Q/V-band feeder links and flexible bandwidth assignment in future very high throughput satellite (VHTS) communication systems

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Abstract
To cope with demands of modern information hungry societies for growing data-rates and ubiquitous coverage, telecommunication system performance and related cost effectiveness need to improve constantly. This can be done by increasing the efficiency of bandwidth utilization up to certain limits or by resorting to frequency bands providing larger chunks of the precious frequency resource for the service envisaged.

In modern very high throughput satellite (VHTS) systems, this can be achieved with the utilization of the Q/V-band for the feeder links. This strategy, while allowing the release of a portion of Ka-band resources increasing the spectrum available at user link level, is sensitive to atmospheric impairments. Those impairments may be limited to some extent by increasing power margins at the feeder link gateway level and with smart site diversity strategies. At the same time, not all technically feasible solutions are actually cost effective and likely to be selected in real deployment scenarios.

In that context, this paper describes operational concepts using Smart Gateway techniques applied to a generic VHTS mission utilizing Q/V-band feeder links and Ka-band user links. The deployment of a minimum number of gateways is envisaged while enabling flexible capacity assignment and soft service degradation in adverse conditions.

Performance evaluations in terms of simulation results are provided comparing the system performance for a selected set of diversity strategies. High level considerations for future satellite systems and related user equipment are provided in that context.

I. Introduction
Communication satellite systems are challenged to provide very high throughput at reasonable cost. Current HTS systems like Ka-Sat [1] are capable to provide a network capacity in the range of 100 Gbps. Recently announced VHTS systems promise a network capacity of up to 1 Tbps to be launched by 2019 [2]. However, at the user end, internet connections available for all households at speeds beyond 30 Mbps are foreseen by the European Commission (EC) as defined in their Digital Agenda for Europe from 2020 onwards. Beyond that at least 50% of households shall be able to subscribe to connections above 100 Mbps and key infrastructures like schools, hospitals, airports, etc. shall have access to connections above 1 Gbps [3][4].

While for most entities a solid ground infrastructure may be assumed, predictably 5% to 15%, depending on the region, will not be able to be properly connected by terrestrial means. VHTS systems are a proper solution in that respect. However, in order to provide high capacity they require large resources of bandwidth and sophisticated technologies for its efficient exploitation.

At present, Ka-band provides a good compromise in terms of available bandwidth, available user equipment at reasonable cost as well as performance. Thus, the number of current (2017) high throughput satellites (HTS) operating in these bands such as Ka-Sat [1], Via-Sat 1 [5], Echostar 17 [6] and others grows. Nevertheless, the Ka-band resource reserved by Radio Regulations of the International Telecommunication Union (ITU) for fixed satellite communications is limited to the bands 17.3 GHz to 21.2 GHz, 24.65 GHz to 25.25 GHz and 27 GHz to 31 GHz, whereas regional differences in use of certain sub-bands exist [7]. In order to use all available Ka-band resources for the user link one either must place the satellite gateways (GWs) outside the coverage zone or utilize another
frequency band for the feeder link providing sufficient bandwidth. Since the former is often not appropriate the exploitation of higher frequency bands for feeder links such as Q/V-band is the necessary consequence [8]. Nevertheless, the fading amplitude in Q/V-band may exceed the capabilities of adaptive fade mitigation technologies like adaptive coding and modulations (ACM) and uplink power control at the GW, thus requiring (smart) GW diversity concepts in order to maintain a high service level [8-11].

Hence, within this paper we discuss, by exemplifying a generic VHTS scenario using Q/V-band feeder links as carried out in the course of the EC QV-LIFT project, diversity concepts considered promising for future VHTS systems. In Chapter 2 we introduce the generic VHTS scenario and in Chapter 3 an analysis is conveyed discussing diversity concepts for operating the generic VHTS scenario. Finally, in Chapter 4 the outcomes are summarized and conclusions are drawn.

II. A generic VHTS mission employing Q/V-band for feeder links and smart GW concepts with soft diversity

Overview

The mission lifetime of a modern satellite mission is typically 15 years. Considering 5 years of lead time for its construction, launch and commissioning, the technology may be considered old towards the end of satellite lifetime. Also for that reason operators typically refrain from launching systems which incorporate complex digital regenerative payload solutions on-board the satellite and resort to transparent solutions, because a change in terrestrial technology will not make the satellite obsolete. Nevertheless, digitalization is about to find its way into satellite transponders opening up potential for on-board signal processing, whereas in the short run this capability might rather be used for on-board routing between feeder uplinks and spot beams replacing complicated switching matrices. Figure 1 depicts a sketch of the generic VHTS scenario with feeder links in Q/V-band and user links in Ka-band making use of a 4 colour frequency/polarization reuse.

![Figure 1: VHTS scenario with Q/V-band feeder links and Ka-band spot beams](image)

Besides a powerful space segment a VHTS system also requires a performant ground system implemented as a network of GWs. A good balance between performance aspects and commercial requirements needs to be found targeting maximum service quality at reasonable cost to the operator. Hence the number of GWs including spare GWs ($P$) shall be minimal whilst maintaining a high service quality and a high level of automation. In that sense diversity concepts and smart GW concepts are addressed later in this document.
An overview of the scenario as foreseen in the EC funded QV-LIFT project [12] can be found underneath.

**User Link**
- 100 Ka-band spot beams.
- 4 frequency/polarization reuse.
- Uplink: 900 MHz circular polarization/beam.
- Downlink: 1.45 GHz circular polarization/beam.
- Each beam is partitioned in up to 15 carriers FL/RL according to a diversity concept capable to employ powerful interference mitigation techniques such as precoding and multi user detection.
- Terminals are able to tune to more than one carrier simultaneously.

**Feeder link**
- \( N = 15 + P \) GWs, where \( P \) shall be minimized.
- Diversity concept.
- Uplink: 10 GHz of bandwidth per GW (5 GHz per polarization).
- Downlink: 6 GHz of bandwidth per GW (3 GHz per polarization).

**Network**
- Network capacity expected to be 400 Gbps.
- Smart GW concept with soft diversity.

Reducing multiple access interference will be of paramount importance for future VHTS in order to optimize the bandwidth efficiency on the user link, thus precoding techniques on the forward link and multi user detection (MUD) techniques on the return link are assumed to play a vital role in that respect. Recently, promising improvements of those techniques have been published suggesting the exploitation of user location and the satellite antenna characteristics to improve the practical performance. Hence the ground segment has to be set up such that an implementation of appropriate interference mitigation technologies is reasonably possible [13-18].

**Smart GW concepts**

The ground segment must ensure the proper delivery of the service at target availability and performance. In Q/V-band severe atmospheric fading of up to 20-30 dB may not be regarded as rare events, thus requiring proper counter measures. A few decibels on the feeder link may be compensated by adaptive fade mitigation techniques utilizing reserves in the ground system without or with acceptable loss of capacity. However, in order to maintain a high availability of the service at a certain performance spare gateways are required able to take over traffic from gateways in outage. Table 1 exemplifies for an \( N+P \) scenario, where \( N \) denotes the number of active GW sites and \( P \) denotes the number of spare sites. It is assumed that weather events amongst all sites are decorrelated. It can easily be seen that in order to achieve a target availability of the feeder links of 99.95% the individual availability may only be relaxed with higher numbers of spare gateways.

<table>
<thead>
<tr>
<th>Backup considered (P)</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feeder link availability</td>
<td>99.950%</td>
<td>99.950%</td>
<td>99.950%</td>
<td>99.950%</td>
<td>99.950%</td>
<td>99.950%</td>
</tr>
<tr>
<td>Availability required per site</td>
<td>99.998%</td>
<td>99.837%</td>
<td>99.221%</td>
<td>98.117%</td>
<td>96.567%</td>
<td>94.602%</td>
</tr>
</tbody>
</table>

Table 1: Computation of required availability per site (\( N=15 \) active sites)

Nevertheless, since bidirectional digital communications may be assumed to employ adaptive fade mitigation technologies such as ACM, a rigid availability analysis might not be representative since it is not able to account for slight performance degradations due to switching to more robust MODCODs.

GW diversity concepts range from simple single site diversity concepts where for each GW a decorrelated backup is available to more complex \( N+P \) solutions where for \( N \) active GWs \( P \) backups are available. For single site diversity concepts high investments into ground infrastructure are necessary, however, simple payload solutions on-board the satellite can be employed and routing schemes remain easy.
N+P concepts without beam multiplexing may be regarded as the next level of complexity in terms of payload and routing. Since whole beams are served by a single GW, its failure/underperformance impacts the service in a whole beam. This can be counteracted by N+P concepts with beam multiplexing, as depicted in Figure 2, which are supposed to offer the best performance but require the highest complexity. P redundant GWs can be used either as cold redundancy, i.e. in case of a GW failure/underperformance the respective GW is replaced by the redundant GW, or N+P GWs serve the satellite each holding back backup-bandwidth as depicted in Figure 3. Concepts where one beam is served by several GWs and traffic may be routed through different GWs often are referred to as smart GW concepts [8-9, 19-21].

![Figure 2: N+P Smart GW concept with beam multiplex](image)

![Figure 3: N+P active GWs with back-up bandwidth architecture – (a) all GWs run at partial load, (b) when GW1 goes in outage its resources are allocated to the available gateways](image)
**Soft Diversity**

Soft diversity denotes the capability of a satellite communication system to route traffic to and from a user terminal through several (more than one) frequency multiplexed carriers originating/terminating in different GWs. It is meant to mitigate the impact on the service quality for users encountering an outage of the serving GW [22]. Its functionality is illustrated in Figure 4 at the example of two serving GWs, namely GW A and GW B. GW A transmits (forward link) a carrier in V-band with central frequency C1 and GW B transmits the neighboring carrier C2 as depicted in a). T1 and T2 represent the traffic from terminals that are managed by the respective GWs A and B. In b) GW A becomes impaired. Traffic managed by GW A is migrated to GW B on carrier C2. Since GW B has now to serve temporarily traffic T1 and T2 both may have to adapt the quality of service to the current circumstances. Upon return of GW A or upon arrival of a replacement GW for GW A in c) the traffic T1 is migrated back to the original carrier C1. The same considerations apply for the return link.

![Figure 4: Soft diversity concept](image)

Soft diversity can be employed for N+P and N+0 gateway architectures:

- In case of N+P (P>0), the impaired or faulty GW A is replaced in due time by a spare GW and the intermediate situation illustrated in Figure 4 b) is only temporary.
- If no spare gateway is available (N+0) and no available carriers in other GWs are available, then the situation in Figure 4 c) will remain upon restoration of the impairment of GW A.

### III. Analysis of the generic VHTS mission with Q/V-band feeder links

Since the described system scenario is generic and the number of parameters to be tuned is vast, the explanatory value lies in the relative comparison of the results rather than in their magnitude. However, if not stated otherwise, the following assumptions apply in addition to the parameters listed for user link, feeder link and network in Chapter 2:

- **N=15** GWs, each serving more than one beam and **P** replacement GWs.
- Each carrier in a beam is served by a different GW.
- Two smart GW models (SGx), whereas SGA is the standard model:
  - SGA: The network routes through \( N=15 \) GWs with the highest \( C/(N+I) \) on the feeder link (out of a set of \( N+P \) GWs).
  - SGB: The network routes through initial set of \( N=15 \) GWs as long as their uplink \( C/(N+I) \) is above 0 dB. If not, the underperforming GWs are replaced by spare GWs out of the \( P \) set.
  - No backup bandwidth is left free at the GWs.
- All user terminals feature 75 cm dish antenna at an efficiency of 70%.
- Statistical models for loss towards the edge of coverage (EoC) and atmospheric attenuation in up and downlink following distribution models presented in [12] are used.
- The uplink EIRP spectral density is 48.4 dBW/MHz and the downlink EIRP spectral density is 34.2 dBW/MHz.
- 10% carrier spacing and 10% roll-off apply.
- It is considered that fading events on feeder links are de-correlated between different GWs and that fading events in one spot beam are fully correlated.
- The antenna temperature is calculated according to
  \[ T_A = \frac{T_{SKY}}{L_{ATM,D}} + T_m \left( 1 - \frac{1}{L_{ATM,D}} \right) + T_{GROUND}, \]
  with \( T_{SKY} = 3K, T_m = 265K \) and \( T_{GROUND} = 50K \) and \( L_{ATM,D} \) the atmospheric attenuation on the downlink [23].
- Considerations in terms of usage statistics and peak to average ratio of usage are out of scope.
- The multiplexing advantage of wider over narrower carriers is not considered.
Simulations are carried out as time invariant Monte Carlo Simulations.

**Link analysis**

A link budget calculation considering 15 carriers per beam is provided in Table 2. Parameters written in blue, i.e. the MODCOD, atmospheric attenuation in up and downlink, receive terminal figure of merit (GS G/T) and EoC loss vary according to statistical models throughout the subsequent simulation as described below. It can be observed that the link can be closed at a total efficiency of 1.97 bits/s/Hz including spacing and roll-off.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth (MHz) per carrier</td>
<td>96.67 MHz</td>
</tr>
<tr>
<td>Spacing</td>
<td>10.00%</td>
</tr>
<tr>
<td>Net Bandwidth per Carrier</td>
<td>88.41 MHz</td>
</tr>
<tr>
<td>Roll-off factor</td>
<td>10.00%</td>
</tr>
<tr>
<td>Symbol-Rate</td>
<td>80.37 Msymb/s</td>
</tr>
<tr>
<td>MODCOD</td>
<td>16APSK 3/5-L</td>
</tr>
<tr>
<td>Spectral Efficiency</td>
<td>2.37 bits/symb</td>
</tr>
<tr>
<td>Required Es/No</td>
<td>2.15 bits/s/Hz</td>
</tr>
<tr>
<td>Target Throughput</td>
<td>8.71 dB</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uplink Range</td>
<td>38285 km</td>
</tr>
<tr>
<td>Frequency (MHz)</td>
<td>47200.00 MHz</td>
</tr>
<tr>
<td>Uplink EIRP toward satellite</td>
<td>68.3 dBW</td>
</tr>
<tr>
<td><strong>Uplink EIRP Density</strong></td>
<td><strong>48.4 dBW/MHz</strong></td>
</tr>
<tr>
<td>IPFD at satellite</td>
<td>-98.3 dBW/m²</td>
</tr>
<tr>
<td>Uplink Free-Space Loss = 4πD/λ</td>
<td>217.6 dB</td>
</tr>
<tr>
<td><em>Atmospheric attenuation</em></td>
<td>3.9 dB</td>
</tr>
<tr>
<td>Satellite G/T towards Transmit GS</td>
<td>27.5 dB/K</td>
</tr>
<tr>
<td>IPFD - G/T</td>
<td>-125.8 dBW/m²</td>
</tr>
<tr>
<td>Uplink C/N = EIRP - L + G/T - k.B</td>
<td>23.9 dB</td>
</tr>
<tr>
<td>Uplink C/im</td>
<td>30.0 dB</td>
</tr>
<tr>
<td>Uplink C/I</td>
<td>23.0 dB</td>
</tr>
<tr>
<td><strong>Uplink C/(N+I)</strong></td>
<td><strong>20.0 dB</strong></td>
</tr>
<tr>
<td>Downlink Range</td>
<td>38285 km</td>
</tr>
<tr>
<td>Downlink Frequency</td>
<td>18700.00 MHz</td>
</tr>
<tr>
<td><em>Receive GS G/T towards Satellite</em></td>
<td>18.0 dB/K</td>
</tr>
<tr>
<td>Downlink EIRP towards GS</td>
<td>57.1 dBW</td>
</tr>
<tr>
<td>OBO</td>
<td>3.0 dB</td>
</tr>
<tr>
<td><strong>EIRP density</strong></td>
<td><strong>34.2 dBW/MHz</strong></td>
</tr>
<tr>
<td>Downlink Free-Space Loss</td>
<td>209.5 dB</td>
</tr>
<tr>
<td><em>Atmospheric attenuation</em></td>
<td>1.2 dB</td>
</tr>
<tr>
<td>EoC loss</td>
<td>0 dB</td>
</tr>
<tr>
<td>Provision (pointing, losses, etc)</td>
<td>0.2 dB</td>
</tr>
<tr>
<td>IPFD at Downlink GS</td>
<td>-109.8 dBW/m²</td>
</tr>
<tr>
<td>Downlink C/N</td>
<td>10.7 dB</td>
</tr>
<tr>
<td>Downlink C/im</td>
<td>18.0 dB</td>
</tr>
<tr>
<td>Downlink C/I</td>
<td>21.0 dB</td>
</tr>
<tr>
<td><strong>Downlink C/(N+I)</strong></td>
<td><strong>9.6 dB</strong></td>
</tr>
<tr>
<td><strong>Overall C/(N+I)</strong></td>
<td><strong>9.2 dB</strong></td>
</tr>
<tr>
<td>Link margin wrt. targeted MODCOD</td>
<td><strong>0.5 dB</strong></td>
</tr>
</tbody>
</table>

Table 2: Link Budget
Figure 5 compares the cumulative distribution functions (CDF) of smart GW modes SGA and SGB for 15 carriers per beam (each routed to a different GW) in terms of unavailability (1-availability) of a certain throughput on a) system level and b) carrier level. The black curves, i.e. SGA/B, P=0 represent the N+0 scenario. In a) it can be seen that adding more than a single redundant station does not bring benefit to the system. Nevertheless, investigations on the average throughput indicate that the difference between SGA and SGB curves with P=0 to P=5 is less than 0.4% thus not reasoning investments into additional GWs. Nevertheless, from a quality of service perspective providing of at least one spare gateway makes sense; it improves the link availability at a minimum bandwidth from 99.8% to 99.94% as can be seen in Figure 5 b). Moreover, the unavailability of higher throughput decreases by applying a spare GW. It can be seen that in the N+1 case 66 Mbps are still available when N+0 already goes in outage. The previous observation that more than one spare GW does not make sense in terms of performance is observed on carrier level as well.

![a) System Throughput](image1)

![b) Carrier Throughput](image2)

Figure 5: Throughput CDF on a) system and b) carrier level with 15 carriers per beam, SGA and SGB GW modes with P=1...5

An advantage of routing one carrier per GW to each beam is that not all GWs must be deployed before the VHTS system is put in operation. After starting with an initial set of GWs additional ones may be deployed anticipating the capacity demand by arriving customers. In practical terms a satellite payload that provides a digital routing of the carriers between GWs and beams will be required since a switching matrix would become rather complex. Another advantage is the possibility to use precoding and MUD per GW considering that each GW serves the same carrier frequency in the beams.

Figure 6 compares the unavailability (1-a) throughput for different GW modes with respect to different beam partitioning, i.e. partitioning in 15 (black), 9 (blue), 6 (red) and 3 (green) carriers respecting 10% of inter carrier spacing. GW modes SGA and SGB with P=0, i.e. N+0 model, are indicated by solid lines, and SGA/B modes with P=1 with dash-dotted and dashed lines, respectively. Observations from before are validated in Figure 6 a) suggesting a performance improvement by providing a backup GW. Nevertheless it is rather reasoned by quality of service aspects as discussed before.

By close investigation it can be observed that by partitioning the beam in 3 carriers rather than in 15, the overall throughput improves by only 1.6%, whereas in case of a GW outage 33% of the capacity in the affected beams vanishes compared to 6.7% in case of 15 carriers. Figure 6 b) indicates the throughput performance per carrier. For clarity, it was refrained from indicating the curves for SGB.
since they exhibit only a slight degradation compared to SGA as could already be observed in Figure 5. Since all carriers share the same beam bandwidth it is not surprising that a partitioning in smaller carriers results into a lower throughput per carrier.

Figure 6: Throughput CDF on a) system and b) carrier level with SGA/B 0.1 GW modes and different number of carriers per beam

Figure 7 depicts the performance in terms of unavailability (1-a) of throughput on beam level for 15 (black), 9 (blue), 6 (red), 3 (green) carriers per beam and SGA 0.1 mode; subplot b) illustrates a zoom into the upper part of subplot a). Interestingly, larger carriers only provide a throughput advantage compared to smaller carriers in about 50% of time, the other 50% throughput is less or equal. The latter mainly depends on the influence of the Ka-band user link, which was for simplicity assumed to be fully correlated in one beam. By investigating in detail the total throughput per beam it turns out that by using 3 carriers it is only 1.6% larger than by employing 15 carriers.

Figure 7 b) suggests that the performance of less carriers per beam degrades faster than with more carriers per beam due to the higher statistical dependency to the performance of the serving feeder link, hence in terms of availability for a user several smaller carriers would be favorable rather than a few larger ones.

In order to be able to provide the same throughput per terminal with smaller carriers it is supposed to resort to terminal hardware capable to transmit and receive from more than one carrier simultaneously. This strategy can also be used for load balancing amongst carriers.

IV. Summary and conclusions

In the course of the EC QV-LIFT project under the framework of the EC Grant Agreement No. 730104 a study is conveyed aiming at fostering technology development for feeder links of VHTS systems.

Future VHTS satellite systems will need to resort to Q/V-band for their feeder links in order to have enough Ka-band resources available for the user link. While Q/V-band provides sufficient frequency
resources it suffers significantly from fading due to adverse weather requiring additional strategies to maintain a high quality of service to the user.

Diversity concepts are of paramount importance in that respect. Different promising technologies were discussed and evaluated by means of simulations. It was found that a smart GW diversity using $N+1$ sites and beam frequency multiplexing best fulfils the demands for operations and quality of service. Each GW is considered to only serve one carrier per beam. It was found that having more smaller carriers routed to different GWs is beneficial in terms of service availability to the user given that user hardware is able to lock on more than a single carrier simultaneously. Moreover, by properly placing the carriers in the spectrum, precoding and MUD technologies can be employed.

![Figure 7: Throughput per beam with SGA P≤1 GW modes and different numbers of carriers per beam](image)

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**References**


[3] Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, “Connectivity for a


