electronics

Article

Dynamic Beam Hopping Time Slots Allocation Based on Genetic Algorithm of Satellite Communication under Time-Varying Rain Attenuation

Chen Zhang [1,2,*], Jiangtao Yang [1,2], Yong Zhang [1,2], Ziwei Liu [1,2] and Gengxin Zhang [1,2]

[1] College of Telecommunications and Information Engineering, Nanjing University of Posts and Telecommunications, Nanjing 210003, China; 1018010329@njupt.edu.cn (J.Y.); qingu9899@163.com (Y.Z.); lzw@njupt.edu.cn (Z.L.); zgx@njupt.edu.cn (G.Z.)

[2] National Engineering Research Center for Communication and Network Technology, Nanjing University of Posts and Telecommunications, Nanjing 210003, China

* Correspondence: zhangchen@njupt.edu.cn

Abstract: Beam hopping technology is considered to provide a high level of flexible resource allocation to manage uneven traffic requests in multi-beam high throughput satellite systems. Conventional beam hopping resource allocation methods assume constant rainfall attenuation. Different from conventional methods, by employing genetic algorithm this paper studies dynamic beam hopping time slots allocation under the effect of time-varying rain attenuation. Firstly, a beam hopping system model as well as rain attenuation time series based on Dirac lognormal distribution are provided. On this basis, the dynamic allocation method by employing genetic algorithm is proposed to obtain both quantity and arrangement of time slots allocated for each beam. Simulation results show that, compared with conventional methods, the proposed algorithm can dynamically adjust time slots allocation to meet the non-uniform traffic requirements of each beam under the effect of time-varying rain attenuation and effectively improve system performance.

Keywords: beam hopping; satellite communication; resource allocation; genetic algorithm; rain attenuation

Citation: Zhang, C.; Yang, J.; Zhang, Y.; Liu, Z.; Zhang, G. Dynamic Beam Hopping Time Slots Allocation Based on Genetic Algorithm of Satellite Communication under Time-Varying Rain Attenuation. *Electronics* **2021**, *10*, 2909. https://doi.org/10.3390/electronics10232909

Academic Editor: Mauro Tropea

Received: 30 September 2021
Accepted: 22 November 2021
Published: 24 November 2021

1. Introduction

Through a large number of beams and frequency-reuse, high-throughput satellites (HTS) have been improving in their system performance. This has attracted considerable research interests. However, a large number of beams would increase the mass of on-board payloads as well as the DC power consumption [1]. At the same time, due to the diversity of users' requirement services, the demand traffic is non-uniform among beams. It means that the demand in some beams greatly exceeds the available capacity of beams, while in other beams the situation is the opposite [2]. However, in conventional multi-beam HTS communication systems, only part of total satellite resources can be utilized and fixedly allocated to each beam. This raises a paradoxical scenario that is "excessive idle or busy" for different beams. Consequently, it results in a huge waste of system resource (e.g., about 50 percent waste of system resource in [3]), which makes it difficult to achieve efficient transmission and on-demand coverage of hot areas.

In this context, beam hopping (BH) for satellite systems has emerged as a promising technology to provide a high level of flexibility to manage uneven traffic requests in the satellite coverage area [4]. With flexible payloads, beam hopping avoids the situation that the complexity of on-board payloads increases with larger number of beams. More importantly, all the available satellite resources can be shared and employed to provide service to a certain subset of beams, which is active for some portion of time, dwelling just long enough to match the traffic demand of each beam [2]. It means not all beams work, but only a portion of the beams are activated on demand. The set of activated beams changes in every time slot according to a well-designed time–space transmission plan [5]. Moreover, each working beam can share the total satellite resources, which means it achieves resource pooling of on-board frequency and power resources. Thus, beam hopping provides a foundation for the flexible allocation and efficient utilization of satellite resources to match the uneven traffic demand.

Many scholars have conducted beam hopping in satellite communication systems. By employing optimization methods such as iterative and heuristic algorithms, previous works respectively proposed preliminary mathematical models of resource allocation in beam hopping systems [6–9]. The work of [3] assessed the performance comparison between beam hopping systems and the non-hopped systems in Ka-band, which demonstrated that beam hopping can improve the utilization rate of system resources. The work of [10] intended to dynamically schedule the time slot number of each beam to realize the long-term delay fairness in a beam hopping system. The work [11–15] proposed a framework based on deep reinforcement learning (DRL) for dynamic resource allocation in beam hopping satellite systems with complicated calculation methods. Moreover, European Telecommunications Standards Institute (ETSI) published DVB-S2X standards [16] to support beam hopping. The work of [17,18] introduced the super-frame structure in Appendix E of DVB-S2X, and also discussed the feasibility of engineering realization. The work of [19] investigated potential synergies of non-orthogonal multiple access (NOMA) and beam hopping for multi-beam satellite systems. Moreover, the work of [20–22] employed precoding to suppress co-channel interference in a beam hopping system.

However, most of these previous works assumed constant channel quality during beam hopping transmission, which is too idealistic in a real satellite communication system. An HTS usually employs Ka or Q/V frequency band to obtain more spectrum resource and achieve broadband transmission. Therefore, channel attenuation especially time-varying rain attenuation in such high frequency band becomes a major factor that dynamically affects channel quality, which should not be ignored [23,24].

To overcome these limitations, this paper studies dynamic beam hopping time slots allocation method under the effect of time-varying rain attenuation. Firstly, a beam hopping system model as well as rain attenuation time series based on Dirac lognormal distribution are provided. On this basis, the genetic algorithm (GA) [25] for beam hopping is proposed by considering uneven traffic demand and changeable spectrum efficiency. Simulation results show that, compared with conventional methods, the proposed algorithm can dynamically adjust time slots allocation to meet the non-uniform traffic requirements of each beam under the effect of time-varying rain attenuation and effectively improve system performance.

Moreover, the reasons for adopting GA for beam hopping under rain environment are as follows. It is noticed that some of the current research interest is focused on applying reinforced learning algorithms for pursuing superior performance. However, except for the high complexity and long processing delay, the reinforced learning algorithm needs a mass of sample data to learn for a certain environment. It may not be suitable for the issue discussed in this paper, since the rain environment is changeable during BH transmission and different beams may be under different rainfall intensities. This problem is avoided by adopting GA. Comparing with the complicated reward function of DRL, the fitness function of GA is easily obtained and suitable for different rainfall environments. Therefore, GA is employed for beam hopping under the rain environment to achieve both better performance and lower algorithm complexity.

The main contributions and innovations of this paper are as follows:

(1) Without the assumption of constant rain attenuation, different beams may suffer different rain attenuations which are also time-varying. Consequently, this situation will bring different and time-varying spectrum efficiency for each beam during the transmission. It makes the design of beam hopping transmission plan become a complicated two-dimensional time–space optimization problem. In this context, this paper introduces genetic algorithm to solve the joint optimization problem. Moreover, in order to validate the

proposed algorithm performance, rain attenuation time series based on Dirac log-normal distribution are provided to simulate the rainfall environment. The proposed algorithm conforms to DVB-S2X with a finer gradation and extension number of modulation and coding modes (MOCODs) to obtain optimal spectrum efficiency for each beam in different time slots. DVB-S2X also guarantees engineering feasibility of the proposed algorithm.

(2) Most of the conventional beam hopping resource methods employ two-step strategies. Firstly, obtain the time slots number allocated to each beam. Then, arrange these time slots into beam hopping periods to determine beam illumination order. These two steps are independent when constant channel condition is assumed during transmission. With this assumption, different arrangements of time slots may not affect system performance. However, the effect of time-varying rain attenuation makes the quantity and arrangement of time slots become coupled. In this paper, the proposed method for BH solves the coupled problem, obtaining both the quantity and arrangement of time slots allocated for each beam.

(3) With the genetic algorithm, there is no need to perform the derivative or transforming operation on the objective function. Therefore, by adding more constrained conditions, the proposed system model, objective function, and algorithm flow can be employed to solve similar problems in beam hopping system such as resource allocation under the effect of co-channel interference.

The following paper is organized as follows. Section 2 describes the beam hopping system model. Section 3 introduces the proposed algorithms. Section 4 analyzes the numerical simulation results. Section 5 presents the conclusions and future works.

2. System Model

2.1. Beam Hopping of Forward Link

This paper considers the forward link of the multi-beam geostationary satellite systems, where broadband services are transmitted from the gateway station (GW) and transparently forwarded by the satellite to user terminals, referring to the DVB-S2X standard. Regarding the beam hopping architecture, the system resource management unit is within network control center (NCC). It pre-generates the beam hopping time plan (BHTP). BHTP determines dwell time and illumination order of each beam to match the traffic demand. The satellite receives the BHTP signaling message via telemetry, tracking, and command (TT&C) [2,26]. Then, the onboard beam hopping controller resolves BHTP and activates corresponding beams by employing a switching matrix or beamformer [27,28].

For the sake of spectral efficiency, a beam hopping system usually employs aggressive frequency reuse scheme. In this paper, it is assumed that all beams share the total frequency resource of satellite. However, full frequency multiplexing scheme will inevitably bring co-channel interference [29]. Thus, in order to avoid co-channel inter-beam interference, in a beam hopping system the downlink beams can be divided into several clusters. In each cluster, only one beam can be activated at a time. Meanwhile, it avoids simultaneous illumination of adjacent beams from different clusters. Another optional method is to employ precoding [30–32] to suppress co-channel interference.

The simplified beam hopping system architecture is shown in Figure 1.

2.2. Beam Hopping Time Plan

As stated above, the beam hopping time plan (BHTP) [33], which is also named as the beam hopping illumination pattern [2], determines dwell time and illumination order of each beam. Obviously, it is the most important system configuration since beam hopping technique is mainly based on time slicing. Figure 2 demonstrates an example of the beam hopping time plan for seven beams in a cluster.

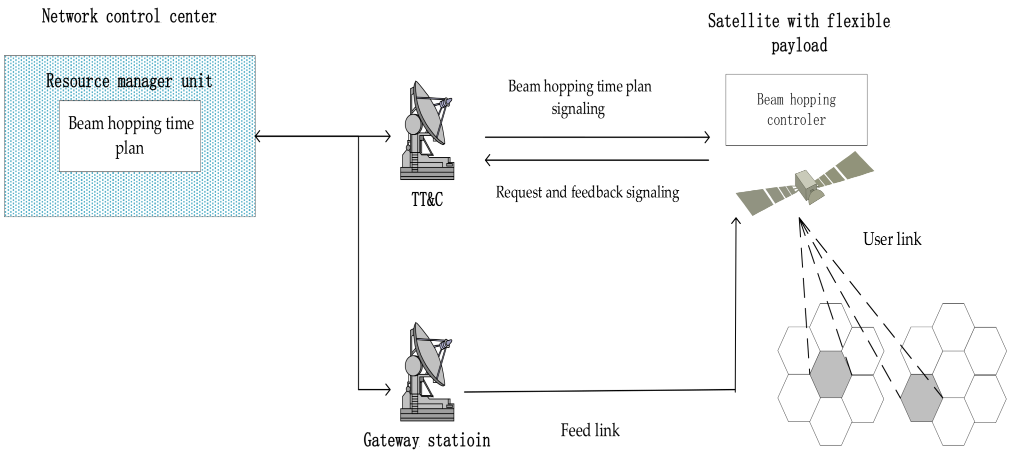

Figure 1. Beam hopping system.

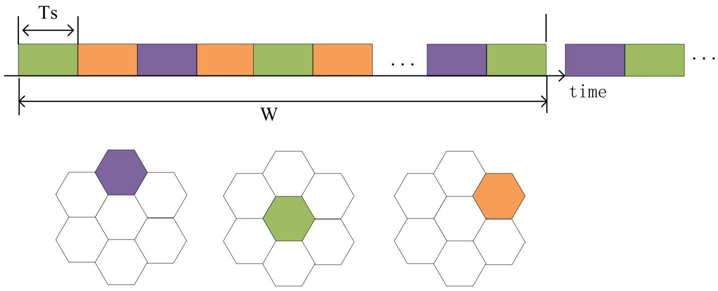

Figure 2. Beam hopping time plan.

As shown in Figure 2, the BHTP consists of multiple beam hopping periods Tw, which are periodically repeated. The duration of one time slot is Ts, which is the smallest time resource scale. Thus, Tw = W × Ts, where W represents the number of time slot in one beam hopping period. Moreover, dwell time represents the length of continuous time slots allocated to a beam.

2.3. Rain Attenuation Time Series

This subsection introduces the Dirac log-normal distribution model, which is proved to be able to accurately characterize rain attenuation [34]. The rain attenuation time series obey Dirac-lognormal distribution, which means the rain attenuation PDF (probability distribution function) $P(A|A>0)$ is a lognormal distribution function with mean μ and variance δ:

$$P(A|A>0) = \frac{e^{-\frac{1}{2}(\frac{lnA-\mu}{\delta})}}{A\delta\sqrt{2\pi}} \tag{1}$$

Consequently, the CCDF (complementary cumulative probability distribution function) of rain attenuation can be expressed as mixture Dirac-lognormal distribution:

$$P(A \geq A_0) = p_0 \int_{A_0}^{+\infty} P(A|A>0)dA_C = \frac{p_0}{2}\left(\frac{lnA_0-\mu}{\sqrt{2}\delta}\right) \tag{2}$$

where p_0 is the rainfall probability of communication link, and the mathematical statistical model of p_0 can be found in ITU-R P.618 [35].

By employing the method in [34], a stationary Gaussian process G(t) with zero mean, one variance and correlation function $c_G(\triangle t)$ should be generated as follows:

(a) Generate $N/2+1$ uncorrelated random complex numbers $(e_k)_{k=0 \ldots N/2}$, whose real part and imaginary part are normally distributed with zero mean and one variance. When k = 0 or k = $N/2$, set the imaginary part of e_k to 0;

(b) Define $e_{N-k} = e_k^*$, with $k = \{0, \ldots, N/2\}$;
(c) Define $h_k = \begin{cases} 1 & k = 0,\ k = N/2 \\ \frac{1}{2} & \text{else} \end{cases}$;
(d) Compute Fourier transform according to correlation function c_G: $\mathcal{F}(G_j) = \frac{1}{N}\sum_{j=0}^{N-1} G_j e^{-\frac{i2\pi}{N}kj}$;
(e) Define $a_k = \sqrt{h_k \mathcal{F}(c_G)} \times e_k$;
(f) Then $G(t) = \mathcal{F}^{-1}(a_k) = \sum_{k=0}^{N-1} a_k e^{\frac{i2\pi}{N}kj}$.
Finally, the desired rain attenuation time series $A(t)$ is:

$$\begin{cases} A(t) = exp\left\{\delta\sqrt{2}erfc^{-1}\left[\frac{erfc\left(\frac{G(t)}{\sqrt{2}}\right)}{p_0}\right] + \mu\right\} & ,G(t) > G_0 \\ A(t) = 0,\ otherwise \end{cases} \tag{3}$$

where $G_0 = \sqrt{2}erfc^{-1}(2 \times p_0)$.

Obviously, it is better to use messured rain attenuation data from a real satellite communication channel. However, the public data we can obtain are not detailed enough for beam hopping research. More importantly, the motivation of this paper is to provide a beam hopping algorithm under rainfall environment. Thus, a reasonable and accurate rain attenuation time series model is sufficient to validate the proposed beam hopping algorithm.

3. Dynamic Time Slots Allocation Based on Genetic Algorithm

3.1. Beam Hopping Time Slots Allocation

As stated above, the motivation of beam hopping technology is utilizing system resources efficiently to meet the user's traffic demand as much as possible. Thus, this paper intends to build an N-order difference objective function [36] as follows.

For K beams, supposing $\hat{R}_i$ and R_i are the request traffic capacity and system offered capacity in one beam hopping period, respectively, (measured by bit), W is the beam hopping period (time window) and N_i is the number of time slots allocated to beam i. $T_{ij} \in [0,1]$ is the element of beam hopping time slot allocation matrix **T**. T_{ij} = 1 means j-th time slot is allocated to i-th beam, which means i-th beam is working in j-th time slot. Thus, $\sum_{j=1}^{W} T_{ij} = N_i$.

N-order difference objective function:

$$\min \sum_{i=1}^{K} |R_i - \hat{R}_i|^n \tag{4}$$

$$s.t\ R_i \le \hat{R}_i,\ \forall i \tag{5}$$

Usually, n = 2, which makes it a second order objective function. Supposing Gaussian coding is used, the offered capacity in one beam hopping period W of the i-th beam is:

$$R_i = N_i B_w log_2(1 + SNR_i) \tag{6}$$

SNR_i is signal-to-noise ration the i-th beam. It can be represented by

$$SNR_i = \frac{P_i}{N_0}\frac{G_T G_R}{L_{SL} L_{RA}} \tag{7}$$

P_i is the transmitter power. G_T and G_R are the transmitter and receiver antenna gain, respectively. L_{SL} is the propagation loss. L_{RA} is the rain attenuation of communication link. Different from previous works, in this paper, rain attenuation is not constant but time-varying and different among beams.

Moreover, as known, DVB standard is the most widely used protocol for high-throughput broadcast satellites. As stated above, ETSI published DVB-S2X standards [16] to support beam hopping. DVB-S2X offers smaller roll-off options, and a finer gradation and extension number of MOCODs, which provide foundation for potentially employing ACM to improve spectral efficiency. Note that this paper is focused on beam hopping under rainfall environment referring to DVB-S2X, rather than studying ACM schemes.

Thus, Equation (4) can be transformed as:

$$\min \sum_{i}^{K} |R_i - \hat{R}_i|^2 \tag{8}$$

$$s.t.\ R_i \leq \hat{R}_i,\ \forall i \tag{9}$$

$$R_i = \sum_{j}^{W} B_w \cdot \eta_{ij} \cdot T_{ij} \tag{10}$$

$$\hat{R}_i = \hat{r}_i \cdot W \tag{11}$$

where η_{ij} is the spectrum efficiency of i-th beam at j-th time slot. The spectrum efficiency $\eta_{ij} = f_{\text{DVB-S2X}}\left(SNR_{ij}\right)$ is a piecewise function in DVB-S2X, where SNR_{ij} represents signal-to noise ratio of i-th beam at j-th time slot. $\hat{r}_i$ represents the request traffic rate (measured by bps) of i-th beam.

3.2. Genetic Algorithm for Beam Hopping

Genetic algorithm is a stochastic method for solving both constrained and unconstrained optimization problems. In genetic algorithm, the set of feasible solutions is considered as a population. Each individual represents a solution. Through selection, crossover and mutation in the evolution process, genetic algorithm repeatedly modifies a population of individual solutions from generation to generation [23]. To be specific, the evolution usually starts from a population of randomly generated individuals and happens in generations. In each generation, the fitness of every individual in the population is evaluated, multiple individuals are stochastically selected from the current population, and modified based on crossover and possibly randomly mutation to obtain a new generation population [37]. Usually, the algorithm can be terminated when either a satisfactory fitness level of the population has been reached, or the maximum number of generations has been produced [23].

Thus, to solve the nonlinear optimization problem of beam hopping under time varying rain attenuation, this paper proposes genetic algorithm. As a global optimization algorithm for BHTP, it mainly includes the chromosome encoding, fitness function, and the design of the genetic operations [23].

(1) Chromosome encoding:

For BHTP design under time-varying rain attenuation, this paper assumes K beams are in one cluster, and one beam hopping period contains W time slots. Consequently, there will be $\left(C_K^1\right)^W = K^W$ possible solutions, which will be a tragedy for searching space dimensions. As stated above, in this paper, only one beam can be activated at a time slot in each cluster. Thus, inspired by [13], multi-action selection method can be employed to simply make the actions select one beam from K beams for illumination and repeat W times. When using a binary encoding manner, the chromosome for BH method should contain at least $log_2 K$ genes for both feasibility and low complexity.

(2) Fitness function:

The fitness function is used to evaluate the goodness of the chromosomes. That is to say, it measures the adaptability of individuals to the living. Individuals are selected according to their fitness value: individuals with higher fitness value are more likely to survive and reproduce the next generation. Generally, for maximization optimization problem fitness function is directly proportional to object function while minimization optimization problem fitness function is inversely proportional to object function [38]. Since the beam hopping object function of this paper is a minimization problem (to meet the user's traffic demand as much as possible with second order manner), the fitness function can be designed as:

$$Fit(X) = \frac{1}{f(X)} = \frac{1}{\min \sum_i^K |R_i - \hat{R}_i|^2} \tag{12}$$

where $R_i = \sum_j^W B_w \cdot f_{\text{DVB-S2X}}\left(SNR_{ij}\right) \cdot T_{ij}$, as previously stated.

Note that, for beam hopping under rain environment, due to time-varying rain attenuation, the SNR of each beam is also time-varying, which can be obtained by bringing Equation (3) into Equation (7).

(3) Genetic operations:

With an initial population of individuals and evaluated through their fitness function, the operators of genetic algorithm begin to generate a new and improve population from the parent generation [38]. Genetic algorithm usually consists of three classical operations: selection, crossover, and mutation. For selection, this paper uses the roulette method, which is the most common selection method, to make the individuals with higher fitness get larger probability of survival. It means that better BHTP solutions are selected as the generation. Moreover, crossover and mutation operators employ single-point exchange and uniform mutation methods respectively [23].

The process chart of proposed method is shown in Figure 3.

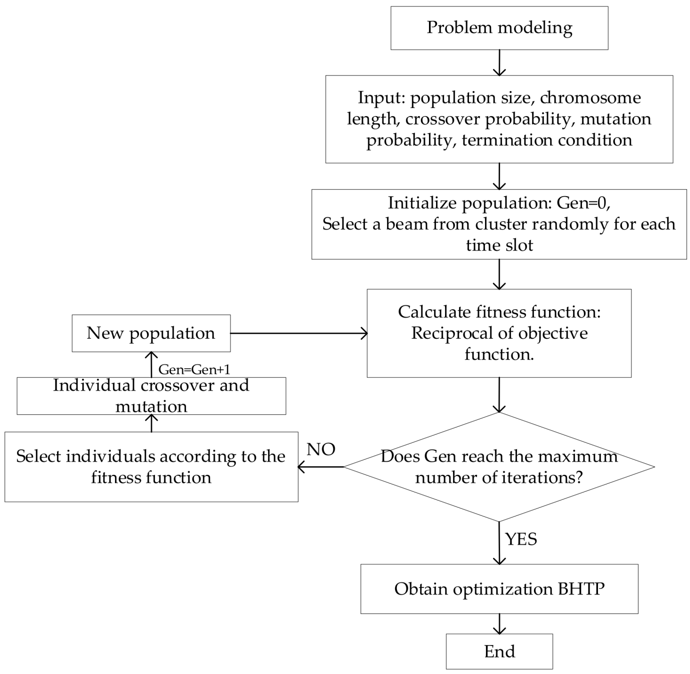

Figure 3. Process chart of beam hopping time plan optimization based on GA.

Other parameters include the number of individuals in the initial population, the probability of crossover and mutation. They should be set appropriately to minimize the complexity while guaranteeing that the optimal solution can be obtained [37]. Finally, the dynamic time slots allocation based on GA for beam hopping is shown in Algorithm 1.

Algorithm 1. Dynamic Time Slots Allocation based on GA under time-varying rain attenuation.

(1) Generate beam hopping satellite communication scenario and build the objective function.
(2) Set algorithm parameters, including population size, the max number of generations, chromosome length, the probability of crossover and mutation.
(3) Generate initial population randomly with individuals as actions: select a beam randomly from K beams for each time slot.
(4) For i = 1, 2, . . . ,W do:
(5) For j = 1,2, ... $generation_{max}$ do:
(6) According to the rain attenuation series of the i-th time slot, calculate SNR_{ij} to obtain system offered capacity.
(7) Calculate objective function of beam hopping, then inverse the results to obtain the fitness value.
(8) Select better BHTP solutions: choose the better individuals as the parent generation by employing the roulette selection method.
(9) Mutate and exchange BHTP solutions: uniform mutation and single-point exchange crossover operation are performed on the selected individuals to produce next generation population.
(10) End For
(11) End For

4. Numerical Simulations and Analysis

The satellite system simulation parameters are listed in Table 1, where the radiation pattern of the multi-beam antenna refers to ITU-S.672 [39] and other parameters conform to the DVB-S2X interface specification [16]. Moreover, in order to fully verify the proposed BH algorithm, the maximum rain attenuations of each beam are chosen as [35.8, 19, 11.65, 6.43, 23] dB to simulate light or heavy rains. The uneven traffic demand of each beam is set as [70, 530, 550, 600, 320] Mbps.

Table 1. Satellite system simulation parameters.

Parameter	Label	Value
Transmission standard	-	DVB-S2X
Beams number	K	5
Total bandwith	B_W	400 Mhz
Beam hopping time slot	T	100 ms
Beam hopping period	W	256
Transmitter power	P	100 W
Carrier frequency	F	20 GHz
Roll-off	α	0.05
Altitude of satellite orbit	H	35,786 km
Transmit antenna gain	G_T	54 dB
Receive antenna gain	G_R	38.5 dB
Propagation loss	L_{SL}	210 dB
Traffic demand of each beam	-	[70, 530, 550, 600, 320] Mbps
Maximum rain attenuation of each beam	-	[35.8, 19, 11.65, 6.43, 23] dB

The genetic algorithm parameters are shown in Table 2. For K = 5 beams in the system, as previously stated, chromosome length can be set as $log_2 K = 3$. Other parameters can be appropriately set as the classic case of GA [25] to minimize the computation complexity while guaranteeing that the optimal solution can be found [37].

Table 2. Genetic algorithm parameters.

Parameter	Value
Crossover probability	0.6
Mutation probability	0.02
Chromosome length	3
Population	100

Firstly, long-term rain attenuation time series based on Dirac log-normal distribution is illustrated in Figure 4. To simplify calculation while ensuring sufficient validation of algorithm, the duration of one rainfall can be chosen from the long-term rain attenuation time series. It is shown in top right corner of Figure 4. Applying the above method to each beam, attenuation time series of one rainfall for each beam can be obtained with different maximum attenuation values. The rain attenuation time series are changed every one second. The reason is for both lower computation complexity and to satisfy beam hopping time slot $< \frac{1}{\text{the rainy environment changing frequncy}} <$ beam hopping period.

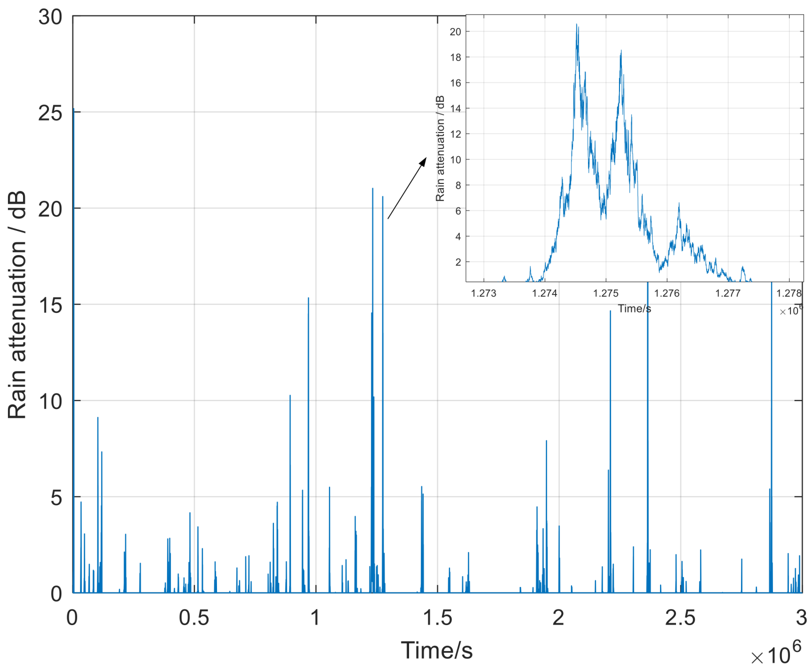

Figure 4. Rain attenuation time series.

On the basis of time-varying rain attenuation, SNR of each beam can be obtained by bringing Equation (3) into Equation (7), which is also time-varying. As previously stated, the interface specification of BH system conform to DVB-S2X, and the spectrum efficiency $\eta_{ij} = f_{\text{DVB-S2X}}\left(SNR_{ij}\right)$ is a piecewise function defined in [16], where SNR_{ij} represents signal-to-noise ratio of i-th beam at j-th time slot. With this function, time-varying SNR leads to different spectrum efficiency. Then, spectrum efficiency of each beam is also a time-varying piecewise curve, as shown in Figure 5.

Due to the finer gradation and extension number of MOCODs in DVB-S2X, when SNR of each beam changes during transmission under the effect of the time-varying attenuation, appropriate MOCOD can be chosen to obtain optima spectrum efficiency.

Note that, in this simulation condition, the short-term rain attenuation time series based on the 'Event-on-Demand' model [40] can also be introduced to validate the proposed beam hopping method. Nevertheless, it is limited to the short term. Thus, without loss of generality, the Dirac log-normal distribution model is recommended (as in Section 2.3) for its time series including rain and no rain, long-term and short-term situations.

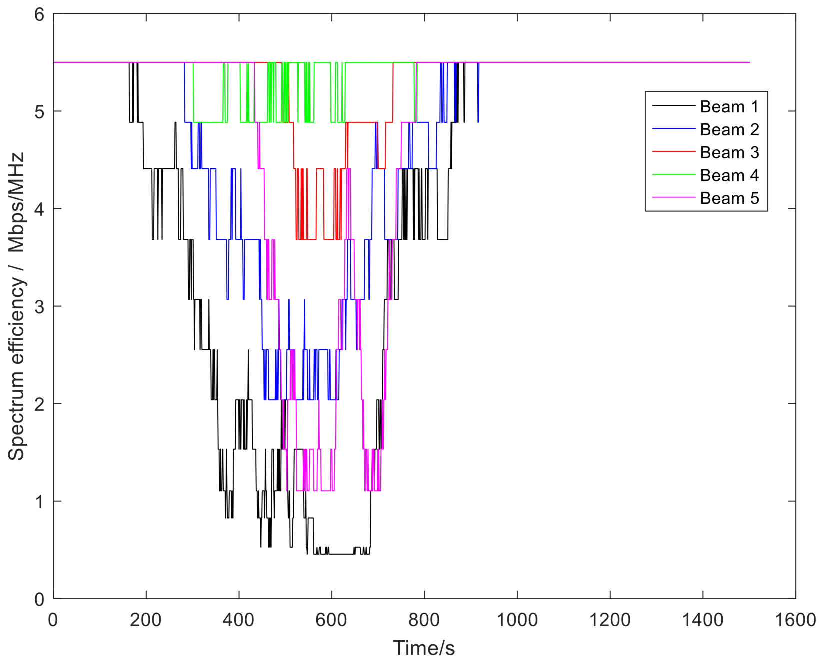

Figure 5. Spectrum efficiency of each beam.

Figure 6 illustrates the iteration graph of proposed method based on GA, where the Y-axis represents the value of objective function $\min \sum_i^K |R_i - \hat{R}_i|^2$. From Figure 6, it can be seen that after 40 more iterations, the average value of objective function of population decreases and finally approaches the minimum value of objective function, which means that the algorithm has good convergence. The reason is that multi-action selection method can reduce computational complexity and the solution space can be adjusted adaptively and effectively reduced by GA [37]. As stated above, the design of BHTP and the corresponding algorithms mainly operate at system resource management unit of network control center. Therefore, powerful processing capabilities of network control center can ensure the strong engineering practicability of the genetic algorithm.

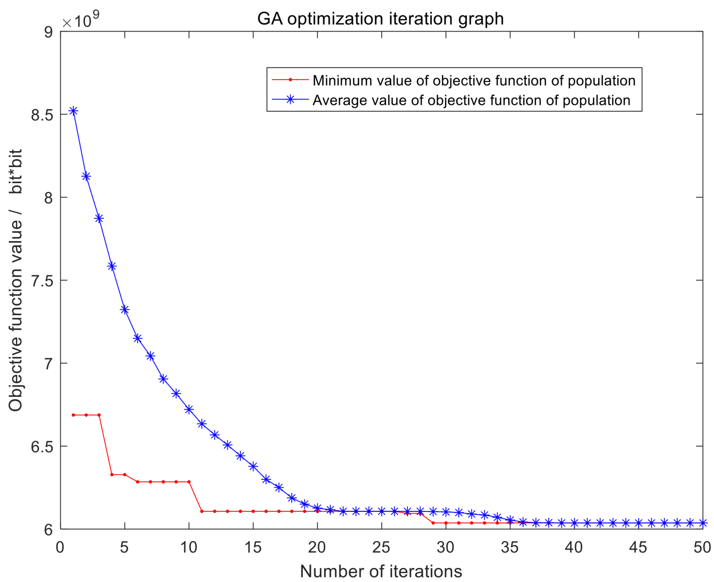

Figure 6. GA optimization iteration graph.

As previously stated, time-varying rain attenuation brings changeable spectrum efficiency for each beam, which makes the quantity and arrangement of beam hopping time slots become coupled. By employing GA as a global optimization method, the dynamic allocation algorithm is proposed to solve the nonlinear problem with multiple constrained conditions. It can obtain not only the number of time slots allocated to each beam, but also the arrangement of time slots in the beam hopping period to determine the order in which the beam is activated. The time slot allocation results of one period for each beam are shown in Figure 7, where the X-axis represents time slot index and the color-block represents the time slot allocated to corresponding beam.

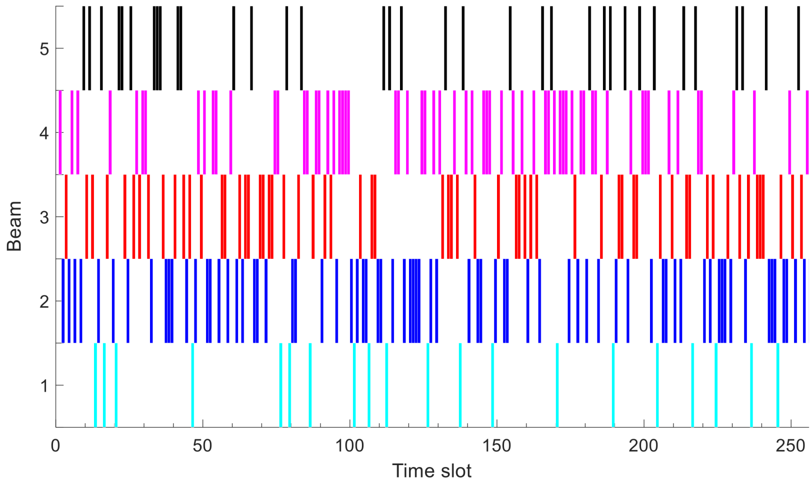

Figure 7. Beam hopping time slots allocation results.

Moreover, the following parameters are introduced to evaluate the system performance.

System actual throughput or capacity: it is the part of the allocated capacity not exceeding the requested traffic under the resource-constrained condition

$$C_A = \sum_{i=1}^{K} \min\{\hat{R}_i, R_i\} \tag{13}$$

where $\hat{R}_i$ is the request traffic of each beam and R_i is the system offered.

Traffic matching ratio: it describes the satisfaction degree of the actual capacity with respect to the total requested traffic. It can be defined as:

$$\rho_s = \frac{C_A}{\sum_{i=1}^{K} \hat{R}_i} \tag{14}$$

Finally, the traffic matching ratio of the beam hopping system is shown in Figure 8. Here, BH method with constant rain attenuation represents the conventional beam hopping time slot allocation method which assumes constant rain attenuation as in [7] and [37]. Multi-beam with ACM represents a traditional fixed multi-beams HTS system employing ACM referring to DVB-S2X. Multi-beam without ACM represents the same but without utilizing ACM. BH method based on GA is our proposed algorithm under the effect of time-varying rain attenuation.

For BH method with constant rain attenuation, it is obvious that the redundant rain loss margin will cause low efficiency utilization of spectrum resource, which leads to the unsatisfaction of demand traffic. For Multi-beam with ACM, although ACM is employed to deal with changeable communication link quality, the fixed resource allocation manner of multi-beam system could not manage the uneven traffic demand among beams.

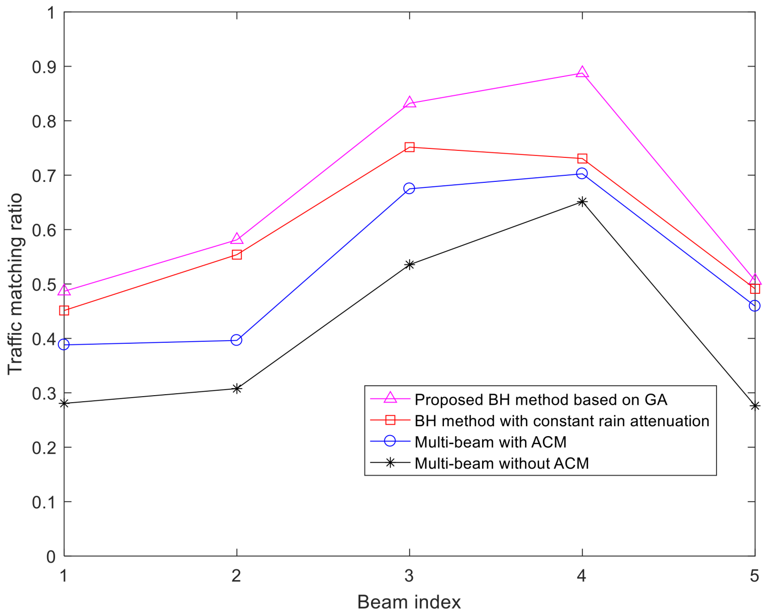

Figure 8. Traffic matching ratio.

Fortunately, compared with conventional algorithms, the proposed BH method still obtains better performance, because the proposed method introduces GA to solve the two-dimensional time–space optimization problem of beam hopping under time-varying rain attenuation. The proposed method flexibly allocates and efficiently utilizes system resources to meet the traffic demand as much as possible. More importantly, different from conventional two-step strategy, through the proposed BH method, it obtains not only the number of time slots allocated to each beam, but also the arrangement of time slots in beam hopping period, which reduces the computational complexity.

5. Conclusions and Future Works

This paper studies dynamic beam hopping time slots allocation under the effect of time-varying rain attenuation. To address this issue, rain attenuation time series based on Dirac and log-normal distribution is first provided. Then, generally considering uneven traffic demand, changeable communication link conditions, and different spectrum efficiency, the dynamic allocation method by employing the genetic algorithm is proposed. It can obtain both the quantity and arrangement of time slots allocated for each beam. Numeric simulation results show that, compared with conventional methods, the proposed algorithm can dynamically adjust time slots allocation to meet the spatial heterogeneity traffic requirements of each beam under the effect of time-varying rain attenuation and effectively improve system performance.

In future work, we will try to obtain the actual measurement data of satellite communication rain attenuation, although it may be difficult to acquire.

Author Contributions: Conceptualization, C.Z. and G.Z.; methodology, C.Z. and J.Y.; software, J.Y. and Y.Z.; validation, C.Z., G.Z. and Z.L.; formal analysis, C.Z.; investigation, Z.L.; resources, C.Z.; data curation, C.Z.; writing—original draft preparation, C.Z. and Y.Z.; writing—review and editing, C.Z. and G.Z.; visualization, C.Z.; supervision, G.Z.; project administration, G.Z.; funding acquisition, C.Z., Z.L. and G.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Fundamental Research Funds of CETC (No. 2020069).

Acknowledgments: The authors acknowledge the anonymous reviewers for their very helpful and useful comments to improve this paper.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Hu, X.; Liu, S.; Wang, Y.; Xu, L.; Zhang, Y.; Wang, C.; Wang, W. Deep reinforcement learning-based beam hopping algorithm in multibeam satellite systems. *IET Commun.* **2019**, *13*, 2485–2491. [CrossRef]
2. Lei, L.; Lagunas, E.; Yuan, Y.; Kibria, M.G.; Chatzinotas, S.; Ottersten, B. Beam Illumination Pattern Design in Satellite Networks: Learning and optimization for efficient beam hopping. *IEEE Access* **2020**, *99*, 1–13. [CrossRef]
3. Anzalchi, J.; Couchman, A.; Gabellini, P.; Gallinaro, G.; Angeletti, P. Beam hopping in multi-beam broadband satellite systems: System simulation and performance comparison with non-hopped systems. In Proceedings of the Advanced Satellite Multimedia Systems Conference & the Signal Processing for Space Communications Workshop, Cagliari, Italy, 13–15 September 2010; pp. 248–255.
4. Maufroid, X.; Rinaldo, R.; Casaleiz, R. Benefits of beam hopping techniques in future multi-beam broadband satellite networks. In Proceedings of the AIAA International Communications Satellite Systems Conference, San Diego, CA, USA, 11 June 2005.
5. Kodheli, O.; Lagunas, E.; Maturo, N.; Sharma, S.K.; Shankar, B.; Montoya, J.F.M.; Merlano Duncan, J.C.; Spano, D.; Chatzinotas, S.; Kisseleff, S.; et al. Satellite communications in the new space era: A survey and future challenges. *IEEE Commun. Surv. Tutor.* **2020**, *23*, 70–109. [CrossRef]
6. Mokhtar, A.; Azizoglu, M. On the downlink throughput of a broadband LEO satellite network with hopping beams. *IEEE Commun. Lett.* **2001**, *4*, 390–393. [CrossRef]
7. Alegre, R.; Alagha, N.; Vázquez-Castro, M.Á. Heuristic algorithms for flexible resource allocation in beam hopping multi-beam satellite systems. In Proceedings of the 29th AIAA International Communications Satellite Systems Conference, Nara, Japan, 28 November 2011; pp. 1–15.
8. Shi, D.; Liu, F.; Zhang, T. Resource allocation in beam hopping communication satellite system. In Proceedings of the International Wireless Communications and Mobile Computing, Byblos, Lebanon, 29–30 June 2020.
9. Zhang, T.; Zhang, L.; Shi, D. Resource allocation in beam hopping communication system. In Proceedings of the 2018 IEEE/AIAA 37th Digital Avionics Systems Conference (DASC), London, UK, 23–27 September 2018; pp. 1–5.
10. Han, H.; Zheng, X.; Huang, Q.; Lin, Y. QoS-equilibrium slot allocation for beam hopping in broadband satellite communication systems. *Wirel. Netw.* **2015**, *21*, 2617–2630. [CrossRef]
11. Zhang, Y.; Hu, X.; Chen, R.; Zhang, Z.; Wang, L.; Wang, W. Dynamic beam hopping for DVB-S2X satellite: A multi-objective deep reinforcement learning approach. In Proceedings of the International Conferences on Ubiquitous Computing & Communications & Data Science and Computational Intelligence & Smart Computing, Networking and Services, Shenyang, China, 21–23 October 2019; pp. 164–169.
12. Lei, L.; Lagunas, E.; Yuan, Y.; Kibria, M.G.; Chatzinotas, S.; Ottersten, B. Deep learning for beam hopping in multibeam satellite systems. In Proceedings of the IEEE 91st Vehicular Technology Conference, Antwerp, Belgium, 25–28 May 2020; pp. 1–5.
13. Hu, X.; Zhang, Y.; Liao, X.; Liu, Z.; Wang, W.; Ghannouchi, F.M. Dynamic beam hopping method based on multi-objective deep reinforcement learning for next generation satellite broadband systems. *IEEE Trans. Broadcast.* **2020**, *66*, 630–646.
14. Hu, X.; Liu, S.; Chen, R.; Wang, W.; Wang, C. A deep reinforcement learning-based framework for dynamic resource allocation in multibeam satellite systems. *IEEE Commun. Lett.* **2018**, *22*, 1612–1615. [CrossRef]
15. Liu, S.; Hu, X.; Wang, W. Deep reinforcement learning based dynamic channel allocation algorithm in multibeam satellite systems. *IEEE Access* **2018**, *6*, 15733–15742. [CrossRef]
16. Digital Video Broadcasting (DVB). *Second Generation Framing Structure, Channel Coding and Modulation Systems for Broadcasting, Interactive Services, News Gathering and Other Broadband Satellite Applications, Part II: S2-Extensions (S2-X) EN 302307-2*; Technical Report; ETSI: Sophia-Antipolis, France, 2014.
17. Rohde, C.; Alagha, N.; De Gaudenzi, R.; Stadali, H.; Mocker, G. Super-framing: A powerful physical layer frame structure for next generation satellite broadband systems. *Int. J. Satell. Commun. Netw.* **2016**, *34*, 501–532. [CrossRef]
18. Mazzali, N.; Boumard, S.; Kinnunen, J.; Kinnunen, B.; Shankar, M.R.; Kiviranta, M.; Alagha, N. Enhancing mobile services with DVB-S2X superframing. *Int. J. Satell. Commun. Netw.* **2018**, *36*, 503–527. [CrossRef]
19. Wang, A.; Lei, L.; Lagunas, E.; Chatzinotas, S.; Neira, A.I.P.; Ottersten, B. Joint beam-hopping scheduling and power allocation in NOMA-assisted satellite systems. In Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC), Nanjing, China, 29 March–1 April 2021; pp. 1–6.
20. Kibria, M.G.; Lagunas, E.; Maturo, N.; Spano, D.; Chatzinotas, S. Precoded cluster hopping in multi-beam high throughput satellite systems. In Proceedings of the 2019 IEEE Global Communications Conference, Waikoloa, HI, USA, 9–13 December 2019; pp. 1–6.
21. Ginesi, A.; Re, E.; Arapoglou, P.D. Joint beam hopping and precoding in HTS systems. In Proceedings of the 9th EAI International Conference on Wireless and Satellite Systems, Oxford, UK, 24–25 July 2017; pp. 43–51.
22. Joroughi, V.; Lagunas, E.; Andrenacci, S.; Maturo, N.; Chatzinotas, S.; Grotz, J.; Ottersten, B. Deploying joint beam hopping and precoding in multibeam satellite networks with time variant traffic. In Proceedings of the IEEE Global Conference on Signal and Information Processing, Anaheim, CA, USA, 26–28 November 2018; pp. 1–6.
23. Laster, J.D.; Stutzman, W.L. Frequency scaling of rain attenuation for satellite communication Links. *IEEE Trans. Antennas Propag.* **1995**, *43*, 1207–1216. [CrossRef]
24. Panagopoulos, A.D.; Kanellopoulos, J.D. On the rain attenuation dynamics: Spatial-temporal analysis of rainfall-rate and fade duration statistics. *Int. J. Satell. Commun. Netw.* **2003**, *21*, 595–611. [CrossRef]

25. Goldberg, D.E. *Genetic Algorithm in Search, Optimization, and Machine Learning*; Addison-Wesley: Boston, MA, USA, 1989.
26. Chronopoulos, S.K.; Koliopanos, C.; Angelis, C.T. Satellite multibeam signaling for multimedia services. In Proceedings of the International Conference on Mobile Multimedia Communications, Nafpaktos, Greece, 27–29 August 2007; pp. 1–4.
27. Angeletti, P.; Prim, F.D.; Rinaldo, R. Beam hopping in multi-beam broadband satellite systems: System performance and payload architecture analysis. In Proceedings of the 24th AIAA International Communications Satellite Systems Conference, San Diego, CA, USA, 11–14 June 2006; pp. 1–6.
28. Feltrin, E.; Amos, S.; Fenech, H.; Weller, E. Eutelsat QUANTUM-class satellite: Beam hopping. In Proceedings of the 3rd ESA Workshop on Advanced Flexible Telecom Payloads, Noordwijk, The Netherlands, 21–24 March 2016; pp. 1–6.
29. Chronopoulos, S.K.; Angelis, C.T.; Koumasis, A.; Drakou, P. Satellite coverage analysis for the investigation of real-time communication in selected areas. *WSEAS Trans. Commun.* **2006**, *5*, 1965–1972.
30. Vázquez, M.Á.; Perez-Neira, A.; Christopoulos, D.; Chatzinotas, S.; Ottersten, B.; Arapoglou, P.D.; Ginesi, A.; Taricco, G. Precoding in multibeam satellite communications: Present and future challenges. *IEEE Wirel. Commun.* **2015**, *23*, 88–95. [CrossRef]
31. Christopoulos, D.; Chatzinotas, S.; Ottersten, B. Multicast multigroup precoding and user scheduling for frame-based satellite communications. *IEEE Trans. Wirel. Commun.* **2015**, *14*, 4695–4707. [CrossRef]
32. Perez-Neira, A.I.; Vazquez, M.A.; Shankar, M.B.; Maleki, S.; Chatzinotas, S. Signal processing for high throughput satellite systems: Challenges in new interference-limited scenarios. *IEEE Signal Process. Mag.* **2018**, *36*, 112–131. [CrossRef]
33. Sunil, P.; Chris, M.; Janet, K. Beam hopping–a flexible satellite communication system for mobility. In Proceedings of the 35th AIAA International Communications Satellite Systems Conference, Trieste, Italy, 16–19 October 2017.
34. Boulanger, X.; Feral, L.; Castanet, L.; Jeannin, N.; Carrie, G.; Lacoste, F. A rain attenuation time-series synthesizer based on a Dirac and lognormal distribution. *IEEE Trans. Antennas Propag.* **2013**, *61*, 1396–1406. [CrossRef]
35. *ITU-R Recommendation P.618-10: Propagation Data and Prediction Methods Required for the Design of Earth-Space Telecommunication Systems*; Technical Report; International Telecommunication Union: Geneva, Switzerland, 2009.
36. Lei, J. Multi-Beam Satellite Resource Allocation Optimization for Beam Hopping Transmission. Ph.D. Thesis, Autonomous University of Barcelona, Barcelona, Spain, 29 September 2010.
37. Wang, L.; Hu, X.; Ma, S.; Xu, S.; Wang, W. Dynamic beam hopping of multi-beam satellite based on genetic algorithm. In Proceedings of the IEEE Intl Conf on Parallel & Distributed Processing with Applications, Big Data & Cloud Computing, Sustainable Computing & Communications, Social Computing & Networking, Exeter, UK, 17–19 December 2020; pp. 1364–1370.
38. Li, W.; Chen, J.; Shi, X.; Liu, A. An optimization beam-position selection method based on genetic algorithm for Distributed Satellite-borne SAR system. In Proceedings of the IEEE CIE International Conference on Radar, Chengdu, China, 24–27 October 2011; pp. 895–898.
39. *ITU-R S.672-4: Satellite Antenna Radiation Pattern for Use as a Design Objective in the Fixed-Satellite Services Employing Geostationary Satellites*; Technical Report; International Telecommunication Union: Geneva, Switzerland, 1997.
40. Carrie, G.; Lacoste, F.; Castanet, L. A new 'event-on-demand' synthesizer of rain attenuation time series at Ku-, Ka- and Q/V-bands. *Int. J. Satell. Commun. Netw.* **2011**, *29*, 47–60. [CrossRef]