# A Hybrid SDN-based Architecture for Secure and QoS aware Routing in Space-Air-Ground Integrated Networks (SAGINs)

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***Abstract*—The dawn of near 100% global coverage and Tbps data rates is not far as the six generation (6G) networks official roll out is expected around 2030. To match these expectations, new paradigm shifts in terms of global coverage and utilised spectrum are currently under investigation. Space-Air-Ground Integrated Networks (SAGINs) are envisaged to be an integral part of 6G networks to achieve network connectivity anywhere on earth using terrestrial, aerial, and satellite communications. However, the provision of end-to-end routes in SAGIN is very complex given its multi-dimensional, multi-tier, and heterogenous nature. Moreover, satisfying the Quality of Service (QoS) requirements and security of these routes is not trivial in SAGINs. In this paper, a novel hybrid Software Defined Networking (SDN)-based architecture for secure and QoS aware routing in SAGINs is proposed. Using Multiple SDN controllers at different levels in SAGINs, the architecture follows a hierarchical structure with different routing provisioning layers, at different levels, to exploit the heterogeneity of SAGINs to find multiple routes that satisfy the security and QoS requirements. To illustrate its efficiency, a case study of Vehicle-to-Everything (V2X) technology is used to show how an end-to-end charging service, for an electric vehicle, can be built on top of the proposed architecture.**

***Keywords—6G, Non-Terrestrial Networks (NTN), SAGIN, QoS, Routing, Security, V2X***

## I. INTRODUCTION

Around 2030, the official roll out of the six generation (6G) networks is expected to meet the demands of mobile communications. The fifth generation (5G) networks will reach its limits by then given the current annual growth of approximately 27% in mobile traffic [1]. 6G is envisaged to provide global coverage and Tbps level transmission data rates for applications such as Virtual Reality (VR), 3D videos, and Augmented Reality (AR). Besides higher data rates, 6G should provide lower latency, higher connection density, and near 100% global coverage in comparison to 5G. To achieve these goals, new paradigm shifts are currently under investigation in terms of global coverage, utilised spectrum, Artificial Intelligence (AI) nativity, and security [2]. In terms of global coverage, 6G will not be bound by terrestrial communication networks and will integrate Non-Terrestrial Networks (NTN) such as Unmanned Aerial Vehicle (UAV) and satellite communications to achieve Space-Air-Ground Integrated communication Networks (SAGINs).

Naturally, SAGINs are multi-dimensional, multi-tier, and heterogenous networks that integrates satellite, aerial, and terrestrial networks with complex and diverse Quality of Service (QoS) requirements of different nodes at different layers. Therefore, the composition of an end-to-end route between two nodes in SAGINs, over a large geographical area, is complicated and challenging as it could span multiple network domains with different network settings and mobility. For instance, Low Earth Orbit (LEO) satellites can provide high link capacity and wide coverage, but the computing resources are very limited, and they are highly mobile. On the other hand, UAVs are flexibly controllable and easy to deploy but, they have limited energy and their support is short lived [3].

The current studies in the literature focus on network services and management in SAGINs rather than data transmission. For instance, in [3], the authors proposed a service oriented SAGINs management framework that manages the network services and orchestrates its resources to achieve on-demand service fulfilment. The on-demand service layer utilises technologies such as Software Defined Networking (SDN), Network Function Virtualisation (NFV), and network slicing for heterogeneous resource orchestration. These technologies have showed promising results to achieve efficient resource allocation, and flexible network operation. The integration of cloud and Mobile Edge Computing (MEC) have been also considered to benefit from their abundant computing capabilities to achieve lower delays and higher energy efficiency.

While bringing all these technologies to work effectively together sounds like a good idea for SAGINs, it makes the routing problem even more complicated for two reasons. Firstly, one will need massive network information including temporal and spatial distribution of services, QoS requirements, network resources availability, mobility, and much more. Secondly, the routing process becomes more challenging due to the complexity associated with the addition of these different technologies. Furthermore, considering the open connectivity and the security vulnerabilities SAGINs bring, due to its heterogenous nature, a different approach to secure and dynamic routing is needed to ensure SAGINs can provide reliable and resilient connections, which satisfy the QoS requirements and thwart threats to routing such as Sybil attacks [4].

Recently, several works have been conducted to solve the various problems SAGINs face in terms of network management, routing, and traffic scheduling. The authors in [5] proposed a hierarchical domain-based SDN-enabled SAGIN architecture using multi controller deployment strategy. They divided the SDN control plane into a primary layer, which is deployed on the ground sub-network and a secondary layer, which is deployed on the space sub-network. The SDN data plane is composed of ground-based, air-based, and space-based networks. The authors constructed a multi objective optimisation model to determine the number of controllers and their relative positions considering the average network delay and the controller load. While the simulation results were promising in terms of reducing average network delay and controller load, more verification is needed since the proposed work focused on controller load and network delay only.

Tao *et al*. [6] designed a load balancing-based traffic scheduling scheme for SAGINs with SDN to enhance the transmission capability of SAGINs. Possible links between a source and a destination are predicted while the deep reinforcement Q-learning learning model is used to make global optimal traffic scheduling decisions. However, the authors only considered LEO satellites in the space sub-network. The simulation results showed that the proposed method achieves better load balancing for satellite nodes while better utilising SAGINs transmission capacities.

In [7], the authors proposed an extended Extreme Learning Machine (ELM) algorithm to predict the communication attenuation caused by rainy weather to satellite communication links. This way, they can obtain predictions for blockage caused by weather so the selection of data transmission links can be based on these predictions. Hence, improving the satellite routing performance. To feed the data to the extended ELM, the authors utilised Internet of Things (IoT) enabled sensors to collect the weather data. The simulation results showed improvement in data transmission efficiency. However, the work is limited to rainy weather conditions, which are not the only factors that influence satellite communication links reliability. Moreover, the simulation results were focusing on the extended ELM algorithm performance.

Li *et al.* [8] have utilised SDN controllers to propose an intelligent flow forwarding scheme with endogenous security based on mimic defence (ESMD-Flow) in SAGINs. The SDN controller plays the role of forwarding flows along the most reliable multiple routes based on evaluating the reliability of nodes and links and isolating malicious nodes. For the multipath routing strategy, the authors considered node reliability, link congestion rate, link delay, link reliability, and route reliability. To guarantee endogenous security, the authors also developed a multi-protocol dynamic forwarding strategy to prevent eavesdropping attacks. The simulation and experimental results were promising in comparison to other schemes such as the Open Shortest Path First (OSPF). However, the assumption of one SDN controller that will periodically inject probes in the network to collect information regarding nodes and links reliability, and perform the multipath routing, is an oversimplification in networks like SAGINs.

In this paper, a hybrid SDN-based architecture for secure and dynamic QoS aware routing in SAGINs is proposed. A hybrid SDN means both traditional and SDN networks' protocols are used to combine the robustness of traditional protocols with the flexibility of SDN [9]. The motivation behind utilising SDN controllers in the routing process is linked to the challenge of collecting huge amount of near real-time network information. The deployment of SDN controllers at different SAGINs levels for orchestrating inter- and intra- operations of heterogeneous nodes means that there will be an abundant amount of information available to use in the routing process. For instance, SDN controllers can provide nodes/links states in terms of available bandwidth and congestion, which can be used to calculate expected delays on these links. However, to the best of the authors' knowledge, there is no work in the literature that considered the integration of hybrid SDN controllers into the routing process in SAGINs to achieve secure and dynamic QoS aware routing. This work leverages the very heterogenous nature of SAGINs to find multiple routes that satisfies different security and QoS requirement thus, improving the resilience and the reliability of data communications in SAGINs.

The main contributions of this paper with respect to the literature in [5]- [8] are summarised as follows:

- A hybrid SDN-based architecture where SDN controllers are deployed at different levels (i.e., sub-networks) to cater for different network domains in SAGINs depending on network density, service requirements, and available resources. This avoids incurring high signalling overhead at SDN controllers especially when resource management can be achieved without the involvement of the controllers (e.g., low network density area).
- Proposing the concept of a routing service composition layer where multiple end-to-end routes can be composed according to services' security and QoS requirements. This layer abstracts away the different protocols at different SAGINs' levels thanks to the involvement of SDN controllers.

To demonstrate the effectiveness of the proposed architecture, a Vehicle-to-Everything (V2X) service will be used as a case study. V2X is one of the industrial verticals in 6G networks [2]. The case study will show how a charging service for an Electric Vehicle (EV) can use the proposed architecture to find charging points and schedule its charging sessions on its route from a suburban area to a remote area, which does not have terrestrial network services.

The rest of the paper is organised as follows. In Section II, the system model and end-to-end routing problem formulation are presented. Section III presents the SDN-based architecture and explains its components in detail. The case study is presented in Section IV and the system workflow is explained. Analysis of the proposed architecture and discussion on future work is provided in Section V. Finally, the paper's conclusions are presented in Section VI.

## II. System Model and Problem Formulation

### A. System Model

In this work, the system model is illustrated in Fig. 1 where the SAGIN is composed of the following sub-networks [10]:

- Space sub-network – this component consists of satellite networks and their terrestrial infrastructures such as ground stations and network operation and control centres. Based on their altitudes, there are three main satellites: Geostationary Earth Orbit (GEO), Medium Earth Orbit (MEO) and LEO. This component of SAGIN offers global coverage however, it suffers from long propagation delay, limited computing capacity, and high mobility.

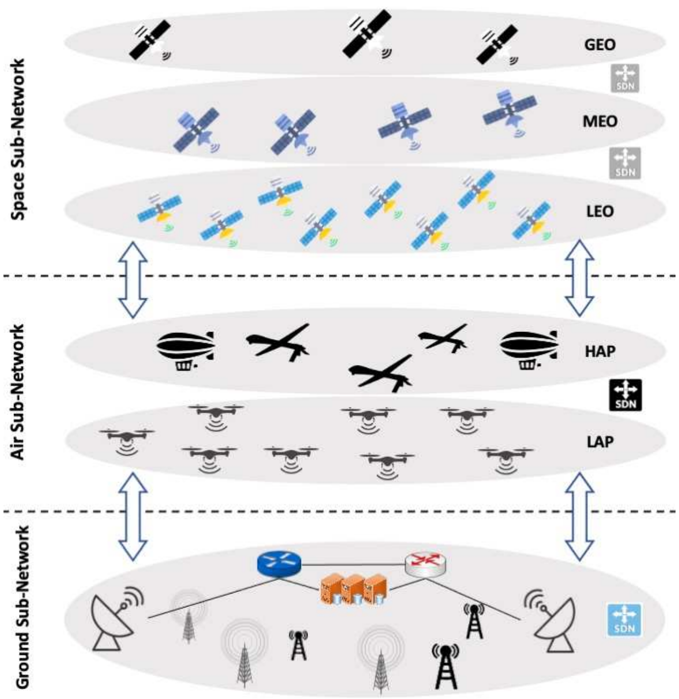


Fig. 1. SAGIN with Hierarchical Hybrid SDN Controllers

- Air sub-network – this component consists of High-Altitude Platforms (HAPs) and Low-Altitude Platforms (LAPs). Airships and UAVs are examples of these platforms. In SAGINs, this component offers high flexibility in terms of deployment and being infrastructure free yet, it suffers from limited computing capacity, unstable links, and high mobility.

- Ground sub-network – this component includes all terrestrial networks such as cellular networks, wireless networks, and mobile ad hoc networks. The main issue with this component is the limited coverage and vulnerability to infrastructure issues. Nonetheless, it offers low delay and high throughput in comparison to the other two sub-networks above.

- Hybrid SDN Controllers – The SDN controller developed for the EU H2020 What to do With the Wi-Fi Wild West (Wi-5) project, which addresses spectrum congestion in Wi-Fi networks, is the basis for the SDN controllers in this system model [11]. This controller can obtain a global view of the network through monitoring and measurements. It can collect information such as Received Signal Strength Indicator (RSSI), available bandwidth, and bit rate requirements of devices connected to the controlled access points. Note that depending on the sub-network segment the controller will be deployed for, Software Defined Wireless Networking (SDWN) controllers can also be used especially for Wi-Fi networks and similar wireless communications.

It can be noted in Fig. 1 that if two nodes are to establish a connection between them, the end-to-end route might span different sub-networks. Unless one has a central routing protocol for SAGINs, which is unrealistic given its heterogeneous components, internal routing within the sub-networks will take place to establish the requested route.

Given its heterogeneity and dynamic nature, in this paper, the Evolving Graph (EG) theory is adopted to formulate the model of routing problem in SAGINs. The EG theory is proposed as a formal abstraction for dynamic networks [12, 13]. An evolving graph is an indexed sequence of $\lambda$ sub graphs, where each, at a given index, corresponds to the network connectivity at the time interval indicated by that index. For ease of illustration, Fig. 2 shows an example of a SAGIN modelled using the EG theory in a three layers format where intra domains connections mean links within the sub-network while inter domains connections mean links across the sub-networks. The indexes on these links represent times and/or intervals when these connections are available.

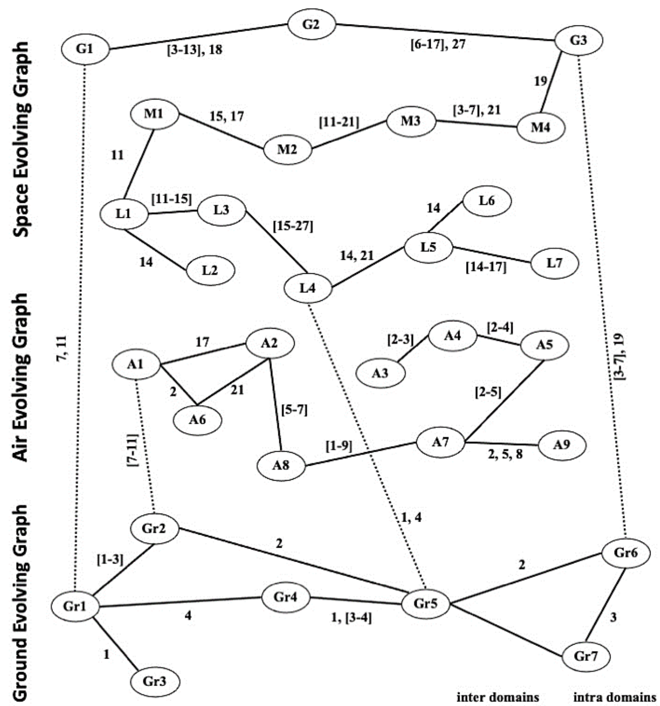


Fig. 2. SAGIN Evolving Graph Model – Gr (Ground sub-network nodes), A (Aerial sub-network nodes), L (LEO satellites nodes), M (MEO satellites nodes), G (GEO satellites nodes)

Each sub-network in SAGINs has its own sequence of $\lambda$ sub graphs (e.g., the ground evolving graph has $\lambda$ sub graphs in Fig. 2, which is composed of *Gr* nodes and their links). Note that the hybrid SDN controllers are part of these sub graphs and their deployment (i.e., locations) depends on network-wide metrics such as closeness centrality [14]. For instance, let $d(c_i, n_j)$ be the geodesic between an SDN controller node $c_i$ and a node $n_j$, the standardised closeness centrality $C(c_i)$ of $c_i$ can be calculated as follows:

$$\mathcal{C}(c_i) = \frac{n-1}{\left(\sum_{i=1, i\neq j}^{n} d\left(c_i,\ n_j\right)\right)} \quad (1)$$

where $n$ is the total number of nodes at the targeted SAGIN sub-network. The closeness centrality index for the controller $c_i$ will be zero if there is at least one node $n_j$ that is unreachable from $c_i$. The optimisation of the deployment of SDN controllers is outside the scope of this paper and left for future work. It is assumed, in this work, that SDN controllers are deployed hierarchically in every sub graph (i.e., sub-network) to ensure connectivity between any two highly connected sub graphs.

The overall SAGIN can be thus modelled as follows. Let $\mathcal{G}_s(\mathcal{V}_s, \mathcal{E}_s)$ be the space sub-network graph and a sequence of its sub graphs $S_{\mathcal{G}_s} = \bigcup_{i=1}^{\lambda} \mathcal{G}_{s_i}\left(\mathcal{V}_{s_i}, \mathcal{E}_{s_i}\right)$. The evolving graph for the space sub-network is defined as $G_s = (S_{\mathcal{G}_s}, \mathcal{G}_s)$. Similarly, the evolving graph for the air sub-network can be defined as $G_a = (S_{\mathcal{G}_a}, \mathcal{G}_a)$ where $\mathcal{G}_a(\mathcal{V}_a, \mathcal{E}_a)$, and the evolving graph for the ground sub-network is $G_r = (S_{\mathcal{G}_r}, \mathcal{G}_r)$ where $\mathcal{G}_r(\mathcal{V}_r, \mathcal{E}_r)$. Let the SAGIN graph be $\mathcal{G}(\mathcal{V}, \mathcal{E})$ where $\mathcal{V} = \mathcal{V}_s \cup \mathcal{V}_a \cup \mathcal{V}_r$ and $\mathcal{E} = \mathcal{E}_s \cup \mathcal{E}_a \cup \mathcal{E}_r$. Therefore, the evolving graph for a SAGIN can be defined as $G = (S_G, \mathcal{G})$ where $S_G = \bigcup_{i=1}^{\lambda} \mathcal{G}_i(\mathcal{V}_i, \mathcal{E}_i)$.

In other words, the SAGIN evolving graph is the union of all evolving graphs of its sub-networks. To incorporate the time domain $\mathcal{T}$ into the model, suppose that the sub graph $\mathcal{G}_i(\mathcal{V}_i, \mathcal{E}_i)$ at a given index $i$ is the underlying graph of the SAGIN during time interval $\mathcal{T} = [t_{i-1}, t_i]$ where $t_0 < t_1 < \ldots < t_\tau$. Let $\mathcal{R}$ be a given route in the evolving graph $G$ where $\mathcal{R} = e_1, e_2, e_3 \ldots e_k$ where $e_i \in \mathcal{E}$. Let $\mathcal{R}_\sigma = \sigma_1, \sigma_2, \sigma_3 \ldots \sigma_k$ where $\sigma_i \in \mathcal{T}$ be the time schedule indicating when each edge (i.e., link) of the route $\mathcal{R}$ is to be traversed (i.e., the link state will be up). A journey can be defined as $\mathcal{J}_{ij} = (\mathcal{R}_{ij}, \mathcal{R}_{ij_\sigma})$ if and only if $\mathcal{R}_{ij_\sigma}$ is in accordance with $\mathcal{R}_{ij}$, $G$ and $\mathcal{T}$. This means that $\mathcal{J}_{ij}$ allows the traverse from node $n_i$ to node $n_j$ in the SAGIN. In fact, using the same logic, one can deduce that $\mathcal{J}_{ij} = n_i \cup \mathcal{J}_s \cup \mathcal{J}_a \cup \mathcal{J}_r \cup n_j$ where $\mathcal{J}_s, \mathcal{J}_a$, and $\mathcal{J}_r$ are sub journeys in their respective sub evolving graphs of each space, air, and ground sub-networks, respectively. Depending on the location of nodes $n_i$ and $n_j$, any sub journey can be null (i.e., the route between the two nodes does not necessarily span all SAGIN sub-networks depending on its requirements as to be shown below).

### B. Problem Formulation

Based on Fig. 2, the following QoS metrics are considered for composing end-to-end routes, in terms of route reliability, end-to-end delay, and security, between two nodes in SAGINs. Note that the terms journeys and routes are used interchangeably here. Let $\beta_e$ be the bandwidth of a link $e$ where $e \in \mathcal{E}$:

- Route reliability $\mathcal{RE}_{ij}$ between two nodes $n_i$ and $n_j$ is defined as the minimum of all nodes' reliability $r_n$ and links' reliability $r_e$ along the journey from $n_i$ and $n_j$. The node reliability $r_n$ can be defined as follows [8]:

$$r_n = \frac{1}{P_{lost}^{n} \alpha_n} \quad (2)$$

where $P_{lost}^{n}$ is the packet loss rate at node $n$ and $\alpha_n$ is the flow request rate. The reliability of a node increases when its $P_{lost}^{n}$ and/or $\alpha_n$ decrease. On the other hand, link reliability can be defined as the probability that the link between two nodes $n_i$ and $n_j$ will stay continuously available over a specific period. Let $e_{ij}(t)$ be the estimated duration for the continuous availability of a link $e_{ij}$ between $n_i$ and $n_j$ at time $t$. The link reliability can be calculated as follows [14]:

$$r_e = \int_{t_1}^{t_1 + e_{ij}(t)} f(T)dT \quad if\ e_{ij}(t) > 0 \quad (3)$$

where $f(T)$ is the distribution function of velocities for nodes $n_i$ and $n_j$. The route reliability can be defined as:

$$\mathcal{RE}_{ij} = \min(r_n, r_e), n \in \mathcal{V}, e \in \mathcal{E} \quad (4)$$

- Route delay $\mathcal{DE}_{ij}$ between two nodes $n_i$ and $n_j$ is defined as the sum of each link's delay $d_e$ along the journey from $n_i$ to $n_j$. Links' delays in SAGINs are related to propagation delay $d_p$, queuing delay $d_q$, and transmission delay $d_T$ at a node. Furthermore, queuing delay is also related to link congestion, especially in satellite nodes in the space sub-network. The link congestion is mainly affected by the link bandwidth $\beta_e$ and the traffic transmitted within a period $\Delta t$. Thus, the route delay can be defined as:

$$\mathcal{DE}_{ij} = \sum_{i,j} \left(d_p(e_{ij}) + d_q(e_{ij}) + d_T(e_{ij})\right), e \in \mathcal{E} \quad (5)$$

- Route security $\mathcal{SE}_{ij}$ between two nodes $n_i$ and $n_j$ is defined from two perspectives. Firstly, depending on the service requirements (e.g., data flow with sensitive data), $\mathcal{SE}_{ij}$ defines the links to avoid while establishing the end-to-end route. Let $\mathcal{U}$ be the set of untrusted links defined for the service data flow, the route $\mathcal{J}_{ij}$ from node $n_i$ to node $n_j$ in the SAGIN is defined as $\mathcal{J}_{ij} = (\mathcal{R}_{ij}, \mathcal{R}_{ij_\sigma})$ where $\mathcal{R}_{ij} = e_i, e_2, e_3 \ldots e_j \nexists e_k \in \mathcal{U}$. In other words, none of the links belongs to the set of untrusted links. Secondly, $\mathcal{SE}_{ij}$ also defines the resiliency of the established connection between two nodes. In case a link is disrupted for any reason, the connection must continue using other links.

Based on the metrics defined above, the objective function for finding an end-to-end route $\mathcal{J}_{ij}$ that satisfies these metrics can be defined as follows: $\mathcal{J}_{ij} = (\mathcal{R}_{ij}, \mathcal{R}_{ij_\sigma}) \rightarrow \exists\, \mathcal{R}_{ij} \in \mathbb{R}_{ij}$ subject to the following constraints:

$$i \neq j \rightarrow \max\left(\mathcal{RE}_{ij}\right) \wedge \left(\mathcal{DE}_{ij} \leq \Psi\right) \wedge \mathcal{SE}_{ij} \equiv \mathsf{T} \quad (6)$$

where $\Psi$ is the delay threshold. $\mathbb{R}_{ij}$ is the set of all possible routes $\mathcal{R}_{ij}$ between two nodes $n_i$ and $n_j$ that satisfies (6) (i.e., maximum route reliability, route delay below the threshold, and security requirements are satisfied). Finding $\mathbb{R}_{ij}$ is an NP-hard problem [13] that will be handled by the routing service composition layer to solve as to be explained in next section.

## III. THE HYBRID SDN-BASED ARCHITECTURE

### A. The Architecture

The proposed architecture is shown in Fig. 3 below where, for illustration purposes, it shows less nodes at each sub-network in comparison to the system model in Fig. 2. The architecture leverages the advantages offered by different SDN controllers in terms of near real-time monitoring and data collection, and management of heterogeneous nodes at different levels.

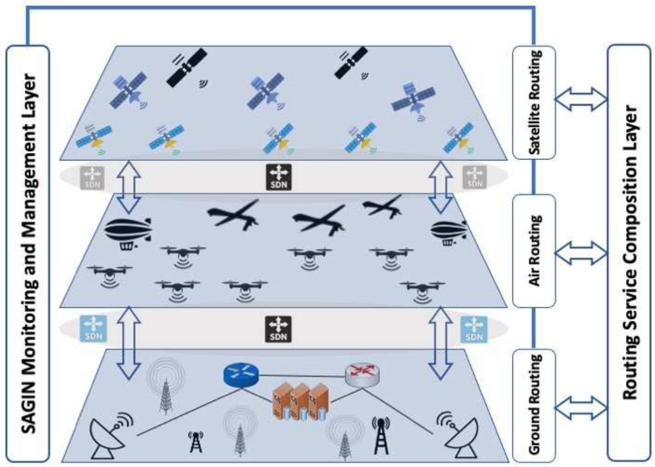


Fig. 3. The Hybrid SDN-based Architecture for SAGIN

Furthermore, the architecture in Fig. 3 is based on the system model in Fig. 2 with the additions of two main layers that rely on the hybrid SDN controllers. Firstly, the SAGIN monitoring and management layer that is responsible for monitoring all sub-networks segments in SAGIN including their nodes/links states, available bandwidth, mobility management, resources orchestration, etc. through the southbound API of the controllers. Secondly, the routing service composition layer. For each sub-network, an internal routing process is implemented as an application on top of the controllers using their northbound API based on the information exchanged with the monitoring and management layer. The details of each internal routing process can be tailored to the sub-network itself and abstracted away from services that are built on top of SAGINs. For instance, Satellite Routing can utilise machine learning algorithms to predict links' reliability based on weather conditions and update its evolving graph accordingly.

### B. Routing Service Composition Layer

To abstract the complexity of provisioning routes in SAGINs from services, the routing service composition layer is proposed. Services should be able to compose the desired route based on their requirements regardless of the current network state and protocols/technologies used in SAGINs' sub-networks. As mentioned before, provisioning these routes in SAGINs subject to satisfying (6) is an NP-hard problem. Therefore, based on the current information about the network, the route composition layer divides the process of finding the end-to-end route into sub-problems that will be assigned to the internal routing processes of the sub-networks.

At each sub-network, the SDN controllers can provide information regarding $P_{lost}^{n}$ the packet loss rate at node $n$ and $\alpha_n$ its flow request rate to calculate the node reliability $r_n$ according to (2). They can also provide specific details on the distribution function of nodes' velocities at their sub-networks segments to calculate a link reliability $r_e$ accurately according to (3). Similarly, information related to propagation delay $d_p$, queuing delay $d_q$, transmission delay $d_T$, link congestion, and link bandwidth $\beta_e$ are used to calculate route delay according to (5). Finally, each internal routing process will use $\mathcal{U}$, the set of untrusted links defined by the service, to exclude these links from the available routes before sending the results back to the routing composition layer.

Based on the information exchanged with the monitoring and management layer, and the sub-solutions provided by different internal routing processes, the routing composition layer can now compose multiple end-to-end routes. It starts by calculating the reliability $\mathcal{RE}_{ij}$ of each route according to (4). Then, it uses the sub graph $\mathcal{G}_i(\mathcal{V}_i, \mathcal{E}_i)$ of SAGIN evolving graph during time interval $\mathcal{T}$, which is sufficient for the data communications to complete, to construct the set $\mathbb{R}_{ij}$ of all eligible end-to-end routes according to (6). This process will be further illustrated through the V2X case study below.

## IV. V2X Case Study

To explain how the proposed architecture can be utilised by services in SAGINs in future 6G networks, the following V2X case study is considered. V2X technologies' benefits in terms of smart charging are considered to minimise the impact on the grid and reduce peak demand (e.g., it is estimated to be the equivalent to the generation capacity of 10 Hinkley Point C power stations by 2050 in the UK [15]). However, the unreliability of the current communication networks causes data deficiencies and charging operation disruption.

Let EV1 be an electric vehicle that is travelling from a suburban area *source* to a remote area *destination* where the traditional network coverage is not available. To avert range anxiety, EV1 needs scheduling and resource allocation mechanisms in place for smart charging including establishing a route between EV1 and the charging points and between the charging points and their operators, to exchange the required messages. EV1 sends a request to its charging service to plan a full end-to-end route with scheduled charging sessions. After that, the service connects with the architecture in Fig. 3 and proceeds as follows. Note *CH* below means the charging data EV1 has, including its current battery charge, capacity, etc.

*Algorithm 1. V2X Case Study Workflow*

**Input:** {*source* = *i*, *destination* = *j*, $G = (S_G, \mathcal{G})$, Ψ, $\mathcal{SE}_{ij}$, *CH*}
**Output:** $\mathbb{R}_{ij}$
**Process:**
**if** (($i \neq j$) and (Ψ > 0)) **do**
    **Send** *i* and *j* coordination to the routing composition layer
    *satisfied* = 0
    **while** (! *satisfied*) **do**
        **collect** network status information via $G$
        **use** *CH* parameters and $d(i,j)$ to estimate the number of charging sessions and locations $NL_{CH}$
        **foreach** $nl_{ch}$ in $NL_{CH}$ **do**
            **connect** to the corresponding controller
            **assign** the routing job to the corresponding sub-network based on nodes' locations
            **perform** link reliability and delay calculations
            **exclude** untrusted links according to $\mathcal{SE}_{ij}$
        **end foreach**
        **collect** all received sub-routes results
        **construct** multiple end-to-end routes subject to (6)

```
15:        if constructed route ≠ null do
16:            add route to ℝ_ij
17:        end if
18:        if ℝ_ij ≠ null do
19:            satisfied = 1
20:        end if
21:    end while
22: end if
```

The workflow in Algorithm 1 above is simplified for the purpose of this paper. It starts by using EV1 trip information and charging data *CH* to determine the number of charging sessions needed and the location of these charging stations $NL_{CH}$ (lines 5-6 of Algorithm 1). Based on the calculated locations, the routing service composition layer will connect to the corresponding controllers in place at that time based on the information it has from the SAGIN monitoring and management layer. Using near real-time information from the hybrid SDN controllers (e.g., node status, link bandwidth, congestion rate) and the data fed by the management layer, the routing jobs are assigned to the corresponding sub-network (line 9 of Algorithm 1). At each sub-network routing process, calculations of each link reliability and delay are done according to (2), (3) and (5) while links exclusion is done according to $\mathcal{SE}_{ij}$ (lines 10-11 of Algorithm 1).

Once all the sub-routes are calculated and returned, the routing service layer will compose multiple end-to-end routes subject to satisfying (6) based on its holistic view of the SAGIN evolving graph. If the constructed route is not null, it will be added to $\mathbb{R}_{ij}$. If $\mathbb{R}_{ij}$ contains at least one route, the process ends and return the set of available multipath routes (lines 15-21 of Algorithm 1). Otherwise, the process restarts again given the fact that new links/routes could emerge over time in a highly dynamic network like SAGINs. Hence, the process must continue until it finds a route.

## V. Analysis and Discussion on Future Work

Without loss of generality, the proposed architecture in Fig. 3 can be considered as a reference to design and develop more advanced systems that can offer the functionalities and services of SAGINs in a transparent manner to other services. The monitoring and management layer, for instance, will need advance capabilities to sense the network conditions and environments considering the multiple radio access networks and heterogenous devices across SAGIN sub-networks. The integration of AI techniques to help with predicting network conditions will be essential. However, the amount of data generated by devices across SAGINs is enormous. These data need to be classified within the network context to make it useful before processing. On the other hand, the SDN technology in terms of the programmability of both control and data planes needs further development to realise its benefits in this context. Finally, solving the identified NP-hard problem in Section II is not trivial and requires further research effort.

## VI. Conclusion

In this work, a novel hybrid SDN-based architecture for routing in SAGINs is proposed. The architecture is a step towards secure, dynamic and QoS aware routing to alleviate the problem of provisioning end-to-end routes in a highly dynamic and multi-dimensional networks such as SAGINs. The evolving graph theory was utilised to capture the evolving nature of links/routes in SAGINs across all its sub-networks. As a result, the problem of provisioning an end-to-end route is formulated considering reliability, delay, and security as QoS metrics. To abstract the complexity of the routing process, a routing service composition layer is introduced to allow services to request routes based on their requirements. To illustrate this, a case study of an electric vehicle charging service utilising V2X technology is used. The workflow of the case study showed how an EV can plan its charging schedule utilising the near 100% global coverage offered by SAGINs without the complexity of dealing with its heterogenous components.

## References


[1] A. Salameh and M. El Tarhuni, "From 5G to 6G-Challenges, Technologies, and Applications," *Future Internet,* vol. 14, no. 117, 2022.

[2] X. You, C.-X. Wang, J. Huang and et al., "Towards 6G wireless communication networks: vision, enabling technologies, and new paradigm shifts," *Sci China Inf Sci,* vol. 64, pp. 1-74, 2021.

[3] N. Cheng, J. He, Z. Yin, C. Zhou, H. Wu, F. Lyu, H. Zhou and X. Shen, "6G service-oriented space-air-ground integrated network: A survey," *China J Aeronaut,* vol. 35, no. 9, pp. 1-18, 2022.

[4] M.H. Eiza, T. Owens and Q. Ni, "Secure and Robust Multi-Constrained QoS aware Routing Algorithm for VANETs," *IEEE Trans. Dependable and Secure Computing,* vol. 13, no. 1, pp. 1545-5971, 2015.

[5] C. Chen, Z. Liao, Y. Ju, C. He, K. Yu and S. Wan, "Hierarchical Domain-Based Multicontroller Deployment Strategy in SDN-Enabled Space–Air–Ground Integrated Network," *IEEE Trans. Aerospace and Electronic Systems,,* vol. 58, no. 6, pp. 4864-4879, 2022.

[6] J. Tao, S. Liu and C. Liu, "A Traffic Scheduling Scheme for Load Balancing in SDN-Based Space-Air-Ground Integrated Networks," in *IEEE 23rd Inter. Conf. (HPSR)*, Taicang, Jiangsu, China, 2022.

[7] X. Yuan, J. Liu, H. Du, Y. Zhang, F. Li and M. Kadoch, "Machine Learning-Based Satellite Routing for SAGIN IoT Networks," *Electronics,* vol. 11, no. 6, p. 862, 2022.

[8] Z. Li, Y. Hu, D. Zhu, J. Wu and Y. Gu, "ESMD-Flow: An Intelligent Flow Forwarding Scheme with Endogenous Security Based on Mimic Defense in Space-Air-Ground Integrated Network," *China Comm.,* vol. 19, no. 1, pp. 40-51, 2022.

[9] X. Huang, S. Cheng, K. Cao, P. Cong, T. Wei and S. Hu, "A Survey of Deployment Solutions and Optimization Strategies for Hybrid SDN Networks," *IEEE Comm Surv. Tuto.,* vol.21, no.2, pp.1483-1507, 2019.

[10] Y. Wang, Z. Su, J. Ni, N. Zhang and X. Shen, "Blockchain-Empowered Space-Air-Ground Integrated Networks: Opportunities, Challenges, and Solutions," *IEEE Comm. Surv. Tuto.,* vol. 24, no. 1, pp. 160-209, 2022.

[11] F. Bouhafs, M. Mackay, A. Raschellà, Q. Shi, F. d. Hartog, J. Saldana, J. Ruiz, J. Fernández-Navajas, R. Munilla, J. Almodovar and N. v. Adrichem, "Wi-5: A Programming Architecture for Unlicensed Frequency Bands," *IEEE Comm. Mag,* vol. 56, no. 12, pp. 178 - 185, 2018.

[12] A. Ferreira, "On models and algorithms for dynamic communication networks: The case for evolving graphs," in *The 4e rencontres francophones sur les ALGOTEL*, Mèze, France, 2002.

[13] M.H. Eiza and Q. Ni, "An evolving graph-based reliable routing scheme for VANETs," *IEEE Trans. Vehicular Technology,* vol. 62, no. 4, pp. 1493-1504, 2013.

[14] M.H. Eiza and Q. Shi, "Social Evolving Graph-Based Connectivity Model for Vehicular Social Networks," in *Vehicular Social Networks*, CRC Press, 2017, pp. 41-56.

[15] National Grid ESO, "Future Energy Scenarios 2021 via Consumer Transformation," National Grid ESO, 2021.