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A Cross Layered Routing Approach for Civil AANET

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Abstract

The thirst for internet access in moving aircraft grows rapidly by air passengers as human's daily activities rely on digital dependency. Currently, in-flight Wi-Fi is provided by satellite-based and cellular-based systems, where the line-of-sight problem, lack of ground infrastructure, high cost, and long delay negatively affect the internet connectivity. To alleviate these demerits associated with the existing systems, the Aeronautical Ad hoc Network (AANET) has been developed as a complementary system. Internet of Things is being realized over the sky with the aid of AANET, whereby the moving flights can share their live information to the corresponding ground stations while they move across oceanic or remote areas. Establishing IoT in AANET for civil aviation systems has a great challenge in providing reliable and efficient data delivery between flight and ground stations due to their unique characteristics. This paper proposes Cross-layered Multi-Channel Automatic Dependent Surveillance based Load Sharing Routing algorithm to improve the performance of civil AANET. The ever-increasing need for proper utilization of available bandwidth is a key factor to introduce multi-channel operation in this work. Instead of allocating channels before acquiring routes, this work attempts to couple the process of packet routing followed by channel assignment to improve the network routing performance by increasing the ratio of successful packet delivery, reducing the overall delay and traffic overhead through a cross-layered approach. The primary aim of the proposed work is to enhance the load balancing, bandwidth utilization and to reduce the delay associated with the queuing of the AANET systems. The simulation setup is carried out by using QualNet 5.2 simulator and the experimental results have been obtained for packet delivery ratio, end-to-end delay, Traffic overhead in various scenarios. The result shows that the proposed work outperforms the existing routing methods.

Keywords Aeronautical ad-hoc networks · Automatic dependent surveillance-broadcast · Multi-channel · Cross layered routing · Internet of Things

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1 Introduction

Internet of Things (IoT) is a revolutionizing technology in the cyber world where real-world objects can be connected to the internet to be accessed at anytime, anywhere by anyone. In the civil aviation system, IoT is implemented by connecting the sensors, actuators present inside the aircraft to connect and share the internet data access from substations. Civil aviation airlines provide internet access to their passengers since 2004 as they wish to enjoy the internet as on the ground [1–4]. IoT in the civil aviation system gained significant attention among the researchers as it makes way for the air passengers to be connected to the ground from the moving aircraft. Aeronautical ad-hoc Networks (AANET) is a subset of mobile ad hoc network and it is multi-hop in nature and provide the communication link between the base stations and airlines [3]. AANET helps to provide internet access in a multi-hop fashion, which enables the passengers to share the onboard-cached data and get internet access in flight with low latency and high loading capacity. National Air Traffic Controllers Association states that the civil flight in the United States alone as 5000 in the count at any instance of the time. The density of the aircraft may vary day by day concerning the time of the day as shown in Fig. 1. In the civil aviation systems, the airliners fly at a very high speed about 600 to 800 km/h and that leads the network topology to change the base stations and network systems frequently and unpredictably [5–9]. Subsequently, the multi-hop network connection may break frequently from the flying airlines and wireless network links cannot provide the data access at the rated speed, which causes decreased performance of the aeronautical network systems [10]. Development of the efficient routing approach and improving the performance of the AANET in such a situation is the hardest task in the civil aviation system.

New network architecture is introduced as shown in Fig. 2 for extending the communication link among aircraft by forming a multi-hop AANET. This network system can be applied in the aircraft to communicate with the ground when the aircraft is in traverse regions. Cellular systems (Layer III) and satellite systems (Layer I) can be used to provide internet access to AANET. The high cost and longer delay natures of satellite systems

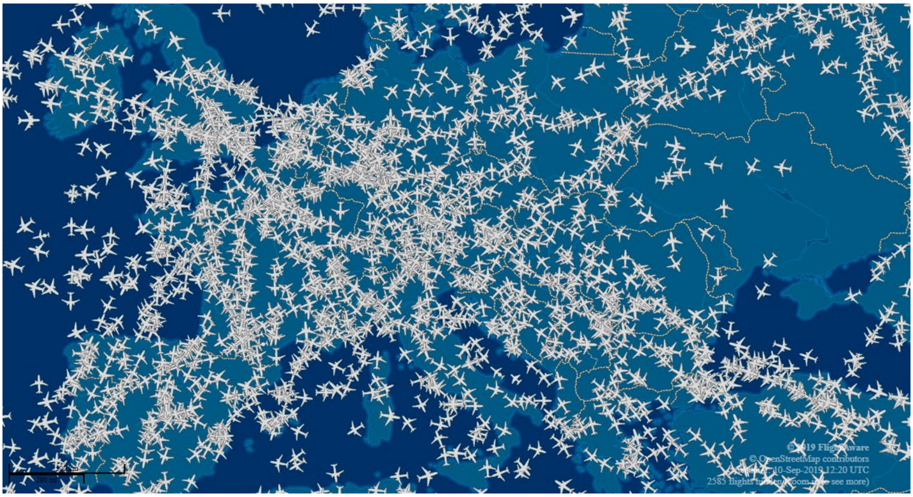


Fig. 1 Air traffic over USA [4]

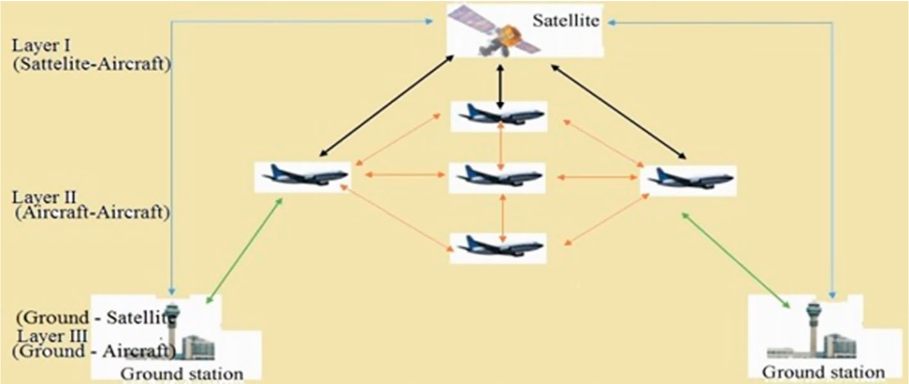


Fig. 2 Typical aeronautical ad hoc network

lead a way to go for cellular systems by some airliners. This work contributes a routing scheme for the air-to-air communication layer by extending the internet access from cellular systems.

2 Related Works

At the initial stage, routing protocols for MANET and their extended works proposed in [11–13] are unsuitable for AANET. In moving airlines [14–27], the shortest network paths may break easily and the communication link has to be rediscovered and reestablished by selecting a reliable set of routes [14–19]. The very high speed and the frequent topology changes made these protocols unsuitable for AANET. The probability of connectivity among aircraft in the low, moderate, and high dense networks has been analyzed. This analysis helps researchers put the effort into framing new routing protocols according to the challenging characteristics of AANET. Due to the frequent topology updates, the routing path is determined based on the stability of the link. Lei et al. [16] have done link availability analysis for establishing a route between source and destination for AANET by taking the load and delay associated with links into account. Vey et al. [17] have proposed an estimation procedure for relative velocity through a Doppler frequency shift method between arbitrary of the two routing nodes. The research [18] concentrates on improving Quality of Service (QoS) by taking metrics namely, path availability period, and residual load capacity of a routing path, and overall delay for a packet transmission into account in highly mobile multi-hop civil AANET. However, the traditional beaconing procedure used for broadcasting the information such as speed, location incurs more delay.

In the AANET implementation, the performance of the transport layer protocols and the implementation cost rely on the reliability of a routing algorithm. Keeping in mind this fact, the works [19–25] have proposed multipath solutions by considering traffic load of the network, network congestion, node selection and stability of the wireless link between pair of nodes. The stability of the communication link between the aircraft and the substations has to be predicted and improved through multiple optimal path selection facilities provided by the network. To assess the real-time status, mobility prediction-based routing protocols have been utilized in [28–33] to get the information related to aircraft location, direction, traditional shortest routing path from network nodes, and the moving speed from the routed nodes with predefined grid topology.

This research work aims to alleviate the unresolved problems of the existing routing methods and makes use of multi-channel for effective channel utilization. The current IEEE 802.11 standards are capable of dividing the available frequency into multiple non-overlapping channels for simultaneous use by neighboring nodes. The multi-channel feature of IEEE 802.11 allows using of the available spectrum completely, while the single-channel utilization wastes more than 90% of that [34]. This work makes use of IEEE 802.11 a standard that is offering 12 non-overlapping channels with a channel spacing of 40 MHz in a 5 GHz frequency band. Research works [34–40] have attained larger throughput by utilizing the multiple orthogonal channels. Some of the previous works [35, 37] allotted a unique channel to each node, but it incurs a high cost and is not practically possible to implement. The majority of channel assignment problems in the mobile environment have been proven to be intractable and NP-complete [38–40]. Thus, cautious assignment of channels to nodes only ensures the spatial reuse inefficient manner and helps to get rid of collisions and contentions. Towards attaining efficiency, this work assigns channels to the aircraft after finding the stable routes, which are accomplished with a cross-layered approach, where the routing takes care of channel assignment. Because of this scheme, the work of the MAC layer is greatly reduced which in turn produces less overhead and higher throughput.

3 Proposed Cross Layered Multi-Channel Assisted A-LSR

This section describes the design and routing procedure of the proposed cross-layered multi-channel A- LSR method. The ultimate aim of cross-layer design is to make use of the network resources efficiently and to attain higher adaptivity [41–43]. In this research work, MAC and Network layer is put under cross-layer design as shown in Fig. 3 to alleviate the communication overhead incurred in the existing routing methods, which is due to the routing and channel assignment are carried out separately. In this work, the decision on channel assignment is made only when the nodes have optimal next hop as discussed (Sect. 3.2.). In this manner, the MAC and Network layer are coupled with the use of cross-layer design.

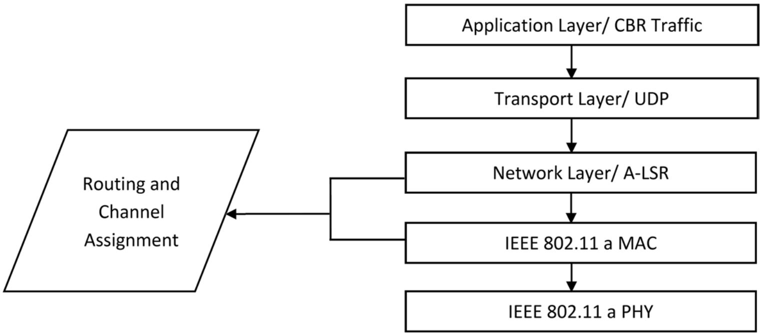


Fig. 3 Cross-layer design

The proposed work has been described in four subsections as follows for developing a civil aviation network protocol. The first section explains the basic operation of ADS-B involved in the neighbor discovery phase. The second section describes the channel assignment procedure. Finally, third section deals Neighbor Discovery and Next Hop Section and finally, the last section illustrates the complete procedure of the ADS-B based load sharing procedure for civil aviation networks.

3.1 ADS-B

Automatic dependent surveillance-broadcast (ADS-B) is a complementary surveillance technology of radar by which the speed, velocity, and position of an aircraft can be determined with the use of GPS with the help of satellite networks and transmissions to the ground station and nearby ADS-B equipped aircraft periodically, enabling it to be tracked in real-time. Recently, Federal Aviation Administration (FAA) has been stated a policy for aircraft, in which FAA strongly commands that to fly over the authorized airspace, the aircraft are mandatory to be equipped with ADS-B In and Out. The CDTI (Cockpit Display of Traffic Information) portion of aircraft displays ADS-B messages to offer situational awareness and maintain self-separation standards. The merits of ADS-B include the capability to cover the remote non-radar areas which enhance aircraft visibility and avoid air-air collisions. Figure 4 shows the working of ADS-B/In and ADS-B/Out modules. Three different categories of ADS-B are available, namely 1090 MHz Mode S Extended Squitter (1090 ES), Universal Access Transceivers (UAT), and VHF Data Link Mode 4 (VDL Mode 4). Civil aircraft makes use of 1090 ES ADS-B systems while general aviation uses UAT.

3.2 Channel Assignment Approach for Supporting Multi-channel

This work considers that there are ’n’ transceivers corresponding ’n’ number of channels and the transceivers can switch among channels dynamically when needed. The dedicated control channel problem is completely neglected here by employing the parallel rendezvous method for channel assignment, where the sender on the available free channel initiates the connection establishment. The pair of nodes involved in transmission first start with negotiating the channel information through the handshaking process, secondly with connection establishment employing RTS and CTS packets. Each node in the network maintains two

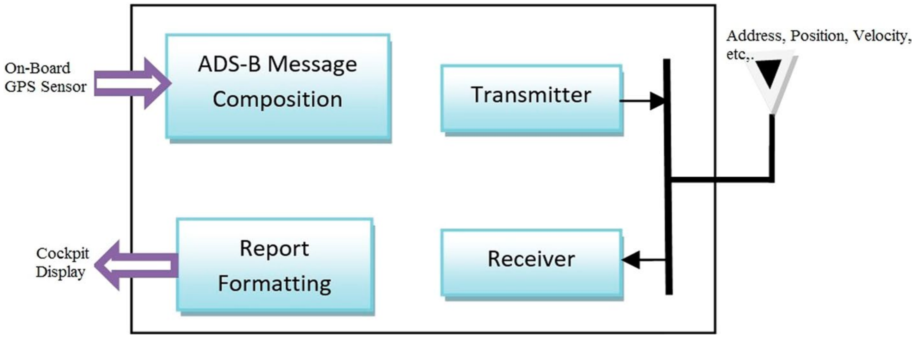
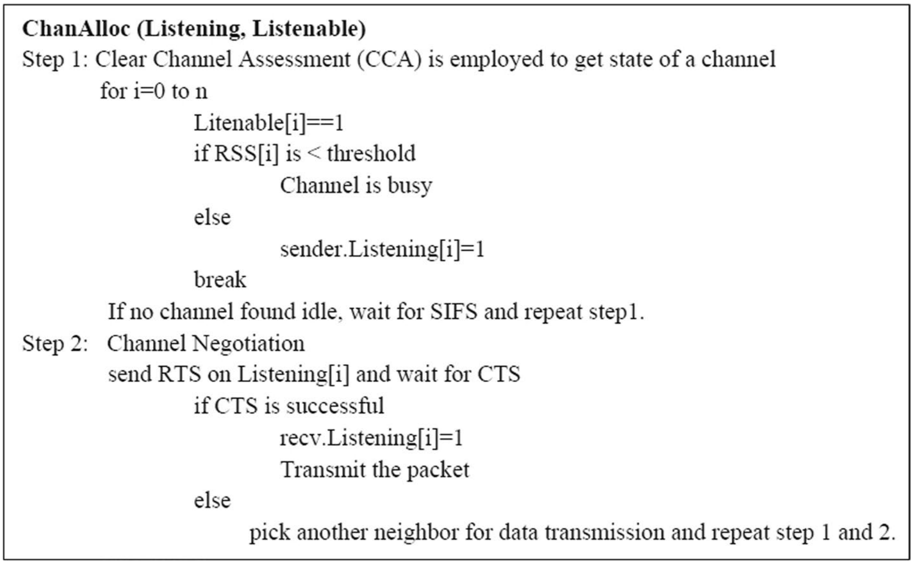


Fig. 4 The working of ADS-B/in and ADS-B/out modules

Table 1 Listening matrix

Participating Nodes	CH1	CH2	CH3	CH4	CH N
Node_1	1	0	0	0	0
Node_2	0	0	0	1	0
Node_3	0	1	0	0	0
Node_m	0	0	1	0	1



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ChanAlloc (Listening, Listenable)
Step 1: Clear Channel Assessment (CCA) is employed to get state of a channel
        for i=0 to n
                Litenable[i]==1
                if RSS[i] is < threshold
                        Channel is busy
                else
                        sender.Listening[i]=1
                break
        If no channel found idle, wait for SIFS and repeat step1.
Step 2: Channel Negotiation
        send RTS on Listening[i] and wait for CTS
                if CTS is successful
                        recv.Listening[i]=1
                        Transmit the packet
                else
                        pick another neighbor for data transmission and repeat step 1 and 2.
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Fig. 5 Psuedo code of proposed channel assignment approach

modes namely, Listenable and Listening. Listenable mode indicates whether a node has the right to access a particular channel or not. Initially, all the channels will be in listenable mode for all nodes. The Listening mode is used to indicate which channel a specific node is currently using. Table. 1 shows the listening modes used in the channel assignment approach. The pseudo code of the channel assignment approach is shown in Fig. 5. This work is carried out by using multi-channel for the first time in AANET to exploit advancements of IEEE 802.11 standards.

3.3 A-LSR

The cross-layer multi-channel A-LSR method-based civil aviation system is described in detail under this section. This work makes use of the advantages of the ADS-B system for gathering positions, velocity, and direction information about the surrounding moving aircraft, keeping the assumption that each civil aircraft is inbuilt with 1090 ES ADS-B in and out. The complexities associated with the existing routing methods, where the nodes have to send their positional and mobility information through beaconing messages frequently, are alleviated by using this evolving ADS-B technology. The position and velocity information received by the ADS-B out the unit of an aircraft is displayed in the CDTI part of the aircraft, by which an initial neighbor list can be formed (Sect. 3.3.1). Based on the calculation of distance between the pair of aircrafts involved in communication, the relative velocity of the nodes, and queuing delay of the nodes, the next hop is found out (Sect. 3.3.2) and consequently, a channel is assigned for the active nodes. The packet is forwarded to the destination through the channel assigned without any conflict (Sect. 3.3.3).

3.3.1 Neighbor Discovery

In general, the neighbor discovery phase is associated with all geographical routing protocols, to come up with the best next hop for packet forwarding to the intended destination. For this purpose, the neighbor table is maintained by each node to keep the information about the neighbors received by Hello beacon routing messages within a specified interval. With a lesser beacon interval, greater accuracy is achieved in updating the neighbor table. The work of beacon messages is replaced in this work by ADS-B messages sent by nearby aircraft, which are updated in the neighbor table every one second, resulting in more accuracy. Hence, the overhead due to beacon messages in existing geographic routing protocols is completely neglected in this work, ensuring the greater throughput with lesser overhead. The ADS-B system and civil AANET is working under different physical layer specification to avoid the interference between AANET packet forwarding and ADS-B message transfer.

3.3.2 Next Hop Selection

The CDTI part of civil aircraft displays the positions and velocity information of the nearby moving aircraft. The shortest distance between two nodes is calculated using the Euclidean distance equation as given in (2). The relative velocity of two nodes ’m’ and ‘n’ moving in the same direction is calculated using Eq. (3)

$$ED_{m,n} = \sqrt{(x_n(t) - x_m(t))^2 + (y_n(t) - y_m(t))^2 + (z_n(t) - z_m(t))^2} \tag{1}$$

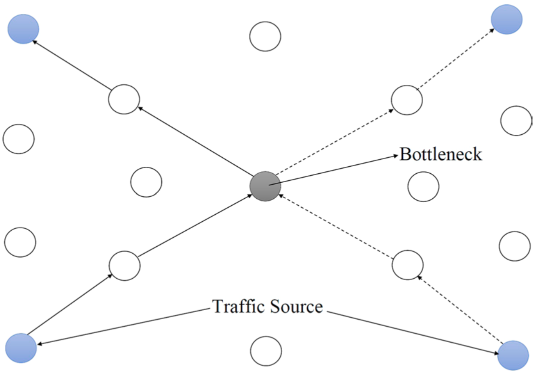
$$RV_{m,n} = \upsilon_m(t) - \upsilon_n(t) \tag{2}$$

Due to the negative effect of Doppler’s shift of the aircraft moving in the opposite direction, aircrafts moving in same direction alone is considered in this work. The coordinates and velocities of nodes m, n at time instant *’t’* have been denoted by *(xm(t),ym(t),zm(t)), (xn(t),yn(t),zn(t))* and ʋ*m(t),*ʋ *n(t).* When a packet arrives at a intermediate node ‘*m’* at an instant *’t’* to be routed for destination *’D’*, the neighbor which is very nearer to the destination is usually selected as the next hop in existing routing protocols. This work deals with the fast-moving nature of civil aircraft efficiently by taking the distance between source node ’*m’* and next-hop ’*n’* towards destination node *’D’* into account, which is derived as follows,

$$\Delta d_{m,n}(t, D) = ED_m(t, D) - ED_n(t, D) \tag{3}$$

When a node is a common neighbor to more than one node, a bottleneck situation may arise as illustrated in Fig. 6. In such a situation, the node may be unable to forward the packets as the node is overwhelmed with too many packets in the queue, which leads to packet dropping and network congestion. Ruben et.al. [26] proposed alternative infrastructures to cope with the delay in AANET by methodological evaluation. To avoid this situation, the load is

Fig. 6 Bottleneck situation



mitigated to nearby suitable neighbors by taking the queuing delay in terms of average queue length and expected waiting time into account by analyzing the queuing system of aircraft. To ensure communication quality in high-speed networks, a higher cost can be tolerated in queuing systems. Hence, this work is implemented with multiple identical servers as shown in Fig. 7. According to Kendall notation, the queuing system of aircraft is illustrated as M/M/a/a where M—Distribution of inter-arrival times of packets, M—Distribution of service times of packets, 'a'—No of servers, and 'a'—queuing capacity.

The aircraft system with multiple parallel servers has the following characteristics:

1. The arrival and service rate μ follow the Poisson distribution.
2. The first packet in the queue is served by any of the first freed servers if all *'a'* servers are busy
3. The utilization factor is $\rho = \lambda/a\mu$.

The service rates of the multi-server queue are described as follows,

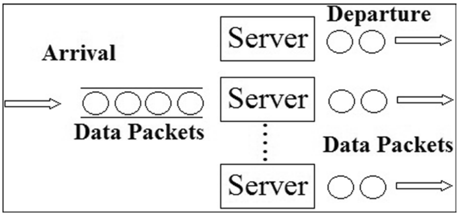
$$\mu_a = \begin{cases} n\mu, n < a, \forall n = 1, 2, ..., a \\ a\mu, n > a, \forall n = n, n+1, .. \end{cases} \tag{4}$$

The probability of having 'n' number of packets in an aircraft is derived as,

$$P_n = \left(\frac{\lambda}{\mu_a}\right)^n P_0 \tag{5}$$

From the above steady-state probability of the aircraft queuing system, the queue length is calculated as follows,

Fig. 7 Multiple identical servers



$$Q_n = \sum_{n=a}^{\infty} (n - a)P_n \tag{6}$$

where (n − a) denotes the number of packets in the queue. After finding the queue length (Qn), the waiting time (Wq) of packets in the queue is calculated as per little's law as given below,

$$W_q = \frac{Q_n}{\lambda} \tag{7}$$

The next-hop among the list of nodes generated by the ADS-B module is selected based on the Swift Reachable Time (SRT) metric as shown in (8). The node with a minimum value is chosen as the next hop for packet transmission.

$$SRT_n = \left(\frac{\Delta d_{m,n}(t, D)}{RV_{m,n}} + W_q \right), SRT_k > 0, \quad s.t \Delta d_{m,n}(t, D) \geq R \tag{8}$$

A-LSR forwards the packet to the next hop, which has the minimum SRT value, thus the load is shared among the next suitable neighbors and the packet delivery ratio is improved with lesser overhead here.

3.3.3 Packet Forwarding

When a source node has a packet for the destination node, it makes use of the neighbor list (Sect. 3.3.1) to choose the next hop (Sect. 3.3.2.) and get confirmation about the channel to be used as discussed in (Sect. 3.2.). If the source node receives a negative reply from the next hop, it again picks up a random channel from the available channel list and starts forwarding the packet again. The flow diagram of the packet forwarding topology is shown in Fig. 8.

4 Simulation Setup

The simulation is carried out by using QualNet simulator 5.2, which is widely used for research purposes in wireless heterogeneous networks. The simulation parameters taken into account are shown in Table 2. The performance of routing protocols is evaluated under various scenarios such as the number of nodes, packet size, and packet inter-arrival time. The results are compared with the existing location-aided routing protocols such as GPSR and GRAA.

4.1 Simulation Results and Analysis

The results are obtained from the simulation and derived the performance metrics namely Packet Delivery Ratio (PDR), Traffic Overhead, and End-to-End Delay, and the results are compared with the existing routing protocols such as GPSR and GRAA.

i. **Traffic overhead**

This metric account for the control packets involved in the neighbor discovery by the routing protocol, by which the data packets goes from the source to the destination

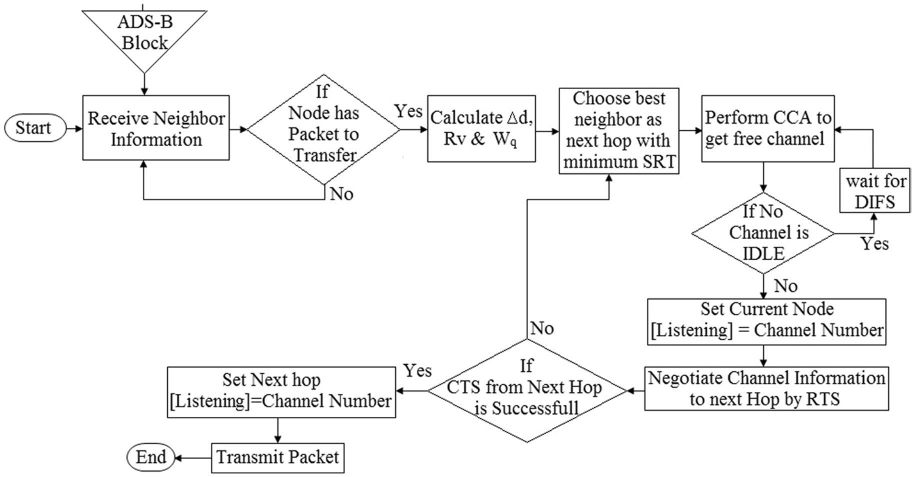


Fig. 8 Flow diagram of packet forwarding topology

Table 2 Simulation parameters

Parameters	Observations
Simulation area	1000 × 30 km
PHY layer	IEEE 802.11 a
CBR packet size	512 KB
CBR packet interval	2 ms
CBR sending rate	50 kbps
SNR threshold	10 dB
Transmit power	60 dBm
No. of nodes (aircraft)	100
Antenna used	Omni directional
Path loss model	Free space
Air-to-air coverage	200 km
Average speed	330 m/s
Simulation time	45 min
Aircraft altitude	26,000 ft

node. In this work, control packets are used only for channel negotiation by the sender node to the destination.

ii. **Packet delivery ratio**

This metric measures the successful ratio of the number of packets received by the destination to the number of packets sent by the source at the application layer. The quality of a route is determined by the metric in a very high dynamic environment.

iii. **End-to-end delay**

This metric account for the complete latency-associated in the processing, transmission, propagation delay, and queuing delay. In high-speed networks, transmission delay is negligible since the higher velocity of the nodes.

4.1.1 Packet Delivery Ratio

Figure 9 shows the performance of A-LSR in terms of packet delivery ratio in various circumstances. By utilizing the multi-server queue and cross-layered approach, the PDR of the A-LSR shows good performance in a moderate density network. As the network size increases beyond 60, the PDR of the proposed scheme starts to degrade slowly because the ADS-B messages increase with an increasing number of aircraft. The PDR of GRAA and GPSR, in contrast, starts to degrade immediately due to the overhead caused by beaconing messages. When the network density increases, control packets are also increased which consumes more network bandwidth, fills the queues shortly and the entire node gets saturated. When the numbers of channels used are increased, the PDR ratio is also increased due to the reason of availability of free channels. The network produces a good result with smaller packet sizes at moderate packet inter-arrival times.

4.1.2 Traffic Overhead

Figure 10 shows the performance of A-LSR in terms of traffic overhead. As the proposed schemes make use of the ADS-B system to get location and mobility information, the overhead of hello beaconing messages for neighbor discovery is completely neglected. The neighbor discovery in GPSR and GRAA is done with the hello beaconing messages, which

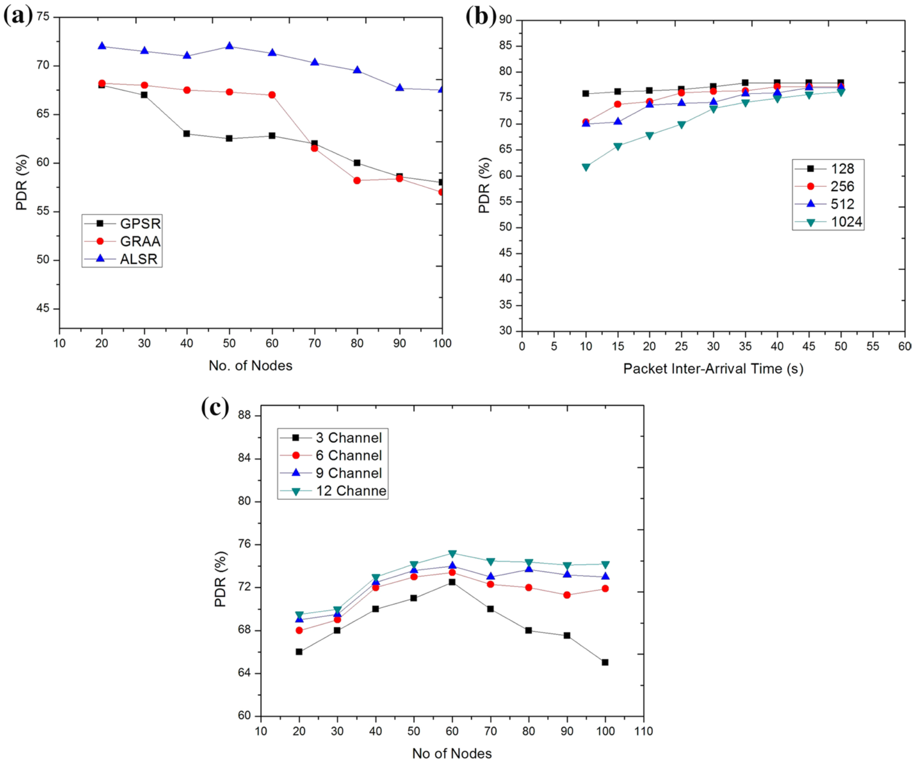


Fig. 9 Packet delivery ratio

lead to higher overhead. The proposed scheme shows a gradual increase in overhead in contrast to existing methods. The GPSR and GRAA show a sudden increase in overhead as the number of nodes increases. By increasing the channel count, the congestion is reduced as shown in the graph. With smaller packet size and smaller inter-arrival time of packets, the networks produce better performances.

4.1.3 End-to-End Delay

The performance of AANET in terms of end-to-end delay for node density, number of channels and packet sizes are shown in Fig. 11. The A-LSR reduces the delay when the network size increases due to the reason that the queued packets have more possibilities to choose the next hop when the numbers of neighbors increase. In contrast, GPSR and GRAA increase the delay with increasing node density because of the overhead caused by too many beaconing messages. By employing more channels, the delay is drastically reduced with smaller packet sizes as shown in the graph.

Table 3 mentioned above illustrates the experimental background of various routing protocols for AANET. The proposed A-LSR technique makes use of cross-layer design, multi-channel support of IEEE 802.11 and ADS-B for neighbor discovery, to achieve higher PDR, lesser End-to-End delay, and traffic overhead. The LEBR are unable to manage the large-sized networks and due to the low transmit power, the signals do not travel

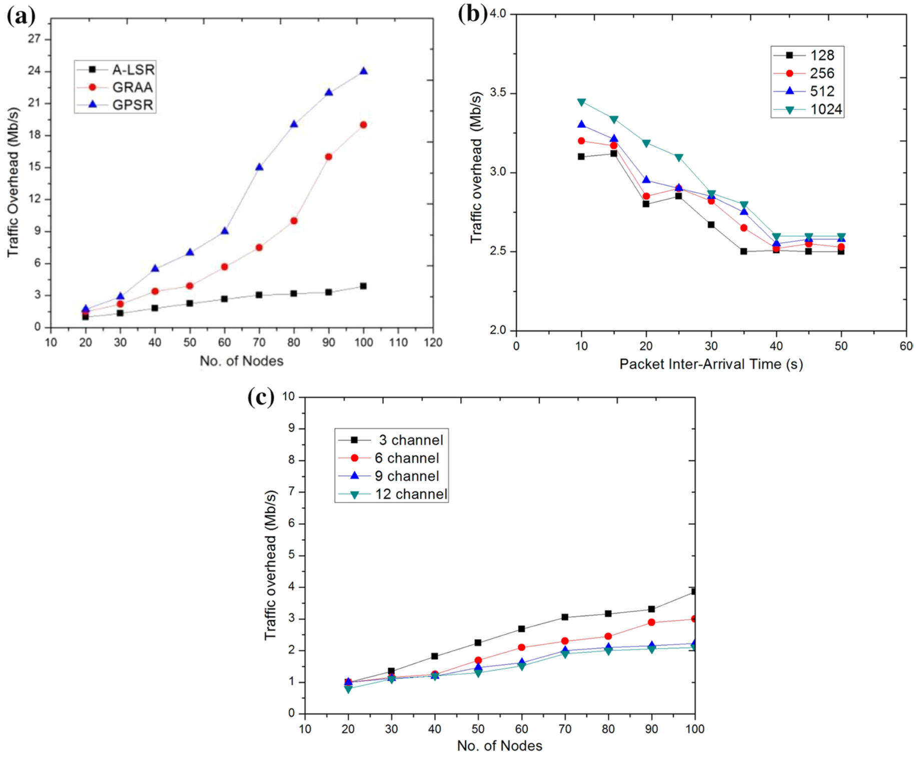


Fig. 10 Traffic overhead

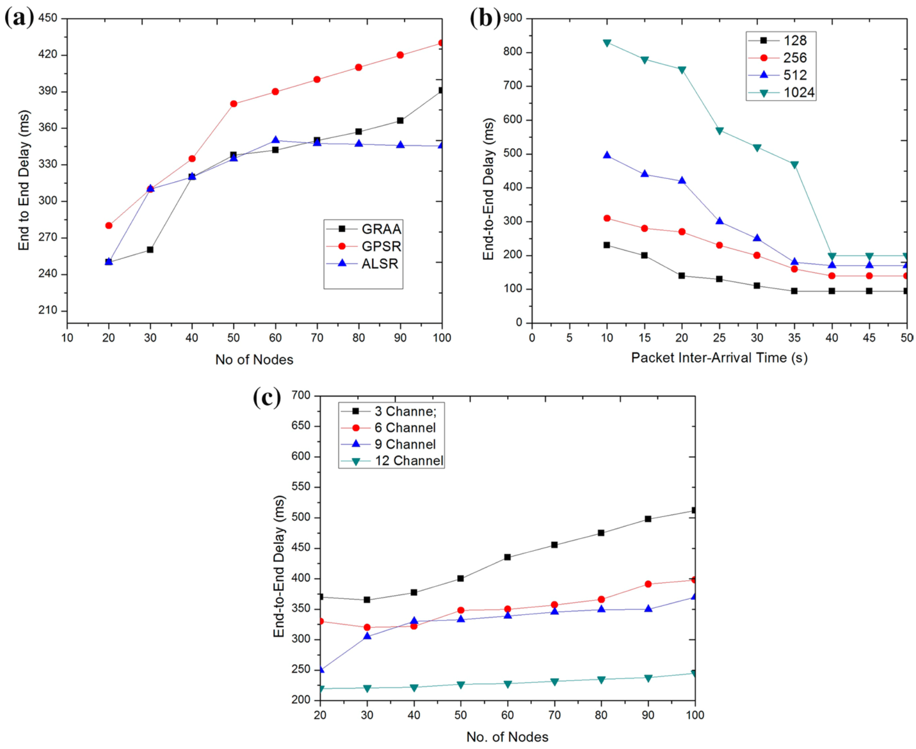


Fig. 11 End-to-end delay

long distances. The LAPR considers only the link metric without considering the density of the networks, speed, and node metrics. The velocity impact is not analyzed by MQPSR despite covering larger regions. Moreover, the beaconing methods for collecting neighbor's details are drawbacks available in the existing works, which is alleviated by employing ADS-B technology.

Table 3 Comparison of AANET for civil aviation

Parameters	This paper	Ref. [13]	Ref. [11]	Ref. [14]
Technique	Proposed A-LSR	MQSPR	LEBR	LPAR
Simulation area	500 × 500 km	2000 × 2000 km	10 × 10 km	500 × 500 km
Multi-channel support	Yes	No	No	No
Air-to-air transmission	100 km	600 km	2 km	75 km
Channel bandwidth	54 Mbps	–	2 Mbps	–
Application type	CBR	CBR	CBR	CBR
Packet size	512 Bytes	50 KB	512 Bytes	–
Average speed (m/s)	330 m/s	–	300 m/s	400 m/s
Path loss model	Free space	Free pace	Two ray	–
Transmit power	50 dbm	–	30 dbm	–
GPS assistance	ADS-B	No	No	No

5 Conclusion

AANET plays a vital role in making IoT to be realized over the sky. Because of the unique features of AANET, it is difficult to come up with efficient data delivery. The civil aviation domain requires an effective technological framework to provide reliable data transfer to passengers on the ground. This work is contributed to an efficient multi-channel cross-layered approach to cope with a highly dynamic environment with a better network guarantee. The emerging ADS-B-based routing proposes the idea of cross layering helps to reduce communication overhead significantly. The results have been compared with the existing methods. The results clearly show that the proposed scheme firstly reduces the traffic overhead and delay with the increasing number of network sizes and by properly utilizing the non-overlapping channel of IEEE 802.11, the performance in terms of delay and overhead is further enhanced. Secondly, a better packet delivery ratio and delay are obtained while in midst of frequent topology changes. Finally, the proposed work makes an easy way to upgrade the routing scheme without the need for a larger transformation. The proposed scheme will be enriched in the future in terms of realistic mobility patterns with real-world scenarios and effort towards real-time testbed implementation will be taken in the future.

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Author Contributions All authors contributed to the study conception and design. TG and Dr. SIG performed material preparation, data collection and analysis. The first draft of the manuscript was written by TG and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data Availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Code Availability The codes generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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