Mohammad Danesh Science & Technology University, and the M.S. degree in electronics engineering from Kyungpook National University, in 2015. He is currently pursuing the Ph.D. degree in electronics engineering from the Telecommunication and Network Laboratory, Kyungpook National University. His current research interest includes UAVs path planning and network management.

YOU-ZE CHO received the B.S. degree in electronics engineering from Seoul National University, South Korea, in 1982, and the M.S. and Ph.D. degrees in electrical engineering from the Korea Advanced Institute of Science and Technology, in 1985 and 1988, respectively. Since 1989, he has been with Kyungpook National University, South Korea, where he is currently a Professor with the School of Electronics Engineering. From 1992 to 1994, he was with the University of Toronto, Canada, as a Visiting Researcher. From 2002 to 2003, he was with the National Institute of Standards and Technology, USA, as a Guest Researcher. His research interests include mobility management and traffic engineering for wireless and mobile networks, and routing protocols for mobile ad-hoc networks.

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