Chapter

# The Internet of Things Space Infrastructure. Current State and Development Prospects

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## Abstract

This chapter presents an overview of possibilities for existing Satellite Communication Systems utilization to provide Internet of Things Services. It is shown that existing Satellite Communication Systems provide traffic transmission for Internet of Things Systems with Cloud Architecture. The propositions on possibility of Fog and Edge computing implementation in Satellite Communication Systems are proposed. The ways for Low-Earth Orbit and Geostationary Orbit Satellite Communication Systems modernization for Fog and Edge computing implementation for the Internet of Things Systems are presented. To increase the efficiency of IoT data processing and the reliability of Internet of Things Data Storage, it is proposed to generate an Orbital Cloud Data Storage in Geostationary Orbit, which consists of several Geostationary Orbit Satellites - Cloud Computing Data Centers. Methods for access provision to the Orbital Cloud Data Storage using Geostationary Orbit High-Throughput Satellites and satellites from the structure of Low-Earth Orbit Satellite Communication Systems are proposed. The issues of interaction between Orbital Cloud Data Storage and ground-based Cloud Data Processing and Storage Infrastructure are briefly considered. The orbital slots in Geostationary Orbit are proposed for location of Geostationary Orbit Satellites - Cloud Computing Data Centers.

**Keywords:** IoT system, satellite communication system, geostationary orbit, low-earth orbit, satellite constellation, IoT smart things

## 1. Introduction

In the last decade, the Internet of Things has become an important component of modern info communications. According to Transforma Insights [1], the total number of active Internet of Things (IoT) devices in 2019 was 7.6 billion. The number of active IoT devices is expected to grow up to 24.1 billion by 2030, with a CAGR of 11%. For the forecasted period, the short-range technologies will remain the main type of IoT device connection: Wi-Fi, Bluetooth, Zigbee. The number of IoT device connections to cellular networks is predicted to increase from 1.2 billion in 2019 up to 4.7 billion in 2030. The need to provide a large number of connections and IoT device traffic transmission has become the main driver for the development and implementation of a new 5G mobile broadband standard [2].

The development of the Internet of Things is constrained by the limited coverage of terrestrial mobile broadband networks, which ones for commercial reasons cover areas with relatively high population densities. It is possible to expand the area of providing IoT services by using the satellite telecommunication systems resource, with specified and widespread application. The purpose of this article is to present the overview of the readiness of existing Satellite Communications Systems to provide IoT Services, and describe potential directions for the development of this communications sector in future.

## 2. The internet of things space infrastructure current state

Up to now, the Cloud Computing [3] technology has been the prevailing architecture for IoT systems. According to this architecture, IoT devices (hereinafter referred to as IoT Smart Things) transform monitored physical parameters into electronic signals and transmit relevant information to the Cloud Computing Data Centers for information processing in accordance with the IoT service purpose, information storage and archiving. If it is necessary to implement any actions, the Cloud Computing Data Center delivers control actions bursts to the IoT Smart Things.

Current satellite telecommunications systems are used to transmit IoT information Traffic for IoT systems based on the Cloud Computing Architecture. **Figure 1** shows the model of the IoT System built on Cloud Computing Architecture and using a satellite telecommunications system. The IoT Smart Things are located at the lowest level

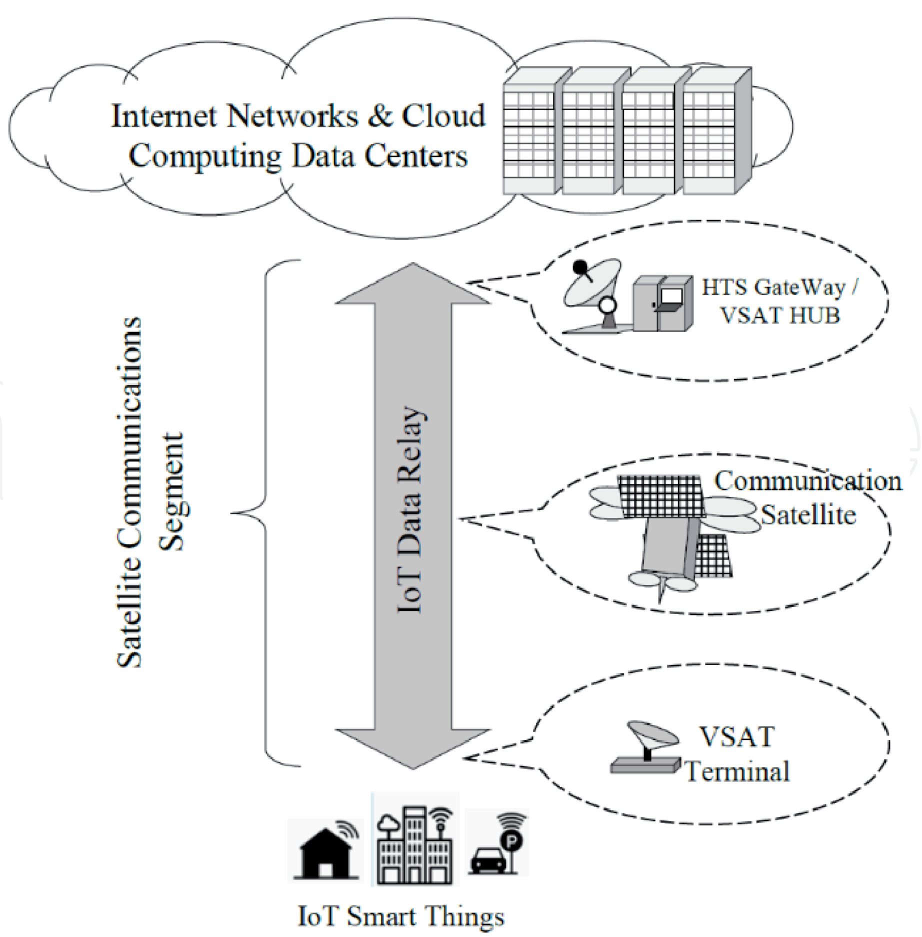


**Figure 1.**
*The IoT system model, built on the basis of the cloud computing architecture and using a satellite telecommunications system.*

of the hierarchical structure of the IoT System. This group of devices includes Sensors, i.e. devices that transform physical processes into electrical signals and form IoT Information Bursts based on these electrical signals, as well as devices that implement physical actions based on received commands - Actuators. The Cloud Computing Data Center is at the top of the hierarchical level of the system.

The Satellite Communication Segment provides with IoT Data Relay Channel from IoT Smart Thing Sensor, to a Cloud Computing Data Center and vice versa, to the IoT Smart Thing Actuator. The satellite communication channel is established with the following elements utilization:

- VSAT terminal, which is located in close proximity to IoT Smart Things, sensors and actuators, and provides connection of these devices on short-range technology basis: Wi-Fi, Bluetooth, Zigbee. The VSAT interface to the local network or to the terrestrial local communication network is the system boundary for a satellite telecommunications system;

- Communication Satellite, which provides retransmission of the IoT Smart Things information. For the hierarchical model of the Cloud IoT System Architecture mission, the type of satellite payload, or repeater of a telecommunications satellite is not essential: either it will be Transparent Transponder or Regenerative Transponder [4];

- The VSAT-Network HUB or Gate Way. Generally, this facility is connected to the Internet Backbone through which IoT data transmission to the Cloud Computing Data Center is provided.

**Figure 2** shows examples of utilization of various types of Satellite Communication Systems to support the operation of the IoT Systems and to provide IoT Services. The **Figure 2** shows Satellite Communication Systems using two orbits types: Low Earth

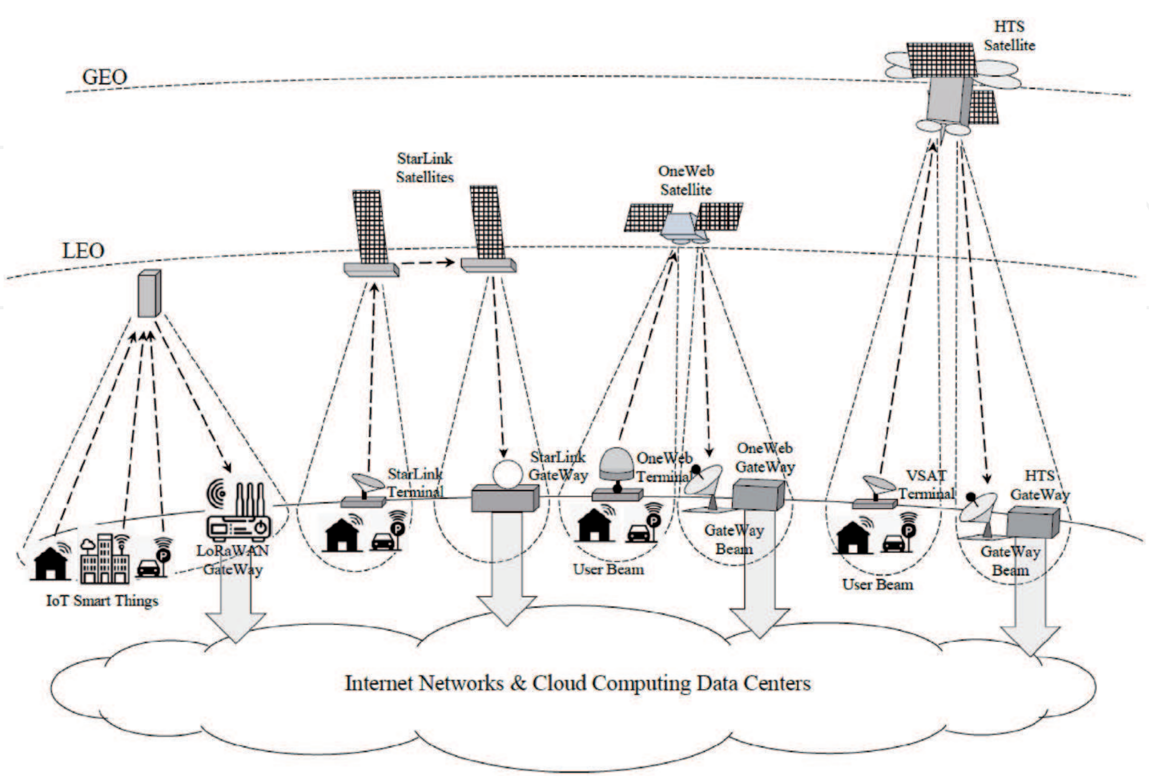


**Figure 2.**
*Satellite communication systems utilization for providing operation of IoT systems.*

Orbit (LEO) and Geostationary Orbit (GEO). Considering the fact that Broadband Access Satellite Systems in LEO and in Medium Earth Orbit (MEO) do not have essential differences in their construction architecture, **Figure 2** does not show MEO Satellite Communication Systems, like O3b System.

The first application option of LEO satellite communication systems is utilization of the IoT narrow-band long range data transmission modified protocol LoRaWAN with exploitation of the CubeSat form factor spacecraft [5]. IoT Smart Things within the CubSat coverage zone, transmit IoT information bursts by LoRaWAN protocol. CubSat receives and retransmits the signals, which come at the LoRaWAN Gate Way. The LoRaWAN Gate Way is connected with the local communication system and provides IoT data transmission through the Internet network to the Cloud Computing Data Center. The IoT Service Control actions bursts are transmitted in the opposite direction. In this architecture, the satellite segment is used as a radio extension link, i.e. as a tool providing the transmission range increase of the LoRaWAN protocol signals.

StarLink and OneWeb are the perspective broadband access satellite systems, which are currently at the different stages of the Satellite Constellation development. These Systems are also capable to provide the IoT data transmission.

The architecture of the StarLink System has been changing several times during the system design and the spacecraft development. The StarLink Constellation with satellites located on LEO with 550 km high is currently in the stage of satellite launches realization and constellation development [6]. StarLink satellites form steerable beams that cover End User Terminals and Gate Ways Earth Station, and provide broadband access satellite service. The external interface of the StarLink end user terminal serves as the StarLink system interface for IoT systems. IoT Smart Things are being connected to a StarLink terminal via a short-range radio access network, for example WiFi or LAN. Then the IoT information packets are being transmitted in the information up-link flow to the StarLink satellite, where it is being routed towards the beam covering the gate way at a given time. It has been often mentioned in the press that StarLink satellites provide an Inter-Satellite Optical (laser) Link [7]. In this case, as shown in **Figure 2**, the IoT information packet can be transmitted over Inter-Satellite Optical Line from the satellite which covers the StarLink end user terminal with connected IoT Smart Things, to a satellite which covers a Gate Way Earth Station. The StarLink Gate Way Earth Station interface is connected to the Internet Backbone and IoT Smart Things information packets come to the Cloud Computing Data Center through this connection.

The OneWeb System Architecture includes two groups of satellite beams: the User Beams providing connection with the User Terminal and the GateWay Beams providing connection with the GateWay Earth Station. The interface of the OneWeb User Terminal to the LAN or WiFi serves as the interface of the OneWeb system and therefore the borderline of the OneWeb system to the IoT Smart Things. The OneWeb User Terminal transmits IoT information bursts of the IoT Smart Things connected to it in the general flow through the Up-Link to the OneWeb satellite, which relays the received User Beams information flow to the Gate Way beam. The OneWeb Gate Way Earth Station is connected to the Internet Backbone. The Gate Way Earth Station receives information bursts of the IoT Smart Things in the general flow, extracts them and provides routing over the Internet Network to the Cloud Computing Data Center.

Currently, GEO communication Regular Satellites and High Throughput Satellites (HTS) are capable to provide the IoT information data transmission services. Both types of GEO satellites can be equipped with a payload with Transparent Transponders or Regenerative Transponders [4]. **Figure 2** shows an example of IoT data transmission using the HTS. Allocation of the separate User Beams and

Gate Way Beams is the feature of the architecture of the HTS geostationary satellite communication systems [8]. The interface of the VSAT Terminal to the LAN or WiFi serves as an external interface of the geostationary satellite communication system to the IoT Smart Things. The VSAT Terminal multiplexes IoT information bursts into a common flow and transmits it over the Up-Link. The HTS satellite transfers the received flow from the VSAT User Terminal to the Gate Way Beam. The GateWay, or its analogue - the HUB of VSAT Network in case of geostationary Regular Satellites utilization, is connected to the Internet Backbone, through which the IoT information bursts get to the Cloud Computing Data Center. To improve the efficiency of cloud services provided with the use of satellite telecommunication systems, the Microsoft Company together with Azure Company started the project implementation on the Cloud Storage Data Centers location in close proximity with satellite teleports [9].

As can be seen from the above presented structure, Satellite Communication Systems take place of data transmission channels between IoT Smart Things and Cloud Computing Data Centers in IoT Systems. The Satellite Communication Systems have to provide two-way transmission of the entire IoT Data Traffic in the Cloud Architecture IoT System, that significantly increases the communication load for channels and systems.

## 3. Perspective development directions of the IoT space infrastructure

The high communication channels load with two-way traffic generated by the IoT system is not the only disadvantage of the conventional IoT cloud architecture, but it is also the delay caused by the IoT information bursts transmission over the data channel through routers and other network equipment. Besides, the propagation time of the radio signal in radio networks and of the light wave in fiber-optic communication systems are of a significant impact. Delay has a particular impact on the IoT Delay Sensitive Service [10].

The solution to the problem is utilization of Fog and Edge Computing [3] in the IoT System Architecture. In this case, some of computations related to the IoT information processing is performed at the intermediate layers of the IoT system hierarchical structure. For this, the corresponding computing capacity is located at intermediate layers. Computing capacity locates nearer to the IoT Smart Things: Sensors and Actuators. As a result, the IoT information processing time is reduced, the IoT system response time to external impact is reduced, and the communication channel load is reduced. Only the results of IoT data processing at the lower layers are being transferred to the higher layers of the hierarchical system, at the same time the value of the transmitted information increases.

### 3.1 Implementation of edge and fog computing in satellite systems

Satellite communication systems are flexible enough to be adapted for implementation of Fog and Edge Computing. **Figure 3** shows the IoT Satellite System Model constructed with implementation of Fog and Edge Computing Architecture.

Edge Computing is a Distributed Computing Model when computation takes place near location where data is collected and analyzed, rather than on a Centralized Server or in the Cloud [11]. As shown earlier, in most cases, the User Terminal or VSAT Terminal Interface acts as the satellite communications system/network boundary to the local area network or to the short-range radio network, for example, Wi-Fi, ZigBee. The User Terminal or VSAT Terminal is located in the immediate vicinity to the location of the IoT Smart Things - Sensors and Actuators. Implementation of Edge Computing in satellite telecommunication systems can

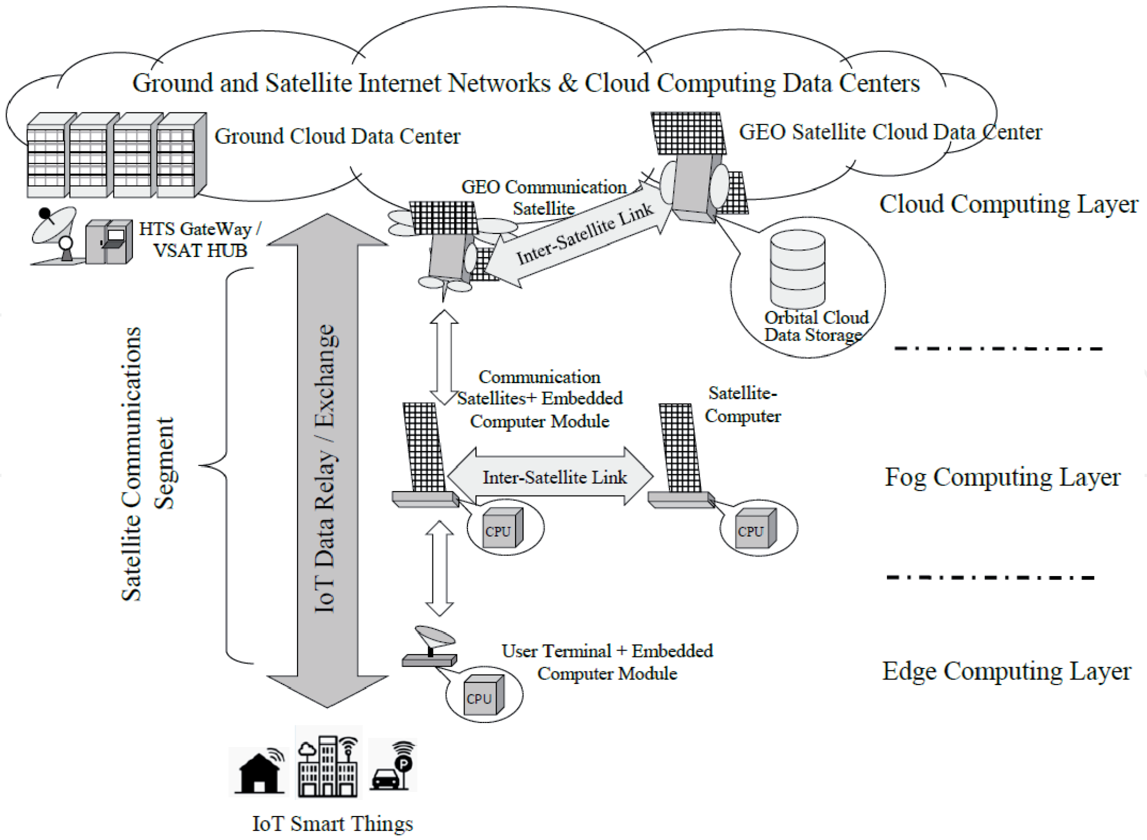


**Figure 3.**
*Hierarchical model of the internet of things satellite system architecture with implementation of fog and edge computing.*

be ensured by supplementing of the User Terminal or VSAT Terminal Modem with an additional Computing Module or Single-Board Computer. Structurally, a User Terminal or VSAT Terminal is a board with modem chips installed on it. Through modernization, such a design can be supplemented with a Single-Board Computer, which will provide the implementation of Edge Computing. An alternative option is to connect a Single-Board Computer to an Ethernet-type Local Area Network with a Wi-Fi router being connected to it as well as other equipment of radio access technology for short-range IoT Smart Things. This added Computing Capacity will support the IoT Smart Things computing needs within the coverage of a short-range radio access network. In this case, only the results information about the IoT local information processing will be transmitted via a satellite communication channel.

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Fog Computing is implemented at intermediate layers of the IoT System Hierarchical Model [12]. A Communication Satellite or a Satellite Constellation is the intermediate layer of the Hierarchical Structure of the Internet of Things System with a Satellite Communications Segment. It includes both GEO Satellites and LEO or MEO Satellite Constellations. The implementation of Fog Computing in the satellite segment of IoT Systems is possible by supplementing the orbital segment with Computing Capacity for the Fog computing implementation. In [13], the Fog computing implementation method was proposed by supplementing Micro-Constellations with separate Satellites-Computers. Considering the fact that the modernization of satellite-repeaters equipment is possible only at the stage of their manufacturing, the implementation of Fog computing in the orbital segment of the IoT Satellite Systems will take a longer period of time. This time period includes the project development of a modernized satellite, its ground tests, expectation time for an Orbital Life Time completion of the already launched satellites and a queuing time for new satellite launch.

Supplementing the Orbital Segment of Satellite Communications Systems with Computing Capacity will allow the implementation of Fog computing for processing of the IoT Information accepted from IoT Smart Things located in the service area of the Satellite. As a result, the efficiency of information processing will increase, and the Delay Time will be reduced. The IoT Information Traffic will load only the section "User Terminal - Satellite Payload" of the Satellite Communication Channel. In the direction "Satellite Payload – Gate Way/VSAT-network HUB" the result of IoT Information processing and summarizing will be transmitted only, that will significantly reduce the amount of information transmitted and increase its value.

Modern Satellite Communications Technologies as well as design and production technologies of Spacecraft for various purposes significantly expand the capabilities of Satellite Communication Systems in terms of Cloud computing implementation, which are at the highest hierarchical layer of the IoT System Architecture. Along with the traditional solution of IoT Information Transfer support to the Cloud Computing Data Center, with utilization of the GateWays or VSAT-network HUB with the Internet backbone connection, an alternative solution is possible – the special Spacecraft-Satellite Cloud Data Centers development and launching them to GEO. Currently the Space Belt project is underway already [14]. However, this project implies the use of Satellites – Data Center (or Cloud Data Storage) located in LEO. Access to Satellites Data Centers implies to be carried out through a GEO Satellite-Repeater.

An alternative solution is the development and launch of GEO Satellite, with a Cloud Data Center Module as a Payload. These Satellites will be accessed via GEO Satellite-Repeaters according with Inter-Satellite Links. To increase data storage and computing operations liability, to increase cloud computing productivity, Satellite Cloud Computing Data Centers will be connected to ground-based Cloud Computing Data Centers provided with special high-speed secure radio links.

### 3.2 LEO system based on LoRaWAN protocol

A LEO Communication system built to ensure the IoT Data Transmission using a modified communication long-range LoRaWAN protocol can be adapted to implement Fog computing by upgrading the System Orbital Segment Architecture by LoRaWAN GateWay equipment and Computing Capacity (see **Figure 4**).

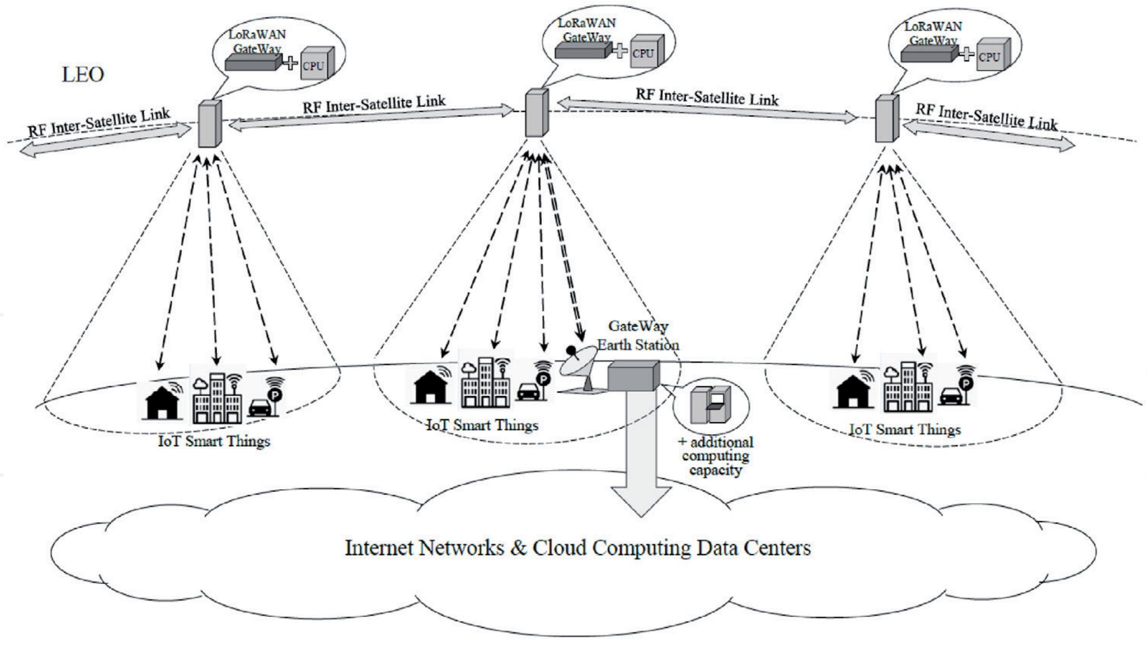


**Figure 4.**
*Architecture of the modified LEO internet of things satellite system based on the LoRaWAN protocol.*

Considering the LoRaWAN Architecture, the CubeSat Payload can be supplemented with the following equipment:

- LoRaWAN Gateway, which provides data collection from Sensors – IoT Smart Things and relays the Sensor Data to the Central Server in the combined Multiplexed Stream;

- Computing Module (CPU), which will act as a LoRaWAN Server directly on-board CubeSat. The CPU installation as the part of Payload will allow the implementation of Fog computing in LEO Satellite System to provide processing of the IoT Smart Things Information Burst directly on the board of CubeSat. The CubeSat provides processing of IoT Smart Things Information located in the service area of the CubeSat.

The proposed changes could be implemented within several years. Since the CubeSats in-orbit life time is rather short and, as a rule, does not exceed 3–5 years, the proposed changes can be implemented via the launch of CubeSats next generation implying to maintain the operation of the orbital constellation of the system.

To ensure the interaction of the orbital and ground segments of the IoT LEO Communication System, constructed with utilization of the CubeSat type of spacecraft and providing IoT services based on the modified LoRaWAN algorithm, it is advisable that the System Orbital Segment/Satellite Constellation will be connected with the ground Internet network through GateWay Earth Station which should be added to the Ground Infrastructure of the IoT Satellite System. The main task of the Gate Way Earth Station is to receive the IoT data combined Multiplexed Stream, i.e. the information on the results from processing of the IoT Sensor information bursts in the Fog computing layer of IoT System, and transferring the received data flow to the Cloud Computing Data Center. The Gate Way Earth Station in a LEO Communications Satellite System provides connection with several Satellites simultaneously. Therefore, it is advisable to add the equipment of the GateWay Earth Station with a computer, which will equip the Earth Station with Computing Capacity. The Computing Capacity implemented into the Earth Station will make it possible to realize Fog computing for generalizing of the IoT information from several CubeSats situated in the GateWay Earth Station radio visibility zone. In the Hierarchical Architecture of the Internet of Things, such a processing of generalized information corresponds to the Fog computing layer.

To improve the efficiency of LEO Satellite Communication Systems developed with utilization of small- and ultra-small satellites, including CubeSats, the Inter-Satellite Links (ISL) are included in the system architecture [15]. The ISL utilization between CubeSats in LEO Communication System allows transmitting the generalized IoT Data Flow to a neighboring CubeSat for its further relaying to the GateWay Earth Station and thus to expand the service area of the GateWay Earth Station and to reduce their number.

### 3.3 OneWeb LEO broadband access satellite system

The Transparent Payload utilization in satellites is a feature of the OneWeb LEO Broadband Access Satellite System Architecture. The OneWeb Satellite Payload provides transfer of the User Beam frequency band to the Gate Way Beam frequency band [16]. There is no information processing in the payload. The OneWeb System architecture does not imply Inter-Satellite Links between Satellites.

For adaptation of the OneWeb System to the peculiarities of the Internet of Things and implementation of Edge and Fog computing, the capabilities of User Terminals and Gateway can be used (see **Figure 5**). In the OneWeb System the network boundary from the End User side is the interface to the Ethernet LAN or to the Wi-Fi radio access network. The equipment of the User Terminal could be supplemented with a computing module in the form of a separate Processor Unit or a Single-Board Computer. An alternative option could be the connection of the Single-Board Computer to the Ethernet LAN. This Computing Capacity, located at the User Terminal layout in the immediate vicinity of the IoT Smart Things (Sensors and Actuators), is introduced into the System in order to implement Edge Computing. Supplementing the User Terminal with a computing facility will make possible primary processing of information packets from IoT Sensors and form control commands for Actuators at the User Terminal Layer. The Satellite Communication Channel will transmit generalized information formed on the

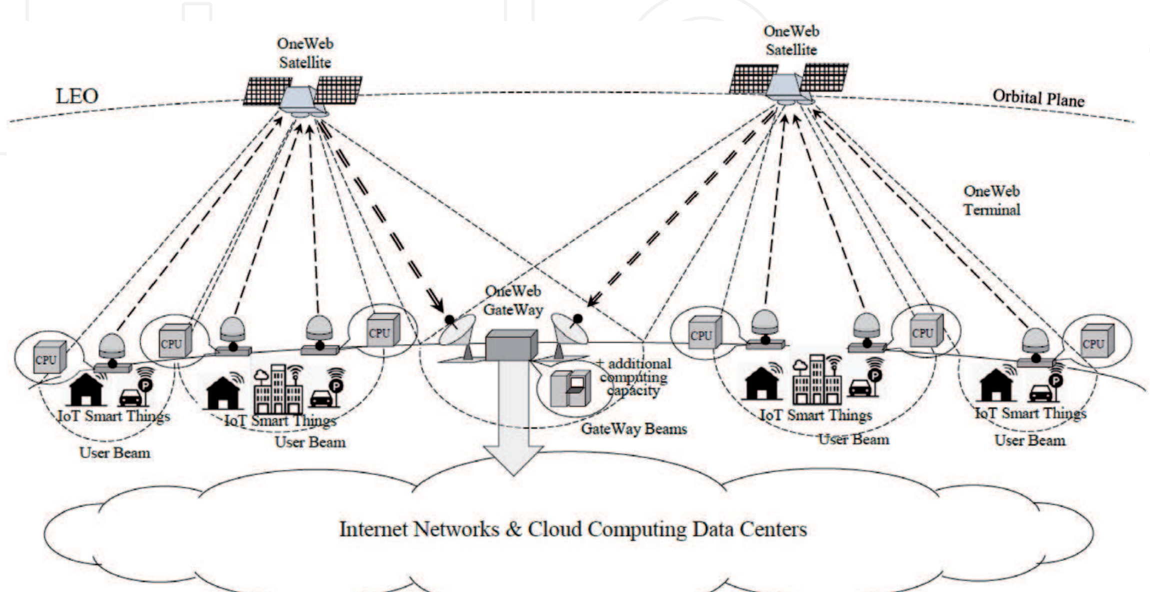


**Figure 5.**
*Adaptation of the OneWeb satellite system for IoT systems.*

results of processing information from the local group of IoT Smart Things located in the coverage area of the short-range radio access technology.

Fog computing can be implemented at the GateWay Layer. For this, the GateWay Earth Station Equipment have to be supplemented with a Computing Module - a Multiprocessor Computer Group installed in additional Rack (see **Figure 5**). This Computation equipment will provide the IoT Data processing received from the service area of the OneWeb Satellite, or from Satellites situated in the service area of the GateWay Earth Station. Control commands for special IoT Smart Things and groups of Smart Things – Actuators, will be transmitted from the GateWay Earth Station via Satellite to the User Terminal. Generalized information on the results of the IoT data processing and about the decisions and generated control commands will be transmitted via the Internet to the Cloud Computing Data Center, as to the highest Layer of the IoT System Hierarchical Architecture.

### 3.4 StarLink LEO broadband access satellite system

LEO Broadband Access Satellite System Starlink, like the OneWeb System, has a formed architecture focused on providing End Users with high-speed Internet Access Services. As it was above mentioned, the existing Starlink System Architecture allows only the IoT Services of a Cloud Architecture.

For adaptation of the StarLink System to the Internet of Things System peculiarities and implementation of Edge and Fog computing, methods similar to those proposed for the OneWeb system can be used, namely (see **Figure 6**):

- supplementing User Terminals with Single-Board Computers or connecting a Single-Board Computer to the WiFi Radio Network for implementation of Edge computing for the data processing of the IoT Smart Things located inside a short-range radio access network;

- supplementing of the equipment of the GateWay Earth Station with a separate multiprocessor computer group/rack for implementation of Fog computing for

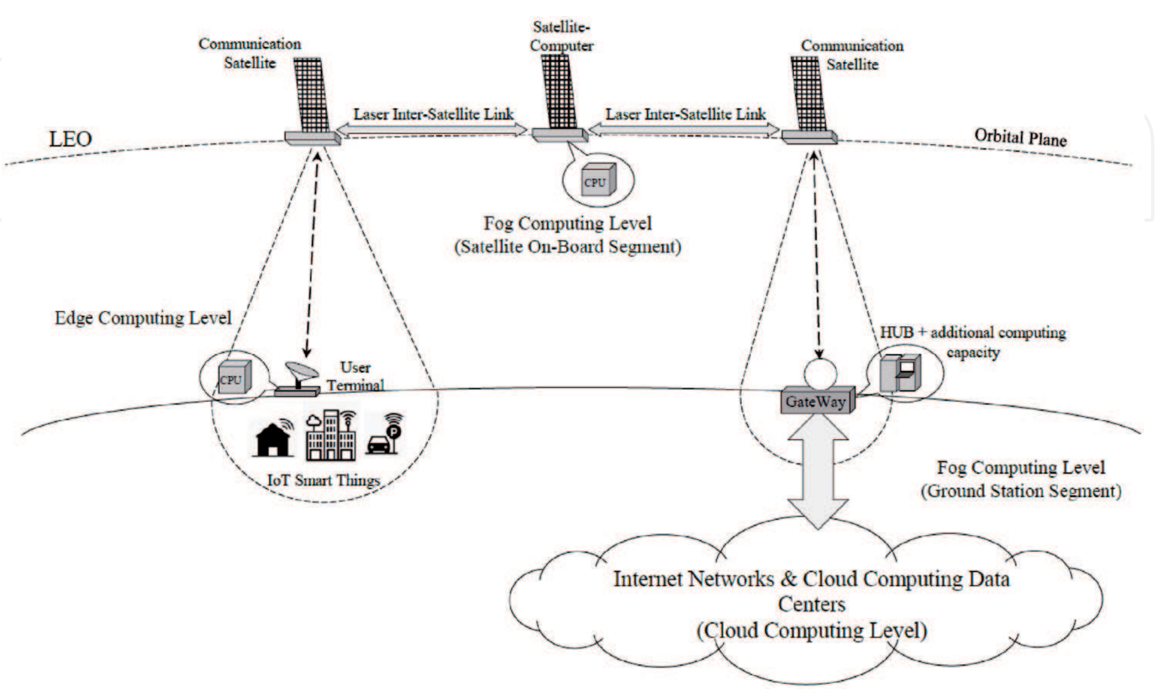


**Figure 6.**
*Adaptation of StarLink system for edge and fog computing IoT services.*

the data processing for the IoT Smart Things located in the service area of all the StarLink satellites in the GateWay radio visibility zone.

At the same time, the Laser Inter-Satellite Links utilization in the StarLink System [7] makes it possible to consider the decision of supplementing the StarLink Constellation with Satellite-Computers (see **Figure 6**). Unlike StarLink Satellite-Repeaters, the Payload of the Satellite-Computer is a Computing Module - a Processor Unit and a long-term Memory Module. Like Satellite-Repeaters, the Satellite-Computer Payload comprises the Router in it. To ensure links with other satellites, the Satellite-Computer is equipped with Optical Heads for the Laser Inter-Satellite Links.

The purpose of the Satellite-Computer is to generate the Computational Capacity directly in LEO in the same Orbital Plane with the Satellite-Repeaters. In each Orbital Plane of the StarLink Constellation, several Satellite-Computers can be placed (see **Figure 7**). The IoT information will be transmitted from Satellite-Repeaters to a Satellite-Computer via Inter-Satellite Links for processing, actuator command generation and aggregation of generalized information. Placing Satellite-Computers in the Orbital Plane and retargeting optical transceivers/optical heads of Laser Inter-Satellite Links towards them will not destroy the integrity of the Orbital Plane Data Transmission Ring Network, as Satellite-Computer, like the Satellite-Receiver, is equipped with a Router that will distribute data streams assigned for further retransmission via the Ring Network of the Orbital Plane and will extract information assigned for processing in the Computing Module of the Satellite-Computer.

Supplementing of the StarLink Constellation with Satellite-Computers will make it possible to create Computing capacity directly in the orbit for the Fog computing implementation for the IoT Systems.

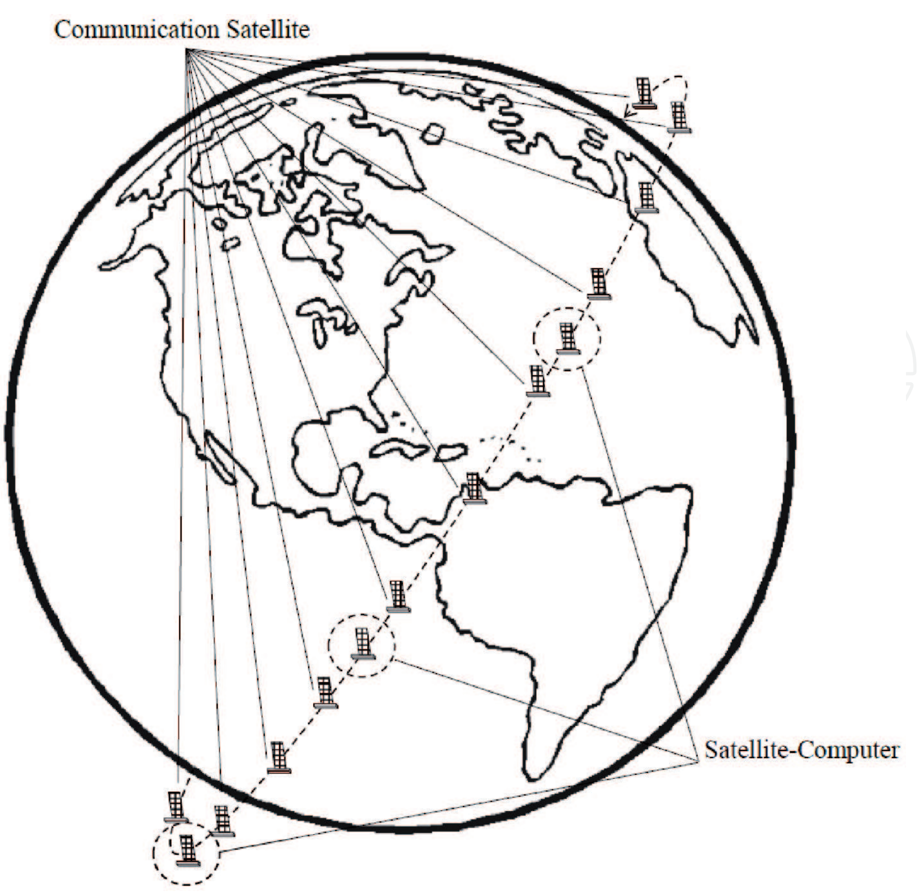


**Figure 7.**
*Location of satellites-computers in one orbital plane of the StarLink constellation.*

### 3.5 GEO high throughput satellite system. Orbital cloud data center

Geostationary Satellite Communication Systems are an important component of modern Satellite Communication Infrastructure. The growing demand for data transmission bandwidth and for provision of information services, primarily for the Internet Access, has become a driver for the HTS, a new class of GEO Satellites, to enter the market. The main advantage of these satellites is the information transmission low cost per one bit between two subscribers [8].

The architecture of GEO HTS Systems has its own characteristics, which were mentioned above. Another feature of HTS is the principle: one Transponder per one Spot Beam [17]. According to this principle, one Transponder provides amplification of signals via the entire frequency band, which can be 150 ÷ 250 MHz and more.

The architecture of GEO HTS Systems can be adapted to the peculiarities of the IoT Systems in several stages as follows (see **Figure 8**). At the first stage, it is possible to upgrade the system elements related to the Ground Communication Segment: User/VSAT Terminals and Gate Way Earth Stations (GateWay). Loading Computing Capacity on these elements will allow the implementation of Edge and Fog computing for the IoT Systems. Possible technical solutions for the Computing Capacity implementation on these elements are similar to the technical solutions discussed above for OneWeb and StarLink LEO Systems.

Currently available design and manufacture technologies for the GEO Satellites with a 15–20 years life time, and the experience accumulated in the construction and operation of Satellite Constellations, in-Orbit Satellites Interaction, makes it possible to consider the issue of creating perspective Orbital Cloud Data Storage, consisting of several Geostationary Satellites – GEO Satellite Cloud Data Centers (see **Figure 8**).

Orbital Cloud Data Storage cannot be considered the alternative to the Ground Cloud Data Processing and Storage Centers, since the Computing Capacity and Storage Capacity for Ground Cloud Data Centers are practically unlimited. Orbital

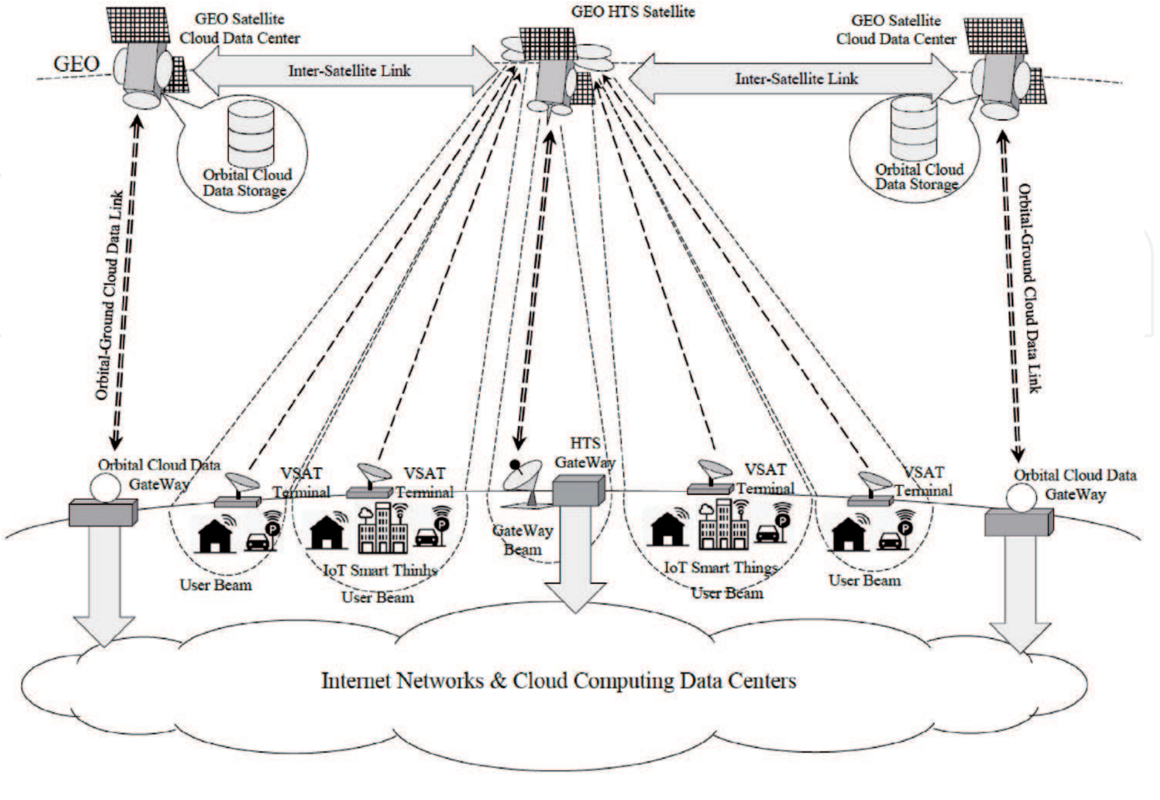


**Figure 8.**
*Adaptation of the geostationary high-throughput systems to the IoT systems peculiarities and interaction with an orbital cloud computing data center.*

Cloud Data Storage is an augmentation to the Ground Cloud Infrastructure and is focused primarily on processing and storing data from IoT Satellite Systems. To improve the reliability of data storage and the Computing Capacity increase, if necessary, the Orbital Cloud Data Storage interacts with the Ground Cloud Centers infrastructure via RF data transmission channels specially dedicated.

GEO High-Throughput Satellites will provide access to GEO Satellites - Cloud Data Centers via Inter-Satellite Link, set up in the radio frequency or optical band. The possibility of the long-distance optical links utilization in space has been practically confirmed on the establishment of the Europe Data Relay System (EDRS), implemented by the European Space Agency order [18].

To route IoT Information to the Satellite - Cloud Data Center, the GEO HTS Satellite have to route IoT Traffic. Routing can be provided by the following method:

- with Regenerative Payload on board the Satellite through extracting IoT information from the Data Transport Stream transmitted by VSAT terminals and IoT Information routing towards GEO Satellite - Cloud Data Center. The Advanced Regenerative On-board Processing Satellite (AR-OBPS) technology can be used as a basic technology for this process [19];

- when separated frequency bands allocated for IoT information in the common frequency band of each user beam. The IoT Information frequency band will be switched in the Satellite Payload separately from the other frequency band and transmitted over the Inter-Satellite Link between satellites to GEO Satellite - Cloud Computing Data Center. The Intelsat Epic$^{NG}$ Platform Digital Payload Technology [20] can be used as a basic technology for this process.

Orbital Cloud Data Storage can provide the IoT Data Processing for LEO IoT Systems (see **Figure 9**). In this case, LEO System based on the LoRaWAN protocol provides the implementation of Fog computing, as shown above, and the Orbital Cloud Data Storage provides the Cloud computing Layer (see **Figure 3**).

Interaction between LEO CubeSats and GEO Satellites – Cloud Computing Data Centers, is provided via LEO-GEO Inter-Satellite Link. To set up GEO-LEO Inter-Satellite Link the CubeSats from the LEO System could be equipped with Deployable Parabolic Dish Antennas [21]. LEO CubeSats should be designed to point Deployable Parabolic Dish Antenna towards GEO Satellite – Cloud Computing Data Center or towards GEO HTS, which in this case will be used as an IoT Data Repeater and Router.

**Figure 10** shows the architecture of the Constellation of the combined LEO-GEO IoT Satellite System. CubeSats are located in LEO and provide the IoT Information/IoT Information Burst reception using modified LoRaWAN protocol directly from IoT Smart Things – Sensors and transmitting control information to IoT Smart Things – Actuators within CubeSat coverage zone. To simplify, in **Figure 10** only the Orbital Plane is shown. The LEO Component of the Constellation consists of several Orbital Planes, which number is determined according to the requirements for continuity of the Service, Power Capacity and the Life Time of IoT Devices - Sensors and Actuators, and other factors. CubeSats are equipped with Deployable Parabolic Dish Antennas of RF LEO-GEO Inter-Satellite link and provide parabolic antennas steering towards the GEO Satellite.

GEO Satellites - Cloud Computing Data Centers or GEO High-Throughput Satellites are located in the Geostationary Orbit and are equipped with GEO-GEO Inter-Satellite Link. GEO Satellite provides the reception of processed IoT Data from LEO CubeSats in the radio visibility zone. To provide a continuous radio interconnection with LEO CubeSats, three GEO Satellites - Cloud Computing Data

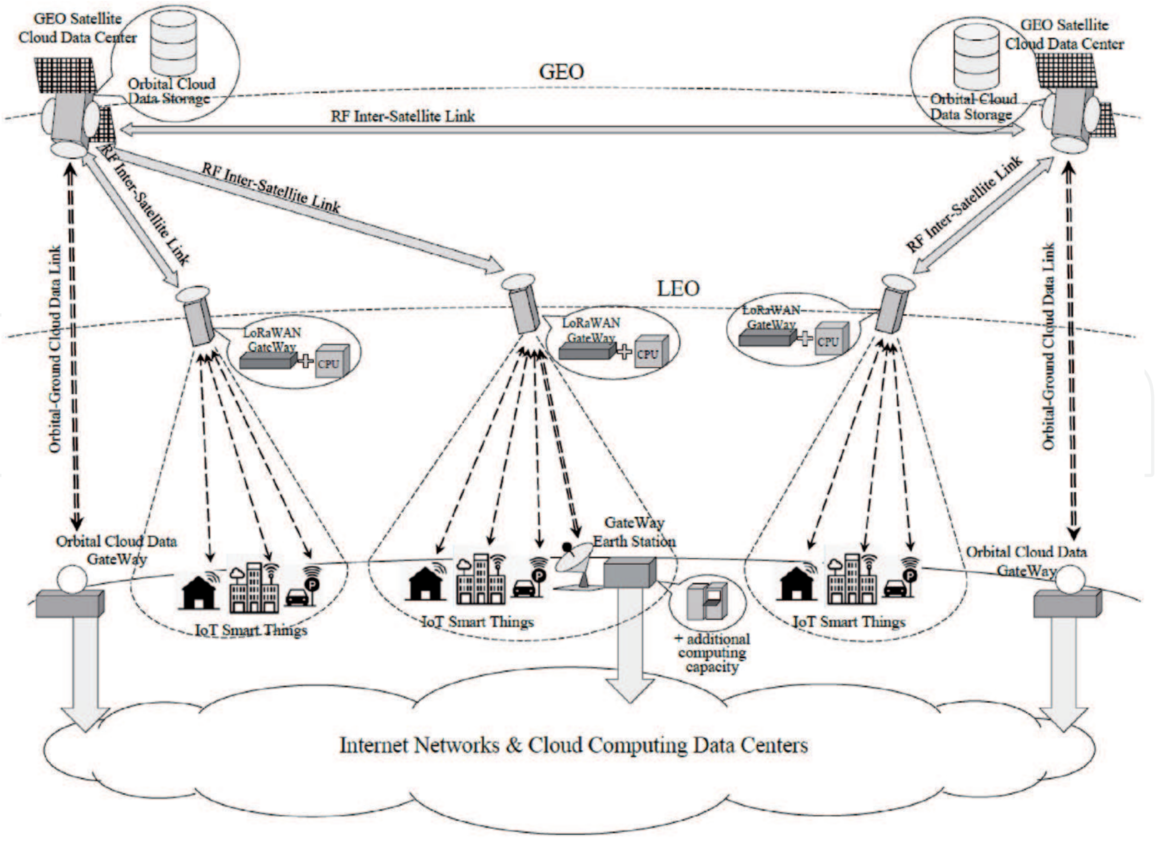


**Figure 9.**
*Interaction between the orbital cloud data storage and the LEO IoT satellite system based on the modified LoRaWAN protocol.*

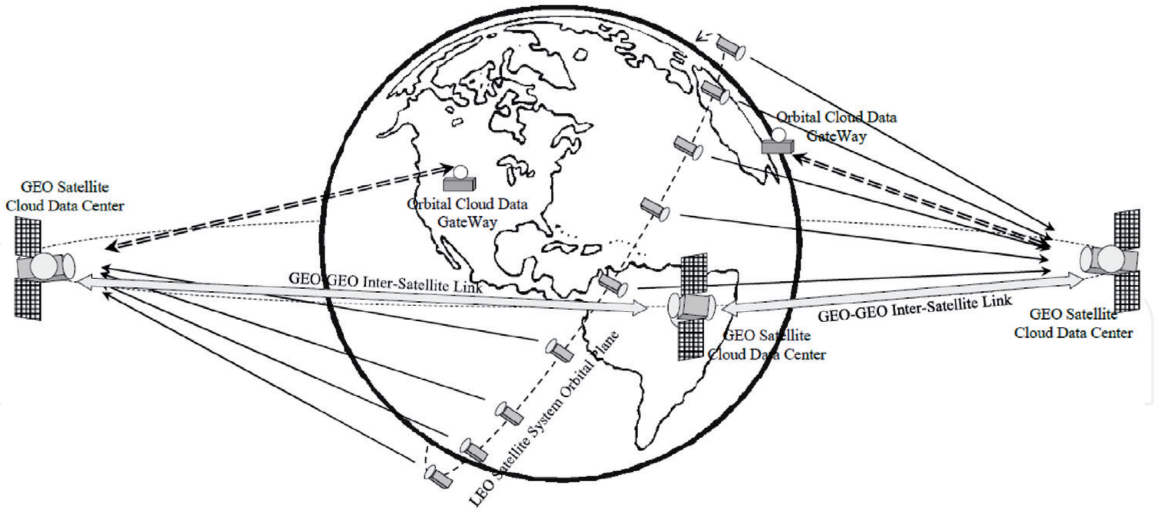


**Figure 10.**
*The combined GEO-LEO IoT satellite system constellation architecture.*

Centers or High-Throughput Satellites is sufficient to be placed in GEO. The integrity of the Orbital and Ground Cloud Data Infrastructure is supported by GEO-GEO Inter-Satellite Links and GEO Satellite - Ground Cloud Computing GateWay Earth Station Links (see **Figure 10**).

Currently, Geostationary Orbit is uploaded enough with operating GEO Satellites of various missions and Satellites that have been taken out of service (inoperative). **Figure 11** shows a chart of the Geostationary Orbit upload by satellites under control [22].

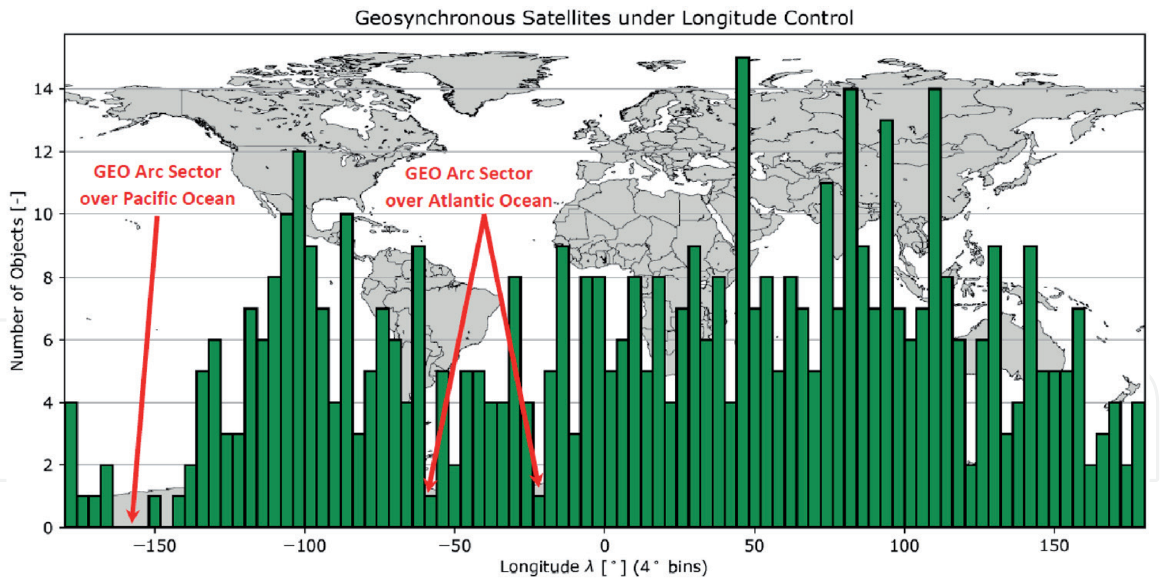


**Figure 11.**
*Geostationary orbit upload [22] and free orbital slots for operation of GEO satellite – Cloud data center*

As can be seen from **Figure 11**, the most free GEO sectors are the ones located over the Pacific and Atlantic oceans: sectors 144° W ÷ 164° W; 56° W ÷ 60° W; 20° W ÷ 24° W. Considering the fact that GEO-GEO Inter-Satellite Link are used to provide access to GEO Satellite - Cloud Data Centers, the GEO Satellites from the Orbital Cloud Data Storage can be placed in these GEO sectors, which are not of interest for the satellite communication services provision to end users on the Earth surface.

## 4. Conclusions

1. Modern Satellite Communication Systems provide data transfer of IoT Systems, based mainly on Cloud Technology. The disadvantage of the IoT Systems Cloud Architecture is the necessity to transfer the entire amount of information from IoT Smart Things to Cloud Computing Data Centers and vice versa, that leads to Satellite Communication Systems inefficient load.

2. Satellite Communication Systems can be adapted to the peculiarities of Data Transport Streams in the IoT Systems, which use Fog and Edge computing Technologies to increase their efficiency. The Satellite Communication Systems adaptation to the peculiarities of IoT Fog and Edge computing is being carried out by placing computers of various capacities as the part of User/VSAT Terminals, Satellite Payloads and Gate Ways Earth Stations or VSAT networks HUB Stations. Such an arrangement of Computing Capacities and distribution of computations allows maintaining the strong IoT System Hierarchical Architecture, reducing the processing time and the transferred data volume, and increasing the value of information transmitted to the Cloud Computing Data Center.

3. The ways for the Satellite Communication Systems transition from the IoT Systems Cloud Architecture to the Multi-Layer Architecture with the Edge and Fog computing utilization are proposed. The implementation variants of Fog computing in LEO Systems are considered: Satellite Constellation of CubeSats with the modernized LoRaWAN protocol - the CubeSat Payload update and CubeSats replacement during the Satellite Constellation planned

update; OneWeb system - the End-User Terminals and GateWay Earth Station equipment update; StarLink System – the User and Gate Way terminals update, the Constellation supplementation with Satellites - Computers.

4. In GEO High-Throughput Systems, the implementation of Edge and Fog computing is possible in two stages. At the first stage, the transition to Fog and Edge computing is possible by the User terminals and GateWay Earth Station modernization to supplement their structure with Computing Modules. At the second stage, during the planned replacement of a GEO High-Throughput Satellite, its Payload can be equipped with additional equipment for the IoT Systems Traffic allocation, traffic processing and carrying out the necessary calculations for the Fog computing system implementation in the Space Segment Structure.

5. To increase the efficiency of processing, storage and the IoT Systems access to Cloud Services, it is reasonable to create a Cloud Services Space Segment - an Orbital Cloud Data Storage, consisting of several GEO Satellites - Cloud Computing Data Centers which are connected via Inter-Satellite Links. The Orbital Cloud Data Storage can be accessed through upgraded GEO High-Throughput Satellites and through LEO CubeSats equipped with a LEO-GEO Inter-Satellite Link.

## List of Acronyms

| | |
|---|---|
| AR-OBPS | Advanced Regenerative On-board Processing Satellite |
| EDRS | Europe Data Relay System |
| GEO | Geostationary Orbit |
| HTS | High Throughput Satellites |
| IoT | Internet of Things |
| ISL | Inter-Satellite Link |
| LAN | Local Area Network |
| LEO | Low Earth Orbit |
| MEO | Medium Earth Orbit |
| VSAT | Very Small Aperture Terminal |

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