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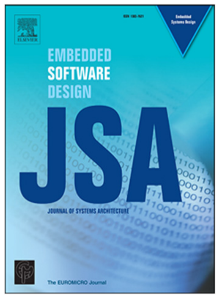

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A survey on FANET Routing from a Cross-Layer Design Perspective

Georgios Amponis[1], Thomas Lagkas[1], Panagiotis Sarigiannidis[2], Vasileios Vitsas[3], Panagiotis Fouliras[4], Shaohua Wan*[5]

Abstract

With the introduction of UAVs to networking, ad hoc communications have evolved past confinement to the terrestrial grid and have moved towards aerial meshes. Until now, Flying Ad-hoc Networks (FANETs) have been relying on strictly layered communication protocols for their function and routing, a tradition set by conventional networks. With layers of said protocols functioning as "black boxes", any form of interaction between non-adjacent layers constitutes a direct violation of the protocols' architecture. The work presented in this survey intends to examine existing protocols of both legacy and cross-layer architectures in terms of their potential in accommodating routing in FANET deployments. Special attention is given to multi-altitude (3D) deployments, where a substantially greater amount of processing and packet route complexity is observed, and a greater amount of node location precision is required. The potential of cross-layer designs is expressed as a function of power budgeting, mobility (and awareness thereof), security, and resource allocation, given their importance for efficient control of flying ad hoc networks.

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1. Introduction

Drone swarms are a type of Flying Ad-hoc Networks (FANETs) whose ancestry can be traced to the well-established Vehicular Ad-hoc Networks (VANETs) and the Mobile Ad-hoc Networks (MANETs). Such swarms can be either directly controlled in real time or pre-programmed to perform specific tasks without human intervention. FANETs began emerging mostly in the context of military deployments, but currently find numerous applications in various fields such as the ones analyzed in a series of papers: [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15]. Table 1 showcases possible applications of drone swarms as well as the specific role played by UAVs comprising the FANET.

Application	UAV's role
Surveillance (civilian, military)	1) Video recording/streaming 2) Target pursuit
Disaster assessment (e.g. wildfires, earthquakes)	1) Area scanning 2) Heatmap generation
Search and rescue missions	1) Target pursuit 2) Message broadcast 3) GPS signaling
Communication relaying	1) Signal forwarding 2) Beamforming
Smart farming and agriculture	1) Crop growth monitoring 2) Thermal imaging 3) Area scanning
Remote sensing	1) Area scanning 2) Sensor data acquisition 3) Metaveillance
Mobile Edge computing	1) Edge data handling 2) Remote sensing 3) Edge node

Table 1: FANET applications

Authors of [1] and [2] consider the deployment of FANETs as a means of achieving military superiority. Both publications argue for the implementation of an AI-enabled swarm-controlling scheme and do not only consider military surveillance applications but move on to suggesting either active or passive weaponization of swarm deployments.

In [3], [4] and [5], communication relaying FANET applications are analyzed. More specifically, in [3], a self-organizing FANET scheme for emergency backup communications is proposed. This scheme considers a post-disaster scenario, in which not all end-users have access to the network. Said FANET deployment shall function as a link between "cut-off" end users, effectively restoring network operation. In [4] a completely different use-case is analyzed: UAV-aided cross-layer routing for MANETs. The proposed cross-layer scheme aims to enhance the routing performance of MANETs by providing aerial support to the network. This technique reduces hops and can provide significantly shorter packet paths. In [5], the researchers developed a FANET control and decision-making architecture which finds application in disaster management (e.g. fire extinguishing) and civil security.

In [6], an entirely different set of UAV applications is proposed: visual monitoring embedded with artificial intelligence (AI) algorithms, centered around traffic surveillance as a means of achieving a smart city.

In [7] and [8], remote-sensing UAV applications are at focus; [7] focuses on UAV-enabled search-and-rescue scenario is at focus. UAVs are autonomously controlled and have two main tasks. UAVs shall aim towards maximizing remote sensing area coverage. UAVs shall at all times maintain links between their peers and the ground stations. All UAVs are GPS-enabled and the entire application framework is coordinate-based. Similarly, the work in [8] addresses disaster management, civil security, infrastructure surveillance and even filming in conditions where human operators can not provide their services.

In [9], UAVs are closely examined and analyzed as members of an IoT framework, with a sizeable range of possible remote sensing/packet relaying/aerial visual sensing applications in which UAVs are treated as IoT "things" being examined. The researchers' work also considers 5G - enabled UAV applications as well as the security and privacy considerations arising in such application environments.

In [10], [11], farming applications of UAVs are analyzed. FANETs in agriculture are deployed in order to address crop scouting and modeling, cultivation management as well as application of chemicals and plant growth monitoring. The deployment of FANETs instead of single UAVs is highly beneficial in a such use-case, as it allows for the acquisition of data from multiple perspectives with different angles and the coverage of a significantly greater area. Given global population growth, smart agriculture is thought to be of utmost importance for a sustainable food production.

Similarly, the authors of [12] and [13] review, examine and propose UAV-based precision agriculture applications, in which drones function as remote sensors enabling smart-farming and guidance of IoT monitoring systems. This work and its derivatives have seen practical applications in research projects, which further validate usage of UAVs in such scenarios.

Researchers in [14] investigated the usage of drone swarms as a means of beamforming. This use-case strongly depends on the correct positioning of UAVs in order to cohere their signal towards a given direction. This is an innovative use-case which would enable signaling and communication relaying in significantly greater distances than conventional (single-antenna directional or omnidirectional) transmitting currently allows for. The authors were able to steer the collective beam by positioning UAVs in a 3D grid in locations computed by considering the swarm's radiation pattern.

Authors in [15] researched the usage of drone swarms for "metaveillance" -i.e., sensing of sensing. Using drones, they were able to capture various sensors' capacity to sense their environment. This application finds use in smart environments and proves especially useful for traffic monitoring: drones can evaluate cars' sensors and report cases of deficiency.

The motivation of the work presented in this paper stems from the lack of research focused on cross-layer designs applied to routing in 3D FANET deployments. Virtually all swarm routing research is focused on usage of conventional (legacy layered) protocols in 2D deployments. The flexibility and massive range of application scenarios of 3D deployments as well as the advantages of the cross-layer approach make it imperative for this research void to be filled. This survey constitutes an attempt to collect, summarize, compare and analyze existing research as well as to examine possible applications of each known cross-layer routing protocol and advantages it offers in a 3D deployment.

According to [16], FANETs differ from MANETs and VANETs in matters of :

- Node Mobility
- Node Speed

- Rate of topology alteration
- Energy constrains

All aforementioned parameters become of increased importance in multi-UAV networked deployments. Routing requirements for FANETs differ from the ones defined for other types of ad hoc networks and stationary networks. In [17] requirements for FANET-specific routing protocols are defined and shown in Table 2 .

Requirement	Effect on FANET
High adaptability	Routing shall adapt to highly dynamic topologies
High scalability	Routing shall accommodate large-scale applications
High residual energy	Available energy shall suffice to provide stable radio links
Low latency	Route discovery, update and maintenance shall have minimal delay
High bandwidth	Routes shall provide sufficient bandwidth for desired application

Table 2: FANET routing schemes requirements

As stated in [16] and [18], FANET control can be achieved through:

- Multi-UAV cooperation (U2U)
- UAV-to-ground cooperation (U2G)
- UAV-to-VANET cooperation (U2V)

A high degree of scalability is a very important goal and selling point of FANETs. The extensive required mobility of each aerial node leads to great alterations of the deployment's topology. High individual UAV node velocity, as well as the overall required mobility impose more severe constrains to an already delicate system, especially considering a 3D FANET comprised of UAVs in multiple altitudes.

Table 3 compares the present work to already existing surveys and ad hoc routing-related papers. The present paper is focused not only on surveying

Related work	Centered around FANETs	Cross-layer schemes	Mobility models analysis	3D FANETs	Routing schemes comparison
Guillen-Perez et al. [16]	✓	X	✓	X	X
Satapathy et al. [19]	✓	X	✓	X	✓
Bekmezci et al. [20]	✓	✓	✓	X	✓
Sang et al. [21]	✓	✓	X	X	✓
Khan et al. [22]	✓	X	X	X	✓
Chriki et al. [23]	✓	✓	✓	X	✓
Srivastava et al. [24]	✓	X	✓	✓	✓
Our work	✓	✓	✓	✓	✓

Table 3: Related surveys

ad hoc routing protocols for UAV networks but also on: **a)** examining the usability of cross-layer designs, **b)** their offered benefits and implications related to security, resource allocation and power consumption, **c)** the method of accommodating routing in multi-altitude drone swarm deployments, and **d)** the comparison of both legacy and cross-layer routing schemes. Our approach proves to be the most complete in terms of the variables considered for the survey comparison.

For the present work, a systematic review research methodology was adopted. In that context, a range of platforms were sourced for information. Most of the sources cited in this survey were found in: **a)** the IEEE Xplore digital library, **b)** the Google scholar platform, and **c)** the online Elsevier platform. Keywords utilized were: "Cross-layer Designs", "Flying Ad Hoc Networks", "3D FANETs", "Drone Swarms", "Energy-aware Routing", "FANET Routing Protocols", "WSNs", "Smart Farming", "UAV Remote Sensing", "Mobility Models", "Ad Hoc Networks", "Mobile Ad Hoc Networks", "Routing Protocols", "Routing Algorithms", "Network topologies". Initially resulting papers (numbering approximately 200) were filtered by choosing the ones referring to protocols and algorithms closely related to FANETs (deployment considerations, applications and use-case specific projects), cross-layering, multi-altitude deployments, quality of service (QoS) metrics, and energy efficiency. In the end, 179 of the aforementioned publications were deemed appropriately relevant, of which 108 made it into the refined version of the present survey.

The layout of this paper is as follows: After this introduction, follows Section 2 which is divided into three parts: one describing 2D FANET topologies, one describing 3D FANET topologies, and a third one describing and analysing mobility models. Section 3 introduces the reader to the concept of cross-layering and the advantages it offers regarding mobility, scalability, security, and reliability. Section 4 is divided into five subsections: the first subsection describes the basic routing algorithms used by the protocols of interest, the second subsection analyzes legacy-layered routing protocols - many of which are ancestors of cross-layer protocols. In turn, the third subsection summarizes and compares all the mentioned legacy-layered routing schemes. The fourth subsection is dedicated to the analysis of several sufficiently matured cross-layer schemes and the fifth one summarizes, compares, and includes all their strengths, weaknesses, main characteristics, application scenarios and efficiency in actual swarm networks. Section 5 concludes this paper with comments regarding further work in this field and possible extensions of existing research. Figure 1 provides a high-level view of the paper's structure, discussed topics and overall flow.

By reading the entirety of this work, a reader will have gained applicable knowledge and the ability to critically compare and choose routing schemes, thus enabling further research in this rapidly evolving field.

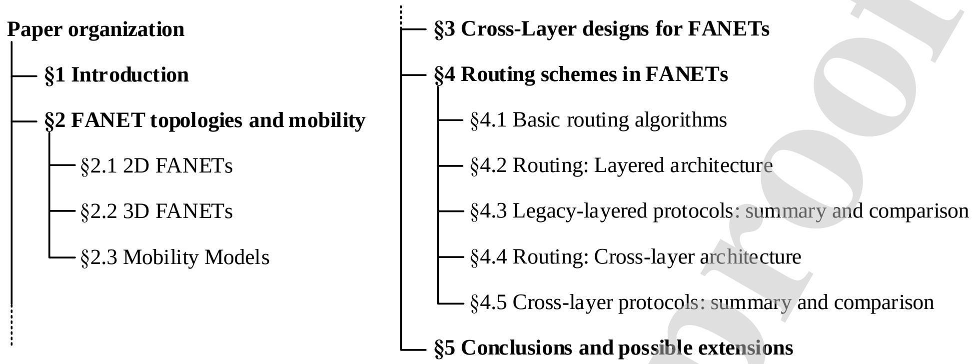


Figure 1: High-level structure of presented work

2. FANET topologies and mobility

This section is dedicated to the analysis of the two FANET deployment topologies of interest (2D and 3D respectively) as well as the swarm-specific mobility models commonly used to simulate and describe their movement and behaviour in different applications, and under various environmental conditions.

2.1. 2D FANETs

A traditional FANET deployment is composed of several UAVs interconnected as a 2-dimensional array (single altitude deployment). Note that not all nodes must be directly communicating with each other; even though a direct link between all individual UAVs comprising a FANET may be feasible for a small number of nodes, it is not possible (or desirable) for larger deployments. Firstly, limitations arise at the physical layer: as swarm size increases, so does required transmission energy for all inter-deployment communications. As autonomy is extremely important for FANET deployments, increases in transmission energy must be avoided. Furthermore, nodes do not have an infinite number of interfaces. If they were to adopt an direct communication approach, all possibility of deployment scalability disappears. The only actual benefit of a such approach would be low transmission latency.

Instead of direct links between all nodes, an efficient routing approach is preferred. Figure 2 shows a 3x3 2D FANET deployment. The central UAV of each swarm layer is the device with the most interfaces to the rest of the

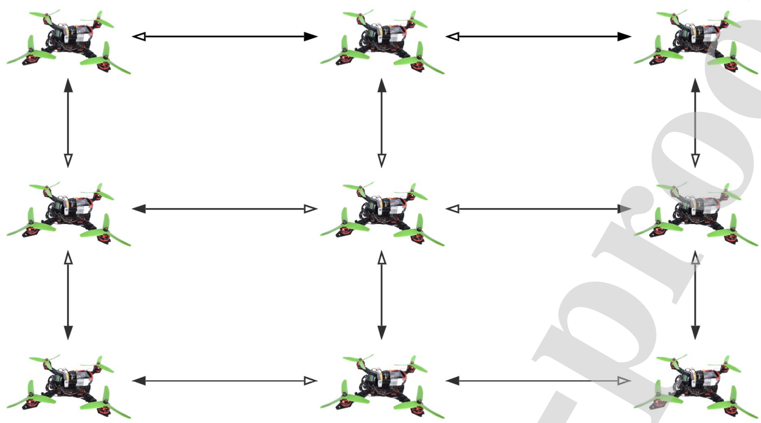


Figure 2: Traditional 2D FANET topology

network and can thus function as a relay between a ground station and the FANET, routing control/data packets from/to each networked device.

2.2. 3D FANETs

A 3D FANET is in turn composed of UAVs positioned as a 3-dimensional array in space. The complexity of both the swarm control and the routing algorithm in such a scenario alike, increase exponentially as a direct function of the array's dimensions measured in number of nodes. The stacked UAV "layers" in a 3D deployment may serve as nodes or redundant relays, increasing swarm efficiency by assigning different roles to each layer. With such a network arises the possibility of having a distinct "payload" swarm layer. For example, in a remote sensing scenario, the first layer may serve as a sensing layer which can provide information from diverse perspectives, altitudes and angles, while a second layer may implement routing; in this manner, the "payload" node array does not have to concern itself with routing, while the "networking" node array can dedicate the entirety of its resources to routing. Furthermore, in the scenario of a redundant swarm layer, the respective FANET becomes practically invulnerable to node loss.

As seen in Figure 3, a 3D FANET deployment is essentially an interconnection between stacked 2D FANETs operating as a multi-altitude constellation. This is the environment in which a routing protocol shall be able to efficiently operate. For such a network, several more parameters need to

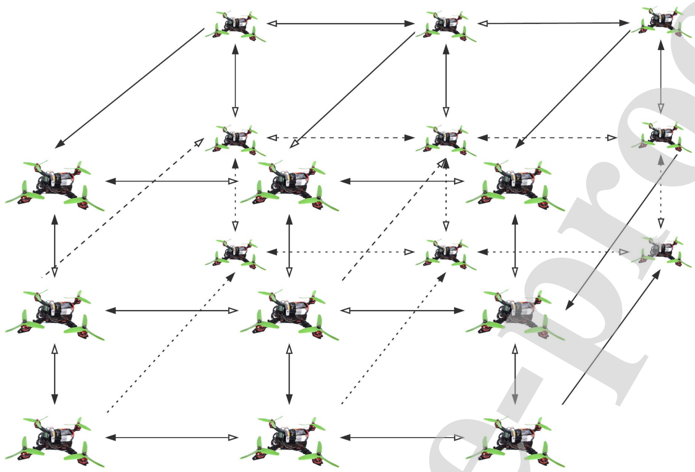


Figure 3: 3D FANET topology

be taken into account and more issues need to be addressed. Three rather important parameters related to the 3D nature of the proposed FANET type are the following:

- Relative altitude of stacked UAV layers
- Relative speed of individual nodes
- Role of each swarm layer

Other important network parameters and characteristics, not exclusively related to the 3D nature of investigated FANET deployments, are network topology, mobility model and propagation model.

It becomes clear that routing efficiency needs to be maximized, as data exchange rates will be increased exponentially. Control, identification, location, ACK packets now need to be routed for each stacked FANET layer in the 3D deployment.

2.3. Mobility Models

Mobility models are essential for a FANET deployment analysis and simulation. Commonly used mobility models are: Gauss-Markov mobility model, Semi Random Circular mobility model, Paparazzi mobility model [25], [26], Random Waypoint mobility model [27] and Pheromone Repel mobility model [27]. Furthermore, in [28], a Particle Swarm Mobility Model specifically designed for FANETs is proposed. Mobility models are divided into the following categories: randomized models, time-dependent models, path-planned models, group models and topology-control based models [29]. The authors of [24] have meticulously taxonomized mobility models. As stated by the researchers in [30], mobility models significantly impact routing and packet handover in wireless networks and thus need to be seriously taken into consideration for the successful and accurate modelling of ad hoc networks. In the spirit of analysing mobility model's impact on wireless communications, K. Kabilan et al. [31] simulated and conducted a comprehensive performance analysis of IoT communication protocols under varying mobility models, in terms of packet delivery ratio (PDR), average power consumption, QoS and hop count.

Mobility models for FANETs are also to be considered for the design of a swarm trajectory due to their inherent relation to power availability and terrestrial area of coverage. The authors of [32] propose an energy-efficient resource allocation and trajectory design system for UAV-enabled communication relaying applications. Proper trajectory design schemes can maximize the system-wide energy efficiency, and shall consider the inherent constraints imposed by ode velocity, altitude, energy consumption and required data rates (a direct function of the expected amount of information and packet size) of the destination node. The authors investigate the impact of a UAV's trajectory and attempt to optimize it to achieve better energy efficiency, while guaranteeing a minimum required data rate for the destination node. The authors eventually solved the optimization problem by considering resource allocation and trajectory separately. Similarly, researchers in [33] investigated and attempted to solve a UAV data collection problem which regards ground stations deployed along a straight line while focusing on trajectory design and control of the UAV's speed to extend battery lifetime. The authors made real-world tests which they mathematically supported and propose a novel "looking before crossing algorithm" which works as a direct function of the UAV's velocity instead of the commonly utilized distance or flight-duration metrics and is proven to significantly (positively) impact not only battery lifetime, but also communication quality - expressed as average required transmission time and average transmission range.

Gauss-Markov Mobility Model. Gauss–Markov Mobility Model utilizes a single tuning parameter in order to accommodate various randomness levels. In this model, nodes' movements are independent from one another. Nodes are assigned an initial direction and velocity, and at constant intervals, those two variables are updated. Previous velocity and direction of each node are taken into account for future values - along with an embedded level of randomness. Thus, any possible abrupt path alterations are avoided [25] [34]. As stated by A. Guillen-Perez et al. [16] there exists a multi-altitude aware variant of the Gauss-Markov model (3D-GM) specifically developed to accommodate FANETs by including mobility in all three dimensions.

Semi Random Circular Mobility Model. Semi-Random Circular Movement Mobility Model accommodates curved and circular UAV trajectories. This mobility model is effective in simulating multi-UAV deployments tasked with surveillance [23]. The semi-random circular mobility model has proven to be more efficient than existing models for the simulation of curved maneuvering, since it is the first one specifically designed for curved scenarios [35]. This mobility model is ideal for scenarios where a surveillance target location is already known.

Paparazzi Mobility Model. The Paparazzi Mobility Model incorporates five possible UAV maneuvers: stay-at, way-point, eight, scan and oval. Those five basic maneuvers cover virtually all realistic UAV movements. The Paparazzi Mobility Model is ideal for simulating maneuvering and routing protocols in a swarm deployment [26]. The paparazzi model provides a more accurate description of a swarm's mobility in a real-life environment in as stated in [36].

Particle Swarm Mobility Model. The particle swarm mobility model maintains a collision-free distribution at all times. It takes the spatial relationship with other UAV nodes in the same group into consideration. Initially, UAV velocities and waypoints are captured. Following this, the mobility model generates new velocity vectors and waypoints for each UAV. The particle swarm mobility model then makes adjustments to avoid collisions. This process is repeated. It succeeds in keeping all UAV nodes in safe distances, while achieving high temporal and spatial correlation and decent path availability [28].

Random Waypoint Mobility Model. The Random Waypoint mobility model attempts to simulate node motion based on linear motion and its derivatives (turns, stops). Each node defines a random destination and engages it at a random velocity. After reaching it and pausing for a random amount of time, nodes have to define a new destination and engage it in a similar (random) manner. This mobility model is non-directional since all nodes move according to randomly defined waypoints [18] [27]. The authors of [37] conducted simulations using NS-2 using this particular model in combination with AODV and DSDV. The Random Waypoint Model is one of the most accurate for the description of node entity mobility.

Pheromone Repel mobility model. The Pheromone mobility model is inspired from observations made in animal swarms. Each node's mobility is dependent on other node's paths. This mobility model focuses on maximizing network coverage area and is therefore ideal for simulation of surveillance scenarios. Since nodes are constantly trying maximize the area their network covers by distancing themselves from their peers, link failures may be caused [27].

The mentioned mobility models are all of high value for the analysis and simulation of UAV swarms' behaviour and even link quality estimation. Each model describes the behaviour of a network engaging in different tasks. Thus arises the need to categorize mobility models according to the scenario each describes. Table 4 summarizes the characteristics and possible application scenarios for which each mobility model would provide sufficient simulation realism and accuracy. It becomes clear that there can be no "superior" mobility model. Each is created to simulate ad hoc networks under different conditions.

3. Cross-Layer designs for FANETs

This section serves as an introduction to cross-layering as well as a justification for the usage of such schemes in UAV swarms . Cross-layer designs are an emerging network architecture, promising to remove several boundaries set by traditional OSI layer stacking. A cross-layer approach allows for usable information to be shared between layers. The possibility of inter-layer feedback provisioning, allows for more efficient congestion control and an increase in overall throughput, QoS, energy management [38, 39] and even Quality of Experience (QoE) (applicable in multimedia-oriented applications).

Cross-layering finds application in conventional (non - ad hoc) networks as well as mobile ones. A great example of a cross-layer application in a

Table 4: Mobility models

Mobility Model	Main characteristic	Application
Gauss-Markov	1) Avoids sudden path changes 2) Prediction of future positions	1) Search-and-rescue 2) Target pursuit 3) Patrolling
Semi-Random Circular	Curved trajectories	1) Monitoring of target(s) with known position 2) Communication relaying 3) Traffic monitoring
Paparazzi	1) Simple maneuvers 2) Accurate swarm modelling	1) Remote sensing 2) Search-and-rescue
Particle Swarm	1) Collision avoidance 2) Path planning	1) (Natural) disaster assessment 2) Traffic monitoring
Random Waypoint	1) Reduced hop number 2) Increased link lifetime	1) Relaying 2) Traffic monitoring
Pheromone Repel	Coverage maximization	Large-area scanning

conventional network is the enabling of QoE awareness for video streaming. In [40], such a streaming-oriented cross-layer scheme is proposed. This QoE-oriented scheme aims to accept and enable new video streaming session while adapting transmission rates to release resources for more sessions, and all that while maintaining QoE of active sessions. This optimization is enabled by making the application layer communicate directly with the network and link layer in order to adapt transmission rates to lower layer network parameters.

By adopting a such approach, a network has the potential of developing a more self-aware behaviour, as adjacent layers are allowed to communicate not just nested datagrams but also information concerning traffic and overall load. The network seizes to function as a set of blocks and instead becomes a system. A cross-layer design can be either *top-to-bottom* or *bottom-to-top*, with the later being more efficient. A bottom-to-top approach is generally used as a means to allow for interaction between cross-layer and classically-layered protocols and designs [41].

Cross-layer designs are primarily focused on Wireless Networks (WNs) [42] and Wireless Sensor Networks (WSNs). They find application in real-time and generally latency-intolerant tasks. In such tasks, the application layer begins to be even more evidently dependent on the MAC layer for required scheduling and provisioning.

Modern WNs and WSNs are directly tied to industrial and even agricultural IoT applications and hence have no tolerance for down-time, energy wastage, unnecessary sensing delay and possible disruptions. WNs' power supplies are also for the greatest part battery-based. Efficiency and autonomy have therefore become one of the most important factors to be considered for WN deployments, especially for FANETs. The MAC layer will be at the center of a battery-friendly packet transmission algorithm [43]. Battery awareness is allowed for by inter-layer communication between non-adjacent layers. The work in [44] investigates security and defence against various attack methods in WSNs and IoT deployments which are important to consider when selecting an ad hoc routing scheme for a similar (decentralized) deployment scenario.

Figure 4 compares the traditional OSI-type stacking approach to an example of the cross-layer one. A receiver configuration scenario is assumed: data is collected at the Physical layer and forwarded towards higher layers for appropriate processing. In the traditional scenario, no decapsulation of incoming packets can take place in a ”wrong” layer, whereas in the cross-layer scenario, layers can freely exchange information instead of just data. The design of a cross-layer system is evidently more complex since a cross-layer design must capable to perform inter-layer forwarding as well as datagram en/de-capsulation between adjacent and non-adjacent layers alike [45]. As explained in [46], there must be inter- and intra-layer entities managing, scheduling and optimizing cross-layer communication.

Resource allocation. A network has a limited amount of resources available for successful communication at a given time. Such resources can be either physical or virtual: available bandwidth, processing power, available energy, latency tolerance etc. In a flying ad-hoc network, due to the nature of the network's topology and inherent characteristics, all aforementioned resources are minimized. Effective resource allocation is of particular importance, as allocation fairness allows for better QoS and not only; resource allocation also allows for higher security level and greater autonomy for the entire FANET.

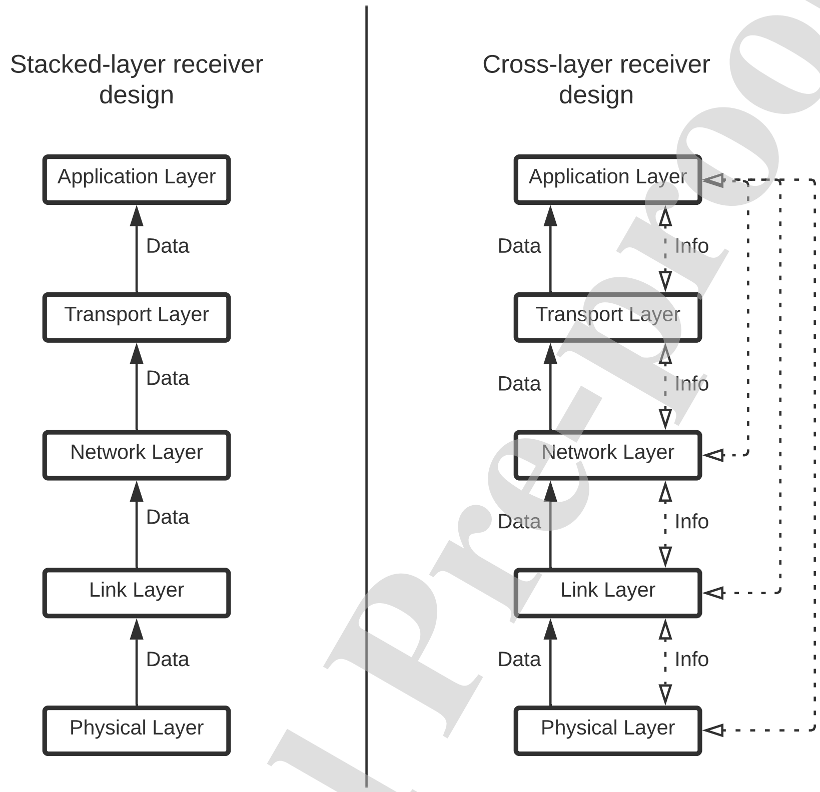


Figure 4: Legacy and Cross-layer design

Power Budgeting. As mentioned, power and efficient use thereof, must be taken into serious consideration during development and deployment of ad hoc networks. Classically, layered designs have been taking energy into consideration, with a great example being the Geographic and Energy Aware Routing (GEAR) protocol [47]. A cross-layer approach allows for comparatively better transmission optimizations: energy required for packet transmission is calculated and evaluated at the lower layers, while network-wide decisions are taken on the higher protocol layers. Cooperation and direct communication between the non-adjacent MAC and Application layers can result in communication energy reduction. In subsection 4.3.8 a cross-layer power aware scheme is analyzed as an example of inter-layer provisioning as a means of achieving battery awareness and the minimization of energy expenditure. The authors of [33] developed an algorithm aimed at minimizing the energy requirements of UAVs by performing speed scheduling aimed at applications with a focus on surveillance of infrastructure. This velocity-considering approach will also benefit from information exchange between lower and higher layers.

Routing efficiency is taken into serious consideration when designing or deploying an energy-aware network [48]. At that point it is important to distinguish between transmission energy and communication energy in order to better understand how they are related to routing efficiency and therefore affect energy expenditure. Transmission energy is the amount of energy required for a packet to be transmitted from the source node to its first hop. Communication energy is the amount of energy required for the successful routing of a packet to its destination. Communication energy therefore, by definition includes reception energy. An isolated/stacked-layer approach does not allow higher layers to communicate with the lower ones and therefore any energy-saving practices would be limited to a local level: transmission energy. This "short-sighted" approach would attempt to minimize energy consumption by limiting transmission energy instead of the total required communication energy, due to higher layers not having access to lower layer data and vice versa. However, in a cross-layer design, system-level energy expenditure can be taken into account: high layers can receive energy related feedback from low levels on a network scale and manage packet transmission accordingly.

When transmission and reception energy are approximately the same, direct transmission is preferable to routing using intermediate nodes [49]. Transmission and reception energy become equated either when distance between communicating nodes is short, or when nodes' antennas require large amounts of energy. A protocol which tries to minimize communication instead of transmission energy must take several parameters into account: network topology, node velocity and acceleration, antenna modules' power consumption. In a 3D FANET, aforementioned parameters for power management need to be calculated for all UAV layers, which significantly increases computational load for the routing protocol.

Figures 5 and 6 constitute comparison between consideration of transmission power and the consideration of communication power for the handling

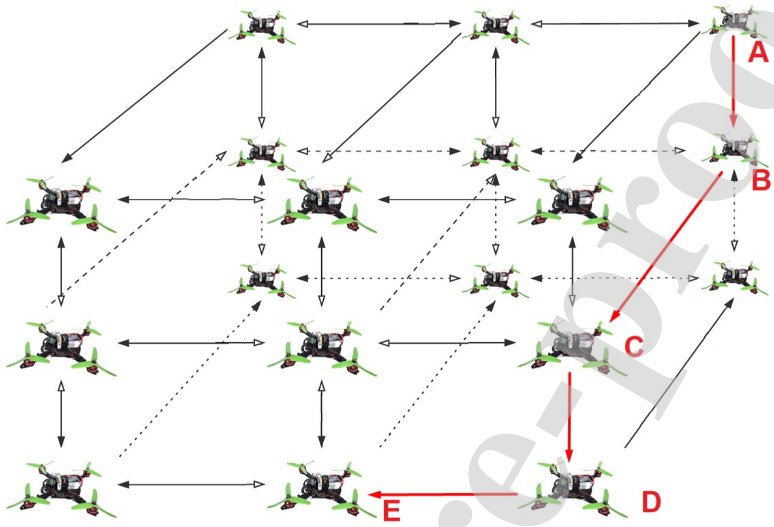


Figure 5: Consideration of transmission energy

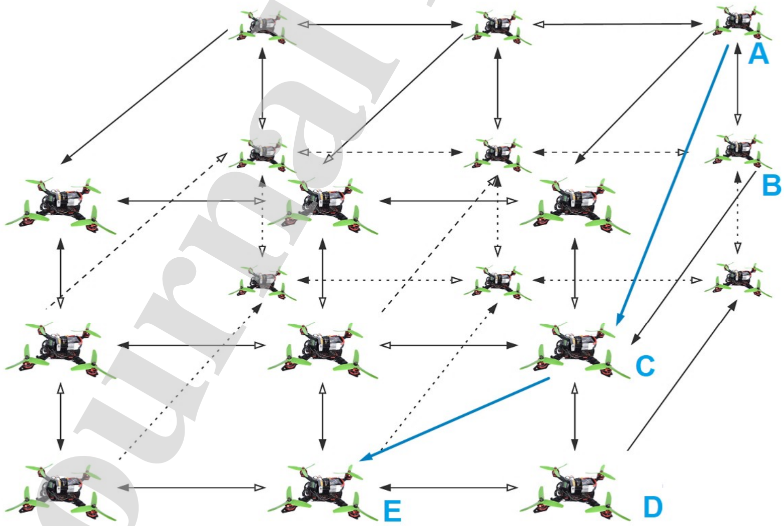


Figure 6: Consideration of communication energy

of route establishment. In the first scenario illustrated in figure 5, the routing scheme is only aware of the transmission energy required for successful packet delivery which may increase energy expenditure in the "long run"; this is a typical type of power budgeting in legacy-layered routing protocols. Assuming P_{tr} is the power required for successful packet delivery from source to destination, this approach can only sense that:

$$P_{tr}(A-B) < P_{tr}(A-C) \tag{1}$$

$$P_{tr}(B-C) < P_{tr}(A-C) \tag{2}$$

$$P_{tr}(C-D) < P_{tr}(C-E) \tag{3}$$

$$P_{tr}(D-E) < P_{tr}(C-E) \tag{4}$$

The later scenario illustrated in figure 6 can be implemented via cross-layer provisioning: instead of considering transmission power, the routing protocol considers physical and network-layer information to chose the ideal next hop so as to achieve the global optimum according to communication energy. Again, assuming P_{tr} is the power required for successful packet delivery, this approach can sense that:

$$P_{tr}(A-C) < P_{tr}(A-B) + P_{tr}(B-C) \tag{5}$$

$$P_{tr}(C-E) < P_{tr}(C-D) + P_{tr}(D-E) \tag{6}$$

There have been however attempts at decreasing power consumption of legacy-layered routing protocols, with a great example being Energy Efficient OLSR (EE-OLSR) as proposed in [50]. The authors modified OLSR's Multi-Point Relay (MPR) selection algorithm (subsection 4.2.8) and succeeded in improving OLSR's overall performance not only in terms of energy consumption but also throughput, link expiration time and overhead.

Congestion Control. A cross-layer protocol design allows for significantly more efficient congestion control. Cross-layer Protocol (XLP) [51] is a functional example of a cross-layer protocol which implements congestion control internally. Congestion control is implemented in the following manner:

1. Creation of links between communicating nodes
2. Limitation of routable traffic per node

Thanks to inter-layer information exchange, no end-to-end congestion control mechanism is required. Instead, a hop-by-hop congestion control mechanism is utilized. This network-wide distributed congestion control mechanism is able to increase network duty cycle and overall reliability.

Security. In [52], an invisible signature-based security system is implemented in a cross-layer fashion for WSNs. This cross-layer authentication system is capable of defending a network against various types of attacks:

1. Correlation attack
2. Playback attack
3. Man-in-the-middle (MITM) attack
4. Invasive content induction attack

Attack detection is implemented at the receiving node's MAC layer by probing and analysing replies originating from suspicious nodes, possibly partaking in a MITM attack. MAC and Network layer need to heavily cooperate in order to successfully implement defense - hence the cross-layer nature of this authentication method. A signature is generated and then integrated into the transmitted video data. Only the receiving node has the correct decryption key required for data extraction. Receiving node verifies the incoming signature by extracting its information and checking whether or not it matches expected signature data. Due to the ease and flexibility of security implementation, a cross-layer design is deemed ideal for mobile ad hoc networks implementing security on a tight energy and overhead budget.

In [53], a cross-layer anti-jamming scheme aimed at defending public transportation infrastructure is proposed and modelled. The proposed scheme combines physical vehicle information with network and link data. The best possible way for the scheme to consider physical, link and application-layer information is obviously by direct inter-layer information exchange. C-OLSR (subsection 4.3.6) is another defensive cross-layer scheme aimed specifically at FANETs. C-OLSR also utilizes physical and link-state information to defend a FANET against jamming. The emerging pattern is quite clear: cross-layer schemes are valid choices in terms of security - due to their ability to consider inter-layer metrics and parameters.

The author of [54] studied the security of UAV networks, while developing a novel security infrastructure. Said infrastructure is based on the use of secret sharing and authenticated encryption and proves its efficiency via simulations. More specifically, the possibilities of internal or external adversaries launching an attack - as well as the respective technicalities are thoroughly examined. Route and node authentication is the main challenge security frameworks are expected to deal with. Authentication Key Exchange (AKE) specifically designed for FANETs, makes use of Elliptic Curve Diffie-Hellman key Exchange (ECDHE). Using said key exchange method, FANET nodes can establish a secure connection over an insecure medium. However, the communication channel is usually authenticated, symmetrically encrypted algorithms like AES-GCM, ACORN and ASCON. It is worth noting that different encryption algorithms have divergent requirements in terms of computational capacity, with ASCON-128 generally being the fastest one in all platforms tested in [54].

As noted in [23], the main security services that an attacker wants to break are:

1. Authentication
2. Availability
3. Confidentiality
4. Integrity

The aforementioned security and privacy concerns, have given rise to FANET-specific security-oriented protocols such as SEEDRP, as proposed by the authors of [55]. To preserve privacy and establish trusted routes, data packet transmissions need to be secure so that the sent information maintains integrity and confidentiality and thus the node's privacy is ensured. The work presented by said authors can be summarized as the development of the SEEDRP-routing algorithm, the aim of which is to mitigate RREQ and HELLO packet flooding and identify the optimal next hops (to obtain a robust route) based on:

- Node's broadcast range
- Node velocity
- Node direction during transmission of a RREQ/control packet

The SEEDRP protocol is comprised of two phases: the route establishment, and one responsible for securing data from unauthorized access. It is worth noting that SEEDRP makes use of a cross-layer optimization technique: upon initiation of the transmission sequence, the transmitting node obtains the data transmission rates and transmission ranges from the MAC layer. The transmitting node then selects the optimal transmission rate out of the obtained values. This information is made available in the "transmission rate" field of the RREQ packet broadcasted by the transmitting node.

Scalability & Dynamic networking. An innovative utilization of the cross-layer approach is the formation of scalable, redundant and dynamically configurable FANET deployments.

Scalability: In [56], the enhancement of the scalability feature of the WNaN protocol is explored. The use-case analyzed considers MANETs (comparatively low mobility nodes). The enhancement takes into account the motion of nodes and uses OLSR-based MPRs as well as Link State Updates (LSUs). In a cross-layer design, link-state awareness can be inherently implemented and embedded into the protocol itself, by letting the link layer inform higher layers of the link state directly. Furthermore, in a cross-layer scheme (again, thanks to direct inter-layer communication) node motion can be significantly more easy to take into consideration when routing: higher layers can have access to hardware information and even data regarding a node's attitude (roll, pitch, yaw). It is therefore highly beneficial - especially in high-mobility FANET deployments to implement cross-layering as a means of achieving network scalability. Node clustering can also become faster and be achieved more efficiently by utilizing physical-layer information to enable mobility awareness. Node mobility awareness is highly valuable for a network, as it may be used in order to predict node paths and cluster them accordingly [57].

Dynamic networking: Authors in [58] and [59] consider the usage of classically layered routing schemes to develop a dynamically configured FANET. The inefficiency of the stacked approach is combated by disabling the RTC/CTS handshake of TCP, but with minimal results. Resorting to UDP could assist in solving this issue, but at the same time packet delivery confirmation would be sacrificed - or implemented at the application layer since UDP does not support it inherently. Another issue which needs to be externally addressed is FANET-wide knowledge of the physical network topology. Adoption of a cross-layer approach would benefit this dynamic networking scenario, as inter-layer communication could allow nodes to become aware of their deployment's physical topology characteristics and attitude. Researchers in

[60] used an open source derivative of OLSR called OLSRd to form the Predictive OLSR (P-OLSR) protocol, aimed at enabling dynamic routing for FANETs. In [61], a clustering scheme was proposed, in which path optimization is implemented via sharing residual energy-related information and geographic data in order to implement load sharing and congestion control. It is obvious that low-layer provisioning implemented in a cross-layer manner would benefit such applications immensely.

4. Routing schemes in FANETs

This section constitutes the main core of this survey; it is comprised of three subsections: subsection 4.1 describes the basic routing algorithms used by the routing protocols of interest (legacy and cross-layer alike), subsection 4.2 analyzes legacy-layered swarm routing protocols and the possibility of their utilization in a 3D deployment, while subsection 4.3 analyzes exclusively cross-layer routing schemes.

4.1. Basic Routing Algorithms

Routing protocols make use of some fundamental techniques-algorithms, which determine the nature and characteristics of each protocol. The most important such algorithms are: greedy algorithm, store-carry-and-forward algorithm and the prediction-based algorithm. Those fundamental techniques can be combined with an on-demand (reactive), a table driven (proactive), or a (hybrid) behavioural element to form an individual FANET routing protocol. On demand (reactive) routing protocols compute and generate packet routes when data transmission is required, whereas table-driven (proactive) protocols have pre-determined paths stored in the form of a cached routing table. Hybrid protocols make use of both proactive and reactive routing in the same network; each technique is used in distinct network zones [22].

Greedy algorithm. The greedy algorithm/routing technique, dictates that packets be routed to each respective node by following the path consisting of the smallest possible number of hops. This algorithm deducts the best result on a local level by making decisions based on first-stage data and is not concerned with network-layer efficiency (the global optimum): the Greedy approach only considers the amount of hops a packet requires until it reaches its target node and disregards parameters such as congestion. It is a straightforward algorithm and commonly utilized in FANETs.

Store-carry-and-forward algorithm. In highly detached networks, directly routing packets may not be an option due to e.g. great distance between nodes. The store-carry-and-forward routing technique allows for nodes to not immediately route packets, but store them in a cache and engage in transmission to packet destination when network conditions allow for it. The store-carry-and-forward technique is used in highly-mobile and latency tolerant deployments and is not suitable for real-time control.

Prediction-based algorithm. When a prediction-based algorithm is in use, all nodes of a FANET share information regarding their location and velocity in each axis. This requirement is particularly augmented in a multi-layered deployment (3D FANET), in which relative positions, heights and velocities need to be calculated for each FANET layer. Each UAV node calculates the most efficient path by taking the aforementioned information into consideration, thereby predicting the next hop's future position and routing accordingly.

4.2. Routing: Layered architecture

This subsection is dedicated to the analysis of various classically-layered routing protocols, so as to provide appropriate reference points for the cross-layer schemes analysis (subsection 4.3) and the final comparison between the two architectures. For each protocol, a brief description is given, following by a short explanation of their core functions. The protocols mentioned in this subsection are: a) those which find adequate correlation with the cross-layer ones, b) those which function as the basis of other schemes, and c) those which are great examples of a routing technique (proactive, reactive, hybrid) or an algorithm implementation (greedy, store-and-carry etc.).

4.2.1. Dynamic Source Routing (DSR)

The DSR protocol is reactive, as it computes a route on-demand upon request by transmitter. Despite being on-demand-driven (on-demand protocols typically utilize pre-existing routes), it does not rely on routes cached at intermediate UAV nodes. Instead, it makes use of source-node routing, as it solely utilizes routes cached inside the transmitter. Its reactive nature eliminates periodical update-table messages which typically flood the network in table-driven protocols. DSR is not required to calculate paths to all other nodes in the network. Instead, it only creates source-destination routes.

Each packet in DSR carries route-related data and intermediate nodes are allowed to add new possible routes proactively to their internal caches. The source-destination route is contained in each packet's header. DSR collects and maintains possible routes for future use. As new routes are discovered and acquired, intermediate nodes' cache is updated to include the new routes. Intermediate nodes also utilize the cached route information in order to reduce overhead. DSR has low overhead and it can accommodate routing response to rapid topology changes [62]. Authors in [63] investigated the usage of AODV (subsection 4.2.2) HELLO-message types in DSR as a means of refreshing network information and achieving higher throughput. The experimental results showed that a such "hybrid" protocol does indeed offer PDR and an increased throughput with a decreased number of control messages.

The DSR scheme makes use of more than one route for packet transmission. This approach does not guarantee the shortest possible route, so more end-to-end delay may be introduced to the communication. DSR is suitable for moderately mobile FANETs; its low overhead can consequently be used in low-power and low-bandwidth networks. It is not ideal for highly mobile FANETs. Route setup delay is higher in comparison to table-driven routing protocols. DSR is one of the most popular routing protocols, alongside AODV.

4.2.2. Ad-hoc On-demand Distance Vector Routing (AODV)

AODV is also a reactive protocol, computing required routes on-demand. In contrast to the DSR protocol, AODV relies on intermediate nodes for route establishment instead of solely the transmitting one [64]. AODV uses the following message types:

- Route Request (RREQ)
- Route Reply (RREP)
- Route Error (REER)
- HELLO message

The source node broadcasts a RREQ message before transmission. RREQ message is forwarded to all nodes. Intermediate nodes containing a cached route to the destination reply with a RREP packet. REER messages inform the source of a failed link. HELLO messages allow for link monitoring. In this manner, AODV obtains a series of possible routes; the source receives the series of possible routes and utilizes the one with the smallest number of hops. Every entry in the routing table is characterized by a sequence number, which allows AODV to monitor routes and keep them up-to-date.

The AODV protocol does not inherently implement route optimization: packets are routed through the same path until it can no longer be used. Route optimization can be implemented either with the use of link-layer feedback or by proactively enabling HELLO-message based re-routing [65]. As shown in [64], congestion-caused link failures can cause AODV to engage in route re-discovery. Authors in [66] simulated and compared the performance of DSR and AODV. In an outdoor scenario, it was found that AODV performs better than DSR in terms of packet loss and end-to-end delay alike. Authors in [67] evaluated and compared AODV and DSDV in FANETs. In their tests, AODV proved to have a slightly better average packet delivery ratio (increased by 0.71% in comparison to DSDV), a better average throughput (increased by 1.46% in comparison to DSDV) while demanding approx. 2.8% less energy. When it comes to average end-to-end delay however, DSDV measures 6.66% better.

4.2.3. Topology Broadcast based on Reverse-Path Forwarding (TBRPF)

In RFC 3684 [68], TBRPF is defined as a proactive, link-state routing protocol. It implements routing along shortest paths to the destination node using a hop-by-hop approach - similarly to AODV. Its main advantage over other routing protocols is reduced packet overhead. In the current version of TBRPF, intermediate TBRPF nodes compute and store a partial source tree which allows for shortest-path routing to destination. This partial source tree is constantly updated in this manner:

- Each node reports it's current partial source tree (reported subtree - RS) to it's neighbors with a small frequency. Subtree reports are called periodic topology updates.
- Each nodes also reports to it's neighbors possible changes of the subtree's routes with a higher frequency - these more frequent updates are called differential updates, as they are used to track route changes.

The combination of periodic and differential subtree updates keeps the network aware of it's routes and link states. As written in [69], older versions of the TBRPF protocol dictate that nodes shall store the entire source tree instead of constantly updated parts of it. This has been changed in the newer protocol versions in order to further reduce overhead. Modern TBRPF optionally allows nodes to provide further route and/or topology information.

4.2.4. Greedy Perimeter Stateless Routing (GPSR)

GPSR is a stateless, greedy-based routing protocol which uses router (node) and destination location information to route packets. GPSR is proactive as it utilizes a beaconing mechanism to inform network nodes of their neighbors' positions. Individual nodes periodically broadcast their identifier and position at the MAC level [70].

Intermediate nodes attach the transmitter's positional data in all packets they forward. Each node within the transmitter's antenna range, also receives a duplicate of the transmitted packets. In this manner, GPSR can reduce the network load. This intermediate node's behaviour also allows for GPSR's routing overhead to be completely independent of routing path length (since nodes broadcast positional information instead of routes). All routing overhead is therefore constant and does not depend on packet paths. Low and constant routing overhead makes GPSR ideal for high-mobility ad hoc networks.

All nodes keep a cached forwarding table containing addresses and locations of neighboring nodes. Therefore, GPSR routes are generated in a hop-by-hop fashion, since forwarding decisions take neighboring nodes' location. This protocol addresses scalability issues more efficiently than typical source-to-destination routing protocols. An inherent deficiency of the protocol is that in specific network topologies, route paths' length may temporarily become greater than necessary [70].

4.2.5. UAV Search Mission Protocol (USMP)

USMP [71] is a surveillance-oriented protocol, based on GPSR (subsection 4.2.4), designed for drone swarms. Its main function is allowing swarms to conduct searches over a 2D terrestrial grid. It constitutes an upgrade from the classical GPSR, as it implements two main additional services:

- Location Update
- Waypoint Conflict Resolution

Location Update allows individual UAVs to become aware of other nodes' locations, which will in turn impact route selection process. Waypoint Conflict Resolution is related directly to the swarm's flight path and behaviour; it avoids waypoint conflicts which would result in UAVs colliding mid-flight. USMP essentially combines GPSR's geographic routing with inter-UAV communication to achieve better overall performance and collision avoidance.

4.2.6. Geographic Load Share Routing (GLSR)

GLSR is an extension of GPSR (subsection 4.2.4). This greedy-based positional protocol was conceived as a means to maximize the throughput of an air-to-ground FANET. Throughput maximization is implemented by balancing network traffic among nodes by sharing forwarded packets' buffer size as well as positional data [72]. In contrast to GPSR, GLSR can establish multiple source-destination paths [29]. Forwarding nodes must distribute traffic amongst numerous possible hops.

In order to successfully carry out its traffic-distribution task, GLSR implements the following strategies [72]:

1. A speed-of-advance-based forwarding strategy
2. A congestion-distance-based handover strategy

These strategies define which of the available paths shall be used to route a stream of packets: incoming packets are forwarded in a such manner that packet's advance shall be maximized and the respective queuing delay shall be minimized concurrently. Every intermediate node can choose the next hop by considering the forwarding node's position and packet buffer size. The two strategies' collective effects augments GLSR's throughput maximization. GLSR is only concerned with position and buffer size; other topological or network parameters are disregarded upon calculation of a possible route. Furthermore, in case an incoming packet meets a full buffer, it is dropped with no recovery mechanism being present. GLSR offers low end-to-end delay and maintains path lengths to their minimum, while achieving almost maximum throughput.

4.2.7. Mobility Prediction based Geographic Routing (MPGR)

MPGR is a single-path, greedy and prediction-based protocol. Just as GPSR (subsection 4.2.4) and GLSR (subsection 4.2.6), MPGR is also a positional protocol. It increases PDR and therefore offers an increased QoS, which is highly valued in military applications (MPGR's main focus area).

The movement of a FANET's UAVs are predicted in order to reduce the negative consequences of high-mobility maneuvering. MPGR secures the existence of a solid link between nodes by maximizing their communication range. Increasing communication range, decreased required number of hops. This is done by sharing velocity and positional information regarding the next two hops.

Routing paths and next hops are chosen by considering not only their current positions, but also possible future positions. Next hop selection is a process involving the fulfilment of two sub-objectives [73]:

- Strong Neighbor Connection Persistence
- Short distance from Destination

Strong Neighbor Connection Persistence objective ensures that the communication between hops will be persistent and stable. Short Distance from Destination, ensures that the minimum possible number of hops are used. The effect of these two sub-objectives is joined with the use of the Reliable Next Hop (RNH) metric [73]. Upon reception of a packet, a forwarding node computes the distance between its neighbors and the packet's destination. MPGR informs forwarding node of the connection persistence between itself and its neighbors. The forwarding node can now select a candidate as a next hop. If a node fails to select a forwarding node or its radio range is not sufficient for successful link, a routing void is unavoidable.

4.2.8. Optimized Link State Routing Protocol (OLSR)

OLSR is a proactive, topology-based, link-state protocol which uses a hop-by-hop approach to packet routing. Its main advantage is decreased message overhead, which is achieved by resorting to contained flooding using MPRs. MPR-based flooding reduces unnecessary packet transmissions occurring in an already covered (aerial) region. MPRs are used to forward packets and flood broadcasted control messages. In this manner, OLSR manages to reduce retransmissions. An MPR node must be a direct neighbor to the node whose packets it forwards and its range shall cover other two hop nodes (with respect to the source-node).

OLSR by default uses the following message types:

- HELLO messages
- Topology Control (TC) messages

- MID messages

HELLO messages are associated with: a) link sensing, b) neighboring node detection and c) and MPR signaling. TC messages are in turn associated with topology declaration. MID messages are associated with declaration of the existence of multiple interfaces [74]. Since control messages are transmitted regularly, a possible packet loss is not irreversible.

OLSR link sensing however can only sense the existence and not the quality of an existing node-to-node link. There has however been an attempt at enabling QoS-awareness in classical (legacy-layer) OLSR in [75]; the resulting routing protocol evaluates link quality by checking incoming ACKs and comparing them to the expected ones while considering the Expected Transmission Count (ETX) metric which regards packet forwarding probability and probability of ACK reception. Link information is cached locally in each node. In this manner, the developers were able to maintain the strictly defined layered stack while gaining the ability to sense link quality in OLSR.

OLSR routing is distributed and decentralized and therefore lacks a governing authority [74]. OLSR is the basis for numerous schemes, such as: Predictive OLSR (POLSR) [76], Directional OLSR (DOLSR) [77], Energy-aware Mobility Prediction OLSR (EMP-OLSR) [78], OLSR Fuzzy Cost (OLSR-FC) [79], Contention-based OLSR (COLSR) [80], Cross-layer OLSR (C-OLSR) [81], QoS Aware Link Defined OLSR (LD-OLSR) [75] and even the Quantum-Genetic based OLSR (QC OLSR) [82].

Researchers in [83] have proposed a reputation-based model to enable trusted route selection in OLSR. This model checks the history of each node participating in routing and in its poor link quality or other temporary networking deficiency makes it drop packets, OLSR avoids using this node for the next path formation. Each node builds "reputation" of which all its neighbors are aware. All routing decisions network-wide therefore consider the reputation metric and an algorithm designed to find the most trusted paths to all destinations is shown in [83]. This method was developed to secure OLSR-based networks from adversaries' attacks. In [84] further research was made regarding trusted path formation and additionally the algorithm for finding a set of most trusted paths is shown. This extension of OLSR enables it to address security issues arising in mobile ad hoc networks and is of utmost interest for military FANET applications.

Similarly, in [85], a blockchain expansion of OLSR is proposed as a means of shielding the network against attacks - more specifically, against the Node

Isolation Attack (NIA) where adversaries effectively isolate and potentially seize control of a networked note. Using blockchain, nodes can securely communicate (even under attack) and inform peers of the attacker's information. Nodes can in this manner, isolate the attacker and protect the network from further attacks.

4.2.9. Time-Slotted On-demand Routing Protocol (TSODR)

TSODR is a hybrid, reactive time-slotted protocol, whose main goal is the reduction of packet loss [19]. TSODR is based on AODV. AODV was chosen as its foundation due to the low packet delay it offers during network congestion [64] and was enriched by embedding an ALOHA-type time-slot element into its core function. Time-slots now dictate the nodes' communication window. This allows TSODR to behave itself both proactively (time-slots element) and reactively (AODV element), hence its hybrid nature.

TSODR addresses the network congestion issues arising from UAVs' high velocity maneuvering in FANETs and packet collisions caused in non- time-slotted (classical) AODV. The "cluster head" can exchange data with each node during a predefined time-slot. Since only designated nodes can exchange packets during a given time-slot, possible collisions and packet failures are significantly reduced. This method also allows for network scalability - at the expense however, of utilized bandwidth [86].

4.2.10. Destination-Sequenced Distance Vector routing (DSDV)

DSDV [87] is a proactive (table-driven) routing protocol, created mainly in order to address the count-to-infinity problem [88]. Avoidance of the count-to-infinity problem is implemented by assigning destination sequence numbers to each forwarding table entry. Recently used routes with high sequence numbers have a higher priority compared to routes with lowest sequence numbers. Each networked node creates an array containing the distances to all other network nodes. This array is then shared with the node's first-hop neighbors via broadcasting HELLO messages into the network. After few such array exchanges, all nodes will know the paths to all the other nodes and can therefore calculate the one consisting of the minimum number of hops. Nodes also monitor who sent the array containing the packet path that was finally used and use this information to calculate the path length and form their forwarding table. A forwarding table entry cumulatively includes: packet destination, next hop, distance and packet sequence number [89].

The main advantages of DSDV are: simplicity of the routing scheme, utilization of route sequence numbers (elimination of infinite-forward-loops), minimal delay for path initialization (since DSDV is a table-driven protocol).The disadvantages of DSDV are as: increased network overhead and power consumption (due to the periodic update of forwarding tables), doesn't support multi-path routing, not suitable for highly mobile networks (since new path sequence number are required for every topology change).

Legacy-layered protocols: summary and comparison. As expected, none of the aforementioned routing protocols explicitly address routing in a 3D swarm deployment, or the congestion/autonomy issues which arise. Those schemes fail to sufficiently address matters such as link quality sensing, energy awareness, high node mobility and network scalability.

DSR (subsection 4.2.1) is capable of providing many of the mentioned services to the network, at the cost of comparatively high route setup delay and inability of adaptation to high-mobility networks.

AODV (subsection 4.2.2) reduces route setup delay but fails to address congestion-caused link failures, which causes more frequent route re-discoveries.

TBRPF (subsection 4.2.3) offers a reduced overhead and reverse path forwarding. Its drawback stems from the high convergence time is presents in stressed scenarios.

GPSR (subsection4.2.4) is the first of the analyzed schemes to perform location-based routing in order to address issues arising in scalable and high-mobility deployments. GPSR's approach reduces packet overhead and renders it independent of path length. The shortcoming of this scheme is that specific network topologies cause routing path length to increase more than necessary, thus increasing congestion and end-to-end delay.

USMP (subsection 4.2.5) constitutes an evolution of GPSR since it utilizes UAVs' location to formulate routes and resolves node movement vector conflicts, effectively avoiding mid-air crashes. The weaknesses of GPSR are (to some extend) addressed with the added services offered by USMP to the network.

Similarly to USMP, GLSR (subsection 4.2.6) is also an extension of GPSR. It's main advantage is the maximization of throughput and the minimization of routing delay. GLSR's shortcoming is derived from the lack of a recovery mechanism and the fact that no other parameters except position and buffer size are taken into consideration for next hop selection.

MPGR (subsection 4.2.7) implements location prediction in order to minimize the negative effect of high node mobility to network performance. It promises an increased PDR; it however does not consider link expiration time or the trajectories of other networked nodes.

OLSR (subsection 4.2.8) decreases packet overhead by resorting to controlled flooding. It monitors link states and neighboring nodes through HELLO messages, yet can not sense or quantify link quality.

TSODR (subsection 4.2.9) uses time-slots to reduce packet collisions and increase PDR, while however increasing bandwidth utilization.

DSDV (subsection 4.2.10) is an outdated routing scheme which however has become the foundation of other ad hoc routing schemes such as AODV. While it utilizes sequence numbers and has a minimal delay for path initialization, it lacks support for multi-path routing and is incompatible with highly mobile networks.

Of all the legacy-layer routing schemes, the one most capable of performing well in a 3D FANET seems to be OLSR, given its low end-to-end delay and high PDR. Should OLSR improve its performance in terms of bandwidth utilization and overhead, it would presumably have no match amongst legacy-layered routing schemes. Another upgrade from which OLSR-based routing would benefit in a 3D drone swarm is node location awareness which may potentially decrease number of hops and stabilize overhead (as is the case with GPSR). These are improvements which require no violation of the OSI stack architecture. OLSR can by default sense existence of links between nodes; a cross-layer feature which would require physical layer information provisioning, is link quality evaluation. This can enable OLSR to perform actions as a function of link quality instead of just link state. Table 6 provides a summary of the provided information regarding legacy-layered routing schemes.

4.3. Routing: Cross-layer architecture

In this subsection, cross-layer architectures are analyzed. In contrast to the respective layered architecture subsection, which only analyzed link-layer protocols, this subsection analyzes entire architectures involving various protocols and combinations thereof. As one can observe, the cross-layer approach enables more application-specific routing schemes to be developed and optimized considering set requirements. Cross-layer designs however, are not without their drawbacks, the most prominent being inter-layer interactions potentially causing a performance drop to the overall system, mostly due to increased overhead (and the addition of inter-layer overhead). As

Table 5: Legacy-layer routing schemes

Legacy-layer scheme	Advantages	Disadvantages
DSR	1) Low overhead 2) Resilient to topology changes	1) Not suitable for high-mobility swarms 2) High route setup delay
AODV	Reduced route setup delay	1) No route optimization 2) Congestion may cause route re-discovery
TBRPF	1) Low overhead 2) Reverse path forwarding	High convergence time (unreliable in terms of end-to-end delay)
GPSR	Overhead independent of path length	Some topologies may unnecessarily increase number of hops
USMP	Collision avoidance	Some topologies may unnecessarily increase number of hops
GLSR	1) High throughput 2) Minimal end-to-end delay	1) No recovery mechanism 2) Next hop only defined by position & buffer size
MPGR	1) Predictive routing 2) High PDR	1) Doesn't consider link expiration 2) Doesn't consider all nodes' trajectories
OLSR	1) Low overhead 2) Link-state awareness	Doesn't consider link quality
TSODR	1) Reduced collisions 2) High PDR	High bandwidth requirements
DSDV	Low route setup delay	1) Only supports single-path routing 2) Not suitable for high mobility swarms

Table 6: Legacy-layer routing schemes

such, the presented survey is not intended to promote the analyzed schemes as replacements to the well-established legacy layered protocols, but rather to showcase interesting (and highly application-specific) advantages of novel communication architectures.

There exist numerous cross-layer schemes and protocols which are not specific or optimized for FANET routing. Some great examples which show the interesting potential of the cross-layer approach are the following:

1. Cross-layer Protocol (XLP) [51]
2. Cross layer routing protocol (XLRP) [90]
3. Routing-Enhanced MAC (RMAC) [91]
4. Mobility Aware Cross-layer Routing approach for Peer-to-Peer Networks (MACARON) [65]
5. UAV-aided Cross-Layer Routing protocol (UCLR) [4]

However in this paper, only those finding direct application in FANETs are analyzed. The only exception is the Integrated MAC/Routing protocol (subsection 4.3.8) which gains an "honourable mention" due to its rather impressive utilization of cross-layering as a means of power budgeting in WSNs. Integrated MAC/Routing is not to be confused with the Mobility Adaptive Cross-layer Routing protocol which also abbreviates as "MACRO".

4.3.1. Intelligent Medium Access Control Protocol (IMAC-UAV) combined with Directional OLSR (DOLSR)

IMAC-UAV with DOLSR is a novel cross-layer design comprised of two protocols: IMAC and DOLSR. According to [92], IMAC serves as a MAC-layer protocol, combining however the three first layers in a new super-layer. The first three layers can freely exchange information regarding the following parameters [92] [20]:

1. Channel BER
2. Aircraft attitude
3. Aircraft locations
4. Retry counter
5. Multipoint relay (MPR) locations
6. Antenna type in use

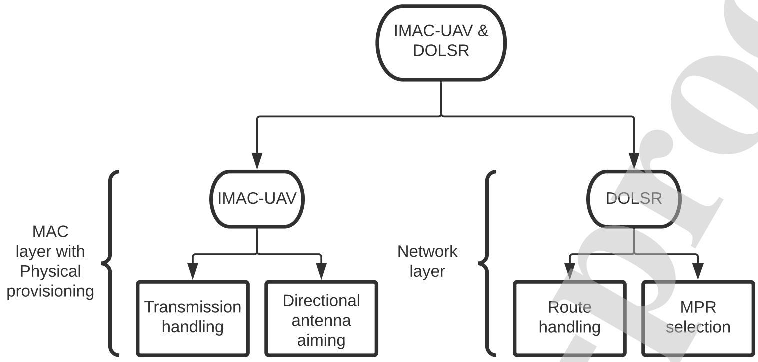


Figure 7: Tasks, layer-specific components and composition of the IMAC-UAV & DOLSR routing protocol, divided in: Link-Physical and Network layers

Thus, MAC-layer awareness and according actions are enabled. DOLSR serves as the network-layer routing protocol allowing for a significant reduction in end-to-end delay in comparison to OLSR. This cross-layer approach allows IMAC to monitor the the aforementioned parameters so that the UAV can switch from transmitting using the directional antenna, to its omnidirectional antenna (in the event any parameter exceed its nominal range [92]). The scheme can be summarized in figure 7.

IMAC-UAV. IMAC-UAV (initially proposed as "Adaptive Medium Access Control Protocol for Unmanned Aerial Vehicles" (AMAC-UAV) in [93]) utilizes a cross-layer approach in order to make use of UAV flight parameters as a means of networking optimization and performance enhancement. This cross-layer MAC protocol enables and supports the use of directional antennas on UAVs - alongside omnidirectional "broadcast" antennas. In total, each UAV shall carry four antennas in total: one directional located on the top side of the UAV, a secondary directional antenna at the bottom of the UAV. Similarly, each UAV carries two omnidirectional dipole antennas. In [94], the researchers analyze the usage of directional antennas as well as topology optimization for power-efficient coverage in 3D FANET deployment. Their ultimate goal is the minimization of the average transmit power using two

Lloyd-like algorithms.

Directional antennas allow for an increase in radio range and coverage, which in turn leads to a decreased number of hops. Channel bit-error-rate (BER) is also (positively) affected by the usage of directional antennas. Thanks to cross-layer provisioning, channel BER can be accounted for, by the new MAC-layer scheme. This scheme which can take BER and UAV trajectory parameters into account when managing the link-layer, is named "Intelligent MAC for Unmanned Aerial Vehicles". The omnidirectional antenna is used to broadcast RTS packets which include the position of the aircraft and duration of transmission [92]. Response to these RTS messages (CTS) shall also be broadcasted via the omnidirectional antenna, and cached for future use by the proactive DOLSR. After a connection has been established, data shall be transmitted using the main directional antenna. As a general rule, a UAV transmits using the directional antenna and receives using the omnidirectional one.

IMAC inherently assumes that individual UAVs operate in different altitudes [92], which makes the IMAC-UAV & DOLSR scheme design ideal for 3D FANET deployments.

Directional Optimized Link State Routing Protocol (DOLSR). In the analysis of the IMAC-UAV protocol, caching of broadcasted data was mentioned. Cached information is utilized by the proactive algorithm of the routing protocol this design incorporates. Directional antennas decrease hops, latency and end-to-end delay while simultaneously increasing PDR. In [92], an OPNET simulation proved DOLSR's superiority in comparison to the IEEE 802.11 standard, regarding aforementioned parameters. Usage of directional antennas allows for a decrease in the number of MPRs in comparison to classical OLSR [19] (for more information on MPRs for OLSR-based protocols, see subsection 4.2.8). As the total number of MPRs decreases, overhead is reduced since packets are forwarded via a decreased number of nodes [92].

Since DOLSR is based on classical OLSR, it is worth mentioning that in [36], an extensive investigation on the performance of OLSR in 3D FANET deployments was conducted. The researchers conclude that OLSR is the most efficient routing choice in terms of end-to-end latency. In [95], a similar study was conducted, confirming OLSR's superiority in comparison to AODV (4.2.2), DSDV (subsection 4.2.10) and DSR (subsection 4.2.1). *As DOLSR is an extension of OLSR, it can be safely assumed that DOLSR will behave efficiently in a 3D environment (as already proven) and may even sur-*

pass OLSR's performance due to its usage of directional transmissions. This, alongside the IMAC-UAV's assumption of different UAV altitudes makes the IMAC-UAV & DOLSR scheme a rather attractive protocol for 3D deployments.

In order to further reduce the communication overhead, DOLSR implements a novel forwarding scheme which involves measurement of communicating nodes' distances (allowed for by the cross-layer IMAC protocol) and appropriately choosing between the directional or omnidirectional antenna for the imminent transmission. More specifically, before each transmission, the source node measures the distance between itself and the packet's destination. A threshold $Dmax$ is defined as the distance after which DOLSR shall switch from directional to omnidirectional antennas. If current distance between communicating UAVs doesn't exceed $Dmax$, DOLSR proceeds to transmit using either the primary or secondary directional antenna after it calculates the following variables:

1. UAV Euler angles
2. Altitude difference between transmitter and receiver

If current values of said variables are not matched in both transmitting and receiving node, DOLSR requires that IMAC compensates for possible Euler angle and altitude miss-match. Compensation is done by electronically steering the lobes of the directional antenna in the right direction. After said compensations, packets are transmitted using directional antenna. If transmission is successful, the target's routing table is updated. If transmission is unsuccessful, the UAV shall make five more attempts, each time updating it's Retry counter. After five unsuccessful transmissions, the UAV shall transmit omnidirectionally using its respective antenna.

In [96] the IMAC-UAV protocol was evaluated using a hexagon-shaped swarm of four UAVs deployed in a 2x2 km grid with a velocity of 144km/h. End-to-end packet latency is limited to less than 2ms while throughput become stabilised at approximately 2.75Mb/s. The same scheme was also simulated using 25 drones; in this case, end-to-end delay initially peaks at 10ms and quickly stabilizes at approximately 2ms.

4.3.2. Multi-meshed-tree Algorithm (MMT Algorithm)

In [97], a Spatial reuse Time Division Multiple Access (STDMA) MAC solution centred around surveillance and tactical applications is proposed. The cross-layer nature of this solution stems from the unification of Link and

Network layer in under the dome of one algorithm, which is this scheme's greatest novelty. Network nodes are addressed using Virtual IDs (VIDs). Nodes receive VIDs upon joining a branch of the meshed tree. Furthermore, network size (and therefore swarm population) can be adjusted by altering VID length.

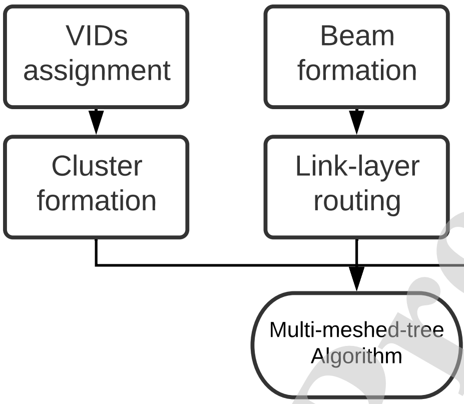


Figure 8: Components of the MMT algorithm and inter-layer interfaces

The MMT Algorithm is based on directional transmissions in order to address issues arising from bandwidth limitations. UAVs utilize four directional antennas each, which allows them to form two distinct beams with widths of 10deg. and 90deg. The narrow beam is used for directional transmissions, while the wider one accommodates broadcasting. Just like the IMAC-DOLSR design, MMT Algorithm requires compensations and scheduling in order to avoid conflicts. This single algorithm is capable of performing the following tasks [97]:

1. Cluster formation
2. Routing
3. Scheduling using STDMA MAC [98]

The incorporation of these functions is implemented as seen in Figure 8.

Thanks to the use of a single VID address for all layers, the MMT Algorithm is highly scalable and robust. It measurably improves end-to-end latency as well as PDR, as shown with the OPNET simulator. For the simulation, circular orbits with a diameter of 20km were used, while transmission range was kept at 15km for each UAV. Swarms of 20, 50 and 75 nodes were used, with velocities ranging from 300 to 400 km/h. Results showed that packet latency is limited to 0.8 sec. (max) for all swarm scenarios [97].

4.3.3. Cross-layer Link quality and Geographical-aware beaconless opportunistic routing protocol (XLinGO)

XLinGO is a position-based cross-layer battery aware routing protocol, specialized for video transmission using FANETs. It's main advantages are elimination of congestion and better bandwidth utilization [99]. XLinGO finds persistent paths using multiple metrics, while being capable of recovering from possible route failures and detecting FANET topology changes. It is similar to the video QoE-aware cross-layer scheme [40] mentioned in the beginning of subsection 3, as it implements application-layer QoE optimizations by using network layer information. In contrast to the previously mentioned video QoE-aware scheme, XLinGO is specifically designed for multimedia routing in FANETs. Figure 9 showcases the fundamental architecture of XLinGO as well as the consideration of human-related parameters for the provision of high QoS.

Upon transmission, the source finds the location of itself and the destination and embeds them in the outgoing packet's header. It then broadcasts a packet to its first hop neighbors. A contention-based forwarding scheme now takes effect. The best next hop candidate is found by limiting forwarding range and calculating following metrics [99]:

1. Dynamic Forwarding Delay (DFD)
2. Transmission energy

When the chosen next hop receives incoming packet, it geographically locates the source and destination embedded in the packet's header. The node then calculates the distance between itself and the destination and compares it with the distance between source and destination. At that point in case the examined node does not present spatial progress in packet delivery, it is expected to stop the process and drop the packet. If the node does present spatial progress in packet delivery, it becomes a relay node and replaces the source node's location in the packet header, with its own. Packet is again forwarded (this time by the relay) in the same manner: broadcasting. The original source becomes aware of the location of the relay node by listening

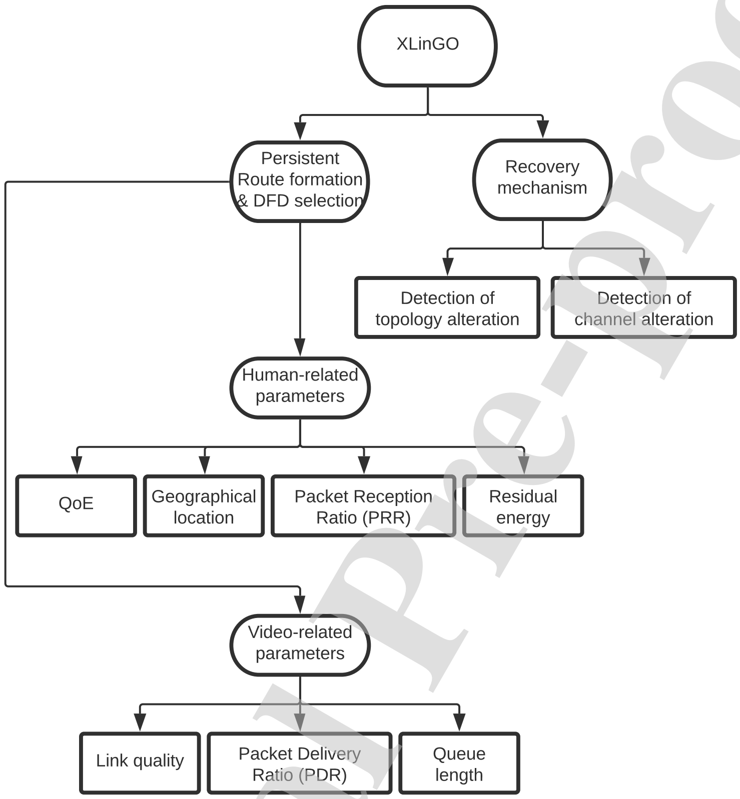


Figure 9: Components, tasks and parameters that XLinGO considers and relies on, for route establishment and reliable video streaming

the relay's broadcast. The original source node can now unicast the next packets to the relay. This is repeated for each hop, until there exists a solid an persistent route from the original source to the packet's destination.

XLinGO functions efficiently in video-related, FANET-specific applications, which makes this design a solid choice for real-time surveillance applications and video relaying deployments. Authors in [100] proves that XLinGO performs significantly better in video-related forwarding in comparison to other legacy-layered multimedia-specific protocols since XLinGO builds a reliable and persistent source-destination route considering link quality, geographical information and queue length. The establishment of reliable and persistent routes is what significantly differentiates XLinGO from other beaconless opportunistic routing (OR) protocols. XLinGO is therefore ideal for applications concerning policing, search-and-rescue mission and natural disaster and environmental monitoring.

4.3.4. Contention-Based OLSR (COLSR)

COLSR [80] a proactive, greedy-based cross-layer design, aims at efficiently implementing a geographic-based routing scheme. It constitutes of two tasks which together compose the design: one which embeds physical and link layer (responsible for relay selection), and one which embeds physical, link and network layer (responsible for contention-based routing and location-awareness). The MAC-PHY component of COLSR addresses the issue of relay node selection, while the MAC-NET component addresses geographic routing. Beaconing and complete neighborhood information are not required in this design. Figure 10 illustrates the components of this cross-layer scheme, as well as the two tasks of which the scheme is comprised.

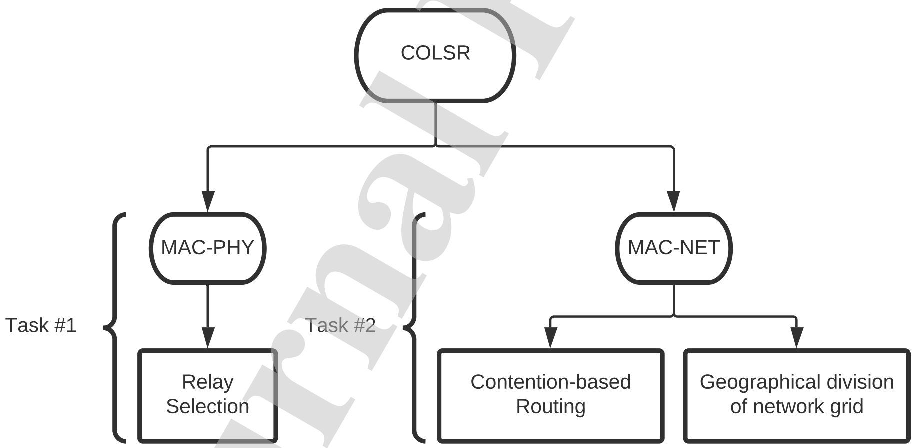


Figure 10: The components of COLSR divided into the two main tasks, as defined by the main inter-layer interfaces

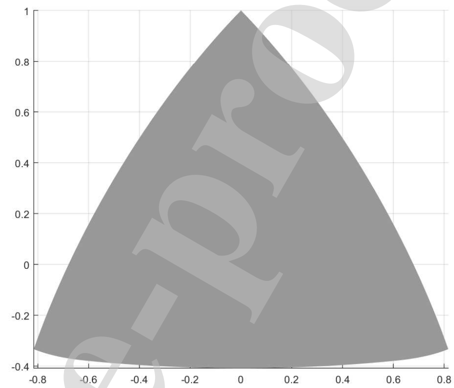
Similarly to XLinGO, a packet's next hop is selected via a contest. The node which maximizes geographic progress of a packet is chosen as a relay. This approach was chosen by the developers of COLSR as they wished to create a design, insensitive to time-dependent topology changes. In order to successfully implement a such task, COLSR is based on following principles:

- Each UAV-node shall be aware of its location at all times
- All UAV-nodes shall be equal in terms of hardware, so that any node can take all possible network roles.

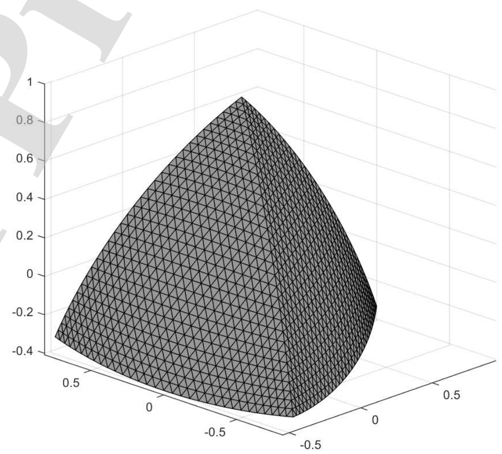
In [80], a simulation of this design's application in a FANET was conducted. Both the physical-MAC and the physical-MAC-network layer combinations were tested. COLSR is capable of using the nodes' geographic information to make the best relay selection and minimize Symbol Error Probability (SEP). COLSR also shows decreased packet error rate in comparison to BOSS [101], as well as low transmission error rate; this allows for: a) high throughput and b) scalable FANET deployments which maintain high end-to-end throughput regardless of swarm size.

4.3.5. Geographic Contention-based Forwarding and Cooperative Communications (CoopGeo)

CoopGeo [102] is a beaconless physical-MAC-network cross-layer design which was created to address issues arising from high mobility in a swarm of UAVs. Its cross-layer nature allows for packet delivery rate to increase and significantly reduce MAC-layer retransmissions - thus, also decreasing energy expenditure. The cross-layer approach allows routing to become more efficient thanks to MAC information on relay-related metrics. Similarly to COLSR (subsection 4.3.4) and XLinGO (subsection 4.3.3), CoopGeo implements a contention-based routing scheme which uses the nodes' positions.



(a) Reuleaux Triangle in a 2D grid



(b) Reuleaux Triangle expanded in a 3D grid

Figure 11: CoopGeo's relay selection area as described in a 2D and 3D space respectively: Reuleaux triangle (top) and Reuleaux tetrahedron (bottom)

Apart from routing, relaying is also contention-based and fully cooperative in order for reliability to be improved. Furthermore, physical-layer feedback allows for higher layers to become aware of physical parameters affecting the FANET's environment. The overall cross-layer architecture of this design, allows routing to consider the "greater good" (global optimum) instead of aiming for a short-sighted optimization (local optimum); inter-layer cooperation allows for a decrease in control messages (which further reduces power consumption and congestion) [102]. This design is comprised of the following sub-schemes:

- An integrated MAC/routing scheme
- A cooperative relaying scheme

Integrated MAC/routing scheme. Before a transmission can occur, the sender-node initiates a contention between its neighboring nodes by broadcasting the packet. At that point, the cross-layer nature of CoopGeo hands the task of contention management to the MAC layer, which also monitors packet progress to its destination. Based on the progress provided to the packet being forwarded, as well as the packet collision probability, the contest eliminates non-suitable candidates. After the forwarding node has been chosen, it is cleared to transmit the packet to its next hop; the aforementioned process is repeated until the packet reaches its destination. CoopGeo implements a chose-and-contest algorithm to avoid routing errors: in case a node considers itself non-suitable to serve as a forwarder despite having (falsely) been chosen by the forwarding contest, it can be relieved of this role.

A cooperative relaying scheme. The cooperative relaying scheme is implemented simultaneous to the aforementioned routing scheme. In the event that a forwarded packet's next hop does not receive it fully intact, the rest of the network cooperates by relaying transmitted packets. The goal of this scheme is to ensure reliability and successful packet delivery in case the chosen forwarding node fails to ensure that on its own. [103] describes the utilized relay-selection scheme which CoopGeo utilizes. This relay selection scheme uses geographic information instead of channel state information, which allows for superior performance in sizable deployments [103] - *which works in favor of network scalability.* The only factor which determines whether or not the best possible relay will be chosen, is the accuracy of provided geographic information. In short, network size does in no way affect a node's relaying ability. In [104], an improvement of CoopGeo is proposed, so that CoopGeo doesn't lose useful relays while trying to avoid the hidden node problem [105]; this is implemented by: a) considering the Reuleaux triangle as the relay area b) considering the Symbol Error Rate (SER) as a relaying metric. Figure 11(a) illustrates the Reuleaux triangle used by CoopGeo for relay selection in a 2D grid. Figure 11(b) illustrates a Reuleaux tetrahedron representing the area of relay selection in a 3D grid. Individual UAVs position themselves at the points of an arbitrary Reuleaux triangle and base their relay choice on its relative position inside the graph. SER is also taken into consideration so as to maximize relaying efficiency.

CoopGeo was simulated and compared against the BOSS protocol [101] using swarms of 4 to 64 UAVs. The results show that CoopGeo offers measurably higher saturated throughput and a lower packet error rate -regardless of the number of neighbors. In conclusion, transmission error probability is non-increasing and significantly lower when using CoopGeo.

4.3.6. Cross-layer Optimized Link State Routing (C-OLSR)

C-OLSR (not to be confused with Contention-based OLSR (subsection 4.3.4)), is a cross-layer FANET routing protocol capable of shielding the network against jamming, while providing additional security services. C-OLSR is based on OLSR (subsection 4.2.8), as many of its services match the requirements set by military networking [81]. Through cross-layer co-operation, the network layer exploits physical-layer information in order to perform route optimizations and reduce packet retransmissions, effectively making the network immune to hostile jamming. This scheme also addresses the main weakness of OLSR: inability to sense link quality. Jamming UAVs is done by introducing high levels of noise to the communication channel, which cause nodes to constantly retransmit lost packets, leading to link failures.

C-OLSR differs from OLSR in the following aspects - witch also constitute the means of network defence against jamming:

- Cross-layer Link Quality Evaluation
- HELLO message upgrade
- Optimization of the MPR algorithm
- Routing calculation

Cross-layer link Quality Evaluation. Cross-layer link Quality Evaluation is service enabled by non-adjacent layer direct communication 4. In order for the packet success rate to be increased, C-OLSR allows the network layer to directly receive data regarding the SNR from the the physical layer. Furthermore, SNR is measured in all first hop neighbors of a source node: the source uses an upgraded HELLO messages to request all its neighbors to reach to the physical layer and calculate their SNR. The neighbor with the greatest SNR value is more likely to become the source's next hop. Each node's "willingness" to become the next hop (=SNR value) is encapsulated into the upgraded HELLO message and used for the optimization of the MPR algorithm.

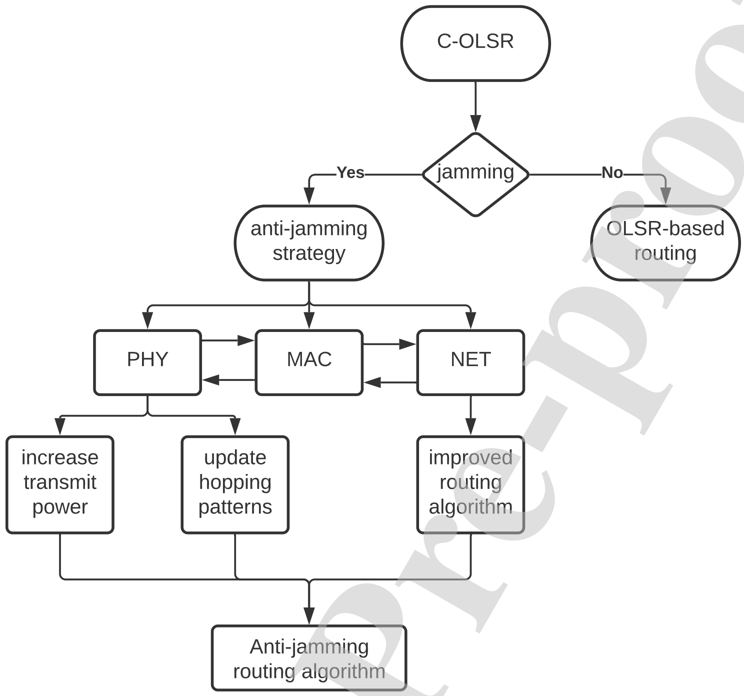


Figure 12: The anti-jamming and OLSR-based interfaces and cross-layer components of C-OLSR

HELLO message upgrade. In traditional OLSR (subsection 4.2.8), HELLO messages are used for link sensing, neighbor detection and MPR signaling. In C-OLSR however, this type of messages are modified so they can carry information regarding the SNR of their sender. The upgraded HELLO messages are at the core of C-OLSR since the cross-layer logic as well as the anti-jamming technique is essentially implemented through them.

Optimization of the MPR algorithm. C-OLSR uses aforementioned SNR parameter to optimize the MPR selection process. C-OLSR bases MPR selection on channel SNR. An SNR threshold is defined, and then neighboring nodes exchange HELLO messages containing their SNR and the most efficient forwarding node is chosen. Each node keeps a "willingness" variable, which quantifies its forwarding ability, depending on whether or not the SNR threshold is reached; the "willingness" parameter is essentially used to select

MPR. Should two first-hop neighboring nodes have an identical "willingness" value, C-OLSR reads the SNR values of their neighbors in order to predict total route noise and make the decision which leads to the global optimum.

Routing calculation. In contrast to traditional OLSR which only uses hop information to form a minimum-hop route, C-OLSR uses the aforementioned SNR information in order to optimize route selection. First, C-OLSR computes possible paths. After possible paths have been established, C-OLSR uses its cross-layering capabilities to measure SNR of each link between hops, which is then used to chose the route which best shields the network against jamming.

C-OLSR was tested on the OMNet platform using 20 highly mobile UAVs, distributed in a 400x400 km grid, with a velocity maxing at 300 m/s (1080 km/h). C-OLSR was compared to the OLSR-ETX protocol [106] in terms of throughput, end-to-end delay and packet loss rate for nine consecutive experiments. During actively jamming the network, C-OLSR maintained a comparatively high throughput with minimal fluctuations. When it comes to throughput, C-OLSR proved to be 142-300% more efficient than OLSR-EXT. Furthermore thanks to its cross-layer nature exploiting physical SNR information, C-OLSR maintained an average end-to-end delay lower than 2ms and a small packet loss rate reaching 2% at a maximum [81].

4.3.7. Mobility Adaptive Cross-layer Routing (MACRO)

This routing scheme was proposed in [107]. MACRO allows the interaction of all five layers (physical, MAC, network, transport, application) to implement route optimization with the goal of maximizing end-to-end reliability and minimizing congestion, link failures and power expenditure alike. It is capable of adapting to changes of network topology.

Flood-caused congestion avoidance. This cross-layer scheme addresses the congestion issue arising from flooding the network with RREQ broadcasted packets by preventing such redundant packets from being sent in the first place. Upon reception of an RREQ packet, a node reaches to the physical layer and calculates the strength of the received signal which is used to update the contents of a received signal strength indication (RSSI) variable. The RSSI value is used to calculate the value of a distance factor (DF) variable. A DF equal to 0 indicates that the RREQ packet's receiver is also the packet's end destination. The closer a node it to the broadcasting one, the higher the DF value it is associated with will be. To avoid congestion, the

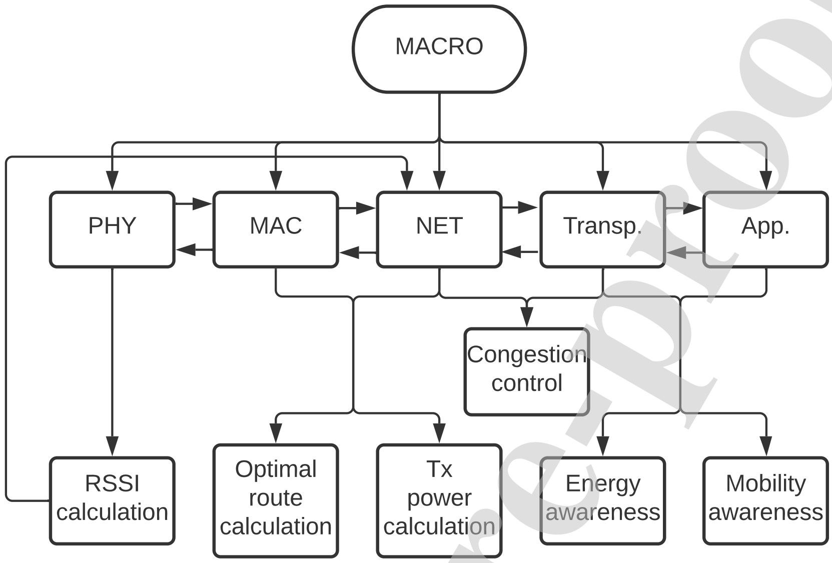


Figure 13: The inter-layer interfaces of MACRO's components and the scheme's achieved results

higher the DF of a node, the longer it will take for it to broadcast. Any necessary re-broadcasting of an RREQ packet only occurs after a local contention between nodes having the same DF value has taken place. Figure 13 illustrates the components and inter-layer communication which enables MACRO to perform described tasks.

Route formation and maintenance. MACRO creates routes by exploiting routing information embedded within the incoming RREQ packet. Each node keeps and updates a cross-layer "relayed packet limit" (RPL) parameter. Both network and transport layer have access to the RPL parameter and use it to perform congestion control; the RPL parameter is unique to each node. This parameter holds the number of packets that can be relayed by the node in a predefined time period. Until this parameter's value exceeds a defined threshold, a node sends a route reply (RREP) packet and it can partake in all route formations. When the value of this parameter reaches its defined threshold, the node is prohibited from taking part in further routing of incoming traffic and is made to drop all packets. Intermediate nodes only maintain next hop information and are not required to know the source of destination. Using a specially designed data forwarding algorithm, MACRO resolves route conflicts arising from the existence of multiple paths to a destination. The data forwarding algorithm considers the following metrics to form the best possible route:

1. Link reliability
2. Number of hops
3. Sequence number of route entry

In order to maintain routes and keep them up-to-date, MACRO utilizes a route management algorithm, which aids in shielding the network from the negative effects of node mobility. More precisely, node velocity and additionally signal strength are considered to address route reliability and perform path maintenance; this information is derived from application and physical layer respectively.

In addition to the above, this routing scheme adjusts transmission power to accommodate different environmental conditions and avoid congestion. An example this adjustment mechanism is the maximization of transmission power for the RTS/CST packets in order to avoid the hidden terminal problem [107]. Each CTS packet contains information which each transmitting node leverages in order to choose transmission power for its data packets.

Macro was simulated on OPNET Modeler using the random waypoint mobility model in a 50x50m grid and a maximum node velocity of 36km/h. It achieved a PDR of almost 100%, with the minimal being 95%, regardless of number of nodes. PDR also proved to be unrelated to node velocity. End-to-end delay is high in comparison to high mobility oriented protocol, yet ranged from (approximately) 900ms to 1.2s regardless of node velocity.

4.3.8. Integrated MAC/Routing Protocol (MACRO)

In [108] a protocol which integrates MAC and routing layers in a single scheme was proposed. Since both this protocol and the one previously analyzed (subsection 4.3.7) both abbreviate as "MACRO", mobility adaptive cross-layer routing will be referred to as "MACRO" and integrated MAC/Routing will be referred to as "MACRO-1". Even though this scheme is not specifically designed for FANETs, it still is worth mentioning due to it's utilization of cross-layering as a means of battery-awareness and power-saving. Using inter-layer provisioning, MACRO allows for power-efficient node-to-node transmissions. MACRO-1's power efficiency is attributed to the following qualities:

- No sharing of geographic locations is required. A transmitting node shall only know of its own location, along with the one of the receiving node.
- MACRO-1 can adjust transmission power of each node and even periodically switch a node's antenna off.

Choosing next hops and routing packets to their destination is a weighted procedure involving nodes deciding on the most efficient route to a packet's destination based on geographic criteria.

The message types used to enable MACRO-1 to periodically activate or deactivate nodes' antennas are the following:

1. Wake-up message
2. Go message

Wake up message: Used to switch peer nodes' antennas back on. It is comprised of several short beacon messages. Upon reception of a WAKE-UP message, nodes shall remain awake until a GO MESSAGE arrives. *Go message*: Used to initiate a "competition" between nodes, as to who will serve as the packet's next hop. It contains information regarding: a) transmission power, b) current maximum weighted progress factor and c) sender's and receiver's location [108].

MACRO-1 finds excellent application in WSNs, thanks to its power-saving capability. When compared to GPSR (subsection 4.2.4), number of required hops are increased, while energy consumption drops. Overall end-to-end delay is increased. This protocol is usable in non time-critical off-grid scenarios, where reduction of power consumption and battery awareness is the highest priority. This scheme supports scalability and in fact demands it, in order to increase network coverage and decrease transmission power.

Cross-layer protocols: summary and comparison. This section is dedicated to comparing the cross-layer schemes and designs which were analyzed in this paper. Table 7 summarizes the main characteristics (and main selling points) of each scheme. Similarly, table 8 checks the application-specific criteria addresses by each cross-layer routing scheme. Table 9 explains the advantages and possible shortcomings of each scheme. Furthermore, in this section a final analysis of the cross-layer schemes is conducted, with the ultimate goal of finding the ideal routing scheme for 3D FANET deployments.

It is quite obvious that classically layered protocols are significantly more mature and somewhat generic, while the newer cross-layer ones can get intensely application-specific. This occurs because different cross-layer schemes implement inter-layer provisioning in a a manner that is best suited for their intended use-case. For example, both CoopGeo and XLinGO are beaconless, contention-based, cross-layer designs which use geographic information to form packet routes; yet they are vastly different - to the point where no comparison between them is even meaningful. For this reason, a protocol can only be recommended in the frame of a specific application.

Cross-layer scheme	Main Characteristic	Application Class
IMAC-UAV & DOLSR	Multi-altitude directional routing	Not application-specific
MMA	MAC & network layer form a single algorithm	Surveillance & tactical applications
XLinGO	Multimedia-oriented routing in FANETs	Surveillance & monitoring
COLSR	Desensitizes swarm against node attitude changes	Surveillance in harsh environments
C-OLSR	Anti-jamming scheme	Military networking
CoopGeo	Route establishment using only node location	Not application-specific
MACRO	1) Robust 2) High PDR	Remote sensing
MACRO-1	1) Battery-aware 2) Geographic routing	WSNs

Table 7: Cross-layer protocols' main characteristics and applications

By closely examining the tables of this section, it can be concluded that as a general-purpose cross-layer routing scheme, IMAC-UAV & DOLSR (subsection 4.3.1) seems to be possibly the safest choice, since it combines low-latency with (omni)directional transmissions enabled by DOLSR. Furthermore, since this design's routing scheme is based on OLSR (subsection 4.2.8), it maintains the functionality is offers in terms of applicability in 3D

Cross-layer scheme	Directional routing	Energy awareness	Geographic routing	Link quality awareness	QoS/QoE awareness	High node mobility	Scalability
	Inherently implemented support for:						
IMAC-UAV & DOLSR	High	Medium	High	No	No	Medium	N/A
MMA	High	No	High	No	No	High	High
XLinGO	No	High	Medium	Medium	High	Medium	N/A
COLSR	No	Medium	High	Medium	No	N/A	High
C-OLSR	No	No	No	High	High	High	N/A
CoopGeo	No	Medium	High	No	No	Medium	High
MACRO	No	Medium	No	High	Medium	Low	High
MACRO-1	No	High	High	No	No	No	High

Table 8: Cross-layer schemes application-specific comparison points

FANET deployments and scalability. Similarly, COLSR (subsection 4.3.4) and C-OLSR (subsection 4.3.6) maintain OLSR's 3D FANET-friendly characteristics and therefore constitute safe choices as well, depending on the use-case.

MMA (subsection 4.3.2) offers a reliable high-throughput routing scheme which can keep an impressively low packet loss rate even when tested with 75 nodes, which is the largest number of nodes in all the cross-layer schemes addressed in this paper. MMA is ideal for scalable and robust FANET deployments requiring a high throughput in non real-time applications (e.g. smart farming, remote sensing and natural disaster assessment).

XLinGO (subsection 4.3.3) is obviously the most multimedia-oriented of all the examined designs. Its capability of congestion elimination and reduction of bandwidth wastage render it an unparalleled choice in the field of real-time military/civilian surveillance and monitoring as well as the relaying of real-time multimedia content.

COLSR (subsection 4.3.4) is capable of maintaining an impressive through-

Cross-layer scheme	Advantages	Disadvantages
IMAC-UAV & DOLSR	1) Considers channel BER, UAV attitude & location 2) Directional antennas decrease number of hops 3) Supports multi-altitude FANET deployments 4) Low end-to-end delay	Requires directional antennas
MMA	1) Allows for scalability 2) High throughput 3) Added nodes do not affect end-to-end delay	1) Considerable end-to-end delay 2) Requires directional antennas
XLinGO	1) Video timeliness & transmission reliability [21] 2) Eliminates congestion 3) Reduces bandwidth wastage	Node mobility & link quality not addressed
COLSR	High throughout regardless of swarm size	Low PDR
C-OLSR	1) Minimal end-to-end delay 2) Unaffected by high mobility 3) High packet delivery ratio	Avoidance of low-SNR routes may cause longer packet paths
CoopGeo	1) Location-based routing 2) Reduced overhead, independent of packet path 3) High saturation throughput	Low PDR
MACRO	1) Reliable 2) Supports network scalability	1) Considerable end-to-end delay 2) Not suitable for high-mobility FANET deployments
MACRO-1	1) Battery-aware 2) Excellent for off-grid WSNs	Considerable end-to-end delay

Table 9: Cross-layer protocols' advantages and disadvantages

put regardless of the number of nodes participating in the network. Thanks to low layers informing higher layers of UAV attitude changes, COLSR can desensitize a FANET against sudden attitude changes of individual UAVs. For the reasons mentioned above, COLSR can be recommended for scalable, 3D FANET-enabled surveillance in extremely harsh environmental conditions (e.g. post-disaster search and rescue missions) demanding a fine-tuned routing scheme to match high-mobility physical requirements.

CoopGeo (subsection 4.3.5) significantly reduces communication overhead in saturation conditions. Routing using this protocol only depends on geographic location; packets do not need to carry path information. It is highly suitable for high-mobility scalable swarms operating in a lossy environment.

C-OLSR (subsection 4.3.6) is an excellent choice for military/battlefield operations which require that a FANET deployment be sent in a hostile environment with the possibility of intentional jamming by adversaries. By employing a defensive cross-layer OLSR-based routing approach, a 3D FANET shall be able to efficiently perform desired functions while avoiding "dangerous" low-SNR routes that would incapacitate the network.

MACRO (subsection 4.3.7) is another excellent choice for moderately mobile networks in non real-time applications (e.g. remote sensing). It is the most genuinely "cross" layer protocol since the developers made sure every single OSI layer actively takes part in inter-layer information exchange. It has showed to be robust and ideal for scalable deployments, since its QoS is completely unaffected by the number of nodes comprising the network or their velocity.

MACRO-1 (subsection 4.3.8) is not primarily focused on FANETs, but rather WSNs. UAVs are not required to be aware of all their peers' location: they can route by knowing solely the location of the packet destination. MACRO's energy-aware and power-saving capabilities make it usable for off-grid remote sensing scenarios where UAV autonomy and mission duration is at the center.

5. Conclusion and Possible Extensions

5.1. Summary

This survey has critically reviewed, compared and evaluated legacy and cross-layer routing schemes alike, as well as the application and performance thereof in 3D (multi-altitude) FANET deployments. Matters of power consumption, congestion control, overhead, security and network scalability were thoroughly investigated. Furthermore, application classes were assigned to each protocol by considering scheme-specific parameters as well as performance under different mobility scenarios.

Cross-layer schemes are certainly not as mature as their classically layered legacy counterparts. As addressed in [89], compartmentalization of an architecture's layers enables designers to work with different protocol modules in a black-box way, without them being concerned with how other layers are affected stack-wide. Cross-layering takes this design-level advantage away, as it forces developers to think of the entire protocol stack, scheme-wide interdependencies on an communication architecture or even system scale. The choice between those two vastly different approaches (legacy stacking vs cross-layering) boils down to leaving the layer stack "comfort zone" in search of efficiency and configurability. Cross-layering introduces not only the possibility of inter-layer feedback provisioning (e.g. consideration of battery voltage as a routing metric for the establishment of next hops and MPRs, consideration of sensor-layer proximity data for collision avoidance) but also dependencies and potential overhead, as expressed by V. Kawadia et al. [89].

By definition, a cross-layer design, introduces inter-layer cooperation and dependencies to optimize network performance. Without proper care and consideration at a programming level, cross-layer designs can cause "spaghetti-like" code that can not possibly be efficiently maintained [109]. Lack of standardization and sufficient testbed frameworks for the implementation of non-legacy designs must be addressed in order for this emerging class of designs to establish themselves as viable alternatives to existing legacy schemes. This class of routing schemes is certainly not to be blindly accepted and to be considered as a nostrum, rather as an interesting alternative to classical networking which still requires a substantial amount of work to reach real-world applicability.

5.2. Open Issues and Future Work

In addition to further research on cross-layer architectures' compartmentalization and standardization, more investigation should be oriented towards 3D deployments. As of 2020, no significant amount of research and development has been centered around 3D FANET deployments, which leaves an entire realm of aerial communications partly undiscovered. More simulations and research in this domain should be conducted. Existing protocols (both legacy and cross-layer ones) can (and should) offer routing optimizations specialized for networks deployed in a 3D aerial grid. A possible extension of the analyzed work is the integration of security optimizations that can be found in legacy-layer derivatives of e.g. OLSR. into cross-layer schemes stemming from the same protocol.

On an experimental level, cross-layer routing schemes have not been tested as of yet. For accurate performance analysis and evaluation, real-life tests of such schemes shall imperatively be conducted. Such testing and evaluation can be performed using conventional wireless networking equipment. OLSRd (and hence OLSR-derived schemes) seems a valid choice as a scheme foundation on a software level due to its open-source availability, configurability and its relatively light computational demands enabling it to be implemented on low-power hardware. Cross-layer optimizations shall therefore be implemented anew as the need for the development of an embedded hardware and software routing test-bed arises. Swarm simulators such as the one developed in [110] as well as MPR selection modellers like the one developed in [111] can be used in combination with a such embedded framework to extract more precise and valuable performance-related information for an even more accurate scheme evaluation. Apart from the enhancement of network simulation software to accommodate cross-layer schemes, experimental hardware-based evaluation would be a step towards the standardization and evaluation of such designs in near deployment-like conditions. Protocols which may prove usable for real-world evaluation include but are not limited to OLSRd and other protocols available as Linux kernel installations.

A significant amount of further research and development is required in order for cross-layer designs to obtain guaranteed longevity and sustainability, and also to reach the levels of maturity offered by legacy routing schemes. Given the amount of work that has already been channeled to implementation of cross-layer designs, there already exist sufficiently advanced and mature schemes that can be used in an actual deployment and the landscape is rather promising.

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References

[1] J. Johnson, Artificial Intelligence, Drone Swarming and Escalation Risks in Future Warfare, RUSI Journal 165 (2020) 26–36.

[2] M. Lehto, B. Hutchinson, Mini-drones swarms and their potential in conflict situations, Proceedings of the 15th International Conference on Cyber Warfare and Security, ICCWS 2020 (2020) 326–334.

[3] M. Di Felice, A. Trotta, L. Bedogni, K. R. Chowdhury, L. Bononi, Self-organizing aerial mesh networks for emergency communication, IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC 2014-June (2014) 1631–1636.

[4] Y. Guo, X. Li, H. Yousefi'zadeh, H. Jafarkhani, UAV-aided cross-layer routing for MANETs, IEEE Wireless Communications and Networking Conference, WCNC (2012) 2928–2933.

[5] I. Maza, F. Caballero, J. Capitán, J. R. Martínez-De-Dios, A. Ollero, Experimental results in multi-UAV coordination for disaster management and civil security applications, in: Journal of Intelligent and Robotic Systems: Theory and Applications, volume 61, pp. 563–585.

[6] A. Nikitas, K. Michalakopoulou, E. T. Njoya, D. Karampatzakis, Artificial intelligence, transport and the smart city: Definitions and dimensions of a new mobility era, Sustainability (Switzerland) 12 (2020) 1–19.

[7] S. Cameron, S. Hailes, S. Julier, S. McClean, G. Parr, N. Trigoni, M. Ahmed, G. McPhillips, R. de Nardi, J. Nie, A. Symington, L. Teacy, S. Waharte, SUAAVE: Combining aerial robots and wireless networking, 25th Bristol International UAV Systems Conference (2010) 1–14.

[8] A. Ollero, K. Kondak, E. Previnaire, I. Maza, F. Caballero, M. Bernard, J. R. Martinez, P. Marrón, K. Herrmann, L. Van Hoesel, J. Lepley, E. De Andrés, Integration of aerial robots and wireless

sensor and actuator networks. The AWARE project, Proceedings - IEEE International Conference on Robotics and Automation (2010) 1104–1105.

[9] T. Lagkas, V. Argyriou, S. Bibi, P. Sarigiannidis, UAV IoT framework views and challenges: Towards protecting drones as "things", Sensors (Switzerland) 18 (2018).

[10] P. Radoglou-Grammatikis, P. Sarigiannidis, T. Lagkas, I. Moscholios, A compilation of UAV applications for precision agriculture, Computer Networks 172 (2020).

[11] G. Kakamoukas, P. Sariciannidis, G. Livanos, M. Zervakis, D. Ramnalis, V. Polychronos, T. Karamitsou, A. Folinas, N. Tsitsiokas, A Multi-collective, IoT-enabled, Adaptive Smart Farming Architecture, IST 2019 - IEEE International Conference on Imaging Systems and Techniques, Proceedings (2019).

[12] A. Triantafyllou, P. Sarigiannidis, S. Bibi, Precision agriculture: A remote sensing monitoring system architecture, Information (Switzerland) 10 (2019).

[13] D. C. Tsouros, S. Bibi, P. G. Sarigiannidis, A review on UAV-based applications for precision agriculture, Information (Switzerland) 10 (2019).

[14] N. J. Egarguin, D. R. Jackson, D. Onofrei, J. Leclerc, A. Becker, Adaptive beamforming using scattering from a drone swarm, Proceedings of the 2020 IEEE Texas Symposium on Wireless and Microwave Circuits and Systems: Making Waves in Texas, WMCS 2020 (2020).

[15] S. Mann, C. Pierce, J. Hernandez, Q. Li, B. C. Zheng, Y. Xin Xiang, Drone Swarms for Sensing-of-Sensing, Proceedings of IEEE Sensors 2019-Octob (2019) 23–26.

[16] A. Guillen-Perez, M. D. Cano, Flying ad hoc networks: A new domain for network communications, Sensors (Switzerland) 18 (2018).

[17] M. F. Khan, K. L. A. Yau, R. M. Noor, M. A. Imran, Routing schemes in FANETs: A survey, Sensors (Switzerland) 20 (2020) 1–33.

[18] O. S. Oubbati, A. Lakas, F. Zhou, M. Güneş, M. B. Yagoubi, A survey on position-based routing protocols for Flying Ad hoc Networks (FANETs), Vehicular Communications 10 (2017) 29–56.

[19] A. Mukherjee, N. Dey, S. Satapathy, Flying Ad-hoc Networks : A Comprehensive Survey, in: Information and decision sciences, Vijaywara, AP, India, pp. 569–580.

[20] I. Bekmezci, O. K. Sahingoz, Temel, Flying Ad-Hoc Networks (FANETs): A survey, Ad Hoc Networks 11 (2013) 1254–1270.

[21] Q. Sang, H. Wu, L. Xing, P. Xie, Review and Comparison of Emerging Routing Protocols in Flying Ad Hoc Networks, Symmetry 12 (2020) 971.

[22] M. A. Khan, A. Safi, I. M. Qureshi, I. U. Khan, Flying ad-hoc networks (FANETs): A review of communication architectures, and routing protocols, 2017 1st International Conference on Latest Trends in Electrical Engineering and Computing Technologies, INTELLECT 2017 2018-Janua (2018) 1–9.

[23] A. Chriki, H. Touati, H. Snoussi, F. Kamoun, FANET: Communication, mobility models and security issues, Computer Networks 163 (2019).

[24] A. Srivastava, J. Prakash, Future FANET with application and enabling techniques: Anatomization and sustainability issues, Computer Science Review 39 (2021) 100359.

[25] T. Camp, J. Boleng, V. Davies, A survey of mobility models for ad hoc network research, Wireless Communications and Mobile Computing 2 (2002) 483–502.

[26] O. Bouachir, A. Abrassart, F. Garcia, N. Larrieu, A mobility model for UAV ad hoc network, 2014 International Conference on Unmanned Aircraft Systems, ICUAS 2014 - Conference Proceedings (2014) 383–388.

[27] E. Kuiper, S. Nadjm-Tehrani, Mobility models for UAV group reconnaissance applications, Second International Conference on Wireless and Mobile Communications, ICWMC 2006 00 (2006) 2–8.

[28] Xianfeng Li, Tao Zhang, Jianfeng Li, A Particle Swarm Mobility Model for Flying Ad Hoc Networks, in: IEEE Global Communications Conference (GLOBECOM).

[29] G. A. Kakamoukas, P. G. Sarigiannidis, A. A. Economides, FANETs in Agriculture - A routing protocol survey, Internet of Things (2020) 100183.

[30] M. Khaki, A. Ghasemi, The impact of mobility model on handover rate in heterogeneous multi-tier wireless networks, Computer Networks 182 (2020).

[31] K. Kabilan, N. Bhalaji, C. Selvaraj, M. Kumaar B, K. P T R, Performance analysis of IoT protocol under different mobility models, Computers and Electrical Engineering 72 (2018) 154–168.

[32] T. Zhang, G. Liu, H. Zhang, W. Kang, G. K. Karagiannidis, A. Nallanathan, Energy-Efficient Resource Allocation and Trajectory Design for UAV Relaying Systems, IEEE Transactions on Communications (2020) 1–1.

[33] F. Shan, J. Luo, R. Xiong, W. Wu, J. Li, Looking before Crossing: An Optimal Algorithm to Minimize UAV Energy by Speed Scheduling with a Practical Flight Energy Model, Proceedings - IEEE INFOCOM 2020-July (2020) 1758–1767.

[34] N. Meghanathan, Impact of the Gauss-Markov mobility model on network connectivity, lifetime and hop count of routes for mobile Ad hoc networks, Journal of Networks 5 (2010) 509–516.

[35] W. Wang, X. Guan, B. Wang, Y. Wang, A novel mobility model based on semi-random circular movement in mobile ad hoc networks, Information Sciences 180 (2010) 399–413.

[36] S. Maakar, Y. Singh, R. Singh, Performance Investigation of OLSR and AODV Routing Protocols for 3D FANET Environment using NS3 Network Security View project M.Tech View project, Technical Report, 2018.

[37] A. K. Gupta, H. Sadawarti, A. K. Verma, Performance Analysis of MANET Routing Protocols in Different Mobility Models, International

Journal of Information Technology and Computer Science 5 (2013) 73–82.

[38] D. K. Sah, T. Amgoth, Parametric survey on cross-layer designs for wireless sensor networks, Computer Science Review 27 (2018) 112–134.

[39] K. Chen, S. H. Shah, K. Nahrstedt, Cross-layer design for data accessibility in mobile ad hoc networks, Wireless Personal Communications 21 (2002) 49–76.

[40] S. Qadir, A. A. Kist, Z. Zhang, QoE-aware cross-layer architecture for video traffic over internet, IEEE TENSYMP 2014 - 2014 IEEE Region 10 Symposium (2014) 522–526.

[41] A. Abdulqader, B. Salem, T.-c. Wan, Y.-w. Chong, A. N. Naeem, Review of Cross-layer Solutions for Packet Loss Review of Cross-layer Solutions for Packet Loss 5 (2013).

[42] S. Shakkottai, T. S. Rappaport, P. C. Karlsson, Cross-layer design for wireless networks, IEEE Communications Magazine 41 (2003) 74–80.

[43] M. Salayma, A. Al-Dubai, I. Romdhani, M. B. Yassein, Battery aware beacon enabled IEEE 802.15.4: An adaptive and cross-layer approach, Proceedings of the 2015 Federated Conference on Computer Science and Information Systems, FedCSIS 2015 5 (2015) 1267–1272.

[44] P. I. Radoglou Grammatikis, P. G. Sarigiannidis, I. D. Moscholios, Securing the Internet of Things: Challenges, threats and solutions, Internet of Things 5 (2019) 41–70.

[45] I. f. I. R. Vineet Srivastava, N. U. of Singapore, N. U. o. S. Mehul Motani, Cross-Layer Design: A Survey and the Road Ahead, IEEE Communications Magazine 43 (2005) 112 – 119.

[46] F. Foukalas, V. Gazis, N. Alonistioti, Cross-layer design proposals for wireless mobile networks: A survey and taxonomy, 2008.

[47] D. Yang, X. Li, R. Sawhney, X. Wang, Geographic and energy-aware routing in Wireless Sensor Networks, International Journal of Ad Hoc and Ubiquitous Computing 4 (2009) 61–70.

[48] S. Yessad, N. Tazarart, L. Bakli, L. Medjkoune-Bouallouche, D. Aissani, Balanced energy efficient routing protocol for WSN, International Conference on Communications and Information Technology - Proceedings (2012) 326–330.

[49] W. R. Heinzelman, A. Chandrakasan, H. Balakrishnan, Energy-Efficient Communication Protocol for Wireless Microsensor Networks, Technical Report, 2000.

[50] F. De Rango, M. Fotino, S. Marano, EE-OLSR: Energy efficient OLSR routing protocol for mobile ad-hoc networks, Proceedings - IEEE Military Communications Conference MILCOM (2008).

[51] Mehmet C. Vuran, Ian F. Akyildiz, XLP A Cross-Layer Protocol for Efficient Communication in Wireless Sensor Networks, IEEE Transactions on Mobile Computing 9 (2010) 1578 – 1591.

[52] J. Wang, G. L. Smith, A cross-layer authentication design for secure video transportation in wireless sensor network, International Journal of Security and Networks 5 (2010) 63–76.

[53] L. Zhu, Y. Li, F. R. Yu, B. Ning, T. Tang, X. Wang, Cross-Layer Defense Methods for Jamming-Resistant CBTC Systems, IEEE Transactions on Intelligent Transportation Systems (2020) 1–13.

[54] N. N. Shenets, Security Infrastructure of FANET Based on Secret Sharing and Authenticated Encryption, Automatic Control and Computer Sciences 53 (2019) 857–864.

[55] V. Bhardwaj, N. Kaur, SEEDRP : a Secure Energy Efficient Dynamic Routing Protocol in Fanets, Wireless Personal Communications (2021).

[56] D. P. Wiggins, Scalability features of the WNaN routing protocol, Proceedings - IEEE Military Communications Conference MILCOM (2011) 861–865.

[57] C. Konstantopoulos, D. Gavalas, G. Pantziou, A mobility aware technique for clustering on mobile ad-hoc networks, in: Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), volume 4308 LNCS, pp. 397–408.

[58] H. Claus Christmann, E. N. Johnson, Design and implementation of a self-configuring ad-hoc network for unmanned aerial systems, in: Collection of Technical Papers - 2007 AIAA InfoTech at Aerospace Conference, volume 1, pp. 698–704.

[59] H. C. Christmann, SELF-CONFIGURING AD-HOC NETWORKS FOR UNMANNED AERIAL SYSTEMS, Technical Report, 2008.

[60] S. Rosati, K. Kruzelecki, G. Heitz, D. Floreano, B. Rimoldi, Dynamic Routing for Flying Ad Hoc Networks, IEEE Transactions on Vehicular Technology 65 (2016) 1690–1700.

[61] A. Khan, F. Aftab, Z. Zhang, Self-organization based clustering scheme for FANETs using Glowworm Swarm Optimization, Physical Communication 36 (2019) 100769.

[62] H. Yang, Z. Liu, An optimization routing protocol for FANETs, Eurasip Journal on Wireless Communications and Networking 2019 (2019).

[63] H. N. Saad, Z. Abbas Harbi, H. Abbas Salman, Hybrid DSR: Evaluating AODV-Hello Messages on DSR Protocol, 2019.

[64] C. E. Perkins, E. M. Royer, Ad-hoc on-demand distance vector routing, in: Proceedings - WMCSA'99: 2nd IEEE Workshop on Mobile Computing Systems and Applications, pp. 90–100.

[65] B. Deokate, C. Lal, D. Trček, M. Conti, Mobility-aware cross-layer routing for peer-to-peer networks, Computers and Electrical Engineering 73 (2019) 209–226.

[66] S. Hou, M. Wu, W. Liao, D. Wang, Performance comparison of AODV and DSR in MANET test-bed based on Internet of Things, 2015 IEEE 82nd Vehicular Technology Conference, VTC Fall 2015 - Proceedings (2016) 3–7.

[67] A. Garcia-Santiago, J. Castaneda-Camacho, J. F. Guerrero-Castellanos, G. Mino-Aguilar, Evaluation of AODV and DSDV routing protocols for a FANET: Further results towards robotic vehicle networks, 9th IEEE Latin American Symposium on Circuits and Systems, LASCAS 2018 - Proceedings (2018) 1–4.

[68] R. Ogier, F. Templin, M. Lewis, Topology Dissemination Based on Reverse-Path Forwarding (TBRPF), Technical Report, 2004.

[69] B. Bellur, R. G. Ogier, A reliable, efficient topology broadcast protocol for dynamic networks, Proceedings - IEEE INFOCOM 1 (1999) 178–186.

[70] B. Karp, H. T. Kung, Greedy Perimeter Stateless Routing for Wireless Networks(GPSR), Proceedings of the Annual International Conference on Mobile Computing and Networking, MOBICOM (2000).

[71] R. L. Lidowski, B. E. Mullins, R. O. Baldwin, A novel communications protocol using geographic routing for swarming UAVs performing a search mission, 7th Annual IEEE International Conference on Pervasive Computing and Communications, PerCom 2009 (2009).

[72] D. Medina, F. Hoffmann, F. Rossetto, C. H. Rokitansky, North atlantic inflight internet connectivity via airborne mesh networking, IEEE Vehicular Technology Conference (2011).

[73] L. Lin, Q. Sun, S. Wang, F. Yang, A geographic mobility prediction routing protocol for Ad Hoc UAV Network, 2012 IEEE Globecom Workshops, GC Wkshps 2012 (2012) 1597–1602.

[74] T. Clausen, P. Jacquet, C. Adjih, A. Laouityi, Optimized link state routing protocol (OLSR), Network Working Group (2003).

[75] R. Jain, I. Kashyap, An QoS Aware Link Defined OLSR (LD-OLSR) Routing Protocol for MANETS, Wireless Personal Communications 108 (2019) 1745–1758.

[76] S. Rosati, K. Kruzelecki, L. Traynard, B. Rimoldi, Speed-aware routing for UAV ad-hoc networks, 2013 IEEE Globecom Workshops, GC Wkshps 2013 (2013) 1367–1373.

[77] A. I. Alshabtat, L. Dong, Low latency routing algorithm for unmanned aerial vehicles ad-hoc networks, World Academy of Science, Engineering and Technology 80 (2011) 705–711.

[78] J. Liu, X. Ji, C. Huang, X. Tan, A novel OLSR protocol with mobility prediction, IET Conference Publications 2015 (2015).

[79] D. A. M. José, R. F. Bulcão-Neto, V. S. Patto, I. G. Sene Júnior, OLSR fuzzy cost (OLSR-FC): An extension to olsr protocol based on fuzzy logic and applied to avoid selfish nodes, Revista de Informatica Teorica e Aplicada 26 (2019) 60–77.

[80] Y. Li, X. Luo, Cross layer optimization for cooperative mobile ad-hoc UAV network, International Journal of Digital Content Technology and its Applications 6 (2012) 367–375.

[81] X. Fan, J. Lin, C. Zhang, S. Zhang, A cross-layer anti-jamming routing protocol for FANETS, 2018 IEEE 4th International Conference on Computer and Communications, ICCC 2018 (2018) 301–305.

[82] D. gan Zhang, Y. ya Cui, T. Zhang, New quantum-genetic based OLSR protocol (QG-OLSR) for Mobile Ad hoc Network, Applied Soft Computing Journal 80 (2019) 285–296.

[83] E. V. Shcherba, G. A. Litvinov, M. V. Shcherba, A Novel Reputation Model for Trusted Path Selection in the OLSR Routing Protocol, International Conference on Information Science and Communications Technologies: Applications, Trends and Opportunities, ICISCT 2019 (2019).

[84] E. V. Shcherba, G. A. Litvinov, M. V. Shcherba, Securing the Multipath Extension of the OLSR Routing Protocol, 13th International IEEE Scientific and Technical Conference Dynamics of Systems, Mechanisms and Machines, Dynamics 2019 - Proceedings (2019) 1–4.

[85] M. T. Lwin, Y. B. Ko, D. Kim, When blockchain takes care of the OLSR network, Proceedings - International Conference on Computer Communications and Networks, ICCCN 2019-July (2019).

[86] J. H. Forsmann, R. E. Hiromoto, J. Svoboda, A time-slotted on-demand routing protocol for mobile ad hoc unmanned vehicle systems, Unmanned Systems Technology IX 6561 (2007).

[87] C. E. Perkins IBM, T. Watson, P. Bhagwat, Highly Dynamic Destination-Sequenced Distance-Vector Routing (DSDV) for Mobile Computers, ACM SIGCOMM Computer Communication Review 24 (1999).

[88] R. Kiruthika, R. Umarani, An exploration of count-to-infinity problem in networks, International Journal of Engineering Science and Technology 2 (2010) 7155–7159.

[89] V. Kawadia, P. R. Kumar, A cautionary perspective on cross-layer design, IEEE Wireless Communications 12 (2005) 3–11.

[90] R. Gunasekaran, H. Qi, XLRP: Cross layer routing protocol for wireless sensor networks, IEEE Wireless Communications and Networking Conference, WCNC (2008) 2135–2140.

[91] D. Shu, A. K. Saha, D. B. Johnson, RMAC: A routing-enhanced duty-cycle MAC protocol for wireless sensor networks, Proceedings - IEEE INFOCOM (2007) 1478–1486.

[92] A. I. Alshbatat, L. Dong, Cross layer design for mobile ad-hoc unmanned aerial vehicle communication networks, in: 2010 International Conference on Networking, Sensing and Control, ICNSC 2010, May 2010, pp. 331–336.

[93] A. I. Alshbatat, L. Dong, Adaptive MAC protocol for UAV communication networks using directional antennas, 2010 International Conference on Networking, Sensing and Control, ICNSC 2010 (2010) 598–603.

[94] J. Guo, P. Walk, H. Jafarkhani, Optimal deployments of UAVs with directional antennas for a power-efficient coverage, IEEE Transactions on Communications 6778 (2020) 1–1.

[95] Megha N, Performance Evaluation of Routing Protocol for FANET using Ns2, International Journal of Engineering Research and V9 (2020) 1128–1132.

[96] A. I. Alshbatat, L. Dong, Performance Analysis of Mobile Ad Hoc Unmanned Aerial Vehicle Communication Networks with Directional Antennas, International Journal of Aerospace Engineering 2010 (2010) 1–14.

[97] W. Huba, N. Shenoy, Airborne Surveillance Networks with Directional Antennas, International Conference on Networking and Services Airborne (2012) 1–7.

[98] W. Huba, N. Martin, Y. Al-Mousa, C. Orakwue, N. Shenoy, A distributed scheduler for airborne backbone networks with directional antennas, 2011 3rd International Conference on Communication Systems and Networks, COMSNETS 2011 (2011) 1–4.

[99] D. Rosario, Z. Zhao, T. Braun, E. Cerqueira, A. Santos, I. Alyafawi, Opportunistic routing for multi-flow video dissemination over Flying Ad-Hoc Networks, Proceeding of IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks 2014, WoWMoM 2014 (2014).

[100] D. Rosário, Z. Zhao, T. Braun, E. Cerqueira, A. Santos, A comparative analysis of beaconless opportunistic routing protocols for video dissemination over flying ad-hoc networks, Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) 8638 LNCS (2014) 253–265.

[101] J. A. Sanchez, R. Marin-Perez, P. M. Ruiz, BOSS: Beacon-less on demand strategy for geographic routing in wireless sensor networks, 2007 IEEE Internatonal Conference on Mobile Adhoc and Sensor Systems, MASS (2007).

[102] T. Aguilar, M. C. Ghedira, S.-J. Syue, V. Gauthier, H. Afifi, C.-L. Wang, A Cross-Layer Design Based on Geographic Information for Cooperative Wireless Networks (2010) 1–5.

[103] C. L. Wang, S. J. Syue, A geographic-based approach to relay selection for wireless ad hoc relay networks, IEEE Vehicular Technology Conference (2009) 1–5.

[104] C. L. Wang, S. J. Syue, T. T. Chen, On the relaying area of contention-based geographic relay selection for cooperative wireless networks, 2011 IEEE Wireless Communications and Networking Conference, WCNC 2011 (2011) 293–297.

[105] A. Tsertou, D. I. Laurenson, Insights into the hidden node problem, IWCMC 2006 - Proceedings of the 2006 International Wireless Communications and Mobile Computing Conference 2006 (2006) 767–772.

[106] B. Hamdaoui, H. Sinky, Optimized link state routing for quality-of-service provisioning: implementation, measurement, and performance

evaluation, Wireless Communications and Mobile Computing (2015) 421–430.

[107] S. Cakici, I. Erturk, S. Atmaca, A. Karahan, A novel cross-layer routing protocol for increasing packet transfer reliability in mobile sensor networks, Wireless Personal Communications 77 (2014) 2235–2254.

[108] D. Ferrara, L. Galluccio, A. Leonardi, G. Morabito, S. Palazzo, MACRO: An integrated MAC/routing protocol for geographic forwarding in wireless sensor networks, Proceedings - IEEE INFOCOM 3 (2005) 1770–1781.

[109] M. Conti, G. Maselli, G. Turi, S. Giordano, Cross-Layering in Mobile Ad Hoc Network Design, Computer 37 (2004).

[110] E. Soria, F. Schiano, D. Floreano, SwarmLab: a Matlab Drone Swarm Simulator (2020).

[111] M. Saleh, MPR Selection in OLSR protocol, 2020.

Conflict of interest

The authors declare that there is no conflict of interests regarding the publication of this article.