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# Design Optimization for Mass Sizing of LEO Communication Satellites

*Luqman Fathurrohim, Ridanto Eko Poetro*, Ahmad Fariz*
*Faculty of Mechanical and Aerospace Engineering*
*Institut Teknologi Bandung*
**ridanto@ae.itb.ac.id*

ABSTRACT

*This paper focuses on the design optimization of communication satellites for the constellation in low earth orbit (LEO). The optimization starts with defining an objective function, which is the total mass of satellites, as a function of their orbit altitude, antenna transmit diameter, and nominal data rates. The optimization routine was done in order to minimize the total mass of satellites in order to reduce the total launch mass and the total cost. The use of three different design parameters has led to a genetic algorithm (GA) as an optimization method to find the best value for each design parameter. The results show that the optimization process using a genetic algorithm is successfully applied in solving complex multidisciplinary design problems such as the design of a communication satellite system with acceptable error.*

**Keywords:** *Optimization, altitude, data rates, genetic algorithm*.

## Introduction

The growth of the small satellites class has significantly increased since the late 1990s. The CubeSat specification was developed at Stanford University and the California Polytechnic State University, San Luis Obispo in 1999 to facilitate the participation of science and engineering students in academic satellite development programs [1]. The evolution of the original picosatellite specification of a 10x10x10cm cube with a maximum mass of 1kg (a 1U CubeSat) has since resulted in the standardization of nanosatellites, which range in size from 1U to 6U (30x20x10cm) and weigh between 1-8 kg. The cost of CubeSat development can be lowered by using commercial off-the-shelf (COTS) components. Their small size and standardized components can

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reduce the launch cost of the satellite. Moreover, it will decrease the chance of failure because COTS components are already certified. Nowadays, multiple small satellites can be used to accomplish a mission instead of a much bigger and costlier conventional satellite.

CubeSat development is similar to other spacecrafts and is a highly coupled problem. Thus, generating optimum design variables values is obligatory. Genetic algorithms have been widely used for generating an optimum design of spacecrafts. Mosher [2] in 1999 proposed a tool based on genetic algorithms for conceptual spacecraft design to generate systematically a wide range of alternatives. Hassan and Crossley [3] use genetic algorithms for the multi-objective optimization of the conceptual design of communication satellites. Genetic algorithms are also used to optimize design variables such as satellite constellation design [4]-[7], beam design [8], and structural design [9]. Recent research uses this method to optimize the layout of satellite components [10, 11], and determine the topology of the satellite network [12].

The objective of this paper is to optimize communication CubeSat-based satellite mass using a genetic algorithm. First, the preliminary satellite payload design is done by following the steps suggested by Wertz [13]. Then, the constellation, subsystems, and cost designs are optimized. The design parameter that provides a good compromise between design variables is chosen as the conceptual design.

## Preliminary Design

### Constellation Preliminary Design

The performance of many space missions is enhanced through the utilization of constellation architecture. Before starting to design the payload of the communication satellite system, the satellite constellation was designed in order to cover all regions of Indonesia. The constellation is restricted at LEO orbit, which has an altitude between 500 km and 1500 km. As Indonesia is located around the equator, the satellites are placed at a 0-degree inclination in order to give a good repetition. However, the maximum angle of the line of sight was set at 5-degree. Therefore, there will be a correlation between the number of satellites and their altitude as shown in Equation (2).

$$\varphi = \sin^{-1}\left(\frac{R_E}{R_E + h}\sin 95^0\right) \tag{1}$$

$$N = \frac{360^0}{(85^0 - \varphi)} \tag{2}$$

where the value of $\varphi$ is measured in degree, $R_E$ indicates the radius of the earth, and $h$ indicates the altitude of the satellites. In the preliminary design phase, the altitude was set at 1500 km. Thus, the initial required number of satellites is four.

## Payload Preliminary Design

This paper focuses on the link budget of communication system between the satellite and users in the coverage region. The authors assume that the users are connected directly through the satellite. However, the focus will be on the satellite-to-user link (uplink and downlink).

The calculations of the satellite-to-user link are based on the formulation that is provided in [13]. Several assumptions are used to simplify the calculations, as shown in Table 1.

Table 1: Parameters Assumptions

| Parameter | Value |
|---|---|
| Frequency | 2.2 GHz |
| Transmitter Line Loss | -1 dB |
| Transmit Antenna Beamwidth | $30^0$ |
| Transmit antenna pointing offset | $15^0$ |
| Polarization loss | -0.3 dB |
| Antenna user's diameter | 0.3 m |
| System Noise Temperature | 614 K |
| Implementation Loss | -2 dB |

Based on the link equation or link budget formulation, the relationship between data rate, antenna size, propagation path length, and transmitter power is shown in Equation (3).

$$\frac{E_b}{N_0} = \frac{P L_t G_t L_S L_a G_r}{k T_S R} \tag{3}$$

where $\frac{E_b}{N_0}$ is the ratio of received energy-per-bit to noise-density (in dB) and $P$ is the transmitter power (in dBW). $L_t$ is the transmitter-to-antenna line loss (in dB). $L_s$ is the space loss and $L_a$ is transmission path loss (in dB). $G_t$ is the transmit antenna gain and $G_r$ is the receive antenna gain (in dBi). $k$ is Boltzmann's constant ($1.38064852 \times 10^{-23}$ J.K$^{-1}$) and $T_s$ is the system noise temperature (in K). $R$ is the data rate (in bps). The value of $L_s$ is determined by propagation path length between the satellite and the user, whereas $L_a$ is a function of environmental factors, such as rainfall density. In most cases, a $\frac{E_b}{N_0}$ ratio between 5 and 10 is a satisfaction for receiving binary data with low probability of error with some forward error correction [13].

Bit Error Rate (BER) is the key parameter used to evaluate the performance of the link. In the link budget calculation, the value of BER will determine the required $\frac{E_b}{N_0}$ between the transmitter and receiver. However, in this design study, we assume the value of BER at $10^{-7}$. Therefore, the required $\frac{E_b}{N_0}$ is 11.3 dB. Based on fact that there will be other losses in $\frac{E_b}{N_0}$ such as bit synchronizing errors, phase noise and frequency drift in local oscillators, and deviations from ideal responses, implementation loss must be added to the calculation of link margin. Thus, -2 dB will provide an adequate estimation for the implementation loss. Higher link availability for the user requires a greater link margin. Link margin is determined from the difference between the theoretical value of $\frac{E_b}{N_0}$ and the required $\frac{E_b}{N_0}$, including implementation loss. In the communication satellite payload design, the excess value of link margin will lead to an increase in cost. On the other hand, a lack of link margin could give an excess bit error rate. To overcome this problem, the link margin of S-band communication payload is assumed 7 dB.

The value of $\frac{E_b}{N_0}$ is determined by changing the design parameters, i.e., data rates, altitude of the satellite, and transmit antenna diameter. All of those key parameters will affect the power required by the satellite as well as its mass. However, the altitude will determine the time access. Therefore, the number of satellites will be determined as the function of altitude so the continuity access requirement is satisfied. The authors assume that all of the satellites are on the same altitude within their constellation.

The simulation of link budget will also lead to the determination of the mass of each individual satellite. Firstly, a particular value of data rates, transmit antenna diameter, and satellite's altitude is chosen. Secondly, the power required is yielded from a simulation of link budget. Thirdly, by using the power required, the calculation can be done to obtain the solar array area and battery mass that must be added into the satellite. Finally, by knowing the area of the solar array, it is possible to determine the mass of the power sub-system in the satellite. In the preliminary phase, the initial values of data rates, altitude, and transmitter antenna diameter are given as shown in Table 3. By using those values, the power required by payload is 88.9 Watt. In order to determine the total power required, the estimation of power distribution from [13] is used. From the preliminary phase, it was known that the power required by the satellite is 111.2 Watt.

Table 2: Power Distribution

| Sub-system name | Fraction Power |
|---|---|
| Payload | 87% |
| Electric System | 5% |
| Attitude Control | 3% |
| Propulsion | 3% |
| Thermal | 2% |

Table 3: Preliminary Input Design

| Input name | Value |
|---|---|
| Transmit Antenna Diameter | 0.3 m |
| Data Rates | 10 Mbps |
| Altitude | 1500 km |

The data of the required power is used to determine the mass of the satellite's power system (including solar array and batteries). GaAs (0.04 kg/W) solar array and NiMH (0.012 kg/W) batteries are used, resulting in 14 kg of mass of the power system. Table 4 shows the mass distribution of the sub-systems. To derive the mass of each satellite, the mass data of the power system is used as input. By knowing both the mass of each satellite and the number of satellites, the launch mass can be predicted. Thus, in this preliminary phase, the total number of satellites is six with a mass of 35 kg for each satellite.

Table 4: Mass Distribution

| Sub-system name | Fraction mass |
|---|---|
| Power system | 40% |
| Payload | 26% |
| Structure | 18% |
| Attitude Control | 7% |
| Command and data handling | 3% |
| Propulsion | 4% |
| Thermal | 2% |

## Optimization Methodology

Adapted from [12], a genetic algorithm is an optimization and search technique based on the principles of genetics and natural selection. The GA has more capabilities compared to conventional optimization methods: GA can be applied with a code consisting both discrete and continues design variables, GA is a population-based method and it can give a better design point by its reproduction in each generation, and finally because GA employ probabilistic choices rather than deterministic rules, it tends to search the entire design space and is not trapped in local minima [14]. The algorithm allows a population to evolve along the cost surface to find the point of minimum cost. Based on these considerations, for this problem a GA has been used as an optimizer. At the beginning, randomly a set of population is generated, process of a specific fitness based selection is applied in GA in order to produce the next generation, which has better fitness than before. This process is iterated until some stopping criterion is reached.

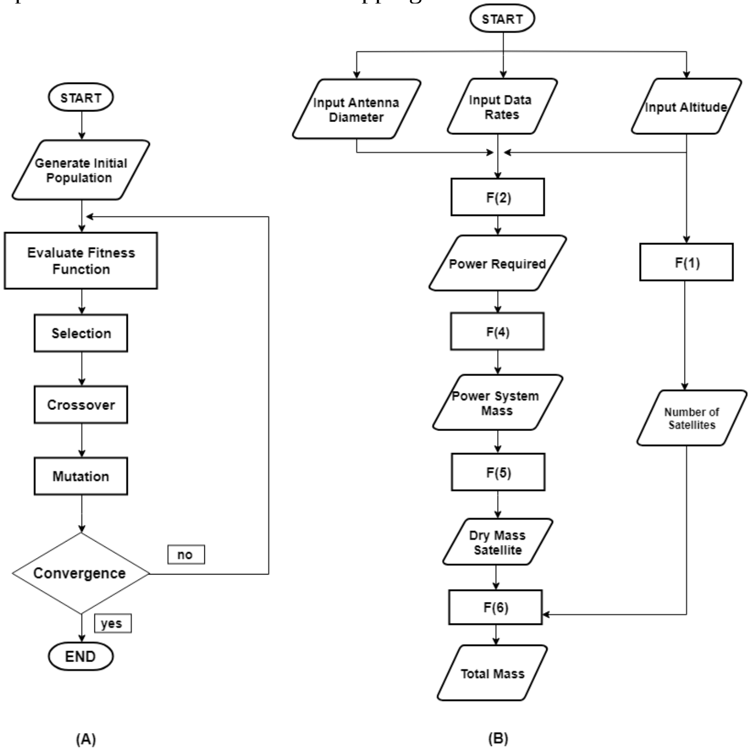


Figure 1: (A) Flowchart of basic real single objective Genetic Algorithm and (B) Fitness calculation functions.

There are two types of GA, which are binary-coded genetic algorithm and real-coded GA. Real-coded GA differ from the binary-coded GA in the coding of the problem variables. Since the problem variables are used directly in real-coded GA, there lies a need for developing new, yet efficient, crossover and mutation operators and when problem variables are directly used in a GA, binary-coded crossover operators can no longer be applied [15]. This study used real-coded GA as an optimization tool.

The multi-variable problem in this study is transformed into an optimization framework. The problem involves a minimization of the total mass of satellites, which depends on the number of satellites and payload mass. The number of satellites is determined as the function of altitude, which is part of the constellation parameter, while the payload mass is justified by the requirements of data rate and size of transmit antenna diameter.

However, the problem is decomposed into three disciplines level optimizers, i.e., altitude, data rate, and dimension of antenna beam; and a system level optimizer, i.e., the total mass of the constellation. The hierarchical structure of fitness calculation is illustrated in Figure 1.

The power required by each satellite can be obtained by function F(2) which can be derived as follows [13].

$$\frac{E_b}{N_0} = P + L_t + G_t + L_{pr} + L_s + L_a + G_r + 203.83 - 10\log R \tag{4}$$

$$L_s = -92.45 - 20\log S - 20\log f \tag{5}$$

$$G = -1559.59 + 20\log D + 20\log f + 10\log \eta \tag{6}$$

Equation (4) is the link equation, which can be used to estimate the required power from a particular configuration and objective of communication performance. Equation (5) shows the relation between the transmitter frequency, altitude of the satellite, and the value of space loss. The value of antenna gain in the transmitter and receiver, $\mathrm{G_t}$ and $\mathrm{G_r}$, can be obtained from Equation (6). All of parameters in equation (4), (5), and (6) have units in dB. The link equation has the following design constraint [13].

$$\left(\frac{E_b}{N_0}\right)_{req} = 7\ dB \tag{7}$$

The value of required power can be determined from Equation (4) due to the constraint in Equation (7). The required power of the payload becomes the input value to determine the required power of each satellite, which is obtained from Table 2. The mass of the satellite’s power system can be obtained from the data of specific energy production of the GaAs solar cell, denoted by F(4). Then, the dry mass of each satellite can be evaluated using Table 4 with mass of power system as the input. The number of satellites can be determined by using Equations (1)-(2), denoted as F(1) in the flowcharts. The total mass of all satellites can be obtained by function F(6) respectively by multiplying the number of satellites and the value of dry mass. The total mass of the satellites was minimized by applying a Genetic Algorithm (GA) with the number of population is 1000, maximum generation is 100, mutation probability is 0.1, and crossover probability is 0.95. The optimization process must have lower and upper bounds to give a limitation in the searching process. Thus, the range of design parameter of data rates between 2.5 Mbps – 10 Mbps, altitude between 500 – 1500 km, and transmit antenna diameter of 10 – 50 cm are given. The optimization routine was done using MATLAB software.

## Optimization Results

The number of satellites is directly related to their altitude. It should be expected that with high altitude, the power required by communication payload and its mass should increase. Therefore, the best design parameters minimize the total mass of the satellites. A smaller antenna diameter will increase the power required by the transmitter to produce constant $\frac{E_b}{N_0}$, whereas a larger antenna diameter could produce more mass of the satellites. Not surprisingly, the best design parameter is the one that gives the minimum satellite mass.

In this optimization effort, the fitness calculation was optimized in order to find the best value of design parameters. By examining the fitness function as shown in Figure 1 and optimizing it using a genetic algorithm, the best value of each design parameter is summarized in Table 5. The mass of each satellite is predicted to be 6.03 kg with a total number of satellites of eight. The power required by each satellite is predicted to be 23 Watt. It is convenient to show the physical phenomena in this optimization process. Figures 2-4 show the variation of each design parameters with respect to the total mass of the satellites near the optimum conditions.

Table 5: Best Value of Design Parameters

| Input name | Best Value |
|---|---|
| Transmit Antenna Diameter | 22 cm |
| Data Rates | 2.5 Mbps |
| Altitude | 785 km |

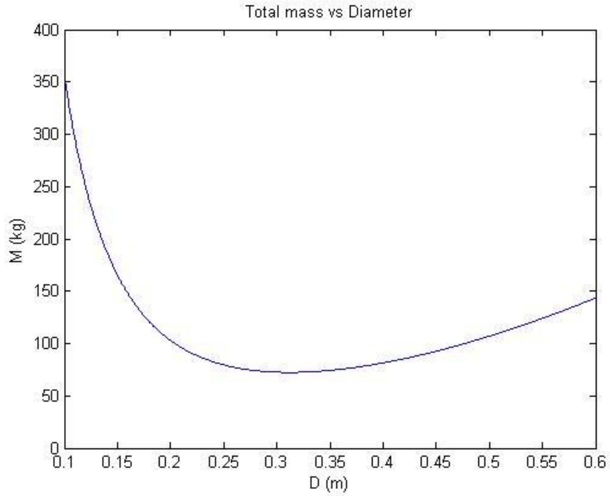


Figure 2: Mass vs Diameter within Data Rates of 2.5 Mbps and Altitude of 785 km.

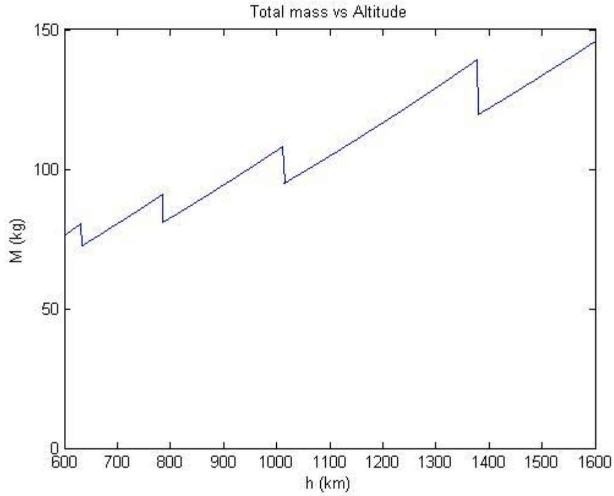


Figure 3: Mass vs Altitude within Data Rates of 2.5 Mbps and Diameter of 22 cm.

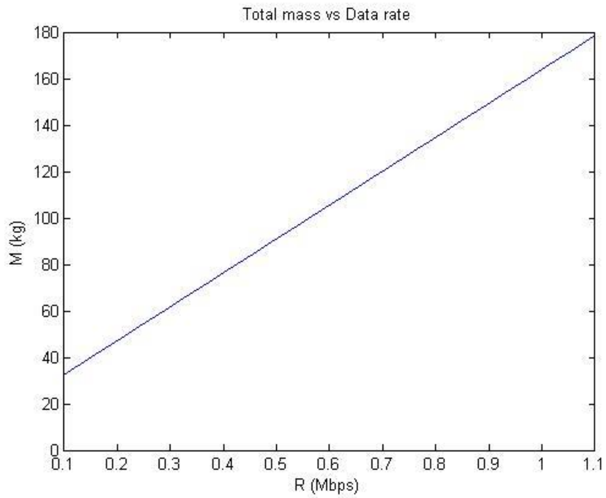


Figure 4: Mass vs Data Rates within Antenna Diameter of 22 cm and Altitude of 785 km.

Interestingly, Figure 2 shows that there is an set optimum value of antenna diameter that will minimize the mass of the satellite. Figures 3-4 show that the increase in the design of data rates and altitude will increase the value of optimum fitness. However, the effect of design parameters to total mass of satellite will be different at the other conditions. Hence, it will be difficult to find the optimum condition based on the graph. The comparison of results from the genetic algorithm optimization (Table 5) and Figure 2-3 show a good agreement of predicted altitude and antenna diameter.

## Conclusions

This paper provided a definition of the communication satellite link budget and mass estimation budget. The correlation between the number of satellites and altitude was calculated using a line of sight constraint to produce a continuous access. The dry mass of each satellite was predicted from the required power, which was derived from link budget analysis. Those conditions were combined to build a fitness function to predict the total mass and the number of satellites.

The fitness function was used as a trade-off in minimizing the total mass of the satellites. The minimizing process was done using a stochastic process named Genetic Algorithm. In order to validate the GA result, the sub-optimum plot of the fitness function was shown in Figures 2-4. However, the plot was limited by only using other optimum conditions. The figures show that the optimum condition has a good agreement with GA optimization results. It can be concluded that design optimization using Genetic Algorithm was successful in predicting the best design point with acceptable error. Finally, in order to summarize the result, Table 6 shows specification of the optimum design.

Table 6: Optimum Specification

| Sub-system name | Value |
|---|---|
| Satellite dry mass | 6.03 kg |
| Maximum power required | 23 Watt |
| Solar array | 0.4 m2 |
| Antenna diameter | 22 cm |
| Altitude | 785 km |
| Inclination | 0 deg |
| Number of satellite | 8 |

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