Abstract

This paper studies the use of W band in a future high throughput satellite (HTS) system alongside the Q/V band. First the available spectrum in W band is reviewed along with the propagation effects that contribute to the signal’s degradation. Then a mathematical framework for the assessment of the global feeder link availability is presented and the design challenges of a combined Q/V+W gateway system are analysed. The advantages and disadvantages are highlighted. A preliminary assessment of the feeder link availability of a combined Q/V+W band systems is given.

1. Introduction

Recent studies on ultra-high throughput satellite (HTS) systems, such as [1],[2], indicate that the system consists of more than 200 user beams operating at Ka band for economic reasons and more than 20 gateway earth stations at Q/V band are needed to provide the capacity for users. In order to gain access to more spectrum for a future high throughput satellite, migrating to higher bands (Q/V/W) is a necessity. These higher frequency bands are more subject to propagation impairments during the crossing of troposphere (8-15km). The level of impairments at these frequency bands (higher than 40GHz) is sufficiently high to prevent their use for user links because even with applicable fade mitigation techniques such as adaptive coding and modulation (ACM), the availability of the links would be limited [3]. Therefore the use of these frequency bands seems for now to be dedicated to gateway feeder links only, for which spatial diversity techniques can be considered, and constitutes an efficient way to cope with the strong impairments. In this respect smart gateway diversity [4],[5] have been shown to be among the most promising solutions. However, a recent and ongoing study [2] indicates that a very large number of gateways (50) at Q/V band, even using all the bandwidth, is still needed to support the user beams (302 user beams). Considering the complexity and the cost of these gateway earth stations compared with those of a state of the art Ka band, they increase tremendously, and they begin to dominate the cost of the system. Therefore, the number of gateway sites needs to be reduced to achieve a more cost effective system.

A perfect candidate to achieve this is to use the available spectrum in W band (70-80 GHz) [9]. The use of this band is attractive to space system as it is a virgin area. For deep space applications, the interest for W band lies in the possible increase of the spacecraft’s antenna gain compared with the bands used currently. For broadband applications, more spectrum is available which gives more options to engineers to design the system. However, the drawback of using these higher bands, Q/V and W bands, is the fact that the signal is susceptible to the impairments caused by the troposphere, resulting in many dBs of attenuation making it more difficult to achieve high availabilities [9][10]. As a result, the design of fade mitigation techniques to counteract the deep fades is more challenging for Smart Gateway diversity [5]. Herein, we focus on a ground network which combines the Q/V and W band. Instead of using only Q/V bands in the feeder link, we consider a combined Q/V and W band ground earth station as in [6] where it was studied for first time. According to [6], it is possible to halve the number of gateway sites combining Q/V gateway stations with W band gateway stations.

This contribution reviews the available spectrum in Q/V and W bands and briefly discusses the atmospheric impairments induced to the signal. Then a mathematical framework for the assessment of the feeder link availability for a combined Q/V and W gateway stations is presented. The design challenges of such a ground segment are discussed and analysed, highlighting their advantages and disadvantages. Lastly, an example is considered to illustrate the impact of a combined Q/V + W ground segment in terms of feeder link availability.
2. Spectrum considerations

As has already been indicated in [1] the spectrum in Ka band, in both feeder links and user links, is not sufficient to satisfy future user demands. For this reason this study will concentrate on the higher bands for the feeder links where more spectrum is available. Therefore, the use of both Q/V and W bands will be examined.

Q/V bands

There are no exclusive bands for Fixed Service Satellites (FSS) in the Q/V bands, and thus all the spectrum in these bands is subject to coordination with other users, even for the UT’s. This is not a show stopper but complicates the business model.

For the uplink, the spectrum between 42.5-43.5 GHz is shared with FS/Mobile/Radio Astronomy (RA). Portions have already been auctioned in the UK (3 operators paired with above); The spectrum between 47.2-50.2 GHz is shared with FS/Mobile but also with military and Outside Broadcast restrictions apply; In addition, the spectrum between 50.4-51.4 GHz is shared with FS/Mobile but in some countries military restrictions also apply.

For the downlink, although the spectrum between 37.5-39.5 GHz is shared with FS/Mobile/Space research, this band is extensively used by FS. The band 40.5-42.5 GHz is shared with FS/Broadcasting/BSS/Mobile. As in the uplink, some portions of this band have been auctioned in UK (3 operators) and in some other countries, requiring coordination.

Hence, 5 GHz is available for the uplink and 4 GHz for the downlink but with restrictions and coordination being required. CEPT ERC/DEC has provisions in some parts of the spectrum and in some countries priority is given to military use.

W band

As in Q/V bands, there are no exclusive bands for Fixed Service Satellites (FSS) in the W bands, and thus all the spectrum in these bands is subject to coordination with other users. For the downlink, the available spectrum is between 71-76 GHz and for the uplink is between 81-86 GHz (CEPT). Thus, in both downlink and uplink 5 GHz are available.

3. Propagation

This section gives a brief description of the tropospheric propagation effects that cause degradation to the signal at Q/V and W bands. While at Ku band rain attenuation is the dominating factor, at Ka band and above, the effects due to gases and clouds must be considered.

Attenuation due to atmospheric gases (water vapour and oxygen absorption)

Oxygen and water vapour are practically the only gaseous components affecting the electromagnetic wave propagation in the 20–300 GHz frequency range [9]. For simplified atmospheric compositions, when integrated water content and average temperature are known, ITU-R Rec P.676 allows computation of the attenuation induced by these gases on an earth space link. Oxygen attenuation is relatively stable with time and space. It does not vary over time and slight variations are observed across the world. However, it depends a lot on frequency. This is due to the resonant absorption band of the oxygen molecules, the specific attenuation exceeds 10 dB/km at 60 GHz whereas decreases from about 0.26 dB/km down to about 0.02 dB/km between 70 and 95 GHz in the W band [9].

Cloud attenuation

Cloud attenuation is caused by liquid water droplets in clouds, iced particles with a different electromagnetic properties causing a marginal residual attenuation on the link [6]. Because in the W band, the size of suspended water droplets in clouds is smaller than the wavelength, the Rayleigh approximation can be used for the computation of the extinction cross sections and, thus, the cloud attenuation depends only on the liquid water content, on the droplets temperature and, obviously, on the frequency [9]. The use of ITU-R Rec. P.840 may provide reasonable results for the specific attenuation caused by cloud at a known integrated liquid water content. The highest uncertainty is
induced by the assessment of the cloud liquid water distribution, whose accurate estimate in the atmosphere is still an issue [9].

Scintillation and depolarisation

The impact of scintillation on the fade margin calculation is quite limited with respect to rain attenuation, at least for high availability systems and elevation angles above 15°. In our case, where only gateways are considered, the dominant effect remains rain attenuation but scintillation due to angle of arrival variations must be considered for large antennas and high frequencies because they scale as the square power of frequency. The troposphere can be anisotropic in presence of ice flakes and in heavy rain, as the large drops lose their spherical properties and are more like oblates, and this may induce a depolarisation of electromagnetic waves. A model of XPD depending on co-polar attenuation is proposed by ITU-R Rec. P.618-10 to link rain co-polar attenuation to rain induced cross-polarization and may be considered. However, especially for feeder uplink, in heavy rain the interference induced by XPD is unlikely to result in significant degradation of the link budget figure as the degradation of the C/N or C/I will be the dominant factor [6].

Rain attenuation

The highest impairments on the links will be caused by rain. At Q/V and more importantly at W band, the results provided by ITU-R Rec P.618-10 have to be carefully considered. In fact the computation of proposed in this recommendation relies on the estimation of specific attenuation due to rain considering a given drop size distribution for the rain particles. There is a one to one correspondence between a given rain rate and a DSD (Drop size distribution) [6]. The rain rate to specific attenuation conversion is in general a very big issue for the radar meteorology community. In propagation applications, the DSD variability from event to event and sometimes within the same event, impacts on the instantaneous frequency scaling, but the average relationships, although partially dependent on the geographical/meteorological region, are well established. It should impact mainly the tail of the attenuation distribution that corresponds to high attenuation levels that can in any case not be compensated. Thus ITU-R Rec. P.618-10 could be used to get indicative values. As there are no experimental measurements are available for Earth-to-satellite links at frequencies above 50 GHz, ITU-R models must be used with care and methods developed on solid physical bases should be preferred, as their estimation accuracy is independent on the frequency. Because the ITU-R models [9] have been validated for frequencies only up to 50 GHz [13], further validation is recommended before their use for system design in W band, even though their performance is not expected to decrease substantially.

Figure 1 shows the rain attenuation, the attenuation by gases and the cloud attenuation from Ka band to W band from [6]. As we move from Q/V bands to W band, rain and cloud attenuation increase significantly. For a specific percentage time, the total atmospheric attenuation may increase by almost 10 dB as we move to W band. As stated in [6], assuming a 10 dB propagation margin enables to maintain the nominal capacity of the link 96-97% of the time all over Europe at Q/V bands, whereas at W band this availability decrease to less than 95%.

Figure 1 (a) CCDF of rain attenuation for various frequencies based on ITU-R recommendation P618-10, (b) attenuation by gases based on ITU-R P.676, (c) Cloud attenuation based on ITU-R P.840, [6].
4. Global feeder link availability – Modelling

For a user link to be in outage due to a feeder link fade, the gateways or the pool of gateways that serve it has to be in outage. For the N-active scheme, all the gateways need to be in outage simultaneously. For the N+P scheme, a methodology to evaluate the feeder link availability is proposed in [3],[4]. However, this methodology assumes equal outage probabilities for each gateway, which is not the case in practise, where the outages differ. The methodology provided in [5] extended that of [3] in order to consider unequal outages probabilities. However, this methodology cannot evaluate the performance of a system whose feeder links combine different frequency band. In the following, the methodology of [5] is revisited and extended to achieve the latter.

The probability of having k gateways in outage, out of N gateways is derived in [5], and is given by:

\[
P^k = Pr \{ Y = k \} = Pr \{ k \text{ gateways in outage} \} = 
\sum_{i=0}^{N+1} \left\{ e^{-2\pi i k/(N+P+1)} \prod_{m=1}^{N+P} \left( p_m e^{2\pi i k/(N+P+1)} + (1 - p_m) \right) \right\} / (N + P + 1)
\]  

(1.1)

Let us consider the configuration in which every user beam is served by one gateway and for every N gateways P redundant gateways are added as provision. For a user beam to loose service (due to a feeder link issue), the regular gateway needs to become unavailable and the P redundant to be unavailable as well (either dedicated to other beams or experiencing deep fades).

According to [3], the expected value of the probability of a user inside a spot beam to be in outage due to a feeder link fade is the probability of the gateway that serves it to experience the outage (or deep fades), plus the probability to belong to one of the k gateways that experience outage.

\[
P_{outage} = \sum \frac{i}{N} Pr \{ P + i \text{ gateways to outage} \} 
\]

(1.2)

For the case, where more than two transmitters are located in a single site, the above is different. Let us consider without loss of generality that M transmitters are located in a single location. Each one of them transmits at a different frequency, for example a combined W + Q/V gateway earth station. The outage probability of kth transmitter at site m is defined as \( p_{m}^{k} \).

For each site, the following events can be true: all transmitters are available, one is available,....., all the transmitter are unavailable. To note that if a transmitter is unavailable and operates in lower frequency than another one, then the latter is also unavailable. In the combined W+Q/V example, if the Q/V system is unavailable then the W system is also unavailable. For each site, the set \( \{ p_{m}^{0}, p_{m}^{2}, \ldots, p_{m}^{M} \} \) denotes the outage probabilities of the transmitters from the highest frequency to the lowest.

Thus, it is clear that for each site \( Pr \{ X_{m} = 0 \} = 1 - p_{m}^{1} \) and \( Pr \{ X_{m} = M \} = p_{m}^{M} \). The probability of having only one transmitter in outage is \( Pr \{ X_{m} = 1 \} = p_{m}^{1} U_{m}^{12} \). This means that transmitter 1 is in outage given that the rest are not. \( U_{m}^{12} \) is the conditional probability of transmitter 1 being in outage while transmitter 2 is available. The probability of having two transmitters in outage is \( Pr \{ X_{m} = 2 \} = p_{m}^{2} U_{m}^{23} \). In the case of combined Q/V + W band gateway, the probability of the W band transmitter to be in outage given that the Q/V not, is \( P(Q | W) = U_{m}^{12} = P(Q \cap W) / P(W) \). This probability is given by:

\[
P(W) = P(Q \cap W) + P(Q' \cap W) \Rightarrow P(Q \cap W) = P(W) - P(Q' \cap W) \Rightarrow 
P(Q' \cap W) = P(W) - P(Q) \Rightarrow P(Q' | W) = P(Q \cap W) / P(W) = \frac{P(W) - P(Q)}{P(W)}
\]

(1.3)

Applying the methodology described above, the probability of having k transmitters in outage is expressed in equation (1.4):
\[ P_k = \Pr \{Y = k\} = \Pr \{k \text{ gateways in outage}\} = \]
\[
\sum_{n=M(N+P)}^{n=M(N+P)} \left\{ \sum_{m=0}^{m=M(N+P)} \prod_{j=0}^{j=M(N+P)} \left\{ \sum_{l=2}^{l=M(N+P)+1} \left( P^{j} e^{2 \pi i/(M(N+P)+1)} + P^{m} \right) \right\} \right\} \frac{e^{-2 \pi i k/(M(N+P)+1)} P^{k}}{(M(N+P)+1)} \]

For the combined W+Q/V band case, equation (1.4) transforms to equation (1.5).

\[ P_k = \Pr \{Y = k\} = \Pr \{k \text{ gateways in outage}\} = \]
\[
\sum_{n=M(N+P)}^{n=M(N+P)} \left\{ \sum_{m=0}^{m=M(N+P)} \prod_{j=0}^{j=M(N+P)} \left\{ \sum_{l=2}^{l=M(N+P)+1} \left( P^{j} e^{2 \pi i/(2(M(N+P)+1))} + P^{m} \right) \right\} \right\} \frac{e^{-2 \pi i k/(2(M(N+P)+1))} P^{k}}{(2(M(N+P)+1))} \]

It is worth noting that equation (1.5) can be used when at one site two gateways are placed, each one looking at a different satellite. The only difference is the derivation of the joint and conditional probabilities of both gateways being in outage and one in outage and the other being available respectively. A method to assess this can be found in [8]. For the examined scenario herein, of collocated satellites, it can be assumed that the one gateway is in outage then the other gateway will also be in outage. Meaning that the joint outage probability equals the outage probability of one of the gateways.

5. System requirements

The requirements of the diversity scheme are related with the availability of the feeder link to be above a specific value, for example 99.9 %, and the reduction it causes to a beam's capacity to be less than a desired value, i.e 25 %. For a gateway to be able to provide a specific percentage of its nominal capacity for p% of time, it means that the margin included in the link budget and any uplink power control (UPC) being applied is able to compensate for the total atmospheric attenuation for p% of time. More details can be found in [11],[12].

6. Design Challenges

Figure 2 and Figure 3 illustrate a system with only Q/V gateway stations and Q/V+W gateway stations respectively. In this particular scenario, a dual satellite system is considered similar to the one described in [12] where one satellite serves the west part of the coverage area and the other satellite serves the east part of the coverage area. In Figure 2 each site has two antennas, each one pointing at a single satellite. In Figure 3 each site has four antennas, where one Q/V and one W point at east satellite and the other Q/V and W antennas point at west satellite. In the latter system, the number of ground sites can be halved. For example, in [12] a dual satellite system is described with 302 beams and 25 dual gateway sites, where one gateway station serves 6 user beams, resulting in 12 user beams to be served by a gateway site. Using gateway stations at W band, the number of sites can be further reduced down to 13. This results in greater number of user beams served by a single gateway site. For this scenario, each gateway site provides the capacity to 24 user beams. Note that each gateway station serves the same number of user beams, while the number of user beams served by a gateway site depends on the number of gateway stations at each site. As mentioned in section 2, the available spectrum in W band is 5GHz, however in order to simplify the analysis we consider the same amount of spectrum used in Q/V band in [12], as 4 GHz.

By using fewer gateway sites, those sites with more favourable conditions can be selected resulting in more favourable propagation conditions, making it easier to ensure given feeder link availability. In addition, as stated in [12][11][12], using fewer sites the angular separation of the sites can be greater, resulting in better isolation of the satellite antenna and better carrier to interference (C/I) values for the feeder links. On the other hand, the backbone dimension becomes more complex when a combined Q/V+W gateway is used. As the backbone cost is an important factor for a future HTS system, special attention is required in this respect. In [12] the authors discuss the backbone dimension and a methodology is proposed to map user beams to the gateways in order to minimise the cost of the backbone. By decreasing the number of gateway sites, the terrestrial links to a country's point of
presence (POP) must carry greater capacity and probably more connections to POPs from a site will be required, resulting in less optimal backbone dimensioning.

In terms of backbone cost, it is not desirable for a gateway site to serve a lot of user beam or alternatively to reduce the number of gateway sites. That is why in [12] the authors propose an alternative design with 40 gateway sites instead of 25 dual sites. However, an emerging concept for HTS systems is interference mitigation according to which advanced signal processing techniques are applied either on transmitter (precoding) or receiver side in order to mitigate the intra-system interference and effectively increase the system’s throughput [13][14][15]. But these techniques require knowledge of the channel. For a multi gateway system as discussed in [13][15][16], in order for these techniques to be effective inter-gateway terrestrial links are required for the gateways to exchange information. But this further increases the backbone cost and the overall cost of the system. If these inter-gateway links are not present, then the effectiveness of these techniques is limited to only the user beams that the gateway has access to. For a combined Q/V+W site the number of user beams the site has access to is greater than in a Q/V only system, resulting in better performance of these techniques if inter-gateway links do not exist. For example, in the dual site Q/V system of [12], a site has access to 12 user beams (only a few of them are co-channel) while in a combined Q/V+W to 24 user beams. In order to provide for a gateway site to gain access to more user beams without inter-gateway links, the frequency multiplexing smart gateway diversity concept from [4][5] can be applied, where a user beam is served simultaneously by a number of gateway stations multiplexed in frequency (assign one or more separate channels to each gateway). For example if a user beam is served simultaneously by 4 gateway stations, then each gateway site of a combined Q/V+W system will have access to 96 user beams.

7. Examples

In order to illustrate the impact of the combined Q/V+W gateways, we borrowed the example from [12], where 25 dual gateways sites are required to provide the capacity to the users. With the combined Q/V+W bands gateways only 13 gateway sites are required as explained in section 6. The original BATS system considers one redundant gateway site to ensure the feeder link availability, N+P diversity scheme [3]. The sizing of the W gateway station is such as to result in similar received signal power and carrier over noise plus interference ratio (C/(N+I)) at the satellite as in the Q/V band only system. For the combined Q/V+W we will also consider one redundant gateway site which has 2 Q/V gateway stations and 2 W band stations. Figure 4 shows the global feeder link availability versus the allowed reduction in user beam capacity, as described in [12]. It is worth noting that in the case of combined Q/V+W system, the sites with the better propagation conditions amongst the 25 dual sites were selected. As can be seen, the feeder link availability is better than for the Q/V band system. For the same reduction in nominal capacity higher feeder link availability can be obtained, or alternatively for the same availability less reduction in nominal capacity is required. The reason is the statistical gain. In Q/V band systems, the ratio active over redundant gateway is 25/1 while in combined Q/V+W it is 13/1. However, the number of gateway stations/antennas is the same in both systems. The only change is the number of gateway sites. As in the latter system, less sites are required, more favourable sites in
terms of propagation conditions can be selected and better spatial isolation can be achieved as the stations are placed further apart resulting in better feeder link C/I performance.

![Graph showing global feeder link availability versus reduction in nominal capacity for Q/V and Q/V+W systems.]

**Figure 4** Global feeder link availability versus reduction in nominal capacity for Q/V and Q/V+W systems

### 8. Conclusions

In this paper, we have studied the use of W band in a future HTS system. It was considered that a ground earth station operates in both Q/V and W band allowing the gateway to have access to more available spectrum and thus to be able to provide capacity to more user beams. The atmospheric impairments in these higher bands were reviewed. A methodology to assess the feeder link availability of a combined Q/V+W gateway was provided. The system was compared with a Q/V only system and the advantages and design challenges were analysed. Lastly, an example regarding the impact on feeder link availability when W band is used was provided, showing that it is easier to achieve greater availabilities regardless of the worst propagation conditions in W band, because the size of the network is smaller. In addition, the impact of the use of W in backbone dimensioning and other aspects of system design were discussed. The use of W band in HTS opens new horizons to the design of a HTS and may alleviate to a certain degree some constraints which are not easy to address with just a Q/V band only system.

### References


