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# A reliable, delay bounded and less complex communication protocol for multicluster FANETs

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ABSTRACT

Recently, Flying Ad-hoc Networks (FANETs), enabling ad-hoc networking between Unmanned Aerial Vehicles (UAVs) is gaining importance in several military and civilian applications. The sensitivity of the applications requires adaptive; efficient; delay bounded and scalable communication network among UAVs for data transmission. Due to communication protocol complexity; rigidity; cost of commercial-off-the-shelf (COT) components; limited radio bandwidth; high mobility and computational resources; maintaining the desired level of Quality of Service (QoS) becomes a daunting task. For the first time in this research we propose multicluster FANETs for efficient network management; the proposed scheme considerably reduces communication cost and optimizes network performance as well as exploit low power; less complex and low cost IEEE 802.15.4 (MAC) protocol for intercluster and intracluster communication. In this research both beacon enabled mode and beaconless modes have been investigated with Guaranteed Time Slots (GTS) and virtual Time Division Multiple Access (TDMA) respectively. The methodology plays a key role towards reserving bandwidth for latency critical applications; eliminate collisions and medium access delays. Moreover analysis ad-hoc routing protocols including two proactive (OLSR, DSDV) and one reactive (AODV) is also presented. The results shows that the proposed scheme guarantees high packet delivery ratios while maintaining acceptable levels of latency requirements comparable with more complex and dedicatedly designed protocols in literature.

## 1. Introduction

Airborne nodes in FANETs move at a high speed of 30–460 km/hr [1], resulting in frequent topology changes which in turn cause link fluctuations and breakages [2]. FANETs are used for highly sensitive applications such as traffic monitoring, remote sensing, disaster monitoring, search operations, border surveillance and relaying networks [3–6], these applicaions require precise and prompt data delivery. Thus, the most important challenges that need to be addressed by FANET MAC and routing layers are of high reliability and delay bounded data delivery [7,8].

Single cluster networks can only cover small mission areas [9], hence, we propose multicluster FANETs, in which cluster head in one cluster communicates with the cluster head in another cluster for efficient network management, reducing communication cost and optimizing network performance. The communication between cluster heads not only shares redundant information enhancing robustness and reliability but also adds to scalability and coverage area of the network.

This article introduces a novel approach of employing IEEE 802.15.4 MAC layer protocol in both beacon enabled and beaconless modes for UAV-to-UAV communication in multicluster FANET scenarios. Both single cluster and multicluster setups have been investigated. Although IEEE 802.15.4 is considered a low data rate protocol i.e. up to 250 kbps at 2.4 GHz band, we propose the use of 802.15.4 MAC protocol for intercluster and intracluster communication in multicluster FANETs that can be deployed for less bandwidth hungry applications such as monitoring and control, wildfire management, remote sensing and relaying networks. Such applications do not necessarily require a high data rate protocol such as 802.11, which is being used in recent FANET studies [10,11], as the nature of the in-network messages exchanged is primarily of time-sensitive control data, UAV location information and tasks assignment updates [12]. Thus, UAV-to-UAV communication can be realized efficiently by deploying a low data rate protocol such as IEEE 802.15.4 which has not been exploited so far for FANETs. For both single cluster and multicluster scenarios, 802.15.4 can be used within the cluster so as to achieve better results in terms of reduced complexity and bandwidth minimization. For a swarm of small UAVs collecting data from remote ground sensor networks, its short range and low data rate can achieve

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the required connectivity offering a line-of-site (LOS) range of more than 75 m. For applications requiring exchange of heavy traffic, 802.15.4 can offer dedicated and guaranteed cyclic time slots (GTS) as used in our scheme.

The rest of this paper is outlined as follows: Section 2 gives an overview of the related works on FANET communication protocols in the literature, Section 3 describes the proposed methodology modeled, Section 4 discusses the simulation setup and performance metrics, Section 5 reports graphical results and analysis followed by conclusion and future work.

## 2. Related work

Not a lot of work is being done over the higher layers of FANETs. In this section we have summarized the recent work that has been done at MAC and routing layer for UAV systems.

### 2.1. MAC protocols

Till date many studies have investigated UAV-to-Ground communication aspect of FANETs. In [13], the authors have used UAV as a relaying network between ground relaying node and sink to limit the transmission range of the relaying nodes (RN). The MAC protocol used for RN-UAV and UAV-sink is IEEE 802.11 (Wi-Fi). Similarly, in [12] a wireless communication infrastructure has been proposed for short range UAV using single 802.15.4 transceiver. In order to enhance the limited offerings of 802.15.4, a computationally complex adaptation layer is implemented between IPv6 stack and 802.15.4 link-layer. The work in [14] suggests the use of 802.11 MAC protocol for UAV swarm in relaying networks by assigning dedicated tasks of collection, facilitation and delivery to each UAV. In all these network models only one UAV has been used to relay the information raising issues of robustness and system collapse in case of UAV failure.

In [15], an adaptive MAC protocol has been designed by adding directional network allocation vector (DNAV) to the existing 802.11 MAC protocol for intra-UAV communication. The proposed MAC protocol employs four antennas on each UAV increasing complexity and cost of the network design. In [16] Location Oriented Directional MAC (LODMAC) protocol has been proposed for FANETs operating in conjunction with High Altitude Platforms (HAPs). The work addresses the problems that arise due to the use of directional antennas in FANETs. The proposed protocol meets performance gains but with the help of COT hardware equipment.

### 2.2. Routing protocols

Some studies have evaluated existing routing protocols used for MANETs for performance analysis in UAV networks. In [17] a comparison of AODV, OLSR and OSPF-MDR has been performed for airborne tactical networks. Similarly, [18] evaluates mesh routing protocols open 80211s, BATMAN, BATMAN Advanced and OLSR for UAV swarming applications. The simulations are performed for very low speeds of the nodes which suppresses the dynamism and high mobility characteristic of FANETs and fails to generalize large scale realistic FANET environments.

Some studies have modified the existing MANET protocols according to the requirements of UAV networks. In [19,20] OLSR has been modified to Predictive-OLSR (P-OLSR) and Mobility and Load aware OLSR (ML-OLSR) respectively. The additional information required for the modifications is appended in HELLO and Topology Control (TC) messages of OLSR. The results presented lack the discussion on routing overhead which is expected to be high. Communications bandwidth is a meager resource in FANETs and routing protocols with excessive overhead are considered inefficient.

Another proactive protocol, Directional Optimized Link State Routing Protocol (DOLSR) has been designed for FANETs in [21] on the assumption that the network uses directional antennas and reflects dependency on COT component to get desired outputs. In [22], Reactive-Greedy-Reactive (RGR) protocol is proposed which adopts reactive routing based on AODV or geographic routing depending on validity of the links. A modification of this protocol [23] addresses the issue of high overhead by broadcasting route request (RREQ) packets to the neighbors instead of flooding them in the network but computational complexity and average packet delays are increased.

Considering the above mentioned issues of scalability, robustness, protocol complexity, rigidity and cost; in this paper we have presented the concept of multicluster FANETs deploying a low cost and simple IEEE 802.15.4 MAC layer protocol for UAV-to-UAV communication, which, to the best of our knowledge, has not been proposed in the literature. Comparing with the existing studies, our work has three noteworthy novelties. Firstly, 802.15.4 can be used within the cluster so as to achieve bandwidth savings for less bandwidth hungry applications. Secondly, the concept of multicluster FANETs facilitates network scalability and robustness. Thirdly, less complex and existing MAC and routing protocols used in multicluster scenario have achieved the QoS gains similar to modified protocols used in single cluster networks [19–22].

## 3. Proposed methodology

In this section we describe the network model, including multicluster formation, cluster head selection, propagation model, mobility model, and IEEE 802.15.4 protocol as it is used in our model.

At the start a swarm of UAVs is deployed in the mission area which is divided into zones. During the mission, formation of clusters takes place adaptively which are then intact till the network operation completes. The movement of clusters occurs in accordance with Reference Point Group Mobility model which is discussed in Section 3.4.

A multicluster FANET is shown in Fig. 1. In the network there are $N$ clusters depending on the mission area and application requirement. Each cluster has $Y$ UAVs among which one is serving as the head UAV called as cluster head in our scheme. In multicluster FANETs, cluster head of each cluster plays an important role in regulating the coordination and collaboration among the UAVs. We assume that when multicluster FANET starts, each UAV is well aware of its neighbors, location, zone ID, SNR value and speed. The work is based on fixed number of UAVs per cluster.

### 3.1. Multicluster formation

At the start of the operation, each UAV in the formation shares its known information with its neighbors by exchanging “node_info” messages. The message structure is shown in Fig. 2.

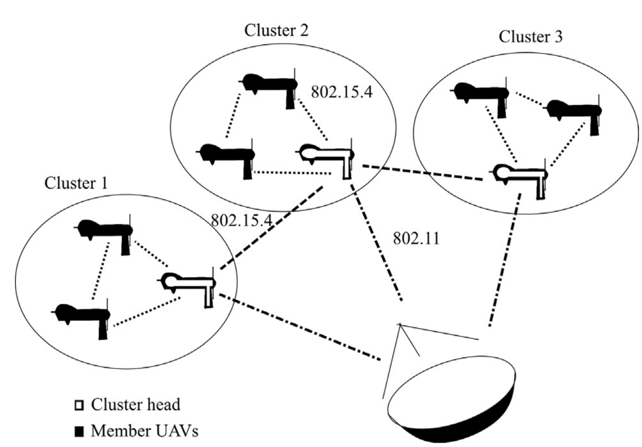


**Fig. 1.** Multicluster FANETs.

| Broadcast ID | Neighbor list | Location coords | SNR | Speed | Zone ID | Assigned task |
|---|---|---|---|---|---|---|

**Fig. 2.** Node_info message structure.

The message fields are described below:

| | |
|---|---|
| Broadcast ID: | 1 if the message is a broadcast message<br>0 if the message is a unicast message |
| Neighbor list: | Contains the pre-learned one hop neighbor IDs |
| Location coords: | Contains the location coordinates obtained via GPS |
| Node SNR: | Contains the node SNR |
| Zone ID: | Contains the pre-assigned zone ID |
| Speed: | Contains average speed of the node |
| Assigned task: | *Nat* (Not any task) at the start of the network<br>1 if selected as cluster head<br>0 if selected as member |

UAVs with similar zone ID group with the help of location coordinates. Once the clusters are formed and cluster heads are selected, each cluster starts following the pre-assigned path according to the group mobility model used in our study. Whenever, during the mission the cluster heads come into radio range of each other, control packets are exchanged between them directing the decision of whether to collaborate with the neighboring UAVs or not.

Each cluster head monitors the wireless link quality during the exchange of information. If the link quality metric *alpha* drops below a certain threshold, the cluster head of that cluster sends a collaboration request to the cluster head of any other cluster within the communication range. *Alpha* is obtained by monitoring Signal to Noise Ratio (SNR) values. Algorithm 1 describes the collaboration phase of multicluster scheme. Hence, collaboration will be done on the basis of the reliability so as to have redundant information of both clusters at the ground station. Similarly, in order to mitigate the problems of latency as well, collaboration between cluster heads can take place. If one cluster head experiences a poor link quality and retransmissions, it may route its information via cluster head of the neighboring cluster.

**Algorithm 1.** Collaboration amongst cluster heads

```
for (i=1 to Y)
    if (alpha < thresh hold for satisfactory link quality)
        if (UAVi is cluster head)
            sense for other network
            forward collaboration request
  else
            notify cluster head of link quality
        end else if
    end if
  end for
```

### 3.2. Cluster head selection

All the UAVs in the cluster maintain a table of link quality. The UAV with the best link quality broadcasts "cluster head declaration" message to all member UAVs of the cluster which reply with "Follow" message. In case of link failure or poor channel condition experienced by the cluster head, the node with the second best link quality becomes the cluster head and broadcasts cluster head declaration message. Algorithm 2 describes the cluster head selection mechanism. Cluster head selection on the basis of link quality, energy and number of neighbors is a well-established approach in Wireless Sensor Networks (WSN) [24]. However, in FANETs there are no energy or battery constraints hence the key factor for cluster head selection is link quality to ensure reliable communication in inter-cluster as well as intra-cluster.

**Algorithm 2.** Cluster head selection algorithm for each cluster in multicluster FANETs

```
for i=1 to Y do
        if (UAVi has SNR of Y nodes)
        Sort SNR against UAV IDs
        end if
        if (UAVi has the highest SNR)
                broadcast "Cluster head declaration" message
        else
                Unicast "follow" message to the UAV with the
  highest SNR
        end if
  end for
```

### 3.3. Propagation model

The propagation model used in our study is freespace propagation model. The reason for selecting this model over shadowing model is that in FANETs there is a clear LoS between the transmitter and receiver UAVs. The synchronization of the nodes is performed using GPS. This leads to valid connection establishment between any two UAVs in the operative circular communication range. Friis equation for freespace propagation model is given as:

$$P(d) = \frac{P_t G_t G_r (\lambda)^2}{4\pi d^2 L} \quad (1)$$

where, $P(d)$ is the received signal power at distance $d$, $P_t$ is the transmission power, $G_t$ and $G_r$ are transmit and receive antenna gain respectively, $\lambda$ is the wavelength, $L$ is the system loss and $d$ is the distance between transmitter and receiver.

### 3.4. Mobility model

Group mobility models can be used to simulate group of UAVs in performing autonomous military operations without centralized control. Based on the previous study [25] by the authors which investigated the performance of different mobility models for FANETs, in this work, Reference Point Group Mobility (RPGM) has been used [26]. Every group or cluster has a reference point upon which the movement, direction, speed and acceleration of all the group members depend. The cluster head is positioned at the reference point during the entire simulation with member nodes following it. Thus, the UAV network within the cluster is in a fully connected state most of the time. The nodes fly in a formation and the cluster remains intact with no new UAVs joining or leaving it.

### 3.5. IEEE 802.15.4 for multicluster FANETs

In this paper we propose the use of IEEE 802.15.4 [27] for carrying reliable and timely intercluster and intracluster communication in FANETs. We have used both the models provided by this MAC standard: beacon enabled mode and non-beacon enabled mode.

#### 3.5.1. Beacon enabled mode

In beacon enabled mode the cluster head periodically sends beacon frames to synchronize member UAVs. The duration between these beacon frames is divided into 16 slots and is termed as Beacon Interval (BI). The metric used to define beacon interval is known as *macBeaconOrder (BO)*. The relationship is expressed in Eq. (2).

$$Beacon\ Interval(BI) = aBaseSuperFrameDuration * 2^{BO} \quad (2)$$

where *aBaseSuperFrameDuration=Number of slots * Slot duration,* for which default values of 16 and 60, respectively, are used.

BI is further divided into two regions: active period defined by *macSuperframeOrder (SO)* and the inactive period during which the

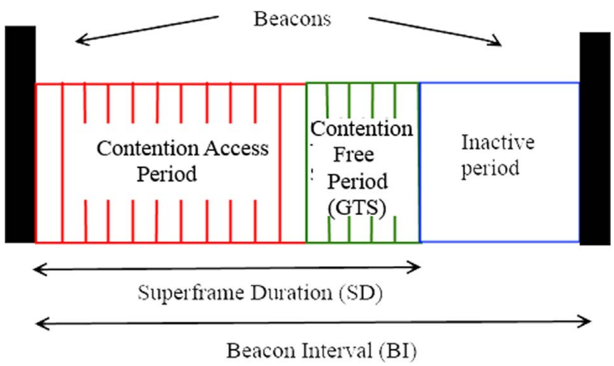


**Fig. 3.** Superframe structure.

node sleeps. The active period is denoted by Superframe Duration (SD) according to Eq. (3).

$$Superframe\ Duration(SD) = aBaseSuperFrameDuration*2^{SO} \tag{3}$$

SD is divided into Contention Access Period (CAP) during which all devices that wish to communicate, compete using slotted CSMA/CA mechanism to win the channel and Contention Free Period (CFP) during which dedicated Guaranteed Time Slots (GTS) are reserved by the devices to utilize the channel alone. The superframe structure of standard IEEE 802.15.4 is shown in Fig. 3.

In our study we have utilized the CFP portion of the superframe since multicluster FANETs can be used in critical and time-sensitive missions. Hence, contention-based transmission has not been considered. The cluster head allocates GTS to the member UAVs using First Come First Serve (FCFS) algorithm. According to the standard, seven UAVs can hold the GTS slots. In our simulations, there are 3 nodes per cluster. So, the default GTS slotting can serve the purpose. As soon as the network starts, the member UAVs consume GTS slots and hold them forever or until the need of explicit deallocation arises which means that the UAV itself requests the cluster head to deallocate the slot. By exploiting GTS in our scheme, we are basically implementing TDMA in the entire active period. As the packets are generated, nodes in their respective reserved allocated time slots start transmitting without competing for the channel. Two critical issues of FANETs are reliability and latency. The use of GTS mechanism satisfies both as the UAVs can transmit time-sensitive data reliably to the cluster head in a collision-free manner avoiding delays due to retransmissions. Also, the GTS slots are utilized to their maximum capacity which means that no bandwidth wastage occurs and the UAVs have data to transmit all the time. The chosen traffic rate is 50 kbps such that one slot is of 19.2 ms and can transmit 120 bytes of data.

FANETs do not encounter energy resource constraints; hence, 100% duty cycle operation is carried in our simulations. The duty cycle is calculated by the ratio of active period (SD) of the superframe to beacon interval (BI) as given in Eq. (4). We have selected $SO=BO=2$ so as to eliminate the inactive period.

$$\text{Duty cycle} = \left(\frac{SD}{BI}\right)*100\% = 2^{(BO-SO)}*100\%(BO = SO = 2) \tag{4}$$

The low value of SO and BO is selected so as to achieve maximum bandwidth savings as higher values of SO increases the slot size.

#### 3.5.2. Non-beacon enabled mode

Since energy efficiency is not the primary issue in FANETs, therefore we have also used non-beacon enabled mode of IEEE 802.15.4. In beaconless mode, there is no transmission of periodic beacons from the cluster head and UAVs use unslotted CSMA/CA for accessing the channel. $SO=BO=15$ has been used to enable this mode. In this mode the UAVs sense the channel and transmit data if found to be idle. If the channel is found to be busy, the algorithm backs off for a random period and sense the channel again. This approach eliminates beaconing overheads. In order to have a fair comparison, we have implemented TDMA approach in beaconless mode also so that the UAVs have periodic transmissions and only one UAV is allowed to transmit in a virtually assigned time slot.

### 3.6. Routing protocols

Following routing protocols have been used for evaluation in this study:

#### 3.6.1. AODV

The Ad-hoc On-demand Distance Vector (AODV) routing protocol is a reactive protocol which determines route to destination only when source initiates it and keeps it as long as the source desires. A Route Request (RREQ) packet is broadcasted by the source node to discover route to the destination. The intermediate nodes not only forward RREQ but also update themselves with the source information as contained in RREQ thus setting up a reverse route entry to the source. Any intermediate node that has route to the destination replies the source with Route Reply (RREP) packet containing the number of hops required to reach the destination. In case of an invalid route, a Route Error Packet (RERR) is generated to inform the source about link failure so that it can re-start the route discovery process. In terms of overhead AODV dominates its proactive counterparts as routes are discovered only on demand. However, it suffers from latency issues since a packet has to wait till the route to the new destination is found [28].

#### 3.6.2. DSDV

The Destination Sequenced Distance Vector (DSDV) is a proactive table-driven protocol. All nodes in the network have routes stored in their tables to all other nodes. Looping is avoided by updating routes periodically and removing stale routes using sequence numbers. The route with the highest sequence number is considered as the most recent route. The updates may contain whole routing table or only the routes that have been changed [29].

#### 3.6.3. OLSR

Optimized Link State Routing (OLSR) protocol maintains a routing table at each network node by gathering topology information through Topology Control (TC) messages. HELLO messages are also used to find one hop and two hop neighbors. An important feature for reducing control messages in OLSR is multi point relaying. Multi Point Relay (MPR) nodes are a subset of nodes responsible for forwarding link state updates. This optimization to pure link state routing protocol proves beneficial in highly dense environments where MPR mechanism is efficiently utilized [30].

### 3.7. Protocol operation

Fig. 4 shows flowchart representation of our proposed multicluster scheme for FANETs.

The steps of our proposed scheme are listed below:

1. All UAVs deployed randomly in the entire coverage area and divided into zones.
2. UAVs with similar zone IDs group together and follow RPGM model for path planning.
3. Every cluster selects its cluster head according to Algorithm 2.
4. In beacon enabled mode all UAVs in the cluster request GTS slot at the start of the network.
5. All UAVs transmit in reserved slots in case of beacon enabled network and accesses channel through unslotted CSMA/CA in beaconless mode.
6. If any other network is sensed by the cluster head, it checks the link

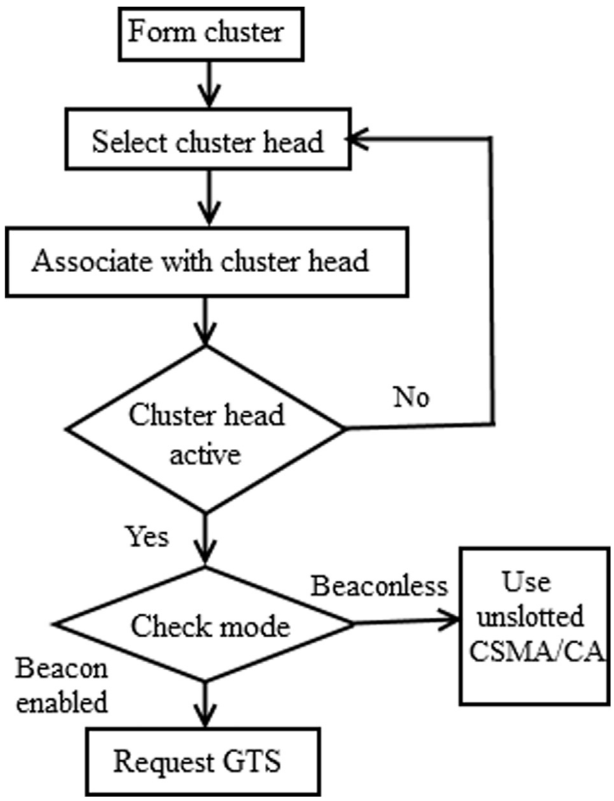


**Fig. 4.** Flow chart representation of proposed multicluster scheme.

quality metric and sends collaboration request to the cluster head of that network.

## 4. Simulation setup and performance metrics

In this section we evaluate the performance of the proposed scheme by employing IEEE 802.15.4 protocol in multicluster FANETs via computer simulations.

The mobility scenarios have been generated using bonnmotion utility which generates node movement patterns according to the mobility models specified by taking certain parameters as input such as maximum minimum speed, number of nodes, speed standard deviations, group change probabilities, pause time and simulation area and duration [31].

The simulations were performed on ns2.35 which is a discrete network simulator. In the physical layer we assume that UAVs operate in 2.4 GHz ISM frequency band with radio bandwidth of 250 Kbps. The network topology at initial time is shown in Fig. 5 in which two clusters of 3 nodes each are deployed in an area of 200 m×200 m. The velocity of the UAVs is varied from 10 m/s to 500 m/s [1] and they move in a multicluster fashion in accordance with RPGM model. The high mobility values have been selected to create more dynamism in the network. Our approach is to evaluate the performance of IEEE 802.15.4 MAC standard in both beacon enabled and beaconless modes as described in Section 3 for UAV-to-UAV communication in combination with existing proactive (DSDV, OLSR) and reactive (AODV) routing protocols. Other details of the simulation parameters are given in Table 1.

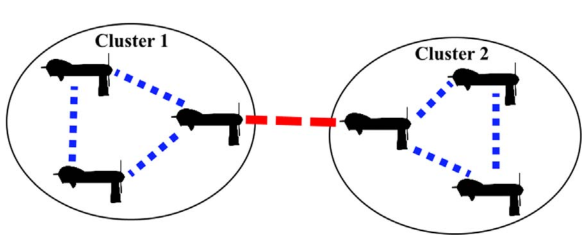


**Fig. 5.** Network topology.

**Table 1**
Simulation parameters.

| Parameter | Value |
|---|---|
| Simulation platform | NS-2.35 |
| Simulation duration | 200 s |
| Simulation area | 200 m×200 m |
| Propagation model | Freespace |
| MAC protocol | 802.15.4, 802.11 |
| Mobility model | Reference Point Group Mobility Model |
| Routing protocols | DSDV, AODV, OLSR |
| Number of clusters | 2 |
| Number of nodes per cluster | 3 |
| Packet size | 100 bytes |
| Traffic type | CBR |
| Data rate | 50 kbps |
| Transmission range | 85 m |

During the simulation duration of 200 s, the cluster heads communicate with each other twice. As per the simulation scenario, the intra cluster communication continues until the link quality metric *alpha* drops below the desired threshold at 80ths. During the interval between (80–100) s the cluster head of first cluster collaborates with the cluster head of the second cluster and data transmission occurs till the threshold limit is retrieved. The same event occurs during the end of the simulation that is (180–200) s when information from the cluster head of the second cluster is transferred to the cluster head of the first cluster.

The evaluation is done on the following performance metrics:

### 4.1. Packet Delivery Ratio (PDR)

It is the ratio of total data packets delivered to the destination node to the data packets generated by the source node as given by Eq. (5). Higher value of PDR corresponds to low packet loss rate and thus reliable communication. It is an important parameter to evaluate the behavior of protocols in our proposed multicluster approach because of the sensitivity of the information exchanged in intercluster and intracluster communication. It also indicates the importance of collaboration between cluster heads as suggested in Algorithm 1.

$$PDR = \frac{\sum_1^N D_{packets}}{\sum_1^N S_{packets}} \tag{5}$$

where,

$D_{packets}$=Total data packet delivered at the destination.
$S_{packets}$= Total data packets generated by the source.
N = Total number of packets.

### 4.2. Average End-to-End (E2E) delay

The average time it takes for the successful transmission of a data packet from source node to destination node as given by Eq. (6). This metric investigates the efficiency of our proposed scheme to meet delay bounds of critical command and control data. This parameter includes all delays:

$$E2Edelay = \sum_1^N (T_t + R_t + B_t + P_{rt}) \tag{6}$$

where,

$T_t$=Transmission time.
$R_t$=Retransmission time.

$B_t$=Buffering time.
$P_{rt}$=Processing time.

### 4.3. Normalized Routing Load (NRL)

NRL is the ratio between routing packets generated to the data packets successfully delivered at the destination as given by Eq. (7). It determines the efficiency of the routing protocol. In order to achieve bandwidth savings, control overhead should be minimum in multi-cluster FANETs.

$$NRL = \frac{\sum_1^N D_{packets}}{\sum_1^N R_{packets}} \tag{7}$$

$R_{packets}$=No. of routing packets transmitted.
$D_{packets}$=No. of data packets received.

## 5. Results and analysis

In this section we describe performance comparison AODV, DSDV and OLSR routing protocols for IEEE 802.15.4 beacon enabled and beaconless modes in multicluster FANETs.

### 5.1. IEEE 802.15.4 beacon enabled mode

Fig. 6 shows that using GTS mechanism in beacon enabled mode of 802.15.4 results in higher PDR values (above 85%) for both reactive and proactive routing protocols. The transmissions are collision free which results in higher average packets received by the destination nodes. Also, as the speed increases, PDR does not drop below 80% because within the cluster UAVs are moving in a swarm and are in the radio range of each other. The effect of high mobility in intra cluster communication nullifies due to RPGM model whereas random movement of clusters causes link breakages in inter cluster communication.

In our scenario of less node density, OLSR gives better and stable performance results for varying node mobility values. The proactive nature of OLSR maintains routing table so that the routes are immediately available when the nodes have data packets to transmit. The highly dynamic scenario of proposed multicluster FANETs cause frequent topology change which is also addressed by OLSR which keeps the routes up-to-date by generating periodic Topology Control (TC) messages. DSDV is also table driven protocol and gives delivery ratios comparable to OLSR in our topology. However, with the increase in mobility, PDR for DSDV drops due to unsuccessful collaboration amongst clusters. AODV exhibits on-demand behavior which means that routes are requested only when needed and there is no maintenance of network topology. In our case the network density is low and there are frequent route breakages so the reactive nature of AODV tends to initiate a route discovery process, making it impossible for immediate route calculations.

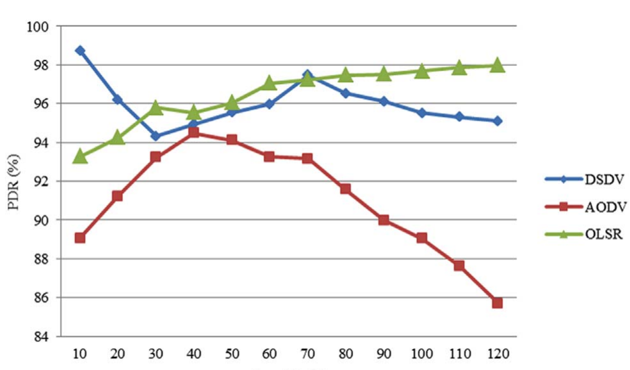


**Fig. 6.** PDR vs. speed for beacon enabled 802.15.4.

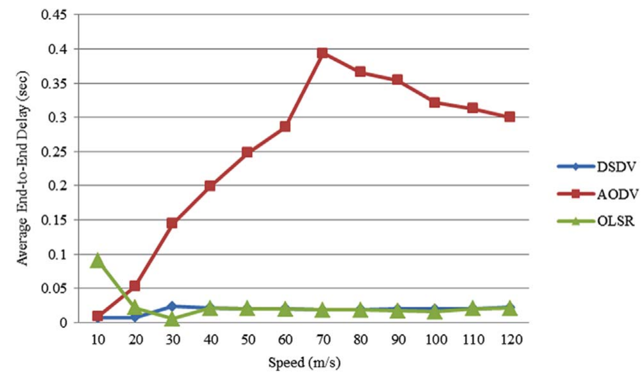


**Fig. 7.** E2E delay vs. speed for beacon enabled 802.15.4.

Fig. 7 shows that the approach of assigning dedicated slot to each UAV in beacon enabled mode in our scheme not only ensures reliable but also well-timed data delivery. The omission of contention based approach suppresses packet collisions and channel access delays. Also, 100% duty cycle ensures and exhibits minimal average end-to-end delay of data packets.

DSDV and OLSR exhibit lowest average end-to-end delay in our network. Being table driven protocols and only 3 nodes per cluster, these protocols do not encounter long route setup time as updated routes are present in the routing tables. AODV on the other hand does not reuse routing information and has to initiate route discovery process again and again when a node wishes to transmit. By the time route reply message reaches the source in response to route request query, the destination has moved away due to high mobility. Hence, in our time-sensitive network topology AODV shows poor delay bounds as compared to proactive protocols: DSDV and OLSR.

Fig. 8 shows Normalized Routing Load (NRL) for AODV, DSDV and OLSR in our network. OLSR exhibits high routing load because of massive generation of Topology Control (TC) and HELLO packets to maintain routing table. OLSR computes Multi-Point Relays (MPRs) through these TC and HELLO messages. MPRs are selected to access two hop neighbors within the network and reduce broadcast overhead but due to less node density and random movement of nodes within the cluster in our network, MPR mechanism is inefficiently used. Although AODV does not generate periodic topology update messages but the dynamic topological behavior of our network causes AODV to broadcast frequent route request messages which results in high routing overhead. DSDV transmits periodic HELLO messages only to update routing tables and shows least routing overhead.

### 5.2. IEEE 802.15.4 beaconless mode

Due to the mobility model used, all UAV nodes within the cluster are in the radio range of each other so hidden node problem does not

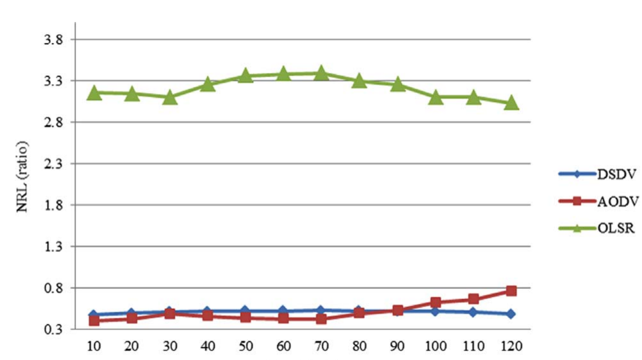


**Fig. 8.** NRL vs. speed for beacon enabled 802.15.4.

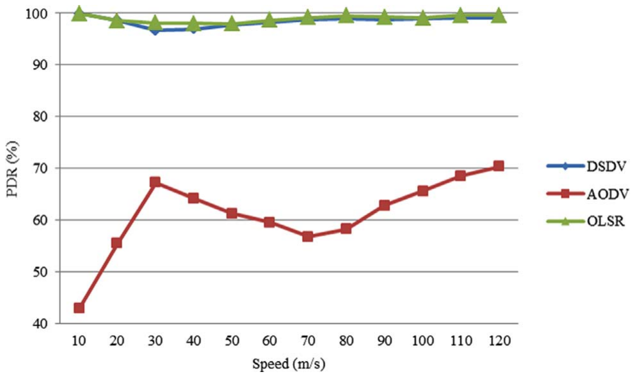


**Fig. 9.** PDR vs. speed for non-beacon enabled 802.15.4.

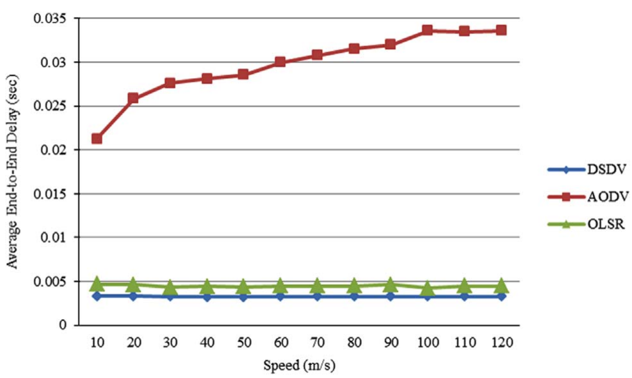


**Fig. 10.** E2E delay vs. speed for non- beacon enabled 802.15.4.

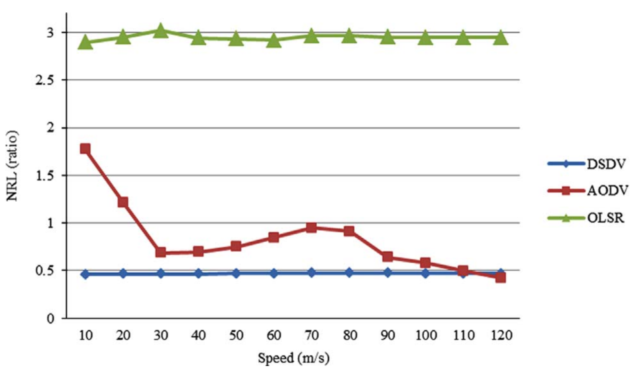


**Fig. 11.** NRL vs. speed for non-beacon enabled 802.15.4.

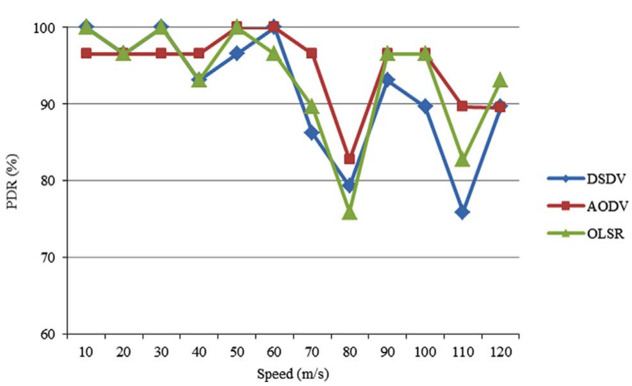


**Fig. 12.** PDR vs. speed for IEEE 802.11.

exist in beaconless mode used in our simulations. To have fair comparison of beacon enabled and non-beacon enabled modes, virtual timeslots have been assigned to each UAV. This type of network scenario is applicable to applications that require reliable data transfer and all UAVs in the cluster monitoring homogeneous data. Hence, Fig. 10 shows that high delivery ratios are obtained in beaconless mode also.

Proactive protocols OLSR and DSDV outperform AODV in terms of PDR because updated routes are present in their routing tables. Although this incurs high overhead and bandwidth usage for both table driven protocols but ensures that only fresh and valid routes are used to deliver the packets to the highly mobile destination.

AODV on the other hand performs worse than beacon enabled mode as shown in Fig. 9. In beaconless mode, since there is no synchronization mechanism, hence, the destination UAV refuses to send route reply message if route request message arrives before the destination has send ACK for the previous transmission. This is due to the unavoidable turn-around time in 802.15.4 during which the node changes from transmit to receive mode.

Fig. 10 shows minimal delay values are obtained in case of beaconless mode in our network. Any UAV that wishes to transmit data to the cluster head does not have to wait to receive beaconing messages from the cluster head before sending data. All transmissions are performed using unslotted CSMA/CA which reduces the beaconing overhead and in turn latency of the network.

DSDV offers lowest average delays as it maintains most updated routes in the table by transmitting periodic HELLO messages. OLSR also shows average delay performance comparable to DSDV due to its table driven nature but the maintenance of MPRs adds to average delays. Due to our network topology of scarce node density, MPRs are not effectively used. AODV shows higher packet delays in beaconless mode than in beacon enabled network because of absence of synchronization mechanism which adds to frequent route discoveries that arise as a result of high mobility induced route breakages.

Fig. 11 shows normalized routing load for beaconless mode. OLSR shows similar behavior to beacon enabled mode due to excessive TC and HELLO messages generation. Although these control messages help to maintain more knowledge of the network than AODV and DSDV but at the expense of increased routing overhead. AODV exhibits more routing overhead in non-beacon mode than in beacon enabled mode because route request messages may suffer failed response from the destination which has not completed previous transmission. Hence, more route request messages are generated which boosts up the routing load offered by the protocol in beaconless mode.

### 5.3. Ieee 802.11

Fig. 12 shows that due to the transmission of Request To Send (RTS) and Clear To Send (CTS) packets in IEEE 802.11, both reactive and proactive protocols exhibit high packet deliveray rates. However, with the increase in speed of the UAVs, more dynamism is incorporated in the network and the collision avoidance mechanism of IEEE 802.11 does not work efficiently as it can be observed that less number of packets reach their destination successfully.

Both reactive and proactive routing protcols exhibit similar behavior with the increase in speed. However, the PDR significanltly decreases at higher speeds for DSDV and OLSR. Due to frequent topology change at high speeds, the number of stale routes increases in the routing tables of these proactive protocols and the rediscovery of the broken link takes time. The dips observed at certain speeds are due to the random scenario generation of bonnmotion utility that has been used, however, the average results show decreasing trend.

Fig. 13 shows that average end-to-end delay of 802.11 based network is comparable to 802.15.4 beaconless mode based network. However, the slightly better results are due to the fact that 802.11 supports higher data rate and requires larger bandwidth as compared to 802.15.4 which is suitable for low data rate applications.

Considering the routing protocols DSDV shows better results but at the cost of low packet delivery rates. It must be noted that the delays are effective delays of data packets that successfully arrive at the

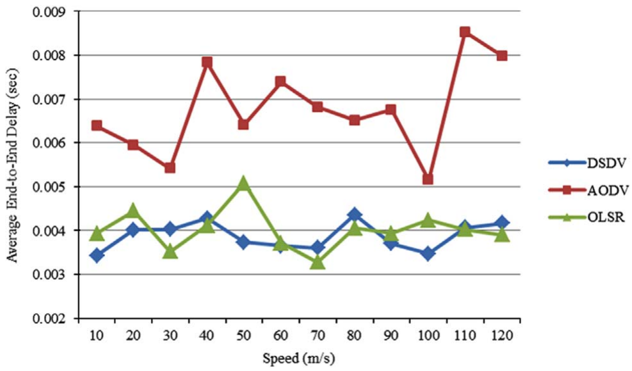


**Fig. 13.** E2E delay vs. speed for IEEE 802.11.

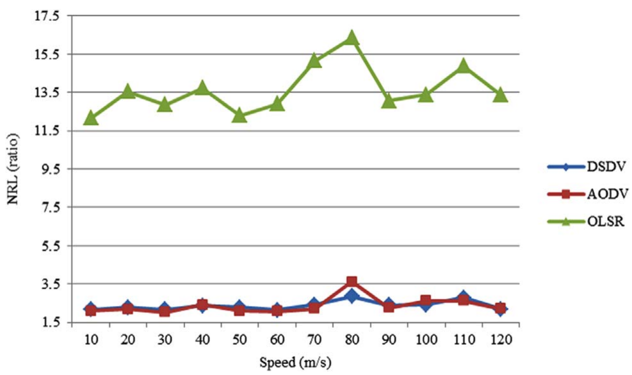


**Fig. 14.** NRL vs. speed for IEEE 802.11.

**Table 2**
Feasibility of multicluster FANETs for various applications.

| Potential Applications | Multicluster FANETs | Performance metric | Suitable routing protocol |
|---|---|---|---|
| Traffic monitoring<br>Agricultural management | **802.15.4 Beacon enabled** | PDR (reliability)<br>E2E delay (latency)<br>NRL (bandwidth efficiency) | OLSR<br>OLSR, DSDV<br>DSDV |
| Relaying networks | **802.15.4 Non-beacon enabled** | PDR (reliability)<br>E2E delay (latency)<br>NRL (bandwidth efficiency) | OLSR<br>OLSR, DSDV<br>DSDV |
| Disaster management<br>Reconnaissance missions | **802.11** | PDR (reliability)<br>E2E delay (latency)<br>NRL (bandwidth efficiency) | OLSR, AODV<br>DSDV<br>DSDV |

destination.

Normalized Routing Load (NRL) for IEEE 802.11 based network follows the same trend as that of IEEE 802.15.4 as seen in Fig. 14. However, the average values for all three routing protocols are higher than IEEE 802.15.4.

The usage of FANETs for several military, civilian and commercial applications is expected to deliver favorable results in terms of reliable and delay bounded data delivery. Table 2 describes the feasibility of our proposed scheme for different applications.

## 6. Conclusion

In this paper the concept of multicluster FANETs employing IEEE 802.15.4 MAC layer protocol for UAV-to-UAV communication is presented which is to the best of author's knowledge the first of its type proposal. The proposed scheme allows collision free, reliable and timely data transmission by employing GTS and virtual TDMA approaches in beacon enabled and beaconless modes of 802.15.4, respectively. In this context the proposed scheme is investigated using ad-hoc routing protocols: OLSR, DSDV and AODV. The results clearly reveal that this novel approach meets the QoS gains comparable to existing studies which are performed for single cluster networks as well as employ more complex routing protocols. 802.15.4 has proved to be a potential candidate showing 80–98% packet delivery rates and comparable network delays to IEEE 802.11 which involves complexity and high bandwidth usage. Hence, IEEE 802.15.4 can be a suitable choice for applications that are not bandwidth exhaustive and require lesser data rate for communication.

This work has been conducted assuming a network of fixed number of UAVs. For the future work, we aim to refine our proposal for the case when new UAVs join the existing clusters during the mission.

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