IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received January 14, 2018, accepted March 23, 2018, date of publication April 6, 2018, date of current version April 25, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2823983

Internet of Satellites (IoSat): Analysis of Network Models and Routing Protocol Requirements

JOAN A. RUIZ DE AZÚA[1,2,3], **(Student Member, IEEE), ANNA CALVERAS**[1], **AND ADRIANO CAMPS**[2,3], **(Fellow, IEEE)**
[1]Department of Network Engineering, Universitat Politècnica de Catalunya, 08034 Barcelona, Spain
[2]Department of Signal Theory and Communications, Universitat Politècnica de Catalunya, 08034 Barcelona, Spain
[3]Space Science and Technology Research Group, Institut d'Estudis Espacials de Catalunya, Universitat Politècnica de Catalunya, 08034 Barcelona, Spain

Corresponding author: Joan A. Ruiz de Azúa (joan.adria@tsc.upc.edu)

This work was supported in part by Operational Network of Individual Observation Nodes under Project H2020-687490-ONION, in part by the Spanish Ministry of Economy and Competitiveness and FEDER EU through the project AGORA: Tecnicas Avanzadas en Teledeteccion Aplicada Usando Senales GNSS y Otras Senales de Oportunidad (MINECO/FEDER) under Grant ESP2015-70014-C2-1-R, and in part by the Agencia Estatal de Investigacion, Spain, and Unidad de Excelencia Maria de Maeztu under Grant MDM-2016-0600.

ABSTRACT The space segment has been evolved from monolithic to distributed satellite systems. One of these distributed systems is called the federated satellite system (FSS) which aims at establishing a win–win collaboration between satellites to improve their mission performance by using the unused on-board resources. The FSS concept requires sporadic and direct communications between satellites, using inter satellite links. However, this point-to-point communication is temporal and thus it can break existent federations. Therefore, the conception of a multi-hop scenario needs to be addressed. This is the goal of the Internet of satellites (IoSat) paradigm which, as opposed to a common backbone, proposes the creation of a network using a peer-to-peer architecture. In particular, the same satellites take part of the network by establishing intermediate collaborations to deploy a FSS. This paradigm supposes a major challenge in terms of network definition and routing protocol. Therefore, this paper not only details the IoSat paradigm, but it also analyses the different satellite network models. Furthermore, it evaluates the routing protocol candidates that could be used to implement the IoSat paradigm.

INDEX TERMS Federated satellite systems, satellite networks, space internet, inter satellite link, inter satellite network, Internet of satellites.

I. INTRODUCTION

Since 1957 with the launch of the first artificial satellite *Sputnik 1*, the space has been populated by a wide range of satellite systems from governmental and private space entities. Monolithic satellites have been ruling the space by providing a custom design that accomplishes a specific mission. However, this kind of satellites has some limitations in terms of coverage range and revisit time. Therefore, the system evolved to a more distributed architecture, so-called Distributed Satellite Systems (DSS). In a DSS the responsibility is fragmented into different spacecrafts to accomplish a global mission.

A satellite constellation is a particular implementation of a DSS. It consists of an ensemble of homogeneous spacecrafts physically distributed to improve revisit and data access time. It has largely been used in different missions: navigation, Earth observation, or broadband communications.

Broadband communications missions are one of the most exploited ones in the space segment due to the user demand, and thus it is really profitable. In particular, Low Earth Orbit (LEO) satellite constellations started to be popular thanks to its proximity to the Earth, which enables real-time services. Following a relay concept, different missions used this kind of constellation in order to provide global communications service (voice and data). *Globalstar* [1] and *OrbComm* [2] constellations are examples of this kind of distributed systems.

These relay systems have some limitations on coverage, because they consist of one-hop strategy. Therefore, the latest research has been focused on the Inter Satellite Communications (ISC) [3] capability to establish a communication between satellites. The ISC can be represented by the well-known Open Systems Interconnection (OSI) model [4], which splits a remote communication into seven layers.

A physical ISC case is the Data Relay Satellite System (DRSS) which proposes a relay system for LEO and Medium Earth Orbit (MEO) satellites. In particular, the ESA European Data Relay System (EDRS) [5] and the NASA Tracking and

2169-3536 © 2018 IEEE. Translations and content mining are permitted for academic research only.
Personal use is also permitted, but republication/redistribution requires IEEE permission.
See http://www.ieee.org/publications_standards/publications/rights/index.html for more information.

Data Relay Satellite System (TDRSS) [6] propose to establish a Geostationary Earth Orbit (GEO) satellite constellation to provide a relay backbone for other lower-altitude satellites. Although this option seems interesting in terms of latency, the distance between satellites becomes a huge resource cost (e.g. transmitted power) for the satellites, especially for nano-satellites.

Research has evolved to a more sophisticated ISC scenario in which satellites have routing capabilities and they are not only bent pipe devices. The *Iridium* system [7] is an example of this new implementation which provides voice and data coverage using a LEO satellite constellation. This system defines an Inter Satellite Link (ISL) as a point-to-point communication between two adjacent satellites. Depending on their placement, an ISL can be classified as intra-orbital (between two satellites in the same orbital plane) or inter-orbital (between two satellites of consecutive planes). Using this new concept, the whole system defines a mesh architecture in which each satellite has the capability to communicate using two intra-orbital and two more inter-orbital ISLs.

With the onset of this interconnected constellation, the literature has focused on defining this new satellite system as a *LEO Satellite Network*. In this context, an important element is the definition of the best routing protocol for this architecture in which satellites are homogeneous in terms of resources, hardware, software, operator entity, and mission.

Different spatial entities are placing their own satellite systems and industry is starting to become an important player in the space exploitation. One of the latest industrial projects is the Mega Constellation [8]–[11] which proposes the deployment and operation of thousands of satellites in a specific constellation to provide global Internet coverage. This new architecture implies an important amount of technological, legal, and managing challenges due to its magnitude. This means that the space will be over-populated, creating an important platform of heterogeneous nodes. Therefore, the interconnection between these systems would provide the possibility to transport the Internet architecture to the space.

This kind of mission has promoted the debate on the Internet of Space (IoS) paradigm [12], which tries to create a satellite backbone in order to provide Internet connectivity to the whole planet. This paradigm is based on the Internet of Things (IoT) [13] concept which promotes the interconnection of heterogeneous embedded devices using Internet technologies.

All this makes the space segment an extreme heterogeneous environment with different resource capabilities. By design, most satellite resources are not exploited during all mission phases, because they work following a duty cycle strategy. Therefore, the capability to share these unused resources with other satellites that need them would optimize the whole space segment. This is the proposal of Federated Satellite Systems (FSS) [14]–[17]. In particular, this type of systems promotes the establishment of a win-win collaboration between satellites in order to improve their mission performance. A federation is thus composed of a customer (which requires a service) and a supplier (which provides the service).

A FSS is different from traditional satellite systems, because it is created opportunistically when the need exists. This means that this system can be conceived as a virtual satellite system, in which satellites from other physical systems decide to create this federation. In terms of the OSI model, a federation can be conceived as an ‘‘application’’. Specifically, this ‘‘application’’ is deployed through satellites and it is focused on improving satellite performance; therefore, it represents an autonomous satellite application.

The FSS concept is presented in [16] as a federation which is created when satellites coincide and a direct communication exists. This point-to-point federation needs a communication link which can be implemented by an ISL, so-called FSS ISL [16]. Nowadays, the possibility to implement a FSS ISL using state-of-the-art technology exists, although a unique solution for all satellites is still far from being implemented. Indeed, a big effort has been performed to evaluate different Radio Frequency (RF) and Free Space Optical (FSO) solutions [3], [18]–[20] concluding that it is still mission-dependent and needs to be standardized.

In addition, a point-to-point FSS is strictly dependent on the opportunistic satellite contacts, which could limit its establishment. In particular, the existence of an ISL active time provokes the disruption of existing federations. Taking as an example a storage sharing federation, a supplier provides memory capacity to store external data from another satellite. In this case, when the ISL is established the customer performs the data transmission, but when the ISL is broken this transmission is stopped. This situation can provoke a partial storage of the whole data block, creating to the customer the need to find another storage supplier. Moreover, the sporadic nature of satellite contacts makes difficult to quickly retrieve the stored data.

To overcome these limitations, the FSS concept needs to be extended to a multi-hop paradigm, i.e. using a satellite network. This extension would accomplish all the FSS benefits in terms of cost, availability, and flexibility. This network can be conceived as a common infrastructure which provides external nodes access to be interconnected (a network backbone). This is the case of the Space Internet [21], [22] which proposes the creation of a network backbone to reduce the cost and standardize the communications for all NASA missions. This paradigm, which follows the same idea as the Heterogeneous Spacecraft Network (HSN) [23], promotes the use of Internet technologies (TCP/IP stack) to integrate its flexibility, scalability, and low cost to the space segment. However, the fact that the backbone is composed of ground infrastructure makes the system ground-dependent, which could limit autonomous satellite applications.

Alternatively to this common infrastructure, this work presents what we call the **Internet of Satellites** (IoSat) paradigm which provides a sporadic end-to-end ISC platform for autonomous satellite applications, such as FSS. This new interconnected space segment paradigm promotes the eventual connection of distant satellites using multiple heterogeneous satellite networks, what we call Inter-Satellite Networks (ISN). As different from other authors, that proposes a backbone, The IoSat paradigm innovation resides in that it is composed by satellites that have their own mission, and decide to participate in this network. Therefore, the network is deployed by the collaboration of intermediate satellites. In other words, this proposal promotes the peer-to-peer (P2P) architecture in the space segment, which supposes new interesting challenges in terms of protocol stack.

Although the physical and link layers have already been investigated with the ISL concept, the research on the network layer is still a premature topic that needs to be addressed. In particular, the network model and the routing protocol are fundamental elements that need to be defined in order to characterize and manage the different ISNs. Therefore, an exploration of the current technologies would evaluate the possibility to translate current solutions in this context.

In [24], an analysis to determine the requirements that impact the routing protocol design was performed. These requirements were classified by dynamism or application needs. Although these network dynamic requirements are common to different satellite networks, application requirements are more focused on broadband communications which could not always be needed in a FSS. In addition, a routing protocol analysis to compare the performance of static and adaptive protocols in different constellation architectures is presented in [25]. Although its results encourage using different routing protocols depending on each scenario, the presented protocol does not follow any current solution and it is a concept-oriented proposal.

More focused on FSS applications, the challenges that need to be addressed in the near-future to deploy this kind of DSS are exposed in [26]. Specifically, a preliminary survey of different physical, link, and network technologies is performed, but they are not deeply analyzed.

This work presents a comprehensive analysis to evaluate the implementation of an ISN in the IoSat context. In particular, it provides: 1) a detailed description of the IoSat concept, extending the initial idea presented in [27], 2) an explanation of the different features that an ISN has, 3) an exploration of the different satellite network models and their applicability in the IoSat context, 4) an evaluation of different routing protocols that could satisfy the ISN requirements, 5) the recommendations to design a routing protocol that implements an ISN, and 6) different routing protocol candidates that could work in the IoSat context.

The reminder of the article is structured as follows. Section II presents the concept of IoSat in detail. The state of the art of current satellite network models is presented in Section III. Section IV explores different routing protocols and their features that could be implemented in an ISN. A comparison between the routing protocols and a selection of candidates is exposed in Section V. Finally, Section VI summarizes the open issues and the recommendations for future research.

II. INTERNET OF SATELLITES

A. CONCEPT

As presented before, a FSS proposes the creation of a win-win collaboration between satellites to improve their missions. As in *cloud computing*, the sharing of the available resources could overcome technological gaps of more limited spacecrafts. This kind of satellite systems differs from the traditional ones because it can be conceived as a virtual satellite system, i.e. the satellites are part of physical systems and they establish a new virtual one. In terms of communications, this can be represented as an autonomous satellite application which deploys some services through and for satellites. Therefore, a communication platform is needed to establish a FSS between two remote satellites.

The IoSat paradigm defines an interconnected space segment to address this situation, and thus to deploy autonomous satellite applications (e.g. FSS). This paradigm does not propose an interconnected space segment based on having a specific backbone infrastructure (as Space Internet proposes). Indeed, it promotes the establishment of a network using a peer-to-peer (P2P) architecture, in which satellites are part of the network. Therefore, it is composed of dynamic, sporadic, and opportunistic satellite networks which are temporally established depending on the required demand.

This opportunistic network, the ISN, is created by the collaboration of intermediate nodes. In particular, the creation of an ISN is achieved thanks to the combination of point-to-point federations between intermediate nodes to forward data. Note that in terminology of FSS, an ISN can be considered as a *distributed* federation in which intermediate nodes play the role of suppliers and customers.

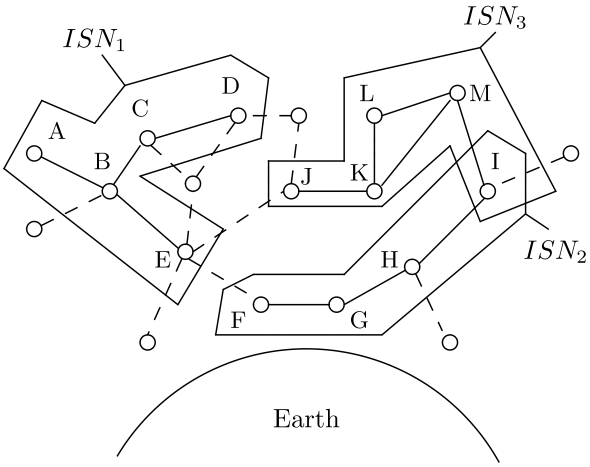


FIGURE 1. **IoSat space segment representation.**

Figure 1 represents the paradigm philosophy by showing three ISNs (ISN_1, ISN_2, and ISN_3) which coexist simultaneously. These ISNs are created depending on the FSS requirements and they adapt themselves to manage network dynamism. Note also that there are some nodes that can participate in multiple ISNs at the same time.

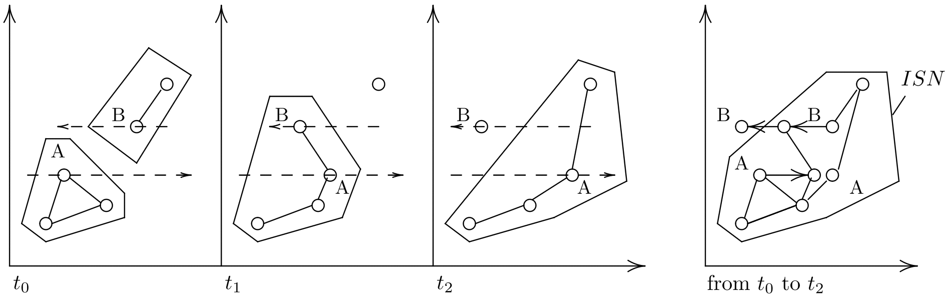


FIGURE 2. Representation of the ISN evolution.

One aspect to take into consideration is that a FSS is active if and only if it is needed. Therefore, an ISN is an opportunistic and temporal network which has also an active lifetime. This implies that an ISN has an establishment phase, a maintenance phase, and a destruction phase.

The establishment of an ISN is the negotiation process in which intermediate federations are created to configure the network. During this phase, its members can decide not accepting this interaction due to their state or strategy interests. Indeed, a probability that a proposed federation would be accepted or at least negotiated is analyzed in [28].

Moreover, the establishment phase ensures that the ISN is able to satisfy FSS requirements by providing the required services. For instance, if a security level is required, intermediate nodes should have secure mechanisms to provide it. This implies that during the ISN establishment, nodes shall indicate which services they can provide.

Once the ISN is established, the maintenance phase ensures that the network adapts to different events. In particular, as a satellite network is a dynamic environment in which nodes are in constant movement, this phase is responsible to update network connections when intermediate links are broken. Therefore, it should be able to replace old intermediate nodes by adding new ones. Moreover, some satellites could request to participate in an existing federation that would need to add more intermediate nodes to increase the current ISN. Thus, the ISN should be able to adhere new satellite nodes as per their request, or by the need to keep the topology stable.

Figure 2 presents an example of how the maintenance phase should address the ISN dynamism. In particular, it shows how two partitions of an ISN evolve through time (from t_0 to t_2) in which node B and node A are moving establishing new links.

Finally, in the destruction phase (once the ISN is no longer required) all the nodes that have participated in the network should perform the destruction process which cleans their internal state and recovers their usual activity. This is an important phase because the resources shall be released when they are no more needed.

There is a common need that should be respected in an ISN. Satellites are embedded systems with severe limitations in terms of energy, computation, and data storage resources, which means that additional ISC capabilities could jeopardize the mission. This could appear because satellites are normally conceived to accomplish a specific mission, and the integration of these new capabilities could suppose an additional resource consumption which could deplete the satellite. In other words, the deployment of an ISN shall not impact the mission of intermediate satellites. Therefore, this network is deployed using a resource-aware strategy while trying to satisfy application requirements.

Moreover, if a satellite decides that its participation in the network compromises the accomplishment of its mission, it can decide to leave the network. Therefore, satellites require a certain level of intelligence to autonomously take this decision. An ISN is a completely dynamic and constant changing scenario, due to satellite mobility, node participation, and node resource state. Therefore, conventional solutions cannot implement this behavior.

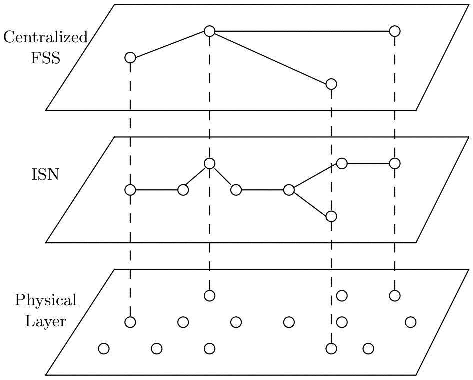


FIGURE 3. Layered representation of a centralized FSS.

To provide an overview of the ISN concept, Figure 3 presents an example of a centralized FSS in the IoSat context. In particular, it can be seen the physical layer which represents the ensemble of all satellites that are physically placed in this region. Some of them accept to participate in the network and can provide the required services to deploy the FSS. Therefore, they create an ISN with intermediate federations. Through this temporal network the end-to-end FSS is then accomplished.

TABLE 1. Summary of ISN features.

Dynamic Topology	
Intermittent connectivity	Due to node movement, node connections change. This makes that satellites are not constantly in the line-of-sight.
Network Partition	Due to its connectivity, an ISN can be partitioned and then merged (e.g. Figure 2).
Node Failures	Although there is component redundancy, space environment can provoke the failure of a spacecraft subsystem, which triggers the death of the node.
Unreliable nodes	The variation of satellite state (e.g. energy) provokes that nodes may not longer be able to participate in an ISN, and thus its withdrawal.
Unreliable channel	Communication is performed through a wireless medium, which is error prone. Furthermore, medium characteristics are time-varying.
Orbital Movement	
Deterministic trajectory	Nodes are satellites which follow well-defined orbital trajectories, determined by specific parameters.
Predictable topology	Due to its nature, orbital trajectories can be predicted with a good level of accuracy, which makes the global topology predictable too.
Duty cycle activity	Orbit movement makes that satellites periodically pass over a target region. Thus, satellite bypass between an operational and standby mode.
Resource-constrained nodes	
Power-limited nodes	Satellites are usually powered by the combination of solar panels and batteries, which makes the node energy limited and its level time-variable.
Memory-limited nodes	A satellite has a limited storage capacity, usually composed of persistent and volatile memories. These memories stores internal house-keeping and mission (science and/or communications) data.
Embedded systems	An in-orbit satellite is an embedded system with limited physical access. This makes impossible its direct maintenance, and thus a control is needed to avoid undesirable behaviors (e.g. maximum depth of discharge).
Custom designed	A spacecraft is designed to accomplish a mission, this implies that additional resource consumption shall not jeopardize its accomplishment.
Heterogeneous nodes	
Different objectives	Each satellite has a different mission to accomplish.
Different state definition	Due to spacecraft diversity, each satellite defines its state differently.
Different bandwidth capacity	Large, medium, and small satellites coexist in the space. Due to its characteristics, each one has different communication capabilities.
Federation over Federations	An ISN is established thanks to the combination of multiple point-to-point federations, which allows executing a federation.
Limited data security	As an ISN is composed of satellites from different entities, forwarded data can be read by undesirable agents. A security level shall be provided to ensure data privacy.
Autonomous network	
Self-configurable network	Satellites shall be able to autonomously configure themselves to create an ISN.
Adaptive network	Due to the dynamic topology, an ISN shall autonomously react against network events, such as link disconnection or node failure.
Traffic Dependence	
Federation-dependent	As a federation is deployed upon an ISN, each federation has different requirements that impacts on the network management.
Many-to-many traffic	Depending on the application, multiple spacecrafts can communicate with multiple ones. In this case, it cannot be predefined a specific traffic model as in other networks.
Opportunistic and Sporadic	As a federation is opportunistic, an sporadic ISN is deployed depending on the opportunity to create this federation. It is thus a sporadic network.

B. SUMMARY OF IoSat FEATURES

The concept of an ISN has been presented in the last section. It is characterized by a set of features which determine its behavior, summarized in Table 1. In particular, an ISN has a topology which is mainly time-varying. Due to node movement, connections are established and broken through time, partitioning or merging the network in different sections. Moreover, nodes are spacecraft placed in an aggressive environment, which can provoke their failure or fluctuate their state. The state variation makes that the satellite is no longer available to participate in an ISN, and thus it can be withdrawal of the network topology.

Although nodes are in a constant movement, they follow orbital dynamics with a deterministic and predictable trajectory. Moreover, satellite activity is determined by a duty cycle pattern, which is directly related to the mission. This kind of activity makes that the satellite is periodically alternating between operational and standby modes.

A satellite is a system deployed in the space with a custom design in order to accomplish a mission. Thus, its hardware architecture is specific and bounded by mission requirements. This makes the satellite a resource-constrained node, in particular with respect to the energy resource. The addition of new communication capabilities can impact the mission performance, which may not be acceptable. Furthermore, as the access to spacecrafts becomes an impossible task when they are in-orbit, the control of undesirable states or behaviors is crucial for node existence.

As presented in last sections, the industry trend is to overpopulate the near-space region with additional satellite systems. Each of them is developed by different space agencies and companies, making the whole space a complex heterogeneous scenario. Each satellite has different goals to accomplish and communication capacities. As an ISN is created through multiple federations, the data privacy of the source-destination flow is an important topic to address.

For all these features, the IoSat paradigm, and in particular the ISN concept, becomes a challenging research field. In terms of communications, it is difficult to be implemented using traditional solutions. Therefore, an analysis in depth related to the different options is presented in the following sections.

III. NETWORK MODELS

The last section has presented a set of properties which shape the behavior of an ISN inside the IoSat context. These properties allow creating a network model which helps to conceive an efficient routing protocol. The routing protocol specifies a set of rules to determine a route (composed of intermediate nodes) between a pair of nodes. In particular, this protocol retrieves metrics of the network topology which are used to identify the best path depending on a specific criterion. For instance, a routing protocol can define the best route between two nodes as the one which contains the minimum number of intermediate nodes.

There are two strategies to address the routing protocol design; the former is based on conceiving a new protocol with an optimal performance for this scenario. On the other hand, there is the option to evaluate current solutions and adapt them to this scenario. This work follows the last strategy because, although the solution may be sub-optimal, it provides a solution that allows interoperability with current systems. Therefore, this section presents the state of the art of different network models which share some properties with ISN.

The first approach is based on the determinism of the satellite movement, representing a satellite network as a time-evolving and predictable network [29]. This kind of network is formally characterized by being node position and link status predictable over a long period of time.

In particular, the Virtual Topology (VT) model is presented in [30]. This model considers a satellite network as a discrete time network, and it assumes a fixed topology in each time interval. Figure 4 shows the different samples of the topology in the time interval from t_1 to t_2. Note that nodes five and four are those which move between samples.

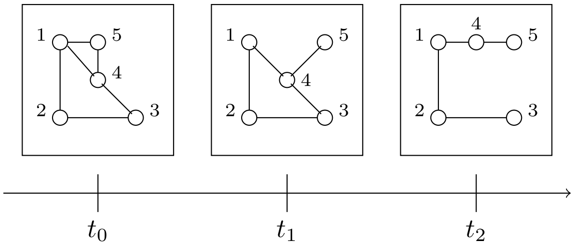


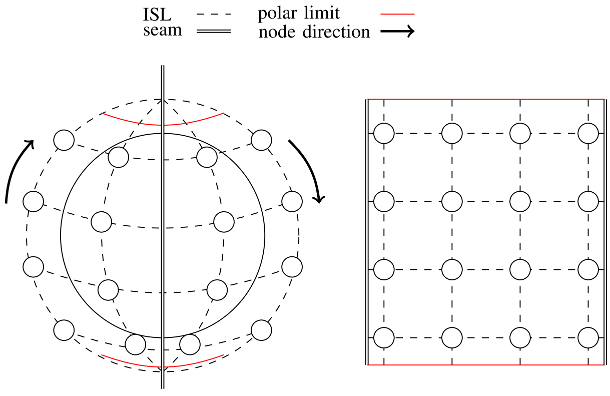
FIGURE 4. Discrete-time representation of a satellite network.

Each sample of the topology is called *snapshot* and it defines a network connectivity state with stable ISLs during specific time. Thanks to deterministic satellite movement, the evolution of these snapshots can be predicted creating a well-known succession of them which is periodically repeated. Using this model, routes are defined at each snapshot and the snapshot transition can also be computed in advance by a central entity to be then uploaded into each satellite. The main issue of this model is that the snapshot sequence is directly related to the number of satellites, i.e. the larger the number of satellites, the larger the number of snapshots. This could be a big issue if there is a large number of satellites, thus this model is not scalable.

In order to address a high-dynamic environment such as a LEO satellite network, the authors in [31] propose the Virtual Node (VN) model as alternative. This model is composed by different logical locations which are static zones of Earth (i.e. latitude and longitude) that are assigned to the nearest satellite. Due to the satellite movement, the logical location is not constantly allocated to a specific satellite. Indeed, the assignment changes to another satellite of the same plane when the last one has already gone. With this architecture, each change on the satellite assignment represents a new snapshot.

Each snapshot represents a state of the network topology which has been conceived as a mesh network. Specifically, each node has four ISL with its neighbors: two intra-plane ISLs, and two inter-plane ISLs. Thanks to this architecture and the logical location, a route can be defined by a set of intra-plane and inter-plane ISLs between two nodes. Thus, this mechanism shields the network dynamics as well as simplifies the routing mechanism. More details about the routing mechanism in this model are found in Section IV-B.

This model has some specific peculiarities due to orbital dynamics. In particular, a *seam* separates the satellites that move in opposed directions, and the model forbids the communication through this boundary. Another aspect is that distances between nodes in this mesh are not constant. Specifically, in polar regions satellites are closer than in equatorial regions. Therefore, in order to avoid packet collision, the model does not contemplate the transmission in the polar zones.



(a) (b)

FIGURE 5. LEO satellite network model in (a) space representation and (b) mesh representation.

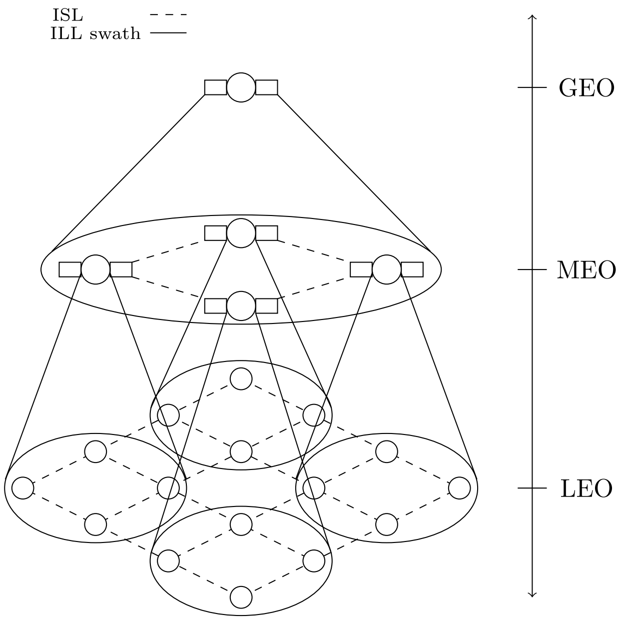


FIGURE 6. Multi-Layered satellite network representation.

Figure 5 presents the VN model with the multiple ISLs and the forbidden regions. Note that the figure presents the global view of the model with a minimalist Earth representation, and a plane view to represent the model as a mesh.

Another satellite network model follows the combination of multiple satellite constellations in order to enhance the network capacity. In particular, Multi-Layered Satellite Network (MLSN) model [32] defines a satellite network as a hierarchical structure composed of satellite systems placed in different altitudes. In order to manage this structure, each higher-layer satellite covers a set of lower-layer satellites using its larger footprint, i.e. creating a satellite group. For instance, a MEO satellite manages the connections with a specific LEO satellite group. In this model, an ISL represents a link between two adjacent satellites in the same layer, and an Inter Layer Link (ILL) represents a link between satellites placed in different layers. Figure 6 shows a representation of this model.

In a MLSN the snapshot is determined by the changes of group members, and not by the topological change of the lower-layer itself [33]. This can produce snapshots with irregular length that could difficult the routing protocol implementation. Therefore, it is proposed to use the VN model for the LEO layer in order to keep the snapshot period stable and simplify the computation of the routing tables for higher-layer satellites.

Using this hierarchical structure, the satellite network becomes a well-organized system in which a high bandwidth communication can be established with low overhead. Although this approach is conceived for broadband communication services, it could also be used for autonomous satellite applications. However, some assumptions are considered with respect to LEO and GEO satellite systems which could not be always true. Specifically, the existence of a higher-layer satellite that could provide forwarding service is not ensured in the IoSat context. Therefore, this structure could be broken in this situation. Therefore, it can be seen that this architecture is really useful for specific satellite systems, which reduces flexibility and adaptability; however, note that [33] remarks the benefits of combining multiple satellite systems to improve global performance, i.e. the benefits of being heterogeneous.

Other proposals [34], [35] have tried to model a satellite network as a Mobile Ad-hoc Network (MANET) [36]. This kind of network is self-organizing and self-configuring, because each node has the ability to retrieve the network status in order to estimate the current topology. Specifically, each node performs the network discovery to retrieve information about the current network behavior and maintains routing tables updated with the different topology changes. This model is focused on high-dynamic networks with unpredictable mobile nodes. However, thanks to its flexibility, scalability, and autonomy this model has been adopted more and more in some predictable scenarios.

During these last years, other wireless networks and concepts have appeared. Wireless Sensor Networks (WSN) and IoT have taken great research interest [39]. A WSN combines three relevant elements: Wireless, Sensors, and Network. In particular, this model conceives a network with the combination of different devices (sensors and actuators) which are interconnected through a wireless medium. Note that these devices are not conventional nodes, because they are resource-constrained embedded systems. Thus, the creation of a network with these nodes becomes a challenging field.

TABLE 2. Summary of network models for satellite context.

Network Model	Interesting for ISN	Detrimental for ISN
VT - Snapshot Network [30]	Snapshot concept Flexible and adaptable model	Scalability issue
VN - LEO Satellite Network [31]	Shielding orbital dynamics Simple routing mechanism	Custom connections for each node
MLSN [32]	Combination of multiple satellite systems Increase of network capacity	Expected to have high-layer nodes available
MANET [36]	Adaptive to topology events Self-organizing	Focused on random mobility
WSN [37]	Same node architecture Energy-efficient model	Different data rate
DTN [38]	Characterization of network partitions Store-and-forward mechanism	Extreme environments Only for delay tolerant applications

This kind of Low-power and Lossy Network (LLN) has some similarities with a satellite network. In particular, a spacecraft can be conceived as a sensor because it is an embedded device with severe constrained resources. A satellite is designed to accomplish a specific mission and additional capacity, such as ISC, could provoke its depletion. Due to this synergy, some researchers have modeled a satellite network as a Satellite Sensor Network (SSN) [40] which defines a central node that aggregates data from other satellites. In this model, an important aspect is the optimization of the network lifetime by reducing the energy consumption of each node.

Another interesting proposed network model is based on the intermittent connectivity nature of a satellite network, e.g. an end-to-end path does not always exist. This kind of network is called Delay/Disrupted Tolerant Network (DTN) [38], and it models a satellite network as a system which suffers frequent partitions and its nodes have opportunistic contacts to exchange data. The store-and-forward mechanism is applied which makes that each intermediate node persistently stores the received message until the next hop is available, being it the responsible of the message.

In conclusion, an ISN needs the self-configuring capability of MANETs or WSNs to better react against satellite movement. However, its predictable nature is something that could be used in order to make it more efficient. Therefore, the VT seems an interesting model to predict local behavior and thus foresee link disconnections. Moreover, MLSN models the mission heterogeneity by combining different orbit architectures in order to improve the network capacity. As an ISN does not fix the type of satellite, spacecrafts from different constellations can interact as a MLSN. Normally, the DTN model is applied to Interplanetary Communications which have long and variable delays, asymmetric data rates, and high error rates. However, an ISN shares the intermittent connection nature due to the different spacecraft movements, and for that reason can be also applied. Finally, an ISN is composed of resource-constrained nodes which can be modeled as sensors in a WSN. However, the data nature and bandwidth are different, which challenge to adapt the WSN model in the satellite context.

Table 2 summarizes the different features of each model related to the IoSat context. It can be seen that it is impossible to directly conceive an ISN as a type of the presented models. Indeed, an ISN shares a set of similarities with all of them. Therefore, an in depth analysis shall be conducted to characterize and conceive a new model for an ISN.

IV. ROUTING PROTOCOLS

As presented in the beginning of Section III, the routing protocol is an important element in a network that defines a route between a pair of nodes. Many of these protocols have been conceived for specific networks, and they present different features. Table 3 summarizes some of them which represent the behavior of a routing protocol. This classification is important to expose which are the features needed that satisfy a network behavior, and thus identify the best routing protocol proposal.

Moreover, a routing protocol uses a set of metrics to evaluate the different possible routes. Thanks to these metrics and following a selection criterion, the best route between a pair of nodes is identified. Therefore, the metrics can impact the entire performance of the communication. Table 4 summarizes the most used metrics in the literature.

In the ISN case, the strategy used consists of evaluating the different routing protocols from last models. With this analysis, a set of candidates are proposed to deploy ISN, and thus to be used in the IoSat paradigm. Note that some of these models have a wide range of proposals, therefore this section only presents those which can accomplish ISN requirements.

A. SNAPSHOT NETWORK

The first routing protocol for the VT model was presented in [30] and [41]. It was called the Discrete-Time Dynamic Virtual Topology Routing (DT-DVTR) protocol. It is specifically designed for the Asynchronous Transfer Mode (ATM) which deploys connection-oriented communications. Following the VT model, this protocol computes off-line the snapshot sequence, also called Instantaneous Virtual Topology (I-VT) sequence, and then, for each snapshot the best path is identified. This path definition is done on-line by using

TABLE 3. Summary of routing protocol features.

Feature	Description
Connection-oriented protocol	It defines a specific path between a pair of nodes that all packets follow
Connectionless protocol	It does not determine a specific route, different packets can follow different paths
Hop-by-Hop protocol	It does not define a route, the packet is forwarded node-by-node
Multi-hop protocol	It defines a route which is composed of intermediate nodes
Static protocol	It does not retrieve information about network state and just applies a predefined routing policy
Adaptive protocol	It adapts the routing table depending on network state
Proactive protocol	It periodically retrieves network state in order to quickly act against a network change
Reactive protocol	It discovers the network state if, and only if, data transmission shall be done
Hybrid protocol	It discovers the network and then periodically evaluates its state (i.e. reactive and proactive)
Link State protocol	It retrieves information about the entire network state
Distance Vector protocol	It provides global information implicitly through local node states
Distributed protocol	Each node computes independently the path to a destination.
Centralized protocol	A central entity computes the entire routing tables of each network node
Hierarchical protocol	It defines routes depending on node ranks, creating a hierarchy
Predictable protocol	It uses node models to predict its state through time (resources, position, etc.)
Single-path protocol	It defines a single route between a pair of nodes
Multi-path protocol	It defines a set of routes between a pair of nodes.

TABLE 4. Summary of cost functions.

Metric	Criteria	Description
Hop	Minimum	Number of hops
Delay	Minimum	Transmission delay
Load	Minimum	Congested route
Resources	Maximum	Free node resources

conventional routing strategies (e.g. the Dijkstra shortest path algorithm [46]). In order to deal with path continuity over the different snapshots, the protocol executes a mechanism which provides this connection-oriented service. This strategy simplifies satellite mobility to a deterministic and periodic sequence, and provides flexibility to use different path definition mechanism for each snapshots.

However, DT-DVTR is not scalable since the number of routing tables depends on the network size (i.e. the number of nodes). In particular, the larger the number of nodes, the larger the number of topology changes happen, and thus the larger the snapshot sequence is (i.e. number of snapshots is related to the topology changes). This makes that a large sequence intrinsically implies a large amount of routing tables. This situation was addressed in [43] performing a constant sampling of the network topology, giving a fixed number of snapshots in a sequence. Using this new sampling and performing a snapshot transition algorithm, the ground segment can compute the whole routing tables and can upload them to the spacecrafts. This routing table distribution strategy is conceived due to the memory capacity limitation of satellites systems. It is interesting to see how the memory limitation problem has been solved using an Earth infrastructure, which provokes a dependence to compute routing tables (i.e. limited autonomy). Although this memory limitation could nowadays not be the same, it is important to be alert with the resource impact of each routing protocol.

The creation of the snapshot sequence has been also discussed in [44] which proposes an optimization method to perform an ISL reassignment in the Iridium case. Specifically, it is based on the specific architecture of the Iridium system to define ISL breakdown situations in the northern latitudes. Although the results presented show an improvement, it is really specific to the Iridium system. However, this work reflects the fact that large research efforts have been put to reduce the number of snapshots, and thus the updates of the routing table.

Another research trend has focused on the routing strategy into each snapshot, which usually is the Minimum Distance Algorithm (MDA) or the Minimum Hops Algorithm (MHA). These strategies manage well the end-to-end delay with low traffic, but they cannot address congestion scenarios and ISL disconnections. Therefore, a solution is presented in [45] which proposes a routing mechanism based on the traffic state and the combination of multiple paths. The results demonstrate that a multi-path scenario manages better the dynamism of a satellite network.

In a different way to previous proposals, a snapshot model with the Predictable Link-State Routing (PLSR) protocol was formalized in [42]. It works in a packet switching communication scheme capable to better handle network dynamics, i.e. each packet is independently routed of last transmitted packets. This link-state protocol addresses the predictable and unpredictable changes of a satellite network using Earth infrastructure, as in [43]. Specifically, ground stations precompute the snapshot sequence and update it using unpredictable changes that satellites detect (e.g. node failures).

TABLE 5. Summary of routing protocols in snapshot networks.

Routing Protocol	Interesting for ISN	Detrimental for ISN
	Routing Protocols	
DT-DVTR [30] [41]	Management by snapshots	Connection-oriented
PLSR [42]	Manage unpredictable events	Earth-dependent
SIR [40]	Predict future connections	Non-scalable
	Creation of the snapshot sequence	
Constant sampling [43]	Reduction of memory consumption	Less accuracy on broken links
Optimized method [44]	Managing high latitude links	Specific of Iridium constellation
	Route mechanism in the snapshot	
MHA	Reduction of broken links	Not aware of other events
Multi-path [45]	More reactive against broken links	Memory consumption
Traffic concerned [45]	Manages congestion	Only per a snapshot

Thanks to this additional information, ground stations can generate the evolved snapshots and thus evaluate the topology changes. The PLSR protocol cannot be executed if the communication between satellites and ground stations is lost, which limits the flexibility and autonomy of the network. Therefore, it seems difficult to be applied for autonomous satellite applications.

The Snapshot Integration Routing protocol was presented in [40]. It uses the integration of a sequence of snapshots into a static direct graph to define a path through time and space. This static direct graph represents the set of possible connections between satellites through time, and allows predicting future optimal paths. Although the snapshot model is used in this proposal, it follows the DTN model too, by accepting the storage and transport of different data packets. The main difference with the PLSR proposal is the prediction, which is not only done between adjacent snapshots, but over the entire snapshot sequence, which allows having global knowledge of the network. However, its performance in terms of resource consumption becomes important for on-board computing.

As Table 5 summarizes, there are different solutions that present interesting features. In particular, the snapshot technique is a mechanism that allows simplifying the complexity of satellite network mobility in a periodic sequence. However, the amount of snapshots is directly related to the number of satellites that compose the network. This could impact the storage consumption of each satellite, when indeed this satellite could not be actively working in the network. Therefore, its direct application in IoSat context is quite limited. Due to the deterministic nature of satellite movement, this mechanism cannot be simply discarded. Indeed, a promising idea would be the use of this mechanism in a local region where the number of satellites can be acceptable, as opposed of the whole network.

B. LEO SATELLITE NETWORK

As presented in Section III, the VN model is defined as a mesh network in which each satellite is linked by four ISLs to its neighbors. Each satellite is identified by a pair of values which represent its position in the network, also called *logical location*. In particular, this logical location is defined by vertical and horizontal coordinates in the mesh network. Using this definition, the comparison of two node identifiers allows determining the minimum-hop path between them.

The Datagram Routing Algorithm (DRA) [31] uses this architecture to perform the path selection in a distributed manner. In particular, each node performs an initial phase in which the minimum-hop path to a destination is computed. The VN architecture promotes the existence of multiple minimum-hop paths. This feature makes more efficient protocols that consider multi-path versatility, such as the DRA.

LEO satellite networks are conceived to provide a satellite backbone for broadband communications of Earth users (i.e. low end-to-end delay). This objective constrains the routing protocol to not only define the minimum-hop route, but also to use additional metrics which quantify the ISL behavior. In particular, DRA executes an additional phase which applies ISL dynamics to select the minimum-hop path with the lowest transmission delay.

However, as explained in [47], Earth users generate an unbalanced traffic distribution, i.e. there are some regions which produce more data than other ones. This makes that some ISLs congest more frequently, increasing the end-to-end delay. Therefore, DRA applies a third phase to compute the best path that considers the congestion state. In particular, each node evaluates its own ISL queue load to determine the congestion state. If this state is unacceptable, the node redirects the traffic to alternative paths (multi-path solution).

Figure 7 shows an example of packet transmission between the source (black node) and the destination (gray node). At the very beginning, the source identifies the six paths with four hops (the minimum value). After evaluating the state of its links, the source decides to transmit the packet to its left neighbor. Successively, the intermediate node performs the same algorithm to define the following hop until the packet reaches the destination.

The DRA has set the basis for future routing protocols which try to extend or improve it. In particular, as DRA uses local queue information, it cannot react against neighbor congestion once it is already appeared. Therefore, the Explicit

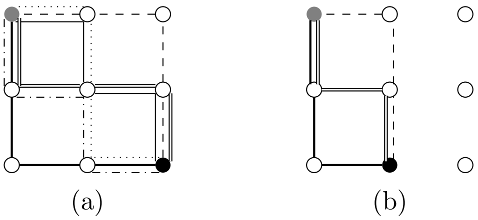


FIGURE 7. Sample of the minimum-hop path determination during the transmission of a packet. (a) First the packet is placed in the source (black node) and shall be transmitted to the destination (gray node). When the packet is transmitted to the left neighbor, (b) the path determination is computed again.

Load Balancing (ELB) [48] proposes a proactive scheme in which congested satellites notify neighbors to decrease transmission data rates. The reduction is achieved because data flow is redirected to alternative next hops. This mechanism allows quickly reacting against congestion scenarios. However, it does not provide any solution if alternative paths are also congested.

To solve this situation, the Priority-based Adaptive Routing (PAR) protocol [49] predicts a congestion situation using queue state. Specifically, it changes the next hop depending on the combination of historic drop/transmission rates, and current queue length of an ISL. Thanks to this strategy, it is capable to dynamically change between the different minimum-hop paths depending on the congestion state. However, this approach assumes that ISL distances are equal, which is not always true. Therefore, PAR for Minimum Delay path (PAR-MD) is also presented in [49] to manage this issue and it is more realistic.

The Traffic-Light-based Routing (TLR) protocol [50] is another proactive distributed proposal that copes traffic management by using a traffic light in each ISL queue. This traffic light represents the congestion state of the ISL, and depending on its "color" it allows the transmission. This "color" is computed using node and its neighbor queue lengths. Combining both metrics, it can predict ISL congestion and re-route the traffic to another path.

All these proposals use the local link state to avoid or manage a congested scenario. This limits the capability to manage the situation of a global network congestion. To address this situation, and thus globally analyze the traffic information, the Agent-based Load Balancing Routing (ALBR) protocol [51] is proposed. This distributed protocol uses agent technology which is based on the integration of a stationary agent that computes path cost and updates the routing table, and a mobile agent that travels through each satellite in order to retrieve its state. Thanks to this algorithm and to the geographical satellite information, the ALBR can correctly manage the traffic. However, the amount of agents is related to the amount of satellites in the network, i.e. a scalability limitation.

The same strategy has been extended to work in a snapshot model. Specifically, the Agent-based Dynamic Routing (ADR) is presented in [52] to manage this situation. In particular, the agent-based algorithm (like ALBR) is executed for each snapshot, while the transition between consecutive snapshots is managed by the Hop-by-hop Adaptive Link-state Optimal (HALO) algorithm [54]. This algorithm is capable to quickly manage the disruption of links between snapshots by computing a link metric related to the link status. Moreover, this algorithm also performs a traffic distribution if the link is still active. The combination of both mechanisms allows reducing the end-to-end delay as well as the packet drop rate. Furthermore, this proposal demonstrates that the combination of different network models makes the resulting model more realistic, and thus providing means to conceive a better routing protocol.

However, LEO satellite networks are composed of a region in which ISLs are disconnected, due to the proximity between satellites, i.e. polar regions. The existence of these regions makes that a node could become a deadlock in a transmission, because it cannot forward packets to a destination that is placed in this forbidden area. This situation spends network capacity without being used, and also increases the probability of congestion appearance.

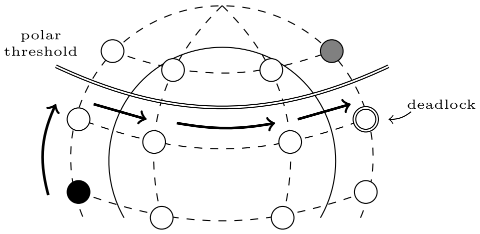


FIGURE 8. Deadlock representation between a source (black node) and a destination (gray node).

Figure 8 shows this issue using an example of transmission. In particular, the source (black node) transmits a packet to the destination (gray node) which is placed in the polar region. As in this region the communication is forbidden, the packet never reaches its destination, and it only arrives to the deadlock node (double-line node).

The Distributed Load-Aware Routing (DLAR) protocol [53] addresses this issue by using deterministic properties of the constellation to detect when the destination is in the polar region (i.e. unreachable) before to send any packet. Moreover, this distributed protocol implements a traffic adaptive mechanism which splits the traffic through a set of paths. This new mechanism allows improving the packet delivery ratio as well as the end-to-end delay, but it is still related to the fact that the satellite system is a constellation.

Big efforts have carried out to introduce multi-path mechanisms [55], and traffic classes [56], among other techniques which improve the traffic management in this scenario. It has been a hot topic during these last years thanks to the emergence of the Iridium system and the discussion of the Next-Generation of Satellites [57]. The progress reached related to congestion avoidance mechanisms in this scenario is interesting to be applied in IoSat context. However, these solutions

TABLE 6. Summary of routing protocols in LEO networks.

Routing Protocol	Interesting for ISN	Detrimental for ISN
Queue state approach		
DRA [31]	Distributed packet forwarding Simple and low signaling	Specific for custom constellations
ELB [48]	Quick reaction against congestion Flow redirection through alternative paths	Large energy consumption Alternative paths congested
PAR [49]	Prediction of congestion Priority-based next-hop selection	Local congestion information
PAR-MD [49]	Improved next-hop selection with delay model	Specific for custom constellations
TLR [50]	Different levels of congestion	Local congestion information
Agent-based approach		
ALBR [51]	Global congestion information	Non-scalable
ALBR and HALO [52]	Combination of multiple network models	Non-scalable
Prediction-based approach		
DLAR [53]	Use of deterministic behavior	Specific for custom constellations

are really bound by the satellite architecture, which in all the cases follows a satellite constellation (difficult to apply in an ISN). Table 6 summarizes the benefits and drawbacks of previous protocols.

C. MULTI-LAYERED SATELLITE NETWORK

In order to address heterogeneity and enhance the network capacity, the MLSN model is defined. The first routing protocol that follows this model in a two-layered (LEO and MEO) structure is the Hierarchical QoS Routing Protocol (HQRP) [58]. The HQRP defines two kinds of information: the Local Routing Information (LRI) and the Global Routing Information (GLI). The LRI allows identifying path candidates in the same layer. On the other hand, the GLI contains path candidates between different layers. Using both information types, LEO nodes can compute the minimum hop path forwarding data through a specific MEO satellite.

The Multi-Layered Satellite Routing (MLSR) [32] proposes a protocol focused on MLSN networks with more than two layers. Specifically, it exposes a solution for LEO, MEO, and GEO layers aiming at reducing the computational complexity, communication overhead and delay. In order to accomplish this performance, this protocol is based on the delay measurement from each LEO satellite which is reported to its MEO satellite manager. This manager forwards this information through the different satellites of the same layer. This process is re-executed by the MEO, and GEO layers. Finally, GEO satellites compute the routing tables which are then transmitted to each lower-layer satellite. This strategy allows reducing signaling overhead and maintaining the hierarchical structure.

If the incoming traffic is large enough to congest the whole LEO layer, previous solutions cannot avoid this situation. Therefore, new proposals are focused not only to manage this in the same layer, but also to use upper layers (e.g. MEO layer). In particular, the Tailored Load-Aware Routing (TLAR) protocol [59] proposes a periodic congestion status transmission from LEO satellites to MEO satellites in order to have a global congestion view. This information allows detouring the traffic to MEO satellites which will reduce LEO layer congestion, although end-to-end delay will increase in the detoured traffic. Its results demonstrate this capability while consuming a small signaling overhead.

However, this approach has not considered the congestion of MEO satellite managers due to simultaneous receptions from different nodes, i.e. congestion of an ILL. This situation is addressed in [60] by applying some constraints in the hierarchical structure in order to have multiple path for LEO satellites. Specifically, it identifies the fact that increasing altitude of MEO satellites, LEO ones can have multiples upper layer satellites in line-of-view. This feature allows having multiple paths through which the traffic can be split, thus reducing the probability to have congestion in MEO layer. Although it is demonstrated that using this enhancement the queuing delay is reduced, the propagation delay increases due to the higher altitude. Thus, there is a compromise between altitude and traffic management.

As other proposals, [61] promotes the combination of two different satellite network models in order to enhance the traffic management while reducing signaling overhead: MLSN and Snapshot. Specifically, it proposes a LEO/GEO two-layered satellite network in which GEO satellites are responsible to manage routing tables of LEO ones, while these ones provide user access to the satellite backbone. In order to achieve this goal, the Hop-Constrained Adaptive Routing (HCAR) protocol uses the sequence of LEO snapshots to predict changes on the topology which are updated from ground stations to GEO satellites and then forwarded to LEO satellites. This approach successfully combines both models, however it is a centralized approach which implies that its flexibility and scalability are limited.

In another research trend, a dynamic satellite grouping strategy is proposed [24], which allows managing different constellation architectures for broadband communications.

TABLE 7. Summary of routing protocols in MLSN.

Routing Protocol	Interesting for ISN	Detrimental for ISN
	LEO-MEO approach	
HQRP [58]	Combination of multiple satellite layers	Distinction between inter and intra layer flow
TLAR [59]	Using multiple layers to manage congestion	Assuming that MEO satellites are available
New architecture [60]	Optimization of satellite system	MEO satellites required
	LEO-GEO approach	
HCAR [61]	Topology changes prediction	Large energy consumption Unique control satellite layer (i.e. GEO) Protocol depends on Earth infrastructure
	Multiple-layers approach	
MLSR [32]	Combination of multiple heterogeneous satellites	High-layer satellites are not always available
Dynamic grouping [24]	Dynamic and adaptive	Protocol depends on Earth infrastructure

Specifically, this centralized proposal defines multiple satellite groups identifying three different roles: the group header (GH), the group member (GF), and the group manager (GM). The GM is responsible to compute predictable network changes and transmit this information to each GH, the MEO satellite that holds the best adjacency with the GM. Then, the GH forwards this information to other GF of the satellite group. In order to reach this goal, the proposed routing protocol performs two phases that compute predictable changes, and then a third one to manage unpredictable congestion status. This variable grouping allows adding configuration flexibility and easy management into the MLSN model, although it is a solution Earth-dependent which limits the autonomy of the network.

As Table 7 summarizes, the concept of having multiple satellites in different layers follows the IoSat context, therefore it is promising how the previous solutions have managed this scenario. Moreover, as authors presents in [62], this multi-layer architecture enhances the network capacity with respect to the LEO satellite networks. However, it is indicated that the network capacity does not increase significantly for architectures in which a LEO satellite only has an ILL. On the other hand, these architectures that promote more connectivity between layers have a larger network capacity. In conclusion, the combination of multiple satellite constellations seems to enhance the global capacity of the network, but a more interconnected architecture would provide a better performance. These results are promising for the establishment of ISNs which are composed of satellites placed in different layers.

D. MOBILE Ad-hoc NETWORK

Previous routing protocols use deterministic satellite movement to predict or map the network in advance, reducing signaling overhead and improving end-to-end latency. However, this approach is designed to work in a predefined satellite system architecture and it cannot easily react against unpredictable network changes, such as node failures.

In other domains, the Mobile Ad-hoc Network (MANET) concept is conceived to manage such kind of situations. In particular, nodes in this network have the capability to adapt their communications depending on topology changes, emphasizing on those related to node mobility. This adaptability is accomplished thanks to the routing protocol which retrieves information about topology state to manage link disruptions.

One of the most popular MANET routing protocols is the Ad-hoc On-demand Distance Vector (AODV) [63]. In this reactive protocol, the source executes a *discovery phase* just before starting the data transmission. As its name indicates, this phase allows discovering a viable path to a destination depending on the network topology at that moment. The accomplishment of this phase is achieved thanks to the transmission of specific control packets which flood the entire network (flooding mechanism). When these packets are received by the destination, this one replies following the same forward path in the opposite sense, which determines the active path. This communication strategy allows consuming less energy, and it is more focused on sporadic transmissions. However, when a path failure occurs, the source node re-launches the discovery phase. This makes the protocol not quick against node failures, i.e. large reaction time.

To cope with this limitation, the Ad-hoc On-demand Multi-path Distance Vector (AOMDV) routing protocol [64] improves its discovery phase by defining more than a single path. Specifically, using the flooding feature of the AODV protocol, the destination responds to each control packet from the source, and returning by multiple paths. Having this set of possible paths makes faster the reaction against network changes. Only when the entire set of paths are not valid, the discovery phase is launched again.

AODV-based protocols fit well for sporadic and short data transmission. However, when a more constant transmission flow and quick reaction are required, another kind of strategy needs to be conceived. The Optimized Link State Routing (OLSR) protocol [65] follows a proactive strategy to cope with these limitations. Especially, each node periodically sends *hello* messages to discover neighbor information and identify its Multi-point Relay (MPR) nodes. Those MPR nodes are responsible of transmitting control packets which notify about topology link status. By limiting the packet flooding to only MPR nodes, OLSR reduces signaling overhead respect other link state routing protocols. This protocol is capable to quickly detect any topology change. However, in a high dynamic environment, the topology is constantly changing which increases the amount of control packets. This overhead affects the energy consumption of each node, which in the satellite case could provoke the depletion of its battery.

Another proactive proposal, based on distance-vector instead of link-state, is the Destination-Sequenced Distance-Vector (DSDV) routing protocol [66]. This protocol discovers a path between a source and a destination by exchanging control data between direct neighbors. Since in this kind of protocol nodes do not have a global view of the topology, the *routing loop problem* can appear. This problem appears when the path to a destination includes a close-loop, which makes that the destination is never reached. DSDV addresses this situation by using a sequence number for each destination entry in the routing table. This sequence number identifies the creation time, which allows nodes to verify if the received information is new. If it is the case, then the entry is updated; if not, the information is rejected. This mechanism provides enough means to be used in a network with mobile nodes, and highlight the loop problem of distance-vector approaches.

Another trend on MANET routing protocols has been focused on combining features from reactive and proactive protocols. The resulting protocols, so-called hybrid routing protocols, have the discovery phase of reactive protocols and the maintenance mechanism of proactive ones. This is the case of the Zone Routing Protocol (ZRP) [67] which estimates a zone radius to limit and reduce the signaling overhead. In particular, this zone delimits the number of nodes that will follow a proactive approach. If one of them establishes a communication with another outside the zone (to a peripheral node), a reactive mechanism is executed. The definition of a delimiting zone is an interesting concept that can be applied in an ISN. However, the ZRP defines a unique and static zone in the network, which limits the flexibility of the protocol.

The Independent ZRP (IZRP) [68] copes with this limitation by computing a specific proactive zone for each node. Thus, each node keeps a proactive communication with its closer nodes and a reactive one with far nodes. In other words, this solution prioritizes closer nodes against further ones. This solution becomes more adaptable and flexible to the needs of each node, however it is quite difficult to generate all zones in a large scenario.

To address this situation, the Fish-eye State Routing (FSR) protocol [69] defines different quality zones for each node. In particular, each node defines different zones in which the resolution of link state information is reduced proportionally to the zone radius (distance). In other words, it exists different quality zones with different information accuracy. Those closer to the source are well-known, but those further are vague (like a fish-eye). This technique allows keeping the entire proactive strategy reducing protocol signaling. However, it considers that the traffic is uniformly distributed over the entire network.

The Two-ZRP (TZRP) proposal [70] combines both concepts of IZRP and FSR to provide a unique solution that is able to manage high-mobility scenarios. In particular, each node defines the Crisp Zone and the Fuzzy Zone. Inside the former, topology updates follow a proactive mechanism as IZRP. However, in the Fuzzy Zone the fish-eye technique is used, reducing thus the accuracy of the network changes (i.e. a vague image). Outside this zone, the communication is purely reactive.

A huge number of routing protocols that exist [71] have been designed to operate in MANET environments, because it has been a hot topic during last years.

Although the more widely known MANET routing protocols have not been directly applied to satellite networks, different researches have tried to extend them in order to cope satellite dynamics. This is the case of the Location-Assisted On-demand Routing (LAOR) protocol [34] which extends the AODV protocol by limiting the number of satellites that are flooding during the discovery phase using deterministic movement of LEO satellites. Therefore, the LAOR executes a preliminary phase before the discovery one, called *request area formation*, which defines the possible interest zone to flood. It has been demonstrated that in a high load LEO satellite network, this protocol can provide less end-to-end delay than a predictable centralized routing protocol. It is interesting how authors have included deterministic satellite physics inside a MANET routing protocol which by default does not assume specific node behavior. This powerful combination allows improving current solutions for satellite context while keeping its essence.

More focused on a FSS, it has been demonstrated [35] that using the OLSR protocol in opportunistic data-forward federations can improve the data time access. Using this proactive protocol, nodes are able to compute routing tables when ISL are changing. However, in [35] the routing protocol resource impact on the satellites that compose the network is not shown. As discussed in [35], this proposal seems promising in terms to implement FSS using well-known technology, but a deeper analysis must be performed in the future.

Nowadays, the application of MANET routing protocols in satellite context is still a research topic of great interest. Thanks to their adaptability, flexibility, and scalability, these protocols are interesting candidates to deploy ISNs in the IoSat context (see Table 8). Satellites are governed by deterministic physics which can be used to adapt current solutions to this scenario. In conclusion, a deep analysis shall still be done in this topic.

E. WIRELESS SENSOR NETWORK

A Wireless Sensor Network (WSN) addresses a specific scenario in which wireless nodes, that senses the environment, are interconnected to establish an autonomous network. These sensors are minimally designed to accomplish their sensing function, and thus they are really

TABLE 8. Summary of routing protocols in MANET.

Routing Protocol	Interesting for ISN	Detrimental for ISN
Reactive approach		
AODV [63]	Low power consumption	Long reaction time Re-execution when path is broken
AOMDV [64]	Multi-path capacity	Increase of memory usage
LAOR [34]	Use of satellite information Discovery phase area bounded	Long reaction time Uploaded satellite position information
Proactive approach		
OLSR [65]	Quick reaction against events Fast transmission	Huge energy consumption For small scenarios
DSDV [66]	Manage multiple updates	Large overhead
Hybrid approach		
ZRP [67]	Combination of reactive and proactive techniques Zone boundary concept	Unique and static zone
IZRP [68]	Each node has its own proactive zone	Difficult to manage in a large scenario
FSR [69]	Different quality zones	Assuming uniformly distributed traffic
TZRP [70]	Manage high-mobility with just two zones	Difficult to manage in a large scenario

resource-constrained. Therefore, the deployment of these sensors over a specific area and interconnect them can suppose a major challenge in terms of energy consumption. Therefore, different routing protocol strategies have been conceived.

One of them is to define smart structures to optimize the global network residual energy, i.e. defining hierarchical topologies. This approach is based on multipoint-to-point communication. In particular, limited energy nodes forwards data to a more capable one that aggregates incoming data and performs a costlier transmission. The discussion on this topic is the selection mechanism of this aggregator node, so-called cluster-head. An approach is presented in the Low-Energy Adaptive Clustering Hierarchy (LEACH) routing protocol [72], which periodically and randomly changes the cluster-head. Specifically, each node randomly publishes to the cluster the possibility to become the cluster-head, and neighbors autonomously decide to communicate with it. This makes that a single node is not only drained because it is always the cluster-head, but it can exist the situation that a node is the cluster-head when it has not enough energy.

In order to address this issue, the Hybrid Energy Efficient Distributed Clustering (HEED) routing protocol [73] uses energy state and data rate values to decide the cluster-head. In particular, each node computes the probability to become the cluster-head analyzing its own state. If the situation is appropriate, the node publishes the intention to become the cluster-head. This enhancement reduces signaling overhead as well as fairly distributes cluster-head across the network (increasing network lifetime). The HEED protocol defines thus two kinds of communications: intra-cluster and inter-cluster. The consumption source analysis is presented in [74], concluding that the transmission distance is an important factor of high consumption. Therefore, the authors propose the Extended HEED (EHEED) which enables the communication between non-cluster-head nodes if, and only if, the transmission is less energy costly. This situation extends the single-hop communication with the cluster-head to a multi-hop strategy.

The benefits on energy-safety with hierarchical topologies have motivated the Internet Engineering Task Force (IETF) to define the Routing Protocol for LLN (RPL) [75] standard. This distance vector routing protocol has the capability to autonomously define a hierarchical structure which its information is distributed to each node. The root of the structure (main node) proactively maintains the network topology knowledge by exchanging downward/upward control messages. Using this periodic signaling, this protocol has the capability to join new nodes into the structure, which is an appropriate feature for the ISN behavior.

The autonomous construction mechanism of RPL is based on a node rank that identifies each node inside the hierarchical structure, i.e. the depth level of each node. During the construction, each node determines its preferred parent to forward incoming packets. The most interesting point of this protocol, at least in the ISN context, is that this standard decouples the route selection mechanism from the routing protocol *core*, which provides flexibility for heterogeneous scenarios. In particular, the standard defines the Objective Function (OF) as a tool to compute the rank and the parent by combining network metrics and constraints.

The RPL standard does not define a specific OF, indeed it promotes the exploration of the differences between metric, constraint, and selection criteria in the OF concept. One of the first proposals is the Objective Function Zero (OF0) standard [76] which proposes a basic and common mechanism to unify the computation of Rank value. However, additional OF have been conceived, such as the Minimum Rank with Hysteresis Objective Function (MRHOF) case [77] which selects a route that minimizes an additive metric using hysteresis to reduce the impact of small metric changes.

Both examples do not restrict to use a specific metric. However, the first metric proposition was the Hop-Count (HC) metric. This metric favors the path of fewer but longer hops. This behavior is related on this metric represents a static property, therefore, more dynamic link metrics have been evaluated. One of them is the Averaged Delay (AD) metric [78] which uses the end-to-end route delay to compute the rank value. This is an interesting approach if the main objective is to reduce the communication latency, however, the performance can vary depending on the link quality.

Another issue that appears using these metrics is that they cannot manage congestion scenarios, increasing thus packet losses. This situation is addressed by the Queue Utilization based RPL (QU-RPL) [79] which enhances an implementation of the RPL with MRHOF and HC metrics to perform load balancing. Specifically, the used metrics are extended with the queue utilization one, which can be used to predict local congestion. Using this enhancement, the protocol is able to define the less congested parent in a set of possible candidates.

As indicated before, an OF computes the node rank using metrics and also constraints. This last one provides a new level of decision capability. An example is the Expected Transmission Count (ETX) [80] which determines the expected number of transmissions to reach the destination. This parameter can be considered as a metric, but it is also related to maximum number of transmissions that can be accepted (constraint). Treating constraints and metrics differently allows selecting a candidate not only by its qualities, but it also respects certain conditions.

Using single metrics cannot be enough to accomplish the desired performance, an example is that if node energy metric is not considered the depletion of nodes can appear. This issue is addressed in the Improved RPL (IRPL) [81], which is based on the Life Cycle Index (LCI) (another OF) that takes into consideration multiple metrics, such as link quality, node energy, success transmission data rate and congestion detection factor. Although the complexity of the algorithm increases, the results indicate that the combination of multiple metrics allows improving end-to-end delay while keeping the network residual energy.

This behavior is desired for IoSat context, however, the RPL standard does not manage mobile nodes which can limit protocol effectiveness. In [85] a solution for the mobility of specific nodes was proposed. In particular, a hybrid protocol based on reactive discovery limited by broadcast zones (like the ZRP [67]) and the RPL maintenance network is proposed. This approach intelligently combines mechanisms from MANET and WSN solutions to improve routing performance.

This is not the unique case that MANET solutions have been used to address energy challenge of WSN [86]. In particular, location-based routing protocols provides information related to the node position. This information can be used to predict transmission consumption using predefined energy model. This is the case of Geographical Adaptive Fidelity (GAF) routing protocol [82] which uses an internal energy model to define cells in which a single master is active. The other nodes that are in the same cell are turned off, avoiding unnecessary consumption. Another approach is the Geographic and Energy Aware Routing (GEAR) routing protocol [83] which uses the combination of geographical position and energy level of neighbors to define the next hop. Using both information, it can manage the residual network energy and thus improve network lifetime.

Similarly to the last proposals, the Kalman Positioning RPL (KP-RPL) [84] implements RPL standard using position information. In particular, it computes node position combining the measure of the Receive Signal Strength Indicator (RSSI) and the Kalman filter to refine it. However, this protocol promotes the communication between static nodes (called anchors) and mobile one, instead of only between mobile nodes. Although further research needs still to be carried out to address the situation of a full-mobile topology, using node position is a powerful information to predict energy consumption.

The RPL is a promising routing protocol to deploy ISNs because its flexibility and autonomy. In particular, the capability to implement different OFs as well as the freedom to select specific metrics makes this protocol a perfect candidate to manage ISN heterogeneity. Furthermore, the decoupling of metrics and constraints allows the developer to define new conditions that cannot only be related to performance, and it can be more oriented on strategy decisions. However, a large effort to translate this solution to a more mobile ad-hoc environment needs still be done. Table 9 summarizes a trade-off between the previous routing protocols.

F. DELAY/DISRUPTION TOLERANT NETWORK

As detailed before, a DTN is focused on working with disruptive connectivity in which a destination could not be reached. This situation implies a major challenge to design a routing protocol. Therefore, a large effort has been done in the last years to provide different solutions that cope with this situation, emphasizing point-to-point strategies.

As there is no certainty that a path to a destination exists, the first strategy was based on static routing protocols, in particular flooding-based protocols. This kind of protocol transmits multiple copies through the network (flooding) hoping that one of them reaches the destination.

One of these protocols is the Epidemic routing protocol [87] which replicates the message without node discrimination, i.e. a node transmits the message to all point-to-point contacts. This protocol is a simple example of a complete flooding mechanism. However, it generates a huge amount of transmissions which are completely useless (because their messages will not reach the destination). These transmissions imply a very large energy consumption which could provoke the depletion of a node. Therefore, efforts have been carried out to conceive a more energy-efficient epidemic routing protocol.

TABLE 9. Summary of routing protocols in WSN.

Routing Protocol	Interesting for ISN	Detrimental for ISN
	Cluster approach	
LEACH [72]	Simple - random distribution	Energy state not considered Cluster strategy - cannot manage mobility
HEED [73]	Energy state-based CH distribution	Communication always through CH Cluster strategy - cannot manage mobility
EHEED [74]	Intelligent communication between non-CH nodes	Cluster strategy - cannot manage mobility
	Dynamic Hierarchical approach	
RPL [75]	Flexible, scalable, and autonomous Topology creation using metrics and constraints	Cannot naturally manage mobility
RPL-OF0 [76]	Simple and easy to implement	Variation effect on rank computation
RPL-MRHOF [77]	Hysteresis to avoid variations on rank computation	More complex mechanism
RPL-HC [76]	Minimum hop path	Cannot manage congestion
RPL-AD [78]	Minimum latency path	Cannot manage congestion
QU-RPL [79]	Manage congestion scenarios	Aware of local congestion only
RPL-ETX [80]	Path with less than a maximum of transmissions	Cannot manage congestion
IRPL [81]	Combination of multiple metrics	A set of constraints are not used
	Location-based approach	
GAF [82]	Use of Energy model Communication depending on energy consumption	Dynamic node activation
GEAR [83]	Combination of position and energy state	Inaccuracy of node position
KP-RPL [84]	Position improvement using Kalman filter Extension of RPL	Important computation cost Mobile-to-static nodes communication only

This is the case of the n-Epidemic routing protocol [88] which tries to reduce the number of transmissions by having a threshold of neighbors. In particular, a node does not transmit any message if it does not have n neighbors to transmit. With this constraint, the source ensures that a minimum of nodes receive the message and thus increase the probability that the message reaches the destination. However, this approach is limited by the density of the network, i.e. if there are not enough neighbors a packet would never be transmitted.

A more sophisticated routing protocol is the Energy Aware Epidemic (EAEpidemic) routing protocol [89]. This protocol is based on exchanging the node energy and reception buffer level states to evaluate if the transmission of the message should be done. Using this additional information, the messages are copied to only those neighbors which have energy enough to avoid the depletion. Using this mechanism, the overall network life is increased and thus the probability of message delivery.

The Spray-and-Wait (SaW) routing protocol [90] is an extension of the Epidemic routing protocol. In particular, it defines a number of message copies that are transmitted and ensures an acceptable reception probability. Intermediate nodes do not copy again the received message; they just relay it to direct contacts nodes. Using this technique, it can better manage the network energy (by sending less messages) as well as ensuring a certain level of delivery.

Due to their nature, the last approaches waste network bandwidth with unnecessary copies of the original message. Therefore, another strategy is based on having a metric to qualify the encountered node and only transmit a single copy of each message. These routing protocols predict or learn about possible future encounters which are quantified by a node metric. That is the case of MobiSpace [91] which uses the deterministic satellite movement to identify potential encounter opportunities. Therefore, the transmission of a message is done by the probability to deliver it to the destination. This approach, however, does not consider or evaluate the probability that a message be stored by intermediate nodes, which directly impacts the transmission delay.

In order to characterize this situation, the Motion VEctor (MOVE) routing protocol [92] combines two probability matrices. In addition to the matrix that represents the probability of reception, this protocol computes a matrix that represents the message sojourn at each node. By combining both metrics, it is possible to predict the probability of reception and transmission delay of each message. However, the knowledge of all the mobility patterns could be difficult to be accomplished in dense networks (i.e. scalability issue).

An alternative that tries to keep delay awareness while reducing computation is the Routing in Cyclic Mobility (RCM) proposal [93]. In particular, it uses the historical encounter at each cycle to quantify the node. Using this information, each node can map the network as a probabilistic state graph enabling the routing decision with the shortest Expected Minimum Delay (EMD). In other words, it computes the transmission delay over a probabilistic model, which simplifies the methodology, but increases result uncertainty.

TABLE 10. **Summary of routing protocols in DTN.**

Routing Protocol	Interesting for ISN	Detrimental for ISN
	Flooding-based approach	
Epidemic [87]	Simple to address network disruption	Always flooding the network Large energy consumption
n-Epidemic [88]	Reducing flooding mechanism	Not energy aware
EAEpidemic [89]	Adapting flooding to energy state	Reaching the destination is not ensured
SaW [90]	Not flooding, just a group of messages Less energy consumption	No consideration of neighbor state
	Prediction-based approach	
MobiSpace [91]	Usage of deterministic satellite movement	Not delay aware Scalability issue
MOVE [92]	Path prediction using multiple metrics	Large computation Scalability issue
RCM [93]	Concept of the encounter historic Simple method	Impossible to manage failures Scalability issue
PROPHET [94]	Combination of multiple metrics Prediction of future encounters	Scalability issue
DQN [95]	No-predefined model used Direct application in satellite context	Specific for LEO satellite networks

The Probabilistic Routing Protocol using Historic of Encounters and Transitivity (PROPHET) [94] is another predictable protocol which uses a non-random mobility patterns to estimate the different encounters. In particular, each node has a mobility pattern of all the last encountered nodes which helps to estimate future encounters. With this estimation, each node can be ready to exchange control data when an encounter appears. This control data is used to update mobility patterns, but also to estimate the probability that the node can reach a specific destination. Moreover, congestion state is also an important element which determines the probability of deliverance. Using both metrics and this model, PROPHET can send specific packets to those which have a high probability of delivery.

It can be seen that DTN solutions have evolved to use deterministic satellite movement to predict disruptions. This mechanism allows adapting message transmissions to reduce delays and to increase the deliverance probability. However, as in the snapshot case, this approach is directly related to the number of nodes that composes the network. Moreover, DTN are networks clearly defined for deep space communications in which the node density is really low and the communication cannot always be accomplished. In the near-Earth context, this situation would not be the same, although the *message storage* concept is a promising technology. For all these features, it is difficult to be applied in the IoSat context, in which it is contemplated a large heterogeneous satellite set. However, if these techniques could be adapted to work in a local region (e.g. in an ISN) it could improve other proposals.

The application of a DTN solution for LEO satellite network is presented in [95]. In particular, authors expose the benefits of the novel DTN routing protocol, called DQN, in quasi-deterministic networks. A LEO satellite network follows a deterministic dynamism, because it is ruled by satellite mobility. However, due to traffic generation and link outages this scenario cannot be considered totally deterministic, and thus quasi-deterministic. In this case, DQN use not a predefined routing policy, indeed it uses the exchange of node contacts to determine the node with the closest destination. Although this approach is really specific for this satellite architecture, it demonstrates the flexibility of DTN routing protocols to be used in different satellite scenarios.

Therefore, this kind of technology is interesting for IoSat paradigm. In particular, satellite mobility can be modeled and thus future encounters can be defined. However, due to node participation decision, this determinism could be compromised and thus it could become a quasi-deterministic scenario. Table 10 presents different features of each presented routing protocol.

V. ROUTING PROTOCOL RECOMMENDATIONS

The last section has presented a wide range of routing protocols that have been used in satellite context or in other network context. These protocols present interesting features that could be used in the IoSat paradigm. Thus, is there a current solution that could be directly used to deploy ISNs? This question can be answered if the features needed for the routing protocol are identified.

Although the ISN has three different phases (one of them the establishment phase), a *connectionless* protocol can better manage network mobility than a connection-oriented. At the very beginning, it seems that a connection-oriented protocol follows the same concept of establishing the ISN by defining fixed paths. However, since after the establishment of the path all the packets are forwarded following it, this protocol is more impacted by the network dynamism. In particular, due to satellite movement, the path would always be broken and thus a management to establish it would be required. Therefore, if the communication can be done without a specific end-to-end connection, the mechanism will be more flexible and adaptable.

TABLE 11. Summary of routing protocols.

Routing Protocol	Connection-oriented	Connectionless	Multi-hop	hop-by-hop	Static	Adaptive	Proactive	Reactive	Hybrid	Link-State	Distance Vector	Distributed	Centralized	Hierarchical	Predictable	Single-path	Multi-path	Hop metric	Delay metric	Load metric	Resources metric
Snapshot Networks																					
DT-DVTR [30]	X		X			X	X			X		X			X	X		X			
PLSR [42]		X	X			X	X			X			X		X	X		X			
SIR [40]		X	X		X					X			X		X	X				X	
LEO Satellite Networks																					
DRA [31]		X		X		X		X			X	X					X	X	X	X	
ELB [48]		X		X		X	X				X	X					X			X	
PAR [49]		X	X			X	X				X	X					X	X		X	
PAR-MD [49]		X	X			X	X				X	X					X		X	X	
TLR [50]		X	X			X	X				X	X			X		X		X	X	
ALBR [51]		X	X			X	X			X		X			X	X			X		
ALBR and HALO [52]		X	X			X	X			X		X			X		X		X	X	
DLAR [53]		X		X		X		X			X	X			X		X	X		X	
Multi-Layered Satellite Networks																					
HQRP [58]	X		X			X	X			X		X		X		X				X	
MLSR [32]		X	X			X	X			X		X		X		X			X		
TLAR [59]		X	X			X	X			X		X		X			X		X	X	
HCAR [61]		X	X			X	X				X		X	X	X	X				X	
Mobile Ad-hoc Networks																					
AODV [63]		X	X			X		X			X	X				X		X			
AOMDV [64]		X	X			X		X			X	X					X	X			
OLSR [65]		X	X			X	X			X		X				X		X			
DSDV [66]		X	X			X	X				X	X				X		X			
ZRP [67]		X	X			X			X	X	X	X				X		X			
IZRP [68]		X	X			X			X	X	X	X				X		X			
TZRP [70]		X	X			X			X	X	X	X				X		X			
FSR [69]		X	X			X			X	X	X	X				X		X			
LAOR [34]		X	X			X		X			X	X			X	X			X		
Wireless Sensor Networks																					
GAF [82]		X	X			X	X			X		X			X	X		X			
GEAR [83]		X	X			X	X				X	X			X	X		X			X
LEACH [72]		X	X			X	X				X	X		X		X					
HEED [74]		X	X			X	X				X	X		X		X				X	X
EHEED [74]		X	X			X	X				X	X		X			X			X	X
RPL [75]		X	X			X	X				X	X		X		X					
RPL-HC		X	X			X	X				X	X		X		X		X			
RPL-AD [78]		X	X			X	X				X	X		X		X			X		
RPL-ETX [80]		X	X			X	X				X	X		X		X		X			X
QU-RPL [79]		X	X			X	X				X	X		X		X				X	
IRPL [81]		X	X			X	X				X	X		X			X	X	X	X	X
KP-RPL [84]		X	X			X	X				X	X		X		X			X		
Delay/Disruption Tolerant Networks																					
Epidemic [87]		X		X	X							X					X				
n-Epidemic [88]		X		X		X			X		X	X					X				
EAEpidemic [89]		X		X		X		X			X	X					X			X	X
SaW [90]		X		X	X							X					X				
MOVE [92]		X		X		X	X			X		X			X	X		X	X		
MobiSpace [91]		X		X		X	X			X		X			X	X		X			
RCM [93]		X		X		X	X			X		X			X	X			X		
PROPHET [94]		X		X		X	X				X	X			X	X		X		X	
DQN [95]		X	X			X	X				X	X				X		X			

An *adaptive* routing protocol knows the network state and reacts against unpredictable events, such as related to detachments of nodes from an ISN or node failures. Moreover, a *distributed* solution would provide a more flexible and agile behavior than a centralized architecture. Those protocols that are Earth-infrastructure depended, such as the PLSR, can have an optimized mechanism to address resource limitations, but this approach could limit network autonomy, which is not desired for an ISN.

Both reactive or proactive protocols have their own benefits which makes them interesting depending on the application service needed, although reactive could be better to have a more energy-efficient mechanism. However, a more conservative proposal should be conceived as a *hybrid* routing protocol, which would have both benefits in contrast to a higher complexity.

As ISN size is variable, and IoSat paradigm is conceived for a future overpopulated space segment, a distance vector protocol consumes less memory, computing, and power resources. Because it is difficult that each node could be capable to compute path candidates using global state, which directly depends on the number of nodes in the network. If the link state information is from a limited region (and not the whole network), it would be interesting to use this strategy. It can be seen that there is a compromise between resource consumption and region of maintenance.

A *multi-path* routing protocol can always better react against path failures or congestion scenarios. Therefore, this feature improves considerably the network behavior, although the complexity and memory consumption will also increase. Hierarchical structures are more energy-efficient, but it is more complex to manage the structure in a high dynamic environment.

Protocols that predict network topology allow having low signaling overhead, but they cannot react well against congestion scenarios or node failures. However, as satellite networks are predictable scenarios, it seems interesting to use this information to improve certain mechanisms of a more ad-hoc-oriented protocol, such as the LAOR case.

After performing an exhaustive analysis, the Table 11 summarizes the different routing protocols features and highlight the desired ones (blue cells). Comparing them with the required properties, LAOR, ZRP, AOMDV, RPL, EAEpidemic, and PROPHET are interesting candidates that could be used in IoSat. However, nowadays a solution which satisfies all the features of an ISN does not exist. In particular, the concept of publishing the possible service when the path is defined is still a topic that needs to be investigated. RPL has good means to manage this using OFs, but it is still something to be designed.

VI. CONCLUSIONS

This article has presented the Internet of Satellites (IoSat) concept, a new paradigm in which multiple heterogeneous satellites networks are sporadically created depending on autonomous satellite applications. It can become an interesting communication platform for Federated Satellite System (FSS) and future satellite missions.

As it supposes a major challenge in terms of network technology, a study and analysis of current network models and related routing protocols has been presented. In particular, different time-evolving and predictable network models used in satellite context have been presented, such as Virtual Topology, Virtual Node and Multi-Layered Satellite Network. A model more focused on connectivity behavior, which is the case of the Delay/Disruptive Tolerant Network, has been exposed. In addition, other more innovative proposals based on Mobile Ad-hoc Networks, and Wireless Sensor Networks have also been presented.

For each of these models different routing protocol solutions have been analyzed providing a wide range of possibilities. All of them are summarized in Table 11 which presents their main characteristics. Comparing these characteristics with the ISN requirements, a set of candidates have been identified. Although this selection has been done after an exhaustive evaluation, no performance analysis of these candidates has been performed yet. Therefore, future work should execute the different candidates in a simulator platform (under development) to evaluate its performance in the IoSat paradigm.

REFERENCES

[1] R. A. Wiedeman and A. J. Viterbi, "The Globalstar mobile satellite system for worldwide personal communications," in *Proc. 3rd Int. Mobile Satellite Conf. (IMSC)*, Pasadena, CA, USA, Jun. 1993, pp. 291–296.

[2] S. D. Ilcev, "Orbcomm space segment for mobile satellite system (MSS)," in *Proc. 10th Int. Conf. Telecommun. Mod. Satellite Cable Broadcast. Services (TELSIKS)*, vol. 2. Niš, Serbia, Oct. 2011, pp. 689–692.

[3] R. Radhakrishnan, W. W. Edmonson, F. Afghah, R. M. Rodriguez-Osorio, F. Pinto, and S. C. Burleigh, "Survey of inter-satellite communication for small satellite systems: Physical layer to network layer view," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 4, pp. 2442–2473, 4th Quart., 2016.

[4] H. Zimmermann, "OSI reference model—The ISO model of architecture for open systems interconnection," *IEEE Trans. Commun.*, vol. COM-28, no. 4, pp. 425–432, Apr. 1980.

[5] F. Heine, G. Mühlnikel, H. Zech, S. Philipp-May, and R. Meyer, "The European data relay system, high speed laser based data links," in *Proc. 7th Adv. Satellite Multimedia Syst. Conf. 13th Signal Process. Space Commun. Workshop (ASMS/SPSC)*, Sep. 2014, pp. 284–286.

[6] J. Teles, M. V. Samii, and C. E. Doll, "Overview of TDRSS," *Adv. Space Res.*, vol. 16, no. 12, pp. 67–76, 1995.

[7] S. R. Pratt, R. A. Raines, C. E. Fossa, and M. A. Temple, "An operational and performance overview of the IRIDIUM low earth orbit satellite system," *IEEE Commun. Surveys*, vol. 2, no. 2, pp. 2–10, 2nd Quart., 1999.

[8] E. Buchen, "Small satellite market observations," in *Proc. 29th Annu. AIAA/USU Conf. Samll Satellites*, Atlanta, GA, USA, 2015, pp. 1–12.

[9] T. Pultarova, "Telecommunications-space tycoons go head to head over mega satellite network," *Eng. Technol.*, vol. 10, no. 2, p. 20, 2015.

[10] P. de Selding, "Virgin, qualcomm invest in OneWeb satellite Internet venture," *Spacenews*, Jan. 2015. [Online]. Available: http://spacenews.com/virgin-qualcomm-invest-in-global-satellite-internet-plan/

[11] I. Lunden, "Google confirmed it has purchased satellite start-up Skybox Imaging for 500 m," TechCrunch, New York, NY, USA, Tech. Rep., 2014. [Online]. Available: https://techcrunch.com/2014/06/10/google-is-confirming-purchase-of-satellite-startup-skybox-imaging-today/

[12] S. Raman, R. Weigel, and T. Lee, "The Internet of space (IoS): A future backbone for the Internet of Things?" *IEEE Internet Things Newslett.*, Mar. 2016. [Online]. Available: https://iot.ieee.org/newsletter/march-2016/the-internet-of-space-ios-a-future-backbone-for-the-internet-of-things.html

[13] L. Atzori, A. Iera, and G. Morabito, "The Internet of Things: A survey," *Comput. Netw.*, vol. 54, no. 15, pp. 2787–2805, Oct. 2010.

[14] A. Golkar, "Federated satellite systems: A case study on sustainability enhancement of space exploration systems architectures," in *Proc. 64th Int. Astron. Congr.*, vol. 4. 2013.

[15] I. Lluch i Cruz and A. Golkar, "Resource balancing analysis of federated satellite systems," in *Proc. AIAA SPACE Conf. Expo.*, 2014, p. 4270.

[16] A. Golkar and I. Lluch i Cruz, "The Federated Satellite Systems paradigm: Concept and business case evaluation," *Acta Astron.*, vol. 111, pp. 230–248, Jun. 2015.

[17] A. Golkar, "Federated satellite systems: An innovation in space systems design," in *Proc. 9th IAA Symp. Small Satellites Earth Observ. Int. Acad. Astron.*, vol. 194. Berlin, Germany, 2013.

[18] H. Kaushal and G. Kaddoum, "Optical communication in space: Challenges and mitigation techniques," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 1, pp. 57–96, 1st Quart., 2017.

[19] R. Alena, Y. Nakamura, N. Faber, and D. Mauro, "Heterogeneous spacecraft networks: Wireless network technology assessment," in *Proc. IEEE Aerosp. Conf.*, Mar. 2014, pp. 1–13.

[20] R. Akhtyamov *et al.*, "An implementation of software defined radios for federated aerospace networks: Informing satellite implementations using an inter-balloon communications experiment," *Acta Astron.*, vol. 123, pp. 470–478, Jun. 2016.

[21] K. Bhasin and J. L. Hayden, "Space Internet architectures and technologies for NASA enterprises," in *Proc. IEEE Aerosp. Conf.*, vol. 2. Mar. 2001, pp. 2-931–2-941.

[22] J. R. Budenske, K. S. Millikin, J. C. Bonney, R. S. Ramanujan, and O. S. Sands, "Space network architecture technologies," in *Proc. IEEE Aerosp. Conf.*, vol. 3. Mar. 2002, pp. 3-1061–3-1069.

[23] Y. Nakamura *et al.*, "Heterogeneous spacecraft networks: Performance analysis for low-cost earth observation missions," in *Proc. IEEE Aerosp. Conf.*, Mar. 2014, pp. 1–14.

[24] X. Yi, Z. Sun, F. Yao, and Y. Miao, "Satellite constellation of MEO and IGSO network routing with dynamic grouping," *Int. J. Satellite Commun. Netw.*, vol. 31, no. 6, pp. 277–302, 2013.

[25] L. Franck and G. Maral, "Static and adaptive routing in ISL networks from a constellation perspective," *Int. J. Satellite Commun. Netw.*, vol. 20, no. 6, pp. 455–475, 2002.

[26] D. Selva *et al.*, "Distributed Earth satellite systems: What is needed to move forward?" *J. Aerosp. Inf. Syst.*, vol. 14, no. 8, pp. 412–438, 2017.

[27] J. A. Ruiz de Azua, A. Calveras, and A. Camps, "Internet of Satellites (IoSat): An interconnected space paradigm," in *Proc. 5th Federated Fractionated Satellite Syst. Workshop*, 2017, pp. 1–8.

[28] P. T. Grogan, K. Ho, A. Golkar, and O. L. de Weck, "Bounding the value of collaboration in federated systems," in *Proc. Annu. IEEE Syst. Conf.*, Apr. 2016, pp. 1–7.

[29] J. Shen, C. Wang, A. Wang, X. Sun, S. Moh, and P. C. K. Hung, "Organized topology based routing protocol in incompletely predictable ad-hoc networks," *Comput. Commun.*, vol. 99, pp. 107–118, Feb. 2017.

[30] M. Werner, "A dynamic routing concept for ATM-based satellite personal communication networks," *IEEE J. Sel. Areas Commun.*, vol. 15, no. 8, pp. 1636–1648, Oct. 1997.

[31] E. Ekici, I. F. Akyildiz, and M. D. Bender, "A distributed routing algorithm for datagram traffic in LEO satellite networks," *IEEE/ACM Trans. Netw.*, vol. 9, no. 2, pp. 137–147, Apr. 2001.

[32] I. F. Akyildiz, E. Ekici, and M. D. Bender, "MLSR: A novel routing algorithm for multilayered satellite IP networks," *IEEE/ACM Trans. Netw.*, vol. 10, no. 3, pp. 411–424, Jun. 2002.

[33] Y. Lu, F. Sun, and Y. Zhao, "Virtual topology for LEO satellite networks based on Earth-fixed footprint mode," *IEEE Commun. Lett.*, vol. 17, no. 2, pp. 357–360, Feb. 2013.

[34] E. Papapetrou, S. Karapantazis, and F. Pavlidou, "Distributed on-demand routing for LEO satellite systems," *Comput. Netw.*, vol. 51, no. 15, pp. 4356–4376, 2007.

[35] I. Lluch, P. T. Grogan, U. Pica, and A. Golkar, "Simulating a proactive ad-hoc network protocol for federated satellite systems," in *Proc. IEEE Aerosp. Conf.*, Mar. 2015, pp. 1–16.

[36] J. Macker, *Mobile Ad Hoc Networking (MANET): Routing Protocol Performance Issues and Evaluation Considerations*, document RFC 2501, 1999.

[37] J. N. Al-Karaki and A. E. Kamal, "Routing techniques in wireless sensor networks: A survey," *IEEE Wireless Commun.*, vol. 11, no. 6, pp. 6–28, Dec. 2004.

[38] V. Cerf *et al.*, *Delay-Tolerant Networking Architecture*, document RFC 4838, 2007.

[39] P. Rawat, K. D. Singh, H. Chaouchi, and J. M. Bonnin, "Wireless sensor networks: A survey on recent developments and potential synergies," *J. Supercomput.*, vol. 68, no. 1, pp. 1–48, 2014.

[40] P. Song *et al.*, "Snapshot integration routing for high-resolution satellite sensor networks based on delay-tolerent network," in *Proc. IEEE Int. Conf. Comput. Inf. Technol., Ubiquitous Comput. Commun., Depend., Auto. Sec. Comput., Pervasive Intell. Comput. (CIT/IUCC/DASC/PICOM)*, Oct. 2015, pp. 2400–2406.

[41] M. Werner, C. Delucchi, H. J. Vogel, G. Maral, and J. J. De Ridder, "ATM-based routing in LEO/MEO satellite networks with intersatellite links," *IEEE J. Sel. Areas Commun.*, vol. 15, no. 1, pp. 69–82, Jan. 1997.

[42] D. Fischer, D. Basin, K. Eckstein, and T. Engel, "Predictable mobile routing for spacecraft networks," *IEEE Trans. Mobile Comput.*, vol. 12, no. 6, pp. 1174–1187, Jun. 2013.

[43] V. Gounder, R. Prakash, and H. Abu-Amara, "Routing in LEO-based satellite networks," in *Proc. IEEE Wireless Commun. Syst., Emerg. Technol. Symp.*, Apr. 1999, pp. 1–22.

[44] Z. Tang, Z. Feng, W. Han, W. Yu, B. Zhao, and C. Wu, "Improving the snapshot routing performance through reassigning the inter-satellite links," in *Proc. IEEE Conf. Comput. Commun. Workshops (INFOCOM WKSHPS)*, Apr. 2015, pp. 97–98.

[45] J.-F. He, J. Yong, B. Dong-Ming, and G.-X. Li, "Routing strategy research based on ISL states and topology snapshot in LEO satellite constellation," in *Proc. 11th IEEE Int. Conf. Commun. Technol. (ICCT)*, Nov. 2008, pp. 13–16.

[46] E. W. Dijkstra, "A note on two problems in connexion with graphs," *Numer. Math.*, vol. 1, no. 1, pp. 269–271, Dec. 1959.

[47] T. Taleb, A. Jamalipour, N. Kato, and Y. Nemoto, "IP traffic load distribution in NGEO broadband satellite networks—(Invited paper)," in *Computer and Information Sciences* (Lecture Notes in Computer Science), vol. 3733. Berlin, Germany: Springer-Verlag, 2005, p. 113.

[48] T. Taleb, D. Mashimo, A. Jamalipour, N. Kato, and Y. Nemoto, "Explicit load balancing technique for NGEO satellite IP networks with on-board processing capabilities," *IEEE/ACM Trans. Netw.*, vol. 17, no. 1, pp. 281–293, Feb. 2009.

[49] Ö. Korçak, F. Alagöz, and A. Jamalipour, "Priority-based adaptive routing in NGEO satellite networks," *Int. J. Commun. Syst.*, vol. 20, no. 3, pp. 313–333, 2007.

[50] G. Song, M. Chao, B. Yang, and Y. Zheng, "TLR: A traffic-light-based intelligent routing strategy for NGEO satellite IP networks," *IEEE Trans. Wireless Commun.*, vol. 13, no. 6, pp. 3380–3393, Jun. 2014.

[51] Y. Rao and R.-C. Wang, "Agent-based load balancing routing for LEO satellite networks," *Comput. Netw.*, vol. 54, no. 17, pp. 3187–3195, 2010.

[52] Z. Wu, G. Hu, F. Jin, B. Jiang, and Y. Fu, "Agent-based dynamic routing in the packet-switched LEO satellite networks," in *Proc. Int. Conf. Wireless Commun. Signal Process. (WCSP)*, Oct. 2015, pp. 1–6.

[53] E. Papapetrou and F.-N. Pavlidou, "Distributed load-aware routing in LEO satellite networks," in *Proc. IEEE Global Telecommun. Conf. (GLOBECOM)*, Nov. 2008, pp. 1–5.

[54] N. Michael and A. Tang, "Halo: Hop-by-hop adaptive link-state optimal routing," *IEEE/ACM Trans. Netw.*, vol. 23, no. 6, pp. 1862–1875, Dec. 2015.

[55] B. Jianjun, L. Xicheng, L. Zexin, and P. Wei, "Compact explicit multipath routing for LEO satellite networks," in *Proc. IEEE Workshop High Perform. Switching Routing*, May 2005, pp. 386–390.

[56] M. Mohorcic, A. Svigelj, and G. Kandus, "Traffic class dependent routing in ISL networks," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 40, no. 4, pp. 1160–1172, Oct. 2004.

[57] F. Alagoz, O. Korcak, and A. Jamalipour, "Exploring the routing strategies in next-generation satellite networks," *IEEE Wireless Commun.*, vol. 14, no. 3, pp. 79–88, Jun. 2007.

[58] J. Lee and S. Kang, "Satellite over satellite (SOS) network: A novel architecture for satellite network," in *Proc. IEEE INFOCOM*, vol. 1. Mar. 2000, pp. 315–321.

[59] Y. Wang *et al.*, "Tailored load-aware routing for load balance in multilayered satellite networks," in *Proc. 82nd IEEE Veh. Technol. Conf.*, Sep. 2015, pp. 1–5.

[60] Y. Kawamoto, H. Nishiyama, N. Kato, and N. Kadowaki, "A traffic distribution technique to minimize packet delivery delay in multilayered satellite networks," *IEEE Trans. Veh. Technol.*, vol. 62, no. 7, pp. 3315–3324, Sep. 2013.

[61] Z. Wu, G. Hu, F. Jin, Y. Song, Y. Fu, and G. Ni, "A novel routing design in the IP-based GEO/LEO hybrid satellite networks," *Int. J. Satellite Commun. Netw.*, vol. 35, no. 3, pp. 179–199, 2017.

[62] R. Liu, M. Sheng, K. Lui, X. Wang, D. Zhou, and Y. Wang, "Capacity analysis of two-layered LEO/MEO satellite networks," in *Proc. 81st IEEE Veh. Technol. Conf.*, May 2015, pp. 1–5.

[63] C. Perkins, E. Belding-Royer, and S. Das, *Ad Hoc on-Demand Distance Vector (AODV) Routing*, document RFC 3561, 2003.

[64] M. K. Marina and S. R. Das, "Ad hoc on-demand multipath distance vector routing," *Wireless Commun. Mobile Comput.*, vol. 6, no. 7, pp. 969–988, Nov. 2006.

[65] T. Clausen and P. Jacquet, *Optimized Link State Routing Protocol (OLSR)*, document RFC 3626, 2003.

[66] C. E. Perkins and P. Bhagwat, "Highly dynamic destination sequence distance vector (DSDV) for moblie computers," in *Proc. SIGCOMM Conf. Commun. Archit., Protocols Appl.*, 1994, pp. 234–244.

[67] Z. J. Haas, M. R. Pearlman, and P. Samar, *The Zone Routing Protocol (ZRP) for Ad Hoc Networks*, document, Mobile Ad-Hoc Network (MANET) Working Group, IETF, Internet-Draft, 2002. [Online]. Available: https://tools.ietf.org/html/draft-ietf-manet-zone-zrp-04

[68] P. Samar, M. R. Pearlman, and Z. J. Haas, "Independent zone routing: An adaptive hybrid routing framework for ad hoc wireless networks," *IEEE/ACM Trans. Netw.*, vol. 12, no. 4, pp. 595–608, Aug. 2004.

[69] P. Guangyu, G. Mario, and C. Tsu-Wei, "Fisheye state routing in mobile ad hoc networks," in *Proc. ICC*, vol. 1. Apr. 2000, pp. 71–78.

[70] L. Wang and S. Olariu, "A two-zone hybrid routing protocol for mobile ad hoc networks," *IEEE Trans. Parallel Distrib. Syst.*, vol. 15, no. 12, pp. 1105–1116, Dec. 2004.

[71] A. Boukerche, B. Turgut, N. Aydin, M. Z. Ahmad, L. Bölöni, and D. Turgut, "Routing protocols in ad hoc networks: A survey," *Comput. Netw.*, vol. 55, no. 13, pp. 3032–3080, 2011.

[72] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks," in *Proc. 33rd IEEE Int. Conf. Syst. Sci.*, Jan. 2000, pp. 1–10.

[73] O. Younis and S. Fahmy, "HEED: A hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks," *IEEE Trans. Mobile Comput.*, vol. 3, no. 4, pp. 366–379, Oct./Dec. 2004.

[74] M. Senouci, A. Mellouk, H. Senouci, and A. Aissani, "Performance evaluation of network lifetime spatial-temporal distribution for WSN routing protocols," *J. Netw. Comput. Appl.*, vol. 35, no. 4, pp. 1317–1328, 2012.

[75] T. Winter, *RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks*, document RFC 6550, 2012.

[76] P. Thubert, *Objective Function Zero for the Routing Protocol for Low-Power and Lossy Networks (RPL)*, document RFC 6552, 2012.

[77] O. Gnawali, *The Minimum Rank with Hysteresis Objective Function (MRHOF)*, document RFC 6719, 2012.

[78] P. Gonizzi, R. Monica, and G. Ferrari, "Design and evaluation of a delay-efficient RPL routing metric," in *Proc. 9th IEEE Wireless Commun. Mobile Comput. Conf. (IWCMC)*, Jul. 2013, pp. 1573–1577.

[79] H.-S. Kim, J. Paek, and S. Bahk, "QU-RPL: Queue utilization based RPL for load balancing in large scale industrial applications," in *Proc. 12th IEEE Int. Conf. Sens., Commun., Netw. (SECON)*, Jun. 2015, pp. 265–273.

[80] J.-P. Vasseur, M. Kim, K. Pister, N. Dejean, and D. Barthel, *Routing Metrics Used for Path Calculation in Low-Power and Lossy Networks*, document RFC 6551, 2012.

[81] Z. Wang, L. Zhang, Z. Zheng, and J. Wang, "Energy balancing RPL protocol with multipath for wireless sensor networks," in *Peer-to-Peer Networking and Applications*. New York, NY, USA: Springer, 2017, pp. 1–16.

[82] T. Inagaki and S. Ishihara, "HGAF: A power saving scheme for wireless sensor networks," *Inf. Media Technol.*, vol. 4, no. 4, pp. 1086–1097, 2009.

[83] Y. Yu, R. Govindan, and D. Estrin, "Geographical and energy aware routing: A recursive data dissemination protocol for wireless sensor networks," Dept. Comput. Sci., UCLA, Los Angeles, CA, USA, Tech. Rep. 463, 2001.

[84] M. Barcelo, A. Correa, J. Vicario, A. Morell, and X. Vilajosana, "Addressing mobility in RPL with position assisted metrics," *IEEE Sensors J.*, vol. 16, no. 7, pp. 2151–2161, Apr. 2016.

[85] V. Safdar, F. Bashir, Z. Hamid, H. Afzal, and J. Pyun, "A hybrid routing protocol for wireless sensor networks with mobile sinks," in *Proc. 7th IEEE Int. Symp. Wireless Pervasive Comput.*, Jul. 2012, pp. 1–5.

[86] W. Jabbar, M. Ismail, R. Nordin, and S. Arif, "Power-efficient routing schemes for MANETs: A survey and open issues," *Wireless Netw.*, vol. 23, no. 6, pp. 1917–1952, 2016.

[87] C. Lee and K. I. Kim, "A deadline aware DTN approach based on epidemic routing," in *Proc. 13th IEEE Int. Symp. Netw. Comput. Appl.*, Aug. 2014, pp. 41–44.

[88] X. Lu and P. Hui, "An energy-efficient n-epidemic routing protocol for delay tolerant networks," in *Proc. IEEE 5th Int. Conf. Netw., Archit. Storage*, Jul. 2010, pp. 341–347.

[89] B. Bista, "Improving energy consumption of epidemic routing in delay tolerant networks," in *Proc. IEEE Int. Conf. Innov. Mobile Internet Services Ubiquitous Comput.*, Jul. 2016, pp. 278–283.

[90] T. Spyropoulos, K. Psounis, and C. Raghavendra, "Spray and wait: An efficient routing scheme for intermittently connected mobile networks," in *Proc. ACM SIGCOMM Workshop Delay-Tolerant Netw.*, 2005, pp. 252–259.

[91] J. Leguay, T. Friedman, and V. Conan, "DTN routing in a mobility pattern space," in *Proc. ACM SIGCOMM Workshop Delay-Tolerant Netw.*, 2005, pp. 276–283.

[92] J. LeBrun, C.-N. Chuah, D. Ghosal, and M. Zhang, "Knowledge-based opportunistic forwarding in vehicular wireless ad hoc networks," in *Proc. IEEE 61st Veh. Technol. Conf. (VTC-Spring)*, vol. 4. May/Jun. 2005, pp. 2289–2293.

[93] C. Liu and J. Wu, "Routing in a cyclic mobispace," in *Proc. 9th ACM Int. Symp. Mobile Ad Hoc Netw. Comput.*, 2008, pp. 351–360.

[94] A. Lindgren, E. Davies, S. Grasic, and A. Doria, *Probabilistic Routing Protocol for Intermittently Connected Networks*, document RFC 6693, 2012.

[95] R. Diana, E. Lochin, L. Franck, C. Baudoin, E. Dubois, and P. Gelard, "DTN routing for quasi-deterministic networks with application to LEO constellations," *Int. J. Satellite Commun. Netw.*, vol. 35, no. 2, pp. 91–108, 2017.

JOAN A. RUIZ DE AZÚA was born in Barcelona, Spain. He received the degree in aerospace engineering from Supaero, Toulouse, France, in 2015, the degree in telecommunications engineering from the Universitat Politècnica de Catalunya, Barcelona, in 2015, and the M.S. degree in network protocols from Supaero in 2015. He is currently pursuing the Ph.D. degree with the Universitat Politècnica de Catalunya. He was awarded with the Best M.S. Thesis on critical communications from the Official Spanish Telecommunications Chartered Institute in 2016. His research interests include satellite architectures, satellite networks, cognitive networks, Internet of Things, and embedded software. He is member of the FSSCat Project, which is the winner of the ESA Sentinel Small Sat (S^3) Challenge of the Copernicus Masters Competition. He has participated in different projects of ground segment for Ariane 5 and Ariane 6 programs in GTD Company, in collaboration CNES and ESA. He is currently participating in the Fly Your Satellite Program from the ESA.

ANNA CALVERAS was born in Barcelona, Spain, in 1969. She received the Ph.D. degree in telecommunications engineering from the Universitat Politècnica de Catalunya, Spain, in 2000. She is currently an Associate Professor with the Wireless Networks Group, Computer Networks Department, Universitat Politècnica de Catalunya. She has been involved in several national and international research or technology transfer projects, and she has published in International and National conferences and journals. Her research interests and expertise areas comprise the design, evaluation, and optimization of communications protocols and architectures for cellular, wireless multihop networks, ad-hoc networks, wireless sensor networks, the Internet of Things, and application domains such as smart cities, building automation, and emergency environments.

ADRIANO CAMPS (S'91–A'97–M'00–SM'03–F'11) was born in Barcelona, Spain, in 1969. He received the degree in telecommunications engineering and Ph.D. degree in telecommunications engineering from the Universitat Politècnica de Catalunya (UPC), Barcelona, Spain, in 1992 and 1996, respectively. From 1991 to 1992, he was with the ENS des Télécommunications de Bretagne, France, with an Erasmus Fellowship. Since 1993, he has been with the Electromagnetics and Photonics Engineering Group, Department of Signal Theory and Communications, UPC, where he was an first Assistant Professor, an Associate Professor in 1997, and a Full Professor since 2007. He has published over 160 journal papers in peer-reviewed journals, and over 350 international conference presentations, and holds 10 patents. His research interests are focused on: 1) microwave remote sensing, with special emphasis in microwave interferometric radiometry by aperture synthesis (ESA's SMOS mission); 2) passive microwave remote sensing using signals of opportunity (GNSS-Reflectometry); and more recently on 3) the use of nano-satellites as cost-effective platforms to test innovative concepts for Earth Observation, such as the 3Cat-2, a 6U-class cubesat mission launched in 2016 carrying onboard an innovative GNSS-R payload.

• • •