

1. Introduction

StarPerf 2.0 is a feature-rich, highly open, and easily extensible constellation performance simulation platform. The platform architecture is

"framework + plug-in"

that is: we have built a basic framework, which is used to implement various underlying functions of StarPerf 2.0 and provides a unified programming interface API to the outside. Various specific functions of the platform exist in the form of plug-ins, which are written based on the API provided by the framework. In this system, plug-ins and framework are decoupled, so StarPerf 2.0 is highly open and easily expandable.

StarPerf 2.0 supports two ways to build a constellation: the first way is to use XML configuration files to build a Walker- δ constellation, and the second way is to use TLE data to build a real constellation (Starlink, etc.).

Currently, we have provided a variety of functional plug-ins, such as the constellation connectivity mode plug-in "+Grid", the constellation routing strategy plug-in "Shortest Path Routing", the constellation high survival simulation plug-in "Solar Storm Damage Model", etc.

Of course, you can also write the functional plug-ins you are interested in based on the interface API provided by the framework to achieve personalized functions. The remainder of this document is used to introduce various API interface specifications provided by the framework so that you can better use StarPerf 2.0 to complete your simulation tasks.

2. Environment & Dependencies

Before we begin, we first introduce the operating environment of StarPerf 2.0 and its dependent libraries so that you can install StarPerf 2.0 correctly.

It is developed based on Python 3.10, so we recommend that your **Python version is ≥ 3.10** . In addition to the Python 3.10 standard library, it also uses the following open source Python third-party libraries:

Table 1 : third-party Python libraries and versions

Library	Version
h3	4.0.0b2
h5py	3.10.0
numpy	1.24.4
openpyxl	3.1.2
importlib-metadata	6.8.0
skyfield	1.46
sgp4	2.22
pandas	2.1.0
poliastro	0.17.0
astropy	5.3.3
networkx	3.1
requests	2.31.0
jenkspy	0.4.0
pycharts	2.0.4

The third-party Python libraries in the above table and their corresponding version numbers are all listed in "docs/third-party_libraries_list.txt" in the form of "LibraryName==LibraryVersion" (such as "numpy==1.24.4"), and you can execute the

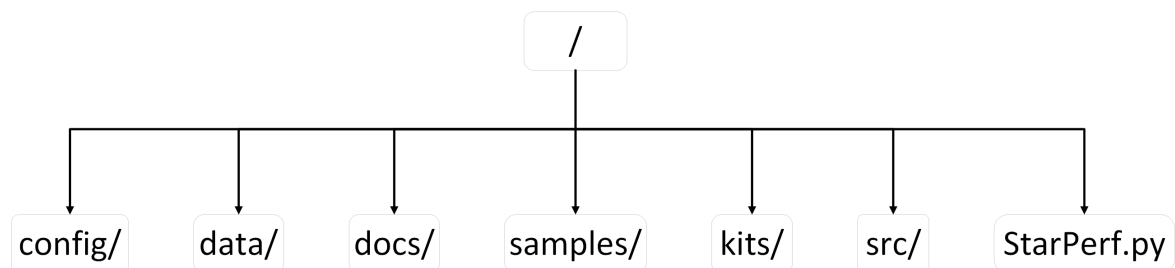
"pip install -r docs/third-party_libraries_list.txt"

command in the root directory of the StarPerf 2.0 project to install all third-party Python libraries at once.

Finally, StarPerf 2.0 does not depend on any non-Python environment, so you do not need to install any third-party orbit analysis/calculation tools (STK, etc.).

3. Architecture

The first-level architecture of StarPerf 2.0 is as follows :



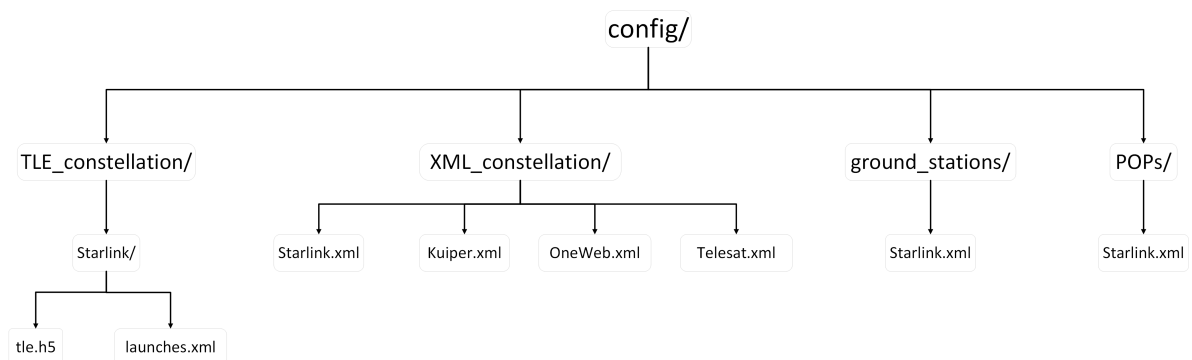
The functions of each first-level module in the above figure are as follows :

Table 2 : StarPerf 2.0 first-level modules and functions

Module	Function
config/	Configuration Information Module , is used to store configuration files, such as constellation configuration information, ground station information, etc.
data/	Data Storage Module , is used to store preloaded data and intermediate data and result data generated during system operation, such as cells of different resolutions in the h3 library, satellite position data, etc.
docs/	Documentation Module , is used to store various documentation, pictures, and dependent library information of StarPerf 2.0, such as this document, the list of third-party Python libraries that the system depends on.
samples/	Test Sample Module , is used to store test case scripts for each functional module, and these scripts are independent of each other and can be directly called and run.
kits/	Auxiliary Script Module , is used to store some auxiliary scripts written to complete system functions, such as ".xlsx" file conversion ".xml" file scripts, etc.
src/	Kernel Module , is the core module of StarPerf 2.0, which contains all the core code of each functional module. The "framework + plug-in" architecture mentioned earlier is this module.
StarPerf.py	StarPerf 2.0 Startup Script , users should start StarPerf 2.0 from this script.

4. Configuration Information Module : config/

This module stores all data information related to constellation configuration in StarPerf 2.0, and the structure diagram of this module is as follows :



The functions of each module in the above figure are as follows :

Table 3 : config module

Module	Function
TLE_constellation/	Stores the data information required to generate constellations using TLE. Each constellation is described by a TLE data file (.h5) and a launch batch information file (.xml).
XML_constellation/	Stores the data information required to generate constellations using XML data. Each constellation is described by an .xml file.
ground_stations/	Stores the ground station data of the constellation. All ground station information for each constellation is described by an .xml file.
POPs/	Store the POP points data of the constellation. All POP points information for each constellation is described by an .xml file.

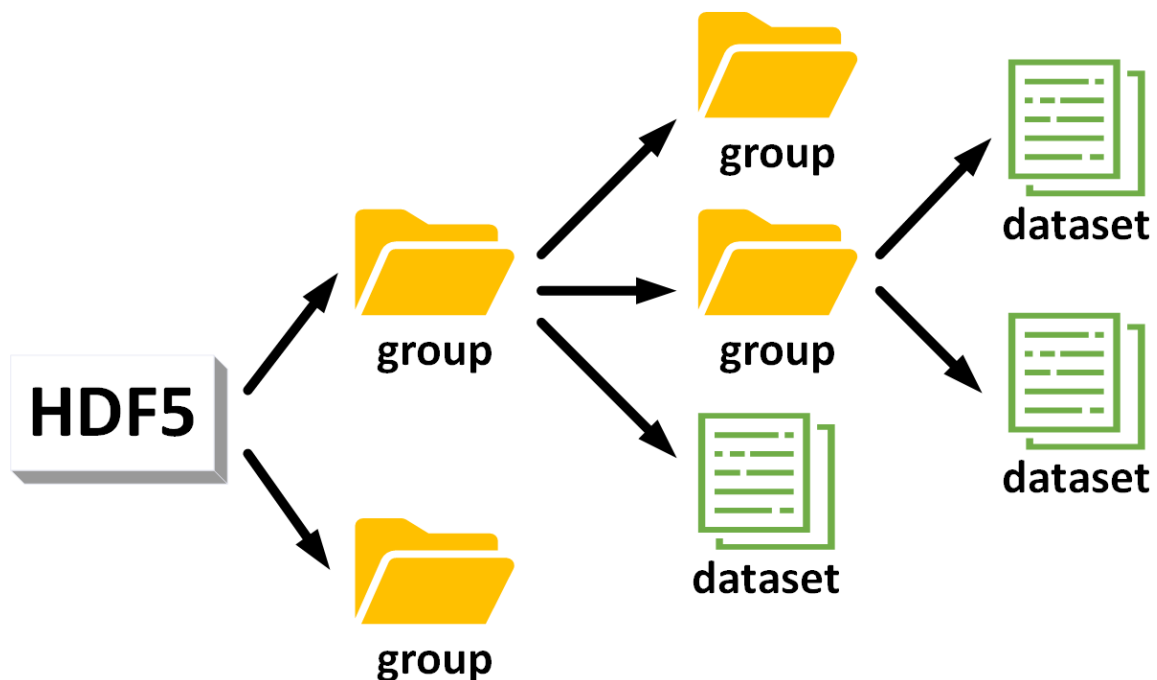
4.1 h5 file introduction

This format file is generally used to store scientific data. It has a structure similar to a "file directory" and allows the data in the file to be organized in many different structured ways, just like working with files on a computer.

There are two main structures in h5 files: **group** and **dataset**. An h5 file is a combination of several groups and datasets.

- **group** : A grouping structure containing 0 or more instances of a dataset or group, along with supporting metadata.
- **dataset** : A data collection organized in an array-like manner, working like a numpy array, a dataset is a numpy.ndarray. The specific dataset can be images, tables, or even pdf files and excel.

Working with groups and datasets is in many ways similar to working with directories and files in UNIX. Like UNIX directories and files, objects in h5 files are usually described by providing full (or absolute) pathnames.



Reading and writing h5 files can be completed through Python's h5py library. For specific usage, see "kits/".

4.2 TLE_constellation/

This folder stores the data information of the constellation generated by TLE. Each constellation is described by a folder named after the constellation. There are two files in this folder, one is the .h5 file that stores TLE, and the other is the .xml file that stores satellite launch information. In the .h5 file that stores TLE, each day's TLE data is a Group, and the Group name is the date of the day. Each Group contains two Datasets. The first Dataset is a TLE containing two rows of information, and the second Dataset is a TLE in JSON format. For example, the tree structure of the "config/TLE_constellation/Starlink/tle.h5" file is as shown below :

```
Group: 20231130
  Dataset: 20231130-2LE
  Dataset: 20231130-json
Group: 20231201
  Dataset: 20231201-2LE
  Dataset: 20231201-json
Group: 20231202
  Dataset: 20231202-2LE
  Dataset: 20231202-json
Group: 20231204
  Dataset: 20231204-2LE
  Dataset: 20231204-json
Group: 20231206
  Dataset: 20231206-2LE
  Dataset: 20231206-json
Group: 20231207
  Dataset: 20231207-2LE
  Dataset: 20231207-json
Group: 20231209
  Dataset: 20231209-2LE
  Dataset: 20231209-json
Group: 20231210
  Dataset: 20231210-2LE
  Dataset: 20231210-json
```

The structure of the .xml file that stores satellite launch information is as follows:

```
<Launches>
  <Launch1>
    <COSPAR_ID>2019-074</COSPAR_ID>
    <Altitude>550</Altitude>
    <Inclination>53</Inclination>
  </Launch1>
  .....
</Launches>
```

The root element of the xml file is "Launches". The root element contains several elements, each element is named with "Launch+<number>" (such as "Launch1", "Launch2", etc.), which is used to represent a satellite launch information. Each launch contains three types of information: [COSPAR ID](#) , orbit altitude Altitude (unit: kilometers) and orbit inclination (unit: °).

4.3 XML_constellation/

This folder stores the data information of the constellation generated by XML. Walker-δ constellations and polar constellations can be generated using XML files. In this way of generating constellations, each constellation only requires a .xml configuration information file, and no TLE is required. Taking Starlink as an example, the .xml configuration information file of the constellation is "config/XML_constellation/Starlink.xml". The content of the file is as follows :

```
<constellation>
  <number_of_shells>4</number_of_shells>
  <shell1>
    <altitude>550</altitude>
    <orbit_cycle>5731</orbit_cycle>
    <inclination>53.0</inclination>
    <phase_shift>1</phase_shift>
    <number_of_orbit>72</number_of_orbit>
    <number_of_satellite_per_orbit>22</number_of_satellite_per_orbit>
  </shell1>
  .....
</constellation>
```

The root element of the document is "<constellation>". The first sub-element inside the root element is "<number_of_shells>", which represents the number of shells in the constellation. In this example, we assume that the value is 4, then there will be 4 sub-elements under the root element "<shell1>" "<shell2>"..."<shell4>", representing different shells respectively. There are 6 sub-elements inside each shell, representing orbital altitude (unit: km), orbital period (unit: s), orbital inclination (unit: °), phase shift, number of orbits and number of satellites in each orbit.

4.4 ground_stations/

This folder stores the ground station information of the constellation. The ground station information of each constellation is described by an .xml file named after the constellation name. The content of Starlink's ground station information file "config/ground_stations/Starlink.xml" is as follows :

```
<GSs>
  <GS1>
    <Latitude>-12.74832</Latitude>
    <Longitude>-38.28305</Longitude>
    <Description>Camaçari, BR</Description>
    <Frequency>Ka</Frequency>
    <Antenna_Count>8</Antenna_Count>
    <Uplink_Ghz>2.1</Uplink_Ghz>
    <Downlink_Ghz>1.3</Downlink_Ghz>
  </GS1>
  .....
</GSs>
```

The root element of the document is "<GSs>". In this example, we assume that there are 10 ground station, then there will be 10 sub-elements under the root element "<GS1>" "<GS2>"..."<GS10>", representing different ground station respectively. There are 7 sub-elements inside each GS, representing ground station latitude, ground station longitude, ground station location description, ground station frequency, ground station antenna count, ground station uplink(GHz) and ground station downlink(GHz).

4.5 POPs/

This folder stores the POP information of the constellation. The POP information of each constellation is described by an .xml file named after the constellation name. The content of Starlink's POP information file "config/POPs/Starlink.xml" is as follows :

```
<POPs>
  <POP1>
    <Latitude>47.6048790423666</Latitude>
    <Longitude>-122.333542912036</Longitude>
    <Name>SEA - STTLWAX1</Name>
  </POP1>
  . . . . .
</POPs>
```

The root element of the document is "<POPs>". In this example, we assume that there are 10 POPs, then there will be 10 sub-elements under the root element "<POP1>" "<POP2>..." "<POP10>", representing different POP respectively. There are 3 sub-elements inside each POP, representing POP latitude, POP longitude and POP name.

5. Data Storage Module : data/

This module stores various data when StarPerf 2.0 is running, which can be divided into three categories :

- **Preloaded data** : the data that StarPerf 2.0 must read when running certain functions, such as the data of Uber h3 library cells, which is located in "data/h3_cells_id_res0-4.h5".
- **Intermediate data** : StarPerf 2.0 needs to temporarily store some data when running certain functions, such as the delay matrix of the constellation, satellite position data, etc. These data are stored in "TLE_constellation/<constellation_name>.h5" (such as "data/TLE_constellation/Starlink.h5") or "XML_constellation/<constellation_name>.h5" (such as "data/XML_constellation/Starlink.h5").
- **Result data** : the final results produced after StarPerf 2.0 runs, such as some output drawings in pdf format, etc.

6. Documentation Module : docs/

Stored under this module are various documentation related to StarPerf 2.0. For example, this document exists under this module, and all illustrations referenced in this document also exist under this module.

In addition, there is an important file under this module: "third-party_libraries_list.txt". This file describes all third-party Python libraries and versions that StarPerf 2.0 depends on. Please refer to the "[Environment & Dependencies](#)" chapter for the specific usage of this document, which will not be described again here.

7. Auxiliary Script Module : kits/

This module stores some auxiliary scripts written to complete the core functions of StarPerf 2.0, such as file format conversion scripts, h5 file reading scripts, etc.

For example, if you want to view the tree structure of an h5 file, you can run "get_h5file_tree_structure.py". This script will read "data/XML_constellation/Starlink.h5" and display the group and dataset information in it. The script execution results are as follows :

```

Group: delay
  Group: shell1
    Dataset: timeslot1
    Dataset: timeslot2
  Group: shell2
    Dataset: timeslot1
    Dataset: timeslot2
  Group: shell3
    Dataset: timeslot1
    Dataset: timeslot2
  Group: shell4
    Dataset: timeslot1
Group: position
  Group: shell1
    Dataset: timeslot1
    Dataset: timeslot2
  Group: shell2
    Dataset: timeslot1
    Dataset: timeslot2
  Group: shell3
    Dataset: timeslot1
    Dataset: timeslot2
  Group: shell4
    Dataset: timeslot1

```

Explanation of execution results: the above figure shows that "data/XML_constellation/Starlink.h5" contains 2 first-level groups: position and delay, which represent satellite position data and constellation delay matrix data respectively. Each first-level group contains 4 second-level groups, which represent each layer of shell data. Each secondary group contains 2 datasets, representing the data of two timestamps.

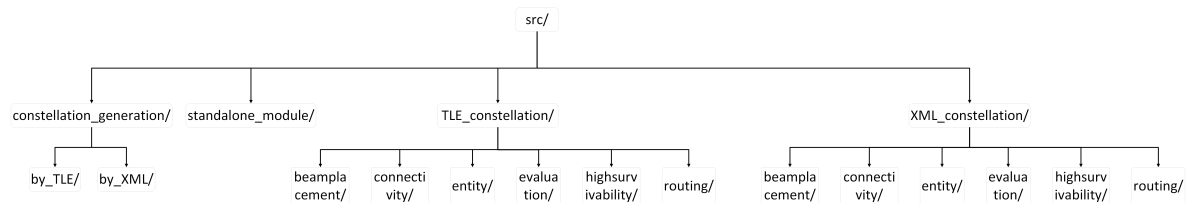
For another example, if you want to view the h3id of all cells at the specified resolution in "data/h3_cells_id_res0-4.h5", you can execute "print_h3_cells_h3id.py". Assume that you now want to view the h3id of all cells with a resolution of 0, part of the execution results of this script are as follows:


```
b'80f1ffffffffffff'
b'8093ffffffffffff'
b'8055ffffffffffff'
b'800dffffffffffff'
b'80b9ffffffffffff'
b'8031ffffffffffff'
b'80ddffffffffffff'
b'800bffffffffffff'
b'8057ffffffffffff'
b'80a5ffffffffffff'
b'801bffffffffffff'
b'8049ffffffffffff'
b'80afffffffffffff'
b'8011ffffffffffff'
b'8013ffffffffffff'
b'8089ffffffffffff'
b'80adffffffffffff'
b'8025ffffffffffff'
b'8047ffffffffffff'
b'80c5ffffffffffff'
b'80e5ffffffffffff'
b'803dffffffffffff'
b'80e7ffffffffffff'
b'80b3ffffffffffff'
b'8067ffffffffffff'
b'80e9ffffffffffff'
b'8079ffffffffffff'
b'80d1ffffffffffff'
```

Explanation of execution results: each row in the above figure represents the h3id of a cell with a resolution of 0. Due to space limitations, only part of the execution results are shown here. More detailed results can be viewed by executing the script.

8. Kernel Module : src/

This module is the kernel code module of StarPerf 2.0, which stores the system's "framework + plug-in". The architecture of this module is as follows :



The function of each module in the above figure are as follows :

Table 4 : kernel module submodules and functions

Module	Function
constellation_generation/	part of the "framework" that implements constellation generation and constellation initialization.
standalone_module/	Provide some independent function modules, such as calculating the length of satellite time that users can see.
TLE_constellation/	Construct constellations using TLE data.
XML_constellation/	Construct constellations using XML data.

8.1 constellation_generation/

This module is used to generate and initialize satellite constellations. StarPerf 2.0 supports two ways of generating constellations: the first is to use XML documents to build Walker- δ or polar constellations, and the second is to use TLE data to build real constellations.

8.1.1 build constellations using XML files

This method uses two scripts to complete the constellation generation : "constellation_configuration.py" and "orbit_configuration.py". After the following two scripts are executed, the constellation is generated. Now, we introduce the execution mechanism of these two scripts respectively.

8.1.1.1 constellation_configuration.py

The startup function of this script is "constellation_configuration". See the table below for relevant information about this function.

Table 5 : constellation_configuration information

Parameter Name	Parameter Type	Parameter Unit	Parameter Meaning
dT	int	second	indicates how often timestamps are recorded, and this value must be less than the orbital period of the satellite
constellation_name	str	-	the name of the constellation, and the value of this parameter must have the same name as an xml file in "config/XML_constellation". The xml file with the same name is the configuration file of the constellation named with that name

When executing the function "constellation_configuration", the xml file under the "config/XML_constellation/" path will be loaded according to the parameter "constellation_name", that is:

```
xml_file_path = "config/XML_constellation/" + constellation_name + ".xml"
```

Afterwards, each shell of the constellation will be generated based on the xml data. Generating each shell consists of two stages.

Stage 1 : Generating the basic parameters of the shell, such as orbital altitude, orbital period, orbital inclination, number of orbits, number of satellites in each orbit, etc. This stage can be completed directly using xml data.

Stage 2 : Generating orbits and satellites in the shell. This stage is implemented by two Python third-party libraries, skyfield and sgp4. We put the specific implementation of this part in "orbit_configuration.py". You only need to just call this script in "constellation_configuration.py".

After the completion of these two stages, the target constellation initialization task has been completed. At this time, we save the position information of each satellite in the constellation at each moment in an h5 file under "data/XML_constellation".

Note : The number of constellation moments is determined by the parameter dT and the orbital period. That is, a total of "(int)(orbit_cycle / dT)" satellite position data needs to be saved to the h5 file.

Finally, the return value of this function represents the generated constellation, which is a constellation object.

8.1.1.2 orbit_configuration.py

The startup function of this script is "orbit_configuration". See the table below for relevant information about this function.

Table 6 : orbit_configuration information

Parameter Name	Parameter Type	Parameter Unit	Parameter Meaning
dT	int	second	indicates how often timestamps are recorded, and this value must be less than the orbital period of the satellite
sh	shell	-	shell to generate orbits and satellites

When this function is executed, the system will generate the Kepler parameters of each orbit based on the existing parameters of "sh" (number of orbits, orbital inclination, number of satellites in each orbit, etc.). Then, in-orbit satellites are generated based on the generated orbits. This process uses the skyfield and sgp4 libraries.

This function is called by "constellation_configuration.py" and is responsible for completing the functions of "[Stage 2](#)". Therefore, this function has no return value. After execution, continue to execute "constellation_configuration.py".

8.1.1.3 case study

Now, we give an example of Walker- δ constellation generation and initialization to facilitate your understanding.

Step 1 : we define the two function parameters in Table 5, as follows :

```
dT = 5730
constellation_name = "Starlink"
```

Step 2 : we call the "constellation_configuration" function of the "constellation_configuration.py" to generate the constellation :

```
# generate the constellations
constellation = constellation_configuration.constellation_configuration(dT=dT,
                               constellation_name=constellation_name)
```

After the above two steps, we have obtained a constellation. Now print out some basic parameter information of the constellation, as follows (part) :

```

Details of the constellations are as follows :
The name of the constellation is : Starlink
There are 4 shell(s) in this constellation
The information for each shell is as follows:
shell name : shell1
shell orbit altitude(km) : 550
The shell contains 1584 satellites
The shell contains 72 orbits
shell orbital inclination(°) : 53.0
shell orbital period (s) : 5731
=====
shell name : shell2
shell orbit altitude(km) : 570
The shell contains 720 satellites
The shell contains 36 orbits
shell orbital inclination(°) : 70.0
shell orbital period (s) : 5755
=====
shell name : shell3
shell orbit altitude(km) : 560
The shell contains 520 satellites
The shell contains 10 orbits
shell orbital inclination(°) : 97.6
shell orbital period (s) : 5743
=====
shell name : shell4
shell orbit altitude(km) : 540
The shell contains 1584 satellites

```

The complete code of the above process can be found at :

"samples/XML_constellation/constellation_generation/constellation_generation_test.py".

8.1.2 build constellations using TLE data

This method uses five scripts to complete the constellation generation : "download_TLE_data.py", "satellite_to_shell_mapping.py", "satellite_to_orbit_mapping.py", "get_satellite_position.py" and "constellation_configuration.py". Overall, the constellation generated by this method can be divided into four stages :

Stage 1 : download TLE data, and this function is implemented by "download_TLE_data.py".

Stage 2 : determine the shell to which the satellite belongs, and this function is implemented by "satellite_to_shell_mapping.py".

Stage 3 : determine the orbit to which the satellite belongs, and this function is implemented by "satellite_to_orbit_mapping.py".

Stage 4 : save the satellite position information of each timeslot to a .h5 file, and this function is implemented by "get_satellite_position.py".

Now, we introduce the execution mechanism of these five scripts respectively.

8.1.2.1 download_TLE_data.py

This method requires the use of two types of data to construct a constellation. The first type is the emission information of the constellation satellites, and the second type is the TLE of all satellites in the constellation.

For the first type of data, in StarPerf 2.0, we provide Starlink satellite launch data by default., and these data are stored at : "config/TLE_constellation/Starlink/launches.xml". Satellite launch data source : https://en.wikipedia.org/wiki/List_of_Starlink_and_Starshield_launches#Launches

For the second type of data, it can be downloaded from here: <https://celestrak.org/NORAD/elements/>

The startup function of this script is "download_TLE_data". This function only accepts one parameter, which is the constellation name of the TLE data to be downloaded.

In order to facilitate the implementation of the following functions, here we will download two types of TLE, 2LE and JSON. 2LE format, that is, TLE data containing only two rows of elements, such as :

```
1 44713U 19074A 24025.32501904 -.00001488 00000+0 -81005-4 0 9997
2 44713 53.0536 62.8760 0001441 94.1015 266.0138 15.06396809232035
```

JSON format, that is, parsing TLE data into JSON data, such as :

```
{
  "OBJECT_NAME": "STARLINK-1007",
  "OBJECT_ID": "2019-074A",
  "EPOCH": "2024-01-25T07:48:01.645056",
  "MEAN_MOTION": 15.06396809,
  "ECCENTRICITY": 0.0001441,
  "INCLINATION": 53.0536,
  "RA_OF_ASC_NODE": 62.876,
  "ARG_OF_PERICENTER": 94.1015,
  "MEAN_ANOMALY": 266.0138,
  "EPHEMERIS_TYPE": 0,
  "CLASSIFICATION_TYPE": "U",
  "NORAD_CAT_ID": 44713,
  "ELEMENT_SET_NO": 999,
  "REV_AT_EPOCH": 23203,
  "BSTAR": -8.1005e-5,
  "MEAN_MOTION_DOT": -1.488e-5,
  "MEAN_MOTION_DDOT": 0
}
```

When the TLE data is downloaded successfully, the system will output prompt information on the terminal, such as :

Starlink's TLE data download was successful on 20240126 !

TLE data in these two formats will eventually be saved in the "config/TLE_constellation/ + <constellation_name> + /tle.h5" file.

Note : When using TLE data to generate constellations, please ensure that your computer can be connected to the Internet because an Internet connection is required to download the data.

8.1.2.2 satellite_to_shell_mapping.py

This script establishes a corresponding relationship between each satellite described in the TLE data and the shell in which it is located, and the satellite's launch information is used to establish this relationship.

Implementation mechanism: In the TLE data in JSON format, there is a field named "OBJECT_ID", from which the launch batch number (COSPAS_ID) of the satellite can be obtained, combined with "config/TLE_constellation/+<constellation_name>+ /launches.xml", the corresponding relationship between COSPAR_ID, orbital altitude and orbital inclination can be used to infer the shell to which a satellite belongs.

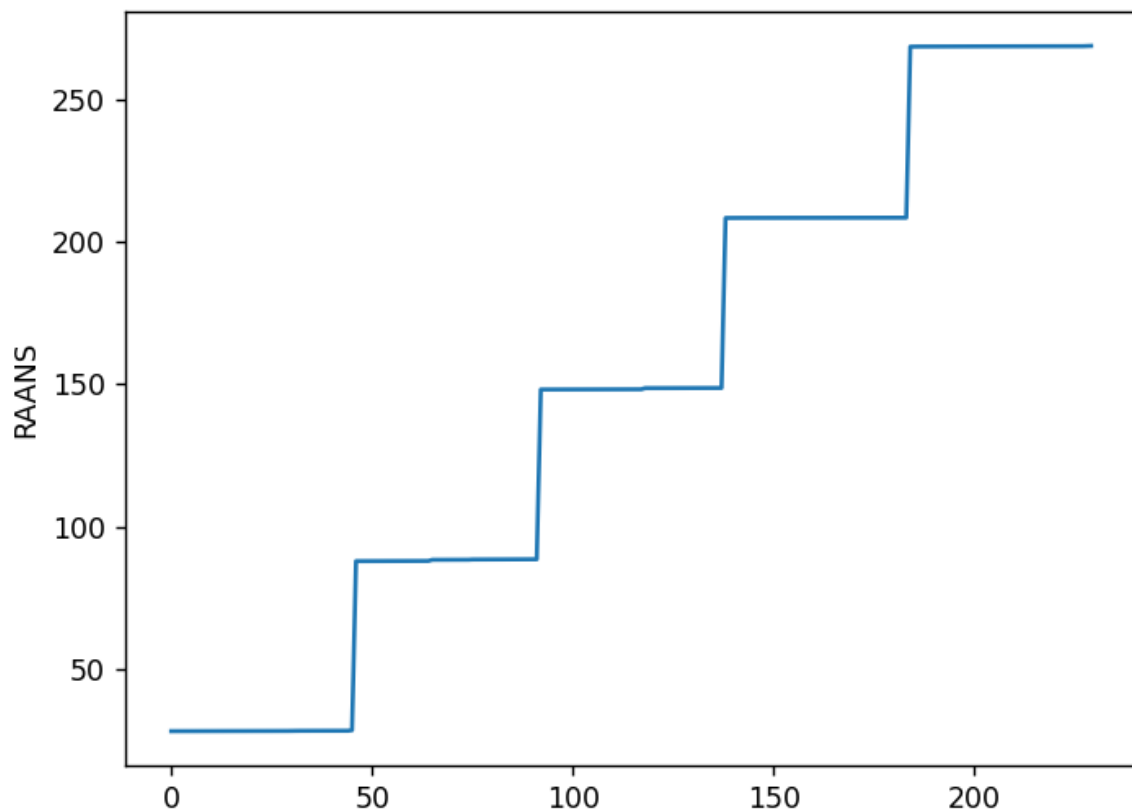
The startup function of this script is "satellite_to_shell_mapping". This function accepts only one parameter, the name of the constellation.

8.1.2.3 satellite_to_orbit_mapping.py

Section 8.1.2.2 determines the shell to which the satellite belongs. This section is used to determine the orbit to which the satellite belongs.

Implementation mechanism: Sort the ascending node right ascension (raan) of all satellites in a shell, and then draw a distribution line chart of raan. The user observes the line chart and manually inputs the number of orbits. Subsequently, based on the number of orbits input by the user, we use the natural breakpoint method to divide these satellites into several orbits to determine the correspondence between satellites and orbits.

When the script is executed, the program will output (some) line charts. The user needs to observe the line charts and determine the approximate number of tracks, and enter the approximate number into the program. For example, the following figure is a line chart output during program execution :



From this line chart, we can see that there are 5 values for raan, which means there are 5 tracks, so you need to manually enter 5 in the console :

```

Please enter the number of orbits (integer) based on the raan distribution result of the line chart : 1
Please enter the number of orbits (integer) based on the raan distribution result of the line chart : 7
Please enter the number of orbits (integer) based on the raan distribution result of the line chart : 5
Please enter the number of orbits (integer) based on the raan distribution result of the line chart : 21
Please enter the number of orbits (integer) based on the raan distribution result of the line chart : 72
Please enter the number of orbits (integer) based on the raan distribution result of the line chart : 23
Please enter the number of orbits (integer) based on the raan distribution result of the line chart : 28
Please enter the number of orbits (integer) based on the raan distribution result of the line chart : 72

```

After you complete the input, the program will continue to run and use the natural breakpoint method to determine the orbit to which the satellite belongs based on the data you entered. A third-party library in Python called `jenks` has implemented the natural breakpoint method, so the `jenks` library is used here to determine the orbit to which the satellite belongs. Regarding the principles of the natural breakpoint method, you can refer here: <https://pbpython.com/natural-breaks.html>

The startup function of this script is "satellite_to_orbit_mapping". This function only accepts one parameter, which is a shell class object.

After the script is executed, the constellation has been generated.

8.1.2.4 get_satellite_position.py

After the end of Section 8.1.2.3, the constellation has been generated. Now the position information (latitude, longitude and altitude) of each satellite needs to be saved, so the position of the satellite needs to be calculated based on TLE data.

Here we use the `skyfield` library to calculate the satellite's position information. The specific implementation is: input the TLE data and the time corresponding to the TLE, and the `skyfield` library can parse out the longitude, latitude and altitude information of the satellite.

Finally, we save the satellite position information of each timeslot into a .h5 file. The storage location of this file: "data/TLE_constellation/".

8.1.2.5 constellation_configuration.py

This script is used to call `download_TLE_data.py`, `satellite_to_shell_mapping.py`, `satellite_to_orbit_mapping.py` and `get_satellite_position.py` to complete the constellation initialization function.

The startup function of this script is "constellation_configuration". See the table below for relevant information about this function.

Table 7 : constellation_configuration

Parameter Name	Parameter Type	Parameter Unit	Parameter Meaning
dT	int	second	indicates how often timestamps are recorded, and this value must be less than the orbital period of the satellite
constellation_name	str	-	the name of the constellation, the value of this parameter must have the same name as the subfolder in "config/TLE_constellation/". The configuration file of the constellation named by that name is stored in a subfolder with the same name.

When you need to use TLE data to generate a constellation, you only need to call this script to complete.

8.1.2.6 case study

Now, we give an example of constellation generation using TLE data for easy understanding.

Step 1 : we define the two function parameters in Table 7, as follows :

```
dT = 1000
constellation_name = "Starlink"
```

Step 2 : we call the "constellation_configuration" function of the "constellation_configuration.py" to generate the constellation :

```
# generate the constellations
constellation = constellation_configuration.constellation_configuration(dT,
constellation_name)
```

After the above two steps, we have obtained a constellation. Now print out some basic parameter information of the constellation, as follows (part) :

```

Details of the constellations are as follows :
The name of the constellation is : Starlink
There are 8 shell(s) in this constellation
The information for each shell is as follows:
shell name : shell1
shell orbit altitude(km) : 560.0
The shell contains 3 satellites
The shell contains 1 orbits
shell orbital inclination(°) : 97.5
shell orbital period (s) : 5755
=====
shell name : shell2
shell orbit altitude(km) : 525.0
The shell contains 149 satellites
The shell contains 7 orbits
shell orbital inclination(°) : 53.05
shell orbital period (s) : 5689
=====
shell name : shell3
shell orbit altitude(km) : 560.0
The shell contains 230 satellites
The shell contains 5 orbits
shell orbital inclination(°) : 97.6
shell orbital period (s) : 5759
=====
shell name : shell4
shell orbit altitude(km) : 570.0
The shell contains 406 satellites
The shell contains 21 orbits

```

The complete code of the above process can be found at :

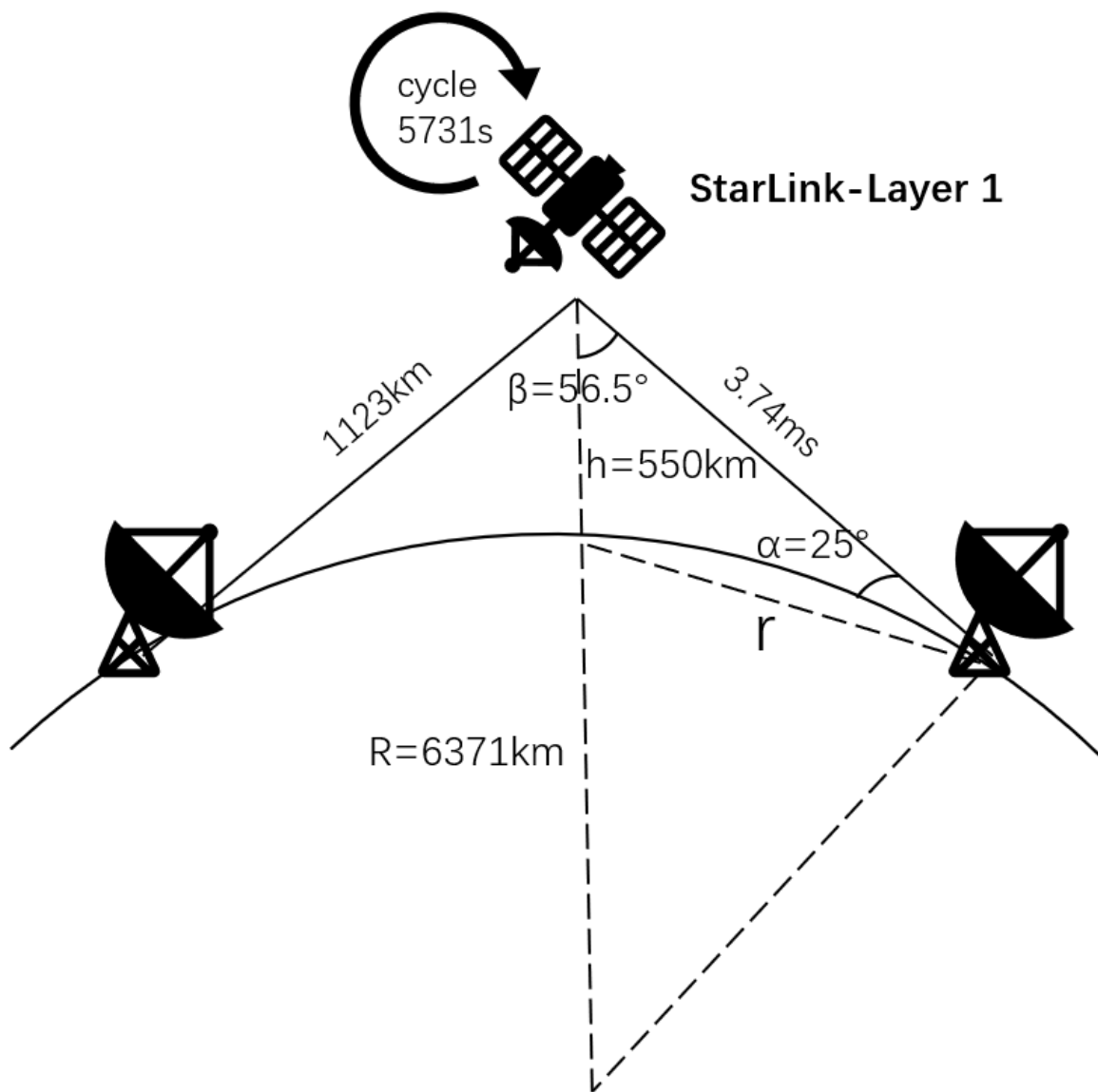
"samples/TLE_constellation/constellation_generation/constellation_generation_test.py".

8.2 standalone_module/

This module is used to implement some relatively independent functions and can be used by users as needed.

8.2.1 satellite visible time calculation

In some cases, it may be necessary to calculate the time a satellite is visible to the user. For example, we need to calculate how long the satellite can be observed by ground users in the scenario shown in the figure below :



This is a simple geometric calculation function implemented by "src/standalone_module/satellite_visibility_time.py". The startup function of this script is "satellite_visibility_time". See the table below for relevant information about this function.

Table 8 : satellite_visibility_time

Parameter Name	Parameter Type	Parameter Unit	Parameter Meaning
θ	float	degree	the lowest elevation angle at which the user can see the satellite
h	float	km	the height of a satellite's orbit above the earth's surface

8.2.2 case study

Now, we give an example of calculating the satellite time visible to ground users for easier understanding :

```
satellite_visibility_time( $\theta=25$  ,  $h=550$ )
```

The results of executing the above code are as follows :

When the lowest elevation angle at which a user can see a satellite is 25° and the satellite orbit height is 550 km, the user can see a satellite for 269.27 s.

The complete code of the above process can be found at :

"samples/standalone_module/standalone_module_test_cases.py".

8.3 TLE_constellation/ & XML_constellation/

We generated the constellation using XML and TLE in Section 8.1. In this section, we will implement some evaluation metrics based on the generated constellations. Whether using XML or TLE, the interface provided by the final constellation is exactly the same, so the constellations generated by these two methods can share a set of codes to write evaluation indicators.

The core functional modules are shown in the following table :

Table 9 : core functional modules and functions

Module	Function
beamplacement/	constellation_beamplacement : implement part of the "framework" related to beam placement, as well as plug-ins related to beam placement algorithms.
connectivity/	constellation_connectivity : implements parts of the "framework" related to the connectivity mode between satellites in the constellation, as well as plug-ins for the connectivity mode.
evaluation/	constellation_evaluation : implement part of the "framework" related to constellation performance evaluation, such as delay, bandwidth, coverage, etc.
entity/	constellation_entity : the entity classes in StarPerf 2.0 are defined, such as orbit, satellite, ground stations, etc., and this module is part of the "framework".
highsurvivability/	constellation_highsurvivability : implement part of the "framework" related to the high survivability aspect of the constellation, as well as some constellation damage model plug-ins.
routing/	constellation_routing : implements part of the "framework" for constellation routing, as well as some routing strategy plug-ins.

8.3.1 constellation_beamplacement

This part includes two aspects. One is "framework" part : beam placement plug-in manager, another is the "plug-in" part : various beam placement algorithms. After explaining these two parts, we give a case study so that you can better understand the working mechanism of this module.

8.3.1.1 plug-ins

All plug-ins under this module are beam placement algorithms, and one plug-in represents a beam placement algorithm. We implement the random beam placement algorithm(i.e. "**random_placement.py**") by default, and you can write other beam placement algorithm plug-ins by yourself according to the interface specifications. The interface specifications for this part are

as follows :

- **Requirement 1** : The storage location of the plug-in is (starting from the root of StarPerf 2.0) : "src/TLE_constellation/constellation_beamplacement/beam_placement_plugin/"(for TLE constellation) or "src/XML_constellation/constellation_beamplacement/beam_placement_plugin/"(for XML constellation).
- **Requirement 2** : Each plug-in is a ".py" file, and all source code for the plug-in must be located in this script file.
- **Requirement 3** : The launch entry for a plug-in is a function with the same name as the plug-in.
- **Requirement 4** : The startup function parameter requirements are as follows :

Table 10 : beam placement plug-ins startup function parameter list

Parameter Name	Parameter Type	Parameter Unit	Parameter Meaning
sh	shell	-	a shell class object, representing a layer of shell in the constellation
h3_resolution	int	-	the resolution of cells divided by h3 library, and currently supported resolutions are: 0/1/2/3/4
antenna_count_per_satellite	int	-	the number of antennas each satellite is equipped with
dT	int	second	indicates how often the beam is scheduled, and this value must be less than the orbital period of the satellite
minimum_elevation	float	degree	the minimum elevation angle at which a satellite can be seen from a point on the ground

- **Requirement 5** : The return value of the startup function is all cells covered after executing the beam placement algorithm.
- **Requirement 6** : If one plug-in needs to save intermediate data or result data, the data should be saved in an h5 format file under "data/".

8.3.1.2 framework

This part of the framework consists of 1 py script: "**beam_placement_plugin_manager.py**". A beam placement plug-in manager is defined in this script to manage all plug-ins under this module.

The so-called beam placement plug-in manager actually defines a class named "beam_placement_plugin_manager". The attributes and methods contained in this class and their functions and meanings are shown in the tables below.

Table 11 : beam placement plug-in manager attributes list

Attribute Name	Attribute Type	Attribute Meaning
plugins	dict	a dictionary composed of all plug-ins. The "key" is the plug-in name, which is a string type, and the "value" is the plug-in startup function in the corresponding plug-in, which is a function
current_beamplacement_policy	str	plug-in name used by the current beam placement plug-in manager

Table 12 : beam placement plug-in manager methods list

Method Name	Parameter List (name : type : unit)	Return Values	Method Function
<code>__init__</code>	-	-	initialize an instance of the beam placement plugin manager
<code>set_beamplacement_policy</code>	(plugin_name : str : -)	-	set the value of <code>current_beamplacement_policy</code> to <code>plugin_name</code>
<code>execute_beamplacement_policy</code>	(sh : shell : - , h3_resolution : int : - , antenna_count_per_satellite : int : - , dT : int : second , minimum_elevation : float : degree)	cells covered by the beam, all cells	according to the value of the <code>current_beamplacement_policy</code> attribute, the startup function of the corresponding plug-in is called to execute the beam placement algorithm.

The operating mechanism of this framework is: first instantiate a beam placement plug-in manager object. This object contains two attributes: "plugins" and "current_beamplacement_policy". "plugins" is a dictionary type attribute used to store various beam placement plugins. "current_beamplacement_policy" is a string type used to represent the beam placement plugin used by the current manager.

During the instantiation of the manager object, the system automatically reads all beam placement plug-ins and stores them in the "plugins". The key of "plugins" is the name of the plugin, and the value of "plugins" is the startup function of the plugin. After reading all plug-ins, the system sets the value of "current_beamplacement_policy" to "random_placement", indicating that the "random_placement" plug-in is used as the default beam placement algorithm.

If you want to execute the beam placement algorithm, you only need to call the "execute_beamplacement_policy" method of the manager object. This method will automatically call the startup function of the plug-in indicated by "current_beamplacement_policy".

If you need to switch the beam placement plug-in, just call the "set_beamplacement_policy" method and pass in the plug-in name you need as a parameter.

After you write your own beam placement algorithm plug-in according to the interface specifications introduced earlier, you only need to set "current_beamplacement_policy" as your plug-in name, and the system will automatically recognize your plug-in and execute it.

8.3.1.3 case study

Now, we take "random_placement" as an example to explain the operation of the beam placement module.

Step 1 : instantiate the beam placement plug-in manager object :

```
beamPlacementPluginManager =  
beam_placement_plugin_manager.beam_placement_plugin_manager()
```

Step 2 : set the currently used beam placement plug-in :

```
beamPlacementPluginManager.set_beamplacement_policy("random_placement")
```

Note : The beam placement plug-in manager already sets the "current_beamplacement_policy" value to "random_placement" when initialized, so this step can be omitted here. But if you want to use other beam placement plug-ins, this step cannot be omitted.

Step 3 : call the "execute_beamplacement_policy" method of "beamPlacementPluginManager" to execute the "random_placement" plug-in :

```
covered_cells_per_timeslot, Cells =  
beamPlacementPluginManager.execute_beamplacement_policy(bent_pipe_constellation.  
shells[0] ,  
h3_resolution , antenna_count_per_satellite  
, dT , minimum_elevation)
```

There are two return values in Step 3 : "covered_cells_per_timeslot" represents the cells covered by the beam, and "Cells" represents all cells (including those covered by the beam and those not covered by the beam).

The code execution results are as follows (part) :

```
The number of cells covered at the current moment is : 740 , and the total number of cells is : 842  
h3id      the longitude of the center point  the latitude of the center point  
8192bfffffffff      -111.7317456382725      -13.151965418934605  
81933fffffffff      -103.7766040799484      -3.1467120956910755  
81937fffffffff      -97.93354550224774      -8.005842805111278  
8193bfffffffff      -110.38174242887938      -5.9157912018788075  
8192fffffffff      -106.43584656664277      -18.252309811641965  
81927fffffffff      -99.19848835508473      -15.882210055630608  
81923fffffffff      -105.08478410411644      -10.770202546102777  
81543fffffffff      -13.37484510475237      16.702868303031238  
8154bfffffffff      -20.875967631929612      13.966628880652204  
8154fffffffff      -14.994110429179171      9.736295972495173  
81557fffffffff      -5.806478706688274      19.12047595149947  
8155bfffffffff      -19.626487072711953      21.449600056147013  
81547fffffffff      -7.9341937215652765      12.207271677703732  
81553fffffffff      -11.49560315658184      24.174058347303657
```

The complete code of the above process can be found at:

"samples/TLE_constellation/beam_placement/random_placement.py" and
"samples/XML_constellation/beam_placement/random_placement.py".

8.3.2 constellation_connectivity

This section is also composed of "framework" and "plug-ins". The "framework" part is the "connectivity mode plugin manager". The "plug-ins" part is the connection method between satellites, such as +Grid.

8.3.2.1 plug-ins

All plug-ins under this module are ISL establishment modes, and one plug-in represents a mode. We implement the +Grid mode and bent-pipe mode by default, and you can write other ISL establishment mode plug-ins by yourself according to the interface specifications. The interface specifications for this part are as follows :

- **Requirement 1** : The storage location of the plug-in is (starting from the root of StarPerf 2.0) : "src/TLE_constellation/constellation_connectivity/connectivity_plugin/"(for TLE constellation) or "src/XML_constellation/constellation_connectivity/connectivity_plugin/"(for XML constellation).
- **Requirement 2** : Each plug-in is a ".py" file, and all source code for the plug-in must be located in this script file.
- **Requirement 3** : The launch entry for a plug-in is a function with the same name as the plug-in.
- **Requirement 4** : The startup function parameter requirements are as follows :

Table 13 : ISL establishment mode plug-ins startup function parameter list

Parameter Name	Parameter Type	Parameter Unit	Parameter Meaning
constellation	constellation	-	the constellation to establish ISL
dT	int	second	indicates how often the beam is scheduled, and this value must be less than the orbital period of the satellite

- **Requirement 5** : The startup function has no return value.
- **Requirement 6** : After establishing the ISL, write the constellation delay matrix into a .h5 file. The Group name is: "delay", and the Dataset name is: "timeslot+<number>" (such as "timeslot1", "timeslot2"), and the .h5 file storage path : "data/TLE_constellation/" (for TLE constellation) or "data/XML_constellation/" (for XML constellation).

8.3.2.2 framework

This part of the framework consists of 1 py script: "**connectivity_mode_plugin_manager.py**". A connectivity mode plugin manager is defined in this script to manage all plug-ins under this module.

The so-called connectivity mode plugin manager actually defines a class named "connectivity_mode_plugin_manager". The attributes and methods contained in this class and their functions and meanings are shown in the tables below.

Table 14 : connectivity mode plugin manager attributes list

Attribute Name	Attribute Type	Attribute Meaning
plugins	dict	a dictionary composed of all plug-ins. The "key" is the plug-in name, which is a string type, and the "value" is the plug-in startup function in the corresponding plug-in, which is a function
current_connection_mode	str	plug-in name used by the current connectivity mode plugin manager

Table 15 : connectivity mode plugin manager methods list

Method Name	Parameter List (name : type : unit)	Return Values	Method Function
<code>__init__</code>	-	-	initialize an instance of the connectivity mode plugin manager
<code>set_connection_mode</code>	(plugin_name : str : -)	-	set the value of <code>current_connection_mode</code> to <code>plugin_name</code>
<code>execute_connection_policy</code>	(constellation : constellation : -, dT : int : second)	-	according to the value of the <code>current_connection_mode</code> attribute, the startup function of the corresponding plug-in is called to execute the ISL establishment.

The operating mechanism of this framework is: first instantiate a connectivity mode plugin manager object. This object contains two attributes: "plugins" and "current_connection_mode". "plugins" is a dictionary type attribute used to store various connectivity mode plugins. "current_connection_mode" is a string type used to represent the connectivity mode plugin used by the current manager.

During the instantiation of the manager object, the system automatically reads all connectivity mode plugins and stores them in the "plugins". The key of "plugins" is the name of the plugin, and the value of "plugins" is the startup function of the plugin. After reading all plug-ins, the system sets the value of "current_connection_mode" to "positive_Grid", indicating that the "positive_Grid" plug-in is used as the default connectivity mode plugin.

If you want to execute the connectivity mode, you only need to call the "execute_connection_policy" method of the manager object. This method will automatically call the startup function of the plug-in indicated by "current_connection_mode".

If you need to switch the connectivity mode plug-in, just call the "set_connection_mode" method and pass in the plug-in name you need as a parameter.

After you write your own connectivity mode plug-in according to the interface specifications introduced earlier, you only need to set "current_connection_mode" as your plug-in name, and the system will automatically recognize your plug-in and execute it.

8.3.2.3 case study

Now, we take "positive_Grid" as an example to explain the operation of the constellation connectivity module.

Step 1 : instantiate the connectivity mode plugin manager object :

```
# initialize the connectivity mode plugin manager
connectionModePluginManager =
connectivity_mode_plugin_manager.connectivity_mode_plugin_manager()
```

Step 2 : set the currently used connectivity mode plug-in :

```
connectionModePluginManager.current_connection_mode = "positive_Grid"
```

Note : The connectivity mode plugin manager already sets the "current_connection_mode" value to "positive_Grid" when initialized, so this step can be omitted here. But if you want to use other connectivity mode plugins, this step cannot be omitted.

Step 3 : call the "execute_connection_policy" method of "connectionModePluginManager" to execute the "positive_Grid" plug-in :

```
connectionModePluginManager.execute_connection_policy(constellation=bent_pipe_co
nstellation , dT=dT)
```

The complete code of the above process can be found at:

"samples/XML_constellation/positive_Grid/*" and "samples/TLE_constellation/positive_Grid/*".

8.3.3 constellation_evaluation

Constellation performance evaluation is generally divided into two categories: with ISL and without ISL. The former is used in +Grid and other modes and includes four evaluation indicators: bandwidth, betweenness, coverage and delay. The latter is used in bent-pipe mode and includes three evaluation indicators: bandwidth, coverage and delay.

8.3.3.1 Performance evaluation in the presence of ISL

In this section, we take the +Grid connection mode as an example to evaluate the constellation performance.

8.3.3.1.1 bandwidth

First, given a shell in a constellation, as well as two ground station objects source and destination, pass in a parameter λ , and then calculate the bandwidth between the source and destination. The calculation of the bandwidth value refers to the total bandwidth of all disjoint paths from the source to the destination whose delay time does not exceed λ times the shortest delay time. λ is a floating point number not less than 1 (that is, the minimum value of λ is 1).

The function that implements this function is introduced in the table below.

Table 16 : bandwidth function attributes list

Parameter Name	Parameter Type	Parameter Unit	Parameter Meaning
constellation_name	str	-	the name of the constellation, such as "Starlink"
source	user	-	the source of the communication pair
target	user	-	the destination of the communication pair
sh	shell	-	a shell in the constellation
λ	float	-	the maximum multiple of the minimum delay time allowed from source to target. The smaller the λ value, the fewer the number of paths from source to target. When $\lambda=1$, only one path meets the requirements (i.e. the shortest path).
isl_capacity	float	Gbps	the capacity of a single ISL, such as 5Gbps
dT	int	second	how often a timeslot is recorded

Calculate the bandwidth between source and target in each timeslot, and finally average it to be the final bandwidth between source and target, and return this final calculation result.

8.3.3.1.2 betweenness

Betweenness is a metric that describes the centrality in a graph based on shortest paths, and it is widely used in telecommunications networks, e.g., a node with higher betweenness centrality would have more traffic passing through that node. Moreover, a node with a high betweenness centrality may also be a potential bottleneck node, since the failure of this node will affect all flows relying on it. In this function we will evaluate the betweenness of each satellite in the constellation.

Specifically, the betweenness of a satellite sat is calculated as :

$betweenness(sat) = \sum_{s \neq d \neq sat} \frac{p_{sd}(sat)}{p_{sd}}$, where p_{sd} is the total number of the shortest paths from source s to destination d , and $p_{sd}(sat)$ is the number of those paths that pass through sat .

The function that implements this function is introduced in the table below.

Table 17 : betweenness function attributes list

Parameter Name	Parameter Type	Parameter Unit	Parameter Meaning
constellation_name	str	-	the name of the constellation, such as "Starlink"
sh	shell	-	a shell in the constellation
t	int	-	a certain time slot (timeslot)

After the calculation is completed, a list will eventually be returned. Each element in the list is of type float, representing the betweenness of each satellite.

8.3.3.1.3 coverage

Calculation method : Divide the longitude of the earth's surface every α and the latitude every α , thus obtaining $\frac{180}{\alpha} * \frac{360}{\alpha}$ fragments. Each fragment represents a certain area of the earth's surface. The default value of α is 10° .

The function that implements this function is introduced in the table below.

Table 18 : coverage function attributes list

Parameter Name	Parameter Type	Parameter Unit	Parameter Meaning
constellation_name	str	-	the name of the constellation, such as "Starlink"
dT	int	second	how often a timeslot is recorded
sh	shell	-	a shell in the constellation
tile_size(α)	float	degree	the size of the square block on the earth's surface, the default is to cut every 10° , that is, each block occupies 10° longitude and 10° latitude.
maximum_depression	float	degree	the maximum depression angle of the satellite, the default value is 56.5°
minimum_elevation	float	degree	the minimum elevation angle of the ground observation point, the default value is 25°

This function calculates the coverage of each timeslot, and finally stores the coverage of each timeslot into a list variable and returns it.

8.3.3.1.4 delay

This function is used to calculate the delay time of two communication endpoints, that is, the total time of sending a packet from the source to the destination, and the total time of sending a packet from the destination to the source (RTT time).

The function that implements this function is introduced in the table below.

Table 19 : delay function attributes list

Parameter Name	Parameter Type	Parameter Unit	Parameter Meaning
constellation_name	str	-	the name of the constellation, such as "Starlink"
source	user	-	source endpoint of the communication pair
target	user	-	destination endpoint of the communication pair
dT	int	second	how often a timeslot is recorded
sh	shell	-	a shell in the constellation

This function calculates the delay time of each timeslot, and finally stores the delay time of each timeslot into a list variable and returns it.

8.3.3.2 Performance evaluation without ISL

In this section, we evaluate the performance of constellations without ISL, i.e. the performance of constellations in bent-pipe operating mode.

8.3.3.2.1 bandwidth

Calculation method: When the bent-pipe mode communicates between two ends (denoted as end A and end B), end A selects a satellite in the sky as a relay (denoted as satellite 1) according to a certain strategy, and end B selects a satellite in the sky as a relay according to a certain strategy. The strategy selects a satellite in the sky as the relay (denoted as satellite 2). Assume that there are n GSs within the visible range of satellite 1, and the bandwidth of each GS is P ; there are m GSs within the visible range of satellite 2, and the bandwidth of each GS is P . Therefore, the bandwidth of satellite 1 \rightarrow satellite 2 can be expressed as $n * P$, and the bandwidth of satellite 2 \rightarrow satellite 1 can be expressed as $m * P$. Since the communication is bidirectional, the communication bandwidth between A and B is $\min\{n * P, m * P\}$. The above calculation is performed for each timeslot within the satellite orbit period. Finally, the average of all timeslot values can be used as the bent-pipe bandwidth for communication between A and B.

The function that implements this function is introduced in the table below.

Table 20 : bandwidth function attributes list

Parameter Name	Parameter Type	Parameter Unit	Parameter Meaning
source	user	-	the source of the communication pair
target	user	-	the destination of the communication pair
dT	int	second	how often a timeslot is recorded
sh	shell	-	a shell in the constellation
ground_station_file	str	-	constellation ground station file path (the path is calculated from the root directory of the project)
minimum_elevation	float	degree	the minimum elevation angle of the ground users
GS_capacity	float	Gbps	the GS capacity of each ground station, such as 10 Gbps

Calculate the bandwidth between source and target in each timeslot, and finally average it to be the final bandwidth between source and target, and return this final calculation result.

8.3.3.2.2 coverage

Calculation method: In bent-pipe mode, the coverage of the constellation is not only related to the satellite itself, but also to the GS. If a user is in an area where a satellite can be seen overhead, but there is no GS within the visible range of the satellite, then the area where the user is located is said to be not covered by bent-pipe. Specifically, the coverage rate in bent-pipe mode can be calculated as follows: First, divide the earth's surface into several tiles, for example, every 10° interval according to the longitude and latitude, so that you will get 18*36 tiles. Then select a point (latitude and longitude) in each tile as the user's position, take the user as the perspective, calculate all satellites visible to the user (note the set of these satellites as S), traverse all satellites in the S set, as long as If at least one satellite in the S set has a GS in its visible field of view, the tile is considered to be covered. Perform this operation on all tiles, and finally divide the number of covered tiles by the total number of tiles, which is the coverage rate of the constellation under the current timeslot. Perform the above operation on all timeslots to obtain the constellation coverage under each timeslot. Constellation coverage, and finally average the value and return it as the final constellation coverage.

The function that implements this function is introduced in the table below.

Table 21 : coverage function attributes list

Parameter Name	Parameter Type	Parameter Unit	Parameter Meaning
dT	int	second	how often a timeslot is recorded
sh	shell	-	a shell in the constellation
ground_station_file	str	-	constellation ground station file path (the path is calculated from the root directory of the project)
minimum_elevation	float	degree	the minimum elevation angle of the ground users
tile_size	float	degree	the size of the square block on the earth's surface, the default is to cut every 10°, that is, each block occupies 10° longitude and 10° latitude.

This function calculates the coverage of each timeslot, and finally stores the coverage of each timeslot into a list variable and returns it.

8.3.3.2.3 delay

Calculation method: When the bent-pipe mode communicates between two terminals (denoted as terminal A and terminal B), the process is: terminal A → satellite 1 → ground station A → POP point 1 → terminal B, or terminal B → Satellite 2 → Ground station B → POP point 2 → Terminal A. Therefore, if you want to calculate the delay between terminal A and terminal B in bent-pipe mode, you can calculate the delay between terminal A → satellite 1 → ground station A → POP point 1 → POP point 2 → ground station B → satellite 2 → terminal B → satellite 2 → ground station B → POP point 2 → POP point 1 → ground station A → satellite 1 → terminal A, use this delay time to represent the bent-pipe delay between terminal A and terminal B. Among them, when calculating the delay between POP point 1 → POP point 2 or POP point 2 → POP point 1, it is expressed by dividing the great circle distance on the earth's surface by a certain speed.

The function that implements this function is introduced in the table below.

Table 22 : delay function attributes list

Parameter Name	Parameter Type	Parameter Unit	Parameter Meaning
source	user	-	the source of the communication pair
target	user	-	the destination of the communication pair
dT	int	second	how often a timeslot is recorded
sh	shell	-	a shell in the constellation
ground_station_file	str	-	constellation ground station file path (the path is calculated from the root directory of the project)
POP_file	str	-	satellite constellation ground POP point data file
α	float	-	the great circle distance coefficient between the source and target points
β	float	-	the communication speed between source and target. The speed of light in vacuum is c, but the speed of communication between source and target may not be c. Therefore, the speed of light c multiplied by the speed coefficient β represents the final communication speed from source to target.
minimum_elevation	float	degree	the minimum elevation angle of the ground users

This function calculates the delay time of each timeslot, and finally stores the delay time of each timeslot into a list variable and returns it.

8.3.4 constellation_entity

This section describes the Python custom classes used in StarPerf 2.0.

8.3.4.1 XML constellation

8.3.4.1.1 constellation

Table 23 : constellation class attributes list

Attribute Name	Attribute Type	Attribute Meaning
constellation_name	str	the name of the constellation, such as "Starlink"
number_of_shells	int	the number of shells contained in the constellation
shells	list	it is a list type object, which stores shell class objects

8.3.4.1.2 ground_station

Table 24 : ground station class attributes list

Attribute Name	Attribute Type	Attribute Meaning
longitude	float	the longitude of GS
latitude	float	the latitude of GS
description	str	the description of GS's position
frequency	str	the frequency of GS, such as Ka,E and so on
antenna_count	int	the number of antenna of GS
uplink_GHz	float	the uplink GHz of GS
downlink_GHz	float	the downlink GHz of GS

8.3.4.1.3 ISL

Table 25 : ISL class attributes list

Attribute Name	Attribute Type	Attribute Meaning
satellite1	int	the id of the first satellite
satellite2	int	the id of the second satellite
data_rate	float	the data transfer rate (Gbps)
frequency_band	float	the laser band
capacity	float	the capacity of ISL
distance	list	the distance between the two satellites connected by ISL, the unit is kilometers km. This parameter is of list type because it needs to store the distances of different timeslots.
delay	list	the delay between the two satellites connected by ISL, in seconds, this parameter is of list type because it needs to store the delay time of different timeslots.

8.3.4.1.4 orbit

Table 26 : orbit class attributes list

Attribute Name	Attribute Type	Attribute Meaning
orbit_cycle	float	orbital period (unit: s)
satellite_orbit	poliastro.twobody.orbit.creation.OrbitCreationMixin	actual satellite orbit
satellites	list	a list type field is used to store satellites in the orbit and stores satellite objects

8.3.4.1.5 POP

Table 27 : POP class attributes list

Attribute Name	Attribute Type	Attribute Meaning
longitude	float	the longitude of POP
latitude	float	the latitude of POP
POP_name	str	the name of POP

8.3.4.1.6 satellite

Table 28 : satellite class attributes list

Attribute Name	Attribute Type	Attribute Meaning
longitude	list	longitude (degree), because the satellite is constantly moving, there are many longitudes. Use the list type to store all the longitudes of the satellite
latitude	list	latitude (degree), because the satellite is constantly moving, there are many latitudes. Use the list type to store all the latitudes of the satellite
altitude	list	altitude (km), because the altitude is constantly moving, there are many altitudes. Use the list type # to store all the altitudes of the satellite
orbit	orbit	the current orbit of the satellite
ISL	list	list type attribute, which stores the current satellite and which satellites have established ISL, stores the ISL object
nu	float	true periapsis angle is a parameter that describes the position of an object in orbit
id	int	id is the number of the satellite in the shell
true_satellite	skyfield.sgp4lib.EarthSatellite	real satellite objects

8.3.4.1.7 shell

Table 29 : shell class attributes list

Attribute Name	Attribute Type	Attribute Meaning
altitude	float	height of shell (km)
number_of_satellites	int	the number of satellites included in this shell
number_of_orbits	int	the number of orbits contained in this shell
inclination	float	the inclination angle of the orbit in this shell
orbit_cycle	float	the orbital period of this layer's shell
number_of_satellite_per_orbit	int	the number of satellites per orbit in this layer's shell
phase_shift	int	phase shift, used when generating satellites
shell_name	str	the name of this layer's shell, name format: shell+number, such as: "shell1", "shell2", etc.
orbits	list	a list type object, is used to store which orbits are included in the shell of this layer. It stores orbit objects.

8.3.4.1.8 user

Table 30 : user class attributes list

Attribute Name	Attribute Type	Attribute Meaning
longitude	float	the longitude of user
latitude	float	the latitude of user
user_name	str	the name of user

8.3.4.2 TLE constellation

8.3.4.2.1 constellation

see [Table 23](#)

8.3.4.2.2 ground_station

see [Table 24](#)

8.3.4.2.3 ISL

see [Table 25](#)

8.3.4.2.4 launch

Table 31 : launch class attributes list

Attribute Name	Attribute Type	Attribute Meaning
cospar_id	str	cospar_id is International Designator, is an international identifier assigned to artificial objects in space
altitude	float	the orbital altitude
inclination	float	the orbital inclination

8.3.4.2.5 orbit

Table 32 : orbit class attributes list

Attribute Name	Attribute Type	Attribute Meaning
shell	shell	shell class variables are used to represent the shell to which the current orbit belongs
satellites	list	satellites in this orbit
raan_lower_bound	float	the lower bound of the right ascension of the ascending node of the satellite in this orbit
raan_upper_bound	float	the upper bound of the right ascension of the ascending node of the satellite in this orbit

8.3.4.2.6 POP

see [Table 27](#)

8.3.4.2.7 satellite

Table 33 : satellite class attributes list

Attribute Name	Attribute Type	Attribute Meaning
tle_json	dict	TLE in json format
tle_2le	tuple	TLE in 2le format
cospar_id	str	cospar_id of current satellite
shell	shell	shell class variables are used to represent the shell to which the current satellite belongs
orbit	orbit	orbit class variables are used to represent the orbit to which the current satellite belongs
longitude	list	longitude (degree), because the satellite is constantly moving, there are many longitudes. Use the list type to store all the longitudes of the satellite
latitude	list	latitude (degree), because the satellite is constantly moving, there are many latitudes. Use the list type to store all the latitudes of the satellite
altitude	list	altitude (km), because the altitude is constantly moving, there are many altitudes. Use the list type to store all the altitudes of the satellite
ISL	list	list type attribute, which stores the current satellite and which satellites have established ISL, stores the ISL object
id	int	the id number of the satellite

8.3.4.2.8 shell

Table 34 : shell class attributes list

Attribute Name	Attribute Type	Attribute Meaning
altitude	float	the altitude of the satellite orbit within this layer
inclination	float	the orbital inclination of the satellite in this layer
shell_name	str	the name of the shell
orbits	list	orbits in this layer of shell
satellites	list	satellites in this layer of shell
orbit_cycle	float	the orbital period of this layer's shell

8.3.4.2.9 user

see [Table 30](#)

8.3.5 constellation_highsurvivability

This section is also composed of "framework" and "plug-ins". The "framework" part is the "damage model plugin manager". The "plug-ins" part is a variety of constellation damage models, such as satellite natural aging damage, solar storm concentrated damage and other models. In StarPerf 2.0, we provide two damage models by default : satellite natural aging damage model and solar storm concentrated damage model.

8.3.5.1 plug-ins

All plug-ins under this module are constellation damage models, and one plug-in represents a model. We implement the satellite natural aging damage model and solar storm concentrated damage model by default, and you can write other constellation damage model plug-ins by yourself according to the interface specifications. The interface specifications for this part are as follows :

- **Requirement 1** : The storage location of the plug-in is (starting from the root of StarPerf 2.0) : "src/TLE_constellation/constellation_highsurvivability/damage_model_plugin/"(for TLE constellation) or "src/XML_constellation/constellation_highsurvivability/damage_model_plugin/"(for XML constellation).
- **Requirement 2** : Each plug-in is a ".py" file, and all source code for the plug-in must be located in this script file.
- **Requirement 3** : The launch entry for a plug-in is a function with the same name as the plug-in.
- **Requirement 4** : The startup function parameter requirements are as follows :

Table 35 : constellation damage model plug-ins startup function parameter list

Parameter Name	Parameter Type	Parameter Unit	Parameter Meaning
constellation	constellation	-	the constellation that needs to be destroyed
sh	shell	-	the shell that needs to be destroyed
num_of_damaged_satellites	int	-	the number of randomly destroyed satellites. If the value is less than 1, it is the number of satellites destroyed as a percentage of the total number; if the value is greater than 1, it is the number of satellites that need to be destroyed
dT	int	second	how often a timeslot is recorded
satrt_satellite_id	int	-	the id of the most central satellite in a group of satellites to be destroyed. If satrt_satellite_id is -1, it means that the id of the center satellite of the destroyed group is not specified, but a randomly generated one.

- **Requirement 5** : The return value of the startup function is the destroyed constellation, which is a brand new constellation completely independent of the original constellation. It is a new constellation class object.
- **Requirement 6** : All plug-ins need to write the position and delay information of the destroyed constellation into the .h5 file. The file name and path are:
"data/XML_constellation/" + <constellation_copy_name> + ".h5"(for XML constellation) or
"data/TLE_constellation/" + <constellation_copy_name> + ".h5"(for TLE constellation).

8.3.5.2 framework

This part of the framework consists of 1 py script: "**damage_model_plugin_manager.py**". A constellation damage model plugin manager is defined in this script to manage all plug-ins under this module.

The so-called constellation damage model plugin manager actually defines a class named "damage_model_plugin_manager". The attributes and methods contained in this class and their functions and meanings are shown in the tables below.

Table 36 : damage model plugin manager attributes list

Attribute Name	Attribute Type	Attribute Meaning
plugins	dict	a dictionary composed of all plug-ins. The "key" is the plug-in name, which is a string type, and the "value" is the plug-in startup function in the corresponding plug-in, which is a function
current_damage_model	str	plug-in name used by the current damage model plugin manager

Table 37 : damage model plugin manager methods list

Method Name	Parameter List (name : type : unit)	Return Values	Method Function
<code>__init__</code>	-	-	initialize an instance of the damage model plugin manager
<code>set_damage_model</code>	(plugin_name : str : -)	-	set the value of <code>current_damage_model</code> to <code>plugin_name</code>
<code>execute_damage_model</code>	(constellation : constellation : - , sh : shell : - , num_of_damaged_satellites : int : - , dT : int : second , satrt_satellite_id : int : -)	-	according to the value of the <code>current_damage_model</code> attribute, the startup function of the corresponding plug-in is called to execute the damage model.

The operating mechanism of this framework is: first instantiate a damage model plugin manager object. This object contains two attributes: "plugins" and "current_damage_model". "plugins" is a dictionary type attribute used to store various damage model plugins. "current_damage_model" is a string type used to represent the damage model plugin used by the current manager.

During the instantiation of the manager object, the system automatically reads all damage model plugins and stores them in the "plugins". The key of "plugins" is the name of the plugin, and the value of "plugins" is the startup function of the plugin. After reading all plug-ins, the system sets the value of "current_damage_model" to "sunstorm_damaged_satellites", indicating that the "sunstorm_damaged_satellites" plug-in is used as the default damage model plugin.

If you want to execute the damage model, you only need to call the "execute_damage_model" method of the manager object. This method will automatically call the startup function of the plug-in indicated by "current_damage_model".

If you need to switch the damage model plug-in, just call the "set_damage_model" method and pass in the plug-in name you need as a parameter.

After you write your own damage model plug-in according to the interface specifications introduced earlier, you only need to set "current_damage_model" as your plug-in name, and the system will automatically recognize your plug-in and execute it.

8.3.5.3 case study

Now, we take "sunstorm_damaged_satellites" as an example to explain the operation of the constellation high survivability module.

Step 1 : instantiate the damage model plugin manager object :

```
# initialize the constellation damage model plugin manager
constellationDamageModelPluginManager =
constellation_damage_model_plugin_manager.damage_model_plugin_manager()
```

Step 2 : set the currently used damage model plug-in :

```
constellationDamageModelPluginManager.current_damage_model =
"sunstorm_damaged_satellites"
```

Note : The damage model plugin manager already sets the "current_damage_model" value to "sunstorm_damaged_satellites" when initialized, so this step can be omitted here. But if you want to use other damage model plugins, this step cannot be omitted.

Step 3 : call the "execute_damage_model" method of "constellationDamageModelPluginManager" to execute the "sunstorm_damaged_satellites" plug-in :

```
constellation_sunstorm_damaged = constellationDamageModelPluginManager.\
    execute_damage_model(constellation , constellation.shells[0] , 0.05 , dt
, 230)
```

The complete code of the above process can be found at:

"samples/XML_constellation/positive_Grid/*" and "samples/TLE_constellation/positive_Grid/*".

8.3.6 constellation_routing

This section is also composed of "framework" and "plug-ins". The "framework" part is the "routing policy plugin manager". The "plug-ins" part is a variety of routing policies, such as shortest path, least hop path and other policies. In StarPerf 2.0, we provide three routing policies by default : shortest path, least hop path and second shortest path.

8.3.6.1 plug-ins

All plug-ins under this module are routing policies, and one plug-in represents a policy. We implement the shortest path, least hop path and second shortest path by default, and you can write other routing policies plug-ins by yourself according to the interface specifications. The interface specifications for this part are as follows :

- **Requirement 1** : The storage location of the plug-in is (starting from the root of StarPerf 2.0) : "src/TLE_constellation/constellation_routing/routing_policy_plugin/"(for TLE constellation) or "src/XML_constellation/constellation_routing/routing_policy_plugin/"(for XML constellation).
- **Requirement 2** : Each plug-in is a ".py" file, and all source code for the plug-in must be located in this script file.
- **Requirement 3** : The launch entry for a plug-in is a function with the same name as the plug-in.
- **Requirement 4** : The startup function parameter requirements are as follows :

Table 38 : routing policy plug-ins startup function parameter list

Parameter Name	Parameter Type	Parameter Unit	Parameter Meaning
constellation_name	str	-	the name of the constellation
source	user	-	the source user
target	user	-	the target user
sh	shell	-	a shell class object, representing a shell in the constellation
t	int	-	a certain time slot (timeslot)

- **Requirement 5** : The return value of the startup function is the routing path after executing the routing policy.
- **Requirement 6** : If one plug-in needs to save intermediate data or result data, the data should be saved in an h5 format file under "data/".

8.3.6.2 framework

This part of the framework consists of 1 py script: "**routing_policy_plugin_manager.py**". A constellation routing policy plugin manager is defined in this script to manage all plug-ins under this module.

The so-called constellation routing policy plugin manager actually defines a class named "routing_policy_plugin_manager". The attributes and methods contained in this class and their functions and meanings are shown in the tables below.

Table 39 : routing policy plugin manager attributes list

Attribute Name	Attribute Type	Attribute Meaning
plugins	dict	a dictionary composed of all plug-ins. The "key" is the plug-in name, which is a string type, and the "value" is the plug-in startup function in the corresponding plug-in, which is a function
current_routing_policy	str	plug-in name used by the current routing policy plugin manager

Table 40 : routing policy plugin manager methods list

Method Name	Parameter List (name : type : unit)	Return Values	Method Function
<code>__init__</code>	-	-	initialize an instance of the routing policy plugin manager
<code>set_routing_policy</code>	(plugin_name : str : -)	-	set the value of current_routing_policy to plugin_name
<code>execute_routing_policy</code>	(constellation_name : str : -, source : user : -, target : user : -, sh : shell : -, t : int : -)	-	according to the value of the current_routing_policy attribute, the startup function of the corresponding plug-in is called to execute the routing policy.

The operating mechanism of this framework is: first instantiate a routing policy plugin manager object. This object contains two attributes: "plugins" and "current_routing_policy". "plugins" is a dictionary type attribute used to store various routing policy plugins. "current_routing_policy" is a string type used to represent the routing policy plugin used by the current manager.

During the instantiation of the manager object, the system automatically reads all routing policy plugins and stores them in the "plugins". The key of "plugins" is the name of the plugin, and the value of "plugins" is the startup function of the plugin. After reading all plug-ins, the system sets the value of "current_routing_policy" to "shortest_path", indicating that the "shortest_path" plug-in is used as the default routing policy plugin.

If you want to execute the routing policy, you only need to call the "execute_routing_policy" method of the manager object. This method will automatically call the startup function of the plug-in indicated by "current_routing_policy".

If you need to switch the routing policy plug-in, just call the "set_routing_policy" method and pass in the plug-in name you need as a parameter.

After you write your own routing policy plug-in according to the interface specifications introduced earlier, you only need to set "current_routing_policy" as your plug-in name, and the system will automatically recognize your plug-in and execute it.

8.3.6.3 case study

Now, we take "shortest_path" as an example to explain the operation of the constellation routing module.

Step 1 : instantiate the routing policy plugin manager object :

```
# initialize the routing policy plugin manager
routingPolicyPluginManager =
routing_policy_plugin_manager.routing_policy_plugin_manager()
```

Step 2 : set the currently used routing policy plug-in :

```
# switch routing policy
routingPolicyPluginManager.set_routing_policy("shortest_path")
```

Note : The routing policy plugin manager already sets the "current_routing_policy" value to "shortest_path" when initialized, so this step can be omitted here. But if you want to use other routing policy plugins, this step cannot be omitted.

Step 3 : call the "execute_routing_policy" method of "routingPolicyPluginManager" to execute the "shortest_path" plug-in :

```
# execute routing policy
least_hop_path = routingPolicyPluginManager.execute_routing_policy(
    constellation.constellation_name , source , target ,
    constellation.shells[0])
```

The complete code of the above process can be found at:

"samples/XML_constellation/positive_Grid/*" and "samples/TLE_constellation/positive_Grid/*".

9. Test Sample Module : samples/

This module stores test cases for each sub-function of StarPerf 2.0. Each test case is a py script, and these scripts are independent of each other. We have written corresponding test scripts for all implemented functions in StarPerf 2.0 and stored them in this module in categories.

Each test script can be launched individually to test a single function. Integrated startup can also be used to test multiple functions at the same time.

10. StarPerf 2.0 Startup Script : StarPerf.py

This is the entrance to the entire system. Starting this script can execute all functions of the StarPerf 2.0 system.

The following information is printed when the script is executed (part) :

```
Test(02/16) : calculate the delay between two locations in +Grid mode
The delay time from London to NewYork for every timeslot is [0.08283360666666666, 0.041923166666666664] s
Test(03/16) : calculate the bandwidth of two locations in +Grid mode
The bandwidth from London to NewYork for the average of all timeslots is 10.0
Test(04/16) : calculate the constellation betweenness centrality value betweenness in +Grid mode
The betweenness values of each satellite in the constellation are : [0.01423188699783495, 0.014231886997834951, 0.0142318869978
Test(05/16) : calculate the constellation coverage rate in +Grid mode
```