Performance Analysis of Selective DF Relaying for Satellite-IoT

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CERTIFICATE

It is certified that the work contained in this thesis, titled "Performance Analysis of Selective Decode-and-Forward Relaying for Satellite-IoT" by Nikhil Lamba, has been carried out under our supervision and is not submitted elsewhere for a degree.

Date

Advisor: Dr. Sachin Chaudhari

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Abstract

As the number of applications of Internet-of-things (IoT) is increasing daily, there is a growing challenge of providing real-time tracking data to users with a larger coverage area. The satellite-based network can provide global coverage to IoT devices. Due to the low power and low complexity of IoT devices using slotted-ALOHA protocol, it is desired to have visible satellites at a lower altitude than that altitude of commonly used GEO satellite constellations. Recently, sizeable Low-earth-orbit (LEO) satellite constellations such as Starlink-SpaceX and OneWeb launched in orbit can address the coverage issues at much lower power and lower latency. In addition to this, there is minimal coordination among IoT devices. Thus, the packets from multiple devices reaching the gateway may cause collisions and thus reduce the throughput at the gateway.

This thesis considers a LEO satellite-based topology for an IoT network, where multiple IoT devices broadcast the information to all the visible satellites over a shared channel using slotted ALOHA. The satellites selectively Decode-and-forward (DF) the data from the IoT devices over orthogonal channels to the Ground station (GS), which does Maximal Ratio Combining (MRC). Capture and Successive interference cancellation (SIC) schemes are considered for decoding at the satellites to mitigate the interference at the satellites in the uplink. For the considered topology, the closed-form expressions are derived for the end-to-end Outage probability (OP) for an arbitrary number of IoT devices and satellites in the capture model and the two-device, two-satellite case in the case of the SIC model. The expressions are derived for both independent and non-identically distributed (inid) and independent and identically distributed (iid) uplink channels. The OP is analyzed as a function of the parameters like the number of satellites, devices, and the desired data rate. The results demonstrate that the proposed approach leverages the benefits of mega-LEO satellites to make the topology feasible and attractive for low-powered and low-complexity IoT networks.

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Abbreviations

AF	Amplify-and-forward
AWGN	additive white Gaussian noise
CDF	cumulative distribution function
CRDSA	Contention resolution diversity slotted Aloha
CSI	Channel State Information
DF	Decode-and-forward
DtS	Direct-to-satellite
GEO	Geostationary-earth-orbit
GLONASS	Global Navigation Satellite System
GPS	Global Positioning System
GS	Ground station
iid	independent and identically distributed
inid	independent and non-identically distributed
IoT	Internet-of-things
LEO	Low-earth-orbit
LoRa	Long range
LoRaWAN	Long-range wide-area network
LoS	line-of-sight
MAC	Medium Access Control
MEO	Medium-earth-orbit
MF-TDMA	Multi-frequency TDMA
MRC	Maximal Ratio Combining
NB-IoT	Narrowband-IoT
NTN	Non-Terrestrial Networks
OP	Outage probability
PDF	probability density function
RTT	Round Trip Time
SIC	Successive interference cancellation
SINR	signal-to-interference-plus-noise ratio

SNR	Signal-to-Noise ratio
SR	shadowed-Rician
SSR	squared shadowed-Rician
TDMA	Time division multiple access

Symbols

$D; S$	Total number of devices;Total number of satellites
d	device ID,$d \in \{1, 2, 3, ..., D\}$
$\mathbf{D}; \mathbf{S}$	Set of all devices in the system; Set of all satellites in the system
y_s	Received signal at satellite s
P_d	Transmit power of d^{th} device
h_{ds}	SR channel from the d^{th} device to the satellite s
x_d	unit energy information signal
r_{ds}	unit energy information signal
α	path loss exponent
w_{ds}	AWGN with mean 0 and variance $\sigma^2_{w_s}$ for a device d
h_{ds}	SR channel from the d^{th} device to the satellite s
u_s	unit energy signal forwarded by s^{th} satellite
g_{ds}	iid SR channel for the d^{th} device from the satellite s to GS
u_{ds}	unit energy signal forwarded by s^{th} satellite
${w_s}'$	AWGN with mean 0 and variance $\sigma^2_{{w_s}'}$
H_{ds}	Uplink channel gain for device $d \in \mathbf{D}$ at satellite $s \in \mathbf{S}$
γ_{ds}	Uplink signal-to-interference-plus-noise ratio (SINR) for device d at satellite s
γ_{ds}^{Cap}	Uplink capture SINR for device d at satellite s
γ_{ls}^{SIC}	Uplink SIC SINR for device l at satellite s
γ_{ds}^{SIC}	Downlink Signal-to-Noise ratio (SNR) at GS for device d and satellite s
G_{ds}	Uplink SIC SINR for device l at satellite s
$\Psi_d(n)$	Downlink SNR at GS for device d after MRC combining from n satellites
$\Delta_s(n)$	Sum of combined SNR from n interfering devices at satellite s for a device
$\mathbf{F}$	Set of all satellites forwarding messages to GS

$P(\gamma_{ds}^{cap} < \gamma_0)$	Probability that the SINR for ds link is less than γ_0 for capture scheme
$P(\gamma_{ds}^{SIC} < \gamma_0)$	Probability that the SINR for ds link is less than γ_0 for SIC scheme
$P(\gamma_{ds}^{SIC} > \gamma_0)$	Probability that the SINR for $\{D = 1, S = 1\}$ is less than γ_0 and $H_{11} > H_{21}$

Chapter 1

Introduction

1.1 Motivation

With the exponential growth of Internet-of-things (IoT) devices, there is a growing demand for internet access anywhere at any time. To cater to these needs, satellite IoT can play an important role. There are many reasons for industries to vouch for satellite-based networks. Firstly, the terrestrial networks, consisting of IoT devices, cover only 15% of the Earth's surface [1]. It leaves a vast planet stretch, mainly comprising remote areas, deserts, oceans, or glaciers, not covered by terrestrial cellular networks. Secondly, there will be proliferation of IoT devices in the future. Over the past few years, the focus has been on developing smart cities in many countries. The aim is to use IoT based physical devices to increase the efficiency of city operations and services, reduce costs and energy consumption, and improve connectivity to citizens. The data is collected from sensors, processed, and analyzed to run applications ranging from air pollution monitoring systems, healthcare, and logistics tracking to disaster management. By 2050, it is expected that up to 70% of the world's population is expected to inhabit a smart city [2].

As the number of smart cities increases, building the infrastructure for their connectivity is becoming critical. Satellite-based IoT networks can prove to be a cost-effective way for such infrastructure. Thirdly, the emergence of Low-earth-orbit (LEO) satellites has further accelerated the evolution of satellite-IoT networks. IoT devices, with direct-to-satellite connectivity features, can transmit data over long distances and help connect far-flung cities and regions. A 3GPP report [3] shows the support of IoT nodes to satellite direct connectivity. The transmission of data between different nodes in the systems, like traffic monitoring, security cameras, and environmental monitoring systems, will make cities more efficient and responsive to changes in their environment. Satellites can share real-time data for the decisions to reduce delays and improve traffic flow. The services can be cost-effectively provided to areas with poor connectivity or areas with low population density. With this, satellite-based services provide the suitable alternative for smart-city development.

With advancements in onboard processing, there is an increase in the number of satellite constellations. With the coming-up of LEO constellations like Starlink-SpaceX and OneWeb, there is a growing interest in the satellite-IoT networks. The standardization process has further accelerated this process. In

Rel-13, 3GPP specified LTE-M and NB-IoT to support massive machine type communications (mMTC) to address the following design targets: low UE complexity and hence reduced device cost, long UE battery life to limit the need for charging or replacement, and coverage enhancements [4]. For areas with no cellular access, connection may be provided via Non-Terrestrial Networks (NTN) to support terrestrial networks.

The major challenges for the satellite-based IoT networks are low power, delay and transmission of IoT devices at random instants directly to the satellites. With a large number of collisions among packets from the IoT devices, there will be a loss of packets. One solution can be the repetition of packets' transmission, which leads to lesser throughput for the networks. However, it is widely known that there is limited bandwidth and the requirement of significant data rates and capacity for the system. To avoid the loss of packets or low data rates, this thesis proposes interference mitigation schemes for the network topology so that multiple sources can transmit symbols to the ground station via LEO satellites with a lesser probability of loss. The performance of the network topology is measured in terms of outage probability (OP), which is directly related to the probability of bit errors at the ground station (GS).

There are several papers in the past on finding Outage probability (OP) of the user in terrestrial and satellite communications. Based on terrestrial networks, the papers have a system model comprising users transmitting the symbols to the base station. The base stations, in turn, apply amplify and forward (AF) or decode and forward (DF) schemes to re-transmit to the Ground station (GS). The GS combines the downlink signals using the diversity schemes. In the case of satellite networks, the symbols from IoT devices reach the satellites via terrestrial relays, or the satellites, through base stations, send packets to the ground station. However, very few papers consider the case of IoT devices communicating directly to the satellites. In the proposed network topology, the IoT devices communicate directly in the uplink to the satellites, and the satellites, in turn, use the selective decode-and-forward scheme to send their signals in orthogonal slots to the GS. The GS applies Maximal Ratio Combining (MRC) combining scheme for each user for proper reception.

1.2 Summary of Contributions

The main contributions of this thesis are in the given chapter:

- **Chapter 3**
  - This paper proposes the use of direct-access based satellite-IoT topology with multiple IoT devices transmitting to multiple satellites in their range using slotted ALOHA. At the satellites, the messages are decoded from the IoT devices in the presence of interference using capture and Successive interference cancellation (SIC) schemes. The satellites selectively DF the information from the IoT devices over orthogonal channels to the GS, which does MRC.

- Generalised closed-form expressions for the end-to-end OP is derived for the capture model in the case of both independent and identically distributed (iid) and independent and non-identically distributed (inid) uplink channels. For the SIC-based system, closed-form expressions for the OP is derived only up to two IoT devices and two satellites network for iid and inid uplink channels.
- The end-to-end OP, as a function of the number of devices, the number of satellites, and the target rate for both capture and SIC-based systems, are discussed.

1.3 Organization of Thesis

The remainder of this thesis is organized as follows:

- *Chapter 2* gives the introduction to IoT and satellite-IoT networks. It also covers recent trends and challenges to them.
- *Chapter 3* discusses the system model for satellite-IoT networks for multiple devices and dealing with the inter-device interference in the uplink. The performance analysis of the performance under consideration follows the description of our system model. The results section highlights the role of satellites in making the topology suitable for low-powered IoT devices.
- *Chapter 4* serves as the conclusion of the thesis.

Chapter 2

IoT Networks

This chapter provides an overview of both IoT and satellite-IoT networks. It focuses on various aspects, including the fundamental components of IoT, technological advancements, challenges encountered in the field, and critical applications. For more information on IoT, the suggested reading are [5–8]. One of the central themes is the growing prominence of satellite networks over terrestrial networks, driven by the goal of achieving global coverage. It discusses the latest cutting-edge constellations that specifically support IoT applications, highlighting their importance in enabling global connectivity. The challenges faced in implementing these satellite-IoT networks are thoroughly examined, shedding light on the complexities involved in making this technology a reality. The books [9–11] are the good references for gaining the knowledge on the design and challenges for the satellites supporting IoT devices.

2.1 IoT

IoT, or Internet of things, devices has found utility in our daily lives ranging from household to industrial spaces. There have been multiple definitions of IoT. As per ITU's Telecommunication Standardization Sector (ITU-T) [12], IoT *is a global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies*. Oracle defines IoT as the interconnection of 'things' that have embedded sensors, software, and other technologies to connect and exchange data with other devices and systems through the Internet [13].

The interaction between IoT devices is facilitated by a service layer, which can be embedded in both hardware and software components, allowing these devices to connect with servers worldwide. OneM2M is introduced as a global entity responsible for creating standards for a common Machine-to-Machine (M2M) service layer. This standardization ensures the seamless connectivity of IoT devices to various services. OneM2M's vision is to establish a world where IoT services are inter-operable and secure, with easy market adoption, ultimately benefiting society at large. Given the increasing number of IoT devices in use, with an expected rise to 22 billion devices by 2025 (from the current 7

Figure 2.1: Components of IoT [14]

billion devices), the importance of standardization procedures is emphasized to meet the growing global demand for IoT connectivity.

2.1.1 Components of IoT

The functions of IoT can be understood by the following building blocks, as stated in Fig. 2.1 from [14]:

1. **Identification**

   Identification for IoT nodes is important in a network to meet the service demands. The relevance of ubiquitous Code (uCode) is stated in [15]. The object ID and address are sufficient parameters to make the IoT uniquely identify the node. The nodes are addressed on the IPv4, IPv6, and 6LoWPAN schemes.

2. **Sensing**

   IoT devices gather data and send it to storage devices or cloud platforms. The collected data is processed, and then necessary actions are taken. Smart devices like AirIoT [16] monitor indoor environments to prevent the spreading viruses like Covid-19.

3. **Communication**

   The main feature of the IoT systems is that the heterogeneous objects communicate with each other to provide services. For this, there is a need for communication protocols for inter-operability, for example, WiFi, Bluetooth, IEEE 802.15.4, Z-wave, and LTE-Advanced.

4. **Computation**

   The hardware and software together form the computational ability of IoT system. Arduino, FriendlyARM, Intel Galileo, Raspberry PI, Gadgeteer, BeagleBone, Cubieboard, Z1, WiSense, Mulle, and T-Mote Sky are some of the options in hardware for IoT. For the software platforms, IoT systems play an essential role as they mainly do processing in the operating modes of devices. The Real-time Operating systems (RTOS) used for software platforms are plenty. For

Mode of operation	**Power Consumption** ($V_{DD} = 3V$)
Power down mode	2.7 uW
Standby-I mode	78 uW
Standby-II mode	960 uW
RX mode (@ 2 Mbps)	41.5 mW
RX mode (@ 1 Mbps)	39.3 mW
RX mode (@ 250 kbps)	37.8 mW
TX mode (@ 0 dBm)	33.9 mW
TX mode (@ -6 dBm)	27 mW

Table 2.1: IoT Power modes for NRF24L01P device [17]

example, the Contiki RTOS uses a simulator for Wireless Sensor Networks (WSN) based applications. Cloud-based platforms are combined to boost further the computational complexity of IoT devices. The device data is uploaded to the cloud and processed to provide services to end users.

5. **Services**

   IoT services are categorized into four main classes: Identity-related Services, Information Aggregation Services, Collaborative-Aware Services, and Ubiquitous Services [14]. Identity-related services are necessary to identify the nodes and take further actions. Information aggregation involves collecting and sending data to the application layer for further processing. Collaborative-aware services come after the information aggregation and involve decision-making and taking necessary actions. Ubiquitous services aim to provide collaborative services anytime to anyone and at any location.

6. **Semantics**

   Semantics play an essential role for IoT. It involves extracting information from the data collected to take the right action. The IoT's, in turn, send the commands to the resource accordingly. Technologies such as Efficient XML Interchange (EXI) support XML applications. They reduce bandwidth and storage size without impacting battery life, code rate, processing energy consumption, and memory.

2.1.2 Technologies that make IoT feasible

With the help of advancements in technology, the usage of IoT devices is increasing at a swift rate. Their existence is made feasible due to the following factors:

1. **Low-cost and low-power sensor technology**
   Traditionally, engineers' primary goal has been lowering costs, not power. Though designing IoT systems with low power is essential, the companies used to bypass power reduction techniques to keep the expenses in check. Recently, companies are prioritizing energy use over time over

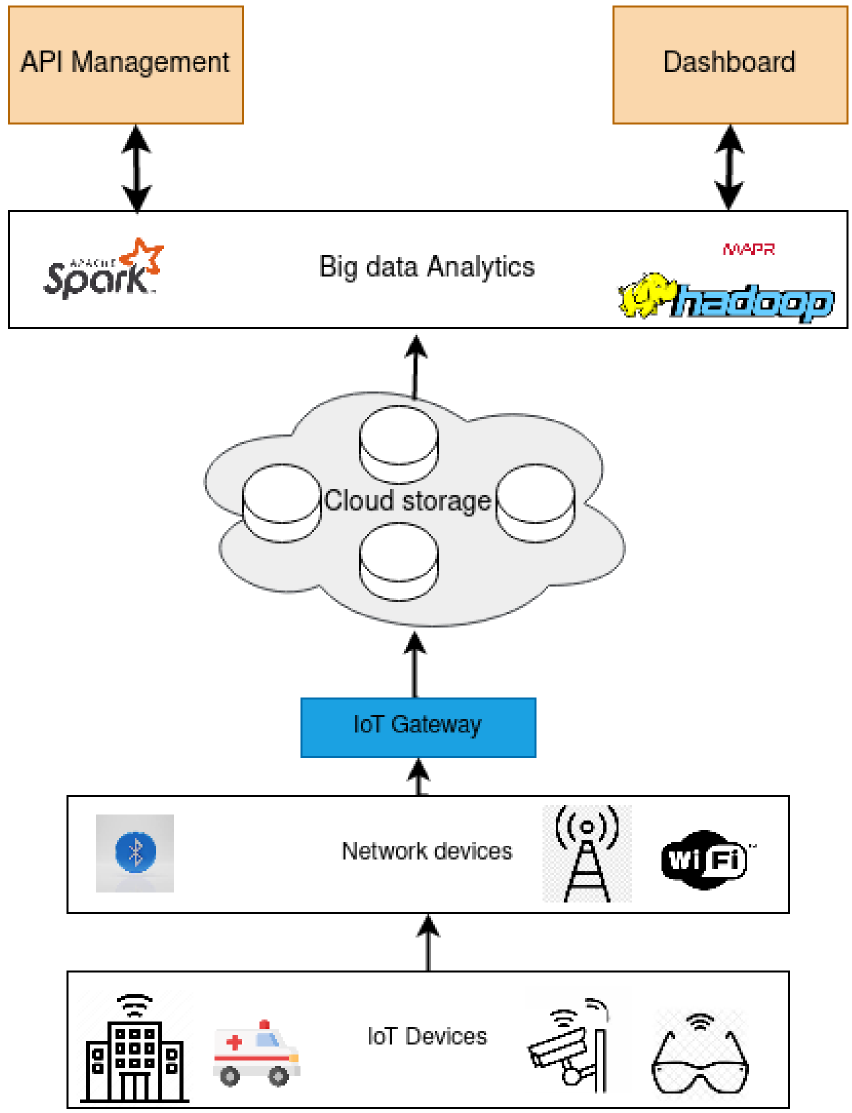

Figure 2.2: Architecture for big data analytics [14]

silicon costs per unit basis. Battery life and power management have become essential aspects of IoT systems. In many application scenarios, the sensors are deployed at locations far from power mains, and replacing batteries can be expensive. It has replaced the barrier of rigid physical systems with a vast array of 'edge devices' [18]. While handling data processing, the chips should be of small form factors and support multiple wireless standards. Thus, there is a need to balance power consumption with performance. With the constraints of a limited battery, the power consumption should be low while maintaining the minimum level of performance. The term 'low power' is a relative term. For example, iPhone 13 has a 3227 mAh battery which can last up to 14 hours. These specifications can satisfy a consumer using a mobile phone for daily affairs. However, they may not be suited for solar-powered IoT systems to monitor the oil and gas assets in vast oil fields. Thus, depending on the type of application, the minimum level of power consumption is set. There are modes of power for the operation of IoT sensors. The sensors can be set to 'idle' mode from 'active' mode when there is a slight variation in the observations, leading to less power consumption. Table 2.1 shows an example of a wireless sensor indicating the power consumption in different modes. Low-power wireless sensor networking (WSN) standards, particularly mesh architectures, utilize time-synchronized channel hopping (TSCH) to allot slots for every node in the network to use batteries or harvested energy without sacrificing reliability or data throughput [19]. It reduces the number of battery changes and the cost of deploying sensors by not running all the operations simultaneously. Further, dividing the operations into time slots can reduce power consumption. For a sensor estimated to work continuously with a life of 40 hours, one can turn the sensor on for only half a day and turn it off for the other half. Thus, we get 80 hours of battery life. Also, turning off some of the operations, say, the transmissions of signals from a transmitter on hold for later transmissions and allowing other operations like data buffering to run can extend the battery life up to 160 hours.

2. **Machine learning and Data Analytics**
   Many IoT devices provide a large amount of data. A forecast by International Data Corporation (IDC) estimates that there will be 41.6 billion IoT devices in 2025, capable of generating 79.4 zettabytes (ZB) of data [20]. For such a vast amount of Big data, the analysis and processing of data is necessary to provide various services. As stated in the Fig.2.2 from [21], there are steps to do big data analytics. In addition to huge volume, IoT data differs from standard data in terms of heterogeneity, space-time correlation, and noise levels [22]. IoT data requires a particular type of analytics, especially where the applications require high-speed streams and prompt actions. Autonomous driving and fire prediction are good examples of these applications. For resource-constrained IoT devices, it is imperative to reduce hidden layers or parameters of deep-learning-based neural networks for processing. With pruning, the models were compressed at least nine times for AlexNet and 13 times at VGG-16, while the accuracy of the models was almost preserved [22]. Also, new hardware platforms and accelerators make the training take less time and power. There is much work on making the processors with strong DL capabilities [23]. With the help of machine learning and analytics, along with access to the vast amounts of data stored in the cloud, businesses can gather insights faster and more efficiently. Industries can create new revenue and business models.

3. **Cloud computing platforms**
   IoT cloud services bring together the potential of IoT devices and cloud services for catering to the customers. With many devices providing big data, it is necessary to process it efficiently through various applications. The devices are connected to the cloud via gateways. To provide diverse applications, IoT cloud platforms can be built on top of generic clouds such as Microsoft Azure, Google Cloud, Amazon Web services, and many more. Some companies offer their cloud

platforms. Vodafone, AT&T, and Verizon have their cloud for network connectivity. Samsung is also offering its cloud service called ARTIK. The IoT cloud is implemented in three different ways [24]:

(a) Infrastructure-as-a-Service (IaaS)

(b) Platform-as-a-Service (PaaS)

(c) Software-as-a-Service (SaaS)

There are two kinds of IoT architectures observed. These are:

(a) Cloud centric:

Data processing from the devices is done at the servers in the data centers where all the analytics and decision making is done. The data centers also control the edge devices.

(b) Device centric:

Data processing is done on the devices only with minimal operations from the cloud for firmware updates.

As compared to traditional cloud computing, which provides on-demand access and services to clients with minimal effort, the IoT cloud computing platforms are more user-centric. In addition, to collect data, they adequately control the devices. It also includes changing the configuration of devices and allows the cloud platforms to scale to different kinds of real-time event processing for various devices. Thus, cloud platform availability enables businesses and consumers to scale up their infrastructure.

2.1.3 Challenges to IoT

Understanding and addressing the challenges for the long-term use of applications based on IoT is necessary. The following are the main challenges:

1. *Identity Management*
   For networks consisting of millions of nodes, it is necessary to identify the sensors and objects over the internet. It, in turn, leads to control over the devices and the selection of services to be provided by the system. A robust identity management system can assign unique identifiers to each object.

2. *Reliability*
   It denotes the success rate of IoT service reception. The communication network must be immune to failures or bit errors for high reliability. In other words, unreliable transmission leads to longer delays, data loss, and eventually wrong decisions, making the system less dependable.

Wireless Standard	Technology Type	Spectrum Type	IoT applications	Main Limitation
EC-GSM-IoT	Cellular	Licensed	mMTC	Temporary solution
Cat-M-LTE	Cellular	Licensed	mMTC	Temporary solution
MulteFire	Cellular	Unlicensed	mMTC	Lack of a strong business case
NR	Cellular	Licensed	URLLC and mMTC	Standardization phase not ended
NB-IoT	LPWAN	Licensed	mMTC	Lack of a strong business case
Sigfox	LPWAN	Unlicensed	mMTC	No alliance of companies behind
LoRaWAN	LPWAN	Unlicensed	mMTC	Constraints to international roaming

Table 2.2: LoRa IoT classification [14]

3. *Availability of services*
   To provide services to clients at any time and place, the IoT devices must be compatible with the other devices and responsive to the commands received for the several tasks.

4. *Mobility*
   One of the significant challenges to the services is the mobility of the users. There is an interruption of services when the devices move out of the coverage area of the internet. In such cases, data caching at the transmitter becomes necessary to send the data to the devices when the connection is re-established.

5. *Management*
   The large number of nodes providing services to service providers need continuous maintenance and monitoring, which light protocols can do. For example, the Lightweight M2M protocol provides an interface between M2M devices and servers to manage devices. NETCONF protocol installs the configuration and modifies the network devices [14]. Also, it is mandatory to maintain compatibility between various OSI model layers to enhance connectivity speed and the continuity of service delivery.

6. *Security and Privacy*
   There is a lack of architecture for IoT security. This feature is essential for the devices to communicate with each other. There is a need for control management so that the customer can read the data and malicious agents do not hack the network. The major problem is the distribution of keys among the devices. IETF's SOLACE has done some work in this regard.

2.1.4 IoT Standards

In order to drive the market of IoT, standards play an important role. They are necessary for providing scalability, reduced costs and integration for customers [25]. Some of the notable standards are as follows:

1. *Cellular Networks (GSM and LTE) for IoT*
   Though cellular technologies are not designed for mMTC commuication, 4G Long Term Evolution (LTE) and 2G(GSM) have the potential to cater to long range IoT. EC-GSM-IoT is the version of GSM designed for energy-constrained devices with extended coverage in uplink and downlink [25]. LTE Cat-M is another standard of 4G that works in any bandwidth with minimum of 6 Physical resource blocks (PRBs) in both downlink and uplink. Both of these standards are the temporary solutions for long-range IoT that can be merged into the 5G technology.

2. *NB-IoT*
   3GPP has developed a new standard called Narrowband-IoT (NB-IoT) for LoRa IoT. It is a Low-power wide-area network (LPWAN) standard on licensed spectrum band. It is obtained from LTE standard and provide services with low power consumption. Though it doesn't support LTE functions like handover, carrier aggregation and dual connectivity, it can be integrated into LTE carrier as a PRBs and also multi-carrier operation [25]. There is also a version of NB-IoT, released by MulteFire (MF) Alliance [26]. Used mainly in USA and European Union (EU), MF NB-IoT has synchronisation and broadcast channels, which are compliant with unlicensed band.

3. *Sigfox*
   Sigfox is unlicensed spectrum-band technology ,which creates a Sigfox network (SNW) connecting IoT nodes to an application server. It uses differential Binary Phase Shift Keying (BPSK) modulation in uplink and Gaussian frequency shift keying (GFSK) modulation in downlink. In uplink, the user equipment (IoT device) initiate the communication by sending the message to SNW. For more reliable communication, the uplink transmissions are repeated. In the bidirectional case, the device, after initiating the communication, sends an uplink message and receives the corresponding downlink message. Then the acknowledgement message is also sent by the device in return.

4. *LoRa and LoRaWAN*
   Long-range wide-area network (LoRaWAN) is another unlicensed spectrum standard maintained by LoRa Alliance . It is based on both Chirp Spread Spectrum (CSS) and Frequency shift keying (FSK) with bandwidths of either 125 kHz, 250 kHz, or 500 kHz for uplink channels and 500 kHz for downlink channels. The devices, communicating to the gateways in the Radio access network (RAN) of this standard, operate in three classes based on the modes of energy saving:

   (a) *Class A:* In this mode, the device goes into listening mode after uplink transmission is done.

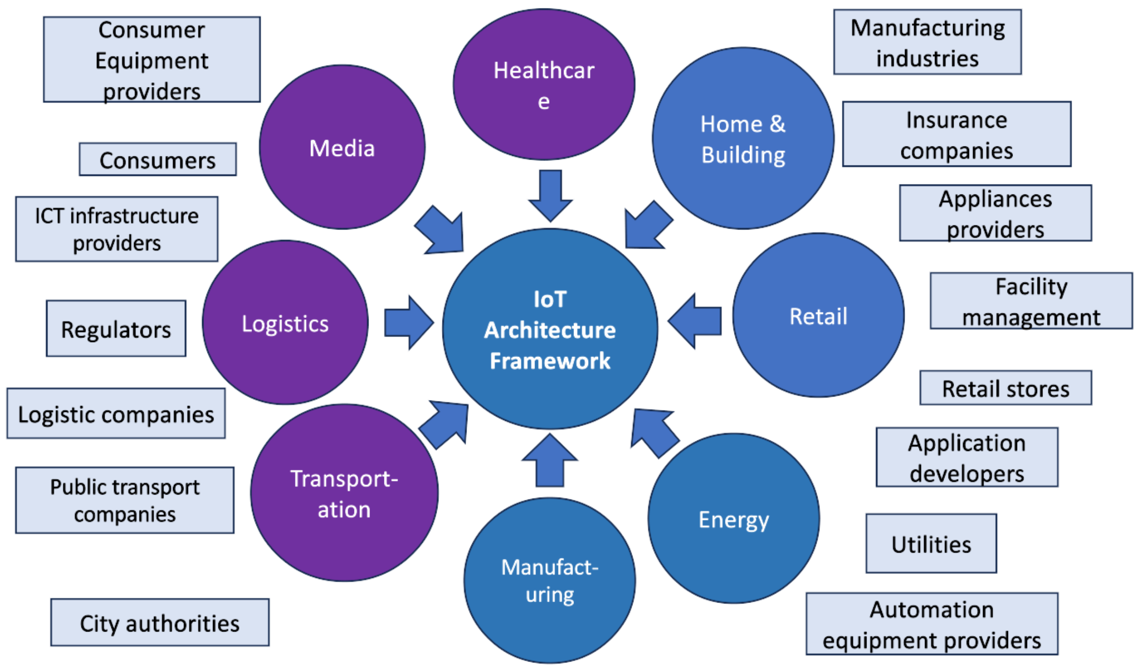

Figure 2.3: IoT applications [27]

(b) *Class B:* The gateways send beacons at periodic intervals for synchronization and activating them for reception.

(c) *Class C:* The device is always listening to the downlink channel when not in uplink.

After going through all the IoT standards, Table 2.2 from [14] gives an overview of long range IoT technologies and their limitations from [25].

2.1.5 Applications of IoT

IoT has found extensive applications in the consumer, industrial, and infrastructure fields. Fig.2.3 shows the overview of IoT applications in various sectors. Some of the applications are as follows:

1. *Home Automation*
   IoT devices comprise a significant part of home automation systems for lighting, air conditioning, temperature monitoring, CCTV surveillance, room temperature monitoring, and many more. Energy and resource savings can be done by automating most home appliances, like switching off lights when not in use, turning off the running taps, automatically turning off geysers after reaching the desired temperatures, and many more. Integrating this energy-efficient monitoring with the internet can make the buildings 'smart'. The category of intelligent appliances, which mobile apps can control, is becoming common in the market. Lenovo's wise home essentials and Samsung's SmartThings Hub are some of the products in this area.

2. *Medical and Healthcare*

   IoT devices can help significantly observe and supervise by planting sensors and actuators in patients or their medicines. Devices like Masimo Radius-7 provide updates and warn about critical changes in oxygen saturation, heart rate, respiratory rate, or hemoglobin which may indicate pulmonary, cardiac, or internal bleeding [28]. Remote health monitoring can store data of implants such as pacemakers, Fitbit electronics waistbands, or hearing aids. Using 'Smart beds' in hospitals has begun, which can sense whether the bed is occupied or the patient is attempting to get up. Health insurance companies can use data available from IoT devices to verify claims and assess health risks [29].

3. *Transportation systems*

   IoT systems require integration of computation and communication to make the transportation systems 'intelligent'. The key features of this system are to suggest the routes to the drivers with the least traffic; the drivers get real-time updates of a particular route; the traffic police get an update on live traffic and any violations captured by surveillance systems to check the number of accidents and smooth management of traffic flow. Sensor nodes that are installed in cars can transfer real-time data, such as vehicles' speed and accuracy state of drivers, which includes state of exhaustion, drunk driving, and so on, to a cloud computing administration center, which can help traffic administrators greatly in managing road traffic [30]. Sensor nodes can also be mounted on the ground to get traffic volume density, queue length, quality of air, and many more.

4. *Environmental monitoring*

   With increased industries and urban cities, there is a growing concern for air quality and environmental resource management. For air quality, IoT based solutions can monitor particulate matter (PM) levels, humidity, temperature, carbon dioxide, nitrogen dioxide, and other atmospheric indices. As per the news report [31], only 12% of India's census cities and towns have air quality monitoring stations. Thus, there is a scope for deploying IoT nodes in urban areas in the coming years. With the emergence of AI/ML, ongoing work has been improvising air pollution monitoring systems. [32] has shown the use of DL-based supervised learning methods to predict air quality by observing the live traffic images in the city. It can help us to deploy high-cost PM sensors at only selected locations in an area considering the spatial invariance property of the pollution data. For checking the water consumption in our houses, analog meters are used, which have to be set manually. The manual tasks can be automated by integrating AI/ML with the analog meters, and efficient management can be done as stated in [33].

5. *Smart city*

   Digital technologies are developing at a fast rate to engage effectively with citizens, reduce operational costs and minimize resource consumption. These technologies can lead to improvement in the operations of cities and resource optimization. Thus, the 'smart cities concept is developed to create a model to maximize revenues and optimize resource usage and asset management. 'Smart

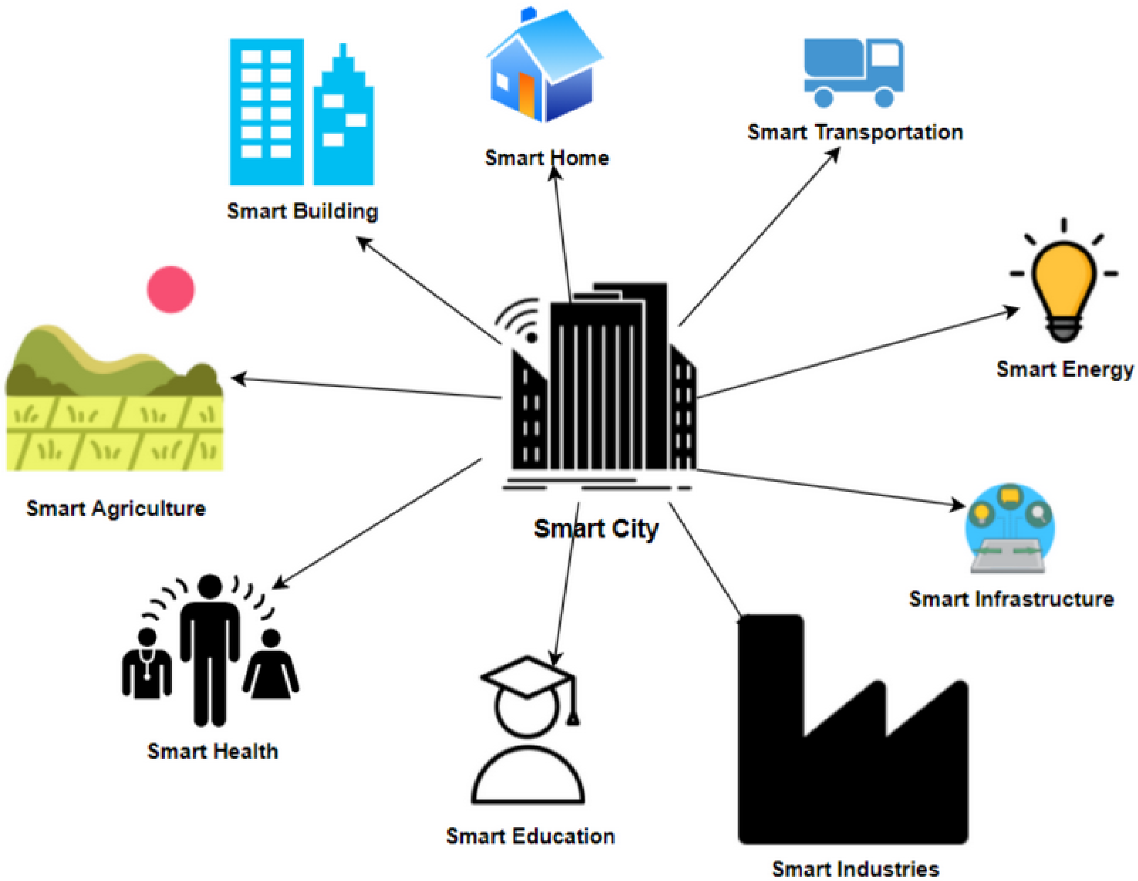

Figure 2.4: Smart city applications [34]

cities' can include city lighting, traffic, waste management, emergency services, tourism management, and many more as shown in Fig.2.4. For the development of smart cities, cloud computing plays an important role, which has been emphasized in [34].

2.2 Satellite-IoT Networks: A Brief Overview

This section introduces the satellite-based IoT networks and their significance. The architecture of satellite-IoT networks provides an insight into its components and the types of topology supporting the network. Then follows the discussion of the advantages of satellite networks over terrestrial networks. To develop satellite networks, the types of satellite constellations that can support IoT and the significance of LEO satellites are studied. The challenges to the satellite-IoT networks, the satellite-IoT protocols, the interference effects, and the types of relaying schemes are other important topics relevant to the section.

2.2.1 Introduction

The long-range terrestrial networks have led to increased applications where their deployment is essential. Their benefits of making the control automatic, low maintenance costs, and increase in responsiveness has made them prominent in the field of disaster management, healthcare, logistics tracking [35], mining, agriculture, air pollution monitoring [36], water quality measurement [37] or other labor-intensive areas. Also, there are cases when monitoring is required in remote or uninhabited regions. In applications like livestock tracking or navigation systems, there will be a requirement for high network reliability and availability over large areas. In such cases, the terrestrial network infrastructure may need to be more feasible and economically viable for deployment. Satellite-based networks are an alternative to terrestrial networks. It is found that around 15% of the earth's surface is covered by terrestrial networks [1]. Satellite networks can cover a large area and provide more than 99.9 % network availability [35]. Satellite-based networks are considered to provide global coverage to the IoT-based systems.

By using minimal resources for M2M networks, these networks can lower operational and business costs [10]. They are also used for remote sensing and applications like atmospheric monitoring, thus making them special sensing devices. Thus, the integration of satellite and terrestrial networks can give rise to a large number of applications. Also, with intelligent onboard processing, the satellites can reduce collisions and traffic congestion, thus making the networks more reliable. By caching the content for cell-edge users in cellular networks, scalable satellite networks can provide better Quality of Service (QoS).

2.2.2 Architecture:

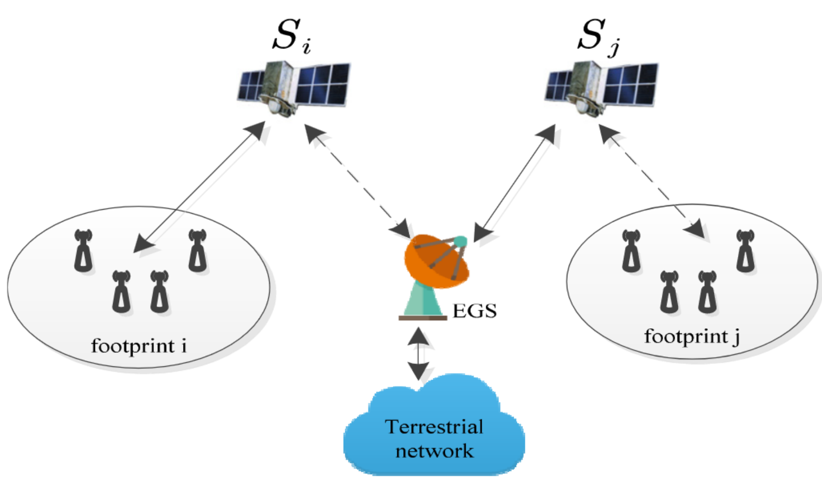

Figure 2.5: Satellite-IoT networks architecture [38]

In accordance with Fig. 2.5, a satellite IoT network has the following infrastructure components:-

1. *User equipments (UE)*

   These are IoT nodes located at various locations (as shown in Fig.2.5) like terrestrial offices, residences, and many more. Their characteristics will depend on the coverage area of the network.

2. *IoT gateways*

   The gateways have direct communication to the satellites. They can uplink the messages from UE and receive them in downlink. For example, the Ecuadorian Civilian Space Agency (EXA) has provided a Hermes-A/Minotaur gateway for connecting remote users (internet) to satellites (in orbit). The Hermes-A/Minotaur gateway converts data received into audio frequency(AF) and can be sent over the internet to the virtual GS at the user end. Only one remote user/virtual GS can gain access to Hermes-A. A virtual GS can be a free software suite, as discussed in [39].

3. *Satellites*

   The constellations of satellites like OneWeb, Starlink etc. covering the Earth's surface in different orbits form the major part of satellite-IoT networks. With the satellites moving at fast orbital speeds, the satellite on-board processing of received signals becomes complex due to Doppler spread. In [40], satellite visibility window estimation is done using the doppler measurement model.

4. *Ground stations*

   They are spread at various earth locations to detect satellite signals and send them via a gateway to the UE.

Based on the way IoT devices communicate with the satellites in the uplink, there are two types of satellite networks- Direct access and Indirect access satellite networks.

In Indirect access communication, devices communicate to the satellites via terrestrial relays. The benefits of such communication are that satellites can connect to end nodes with terrestrial gateways, with LPWAN or Sigfox protocols. Recently, indirect access deployment has gained more attention as it reduces the implementation cost with lesser satellite terminals compared with direct access deployment and requires every sensor to equip with a satellite terminal [41]. However, this system will largely depend on terrestrial coverage. As shown in Fig.2.6, LPWAN gateway has a radio interface to communicate to IoT nodes and satellite terminal for link with satellites. The gateway, in turn, connects to many end devices in its vicinity, but the coverage depends on the gateway. Also, the setting of terrestrial infrastructure in remote areas or areas with minimal monitoring will increase the cost of the system.

Direct access satellite networks have IoT devices communicating directly with the LEO satellites. It is known popularly as Direct-to-satellite (DtS) communication. The LEO satellites orbiting around the Earth can be considered gateways. For comprehensive coverage, there is a requirement for a large number of satellites and their compatibility with IoT protocols like Long-range wide-area network (LoRaWAN) and Narrowband-IoT (NB-IoT). The main challenges considered for the DtS connectivity are a low transmit power of IoT devices, a considerable distance for uplink, and a short communication window for the device-satellite link. Also, most of the existing satellites are not supporting direct

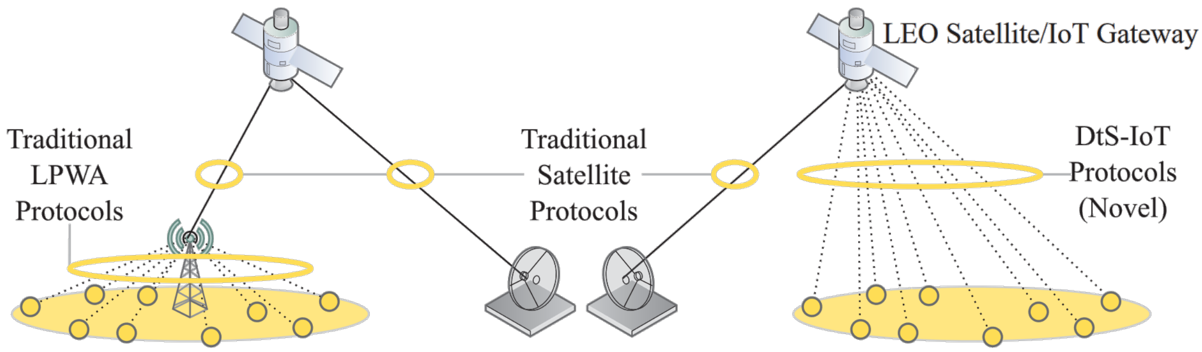

Figure 2.6: Direct vs Indirect topologies [43]

satellite-to-device connection [42]. Lacunasat-I and Enxanet provide interoperability with LoRaWAN or NB-IoT protocols and direct-to-satellite connectivity to IoT devices [43]. Recently, Qualcomm has also launched Qualcomm 212S Modem and the Qualcomm 9205S modem chipsets with DtS support for applications like monitoring water tanks, livestock monitoring, supply chain management, and many more [44]. In [45], DtS technology has been used for a soil moisture measurement system. There has been progressive work to meet the challenges to DtS communication. The feasibility of DtS-IoT communication is presented in [43]. There are devices in the market like Astrocast [46] and Lacuna Space [47]. In addition to this, there is an aggregator model, which is a variant of DtS satellite-IoT model [42]. As shown in Fig. 2.7, the devices, called aggregators, collect the data from various surrounding sensors via WiFi, Bluetooth, ZigBee, or other protocols and send the data directly to satellites. The aggregators are powered mostly by solar panels and can be deployed on any stationary or mobile platform. They support two-way communication as they can receive data from satellites also.

In discussions with various stakeholders in the IoT industry, it was concluded that the above architectures or their combinations should be freely used by service providers with flexibility [42]. Factors like cost, capacity, and latency of satellite terminals should determine the type of topology used for satellite-IoT. The selection should also be made on the type of use cases, like agriculture or mining; several devices can aggregate the sensory information and communicate directly to the gateway through satellites. For disasters or natural calamities, the DtS technology is beneficial as the deployments need to be fast and not hardware constrained.

2.2.3 Comparison with terrestrial networks

The comparison of satellite-IoTs with terrestrial IoT is done in the following way:

1. *Coverage Area*
   Satellites at higher altitudes provide higher coverage areas than base stations in terrestrial networks. It provides coverage in less populated areas and is inaccessible to the terrestrial infrastructure. In contrast, terrestrial networks are mainly concentrated in remote or urban areas.

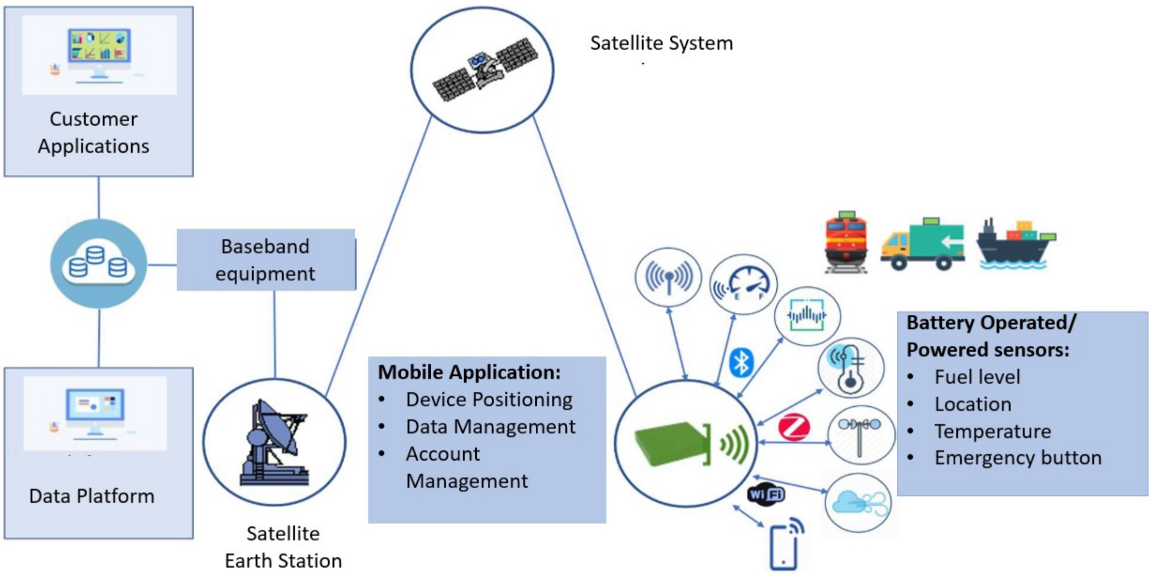

Figure 2.7: Aggregator model [42]

2. *Uplink Capacity*
   In areas where terrestrial networks are not set up, satellite networks provide more uplink capacity than terrestrial networks. They are used for industries like oil and gas, environmental monitoring, etc. They are less vulnerable to natural disasters and infrastructural failures than terrestrial networks.

3. *Spectrum Availability*
   Organisations like International Telecommunication Union (ITU) have allocated specific Ku and Ka bands for transmission. Thus, using these spectrum bands for satellite communication relatively minimizes interference, similar to licensed-spectrum mobile networks. The spectrum bands availability of satellite IoT provides more roaming support than the terrestrial ones. However, many satellites launched are using ISM bands or other bands.

4. *Data Rates*
   The data rates for satellite-IoT are relatively low, in the order of kbps, compared to cellular networks' capacity in the range of Mbps.

2.2.4 IoT supporting satellites

There are three main types of satellites supporting the IoT depending on the altitude and the shape of the orbit of the satellites: Low-earth-orbit (LEO), Medium-earth-orbit (MEO), and Geostationary-earth-orbit (GEO) satellites. Fig. 2.8 shows satellites orbiting around the Earth at different altitudes.

1. *LEO satellites*

   These satellites are between 160 km and 1000 km from the Earth's surface. They travel at a much faster speed in orbit than their counterparts. For this reason, it is tough to keep track of the satellite in orbit. Thus, these satellites form a constellation around the Earth. The number of satellites in a constellation determines their quality of connectivity with IoT devices. When there are many satellites in orbit, there are fewer chances of signal interruptions and more coverage. The signals to satellites can be low-powered as they have to travel a lesser distance, and the latency is also comparatively low. It also implies that the path loss of the signals from the IoT devices will be smaller than the other kinds of satellites due to lesser altitude. The LEO systems use higher frequencies (Ku-band and Ka-band), thus offering a much-increased bandwidth, and take advantage of the reduced launch costs and cheaper satellites that are available now. Lower costs can lead to massive increases in user data rates and system traffic capacity [48]. For the satellite-IoT systems, LEO constellation satellites are preferable over GEO constellations. Several new initiatives on mega-constellations of small satellites in LEO are taken. The most well-known frontrunners are OneWeb and StarLink, but many others aim to make similar systems, for example, LeoSat, Telesat (Canada), and Honyan (China).

2. *MEO satellites*

   MEO satellites orbit the earth at a higher altitude than the LEO satellites and lower than GEO satellites. At 8000 km, MEO can cover 96% of the Earth's surface with low latency and high thought up to multiple gigabits [49]. Thus, they provide higher coverage and require fewer satellites than LEO satellites. These orbits can be used in outages due to extreme weather and obstructive objects. This orbit has been used for Global Positioning System (GPS), Global Navigation Satellite System (GLONASS), Galileo, and BeiDou.

3. *GEO satellites*

   GEO satellites revolve around the Earth at the same speed as that of the Earth. Due to higher altitude, they have high coverage area and need few satellites to cover the Earth. GEO satellites are considered 'stable' due to their longer life span. They continuously update their firmware and remain operational for a long time. However, they need maintenance at regular intervals. Due to longer orbits, the data has to travel farther distances, and latency is high. However, this usually equates to 2 seconds, thus making them suitable for IoT [50].

2.2.5 Challenges to Satellite-IoT networks

The LEO-based satellite-IoT networks are quite different from terrestrial networks. Thus, the protocols and access methods for terrestrial networks cannot work for satellites. There are some notable challenges to the interaction of IoTS with satellites as follows:

1. *Massive number of connections*

   The number of devices demanding services are large. However, at a time, only a fraction of the

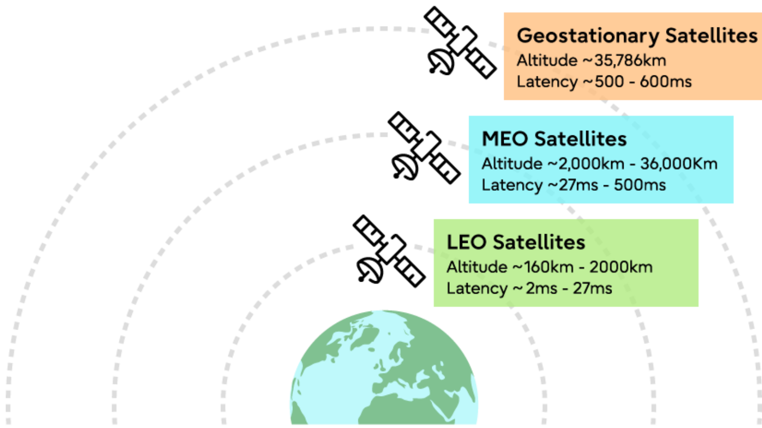

Figure 2.8: Orbits of different satellites [51]

number of devices are active. The satellites must identify the active devices and thus conserve energy by communicating only with active devices. The satellites perform this operation through multiple negotiations, leading to signaling overhead. Also, there is a limited spectrum, and many devices' orthogonal data transmissions over the channel are limited.

2. *Wide coverage*
Satellites benefit from comprehensive coverage over terrestrial networks using multi-beam techniques. However, a beam can serve only one device at a time; otherwise, it leads to co-channel interference. The second challenge is that the scenarios in which there is the deployment of devices range from forests, oil fields, oceans, and deserts, which leads to significant variations in a channel to the satellite, complicating the precoder design for beams, especially with partial capturing of Channel State Information (CSI). Thus, for broad coverage, the precoder design becomes complex.

3. *High Mobility*
LEO satellites orbit around the earth at a swift rate. It causes the channel to fade quickly and the CSI available at the satellites to be outdated. The Doppler and phase impairments can degrade the reception at satellites. The fast varying channel also causes satellites to support only short-time services.

4. *Low Power*
The transmit power of small-sized IoT devices is 23-26 dBm. In addition to this, path loss and atmospheric attenuation can further degrade the quality of signal reception. With larger Round Trip Time (RTT), the wake-up period of the devices gets longer, leading to more significant power consumption. It could prevent the longer duration of batteries. Also, the LEO satellites with small payloads have hardware constraints, and the processing algorithms with high power consumption can degrade the performance of the satellites.

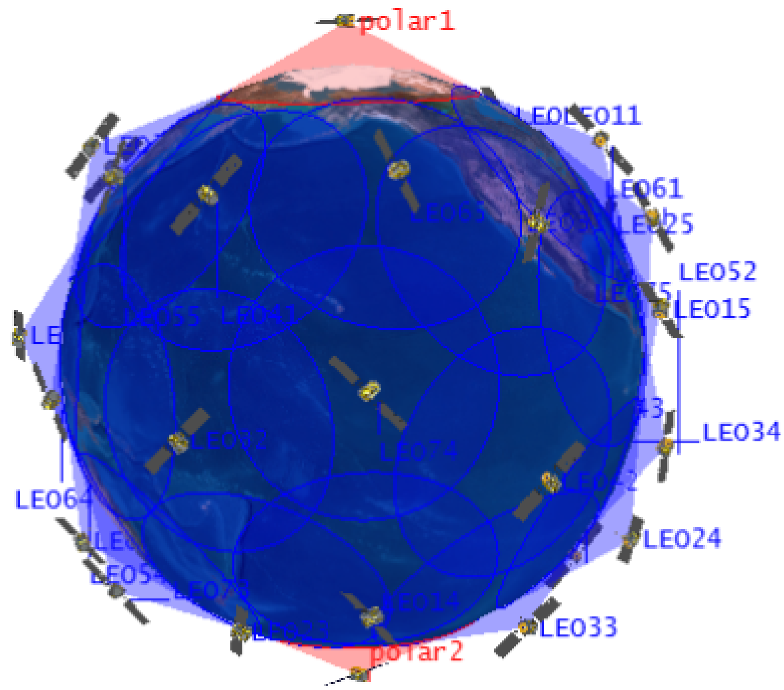

Figure 2.9: LEO satellites [52]

2.2.6 Satellite-IoT protocols

The major focus of IoT protocols is to provide interoperability between satellites and IoT sensors. For the satellite-IoT, there is ongoing work to design protocols for supporting communication. For this, there is a prime focus on developing Medium Access Control (MAC) protocols and supporting IPv6 over the internet [53].

1. *MAC protocols*

   The sensor nodes used for various applications generate the data periodically or event-based. Proper data transmission requires multiple-access schemes that utilize satellite resources efficiently. Time division multiple access (TDMA) can be considered as it gives energy efficiency, but due to random data transmissions, it is unsuitable [53]. IoT devices use random access (RA) protocols, as the devices do not require coordination to access the communication channel. DVB-RCS2 standard provides Multi-frequency TDMA (MF-TDMA) access with contention-free and contention-based access [53]. In DVB-RCS2, slotted-Aloha and Contention resolution diversity slotted Aloha (CRDSA) provide random access. Slotted Aloha will suit burst traffic sources with end-to-end delay. Some of the applications of slotted Aloha are suggested in machine-to-machine communication with the satellites, where Spread Spectrum Aloha(SSA) with Direct Sequence Spread Spectrum (DSSS) has been considered suitable [54]. Long range (LoRa)'s adaptation to satellite networks in the form of Symmetric Chirp signal (SCS) in place of chirp spread spectrum(CSS) has been studied in [55], and its further revision to Asymmetric Chirp signal(ACS) with better cross-correlation is proposed in [56]. In [57], a performance analysis for a system simulator involving LoRa signals transmitted to a central server via satellites is shown. In CRDSA, timeslots combine to form a frame. The frame is sent multiple times, and time slots are selected randomly [58]. In a particular slot, the transmission of different frames leads to collisions.

2. *IPv6*

   The IPv6 protocol has ample address space to provide the IP address to the IoT devices. DVB-RCS2 is compatible with IPv6. It is widely used for terrestrial networks. The main challenge is to modify it for the networks over satellites. The solution is tunneling [53]. Tunneling helps encapsulate the IPv6 packets into IPv4. It, however, generates overhead.

2.2.7 Interference effect

Since the visible LEO satellites have large coverage area, the packets from multiple devices can be simultaneously received, causing interference.In urban or sub-urban areas, the bandwidth for transmission is limited, and the number of devices is large; thus, for each frequency band, multiple sources will be accessing the channel. For the downlink from satellites, it is shown in [59] that the throughput of a satellite link can be improved for the GEO satellites with the repetitions of the data packets and iterative use of SIC. The throughput will be further improved for power unbalances in the case of SIC. In the thesis, we are considering LEO satellites and avoiding the repetition of packets to get higher data rates.

2.2.8 Relaying schemes

For satellite-IoT networks, the communication between IoT nodes and gateway is done via satellites. Satellites relay the data to the destination and provide multiple paths for propagating symbols. From now onwards, we will use satellites and relays interchangeably. The signals received at the GS depends on the type of processing at the satellites. Based on that, the forwarding schemes used at the relays can be classified into fixed relaying schemes and adaptive relaying schemes [9].

In fixed relaying, the channel resources are divided equally between the source and relays if the source has direct line-of-sight (LoS) links to the destination in a network. In a fixed Amplify-and-forward (AF) scheme, the received signals are scaled at the relays and then transmitted to the destination. Though the gain at the relayed equalizes the effect of channels from the source to the relays, it also amplifies the noise at the relays and causes erroneous signals at the destination.

Another type of scheme is to decode the signal at the relays, re-encode it and transmit it to the destination. Such a scheme is termed a fixed decode and forward scheme. Compared to AF relaying, though the scheme reduces the effect of received noise at the relays, it may still lead to erroneous signal detection at the destination. Thus, the system's performance is limited by the worst link from the source-relay and relay-destination [9]. It leads to the diversity gain of one. So, for improving the diversity, the

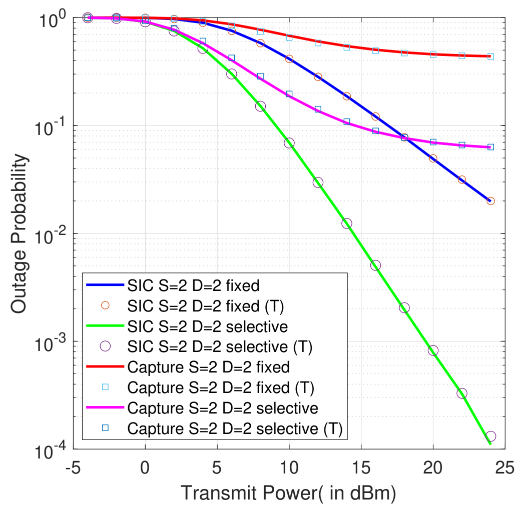

Figure 2.10: Comparison between selective DF and Fixed DF for $D = 2$ and $S = 2$ system model over varying transmit powers of IoT nodes

adaptive relaying schemes are used [9]. Selective and incremental relaying schemes are considered adaptive relaying schemes.

The selective DF scheme is considered at all relays in our system model. In a selective DF scheme, if the Signal-to-Noise ratio (SNR) of a signal received at the relay exceeds a certain threshold, the relay decodes the received signal and forwards the decoded information to the destination. If the SNR of the signal falls below the threshold, the relay idles. The selective DF scheme improves upon the fixed DF scheme in the sense that the erroneous signals are not forwarded to the destination in the former. It is clearly shown with the results in Fig.2.10 how the performance of selective DF is better than that of fixed DF for the system of two users and two satellites with interference mitigation.

Chapter 3

System Model, Performance Analysis and Results

This chapter discusses the system model for satellite-IoT networks. Multiple devices are sending the signals to the satellites. To overcome the interference from the multiple devices, the capture-based selective DF and SIC-based selective DF schemes are introduced and applied in the system model. For the capture-based analysis, the probability density function (PDF) for the sum of channel gains for iid and inid cases are also found. The description of our system model is followed by the end-to-end OP analysis for the system model for both capture and SIC cases. The result section highlights the comparison between capture and SIC-based models. Also, the theoretical results match the simulations.

3.1 System Model

A LEO satellite-based IoT network is considered such that D devices $(d = 1, 2, ..., D)$ transmit simultaneously to S satellites utilizing a single resource block as per the slotted-ALOHA scheme similar to the case shown in [60].All the channel resources are allocated to the relays as we assume source-destination line-of-sight (LoS) links to be highly attenuated due to the large distance between them. In Fig.3.1, all the D devices have direct-access communication to the S LEO satellites $(s = 1, 2, ...S)$. For mathematical tractability, it is assumed that D and S remain constant for every slot. The end-to-end transmission takes place in two phases. In the first phase, the received signal (y_s) at the s^{th} satellite, transmitted from the D IoT devices, can be written as

$$y_s = \sum_{d=1}^{D} \sqrt{P_d\, r_{ds}^{-\alpha}} h_{ds}\, x_d + w_s, \tag{3.1}$$

where P_d is the transmit power of the d^{th} device, h_{ds} denotes the shadowed-Rician (SR) channel from the d^{th} device to the satellite s, x_d is the unit energy information signal, r_{ds} is the distance from the device to the satellite with the path loss exponent α, and w_s is the additive white Gaussian noise (AWGN) with mean zero and variance $\sigma^2_{w_s}$.

In the second phase, the satellites forward the decoded messages of the device as per the selective DF scheme to the GS using dedicated orthogonal resources without interference. The received signal

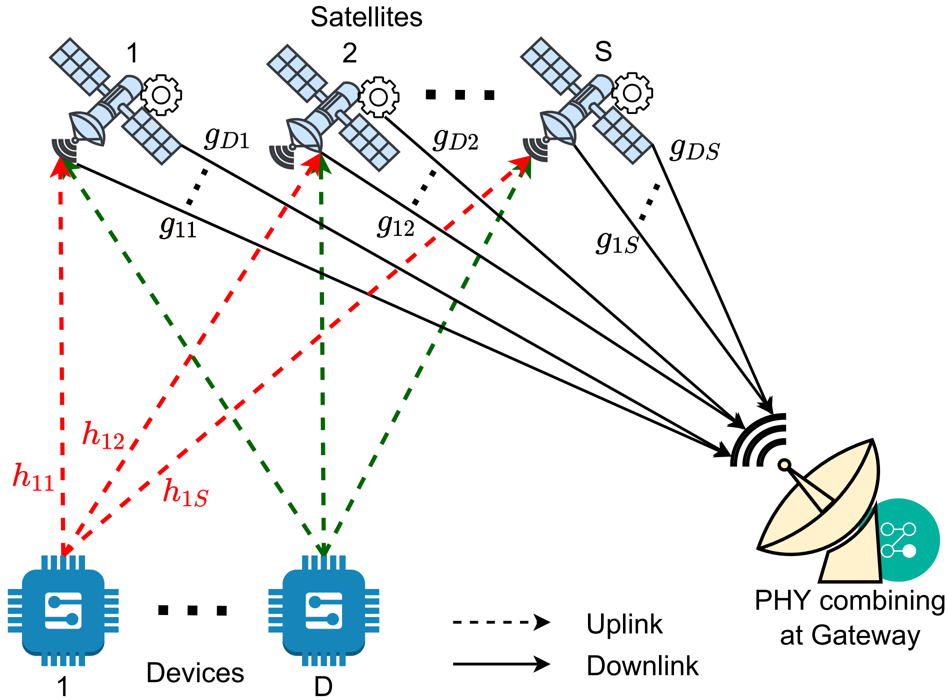

Figure 3.1: Considered system model.

(z_{ds}) at the GS corresponding to the d^{th} device and s^{th} satellite can be written as

$$z_{ds} = \sqrt{P_s \, r_s^{-\alpha}} \, g_{ds} \, u_{ds} + {w_s}', \tag{3.2}$$

where P_s is the transmit power of the satellite s, g_{ds} denotes the iid shadowed-Rician (SR) channel, r_s is the distance from the satellite s to the GS with the path loss exponent α, u_{ds} is the unit energy signal forwarded by the s^{th} satellite and ${w_s}'$ is the AWGN noise with mean zero and variance $\sigma^2_{w'_s}$. The messages from each satellite for a device d are combined using the MRC scheme at the GS in a single slot. To incorporate the effect of device locations on the channel fading condition, both iid and inid channels for the uplink are considered. However, it is assumed that the links from all the satellites to the GS are iid. Additionally, to keep the analysis focused on the topology, it is assumed that perfect Channel State Information (CSI) is available at the satellites and the GS. It is considered that the devices are located in a small region such that the inter-device distances are negligible compared to the distances, r_{ds} and r_s, from the devices to the satellites and satellites to GS respectively. Thus, we can approximate r_{ds} and r_s to be same for each device. Keeping in mind the low complexity of IoT devices and design for a common application, we assume the transmission power P_d to be equal for all the devices.

In this system model, one of the major challenges is intra-system interference. This interference is caused by the carriers transmitted by the $(D-1)$ IoT devices to the carrier of the desired device in the allocated resource block. It is mainly the co-channel interference [10] To overcome this interference, two decoding schemes are proposed.

3.1.1 Capture-based selective decode-and-forward

It is basically, the *capture effect* [61] where the strongest signals are decoded even in the presence of interference due to other devices. In a capture-based selective DF scheme, the satellites calculate the received signal-to-interference-plus-noise ratio (SINR) for a device by considering the signals from other devices as interference. Thus, the SINR for decoding any arbitrary device at the satellite can be written as

$$\gamma_{ds}^{\text{cap}} = \frac{H_{ds}}{\sum\limits_{\substack{p=1 \\ p\neq d}}^{D} H_{ps} + 1}, \tag{3.3}$$

where, $H_{ds} = \frac{P_d}{\sigma_{w_s}^2}|h_{ds}|^2 r_{ds}^{-\alpha} = \eta_d |h_{ds}|^2$ represents the instantaneous SNR of the device-satellite link with $\eta_d = \frac{P_d}{\sigma_{w_s}^2} r_{ds}^{-\alpha}$.

3.1.2 SIC based selective decode-and-forward

SIC is an orderly scheme where the satellites decode the information signals from various devices in the decreasing order of their SINR [62]. The device with the greatest SINR is decoded first, provided its SINR is greater than a given threshold. The decoded signal is then reconstructed and subtracted from the received superimposed signal as in (3.1). The resultant signal is used to decode the next best device. The decoding continues till the SINR of the signal for a device is less than the threshold or signals for all the devices are successfully decoded. For example, at the s^{th} satellite, if the devices are considered to be ordered such that $H_{1s} \geq H_{2s} \cdots \geq H_{Ds}$, then the SINR of an arbitrary l^{th} device in the ordered decoding can be written as

$$\gamma_{ls}^{\text{SIC}} = \begin{cases} \frac{H_{ls}}{\sum\limits_{d=2}^{D} H_{ds}+1}, & l = 1, \\ \frac{H_{ls}}{\sum\limits_{d=l+1}^{D} H_{ds}+1}, & \gamma_{(l-1)s}^{\text{SIC}} \geq \gamma_0, \forall 1 < l < D, \\ H_{Ds}, & \gamma_{(D-1)s}^{\text{SIC}} \geq \gamma_0,\ l = D. \end{cases} \tag{3.4}$$

The decoding order changes as per the instantaneous CSI at the satellites in our system.

The SNR of the received signal in (3.2) at the GS can be written as

$$G_{ds} = \begin{cases} \frac{P_s}{\sigma_{w_s'}^2} r_s^{-\alpha} |g_{ds}|^2 = \eta_s |g_{ds}|^2, & \gamma_{ds}^{\text{cap}} \text{ or } \gamma_{ds}^{\text{SIC}} \geq \gamma_0 \\ 0, & \text{otherwise}, \end{cases} \tag{3.5}$$

where $\eta_s = \frac{P_s}{\sigma^2_{w'_s}} r_s^{-\alpha}$. If there are n satellites forwarding to the GS, then by MRC diversity scheme, the SNR of the resultant signal for the device d at the GS can be written as $\Psi_d(n) = \sum_{s=1}^{n} G_{ds}$.

3.1.3 Related Works

In our system model for satellite-IoT, we are using one of the most popular relaying schemes of DF, where satellites relay the information from IoT devices to the GS. There have been several papers on the DF relaying in terrestrial communication [63–65] and satellite communication [66, 67]. In [63], the OP is derived for selective DF relaying for the case with multiple interferences at relays and the destination where the channels are considered inid with Nakagami fading. In [64], the OP is derived for fixed DF relaying for the case with multiple interferences at the single relay and the destination where the channels are considered independent and identically distributed with Weibull fading. In addition to relays, there is also a direct link from source to destination. A similar system model is used in [65] with optimum combining. However, only one source is considered in [63–65]. In [66], the OP is derived for satellite-IoT scenario, where one source is transmitting to multiple satellites with amplify-and-forward (AF) relaying. However, none of the works in [63–66], consider multiple sources sharing the same channel in an uncoordinated fashion, which will be a common scenario in extensive IoT network and is the focus of this thesis.

The most related prior work in satellite-IoT to our work is [67], where multiple IoT devices transmit to multiple satellites using slotted ALOHA. Instead of actual channels, the uplink and downlink channels are modeled using erasure collision channel with the same probabilities of success and failure. On the other hand, the analysis in our work is done on actual channel models and is applicable to even non-identical uplink channels. Moreover, our work is applicable to more than two IoT devices which is not the case in [67], where the collision happens if more than one message of the same priority (critical and non-critical) arrives at the satellite.

3.1.4 Statistical characteristics of channel model

The SR fading models is used for characterizing the satellite communication links [68]. The PDF and cumulative distribution function (CDF) of the weighted squared shadowed-Rician (SSR) $H_{ds} = \eta_d |h_{ds}|^2$, where $d \in \{1, 2, \ldots, D\}$ denoting devices and $s \in \{1, 2, \ldots, S\}$ denoting satellites are given, respectively, by [69]

$$f_{H_{ds}}(z) = \alpha_{ds} \sum_{\kappa=0}^{m_{ds}-1} \frac{\zeta(\kappa)}{\eta_d^{\kappa+1}} z^{\kappa} e^{-\left(\frac{\beta_{ds}-\delta_{ds}}{\eta_d}\right) z}, \tag{3.6}$$

$$F_{H_{ds}}(z) = 1 - \alpha_{ds} \sum_{\kappa=0}^{m_{ds}-1} \frac{\zeta(\kappa)}{\eta_d^{\kappa+1}} \sum_{p=0}^{\kappa} \left(\frac{\beta_{ds}-\delta_{ds}}{\eta_d}\right)^{-(\kappa+1-p)} \frac{\kappa!}{p!} z^p \, e^{-\left(\frac{\beta_{ds}-\delta_{ds}}{\eta_d}\right) z}, \tag{3.7}$$

where $\alpha_{ds} = ((2b_{ds}m_{ds})/(2b_{ds}m_{ds}+\Omega_{ds}))^{m_{ds}}/2b_{ds}$, $\beta_{ds} = 1/2b_{ds}$, $\delta_{ds} = \Omega_{ds}/(2b_{ds})(2b_{ds}m_{ds}+\Omega_{ds})$ and $\zeta(\kappa) = (-1)^{\kappa}(1-m_{ds})_{\kappa}\delta_{ds}^{\kappa}/(\kappa!)^2$ in which $(\cdot)_{\kappa}$ is the Pochhammer symbol [70]. Here, $2b_{ds}$ denotes the average power of the multipath component, m_{ds} is the Nakagami-*m* parameter and Ω_{ds} is the average power of the Line-of-sight (LOS) component. The probability density function (PDF) of the sum of n iid squared shadowed-Rician (SSR) random variables is given in [71]. Considering that all the visible satellites are part of the same constellation, η_s can be assumed to be the same for each satellite-GS link such that η_s=η. Therefore, the cumulative distribution function (CDF) of $\Psi_d(n) = \eta \sum_{s=1}^{n} |g_{ds}|^2$ can be derived as

$$F_{\Psi_{d(n)}}(z) = \sum_{p=0}^{(m_n-n)} \frac{(m_n-n)!\,(2bm_n)^{m_n-p-n}\,(2bm_n+\Omega_n)^{n-m_n}\,\Omega_n{}^p}{(m_n-n-p)!\,p!\,(n+p-1)!}\Gamma\left(p+n, \frac{z\,m_n}{\eta(2bm_n+\Omega_n)}\right), \tag{3.8}$$

where $m_n = n \cdot m$, $\Omega_n = n \cdot \Omega$, (m, b, Ω) are the parameters of individual SSR random variables and $\Gamma(\cdot)$ is the lower incomplete Gamma function as given in Eq. (8.350.10) of [70].

Proof: The PDF of the sum of n iid SSR random variables is given [71] as follows. Considering $\varphi(n) = \sum_{s=1}^{n} |g_{ds}|^2$

$$\begin{aligned} f_{\Psi_{d(n)}}(y) &= \left.\frac{f_{\varphi(n)}(\varphi)}{\eta}\right|_{\varphi=\frac{y}{\eta}} \\ &= \frac{(2bm_n)^{m_n}\,y^{n-1}\exp\left(\frac{-y}{2\eta b}\right)}{(2bm_n+\Omega_n)^{m_n}\,\eta^n(2b)^n(n-1)!}\,{}_1F_1\left(m_n; n; \frac{\Omega y}{(2bm_n+\Omega)}\right) \end{aligned}$$

The CDF $F_{\Psi_{d(n)}}(z)$ is given as,

$$\begin{aligned} F_{\Psi_{d(n)}}(z) &= \int_0^z f_{\Psi_{d(n)}}(y)\,dy \\ &= \sum_{p=0}^{(m_n-n)} \frac{(m_n-n)!(2bm_n)^{m_n-p-n}\,(2bm_n+\Omega_n)^{n-m_n}\,\Omega_n{}^p}{(m_n-n-p)!\,p!\,(n+p-1)!}\Gamma\left(p+n, \frac{z\,m_n}{\eta(2bm_n+\Omega_n)}\right) \end{aligned}$$

3.2 Outage Probability Calculation

For the ease of understanding, the OP for a two-user, two-satellite system is discussed initially and then generalised later. The OP for any device can be written as,

$$\begin{aligned} &P_{\text{out},d}(\gamma_0) = P(\text{both satellites in outage}) + P(\text{both satellites forward, GS in outage}) \\ &+ P(\text{S1 forward, S2 in outage, GS in outage}) + P(\text{S2 forward, S1 in outage, GS in outage}), \end{aligned} \tag{3.9}$$

where, $\gamma_0 \triangleq (2^{\frac{R_d}{B}} - 1)$ is the threshold SINR for the desired rate R_d and the bandwidth B. The probability terms in (3.9) are generic and need to be calculated separately for capture and SIC-based decoding schemes as per (3.3) and (3.4). Since all the devices can encounter different channel conditions equally likely, the OP for all the devices will be the same. Hence any device can be used as a reference for calculating the closed-form expressions. The closed-form expressions for the end-to-end OP are derived in the subsequent sections for capture and SIC-based schemes.

3.2.1 OP in case of capture-based decoding

The SINRs of the received signals at both the satellites are independent. Hence, using (3.3) and (3.9), the OP for a device (say $d = 1$) in a 2-device and 2-satellite system using capture-based decoding at the satellite can be written as

$$P^{\text{cap}}_{\text{out},d=1}(\gamma_0) = P(\gamma^{\text{cap}}_{11} \leq \gamma_0)\, P(\gamma^{\text{cap}}_{12} \leq \gamma_0) + P(\gamma^{\text{cap}}_{11} > \gamma_0)\, P(\gamma^{\text{cap}}_{12} > \gamma_0)\, P(\Psi_1(2) \leq \gamma_0) \\ +\ P(\gamma^{\text{cap}}_{11} > \gamma_0)\, P(\gamma^{\text{cap}}_{12} \leq \gamma_0)\ P(G_{11} \leq \gamma_0) + P(\gamma^{\text{cap}}_{11} \leq \gamma_0)\, P(\gamma^{\text{cap}}_{12} > \gamma_0)\, P(G_{12} \leq \gamma_0), \quad (3.10)$$

where $P(\gamma^{\text{cap}}_{11} \leq \gamma_0)$ can be calculated using theorem of transformation of random variables as [72]

$$\begin{aligned} P(\gamma^{\text{cap}}_{11} \leq \gamma_0) &= P\left(\frac{H_{11}}{H_{21}+1} \leq \gamma_0\right) \\ &= \int_{x=0}^{\infty} F_{H_{11}}\left(\gamma_0(x+1)\right) f_{H_{21}}(x)\, dx \\ &= \alpha_{11}\,\alpha_{21} \sum_{k_1=0}^{m_1-1}\sum_{k_2=0}^{m_2-1} \frac{A\, k_1!\, k_2!}{{B_1}^{k_1+1}{B_2}^{k_2+1}} - \alpha_{11}\,\alpha_{21}\, e^{-\gamma_0 B_1} \times \\ & \sum_{k_1=0}^{m_1-1}\sum_{k_2=0}^{m_2-1}\sum_{l=0}^{k_1} \frac{A\, k_1!\, \gamma_0^l}{l!\, {B_2}^{k_1-l+1}} \sum_{n=0}^{l} \frac{\binom{l}{n}(k_2+n)!}{[B_2+B_1\gamma_0]^{k_2+n+1}}. \end{aligned} \quad (3.11)$$

In the above equation, $A = \frac{\zeta_1(k_1)\,\zeta_2(k_2)}{\eta_d^{k_1+k_2+2}}$, $B_d = \left(\frac{\beta_d-\delta_d}{\eta_d}\right)$ for $d \in \{1,2\}$ and the integral is solved using Eq. (3.351.1,3.351.2) of [70]. The probability term $P(\gamma^{\text{cap}}_{12} \leq \gamma_0)$ can also be calculated following similar steps. Further, we can write $P(\gamma^{\text{cap}}_{11} > \gamma_0) = 1 - P(\gamma^{\text{cap}}_{11} \leq \gamma_0)$ and $P(\gamma^{\text{cap}}_{12} > \gamma_0) = 1 - P(\gamma^{\text{cap}}_{12} \leq \gamma_0)$. The other terms in the (3.10) can subsequently be calculated as: $P(G_{1s} \leq \gamma_0) = F_{G_{1s}}(\gamma_0)$ for $s \in \{1,2\}$ using (3.7) and $P(\Psi_1(2) \leq \gamma_0) = F_{\Psi_1(2)}(\gamma_0)$ using (3.8). Upon finding the above terms, closed-form expression for (3.10) is obtained.

The end-to-end OP can be generalised for the D devices and S satellites capture-based system. For a device d at a satellite s, the interference from remaining $(D-1)$ devices is denoted as $\Delta^s_d = \sum\limits_{\substack{i=1 \\ i\neq d}}^{D} H_{is}$.

The probability $P\left(\gamma_{ds}^{\text{cap}} \leq \gamma_0\right)$ can be generalised as

$$P\left(\gamma_{ds}^{\text{cap}} \leq \gamma_0\right) = \int_{x=0}^{\infty} F_{H_{ds}}\left(\gamma_0(x+1)\right) f_{\Delta_d^s}(x)\, dx, \tag{3.12}$$

where, $f_{\Delta_d^s}(x)$ is the PDF of the random variable Δ_d^s .

If the uplink channels are inid, then $f_{\Delta_d^s}(x)$ is obtained by taking the inverse Laplace transform of the MGF of Δ_d^s. Since the weighted SSR random variable H_{ds} for the devices are independent of each other, the MGF for Δ_d^s can be obtained by taking the product of the MGF of the weighted SSR of each interfering device. The PDF $f_{\Delta_d^s}(x)$ is calculated as

$$f_{\Delta_d^s}(x) = \mathcal{L}^{-1}\left[\prod_{\substack{i=1\\ i\neq d}}^{D-1} \mathcal{M}_{H_{is}}(-s)\right], \tag{3.13}$$

where, $\mathcal{M}_{H_{is}}(s)$ denotes the MGF for H_{is} [73] for a device i, where $i \in \{1, 2, ..., D; i \neq d\}$, denotes an interfering device ID. The PDF, obtained above, can be used in (3.12) to obtain $P\left(\gamma_{ds}^{\text{cap}} \leq \gamma_0\right)$. Therefore, the generalised OP for the capture model consisting of D devices and S satellites can be obtained from

$$P_{\text{out},d}(\gamma_0) = \sum_{\nu=0}^{S} \sum_{\forall \mathbf{F}\subset \mathbf{S}} \prod_{\forall s\in \mathbf{S}\backslash \mathbf{F}} \left[P\left(\gamma_{ds}^{\text{cap}} \leq \gamma_0\right)\right] \prod_{\forall k\in \mathbf{F}, |\mathbf{F}|=S-\nu} \left[1 - P(\gamma_{dk}^{\text{cap}} \leq \gamma_0)\right] P\left(\Psi_d(S-\nu) < \gamma_0\right), \tag{3.14}$$

where ν is the number of satellites under outage and **F** is the set of all satellite indices forwarding the device information to the GS for the device d. The set **S** comprises the total satellites S. In the above equation (3.14), k denotes the satellite ID belonging to the set **F**. Also, $s \in \mathbf{S}\backslash\mathbf{F}$ means the satellite ID s belongs to the set **S** but not to **F**. The cardinal number of the set **F** for the total satellites S is $(S-\nu)$.

For the special case of uplink channels being iid, $P\left(\gamma_{ds}^{\text{cap}} \leq \gamma_0\right)$ will be equal for all the devices and $f_{\Delta_d^s}(x)$ can be obtained as shown in section 3.1.4 for $\Psi_d(n)$. Therefore, the generalized OP for the capture model of a system consisting of D devices and S satellites can be written as

$$P_{\text{out},d}(\gamma_0) = \sum_{\nu=0}^{S} \binom{S}{\nu} \left[P\left(\gamma_{ds}^{\text{cap}} \leq \gamma_0\right)\right]^{\nu} \left[1 - P(\gamma_{ds}^{\text{cap}} \leq \gamma_0)\right]^{(S-\nu)} \times P\left(\Psi_d(S-\nu) \leq \gamma_0\right). \tag{3.15}$$

3.2.2 OP in case of SIC-based decoding

The OP of a device (say $d = 1$) for SIC-based decoding in the two-device and two-satellite system can be written using (3.4) and (3.9) as

$$
\begin{aligned}
P_{\text{out},d=1}(\gamma_0) &= P(\gamma_{11}^{\text{SIC}} \le \gamma_0)\, P(\gamma_{12}^{\text{SIC}} \le \gamma_0) + P(\gamma_{11}^{\text{SIC}} > \gamma_0)\, P(\gamma_{12}^{\text{SIC}} > \gamma_0)\, P(\Psi_1(2) \le \gamma_0) \\
&+ P(\gamma_{11}^{\text{SIC}} > \gamma_0)\, P(\gamma_{12}^{\text{SIC}} \le \gamma_0)\, P(G_{11} \le \gamma_0) + P(\gamma_{11}^{\text{SIC}} \le \gamma_0)\, P(\gamma_{12}^{\text{SIC}} > \gamma_0)\, P(G_{12} \le \gamma_0), \quad (3.16)
\end{aligned}
$$

where,

$$
\begin{aligned}
P(\gamma_{11}^{\text{SIC}} \le \gamma_0) &= P\left((\gamma_{11} \le \gamma_0) \cap E_1\right) + P\left((\gamma_{21} \le \gamma_0) \cap \bar{E}_1\right) \\
&\quad + P\left((H_{11} \le \gamma_0) \cap (\gamma_{21} > \gamma_0) \cap \bar{E}_1\right), \quad (3.17) \\
P(\gamma_{12}^{\text{SIC}} \le \gamma_0) &= P\left((\gamma_{12} \le \gamma_0) \cap E_2\right) + P\left((\gamma_{22} \le \gamma_0) \cap \bar{E}_2\right) \\
&\quad + P\left((H_{12} \le \gamma_0) \cap (\gamma_{22} > \gamma_0) \cap \bar{E}_2\right), , \quad (3.18)
\end{aligned}
$$

$$P(\gamma_{11}^{\text{SIC}} > \gamma_0) = 1 - P(\gamma_{11}^{\text{SIC}} \le \gamma_0), \quad (3.19)$$

$$P(\gamma_{12}^{\text{SIC}} > \gamma_0) = 1 - P(\gamma_{12}^{\text{SIC}} \le \gamma_0), \quad (3.20)$$

and $\gamma_{11} = \frac{H_{11}}{H_{21}+1}$, $\gamma_{12} = \frac{H_{12}}{H_{22}+1}$, $\gamma_{21} = \frac{H_{21}}{H_{11}+1}$ and $\gamma_{22} = \frac{H_{22}}{H_{12}+1}$ are the SINRs at the satellites. E_1 and E_2 are the events such that $H_{11} \ge H_{21}$ and $H_{12} \ge H_{22}$ respectively. Also, $\bar{E}_1$ and $\bar{E}_2$ denote the complement of the corresponding events. The term $P(\Psi_1(2) \le \gamma_0)$ in (3.16) can be written as $F_{\Psi_1(2)}(\gamma_0)$ using (3.8) and $P(G_{11} < \gamma_0)$ can be written as $F_{G_{11}}(\gamma_0)$ using (3.7). Since H_{11} and H_{21} are

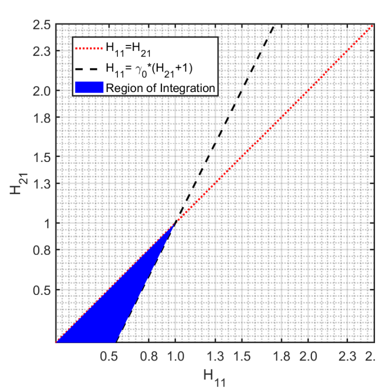

Figure 3.2: $P\left((\gamma_{11} \le \gamma_0) \cap E_1\right)$

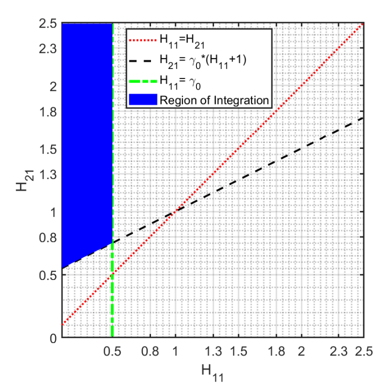

Figure 3.3: $P\left((H_{11} \le \gamma_0) \cap (\gamma_{21} > \gamma_0) \cap \bar{E}_1\right)$

mutually independent, the terms $P\left((H_{11} \le \gamma_0) \cap (\gamma_{21} > \gamma_0) \cap \bar{E}_1\right)$ and $P\left((\gamma_{11} \le \gamma_0) \cap E_1\right)$ in (3.17) can be written as

$$P\left((\gamma_{11} \le \gamma_0) \cap E_1\right) = \int_{y=0}^{\frac{\gamma_0}{1-\gamma_0}} \left(F_{H_{11}}(\gamma_0(y+1)) - F_{H_{11}}(y)\right) f_{H_{21}}(y)\, dy, \tag{3.21}$$

$$P\left((H_{11} \le \gamma_0) \cap (\gamma_{21} > \gamma_0) \cap \bar{E}_1\right) = \int_{y=0}^{\gamma_0} \left(1 - F_{H_{21}}(\gamma_0(y+1))\right) f_{H_{11}}(y)\, dy. \tag{3.22}$$

Here, $P\left((\gamma_{11} \le \gamma_0) \cap E_1\right)$ denotes the probability that the SINR at $s = 1$ for $d = 1$ in the presence of the device $d = 2$ is less than γ_0 and $H_{11} \ge H_{21}$. The region of integrations for some terms are shown in Fig.3.2 and Fig. 3.3. Also, $P((H_{11} \le \gamma_0) \cap (\gamma_{21} > \gamma_0) \cap \bar{E}_1)$ is the probability that at $s = 1$, the SNR for $d = 1$, obtained by removing the decoded symbol for $d = 2$, is less than γ_0 and $\gamma_{21} > \gamma_0$ and $H_{11} < H_{21}$. The region of integration is shown in 3.3.

$$P\left((\gamma_{11} \le \gamma_0) \cap E_1\right) = \left[\sum_{k_2=0}^{m_2-1} \sum_{k_1=0}^{m_1-1} \sum_{p=0}^{k_1} \left\{ \frac{\alpha_{11}\, \alpha_{21}\, A \binom{k_1}{p} p!\, \mu!}{(B_1+B_2)^{\mu+1} {B_1}^{(p+1)}} \left\{ 1 - \sum_{q=0}^{\mu} \frac{e^{-\Upsilon(B_1+B_2)}\, \Upsilon^q}{q!\, (B_1+B_2)^{(-q)}} \right\} \right\} \right.$$
$$- \sum_{k_2=0}^{m_2-1} \sum_{k_1=0}^{m_1-1} \sum_{p=0}^{k_1} \sum_{q=0}^{p} \sum_{r=0}^{q} \frac{\alpha_{11}\, \alpha_{21} \binom{q}{r} e^{(-\gamma_0 B_1)}\, A\, p! \binom{k_1}{p} {\gamma_0}^{q-r} (\mu+r)! (\gamma_0 - 1)^r}{q!\, {B_1}^{(p-q+1)} (B_1\gamma_0 + B_2)^{\mu+r+1}}$$
$$\left. \left\{ 1 - \sum_{d=0}^{\mu+r} \frac{\Upsilon^d\, e^{-\Upsilon(B_1\gamma_0+B_2)}}{d!\, (B_1\gamma_0+B_2)^{(-d)}} \right\} \right]. \tag{3.23}$$

$$P\left((H_{11} \le \gamma_0) \cap (\gamma_{21} > \gamma_0) \cap \bar{E}_1\right) = \alpha_{11}\, \alpha_{21} \sum_{k_1=0}^{m_1-1} \sum_{k_2=0}^{m_2-1} A\, e^{-B_2\gamma_0} \sum_{l=0}^{k_2} \frac{k_2!\, {\gamma_0}^l}{l!\, {B_2}^{(k_2-l+1)}}$$
$$\sum_{p=0}^{l} \binom{l}{p} \frac{(p+k_1)!}{(B_2\gamma_0+B_1)^{(p+k_1+1)}} \left[1 - e^{-\gamma_0(B_2\gamma_0+B_1)} \sum_{q=0}^{(p+k_1)} \frac{{\gamma_0}^q}{q!\, (B_2\gamma_0+B_1)^{(-q)}} \right]. \tag{3.24}$$

The integral in (3.21) and (3.22) can be solved using Eq. (3.351.1,3.351.2) of [70] to obtain the closed form expression as in (3.23) and (3.24) respectively, where $A = \frac{\zeta_1(k_1)\, \zeta_2(k_2)}{\eta_d^{k_1+k_2+2}}$, $B_d = \left(\frac{\beta_d - \delta_d}{\eta_d}\right)$ for $d \in \{1, 2\}$, $\Upsilon = \frac{\gamma_0}{1-\gamma_0}$ and $\mu = k_1 - p + k_2$. The closed form expressions of the remaining terms in (3.17) and (3.18) can also be obtained by evaluating the following integrals using the similar steps as above

$$P\left((\gamma_{21} \leq \gamma_0) \cap \bar{E}_1\right) = \int_{y=0}^{\frac{\gamma_0}{1-\gamma_0}} \left(F_{H_{21}}(\gamma_0(y+1)) - F_{H_{21}}(y)\right) f_{H_{11}}(y)\, dy, \tag{3.25}$$

$$P\left((H_{12} \leq \gamma_0) \cap (\gamma_{22} > \gamma_0) \cap \bar{E}_2\right) = \int_{y=0}^{\gamma_0} \left(1 - F_{H_{22}}(\gamma_0(y+1))\right) f_{H_{12}}(y) dy, \tag{3.26}$$

$$P\left((\gamma_{12} \leq \gamma_0) \cap E_2\right) = \int_{y=0}^{\frac{\gamma_0}{1-\gamma_0}} \left(F_{H_{12}}(\gamma_0(y+1)) - F_{H_{12}}(y)\right) f_{H_{22}}(y)\, dy, \tag{3.27}$$

$$P\left((\gamma_{22} \leq \gamma_0) \cap \bar{E}_2\right) = \int_{y=0}^{\frac{\gamma_0}{1-\gamma_0}} \left(F_{H_{22}}(\gamma_0(y+1)) - F_{H_{22}}(y)\right) f_{H_{12}}(y)\, dy. \tag{3.28}$$

This completes the evaluation of the closed-form expression for (3.9) using SIC. The obtained expression is valid for both iid and inid cases in uplink. Evaluating the closed form expression for arbitrary number of devices and satellites in case of SIC-based decoding is beyond the scope of this thesis.

Description	**Values**
Number of simulations (N)	10^5
Heavy shadowed rician parameters	$m = 2$, $b = 0.063$, $\Omega = 0.0005$
Average shadowed rician parameters	$m = 5$, $b = 0.251$, $\Omega = 0.279$
Distance from devices to satellites (r_{ds})	1200 km
Distance from satellites to GS (r_s)	1200 km
Path loss exponent (α)	2
Variance of AWGN noise ($\sigma_{w_s}^2 = \sigma_{'w_s}^2$)	-123 dBm

Table 3.1: Parameters for Simulation

3.3 Analysis and Results

The simulations are performed for 10^5 channel realizations using MATLAB. Table 3.1 shows the values of parameters for simulations. In case of iid, the channels between all the devices and the satellites are assumed to be heavy shadowed with parameters m=2, b=0.063 and Ω=0.0005 [69]. For the inid case, it is assumed that half of the devices are undergoing average shadowing with parameters m=5, b=0.251, and Ω=0.279 and the rest are heavy shadowed. The values of r_{ds} and r_s are set as 1200 km [74] with path loss exponents set as $\alpha = 2$. It is assumed that $\sigma_{w_s}^2 = -123$ dBm. For the ease of simulations, we assume $\eta_d = \eta_s$. The downlink channels between the satellites and the GS are assumed to be iid average shadowed. Unless specified, the data rate R_d is set to 50 kbps and the bandwidth B is fixed at 125 kHz [75]. The OP curves for the system model are obtained by taking the average over the number of devices.

Fig. 3.4 shows the OP of a two-device two-satellite system versus transmit power P_d under iid and inid channel conditions. The theoretical expressions of the capture-based scheme and SIC match with the simulations. For the SIC-based system, the theoretical results are only for the two-device two-satellite topology. At low transmit powers, upto P_d=2 dBm for iid, the capture and SIC plots overlap. This is because at low P_d, the performance of both SIC and capture models is limited by noise. For the case of inid, the overlap is only upto $P_d = -2$ dBm. With an increase in P_d, the performance variation between the SIC and capture scheme widens with the SIC scheme performing better. It is because of the interference cancellations done for the devices in the SIC scheme. Due to the increase in interference, the OP for the capture scheme reaches a floor at P_d=18 dBm. For the case of inid, the OP of the SIC scheme is lower than that for the iid case as the difference in the received SINRs for the devices lead to improved decoding at the satellites. The same trend is observed for the capture model in the inid case up to P_d=5 dBm, after that the performance of capture for the inid case is worse than that in iid case. There is more interference from the device with average shadowing in inid channels for the capture-based decoding. From now onwards, we are considering only the inid cases as they seem more plausible from the perspective of satellite-IoT.

Fig. 3.5 shows the OP versus the number of satellites at P_d=10 dBm at D=2 and 6. With the increase in D, the interference increases leading to more errors in decoding and thus increasing the outages for both SIC and capture schemes. However, in both the cases, the OP decreases as the number of satellites increase. This is because of the increasing diversity gain of MRC as S increases. It can be seen for SIC scheme that very low OP can be achieved even for 2-6 satellites. For the capture scheme, the practical OP values (10^{-5}-10^{-2}) can be obtained using higher number of satellites for lower D. Using upcoming mega-LEO constellations, 5 to 30 satellites can be visible at latitudes where most of the world population exists [76]. Thus, leveraging the benefits of multiple satellites, the direct-access satellite-based low-power and low-complexity IoT network becomes not only feasible but also attractive.

Fig. 3.6 shows the effect of target rate R_d for P_d=10 dBm and D=2. With the increase in R_d, the threshold for the selective DF at the satellites increases, and thus the OP also increases. As the IoT devices operate with low data rates, the SIC and capture schemes are suitable for the topology. The increase in S will further assist the topology in achieving the desired data rates.

Fig.3.7 shows how with an increase in the number of devices(D), the OP increases. The outage probability is considered for device 1 in the presence of other devices in the inid channels. The inter-device interference at the satellites in the uplink channel causes the processing by both SIC and capture schemes to degrade. With a large number of devices, the detection at the satellites becomes infeasible, and thus, forwarding of error-free packets to the GS decreases. To improve this, one can think of allocating different powers to the users for improving SIC performance as discussed in [77], [78] and [79].

Fig. 3.8 shows the ratio of outages at satellites to that at GS for 2-device and 2-satellite systems versus the transmit power. In the SIC scheme, the outage ratios go down more rapidly than that for the capture scheme. Another way of showing the effectiveness of SIC over the capture-based scheme. With the increase in transmit power, the interference from other devices causes the OP at satellites to saturate, and thus end-to-end OP remains at a constant level. In the case of SIC, the probability of decoding each user at the satellite improves and thus the outages reduce at the satellites.

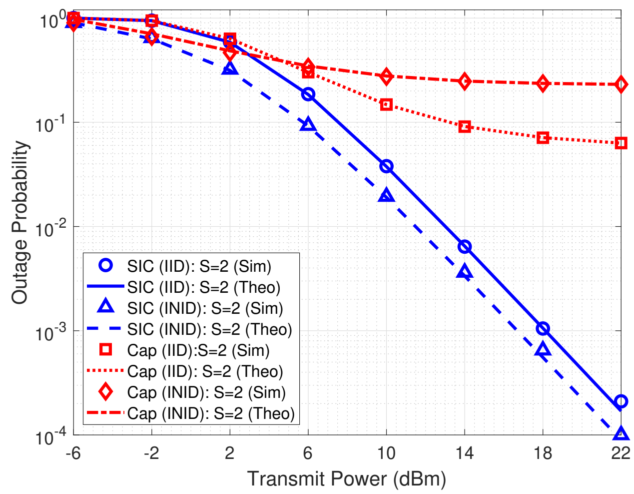

Figure 3.4: OP vs P_d for D=2, R_d=50 kbps and S=2 for both iid and inid uplink channels.

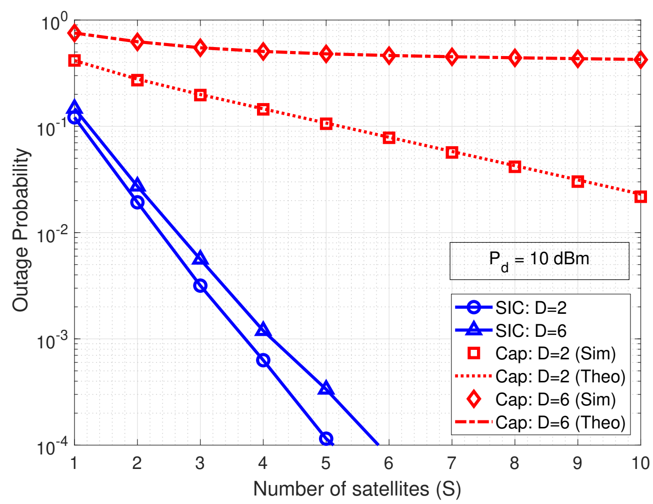

Figure 3.5: OP vs S at P_d=10 dBm and $S = 2, 6$ kbps for iid uplink channels.

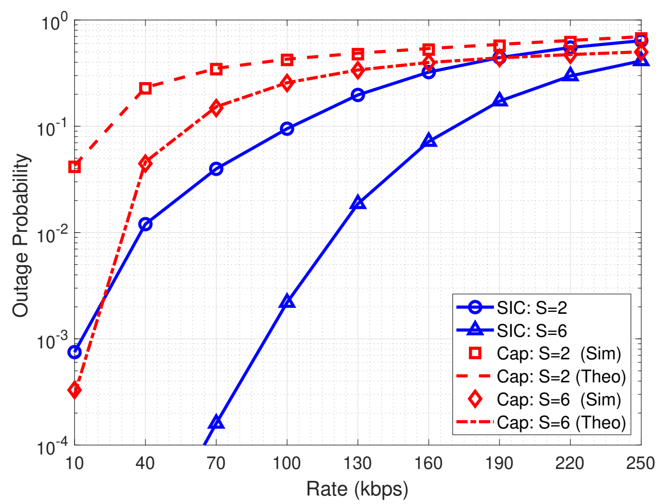

Figure 3.6: OP vs R_d at P_d=10 dBm, D=2 and S=$\{2, 6\}$ for inid uplink channels.

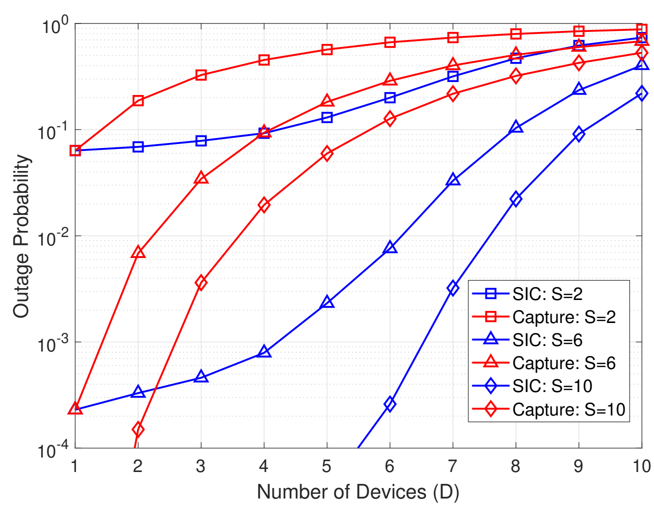

Figure 3.7: OP vs D at P_d=10 dBm, D=2 and S=$\{2, 6\}$ for inid uplink channels.

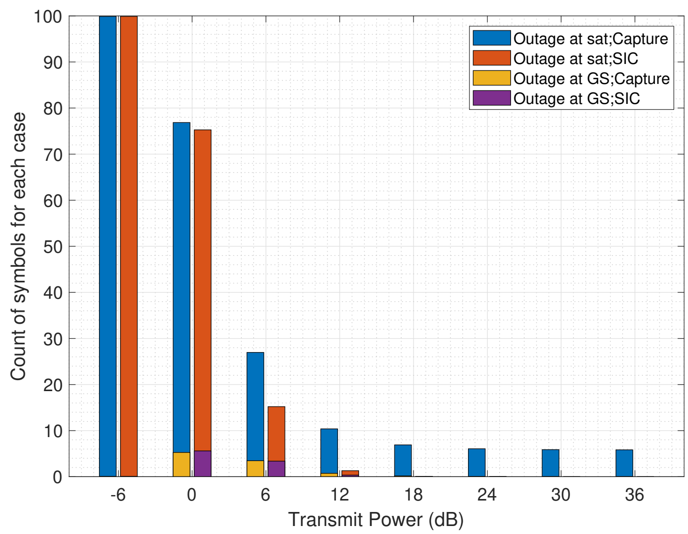

Figure 3.8: Ratio of outages at satellites to GS vs P_d for D=2 and S=2 for iid uplink channels.

Chapter 4

Conclusion

4.1 Conclusion and Future scope

This thesis analyses the performance of direct-access topology using Mega LEO satellites for transmitting to the ground station. The topology aims to provide multiple access to the transmitting devices simultaneously at random time instants. As a performance measure, the OP is analyzed for the selective DF topology using the slotted-Aloha with SIC or capture scheme for the multiple IoT devices. While the SIC scheme performs better than the capture, it is found that at low transmit powers, the performance gap is not too large. Thus, capture-based decoding is preferred in scenarios with fewer devices and low transmit powers. When the number of devices sharing the same slot is large, and the transmit powers are high, SIC scheme is more suitable for the topology. For the inid uplink channels, the SIC performance further improves compared to the iid, while this is not the case in the capture-based model. It is also demonstrated that leveraging the benefits of mega-LEO satellites makes the topology feasible and attractive for low-powered, low-complexity IoT networks. This topology can be a starting point for further research in the satellite-IoT domain.

As an extension to our work, we will consider LEO satellites to be distributed as a binomial point process (BPP) for the same system model with the devices at the fixed locations. We aim to find the meta distribution for our system model of end-to-end SINR. The BPP distribution of satellites can bring more generalization to the LEO satellite networks. The satellites distributed across the orbits will be assumed to have the same period and fixed inclination. The other direction of future work can be to optimize the topology to determine the minimum number of satellites for a particular number of devices or the maximum number of devices served by a given number of satellites. The optimization techniques for theoretical expressions can be used to determine the system model parameters at a given altitude or inclination to achieve the target performance.

List of Related Publications

[P1] N. Lamba, A. K. Dwivedi and S. Chaudhari, Performance Analysis of Selective Decode-and-Forward Relaying for Satellite-IoT, IEEE Globecom Workshops (GC Wkshps), Rio de Janeiro, Brazil, 2022, pp. 1127-1132, doi: 10.1109/GCWkshps56602.2022.100087600.

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