Basic of Mission and System Design for IoT Mission

Shinichi Nakasuka, Ritsumeikan University

1． IoT Mission

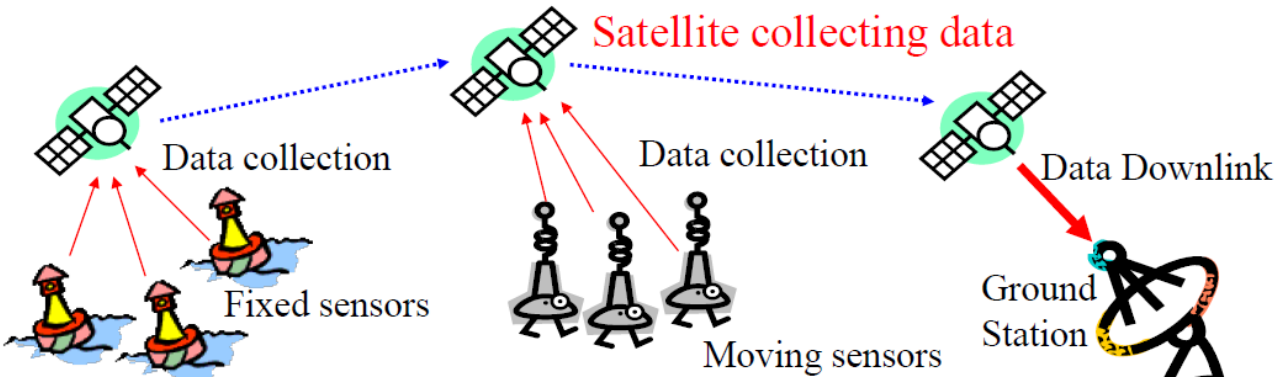


Fig. 1 Overview of IoT Mission

2. IoT Mission Requirements and System Performance Specifications

For the IoT mission, the top-level mission requirements are as follows.

1) How frequently should the sensor get data and send it to satellites?
Example) Once per day, 2-hour interval, 30-minute interval, etc.

2) How much data has to be sent to the satellite in one data transmission?
Example) If it includes 8 data items of 1 byte, then the packet size is 8 bytes.

3) How much delay is allowed from the time when a satellite receives the data from the ground to the time when the data is then downlinked to the ground station?
Example) If the data to be downlinked is urgent data, the allowed time may be one or two hours, but if it is long-term agriculture related information, it may be one or two days.

4) How many sensors will be placed in a vicinity, for example, within a 10km x 10km area, in order to make your IoT mission meaningful?
Example) If you want to install sensors with a 1km interval, then the number of sensors within a 10km x 10km area will be 100.

Based on these mission requirements, we have to derive various parameters which define the satellite functions. The following items are the most “upstream” performance specifications of the overall IoT constellation system or its member satellites, from which the system analysis and design of the satellites or their constellation will start.

These specifications can be derived in the following 4 cases.
Case A: directly from the mission requirements
Case B: from state-of-the-art components which we can obtain with reasonable cost and

affordability (so, almost not changeable)
Case C: sometimes we should find a compromise considering both of the above two factors
Case D: we cannot control the performance in the initial phase when we don't have many satellites or ground stations

1) IoT uplink bit rate (bps)
Case B: we are considering the usage of the **LoRa protocol**. In that case, the bit rate will be **400-1900bps.**

2) Total amount of data per one transmission (bytes)
Case C: If we need to send large data amounts to the satellites, we can do it by extending the duration of packet transmission to the satellites. But if it is too long, it will not be feasible to send all the data while the satellite is visible from the IoT sensor on the ground, and it will increase the probability of data collision. The best choice is to define a "maximum duration", and to adjust the actual duration (while keeping it less than the above maximum duration) according to the amount of data to be transmitted.

3) IoT transmission power (W)
Case B: We would like to use a license-free frequency. This can be used under the condition that the RF power is less than a certain value, which defines the maximum power for RF transmission from IoT sensors to satellites.

4) Interval between successive data reception from one sensor (minutes/hours)
Case C: This is determined by how the object to observe changes over time

5) Latency from data reception by satellites until downlink to one of the ground stations (hours/days)
Case C: This will affect the number and locations of ground stations and downlink speed.

6) Error rate in the data transmission (%)
Case B: If the data to be sent is important data such as a password or a triggering command, the error rate should be small. Also, you can add "error detection and correction code", which reduces error rate at the cost of reducing the bit rate of actual data transmission.

7) Decoding capability to correctly decode many packets which are coming to one satellite at the same time
Case C: This is the biggest technological issue to be solved for the IoT mission. Based on the mission requirement we can estimate how many data packets will be transmitted to the satellite at (almost) the same time, and we have to find some technique (such as FDMA, TDMA, or their combination, etc.) to separately decode these incoming RF signals. A 100% decode rate is probably infeasible, so we should also define with what error rate the receiver system on the satellite should decode the incoming RF signals. (such as 10^{-3} – 10^{-6})

8) IoT Uplink Frequency (MHz-GHz)

Case C: Participants surveyed the license-free frequencies in their countries, and we found two regions **400-435MHz** and **860-930 MHz** which are widely utilized as license-free frequencies. We must select either of the above regions or both regions, considering the trade-off between number of participating countries and technological difficulties, workload, and cost.

As you can see from the above analyses, there is no **"Case A"**. Therefore, all the performance specifications have to be designed not only considering mission requirements, but also technological availability or difficulties, regulations, and other factors such as cost, user community, future growth possibilities, etc.

3. IoT Communication System Design

The first important task of satellite system design is to design the mission subsystem, which is the IoT transmitter (on ground) and IoT receiver (in the satellite). From the discussions in the previous section, many factors should be taken into account when designing the mission subsystem, and there may be multiple options for the solution. If the exact design can already be decided, it would be good to use it for the following design process. But if you cannot decide on the design yet, it would be appropriate to decide on a tentative setting of the mission subsystem, or pick up two or three settings and conduct the follow-on design process in parallel. In this tutorial, we will pick up LoRa as the IoT uplink method and tentatively define its performance specifications as in Table 1. Some parameters which are related to the number of satellites or ground stations don't have to be specified at this point, as we first want to focus on individual satellite design.

Table 1 Tentative Settings of Performance Specifications

Items	Tentative Setting	Reason and notes
1. Uplink bit rate	300 bps	Within LoRa standard
2. Total amount of data per transmission	25 byte max	Maximum duration is 5 sec
3. IoT Transmission power (W)	20 mW	Most widely used limit value
4. Maximum duration of data uplink (s)	4 sec	LoRa standard rule
5. IoT uplink frequency (MHz)	860-920MHz 400-433MHz	Two options exist

4. System Analysis and Design of Satellite

Based on these performance specifications, we have to conduct a "system analysis and design" of the satellites and/or their constellation. In the following section, we will pick up several system design tasks and explain how to obtain important design parameters for the satellite. The derivation of other design parameters will be explained in the later subsystem tutorials.

1) **“Amount of data” sizing study**

How much data will be received by a satellite per day, which will determine the memory size, C&DH subsystem performance, and downlink speed of the communication subsystem.

2) **“Communication link” study**

There are three communication systems, IoT data uplink, H/K (House Keeping) data uplink, and H/K data downlink. For each path, a link equation will be used to derive communication subsystem parameters such as antenna gain, RF power, communication speed and BER (Bit Error Rate), etc. The details will be explained in “communication subsystem” tutorial.

3) **“Attitude control capability” study**

How much accuracy is required for attitude determination, orientation and stability, which will determine attitude control sensors and actuators, control algorithm, and interval of attitude control, etc.

4) **“Weight and size budget” study**

After the components to be implemented are selected, we have to check whether all components can be installed within the satellite size. If we utilize a CubeSat, we should follow the form factor, such as by referring to the handbook “CubeSat Design Specifications.”

https://www.nasa.gov/wp-content/uploads/2018/01/cubesatdesignspecificationrev14_12022-02-09.pdf#:~:text=A%20CubeSat%20is%20a%20class%20of%20satellites%20that,with%20a%20mass%20of%20up%20to%202%20kg.

5) **“Power budget” study**

How much power is required for the satellite, which will define the area of solar cells, battery size, and other performance parameters of the electric power subsystem, etc.

6) **“Required quantity of satellites” study**

This is related to the satellite coverage over each area. If many satellites exist, IoT uplink can be done every time. If only one satellite exist, the coverage of each area is roughly about 40 minutes per day. (10 minutes x 4 times) for SSO satellite case.

7) **“Required quantity of ground stations” study**

This is related to the allowance of data latency (time from data uplink to downlink to ground station). If there are many ground stations all over the world, the uplinked data can be quickly downlinked to ground. Usually one ground station can access to one satellite for 40minutes (10 minutes x 4 times) per day for SSO satellite case.

4.1“Amount of data” sizing study for IoT mission

The amount of IoT data to be received by one satellite per day can be roughly calculated by the following sequence.

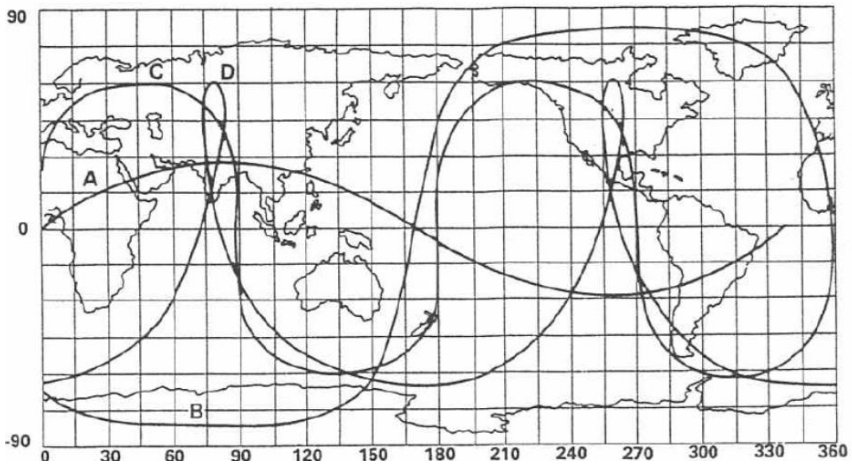


Fig. 2 Examples of SSP for Various Orbits (B is SSO)

1. Using knowledge of "Orbital Mechanics", draw the SSP (Sub-Satellite Point) of the satellite's trajectory on an Earth map. Fig. 2 shows an example of SSP for various orbits. The detail of how SSP can be calculated will be explained in the "Orbit Design" tutorial. If you face difficulties, you can assume a typical trajectory such as a Sun Synchronous Orbit (SSO), ISS orbit, or other popular orbits. All the SSP for one day should be drawn.

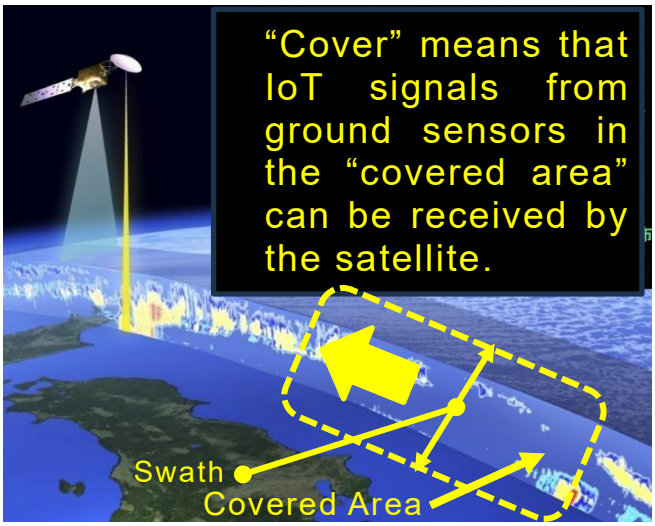


Fig. 3 Concept of SSP, Swath and Covered Area

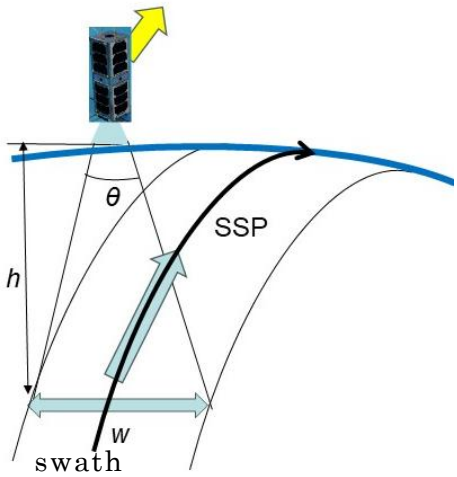


Fig.4 Calculation of Swath

2. Calculate the swath of the "covered area" for IoT uplink communication. Swath ***W*** can be calculated using the height ***h*** and beam width ***θ*** of the IoT receiving antenna.

θ is the antenna effective angle, which indicates that IoT signal coming from this area can be received by a satellite, as will be explained in the "communication subsystem" tutorial. Swath ***W*** can be roughly calculated as $W = h \times \theta$ (with θ in rad).

3. Draw the covered areas on both sides of the SSP using the trajectory of SSP over one day.

4. Considering that your IoT missions will be conducted all over the world, you can sum up all the IoT data to be uplinked from the covered area per day. Please assume a certain amount of mission need all over the world.

5. By considering the future growth of the IoT data transmission needs, the amount of data calculated in step 4 will be multiplied by a certain factor such as 10.

4.2"Communication link" study

There are three communication paths: IoT data uplink, House Keeping (H/K) data uplink, and H/K data downlink. For each path, you should use the "Link Equation" to determine RF power, antenna gain (deciding the antenna shape and size), bit rate (bps), and bit error rate (BER). Sufficient "Link Margin" has to be obtained for each path so that the communication is reliable under various disturbances.

4.3 "Attitude control capability" study

Attitude control of the satellite is required in order to conduct the mission, to obtain enough solar power from its solar cells, and/or to keep a stable attitude while the satellite receives uplink commands from the ground and/or sends downlink data to the ground. At this stage, requirements on attitude control have to be clarified, and will guide what kind of attitude sensors/actuators will be needed and what kind of estimation and control algorithms have to be implemented.

There are three accuracy requirements regarding attitude control, as follows:

A) <u>Attitude determination accuracy</u>

This describes the accuracy of knowledge on the satellite's attitude. For example, if a satellite detects a forest fire on Earth and tries to estimate the location of the fire, then knowledge about the satellite's attitude directly affects the accuracy of the estimated location of the fire. For an IoT mission, strict accuracy is likely not required as the uplink system's position is known beforehand or estimated by GPS information attached to the uplink system.

B) <u>Attitude orientation accuracy</u>

This relates to how accurately the attitude of the satellite can be controlled. For an IoT mission, usually the antenna of the IoT receiver system has to be directed towards the nadir direction, and if the accuracy is not good enough, the antenna cannot receive a signal.

However, this accuracy is not a big issue for an IoT mission. It is sufficient if the antenna is roughly directed towards the Earth. Therefore, the accuracy requirement is very rough such as 30-45 degrees.

On the other hand, when the satellite receives uplink commands or downlinks data, this accuracy is important as the respective antenna should be directed towards the ground station.

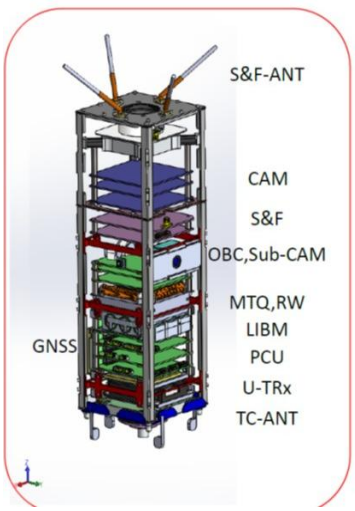
C) **Attitude stability**

This relates to how stable the attitude is. For an IoT mission, this is not a big issue, for the same reason as the above two items. At the time of command uplink or data downlink, it should be controlled so that the attitude does not deviate beyond the above orientation accuracy requirement value for the duration of uplink or downlink.

As for the attitude orientation accuracy requirement, the value will be determined in detail together with communication subsystem design in the later tutorial.

4.4 "Weight and size budget" study

This study lists up candidates of components to be installed in the satellite, and checks whether the components can be put into the satellite size and whether the total weight is within the limitation. At this point, we have not yet designed the structure and wire harnesses, so these weights are respectively assumed to be about 10% and 7% of the sum of the component weights. You should also include information about the required power and allowable temperature range for each component. Fig. 5 shows the basic specifications and Table 2 shows the component list for TRICOM-1R, a 3U IoT CubeSat launched in 2018. These will be used for power budget calculation in the power budget section.



Items	Values	Miscellaneous
Size	10x10x30cm	3U size
Weight	< 3kg	
OBC	"Bocchan"board	Internal made
Power (average)	4W	AZUR GaAs cell
Battery	Li-Ion 41 wh	LIBM
Downlink (H/K&data)	W 1.2kbps	460MHz AFSK "U-TRx"
Uplink(H/K)	50W 9600bps	401MHz
Attitude	Simple 3 axis	B-dot law only
Sensor	magnetic sensor, gyro GPS receiver	"GNSS"
Actuators	magnet torquer despun wheel	"MTQ" "RW"
Camera	GSD 314 m VGA @180km	"CAM"
Sub-Camera	GSD 67 m @600km	"Sub-CAM"

Fig. 5 Image and Specifications of TRICOM-1R launched in 2018

Table 2 Component list for TRICOM-1R satellite

Component name	Size	Weight (per unit)	Required power	Allowable Temperature	Specifications
Communication Subsystem					
UHF Transceiver	W77mm x 59mm x H16mm	122g	6W (Transmitter) 0.1W: (Receiver)	-20℃～+50℃	Transmitter RF Power: 2W GFSK, 1.2 - 76.8kbps
Attitude Control Subsystem					
MTQ-X, Y, Z	Φ10mm x 60mm	44.1g	0.1W	—	
GNSSR	50mm x 50mm x 5mm	30g	0.15W (3.3V, 45mA)	-40℃～+85℃	
Power Subsystem					
PCU	90mm x 87.3mm	47g	0.1W	-10℃～+50℃	
PDU	90mm x 87.3mm	47g	0.1W	-10℃～+50℃	
Li-Ion Battery	92mm x 76mm	318g	—	0℃～+40℃	18650 cell 2 serial x 2 (8.4V, 5.8Ah)
Solar Cells	80mm x 40mm	50mg/cm^2	—	lower, the better	AZUR-3G30A Body Mount 6 serial
C&DH Subsystem					
MOBC (PIC32)	90mm x 87.3mm	42g	0.7W (7V, 102mA)	-10℃～+50℃	PIC32MX795F512L 512kB ROM 128kB RAM 30MHz 1.65DMIPS/MHz Input voltage: 3.3V SPI FLASH ROM 8MB(M25P80) SPI FRAM 8kB(FM25CL64B) 9-axis sensor: MPU-9250 (I2C, 3-axis gyros, magnetometers, accelerometers)
Mission Com					
S&F Receiver	95mm x 92.8mm	80g	0.4W	-10℃～+50℃	
Camera	95mm x 92.8mm	50g	3W (design value)	-10℃～+50℃	

4.5 “Power budget” study

This study determines the area of solar cells, configuration of solar cells (body mounted or solar paddle) and battery sizing. The first thing to do is to analyze the direction of sunlight with

respect to the satellite's nominal attitude, and the percentage of eclipse. Fig. 6 shows the relationship between sunlight direction and the orbital plane. In the left figure, the sunlight is coming from the perpendicular direction to the orbital plane, therefore the sunlight is always shining on the satellite. In the right figure, the sun is occulted by the Earth for around 50% of the time. Once we define the attitude orientation scenario (nadir pointing of the IoT antenna is the most popular scenario for an IoT mission), then the time history of the sunlight incidence angle on each surface of the satellite can be calculated. This eclipse rate will be changed if the satellite orbit is subject to a perturbation (which is the usual case for an IoT satellite), so if the orbit is not maintained using thrusters, you should assume the maximum eclipse rate (right figure in Fig. 6) for the next steps of satellite design.

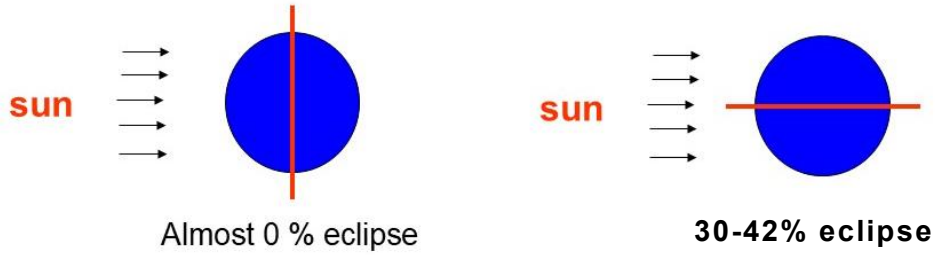
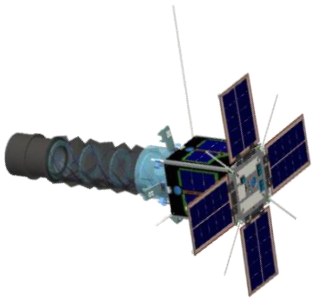


Fig. 6 Relationships between sunlight direction, orbital plane, and "eclipse rate"

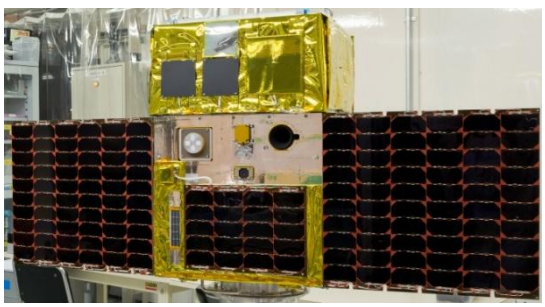
Based on the history of the sun incidence angle, you should calculate the total solar power generation per orbital cycle. For this calculation, you first should assume a certain solar cell configuration. There are two typical options: "body mounted" type and "solar paddle" type as in Fig. 7.



PRISM (launched in 2009)

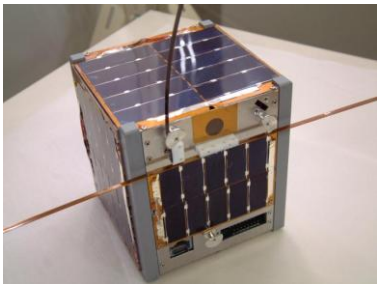


TRICOM-1R
(launched in 2018)



Hodoyoshi-4 (launched in 2014)

< Solar paddle type >



XI-IV (launched in 2003)

< Body mounted type >

Fig.7 Solar cell configuration: "solar paddle" type and "body mounted" type

The solar paddle type has the advantage that large power generation is possible, so it is suitable for satellites and missions requiring large electric power. The drawback is that power generation heavily depends on the attitude control capability; if the attitude control system fails and the solar cells are not directed towards the sun for a long time, the satellite may fail. Another difficulty is that if an Earth-pointing attitude is continuously required for the mission, such that an antenna should be directed towards the Earth, then it would be difficult to direct the solar paddle towards the sun direction all the time.

On the other hand, the body mounted type cannot produce large solar power since the solar cell area is small, but power generation does not depend on attitude control; even if the attitude is not controlled, a certain amount of power is continuously generated.

The IoT mission does not require so much power, and the antenna bore sight should be directed towards the Earth almost all the time. Therefore, it would be appropriate to employ a "body mounted" type configuration with the IoT antenna pointing towards the Earth as in Fig. 8. Then, you should design how the solar cells, with what efficiency, are attached to each surface. If you obtain the area of each surface and the efficiency, together with the time history of the sun incidence angle for each surface as explained before, you can calculate the power generation history for one orbital cycle.

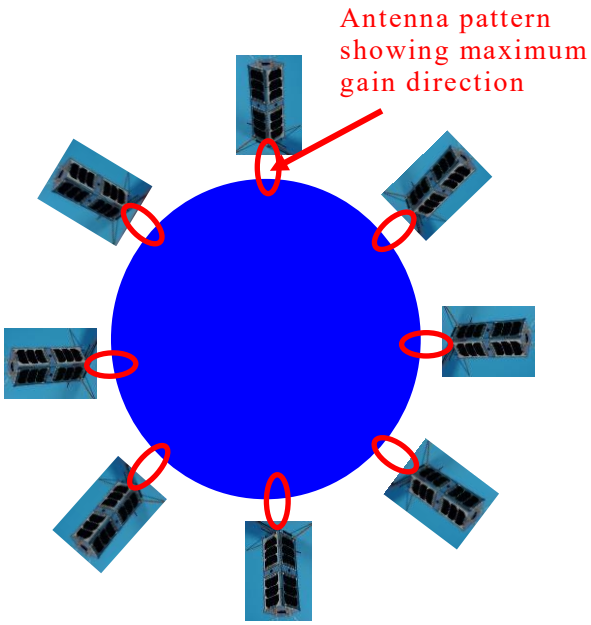


Fig. 8 Suggested solar cell configuration and attitude history for IoT satellite

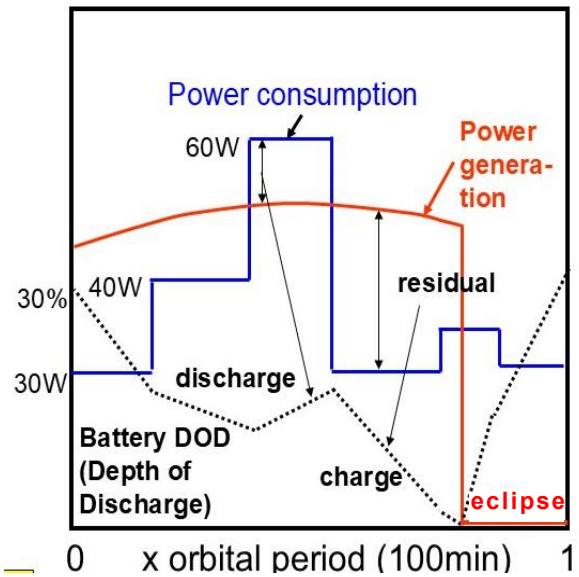


Fig. 9 Power balance and battery sizing study

The next step is the component power on-off history design and the battery sizing. For this process, you should first define the power requirements based on the components inside the satellite. Therefore, you should roughly decide what kind of components have to be installed, when these components are turned on, and for how much time, etc.

Fig. 9 shows the battery sizing process. The red line shows the solar power generation which

is calculated in the previous step. The blue line shows the power consumption history obtained based on the on-off history of the components inside the satellite. For example, at the time when the RF transmitter is turned on, power consumption quickly becomes very high (such as 60W in the figure). The area between the red or blue line and the horizontal axis of the figure tells us how much energy is generated (red line) or consumed (blue line). Therefore, these two areas should be matched, which means that the power balance between generation and consumption is maintained. If these two areas are not matched, you should change the on-off history of some components until these two areas become the same.

Then, after assuming a certain type and size of the battery, you can draw a line showing the battery DOD (Depth Of Discharge) history. At times when the red line is higher than the blue line, DOD decreases as battery charging is occurring. If the above power balance is maintained, the DOD at the rightmost position is the same as the value at the leftmost position (in the figure, denoted as "30%"). This DOD should be less than around 30% for a Lithium-Ion battery as the number of charge-discharge cycles is very large in space (such as 16-17 times per day), which damages the battery if the DOD is large. If in Fig. 8 the maximum DOD is higher than 30%, you should increase the battery size to decrease this maximum DOD.

At the end of this power budget study, you obtain the solar cell configuration including the area of the solar cells, on-off history of the components inside the satellite, and the size of the battery.

4.6 "Required quantity of satellites" study

This is related to the satellite coverage over each area. If you assume the satellite is SSO (Sun-Synchronous Orbit), the satellite flies over the area in average for 40 minutes per day. (10 minutes x 4 times), and the uplink timing will occur in the following schedule.

1) 10 minutes IoT possible time
2) **90 minutes IoT impossible time**
3) 10 minutes IoT possible time
4) **10.2 hours of IoT impossible time**
5) 10 minutes IoT possible time
6) **90 minutes IoT impossible time**
7) 10 minutes IoT possible time
8) **10.2 hours IoT impossible time**

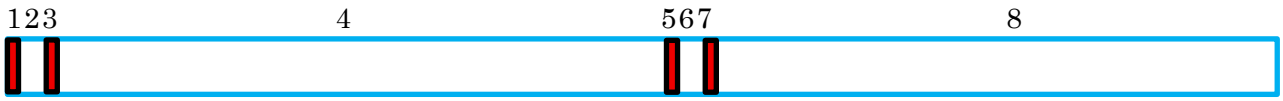


Fig. 10 IoT possible regions (red area) per day

If you add one more satellite and carefully design its orbit, the above 4) and 8) "IoT impossible time" can be reduced. For example, if the second satellite is allocated like this, you can reduce the maximum "IoT impossible time" can be reduced by half.

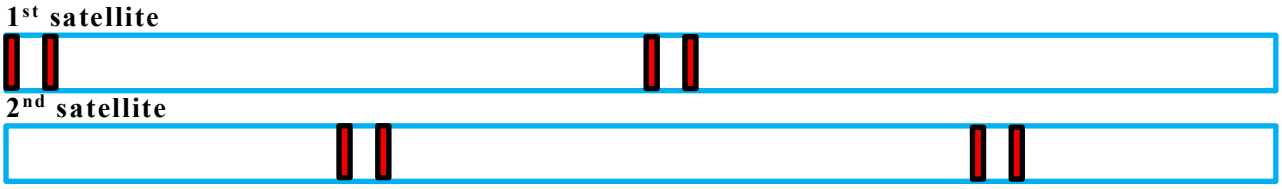


Fig.11　2nd satellite addition

4.7 "Required quantity of ground stations" study

This also requires similar analysis as 4.6.　For SSO satellites, downlink timing occurs roughly as the same as IoT uplink timing, i.e., 4 times of 10 minutes each with the same interval.　By combining the IoT uplink and this downlink timing, you can design latency such as in Fig.12. This relationship between IoT uplink timing and downlink timing is only for your interested areas (for your country, etc.), so if you want to realize this latency requirement all over the world, different analysis will be required.

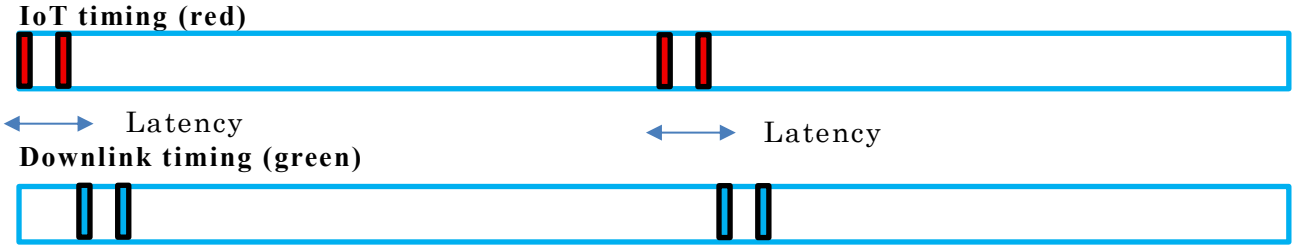


Fig.12　IoT timing and Downlink timing

Exercise (options to the next page's presentation)

1) **Calculate the required quantity of satellites and location of ground stations for your IoT mission**

Please design IoT timing and downlink timing as in Fig.11 and Fig.12 to realize the required uplink interval and downlink latency for your IoT mission.　You don't have to consider the mission all over the world, focusing on IoT mission in your country or interested areas. Through this process, finally please obtain the required quantity of IoT satellites and decide where your ground stations should be located.

Group Work

Please pick up one or more promising IoT missions and conduct a quantitative analysis of the proposed IoT missions and prepare to present them as realistic, technically feasible mission concepts with some quantitative analysis.

Each team will calculate and determine key design parameters, including:

- the number and geographical distribution of ground sensors;
- the maximum acceptable latency;
- the required interval of observation or data-collection;
- the volume of data to be transmitted;
- the number of required satellites;
- (optional) number and locations of ground stations
- other relevant system requirements.

Based on this analysis, each team is to prepare a presentation outlining its mission concept and demonstrating its feasibility.

< Example of presentation >

1) Proposed IoT mission concept (One or more missions are acceptable)

2) Why they are required? How they contribute to the society in which countries or regions?

3) Who will pay for these missions? How you can make them continue?

4) System design of IoT mission including several quantitative design parameters as above.