A Practical Q/V Band Smart Gateway Diversity Scheme for Very High Throughput Satellite Systems

Xinhua Li¹*, Xinrong Wang¹, Ruoke Li¹, Hongtao Wang¹, and Jilin Li¹

¹ Space Star Technology Co., Ltd, Zhongguancun Environmental Science and Technology Park, Haidian District, Beijing, China

Abstract. The use of Q/V band feeder links and Ka band user links is a feasible solution to support the next iteration of High Throughput Satellite. The gateway transmit diversity technique is a way to compensate the rain attenuation of Q/V band feeder links. This paper analyzes a practical combination scheme that combines N-active (K=2) with N+1 diversity method in detail from the working principle, gateway handover status transfer process, evaluation of system availability and implementation complexity. Compared with the existing N+P scheme, the proposed scheme can provide higher system availability and more stable user experience under the condition of properly increasing the complexity of payload design. Compared with N-active scheme that has been reported, it is much easier to implement in engineering and more cost-effective. As a result, the combination scheme is an optimized solution based on a trade-off between performance improvement and complexity of the payload.

1 Introduction

As the use of traditional satellite frequency band resources tends to be saturated, Q/V frequency band has the advantages of high bandwidth, narrow beam, etc., making it widely regarded as the preferred frequency band for the feed links of very high throughput satellite (VHTS)[1][2]. It’s also regarded as the focus of mainstream satellite operators. The KONNECT VHTS from Eutelsat Communications and the JUPITER 3 VHTS from Hughes are expected to launch in 2021[3]. Both these two satellites utilize of Q/V-band feeder links and Ka-band user links. Their system throughputs can reach 500Gbps, so as to provide high-speed Internet access service for the end users on land, in the air and at the seas. It’s comparable to terrestrial fiber services in price and speed.

At present, the configurations of Ka and Q/V frequency band have become a consensus in the VHTS frequency scheme design. Compared to the traditional Ka band HTS satellite, VHTS can completely assign Ka band resources to the users, the system capacity would increase greatly. Moreover, in VHTS system, a single gateway has larger capacity, which can manage more user beams. Under the same satellite capacity, less gateways will be needed, so as to reduce the total cost of system construction. However, the use of Q/V band spectrum for the feeder link is more vulnerable to adverse meteorological conditions, which is of the order of 15–20 dB or more predominantly due to heavy rain attenuation[4].
Figure 1. CDF of total atmospheric attenuation for a Gateway (GW) located in Beijing, Q/V band.

In Figure 1, an example of the Cumulative Distribution Function (CDF) of total atmospheric attenuations at 40/50GHz for an earth station located in Beijing is illustrated. It can be seen that in order to provide availability of 99.9%, a margin of 40 dB would be required in V band by ITU model. At present, the rain fade mitigation techniques, with fully researched and widely used, include Uplink Power Control (UPC), Adaptive Coding Modulation (ACM) and Gateway Transmit Diversity (GTD) techniques. To cope with these high degradations, these three techniques mentioned above needed to be used in combination, so as to achieve the required availability on the Q/V band feeder link. This paper will focus on GTD technique.

2 Current gateway transmit diversity scheme

2.1 N+P diversity scheme

Professor Argyrios Kyrgiazos is a key figure in researching the diversity scheme of Q/V frequency band. He analysed the N+P diversity scheme with N active GWs and P idle GWs[5]. When one of the N active GWs is in outage, switching occurs and traffic of the active GW is rerouted to one of the P idle GWs, which is shown in Figure 2. Dr. Ahmad Gharanjik deduced the closed expression of average outage performance and switching probability, and concluded that the selection of switching threshold value depends on the result of the trade-off of outage probability, switching rate and spectrum efficiency[6-8]. Dr. Nicolas Jeannin pointed out that the disadvantage of the N + P scheme was that a large number of users would be reconnected to an idle GW at the same time as switching the gateways. Therefore, a couple of minutes or even more will be needed because of congestion problems[9][10]. This is intolerable for high availability services such as video conference and telemedicine.
2.2 N-active diversity scheme

The N-active scheme is another diversity scheme of interest to scholars. In[5] and [6], Professor Argyrios Kyrgiazos and Dr. Ahmad Gharanjik carried out a preliminary analysis of its principle, availability and capacity offered by feeder links respectively. In this scheme, each user beam is connected to a number of gateways with multiple separate channels, which is shown in Figure 3. If a gateway is experiencing heavy rain fading, then it route its traffic to unfading gateways where the traffic is forwarded to the user beams using the carriers that have already allocated to transmit the normal traffic towards the corresponding user beams, which have to adapt the Quality of Service(QoS) to the current circumstances. All the active gateways are monitored by Network Control Center (NCC) that is responsible for detecting feeder link outage conditions and for deciding the start of GW handover procedures[11]. After the further analysis, professor Argyrios Kyrgiazos points out that the throughput of the users will be reduced when one gateway or a few gateways outage due to heavy rain fading[12]. But, for User Terminal (UT), no traffic interrupts and back online occurs during GWs’ handover process. However, N-active faces a problem which is the tremendous complexity of the onboard payload and the enormous increasement of onboard equipment[9].
3 Proposed gateway transmit diversity scheme

Considering that the disadvantages of N-active scheme and N+P scheme, we are trying to find a solution that satisfies both a good user experience and not overly complex in the design of the system or payload. In the VHTS system, we define that N is the number of active gateways, and K is the number of gateways connected by a user beam through the feeder links. A practical combination N-active (K=2) with N+1 diversity scheme is proposed, abbreviated as combination scheme.

3.1 Principle

The basic principle of N-active (K=2) diversity is to serve a user beam through the carriers of two different gateways. On the basis of N-active (K=2) scheme, an extra gateway is deployed, which will start to work when any one of N active gateways encounters heavy rain attenuation. Figure 4(a) shows the working state of the combination scheme in sunny days, and Figure 4(b) shows the working state of the combination scheme under rainfall conditions.

![Figure 4(a). Combination scheme operation in the clear sky.](image)

![Figure 4(b). Combination scheme operation under rain fade.](image)
As shown in Figure 4, when N is even, every two gateways pair, such as GW1 and GW2, and GW (N-1) and GW (N). Every one pair GW, named one (1) GW cluster, serves to a part of the user beam clusters. When N is an odd number and N is not equal to 1, there are at least one (1) GW cluster which is composed of three (3) active GWs. In this case, satellite payload requires more signal splitters, filters, and signal combiners. Furthermore, the user terminal shall be equipped with a multi-carrier receiver so that the terminal can simultaneously receive multiple carriers from three (3) active GWs. Thus, when N is an odd number, the complexity and cost of satellite payload and user terminal receiver will be much higher than the one as N is an adjacent even number. During overall design of VHTS, the number of active GWs prefers to be an even number as possible. In this paper, we will focus on the combination scheme (N is an even number) and present our contributions for this scenario.

3.2 GW handover status transfer process

In general, the GW handover status transfer process can be decomposed in three steps:
- First, any one of N active gateways experiencing heavy fading will switch to the extra gateway.
- Second, after the re-pairing of the two gateways, if a second gateway is in outage at the same time as the first, the users need to switch to the paired gateway.
- Third, upon return of the first affected GW or the second outage GW, the traffic is migrated back to the original carrier.

GW handover status transfer process is illustrated in Figure 5. GW A and GW B are working in V frequency band for the forward link, and the center frequencies of the transmitting carriers are C1 and C2 respectively as depicted in status a). T1 and T2 represent the flows to the user terminals managed by the respective GW A and GW B. Under the condition of b1), GW A is in outage state. When the extra gateway is available, the traffic managed by GW A is migrated to the carrier C3 of the extra gateway. In the state of b2), when the extra GW and GW A becomes in outage simultaneously, traffic managed by extra GW is migrated to GW B on carrier C2. Since now, GW B has to serve temporarily traffic T1 and T2, both of which may have to adapt the QoS policy to the current circumstances. The data rate of individual UT that connects GW B drops by half accordingly. When GW A is available in c), the traffic T1 is migrated back to the original carrier C1. If the extra GW recovers firstly, the traffic T1 is migrated back to C3 and then back to the original carrier C1, which is shown with the dotted line in Figure 5. The gateway handover state transfer process for the return link is similar.

Another handover operation status transfer process including two (2) stages is illustrated in Figure 6. In a), T1 and T2 represent the traffic from GW A and GW B to user terminals.
respectively. In b), GW A is in outage because of heavy rain fading. Traffic managed by GW A is migrated to carrier C2 managed by GW B when the extra gateway has already occupied or been in outage due to the rainfall attenuation. When GW A is available, traffic T1 is migrated back to the original carrier C1, as shown in c).

![Diagram](image)

**Figure 6.** Another GW handover status transfer process.

### 3.3 Average outage probability

For the N + P scheme, the outage probability of the users can be obtained as (1) and (2) (for details kindly refer to [11]).

\[
P_{k \text{ gateways in outage}} = C_{N+P}^k p^k (1 - p)^{N-k}
\]  

(1)

\[
P_{\text{outage}} = \frac{1}{N} P(1 \text{ gateway in outage}) + \ldots
\]

\[
+ \frac{i}{N} P(i \text{ gateway in outage})
\]

\[
= \sum_{i=0}^{N} \frac{i}{N} P(i \text{ gateway in outage})
\]  

(2)

If less than P gateways are simultaneously in outage, all user beams can still be served in the N+P scheme. If \(P + i\) gateways are in outage simultaneously, a fraction \(i/N\) of the user beams will not be served by any gateways. From the view of user terminal, it results in a probability \(i/N\) of outage if \(P + i\) gateway are unavailable, as it can be assumed that the redundant gateway can be allocated randomly to any of the \(i\) gateways in outage.

The equation (2) cannot be used to calculate the probability of users in the combination scheme, because the number of outage gateways in the system is no longer necessarily related to whether the user is outage or not. It is possible that the number of outage gateways is large but users are not connected to the affected GW, whereas the number of gateways in outage situation is small but users are connected to the affected GW. In other words, the number of gateways in outage is no longer the key parameter to judge whether the user is in outage situation. Whether the pairing gateways in the system are in outage status at the same time due to fading events is the decisive factor to determine whether the user outage occurs in the system. The user will be in outage status only if the paired gateways are in outage and the extra gateway is in outage or occupied. Therefore, the availability calculation of the combination scheme can be divided into two steps:

- First, regarding two (2) active gateways as a pair, and calculating the outage probability of the pairing gateways.

- Second, paired gateways, combined with the extra gateway, are regarded as N + P system, and then the availability model of N + P scheme is used for calculation.

The equivalent model of outage probability is shown in the Figure 7. Now suppose that the number of the active gateways is \(N=2N'\). After pairing, the number of the active
gateway pairs is N'. The number of idle gateways is P. In order to simplify the calculation and find out the optimal situation that the system can achieve under the equivalent model, the following assumptions are made:

- The rainfall events of the active and idle gateways obey the same probability distribution and have the same outage probability, which is set as $p_0$.
- The distance between gateways (including active gateways and an idle gateway) is more than 100km, and rainfall events are independent of each other[6].

![Diagram showing gateway pairs and user connections]

**Figure 7.** The equivalent model of outage probability calculation for combination scheme.

According to the above assumptions, it can be concluded that:

$$P_{(a \text{ pair of gateways in outage})} = p_0^* p_0^* = p_0^2 = q$$  \hspace{2cm} (3)$$

Therefore, the probability of outage i pairs of gateways and j idle gateways in the system is as follows:

$$P_{(i \text{ groups of gateways and } j \text{ idle gateways in outage})} = C^i_N q^i (1-q)^{N-i} C^j_p p_0^i (1-p_0)^{P-j}$$  \hspace{2cm} (4)$$

Among them:

$$i \in [0, N'] \land i \in N'$$

$$j \in [0, P] \land j \in N'$$

Therefore, the outage probability of combination scheme (P=1) is:

$$P_{\text{outage}} = \sum_{i=0}^{N'} \frac{i}{N'} P_{(i \text{ groups of gateways and 1 gateway in outage})}$$

$$+ \sum_{i=2}^{N'} \frac{i}{N'} P_{(i \text{ groups of gateways and 0 gateway in outage})}$$  \hspace{2cm} (5)$$

$$= p_0^3 + (1-p_0) \sum_{i=2}^{N'} \frac{C^i_N p_0^2 (1-p_0)^{N-i} i-1}{N'}$$

Among them:
\( p_0 \) is the outage probability of the active or idle gateway(s).

\( N' \) is the number of the active gateway pairs in the system.

\[
\sum_{i=0}^{N'} \frac{i}{N'} P \left( i \text{ groups of gateways and 1 gateway in outage} \right) = q P_0 = p_0^3
\]  \( (6) \)

Using (5) and assuming that the number of active gateways \( N = 10, 20 \), and \( 50 \), we draw the curve of availability of a user varying with the outage probability of a single gateway, which is shown in Figure 8. The availability of a user (ideal UT link) is greater than 99.9% even when the outage probability of each gateway is equal to 7% and the number of active gateways reach 50.

![Figure 8. A user’s availability vs. gateway’s outage probability for combination scheme.](image)

We are also interested in the number of active gateway \( N \) that the system can support at most under the condition of one idle gateway to ensure that the user's availability is more than 99.9%. Using (5), we calculate the user availability under the condition that the unavailability of each gateway is 7%, 5%, and 3%. The variable \( N \) is the number of active gateways in the system. Some calculation results are shown in the Table 1.

<table>
<thead>
<tr>
<th>Number of gateways</th>
<th>Unavailability of each gateway 7%</th>
<th>Unavailability of each gateway 5%</th>
<th>Unavailability of each gateway 3%</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N=10 )</td>
<td>99.9613</td>
<td>99.9863</td>
<td>99.9971</td>
</tr>
<tr>
<td>( N=50 )</td>
<td>99.9399</td>
<td>99.9805</td>
<td>99.9964</td>
</tr>
<tr>
<td>( N=100 )</td>
<td>99.9150</td>
<td>99.9735</td>
<td>99.9954</td>
</tr>
<tr>
<td>( N=132 )</td>
<td>99.9002</td>
<td>99.9713</td>
<td>99.9948</td>
</tr>
<tr>
<td>( N=134 )</td>
<td>99.8993</td>
<td>99.9689</td>
<td>99.9948</td>
</tr>
</tbody>
</table>

![Table 1. The availability of a user varying outage probability of each gateway for combination scheme.](table)

The results show that when the outage probability of each gateway is equal to 7%, the system can support the number of gateways \( N = 132 \) at most, meeting the requirement that
the availability of a user (ideal UT link) is greater than or equal to 99.9%. VHTS systems barely need so many active gateways when system sizing, so an extra gateway is sufficient for the combination scheme.

4 Performance comparison of various diversity schemes

In order to compare the performance among proposed combination scheme, current N+P scheme and N-active scheme, we make the following assumptions for a VHTS system:
- Number of the active gateways in the system N= 10.
- Number of user beams in the system M=160.
- N gateways are more than 100 km apart from each other, their rainfall events can be considered irrelevant.
- The system availability is greater than 99.9%. The feeder link availability of each gateway is equal, ranging from 97% to 98%, and the UT link is ideal.
- Uplink of feeder link: 8GHz bandwidth per GW (4GHz per polarization).
- Downlink of feeder link: 4GHz bandwidth per GW (2GHz per polarization).
- Uplink of user link: 250MHz per beam (8 frequency/polarization reuse).
- Downlink of user link: 500MHz per beam (8 frequency/polarization reuse).

4.1 Average outage probability comparison

According to the above assumptions, for N-active scheme, the probability of a user inside a UT beam to be in outage is the probability of all the active gateways that serve it to experience an outage. In this case, each gateway has an outage probability $p_i$. Then:

$$P_{\text{outage}} = P(A_1 \geq A_i \cap \ldots \cap A_N \geq A_N) = p_1 \cdots p_N$$

(7)

For N+P scheme, according to equation (2), the probability of a user inside a UT beam to be in outage can be calculated, and the calculation results are shown in the Table 2.

Table 2. The availability of a user varying outage probability of each gateway for N+P scheme.

<table>
<thead>
<tr>
<th>Number of idle gateway(s)</th>
<th>Unavailability of each gateway 4%</th>
<th>Unavailability of each gateway 3%</th>
<th>Unavailability of each gateway 2%</th>
</tr>
</thead>
<tbody>
<tr>
<td>P=1</td>
<td>99.22%</td>
<td>99.55%</td>
<td>99.79%</td>
</tr>
<tr>
<td>P=2</td>
<td>99.88%</td>
<td>99.95%</td>
<td>99.98%</td>
</tr>
</tbody>
</table>

From Table 2, we can see that at least two (2) redundant gateways is needed in order to ensure that the system availability of is greater than 99.9% (ideal UT link) assuming that the availability of each gateway is less than or equal to 98%.
Figure 9. A user’s availability vs. gateway’s outage probability for combination scheme.

Then, we draw the user’s availability curve changing with the outage probability of a single gateway for the three (3) schemes. The results are shown in Figure 9. The simulation results show that the combination scheme is close to the N-active scheme, and it’s far better than the N+P (P=2) scheme in terms of system availability.

4.2 Payload complexity comparison

In this paper, we compare the payload design of different diversity schemes with the forward link payload design, as this is the most challenging part of the diversity schemes. The concepts discussed are intended to be also applicable to the return link payload design.

4.2.1 N+P (P=2) scheme forward link payload

For the forward link, the special feature of the N+P scheme payload is the microwave switching matrix. The function of the switching matrix is to switch between the active gateways and idle gateways. After the signal from the gateways is selected by the switching matrix, the signal is amplified by the Low Noise Amplifier (LNA), and then the frequency will be transformed from the V-band signal to the Ka band signal. The Ka band signal passes through the channel filter, the interference will be filtered out. Finally, it is sent to the free space through the antenna after being amplified by TWTA high power amplifier. The forward payload block diagram is shown in Figure 10.

Figure 10. Forward link payload block diagram of N+P (P=2) scheme.
4.2.2 N-active scheme forward link payload

Under the N-active scheme, if the microwave network is chosen to implement the payload, the bandwidth of a single user beam of 500MHz needs to be divided into 10 sub-bands. Each sub-band has a bandwidth of 50MHz and a protection band of 5MHz. Therefore, the utilization rate of available frequency resources decreases. In addition, if the N-active is adopted, a user beam corresponds to N gateways. With the increase of N, the payload system complexity continues to increase. As a result, the number of forward payload channels will increase N times, and the number of return payload channels will increase N times as well. Assuming that VHTS system has 160 user beams, and the number of channels is normally 160 channels, both the number of forward payload channels and the number of return payload channels are N*160 after the use of N-active scheme. Frequency resources and weight resources will be seriously wasted. Furthermore, it is almost impossible to implement practically.

N-active scheme forward link payload diagram is shown in Figure 11. The V-band signal is converted to low-frequency signal after the LNA, so as to realize the payload through Digital Transmitting Process (DTP) technology. There are 10 active gateways in the VHTS system architecture, and each gateway has 12GHz frequency resources. If DTP technology can achieve 24GHz bandwidth processing capacity, five (5) digital transmitting processors can meet the system requirements under this architecture. It can guarantee the smaller channel granularity and the exchange flexibility through the digital transmitting processor. The disadvantages are the need for channel switching in baseband and the high-performance requirements for the digital devices.

![Figure 11. Forward link payload block diagram of N-active scheme.](image)

4.2.3 Combination Scheme forward link payload

The key payload of combination scheme includes microwave switching matrix, power divider and fusion microwave network. Among the 11 gateways, 10 gateways are selected by microwave switching matrix as the active gateways to receive 20 channels of dual-polarization V-band signals. The received V-band signals are amplified by LNA, and each signal is divided into two channels by power divider. After the power division, the two channel signals enter into the fusion microwave network, and are synthesized with the two channel signals from paired active gateway to form a new frequency combination. After that, the two channel signals with recombination frequency are transformed into Ka frequency band through V/Ka frequency converter. Finally, it is sent to the free space...
through the antenna after being amplified by TWTA high power amplifier. The forward payload diagram is shown in Figure 12.

![Figure 12. Forward link payload block diagram of combination scheme.](image)

According to simulation design and calculation, the comparison of payload design results of different diversity schemes is shown as Table 3.

<table>
<thead>
<tr>
<th>Diversity Scheme</th>
<th>Critical Payload Configuration</th>
<th>Quantity (pcs)</th>
<th>Weight (Kg)</th>
<th>Power consumption(W)</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>N+P(P=2)</td>
<td>Four(4) microwave switching matrixes</td>
<td>1070</td>
<td>1040</td>
<td>13925</td>
<td>Low</td>
</tr>
<tr>
<td>N-active</td>
<td>Five(5) digital transmitting processors</td>
<td>2078</td>
<td>1447</td>
<td>19481</td>
<td>Very High</td>
</tr>
<tr>
<td>Combination</td>
<td>40 fusion microwave networks</td>
<td>1892</td>
<td>1349</td>
<td>13925</td>
<td>Medium</td>
</tr>
</tbody>
</table>

### 4.3 Other performance comparison

From communication protocol standard, UT and user experience aspects, the performance comparison among various diversity schemes is shown in Table 4.

<table>
<thead>
<tr>
<th>Diversity Scheme</th>
<th>Protocol Standard</th>
<th>UT</th>
<th>User experience</th>
</tr>
</thead>
<tbody>
<tr>
<td>N+P(P=2)</td>
<td>Single carrier TDM forward link &amp;MF-TDMA return links (compatible with DVB-S2x &amp; DVB-RCS2).</td>
<td>Single carrier receiver</td>
<td>Traffic interruption a few minutes during GWs handover.</td>
</tr>
<tr>
<td>N-active</td>
<td>Multi-carrier TDM forward links &amp; MF-TDMA return links (compatible with DVB-RCS2).</td>
<td>Multi-carrier receiver</td>
<td>Traffic speed declines slightly without interruption during GWs handover.</td>
</tr>
<tr>
<td>Combination</td>
<td>Dual-carrier TDM forward links &amp; MF-TDMA return links (compatible with DVB-RCS2).</td>
<td>Dual-carrier receiver</td>
<td>Traffic speed declines by half without interruption during GWs handover.</td>
</tr>
</tbody>
</table>
4.4 Summary of the above Comparisons

For N+P scheme, the satellite payload, gateways and the terminals are realized simplest. However, the gateways handover will cause the interruption of the user terminal business.

For N-active scheme, the user terminal experience is the best. However, the system design complexity, satellite payload and user terminal complexity will be increased greatly.

The combination scheme can be considered as a compromise between the N+P scheme and N-active scheme. It guarantees the user terminal experience under the premise of slightly increasing the complexity of the satellite payload and the user terminal.

5 Conclusion

The next generation VHTS system will be built on the Smart Gateway Diversity (SGD) architecture utilizing Q/V-band feeder links and Ka-band user links, so as to achieve very high system availability that is larger than 99.9%. In this paper, the combination N-active (K=2) with N+1 diversity scheme is proposed in this paper, which is a better realizability SGD architecture. We present its principle and GW handover status transfer process. The system availability formula is deduced and simulated. Compared with N+P and N-active scheme, the combination scheme is a system balance scheme, which can well balance the system design complexity, payload complexity, system availability and user experience. This scheme is the most feasible and practical solution among SGD schemes at present.

References


