Heterogeneous LoRaWAN & LEO Satellites Networks
Concepts, Architectures and Future directions

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Abstract: Nowadays, Low Earth Orbit Satellites (LEO) regains much attention, especially where the satellites play the relay role in the communication networks and particularly for the internet of things networks. In this article, we emphasis on the deployment of the LEO satellite for IoT and on the correlation between LoRaWAN and LEO satellites networks. We first propose an IoT architecture based heterogeneous space and terrestrial integrated network. Then a novel architecture for LEO satellites remote monitoring based on the use of LoRaWAN modules for data plane and Software-Defined Networking for the control plane was suggested. Finally, some challenging open issues related to the use of SDN controllers in space are revealed.

Keywords— LoRaWAN, Communication System, Small Satellite, Internet of Space, Internet of Things, LEO, SDN

I. INTRODUCTION

Nowadays, the number of Low Earth Orbit (LEO) dedicated for small, mini, micro, nano and pico satellites has increased considerably [1]. The number of launched satellites at LEO orbit represent 62.9% of the total earth orbit satellites above the Earth which varying between 250 km and 2000 km. This new generation of satellites emanates with different sizes and shapes. Table 1 highlights the weight of each category. The main characteristics of these LEO satellites are the miniaturisation due to the advancement of the technology.

Table 1: Weights of LEO satellites

Satellites Type	Mini	Micro	Nano	Pico	Femto
Weight	range of 100 to 500 Kg	range of 10 to 100 Kg	range of 1 to 10 Kg	range of 0.1 to 1 Kg	below 100 g

The number of this new generation of satellites increased due to the use of Leo Satellites for the Internet of things [2] and Smart grids [3]. In fact, for many scenarios IoT end devices are distributed in harsh remote areas (such as forest, an ocean, and desert..) where sometimes it is difficult to have terrestrial network access. LEO satellite constellation is the best solution to provide the connection to IoT devices in a harsh and inaccessible environment. LEO satellite constellation is more advantageous then geostationary earth orbit (GEO) systems. They provide small propagation loss as well as low propagation delay and global coverage. The one-way propagation delay for LEO satellites ranges from 1 to 15 ms and for GEO satellites it ranges from 120 to 140 ms. An adaptation between LEO satellite constellation dedicated to IoT and terrestrial IoT systems is necessary. Recently, new networks named Internet of space will deliver high bandwidth information to every part of the world using Nano-satellites as access points to extend the coverage to the IoT and Machine-to-Machine communications [4]. The convergence between terrestrial technologies and satellite requires considering recent trends in networking with special focus on new architectures and frameworks that proposed recently for the future Internet of everything.

Nevertheless, communication systems for small and nano-satellites still facing many challenges. No wireless network service is obtainable in space. Consequently, satellite developers should deploy and implement their own effective satellite communication system to offer services to satellites in orbit. In this context, this paper focusing on two points. The first one corresponds to the design of the network and a communication system based on the LoRaWAN technology to provide a remote control for LEO satellites from the earth and connect Satellites in orbit to the Internet. The second point is the reverse objective that considers the use of the LEO satellites network to provide the required connectivity to IoT networks. Therefore, we summarize our contributions in this paper as follows:

(1) We introduce LoRaWAN technology and its deployment for LEO Satellites. (2) We describe and present Internet of Space architecture and its potentialities for the IoT networks and its related applications. We emphasise on the engineering challenges confronted in the Earth-to-space communication link design phase. (3) We design a LEO-SRM architecture to provide a remote control for LEO satellites. (4) We identify key issues and discuss future directions towards an efficient communication system for LEO remote control.

We organized the remainder of the paper as follows: Section II reviews recent research works dealing with the newest contributions that focus on the deployment of the LEO Satellites for the Internet of things in the first subsection and cites the new proposals sketching the use of LoRaWAN technology in Space for LEO Satellites in the second subsection. Then, section III introduces the basic concepts related to LoRaWAN with focus on its physical, MAC and security layers. Section IV delivers the design of an IoT architecture based heterogeneous space and terrestrial integrated network. Section V provides a deep study about the design of an architecture dedicated to controlling remotely LEO Satellites with an emphasis on the use of LoRaWAN and SDN. In section VI, we identify key issues and future directions towards an efficient communication system for LEO remote control. Finally, section VII concludes this work.

II. RELATED WORKS

A- Deployment of the LEO Satellites for IoT

The widespread deployment of the LEO satellites is especially to provide connectivity's and to extend communication coverage between IoT devices [13]. Accordingly, researchers proposed new systems and approaches to tackle these emerging issues. In this context, authors in [4] discussed how the use of CubeSats enabling IoT global coverage. They proposed an efficient multiple-access scheme to ensure large number of IoT nodes connectivity. Understanding earth science such as weather prediction, disasters monitoring and climate change are among the principal CubeSats missions. Nowadays, CubeSat is used in many projects for IoT application. In the same context, authors in [7] described a new system using a constellation of LEO satellites to spread worldwide the terrestrial coverage of 3GPP NB-IoT systems. Authors in [8] studied data upload gathered from the distributed IoT networks via the use of LEO based communication technology. To address energy-efficient they suggested an online scheduling algorithm. The seamless integration of high altitude platforms and satellites and into 5G networks was studied in [6]. They prove that 5G user equipment can function through satellite components at low bitrate by minimum configuration update. The LEO satellites will provide the narrowband IoT service continuity and completing terrestrial infrastructure services. Therefore, the number of served objects (users) per square kilometre will increase considerably. Authors in [5] discussed the deployment of satellite-based M2M and wireless services to the smart grid, as well as the use of IoT for the transmission and distribution space sector. A critical mission such as disasters management could be addressed via the hybridization of NB-IoT through satellite networks [9].

NS3-Based simulation framework supporting LEO satellite constellation designed for IoTs was proposed in [17] with focus on the radio protocol stack architecture, network architecture, signalling messages and the procedure of authentication.

An exhaustive review of the suitability of MAC protocols for satellite-IoT networks with a focus on the IoT specific characteristics was carried in [18]. The study revealed that many of the studied protocols are not appropriate to be deployed in the IoT context, while they have been effectively used within other satellite systems.

B- LoRaWAN technology and LEO Satellites

We classified recent researches related to the correlation between LoRaWAN networks and LEO satellites networks into two categories. The first category corresponds to the works focusing on how LEO satellites serving IoT devices via LoRaWAN networks. The second category matches contributions that consider the use of LoRaWAN technology to provide a remote control for LEO satellites.

1) LEO satellites serving IoT devices via LoRaWAN

This topic requires a deep investigation from researchers. Authors in [10] confirm that LoRaWAN networks and satellite interconnection facing technical challenges such as synchronisation, gateways selection, resources allocation and cross-layer optimisation.

Authors in [11] proposed a system assuring self-organization satellite terrestrial integrated based on three layers (perception, cognition and intelligence). The perception layer dedicated to perceiving the network information in a space network and terrestrial network, including network speed, traffic load, signal-to-interference-plus-noise ratio and so on. An SDN/NFV based network will manage this layer and hide the complexity of the underlying physical network. The cognition layer monitor the network information taking in consideration the perceived data. In order to predict accurately the network traffic and the state of the environment, data mining methods are required for this layer. The intelligence layer is committed for resource management and route planning...

In [12] authors studied architectures, protocols and technologies for data dissemination in heterogeneous IoT-Satellite network. The proposed architecture deploys LoRa as an LPWAN terrestrial network for data gathering and an Iridium satellite system to provide backhaul connectivity. Besides that, they suggested a scheme to encode and package data called GDEP. In the same context, authors in [19] outlined the technical challenges that should be resolved to enable interoperability between LoRaWAN networks and satellite systems. They sketched two different configurations (direct or indirect) related to how the LoRaWAN end-devices have access to the satellite.

In [16] authors suggested for heterogeneous IoT-satellite networks a new MAC protocol named SA-LoRaWAN that adapts power regarding to the information concerning the sensors and satellite positions.

2) *Remote control for LEO inter-satellite networks*

The implementation of inter-satellite communication between LEO satellite systems faced many defies. Authors in [14] resolved some of the data link and the physical layers challenges. According to the Internet in space concept, satellite developers could control remotely their satellites when it is required through the Internet. They do not need to have their ground stations. The exportation of the Internet into space necessitates the integration of a communication system within LEO satellites and the deployment of an Internet gateway acting as a ground station and as a gateway to the terrestrial Internet. In this context, authors in [15] introduced LoRa technology as a suitable technology providing the connectivity between satellites and terrestrial Internet gateway. The LoRa modulation feasibility in CubeSat systems and the Doppler effect were explored and experimented in [20]. According to the authors [20], LoRa modulation has high immunity level to the Doppler effect in orbits above 550 km. Furthermore, the feasibility of deploying LoRa as the inter-satellite communication technology for a cluster of LEO satellites was demonstrated in [21]. Some modifications have been suggested to overcome the limitation in network capacity and data rate.

III. General Concepts of LoRa® and LoRaWAN

Long Range LoRa® is Semtech trademark for the wireless modulation dedicated to creating the long-range communication link. LoRa operates in a non-licensed band in the ISM (lower Industrial, Scientific, and Medical) bandwidths (that corresponds to 915MHz for USA, 433MHz and 868MHz for EU). For long-range communication. LoRa is a patented for chirp spread spectrum modulation scheme (CSS) [22] which was developed in the 1940s. CSS has been used in space communication and military and for many years due to its robustness to interference and the long communication distances that can be reached. LoRa® is the first low-cost implementation dedicated to commercial deployment. LoRa modulation features six orthogonal spreading factors (SF7, SF8, SF9, SF10, SF11 and SF12) resulting in different data rates (see Eq.1) which enhance the efficiency and rise the network capacity. This approach allows the transmission at the same time and on the same frequency channel of multiple differently spread signals.

$$R_b = SF * \frac{\left[\frac{4}{4+CR}\right]}{\left[\frac{2^{SF}}{BW}\right]} * 1000 \qquad \text{Eq.1}$$

Where SF= corresponds to Spreading Factor (integer ranging from 6 to 12); CR=code (integer ranging from 1 to 4); BW= bandwidth in KHz (10.4, 15.6, 20.8, 31.25, 41.7, 62.5, 125, 250, 500); Rb= Bit rate in bps.

The LoRa modulation is susceptible to be deployed by different protocol architectures. The LoRa physical layer features are regrouped in table 3.

Table 3: Physical features of LoRa

Modulation	Bandwidth	Peak Data Rate	Energy Efficiency	Spectrum Efficiency	Interference immunity	Link Budget	Range
CSS	500 kHz–125 KHz	290 bps-50 Kbps (DL/UL)	>10 years: devices battery life	Chirp SS CDMA	Very High	154 dB	2-5km urban 15km suburban 45km rural

LoRaWAN is the MAC protocol standardized by LoRa Alliance (the current version of the LoRaWAN is 1.1 was published in 2017 [23]). LoRaWAN uses "star of stars" architecture as illustrated in Fig.1 in which LoRa gateways communicate the messages between network server and end-devices (LoRa nodes).

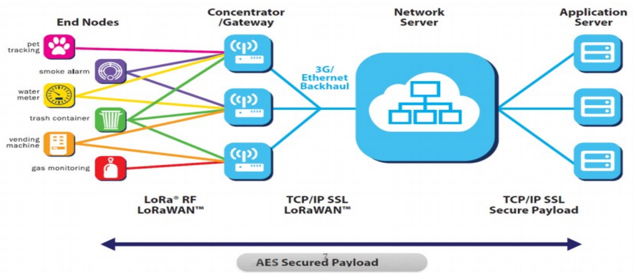

Fig.1 Illustration of LoRaWAN network architecture

LoRa nodes are not linked with a specific gateway. Accordingly, multiple gateways receive data transmitted by a LoRa node. Each gateway forwards the received messages to the network server through some backhaul (such as cellular, Wi-Fi or satellite…). Therefore, sensors and applications communicate with gateways via a single-hop LoRa communication. Gateways are linked to the core network server via a standard IP connection as illustrated in fig.1.

Besides, LoRaWAN defines three MAC protocols for tree classes of devices. Depending on the application needs LoRa nodes select a device class and therefore a MAC protocol which allows LoRa nodes to negotiate the battery lifetime versus the network downlink communication latency.

Class-A end devices: is intended for battery-powered sensors. This class is the most energy efficient mode. However, compared to the two others classes (B and C: see later) class-A has the biggest latency time. Class-A devices do not transmit data all the time. Furthermore, class is mandatory which means that all the LoRaWAN devices must support class-A functionalities. Class-A devices define two receive windows. The first receive window comes exactly one second after the end of the uplink modulation and the second receive window comes exactly two second after the end of the uplink modulation. The receiver should be active until the demodulation of the downlink frame.

- **Class-B end devices:** proposed for devices powered with battery, such as actuators. This class considered as an energy efficient class with a controlled latency. An external beacon synchronizes the communication based on slot-times. The gateway sends periodically a beacon, when a LoRa node receives the beacon, it opens predictably a short reception window named “ping slot”. All end devices join the network as Class A end devices and when it is required, they can switch to Class B.

- **Class-C end devices:** have practically continuously open window for the reception. Class-C devices compared to the other two classes have the minimum latency in downlink communication and the maximum receive slots. These devices require an external power source to listen the whole time to the air interface.

LoRaWAN guarantees security and data confidentiality that are essential aspects of IoT systems. For this, the protocol uses two AES-128 cyphers at the network layer and the application layer. The network layer is in charge of the end node data authentication using a shared AES128 secret key (between the Lora Nodes and the network server). The application layer is responsible for guaranteeing the device data privacy via the use of an AES128 shared secret key between the end node and the user applications first, which is the network session key (NwkSkey), ensures the authenticity of a node on the network. The second is the application session key (AppSKey) provides confidentiality of the transmitted data by second encryption.

IV- Heterogeneous IoT Architecture based Space and Terrestrial Integrated Networks

Heterogeneous space and terrestrial integrated network is a viable solution to provide anytime and anywhere ultra-reliable communication and connectivity for Internet of things devices. The integration of the space and terrestrial networks include several communications technologies. This heterogeneity offers large network coverage and high network performances through the advantage of each communication technology. LEO constellation based IoT system is a complementary to terrestrial networks to support remote or inaccessible zones, which are not reachable by terrestrial system. In a typical LEO constellation based IoT system, each satellite has at least three communication links symbolised as (L_s, L_g and L_v). Where:

- L_s: is the inter-satellites links to enable communications between neighboring satellites.
- L_g: is the communication link between a LEO satellite and an earth gateway station (EGS).
- L_v: is the communication link between satellite and visible IoT terminals (known as satellite's footprint). Accordingly, IoT terminals within a satellite perceptible zone can communicate and exchange data with IoT terminals in another satellite footprint without requiring any support from terrestrial infrastructures.

L_i: is the communication link between the IoT gateways and sensing devices. The IoT gateway forwards to the CubeSats the aggregated data.

Figure 2 illustrates the architecture, communication links and components of the heterogeneous network architecture including the space and the terrestrial IoT networks to connect IoT devices dispersed in wide areas.

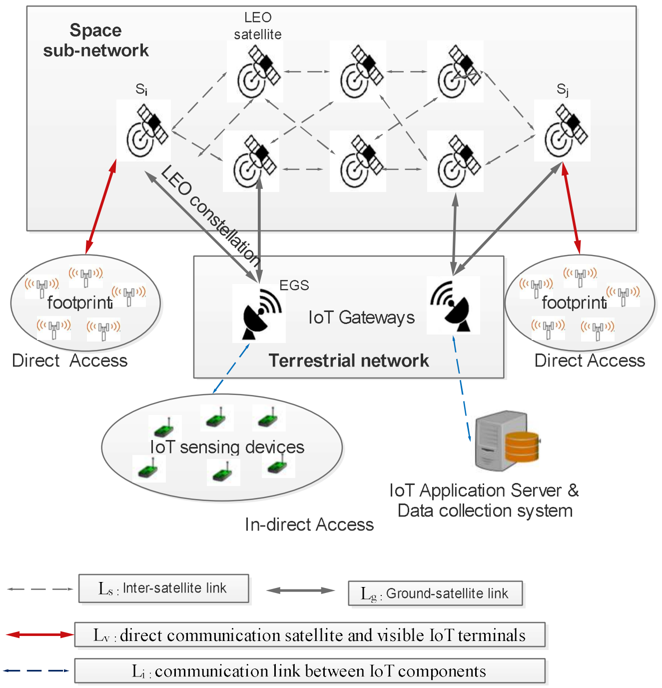

Fig.2 Heterogeneous network architecture including the space and the terrestrial IoT networks

V- ARCHITECTURES FOR LEO Satellites remote monitoring

The growth related to satellite communication and networking technologies improves satellite networks prosperity and lead to rapid growth of new satellites services and applications. However, the establishment and the configuration of new services and applications require high-investment in the current satellite networks. To overcome this issue, new architectures for satellites remote monitoring are necessary. In this section, we detail the proposed architecture for LEO satellites remote monitoring named LEO-SRM (LEO Satellite Remote Monitoring). In the following, we detail the data plane and the control plane of the LEO-SRM architecture.

A- LEO-SRM Control Plane

The LEO-SRM control plane is based on the deployment of a Software Defined Networking (SDN) controller in the space. SDN is a new paradigm based on the separation between the data plane (including network devices) and the control plane . It affords a complete view of the completely underlying network infrastructure. The centralized SDN controller enables the implementation of applications and services controlling the network via a software abstraction layer. The network elements interact with SDN Controller via a southbound interface using a well-known protocol named OpenFlow protocol. In LEO-SRM control plane each satellite acts as an SDN switch and all of them are controlled and supervised by a centralized SDN controller attached to a centralized satellite. The purpose of the SDN controller is to configure and to control the different LEO satellites integrating SDN-Switch. Furthermore, it is also in charge of non-conflicting multidimensional network resources allocation to LEO satellite network applications. The SDN controller provide also a map interface connection between all satellites, in order to improve network management. Figure 3 illustrates the control plane of the LEO-SRM architecture.

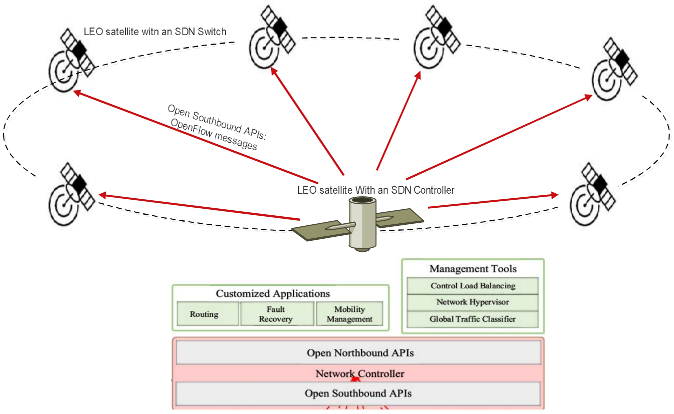

Fig.3 Architecture of LEO-SRM Control plane

B- LEO-SRM Data Plane

The LEO-SRM data plane is based on the use of the Internet and the LoRaWAN gateways. The main concept is that LEO satellites will be able have an Internet connection while working in orbit. Consequently, satellite owners could supervise remotely their satellites through the Internet. The extension of the Internet into space requires the development a communication system between small satellites and an Internet gateway. The Internet gateway acts as a ground station and a gateway to the terrestrial Internet. It forwards data from a satellite to the Internet that forwards is to a remote controller server giving the opportunity to satellite owners to get to data collected from their satellites. Satellites formalize aerial sensed data into an application layer that could connect to the internet via an internet application layer protocols (such as HTTP, FTP...). Figure 4 illustrates the architecture for LEO-SRM data plane.

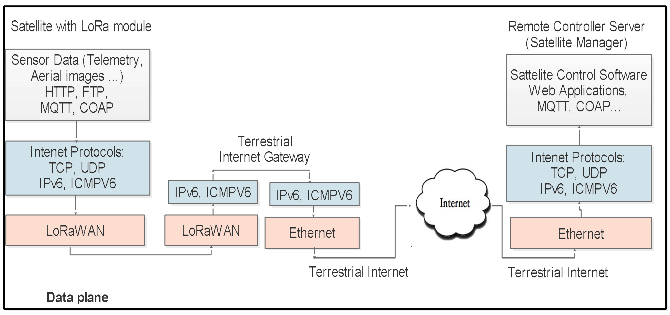

Fig.4 LEO-SRM data plane.

VI- OPEN ISSUES AND FUTURE DIRECTIONS

Satellite Network as a Service: The SDN controller has many potentialities, which lead to flexible satellite exploitation. Accordingly, the virtualization of the satellite communication system lets to offer satellite network as a service. Thus, a satellite virtual network operator that does not possess the complete underlying infrastructure can manage an E2E virtual satellite network. He can request via customer portals the customized software and hardware network resources from satellite network operators. The virtualisation of satellite require a dynamic configuration of satellites provided by the SDN controller. The virtualisation of network satellites is an emerging open issue requiring more investigation.

Multi-SDN controllers based architecture: The forthcoming satellite-Internet will be composed of thousands of satellites [24]. Accordingly, to sketch with the scalability issue *(network size expansion, the number of flows increases…)* a distributed architecture based on a multi-SDN controller is required. To guarantee a holistic control view of the satellite networks, an exchange protocol between the multi-SDN controllers should be developed. In our knowledge's, there is no standardized protocol regularizing the communication between the SDN Controllers in space domain.

Dynamic Placement of SDN Controller for a LEO Satellite Constellation: A Dynamic Controller Placement Problem (DCPP) considered for a LEO constellation especially when the traffic demands alters based on time zone and users' geographical position. An optimal controller placement and a perfect assignment of satellites to controller were introduced for the first time in [25]. DCPP is a potential open issue and researchers taking in consideration diverse constraints could suggest diverse proposals.

VI. CONCLUSION

In this paper, we have overviewed the deployment of the LEO Satellites for IoT systems to extend communication coverage between IoT devices and we highlights the main contributions related to the remote control of LEO satellites. Besides that, we presented in a simple way the main concepts of LoRaWAN. Furthermore, we presented a heterogeneous IoT architecture involving terrestrial and space integrated networks. We suggested an architecture based on SDN and LoRa technologies for LEO satellites remote control. In the last section, we provided open issues focusing on the deployment of SDN controllers in space.

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