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Benefits of using Mobile Ad-hoc Network protocols in Federated Satellite Systems for Polar Satellite Missions

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ABSTRACT The Operational Network of Individual Observation Nodes (ONION) project evaluated the benefits of applying Distributed Satellite System (DSS) architectures to Earth Observation. One of its outcomes is the identification of Arctic services as top priority current user needs that require near-real-time observations. Using Inter-Satellite Communications (ISC) capabilities, a Federated Satellite System (FSS) can establish a win-win collaboration between two spacecrafts to provide these services. However, as a FSS is established during the contact between two satellites, the service duration is limited. Therefore, the Internet of Satellites (IoSat) paradigm promotes the use of multi-hop sporadic networks to deploy FSS. In this context, the routing protocol (which identifies routes between a source-destination pair) becomes crucial. One of the most extended networks is the Mobile Ad-hoc Network (MANET), in which nodes are constantly moving and changing the network topology. In principle, applying MANET technologies in the IoSat context would provide self-organization, self-configuration, and flexibility to satellite systems. The Optimized Link-State Routing (OLSR) protocol is the predominant solution in MANET, because it quickly reacts against topology changes. This article aims at studying the benefits of using satellite networks with MANET solutions (e.g. OLSR) for polar satellite missions. The results presented in this article demonstrate that the access time is significantly improved, and thus these new Arctic services can be achieved.

INDEX TERMS Federated Satellite Systems, Satellite Networks, Inter Satellite Network, Internet of Satellites, Mobile Ad-hoc Networks, Earth Observation

I. INTRODUCTION

The Horizon 2020 Operational Network of Individual Observation Nodes (ONION) project [1], [2] investigated how new satellite architectures could be applied in benefit of Earth Observation (EO). One of the project outcomes is the identification of the European EO market emerging needs, and their requirements. Currently, the *Arctic services* are the most potential and highly demanded needs by the scientific and industrial community. Three of them have been highlighted:

- Sea Ice Monitoring - The melting of the poles has become a reality that will impact the environment, as well as the global economy. For instance, new maritime traffic trajectories have been established in the Arctic region because of the reduction of ice [3]. Therefore, delivering information about ice state in a near-real-time condition could enable the possibility to perform maps, service alerts, and route optimization, among other applications.
- Marine Weather Forecast - Monitoring the sea conditions would provide accurate information for the different offshore operations performed in the Arctic zone. In particular, Oil/Gas/Mining industry, as well as fishing and aquaculture industry could be improved if a warning system can deliver in near-real-time information about marine weather.
- Marine Fishery Pressure - Having knowledge of oceanographic conditions and fishing pressure would provide information about fish behavior, as well as to identify natural vulnerabilities and anthropogenic factors. Moreover, a near-real-time surveillance of the marine resources would establish a protection and detection of illegal and unregulated fishing activity.

As authors in [4] remark, the previous services are based on monitoring the Arctic region, which requires a revisit time less than 3 hours and an access time less than 1 hour. These performance requirements indicate that a near-real-time service is needed. Traditional satellite systems cannot accomplish this goal.

Therefore, a Distributed Satellite System (DSS) [5], rather than monolithic satellites, becomes a powerful architecture for such kind of services. In a DSS the responsibility is fragmented into different spacecrafts to accomplish a common mission. The most famous DSS is the satellite constellation, composed of multiple homogeneous satellites that follow an organized structure defined by orbit planes. Constellations for Earth monitoring have already been conceived [6] with the objective to reduce the revisit time. However, the access time is still a feature to be addressed. Including Inter Satellite Communications (ISC) capabilities [7] would enable to exchange data between satellites, and thus reaching a ground station faster.

Using this new capabiltity, a Federated Satellite System (FSS) [8] proposes the establishment of a win-win collaboration (i.e. a federation) between spacecrafts to improve current services, such as access time. The original concept of a FSS was presented as a point-to-point federation, in which the satellites are in direct contact to communicate between them. However, this definition has different limitations in terms of federation duration and accessibility of the same satellite.

Therefore, the Internet of Satellites (IoSat) [9] paradigm expands the concept using a multi-hop scenario in which satellites decide to deploy a sporadic network, depending on the need to create a federation. In this context, an Inter-Satellite Network (ISN) [10] is defined as a set of satellites that decide to create multiple federations in order to provide a connection between a source and a destination. The ISN becomes thus the communication means needed to deploy autonomous satellite applications, such as a FSS.

One of the main challenges that IoSat shall address is how the route between a source-destination pair is determined in this dynamic scenario, i.e. the definition of the routing protocol. Different protocol candidates were presented and evaluated in previous work [10]. An ISN is characterized by having link disruptions, slpitting the network, due to the node mobility and the low node density. Some researchers have addressed this feature by using Delay/Disruption Tolerant Network (DTN) [11] routing protocols. They are able to manage the different disruptions by predicting future contacts, and applying store & forward mechanism on each node. However, these solutions are conceived for delay-tolerant applications, which are not suitable for near-real-time requirements.

Therefore, the most suitable alternative is the Mobile Ad-hoc Network (MANET) [12] protocols. They are able to autonomously determine the route in a context in which all the nodes are constantly moving. Although the different solutions have been conceived to address high-dynamic networks with unpredictable mobile nodes, thanks to its flexibility, scalability, and autonomy these solutions can also be used in predictable scenarios (such as a satellite network).

The apparition of Mega-Constellations [13] encourages also to think that the space will be over-populated by constellations of hundreds or even thousands of satellites. This will reduce the network disruptions, and thus it will promote the possibility to apply MANET solutions. This option has been investigated, and the Location-Assisted On-demand Routing (LAOR) protocol [14] is an example of how a traditional MANET routing protocol can be adapted to satellite context. The LAOR is based on the Ad-hoc On-demand Distance Vector (AODV) protocol [15], which discovers the network only when a transmission shall be done. This option is less energy consuming because it only reacts when it is required, but it is a slow solution in dynamic networks.

On the other hand, the Optimized Link State Routing (OLSR) protocol [16] has prevailed in the different MANET scenarios as being a more reliable and efficient protocol. This protocol discovers the network state once, and then proactively updates the changes of the topology. Therefore, the OLSR quicker reacts against any network change rather than the AODV. The use of OLSR in the satellite context has been studied to interconnect ground networks with satellite nodes [17]. However, an analysis of its performance in ISNs has not yet been conducted. Only in [18], authors have been first highlighted the benefits of this protocol by using it to deploy a FSS. However, the analysis proposes a preliminary solution to promote future investigations.

This article aims at studying the deployment and use of satellite networks to improve polar satellite missions in terms of access time. Due to its capability on quicker reacting against network changes, the OLSR protocol has been selected to demonstrate the benefits of applying MANET solutions in satellite networks. Thanks to the different results, it is possible to conclude that this protocol can enhance polar satellite missions by reducing the access time at certain transmission windows (when the network is not disrupted).

The remaining of the article is structured as follows. First, Section II presents the details about the OLSR algorithm. The simulation scenario and the satellite models are then presented in Section III. Characteristics of the simulation engine are detailed in Section IV. The analysis and results are discussed in Section V. Finally, Section VI concludes the work.

II. OPTIMIZED LINK-STATE ROUTING PROTOCOL

The OLSR protocol [16] aims at defining a route between a source-destination pair in a network in which all the nodes are constantly moving (i.e. MANET). In particular, this protocol makes that each node periodically senses the state of the network topology to identify if any change has appeared. In particular, each node performs the link sensing mechanism which enables to retrieve the link state. The implementation of this link sensing is done by using periodic *hello* messages.

One important parameter of a *hello* message is the Link Code, which indicates if the link is active or not. In the active case, it can also indicate if the link is symmetric or asymmetric. When a link is no longer active, this is traced in the *hello* message and it enables to properly process this situation. Moreover, *hello* messages allow a node to identify its neighbors at certain moment. In the case that a single interface is used per node, the neighbor assignation is direct. However, with multiple interfaces, an additional information in the *hello* message is required to identify the neighbors.

Once the link-state of each neighbor is retrieved, a node diffuses a Topology Control (TC) message to provide its local information to the Multi-Point Relay (MPR) node. This node periodically advertises the received link-state information to other MPRs, which will continue forwarding to their neighbors. Combining these multiple TC messages, all the nodes can have a global view of the entire network. Therefore, each node can compute the routing table to determine which is the best route for each destination.

Note that the MPR nodes are autonomously selected among a set of nodes because they have more connectivity. This is possible thanks to the information included in the *hello* messages. With this architecture, it is possible to reduce the signaling, and thus not flooding the network with unnecessary control packets.

OLSR quickly detects and reacts against any topology change, which makes it key to manage dynamic networks. Therefore, this protocol becomes a serious candidate to enhance observation polar missions providing multi-hop communications between satellites.

III. POLAR SATELLITE MISSION SCENARIO

The selected scenario is focused on evaluating satellite networks to polar satellite missions. It is important thus to correctly model the corresponding scenario. Specifically, the satellite model is crucial to better understand which are the features and the technological limitations of the nodes. This model combines a spacecraft platform and a payload/instrument.

Section III-A presents the different details of how a spacecraft platform is modeled. This model is based on the definition of three platform classes differentiated by the mass. Moreover, the payload model is detailed in Section III-B as a system that generates data, at a constant rate, when the satellite is placed over the North pole.

Section III-C presents the set of current operational satellites and their orbit parameters that have been selected as individual nodes.

A. PLATFORM MODEL

The ONION project [2] has based its study on the definition of a spacecraft platform as an entity with different kind of resources. Depending on the mass characteristics, and following the classification that authors in [19] have done, the project has identified three different types of satellites:

- The *Heavy* platform mass is larger than 1000 kg. This class corresponds to the *Conventional* type in [19].
- The *Medium* platform mass is larger than 100 kg, but smaller than a heavy one. This class corresponds to the *Mini* type in [19].
- The *Small* platform mass is smaller than 100 kg. This class corresponds to the *Micro* type in [19].

A platform also has a transceiver to communicate with other satellites. During the same ONION project, a transceiver has been modeled with a transmission rate at a certain communications range. In particular, it is fixed that the maximum range of a transceiver is 1500 km, and only the transmission rate changes according to the type of the transceiver. Therefore, three different transceivers are defined:

- The *Heavy* transceiver with 4000 kbps at 1500 km.
- The *Medium* transceiver with 750 kbps at 1500 km.
- The *Small* transceiver with 100 kbps at 1500 km.

Depending on the performance, the power consumption and the mass of each transceiver is different. Therefore, not all the platforms can be loaded with all the possible transceivers. This is the case of *small platforms*, which can only afford a small transceiver. However, the *heavy platform* has enough resources to incorporate one transceiver of each type, as well as the *medium platform* which includes one at 750 kbps and one at 100 kbps.

This design enables the communication between different platform types using the most restrictive transceiver, which is the common one. For instance, a heavy platform can only communicate with a small platform using the transceiver with 100 kbps. However, it can communicate with a medium platform using the transceiver with 750 kbps. Note that the negotiation process to determine at which transmission rate the communication is established has not been included in the current study. Table 1 presents a summary of the different transceiver configurations for each platform.

TABLE 1. Transceiver configuration per platform type

	Transceivers		
	At 100 kbps	At 750 kbps	At 4 Mbps
Heavy	X	X	X
Medium	X	X	
Small	X		

In addition to the previous model, the ONION project also proposed a first spacecraft design which included a set of S-band antennas (normally four) distributed through the spacecraft faces to accomplish an omnidirectional radiation pattern. This kind of pattern enhances the possibility to interconnect a spacecraft with others, and thus it increases the probability to have a path between a source and the desired destination.

Table 2 summarizes the characteristics of each platform type.

TABLE 2. Type of satellites

Platform Type	Mass (m)	Transceiver	Range
Heavy	m > 1000 kg	4000 kbps 750 kbps 100 kbps	1500 km
Medium	1000 kg ≥ m > 100 kg	750 kbps 100 kbps	1500 km
Small	100 kg ≥ m	100 kbps	1500 km

B. PAYLOAD AND TRAFFIC MODELS

Another important entity in a satellite is the payload, which generates data when the satellite overpasses a specific target area. In this scenario, a payload is modeled as a Constant Bit Rate (CBR) application that is executed only over these target areas. Therefore, it periodically generates data according to a constant bit rate. In this study case, the target area is the North pole latitudes (i.e. higher than 60º).

The ONION project has published a survey and analysis of the different payloads that can be used for EO [2]. The investigation has concluded with a set of instruments that are suitable to monitor ice: The Synthetic Aperture Radar (SAR) at C-band and X-band, the SAR altimeter, the Microwave Radiometer (MWR), the Microwave Radiation Imager (MWRI), the Advanced Microwave Scanning Radiometer (AMSR), and the Radar Altimeter. The data rate of these payloads has been retrieved from the Observing Systems Capability Analysis and Review (OSCAR) database[1].

Authors in [4] highlight that the instruments require a minimum spatial resolution of 10 km to perform ice monitoring. Therefore, it has been considered that the SAR-C works in a *low resolution mode*, in which the spatial resolution would be 150 m and the swath 1500 km (generating 12 Mbps). A summary of the payload data rate values is presented in Table 3.

TABLE 3. Payload model values

	Data Rate
SAR-C (low resolution)	12.0 Mbps
SAR-X	35.5 Mbps
SAR-Altimeter	10.1 Mbps
AMSR-E	87.4 kbps
Radar Altimeter	35.0 kbps
MWR	10.6 kbps
MWRI	100.0 kbps

Although a ground station network is deployed in the Arctic region, the study presented in this article aims at motivating the benefits of applying satellite network technologies for pole missions. Therefore, it has been omitted these ground stations in benefit of analyzing the impact of ISC. The *reception zone* has been defined according to the localization of different ground stations (presented in Table 4). It is delimited by two regions:

- The American region characterized by longitudes between 120 ºW and 45 ºW, and latitudes between 0 ºN and 55 ºN.
- The European-Asian region characterized by longitudes between 15 ºW and 150 ºE, and latitudes between 0 ºN and 55 ºN.

TABLE 4. Ground Station candidates

Ground Station	Country	Latitude	Longitude
Beijing	China	40.5º N	116.9º E
KaShi	China	39.5º N	76.0º E
Kumamoto	Japan	32.8º N	130.9º E
Libreville	Gabon	0.4º N	9.6º E
Sioux Falls	USA	43.7º N	96.6º W
Matera	Italy	40.7º N	16.7º E
Neustrelitz	Germany	53.4º N	13.1º E
Prince Albert	Canada	53.2º N	105.9º W
Shadnagar	India	17º N	78.2º E
SanYa	China	18.3º N	109.3º E
Si Racha	Thailand	13.1º N	100.9º E
Ulsan	South Korea	35.6º N	129.3º E
Chilton	United Kingdom	51.6º N	1.3º W
Redu	Belgium	50.0º N	5.1º E

Figure 1 presents a summary of the satellite behavior depending on its location. When the satellite is placed in the Arctic region, it generates data (represented in the figure by a red line). This data is internally stored and if a route to a destination is available, then the data is transmitted. A node can only be a destination if it is placed in the *reception zone* (previously presented). This status is represented in the figure by a blue line. For those satellites that are not placed in the target area or in the reception region, they can stay in two operational modes. Specifically, if the satellite has still stored data, it keeps transmitting them through the network; otherwise, the satellite remains in standby. In this last mode the satellite becomes crucial to compose the network, because it is a potential candidate to forward messages to other satellites.

C. SATELLITE CANDIDATES

The selection of which spacecrafts should compose the scenario has been deeply studied. One of the objectives is to demonstrate that current satellites would be useful to improve polar missions if they would have ISC capability. Therefore, the selected spacecrafts are those which are currently active and operative.

Considering the heterogeneity of a FSS, it has been considered spacecrafts from different nationalities (e.g. European, American, and Asian satellites). Moreover, satellites with different objectives have been combined, such as EO and Telecommunications ones. However, only those that perform EO are the ones that produce data, the others help to form the network.

[1]OSCAR website: https://www.wmo-sat.info/oscar/spacecapabilities (last access at July 24, 2018)

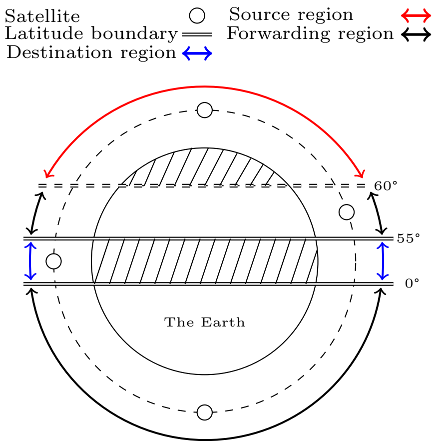

FIGURE 1. Representation of the transmission and reception regions.

In addition, the International Space Station (ISS) is included in the spacecraft list due to the different projects that are expected to be performed there [20]. One of them is the platform *Bartolomeo* that enables the host of external payloads in the ISS. This also implies the possibility to include any subsystem that interacts with satellites. The ISS trajectory becomes interesting to interconnect satellites in Arctic areas with other ones.

Table 5 presents the list and the characteristics of each satellite. The orbital parameters of each satellite have been extracted from the Celestrack database[2]. With this configuration, it is possible to determine if the combination of multiple spacecrafts with different features and objectives is beneficial for the observation and monitoring of the Arctic zone.

IV. SIMULATION ENGINE AND PROTOCOL STACK

The analysis presented in this article has been performed with a simulation tool specifically developed to execute satellite networks [21]. This tool allows testing and validating satellite systems which have ISC capabilities. It is an integrated simulation framework which can be easily adapted and extended to each Earth-observing satellite network scenario.
The implemented framework is based on the Network Simulator version 3 (NS-3)[3] which is an event-based simulation engine core. In particular, it provides different mechanisms to manage the simulation events and schedule their execution. Using this core, it is possible to have access to an open, well documented, and fully tested collection of network protocols with an active community.

In this context, a spacecraft is modeled with a networking component which represents the protocol stack and socket-like interfaces. During the execution of the simulation scenario, data probes continuously capture the state of internal spacecraft components, which enable to perform the analysis of the results afterwards. As part of the built-in library of this simulator, a Keplerian two-body orbit propagator is included to provide position and velocity to each node.

The communication is thus modeled by five layers: Application, Transport, Network, Link, and Physical ones. The latter is represented by a communication channel, which simulates the mobility effects of the satellites over the channel. This channel is characterized by sporadic connections based on the line-of-sight between two spacecrafts, as well as other transceiver parameters. If the communication modules are compatible, then the satellite devices can exchange data. One of these devices represents a bent pipe with a constant transmission rate.

Over this device, the network layer is implemented using the Internet Protocol (IP) with the OLSR protocol. In order not to impact the protocol analysis, the transport layer is implemented using the User Datagram Protocol (UDP) [22] which does not provide any mechanism to ensure the reliability of the communication. Finally, the payload application (presented in Section III-B) is interconnected with the communication stack using a socket interface.

Figure 2 presents the complete protocol stack.

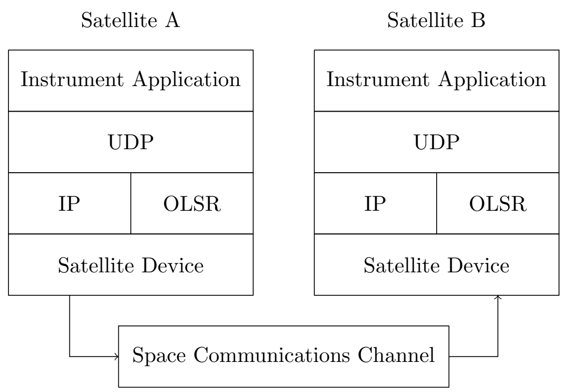

FIGURE 2. Interaction between protocol stacks.

V. RESULTS AND DISCUSSION

The OLSR protocol is able to determine an existing path between a source and a destination at certain moment. If this path is broken, then the communication is also broken until the path is restored. This protocol is not able to predict future contacts between satellites like DTN solutions.

Therefore, it is crucial to understand how the mobility of the satellites impacts in the path creation and destruction. The first sub-section addresses this study to probabilistically estimate the path characteristics. With this information, it is possible to evaluate if an ideal case can ensure certain quality of the communication. Once this study is performed, the analysis to apply satellite networks to polar missions is conducted.

A satellite system is composed of nodes that are in movement following a periodic trajectory. Considering a Keplerian orbit, this means that the entire system is also periodic, with a global period determined by all the orbital periods of

[2]Celestrack website: https://celestrak.com (last access at July 24, 2018)
[3]NS-3 website: https://www.nsnam.org (last access at July 24, 2018)

TABLE 5. Satellite features used to perform the analysis

Satellite	Mass	Type	Payload	Semi-major axis	Eccentricity	Inclination	RAAN*	AP**	Mean Anomaly
Europe - Ice Observation Satellites									
Sentinel-1A	2300 kg	Heavy	SAR-C	7064 km	0	98º	57º	0º	287º
Sentinel-3A	1250 kg	Heavy	MWR	7181 km	0	99º	117º	0º	261º
CryoSat-2	720 kg	Medium	SAR-Alt	7088 km	0	92º	261º	0º	147º
TanDEM-X	1340 kg	Heavy	SAR-X	6886 km	0	97º	62º	0º	271º
TerraSAR-X	1230 kg	Heavy	SAR-X	6886 km	0	97º	58º	0º	46º
SEOSAR/Paz	1341 kg	Heavy	SAR-X	6885 km	0	97º	66º	0º	121º
Europe - Other Satellites									
SWARM-A	473 kg	Medium	-	6831 km	0	87º	72º	0º	279º
SWARM-B	473 kg	Medium	-	6901 km	0	88º	173º	0º	252º
SWARM-C	473 kg	Medium	-	6831 km	0	87º	81º	0º	279º
Metop-A	4085 kg	Heavy	-	7198 km	0	99º	114º	0º	0º
Metop-B	4085 kg	Heavy	-	7198 km	0	99º	115º	0º	316º
PROBA-V	160 kg	Medium	-	7191 km	0	99º	127º	0º	127º
American - Ice Observation Satellites									
Aqua	2934 kg	Heavy	AMSR-E	7076 km	0	98º	351º	0º	293º
RadarSat-2	2200 kg	Heavy	SAR-C	7169 km	0	98º	56º	0º	27º
American - Other Satellites									
Terra	5190 kg	Heavy	-	7076 km	0	98º	141º	0º	285º
Aura	2967 kg	Heavy	-	7076 km	0	98º	10º	0º	303º
SCISAT-1	152 kg	Medium	-	7021 km	0	74º	32º	0º	291º
CASSIOPE	490 kg	Medium	-	7041 km	0.07	81º	104º	212º	140º
ODIN	250 kg	Medium	-	6923 km	0	98º	84º	0º	125º
CYGNSS-1	25 kg	Small	-	6881 km	0	35º	312º	0º	210º
CYGNSS-3	25 kg	Small	-	6881 km	0	35º	304º	0º	212º
CYGNSS-4	25 kg	Small	-	6881 km	0	35º	310º	0º	211º
CYGNSS-8	25 kg	Small	-	6881 km	0	35º	210º	0º	212º
Asian - Ice Observation Satellites									
FY-3D	2300 kg	Heavy	MWRI	7207 km	0	99º	351º	0º	348º
HY-2A	1500 kg	Heavy	Radar Alt	7335 km	0	99º	60º	0º	293º
SARAL	630 kg	Medium	Radar Alt	7171 km	0	99º	237º	0º	214º
RISAT-1	1858 kg	Heavy	SAR-C	6917 km	0	98º	58º	0º	219º
GaoFen-3	2950 kg	Heavy	SAR-C	7129 km	0	98º	58º	0º	303º
Asian - Other Satellites									
RISAT-2	300 kg	Medium	-	6811 km	0	41º	259º	0º	25º
GaoFen-1	1080 kg	Heavy	-	7016 km	0	98º	149º	0º	64º
GaoFen-2	2100 kg	Heavy	-	7002 km	0	98º	148º	0º	350º
GaoFen-8	2100 kg	Heavy	-	6861 km	0	97º	184º	0º	278º
GaoFen-9	2100 kg	Heavy	-	7021 km	0	98º	151º	0º	144º
CartoSat-2C	727 kg	Medium	-	6876 km	0	97º	128º	0º	208º
CartoSat-2D	714 kg	Medium	-	6871 km	0	97º	128º	0º	320º
CartoSat-2E	712 kg	Medium	-	6876 km	0	97º	126º	0º	288º
CartoSat-2F	710 kg	Medium	-	6871 km	0	97º	127º	0º	274º
Additional Spacecraft									
ISS	419455 kg	Heavy	-	6782 km	0	52º	233º	0º	49º

*Right Ascension of the Ascending Node; **Argument of Periapsis

satellites. If we take into consideration the list of satellites presented in Table 5, the system period is around 43910 weeks. Computationally, this cannot be simulated with the previous tool. Therefore, it has been considered to simulate less time, but long enough to perform a representative analysis. The connectivity analysis has been performed with two days of simulation. To characterize the benefits of applying OLSR to polar satellite missions, it has been simulated nine hours.

The following sub-sections present the results of the simulation, as well as the corresponding discussion.

A. CONNECTIVITY ANALYSIS

This study aims at evaluating the feasibility of using MANET routing protocols in the satellite context. These protocols can only identify routes between a source and a destination

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at a certain instant time. Therefore, if the destination is not reachable (i.e. no destination in the reception zone or network partition), these solutions are not able to predict future contacts. Therefore, it is important to characterize the behavior of a route in this context.

The main cause of network disruption is the limited number of satellites and their mobility. A snapshot is the temporal representation of a satellite network in which all the links remain stable depending on the node position and mobility. When a link between two satellites changes, the remaining topology generates a new snapshot [10]. If the network has a low node density, the probability to have a route between a satellite placed in the Arctic zone and another to the reception zone at certain snapshot is small. Figure 3 shows if a route between a source-destination pair in a snapshot exists. When a route is physically established, the plot presents the value one at this snapshot, if not, the value is zero. The presented results correspond to a simulation in which only the European satellites have been considered, i.e. twelve satellites. This configuration makes that only three snapshots have the physical routes between the North polar area and reception zone.

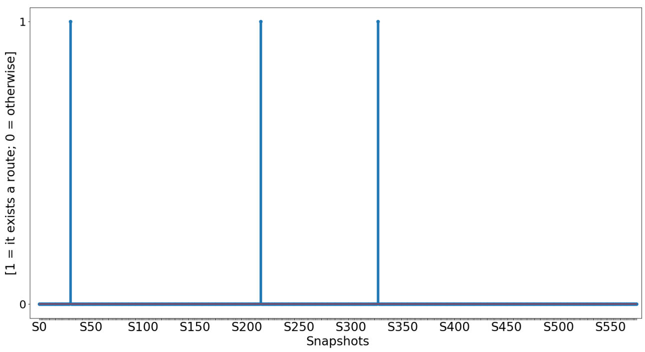

FIGURE 3. Possibility of having a route for the European case.

This low connectivity makes it difficult to provide communications means to provide near-real-time services. Therefore, using a set of existing satellites of one single organization it is not enough. Figure 4 represents the same metrics, but in this case, all the satellites from Table 5 are used, i.e. 38 satellites. Unlike the previous case, a significant improvement on the route opportunities has made it possible to deploy ISN.

One of the interesting parameters is how many hops these routes have. Figure 5 presents a histogram of the number of hops that a route is composed. It shows that the 70.29 % of routes has at least seven hops to connect a source with a destination. Intuitively, these routes are more sensitive to any change rather than those having less hops, because if a single intermediate link is broken the entire route is also broken. For this reason, and although they are less probable, routes with less hops are preferred.

The lifetime of a route represents the duration that the route remains active (unbroken). This important parameter

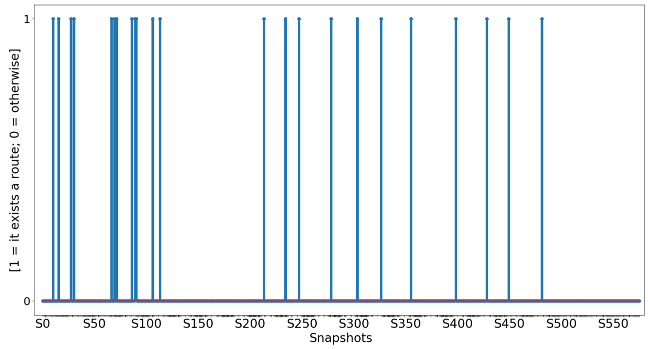

FIGURE 4. Possibility of having a route for the International case.

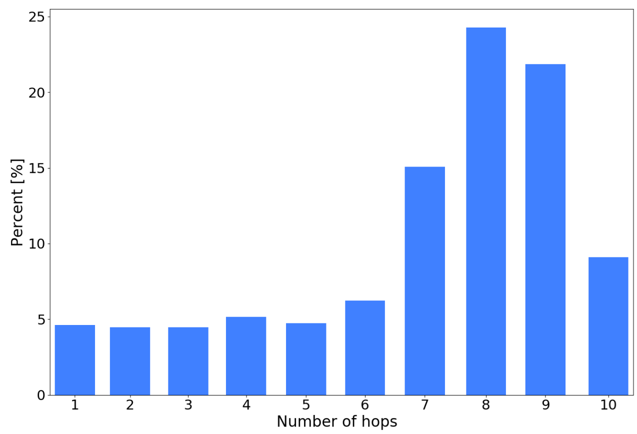

FIGURE 5. Histogram of the amount of hops per routes.

enables to quantify the stability of a route in this scenario. Figure 6 shows the percentage of routes regarding their lifetime. All the generated routes have at least one second of lifetime, while less than 20 % have at least 40 seconds. Moreover, more than 75 % of routes have at least 5 seconds of lifetime, while approximately the 50 % of routes have a lifetime larger than 13 seconds. This information indicates that the route lifetime decreases quickly while having some flat points at 37 seconds and 8 seconds. In addition, the maximum lifetime of a route is 136 seconds, which provides a stable and large route to exchange data.

A route can be usable depending on its lifetime and the number of hops that compose it. For example, if a route has a small lifetime and it is composed of one single hop, a useful communication can be established. However, if the lifetime is small and the route is large, the communication is not possible because the route is not stable enough regarding its composition. Therefore, it is important to correlate the lifetime of a route with its number of hops.

This information is shown using the statistical box plot, in which a box represents a distribution function that the Inter-Quantile Range (IRQ) is delimited by the third quartile (Q3) and the first quartile (Q1). The median is also represented in the IRQ and it enables to understand which of these quartiles are more important. The different dots placed outside the box

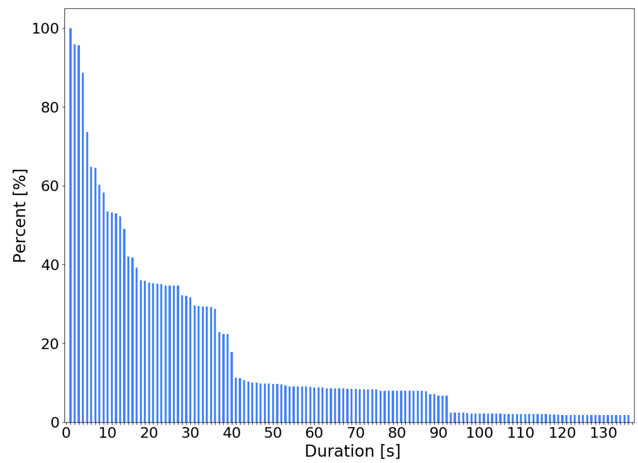

FIGURE 6. Percentage of routes with respect to their lifetimes.

represent outliers (sporadic values). Figure 7 summarizes this type of plot.

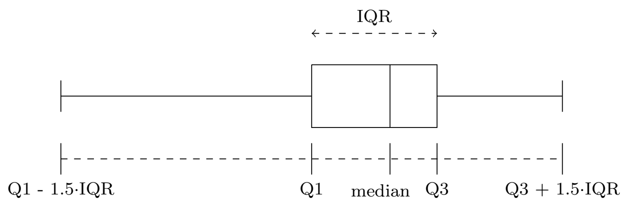

FIGURE 7. Explanation of box parameters in a box plot.

The corresponding box plot with the correlation between route lifetime and hops is represented in Figure 8. Median values of four and five hops routes are the ones with larger lifetime, which means that they are the most stable ones. Therefore, this kind of routes seems to be usable. However, these routes are not the most probable ones, only 9.91 % of the routes have four or five hops (see Figure 5). Moreover, for the routes with more than eight hops (the most probable ones), the lifetime is less than 15 seconds.

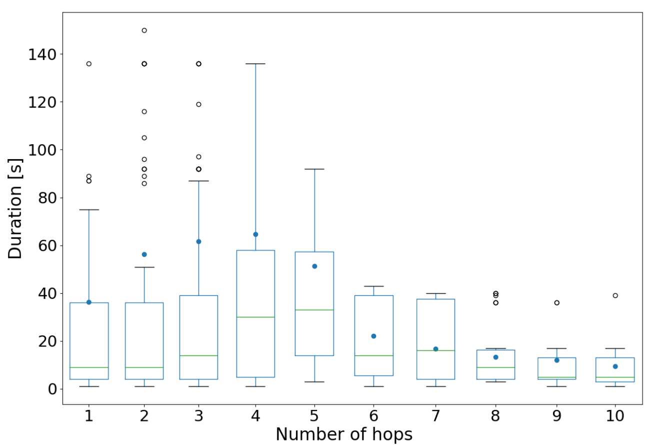

FIGURE 8. Box plot of the route lifetime depending on the number of hops.

These results indicates that there is no predominant type of route in terms of creation probability and stability. Therefore, it is necessary to put these values in data context: a route is useful if its lifetime is long enough to forward a block of payload data. In other words, a route is useful if the end-to-end transmission time t_{E2E} is less or equal to its lifetime t_{LT}:

$$t_{E2E} \leq t_{LT} \quad (1)$$

The end-to-end transmission time depends on different parameters. One of them is the transmission time of a packet t_{TX}, which represents the amount of time that a node needs to send a packet. Thus, it depends on the size of the packet l and the transmission capacity C of the node. Considering that all the transmitted packets have the same size, the transmission time in a node i is determined by the capacity of its link C_i:

$$t_{TX_i} = \frac{l}{C_i} \quad (2)$$

For a specific link j, the propagation time t_P is characterized by the distance of the link d_j and the speed of light c:

$$t_{P_j} = \frac{d_j}{c} \quad (3)$$

Using both concepts, the amount of end-to-end time needed to transmit a payload data block, composed of N_p packets, through a route is defined by the following equation:

$$t_{E2E} = \sum_i t_{TX_i} + \sum_j t_{P_j} + (N_p - 1) \cdot \max_i\{t_{TX_i}\} \quad (4)$$

where i is the index that represents the nodes and j the index that represents the hops that compose the route. Note also that the following relationship applies: $j = i - 1$.

With this definition it is possible to identify the amount of packets that can be transmitted during the lifetime of each route t_{LT}:

$$N_p = \left\lfloor \frac{t_{LT} - \sum_i t_{TX_i} - \sum_j t_{P_j}}{\max_i\{t_{TX_i}\}} \right\rfloor + 1 \quad (5)$$

The size of the payload data block L that can be transmitted during the path lifetime is characterized as follows:

$$L = N_p \cdot (l - h) \quad (6)$$

where h represents all the header bytes of a packet.

Using this definition, the amount of payload data that can be transmitted during the path lifetime is represented in Figure 9. The lifetime of a route is an important parameter to determine the amount of payload data that can be transmitted. In this case, routes with four and five hops remain the most useful in terms of transmitted data. However, their creation probability is not the biggest one (see Figure 5).

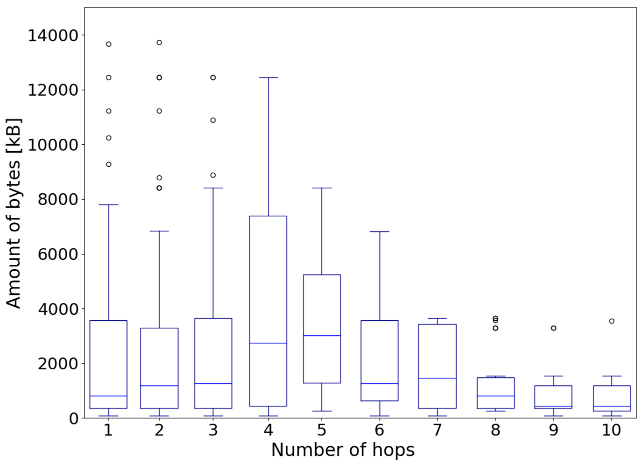

FIGURE 9. Maximum amount of bytes that can be transmitted through active routes.

This information needs to be seen from the perspective of the payload, i.e. the comparison between data forwarding capacity of a route and data generated by the payload. Table 6 presents the execution time of each payload that can be transmitted through each type of route. The value has been computed using the median of each box in Figure 9. This table indicates that the payloads with the highest data rate, e.g. SAR family, cannot deliver a huge amount of data. On the other hand, the other less demanding payloads can use the network to transmit significant data. In both cases, however, the deployment of a network makes it possible to deliver certain amount of payload data, and thus the possibility to achieve the desired near-real-time service.

At the end of this connectivity analysis, the results have demonstrated that the deployment of a network would enable the possibility to transfer data (no matter which kind of payload) from satellites placed in the Arctic area to other satellites in the reception zone. However, the improvement in terms of access time needs still to be analyzed, which depends on the used routing protocol.

B. PERFORMANCE ANALYSIS

Previous section has evaluated the feasibility of the scenario without considering a specific implementation of a routing protocol. This section aims at quantifying the improvement of access time while a network is deployed using the OLSR protocol. Therefore, different performance metrics have been defined:

- Packet Delivery Ratio (PDR) – The fraction of the data packets, regarding all transmitted ones, that has been correctly delivered to the destinations.
- Local Packet Loss Ratio (LPLR) – The fraction of data packets, regarding all the generated ones, that cannot be transmitted because the source does not have a valid route to the destination. This parameter characterizes the disruption of the network at each snapshot. It is thus an interesting parameter to consider for instantaneous routings, such as the OLSR.
- Packet Delivery In Route Ratio (PDIRR) – The fraction of data packets that has been correctly delivered to the destinations, when a valid route exists. By definition, the following relationship is established:

$$PDIRR = \frac{PDR}{1 - LPLR} \tag{7}$$

- Average end-to-end delay of data packets – It is the mean time of a packet that needs to forward from a source to a destination. It includes all the propagation, transmission and queue times.
- Average access time of data packets – It is the mean time that a satellite needs to reach a zone to download a packet, if it would not transmit the packet through the network. The comparison of the average end-to-end delay with the average access time enables to evaluate how beneficial is the satellite network against not having it.

The study has been performed simulating 33496 seconds (9.3 hours). This time has been split in different slots of random size. This enables to retrieve statistics at different conditions and thus to identify possible transmission windows. A transmission window is a time slot in which the conditions to transmit data are better than in other slot, e.g. a time slot with a snapshot that has an active route.

With the objective to better evaluate the impact of the payload data rates, two separate scenarios with different data generators are considered for the following analysis. The former configuration is composed of the highest data rate payloads, i.e. eight satellites that have a SAR-C, a SAR-X or a SAR-Altimeter. The other configuration is composed of the least demanding payloads, i.e. five satellites with MWR, MWRI, Radar Altimeter or AMSR-E payloads.

Table 7 presents the resulting metrics, retrieved after the simulation, related to the exchange of packets (i.e. PDR, PLRL, and PDIRR). In this scenario, the value of the PDR is less than 11% in all the cases. This implies that the delivery of the packets is not always accomplished. However, the discussion is to understand if this result is due to the protocol implementation or to the network topology. The LPLR value enables to clarify this situation, because it has a value always higher than 89% in both configurations. Therefore, it is indicating that during the major time of the simulation the network is disrupted and the protocol cannot identify a route between the Arctic area and the reception zone. In this case, solutions that could perform store & forward could improve this situation.

Although the network disruption is predominant, when a route between a source and a destination is established, it is interesting to evaluate if the packets are correctly delivered. The PDIRR clarifies this by representing the probability that a packet can be correctly delivered in an active route. In the configuration with instruments of low data rate, the PDIRR value is always larger than 90%. On the other hand, the payloads with high data rate have a lower ratio, because

TABLE 6. Amount of time (in seconds) of payload execution that the resulting data can be transmitted through each route type while it is active

	Number of route hops									
	1	2	3	4	5	6	7	8	9	10
SAR-C	0.82 s	0.75 s	0.88 s	2.32 s	2.46 s	0.85 s	0.82 s	0.61 s	0.41 s	0.35 s
SAR-X	0.28 s	0.25 s	0.30 s	0.78 s	0.83 s	0.29 s	0.28 s	0.21 s	0.14 s	0.12 s
SAR-Altimeter	0.97 s	0.89 s	1.05 s	2.76 s	2.92 s	1.01 s	0.97 s	0.73 s	0.49 s	0.41 s
AMSR-E	112.48 s	103.10 s	121.85 s	318.68 s	337.43 s	117.16 s	112.48 s	84.36 s	53.24 s	46.86 s
Radar Altimeter	280.87 s	257.46 s	304.27 s	795.79 s	842.61 s	292.57 s	280.87 s	210.65 s	140.43 s	117.03 s
MWR	927.40 s	850.11 s	1004.68 s	2627.62 s	2782.19 s	966.04 s	927.40 s	695.55 s	463.70 s	386.42 s
MWRI	98.304 s	90.11 s	106.50 s	278.53 s	294.91 s	102.40 s	98.304 s	73.73 s	49.152 s	40.96 s

TABLE 7. Results of the packet metrics

	Low data rate payloads				High data rate payloads			
Time slot	Received packets	PDR	LPLR	PDIRR	Received packets	PDR	LPLR	PDIRR
0 - 3679	1073	5.39%	94.41%	96.42%	96382	1.12%	97.50%	44.80%
3679 - 11335	864	4.03%	95.63%	92.22%	135996	0.82%	97.66%	35.04%
11335 - 18843	929	4.19%	95.81%	100.00%	11861	0.08%	99.65%	22.86%
18843 - 24505	1466	6.60%	92.95%	93.62%	14687	0.12%	99.82%	66.67%
24505 - 28616	2265	10.22%	89.78%	100.00%	451139	4.61%	95.19%	95.84%
28616 - 33496	1021	6.40%	93.60%	100.00%	161364	1.59%	98.41%	100.00%

TABLE 8. Results of the time metrics

	Low data rate payloads		High data rate payloads	
Time slot	Average Delay	Average Access Time	Average Delay	Average Access Time
0 - 3679	24.42 ms	279.35 s	89.56 s	818.64 s
3679 - 11335	22.31 ms	335.55 s	177.00 s	569.60 s
11335 - 18843	17.92 ms	131.98 s	76.90 s	994.36 s
18843 - 24505	34.87 ms	219.11 s	67.94 s	316.47 s
24505 - 28616	21.32 ms	187.57 s	157.07 s	530.19 s
28616 - 33496	13.87 ms	119.84 s	75.64 s	535.17 s

the network cannot support the input flow. It is important to highlight that for this configuration, certain time intervals exist in which the PDIRR reaches values higher than 90% (last two rows of the table). This result indicates that there are two transmission windows that, if the transmissions can be scheduled in specific intervals, the data reception can be optimized.

Another performance aspect, and the most interesting one for Arctic services, is the evaluation of the time needed to deliver the payload data. This is possible by comparing the average end-to-end delay of transmitted payload data with the average access time that a satellite with no ISC needs to download the data. Table 8 indicates that in both configurations the average end-to-end delay is lower then the average access time. This means that when a route is established, the delivery time of the payload data is always improved, reducing in some times from 279.35 seconds to 24.42 milliseconds. Moreover, the reached delays are values that can provide near-real-time services.

Note also that in the high data rate case the end-to-end average delay is larger than in the low data rate case. This is mainly due to the fact that node queues are saturated and that a packet spends more time in the queue before to be processed.

The performance analysis concludes that using the well-known OLSR protocol it is possible to accomplish the requirements of the near-real-time Artic services. Therefore, it is demonstrated that the deployment of satellite networks can improve polar satellite missions. Moreover, these results have been retrieved using MANET technologies, which indicates that the establishment of this architecture could start to be considered as a reality. However, the network disruption is still a point that needs to be investigated by detecting transmission windows that optimize the communications.

VI. CONCLUSIONS AND FUTURE RESEARCH

This work has motivated the introduction of ISC to enhance polar Earth observation missions. The application of FSS in this context would establish different collaborations between satellites to share a common service. One of these services is to provide connectivity in order to download generated data over Arctic regions. With this new architecture, it would be possible to deploy the new Arctic services that the end-users are requesting, as the project ONION highlights. However, the FSS is conceived as a point-to-point interaction, limiting the applicability distance. Therefore, the IoSat paradigm proposes to extend the concept to a multi-hop scenario in which ISNs are sporadically deployed.

The presented work has evaluated if the deployment of satellite networks, as IoSat proposes, could improve current polar satellite missions and deploy the new Arctic services. As an example, the OLSR protocol has been used to deploy the network in this satellite context, although it was conceived for MANET. The analysis has been composed of a first connectivity study, which has demonstrated that the application of MANET technologies is feasible, although limited to certain transmission windows. Moreover, it has been demonstrated that a huge improvement in the data access time is accomplished by using satellite networks. For instance, when a route is active, the OLSR protocol is able to deliver more than the 90% of the packets for those satellites that has a low data rate in the payload. Moreover, the delivery time of the payload data can be reduced to seconds or in some cases milliseconds. This clearly highlights the benefits of using ISC in satellite systems.

With these results, it is possible to conclude that using this technology near-real-time services can be deployed. However, network disruption is still a satellite network feature that needs to be addressed in future research, such as combining MANET features with the store & forward mechanism.

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