Power Allocation Algorithm for IDMA-based Multi-Beam Satellite Communication Systems

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Abstract—Rain attenuation is one of the most dominant impairment factors that degrade the performance of satellite communications at Ka band and above. In order to solve the technical bottlenecks in the existing Ka-band satellite communication schemes, the authors have introduced the emerging Interleave Division Multiple Access (IDMA) technology into multi-beam satellite communication systems, and consequently, a novel power allocation algorithm is proposed for the emerging and promising system in this paper. The main goal of the proposed scheme is to provide sufficient transmission quality to as many mobiles as possible, even for the users suffering heavy rain attenuation. Analysis and simulation results show that compared to the traditional power allocation schemes, the proposed scheme can guarantee high power efficiency even in heavy rain attenuation conditions, illustrating the high efficiency of the Chip-by-Chip (CBC) Multi-user Detection (MUD) technique in IDMA. Furthermore, in virtue of the Signal to Interference plus Noise Ratio (SINR) evolution technique, the proposed scheme can make accurate estimation of available resource on considering the effect of MUD, leading to low outage probability.

Index Terms—interleave division multiple access (IDMA), multi-beam satellite communication networks, power allocation, rain attenuation, signal to interference plus noise ratio (SINR)

I. INTRODUCTION

In the past few years, CDMA is widely regarded as a promising candidate for satellite communication systems, while the computational cost of multi-user detection (MUD) limits its application in practical satellite systems due to the limited onboard processing capacity. Consequently, the current key issue is to select a multiple access (MA) technology with low cost MUD to further explore the advantage of the satellite systems. The newly arising access technique, named interleave-division multiple access (IDMA), is a potential solution to this problem. As a new wireless access technology, the key thought of IDMA is to use different interleavers for distinguishing multiple users. Furthermore, it adopts iterative chip-by-chip (CBC) detection scheme to combat multiple access interference (MAI), and compared to CDMA, IDMA solves the problem of MAI at a very low computational complexity which has linear complexity with the number of users [1].

Considering the advantage of IDMA technique and the technical bottlenecks in the existing satellite systems, IDMA has been introduced into satellite communication networks in the existing literature [2]. The advantage of IDMA technology for satellite communication systems is the high efficiency to overcome both intra-cell and inter-cells MAI with simple CBC MUD. Thus, as a prominent countermeasure, the technique of frequency reuse and multi-beam antennas [3] is also used to further increase the system capacity in IDMA-based satellite system. However this technique can bring cochannel interference and competition during all of the beams. Meanwhile for data services over satellite networks, the efficient management of satellite downlink communication resources is crucial for economic competitiveness of the medium [4].

On the other hand to support the emerging interest in provisioning broadband and multimedia services, satellite networks has resulted in the use of higher frequency bands such as Ka (20/30GHz), Q/V (40/50GHz) bands. However at these high frequencies, the transmitted signals heavily suffer from the troposphere attenuation due to atmospheric precipitation (rain, clouds, fog, gazes etc) [5]. In light of the above reasons, it is important to design a unique power allocation algorithm for satisfying the minimum SINR by combining the peculiarity of IDMA and the diversity of attenuation in different cells. The main goal of the proposed algorithm is to further maximize the resource utilization and compensate rain attenuation for the system.

In the current literatures, there are several power allocation algorithms for multi-beam satellite communication systems. However it has not been well studied whether these algorithms are also suitable for IDMA-based multi-beam satellite communication systems. In views of this, in this paper a novel multi-beam power allocation scheme for IDMA-based satellite system is proposed based on the two influential algorithms as follows. The first one is the algorithm for the dynamic power allocation using a physical-mathematical model for rain attenuation prediction, which can greatly increase the number of served users in cells with serious rain attenuation [3]. The other
The algorithm is a distributed balancing algorithm using only local SINR information, which can achieve SINR balancing and obtain a lower outage probability combining with cell removal algorithms [6].

The rest of this paper is organized as follows. The IDMA-based multi-beam downlink system and channel is built to obtain a mathematical expression of SINR in section II. In section III, the algorithm of multi-beam power allocation scheme for IDMA-based satellite communication is formulated and solved. And then, the simulation and performance evaluation are presented in Section IV. In Section V, we conclude the paper.

II. IDMA-BASED MULTI-BEAM SATELLITE SYSTEM AND CHANNEL MODEL

A. Multi-beam System Model

Fig.1 gives the interference calculation model and the characteristics of the spot-beam antenna. Suppose there are \( M \) mobiles and \( N \) beam cells in the system and the locations of the user terminals are fixed, something that is typical for broadband satellite communication networks operating at high frequencies. Another assumption is that user \( r_j \) represents the i-th user severed by beam \( j \). Thus in Fig.1 \( h_{ij} \) represents the power channel gain coefficient from the given satellite to user \( r_j \), which can be calculated as follows.

\[
h_{ij} = \frac{G_{s,ij} G_{r,ij}^2}{(4\pi d_{ij} / \lambda)^2} 10^{-\frac{10}{10}}
\]

Where \( \lambda \) represents the working wavelength of the satellite, \( d_{ij} \) is the distance from satellite to user \( r_j \), \( G_{s,ij} \) and \( G_{r,ij} \) are the association gains at the satellite antenna and the receiver antenna respectively and \( A_{c,ij} \) is the rain attenuation, explained as follows.

\[
V_i = 1 - \tanh^2 \left( \frac{Y_i}{2} \right), i = 1,....,M
\]

As shown in (4), the variance of an arbitrary chip from user-i, \( V_i \), is a function of SINR, which by definition is the power factor of the interference introduced by user-i. Here we define

\[
f(SINR_i) = E(V_i) = 1 - E \left( \tanh^2 \left( \frac{Y_i}{2} \right) \right), i = 1,....,M
\]

The function \( f(SINR) \) can be referred as the uneliminated percentage of the interference power in the downlink, which affects the power of user-i at the next iteration. Moreover as IDMA-based satellite system adopts frequency reuse technique, so the desired user suffers co-channel interference from own cell and the neighbor cells, which can be calculated as

\[
I_{int,cc} = \sum_{j=1}^{M} \sum_{i=1}^{M} p_{ij} h_{ij} - p_{ij} h_{ii}
\]
Meanwhile the SINR of the user- \( i \) in cell \( j \) for IDMA-based multi-beam satellite communication can be calculated as:

\[
(SINR)_{i,j} = \frac{h_{i,j}P_{i,j}}{(I_{int} + f(SINR_{i,j}) + N_r B)}
\]  

(6)

Where \( N_r \) is the power spectral density of background noise, \( B \) represents system bandwidth. Equation (6) involves SINR evolution technique which can obviously improve the system capacity because of iteration. It has been demonstrated that \( f(SINR) \) decreases when the SINR increases and its value is always between zero and one.

For the IDMA-based satellite communication system, when SINR threshold \( \gamma > 0 \) is given, to maintain adequate transmission quality, the SINR of mobile \( i \) in \( j^{th} \) cell requires

\[
(SINR)_{i,j} \geq \gamma
\]  

(7)

III. THE PROPOSED ALGORITHM

From the current literature it can be seen there are many metrics to evaluate the performance of power allocation schemes, such as total capacity, fairness and outage probability[9][10][11][12]. Here, the outage probability is used to be the user allocation algorithm. The outage probability is obtained as

\[
P_{out} = \frac{1}{NM} \sum_{j=1}^{N} \sum_{i=1}^{M} P_i \{SINR_{i,j} < \gamma \}
\]  

(8)

Therefore the problem of the power allocation can be represented as follows [12].

\[
\text{minimize } P_{out}, \text{ subject to } \sum_{j=1}^{N} \sum_{i=1}^{M} P_i \leq P_{out} \quad (9)
\]

Where \( P_{out} \) is the total available power of satellite.

To solve this problem this paper comes up with a novel power allocation algorithm. The algorithm consists of two processes: one is to obtain the available power of every beam according to the different rain attenuation and the other process is to adjust the beam power and allocate every user’s power by employing the principle of link quality balancing problem (LBP) [13].

A. Obtaining the Available Power for Each beam

The power allocation of each beam in this process is briefly described for the sake of completeness and comparison. Suppose that the threshold of received power is common to all users and it is denoted as \( P_{th} \). Thus for IDMA-based satellite communication system the received power at the input of decoder of user \( i \), \( P_{r,i,j} \) is obtained as

\[
P_{r,i,j} = P_{th,i,j} \quad \text{where } P_j = \text{the power of the } j^{th} \text{ beam and it can be calculated as } P_j = \sum_{i=1}^{N} P_i \quad . \text{For every user } i \text{ served by beam } j \text{ the condition } P_j h_{i,j} \geq P_{th,i,j} \text{ must be valid in order to have reliable communication. Thus on the base of this principle a dynamic power allocation algorithm is proposed in literature [3]. The key steps are described as follows}

\text{Initialization: } \text{Predict the rain attenuation for every user and calculate all the corresponding coefficients } H \text{ according to equation (1), } H = \{h_{j} \mid 0 \leq i \leq N, 0 \leq j \leq M \}. \text{ Set the original power of every beam as } P_j = P_{th} / \min(h_{j,c}) \text{, where } h_{j,c} \text{ is the link coefficient under clear sky conditions and in other word the attenuation } A_{c,j} \text{ equals zero and } i \in j \text{ means user } i \text{ is served by beam } j.

\text{Step A.1: } \text{Select the maximum element of } h_{c,j} \text{ set of } H \text{ and update: } H \leftarrow H - \{h_{c,j}\}, \text{ } P_j = P_{th} / h_{c,j}

\text{Step A.2: } \text{If } P_j + \sum_{j=1}^{N} P_j \geq P_{out} \text{, then the algorithm terminates. Else, update } P_j \leftarrow P_j.

\text{Step A.3: } \text{if the set } H \text{ is empty, then the algorithm terminates. Else, go back to step A.1.}

Thus after this algorithm, we obtain the power and this power can also be used as available power \( P_{max,j} = P_j \) for every cell in next process.

B. Adjusting the Beam Power and Allocating Each User’s Power

In this procedure the SINR threshold and the LBP principle is used to allocate the power of every user. The LBP principle is to let all the mobiles in the cell enjoy an equal link quality and is described as follows.

The LBP for beam cell \( j \) in IDMA-based satellite communication system is represented as

\[
\gamma_j = \max_{p_{i,j}} \min_{i \in j} \left\{ \frac{h_{i,j} p_{i,j}}{(I_{int} + f(SINR_{i,j}) + N_r B)} : i \in j \right\}
\]

subject to \( \sum_{j=1}^{N} p_{i,j} = P_j \quad \text{for } i \in j \quad p_{i,j} \geq 0 \quad (10) \)

LBP is a problem for finding individual power levels that maximize the minimum transmission quality among users served by cell \( j \), and can be easily and independently solved for each cell [14]. Let equations (5) plug in equation (10) and elide \( p_{i,j} h_{i,j} \text{ in } I_{int} \), then the following variable can be defined:

\[
\phi_{j} = \sum_{i=1}^{N} \sum_{j=1}^{M} h_{j} p_{i,j} f(SINR_{i,j}) + N_r B
\]

\[
\Phi_j = \sum_{i=1}^{N} \phi_{j} \quad (11)
\]
Thus the \( p' \) and \( \gamma' \) can be derived as \[
\hat{p}_i = \frac{\phi_i}{\Phi} - P_f \quad \text{and} \quad \hat{\gamma}_j = \frac{P_f}{\Phi}
\]
(13)

With the above definition, the whole procedures of power allocation can be described as

Step B.0: Give max, \( j P_j \), set \( l = 0 \) and \( N_j^0 = \{P_j^0, j = 1, ..., N \} \).

Step B.1: For all users, obtain individual power levels \( p'_i \) and \( \gamma'_j \) by equation (13) with \( P_j \).

Step B.2: For \( j = 1 \ldots N \), update the power of every beam as \( P_j^{l+1} = \min\{P_{\max}, \frac{P_j'}{\gamma'_j} \} \). Then set \( l = l + 1 \) and go to Step B.1. The algorithm stops until reaching convergence.

Consequently, the final power for every user can be obtained after the two procedures. However if there are too many mobile users in the network, an effective solution may not exist, this lead to that it is impossible to provide all the users with satisfying transmission quality. In this case several users should be disconnected or handed over to other system to ensure the quality of services (QoS) of the rest users. This paper a removal strategy of giving up the users which has the worst link gain is adopted. In order to clearly describe, Fig.2 gives the flow diagram of the whole algorithm and the \( T \) presents the interval of judgment. It means that once the number of iteration reaches at \( T \), the removal strategy should be adopted if the algorithm hasn’t achieved the system goal.

IV. SIMULATION RESULTS AND DISCUSSION

In this Section, simulation results of the proposed power allocation algorithm are presented. The simulator of MATLAB is used to allocate power between multi-beams.

A. Results of Power Allocation

The value of part of parameters is listed in Table I [15].

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>system bandwidth ( B )</td>
<td>3.84 MHz</td>
</tr>
<tr>
<td>speech rate ( R_s )</td>
<td>12.2 kps</td>
</tr>
<tr>
<td>chip rate ( R_c )</td>
<td>2.048 Mbps</td>
</tr>
<tr>
<td>beam radius ( r )</td>
<td>400 km</td>
</tr>
<tr>
<td>working frequency ( f )</td>
<td>30 GHz</td>
</tr>
<tr>
<td>SINR threshold ( \gamma )</td>
<td>-24 dB</td>
</tr>
<tr>
<td>power of background noise ( P_n )</td>
<td>-174 dBm</td>
</tr>
<tr>
<td>total available power of satellite ( P_{tot} )</td>
<td>200 W</td>
</tr>
<tr>
<td>radius of satellite trajectory ( R_t )</td>
<td>42164 km</td>
</tr>
<tr>
<td>radius of the earth ( r_b )</td>
<td>6371 km</td>
</tr>
<tr>
<td>gain of the satellite antenna ( G_s )</td>
<td>26 dB</td>
</tr>
<tr>
<td>gain of the receiver antenna ( G_r )</td>
<td>75 dB</td>
</tr>
</tbody>
</table>

Here a hypothetical satellite network of Hellas Sat 2 (39°E) is assumed. The multi-beam antenna has 14 beams and the coverage area of the satellite network in China is taken from 25°E to 45°E in geographic longitude and 100°N to 120°N in geographic latitude. Table II gives the average value of rain attenuation in these areas which is obtained by utilizing the model of ITU-R and the rainfall distribution of China. Here the value of rain attenuation nearly approaches the real situation for the reason that the data of rainfall distribution comes from meteorological department.

<table>
<thead>
<tr>
<th>Beam index</th>
<th>Average value of rain attenuation (dB)</th>
<th>Beam index</th>
<th>Average value of rain attenuation (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>2</td>
<td>16</td>
<td>9</td>
<td>32.72</td>
</tr>
<tr>
<td>3</td>
<td>31.21</td>
<td>10</td>
<td>35.39</td>
</tr>
<tr>
<td>4</td>
<td>7.24</td>
<td>11</td>
<td>21</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>12</td>
<td>32.53</td>
</tr>
<tr>
<td>6</td>
<td>31.78</td>
<td>13</td>
<td>38.12</td>
</tr>
<tr>
<td>7</td>
<td>4.98</td>
<td>14</td>
<td>36.46</td>
</tr>
</tbody>
</table>

Fig.3 gives the location of users and the center of the beams. The number of users \( M \) in every beam is 22 and the users are set to be uniformly distributed with distance of 0.25° both in latitude and longitude from each other in each cell.

Fig.4 gives the result of power allocation between beams. It’s obvious that the more serious attenuation the more power allocated. \( P_{\max, j} \) is the power after procedure 1 which has been stated in Section III. It can be seen the power for every beam of the proposed algorithm is...
slightly less than $P_{\text{max}, j}$ and this can reduce the interference to other beams. Due to the sum of $P_{\text{max}, j}$ is under $P_{\text{tot}, j}$, so the proposed algorithm satisfies the condition of constraint in equation 9.

![Figure 4. Power allocation results per satellite beam](image)

Fig. 4. Power allocation results per satellite beam

![Figure 5. Results for user power allocation in the tenth cell](image)

Figure 5. Results for user power allocation in the tenth cell

**B. Outage Probability**

In order to examine the ability of the proposed algorithm to assure the QoS of all users during their whole service time, the schemes are assessed in terms of outage probability. Outage probability has been defined in equation (8).

![Figure 6. Comparison of outage probability of various algorithms for increasing number of mobiles per cell](image)

Figure 6. Comparison of outage probability of various algorithms for increasing number of mobiles per cell

**C. Convergence Speed**

As stated in Section III, the proposed algorithm derives from LBP; consequently, the performance of convergence can be discussed according to LBP. If the link coefficients and SINR threshold $\gamma$ are given, the final power of each beam $P = \{P_j, j=1,2,\ldots,N\}$ is considered effective if it satisfies the lemma as follows [17]. Suppose the power allocation algorithm $\chi$ represents $P^{(i+1)} = \chi(P^{(i)})$, it satisfies:

1) Positivity: $\chi(P) > 0$
2) Monotonicity: if $P' \geq P$, then $\chi(P') \geq \chi(P)$
3) Scalability: for all $\beta > 1$, $\beta\chi(P) > \chi(\beta P)$

From literature [18], if the algorithm $\chi$ is effective, then any initial power vector will converge to a unique power vector that all the users achieve the SINR of $\gamma$. From the Section III.B, the proposed algorithm $\chi$ can be expressed as follows:

$$\chi_i(P) = \min\{P_{\text{max}, i} - \gamma, \frac{P^{(i)}}{\gamma_i} \}$$

$$= \min\{P_{\text{max}, i} - \gamma, \sum_{i=1}^{N} \frac{\sum_{j=1}^{N} h_{ij} P_j f(SINR_{i,j}) + N_i B}{h_{ij}} \}$$

$$= \min\{P_{\text{max}, i} - \gamma, \sum_{i=1}^{N} \frac{\sum_{j=1}^{N} h_{ij} P_j f(SINR_j) + N_j B}{h_{ij}} \}$$

$$= \min\{P_{\text{max}, i} - \gamma, \sum_{i=1}^{N} \frac{\sum_{j=1}^{N} h_{ij} f(SINR_j) / h_{ij} + \sum_{j=1}^{N} (N_j B / h_{ij})}{h_{ij}} \}$$

$$= \min\{P_{\text{max}, i} - \gamma, \sum_{i=1}^{N} \frac{\sum_{j=1}^{N} h_{ij} f(SINR_j) / h_{ij} + \sum_{j=1}^{N} (N_j B / h_{ij})}{h_{ij}} \}$$
During the derivation of above equation, the $h_{ik}$ and $f(SINR_{old,ik})$ are regard as the same in the $j$-th cell due to the slightly difference between users in one cell. Since the link coefficients, $f(SINR)$ and the background noises at receivers are positive, so equation 14 satisfies positivity and monotonicity. The scalability has been proven as proof 1.

**proof 1:** the algorithm is scalability.

**Proof:**

Equation (14) can be presented as:

$$\chi_{j}(P) = \min\{P_{\text{max},j}, \gamma \left( \sum_{k=1}^{M} X_{jk} \cdot P_{j} + Y_{j} \right) \}$$

(15)

Where $X_{jk} = (\sum_{i=1}^{N} h_{ij} f(SINR_{i}/h_{ij})$ and $Y_{j} = \sum_{i=1}^{N} (N_{i}B/h_{ij})$

If $\chi_{j}(P) = P_{\text{max},j}$, then, for all $\beta > 1$

$$\beta \chi_{j}(P) = \beta P_{\text{max},j} > P_{\text{max},j} \geq \chi_{j}(\beta P)$$

(16)

If $\chi_{j}(P) \neq P_{\text{max},j}$, then, for all $\beta > 1$

$$\chi_{j}(\beta P) = \min\{P_{\text{max},j}, \gamma \left( \sum_{k=1}^{M} X_{jk} \cdot \beta P_{j} + Y_{j} \right) \}$$

$$= \gamma \left( \sum_{k=1}^{M} X_{jk} \cdot \beta P_{j} + Y_{j} \right) + \gamma (1-\beta) Y_{j} \leq \beta \chi_{j}(P)$$

(17)

Thus for all $\beta > 1$ from equation (16) and (17) the scalability is satisfied. Therefore the proposed algorithm convergences a certain power vector. Fig.7 gives the convergence behavior of proposed algorithm. As can be seen from the graph, the proposed algorithm converges to the certain value at the eighth iteration. Moreover the convergence speed is acceptable.

**REFERENCES**


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