Mitigating the Effect of Weather on Ka-band High-Capacity Satellites

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Introduction

HCS (High-Capacity Satellite) technology operating in Ka-band offers significant advantages over conventional satellite networks operating in Ku-band and lower frequencies. More bandwidth is available at the higher Ka-band frequencies. Ka-band antennas experience higher gain than comparably sized antennas operating at lower frequencies. Finally, Ka-band offers a new spectral environment, enabling deployment of new, advanced satellite system architectures with new features. HCS satellites in operation today, such as ViaSat-1 and KA-SAT, offer much higher data capacity than conventional satellite systems, enabling a host of new services as well as a superior user experience on existing services.

There is a downside to using Ka-band though; adverse weather conditions impact Ka-band more than at lower frequencies. However, with appropriate planning and the implementation of well-designed ground systems, there are mechanisms that can mitigate these adverse weather effects. In this paper we will provide background on High-Capacity Satellites and the effects of weather at different frequency bands, and then discuss how Ka-band HCS using appropriate ground segment design can mitigate weather effects.

High-Capacity Satellites

The first ViaSat-designed HCS satellites to be launched are KA-SAT and ViaSat-1. The Eutelsat KA-SAT, with a capacity of more than 70 Gbps, provides broadband services over Europe, the Middle East, and the Mediterranean basin. In North America, the ViaSat-1 satellite, owned and operated by ViaSat, has a broadband capacity of 140 Gbps. These HCS satellites offer approximately 10 times the throughput of conventional Ka-band satellites or 100 times the capacity of Ku-band satellites. HCS can now enable Internet connectivity with an online experience comparable to (and often superior to) terrestrial services such as DSL, mobile 3G/4G, and many cable systems.

The coverage area of an HCS is divided into many spot beams in a cellular coverage pattern (unlike a conventional satellite, which provides coverage though one large shaped beam). The use of spot beams enables large-scale frequency re-use, with adjacent cells using alternate frequencies and polarizations (left-hand circular or right-hand polarization) as shown in Figure 1. The spot beams concentrate the electromagnetic energy into a smaller area than conventional satellites, making the spot beams “hotter” than a wider conventional satellite beam.

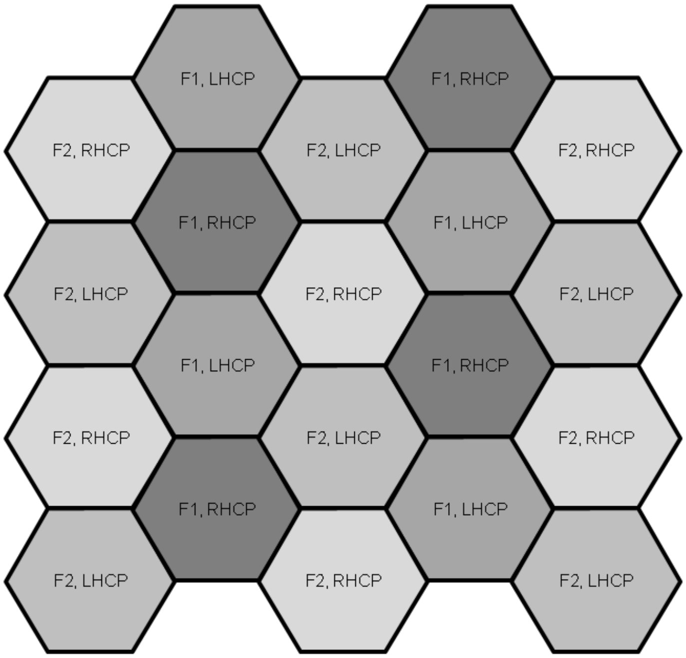

Figure 1 HCS Spot Beam with Frequency and Polarization Re-Use

Unlike conventional satellites which often service an entire satellite through a single hub, each set of four HCS spot beams is generally serviced by one gateway. For example, the ViaSat-1 satellite includes 72 spot beams serviced by 20 gateways. With proper planning, the gateways can be located outside the coverage area of the spot beams, allowing for additional frequency reuse and resulting in what is called a cross-strapped architecture, as shown in Figure 2.

The elements of an HCS satellite are:

- Terminals: Subscriber devices located anywhere in the area of coverage. Terminals are specifically designed to operate with their HCS satellite; terminal equipment is somewhat standardized (it is not customized for each individual user). A terminal includes a relatively small antenna (in most cases a small aperture parabolic reflector). Terminals may either be in fixed locations or mobile.
- The satellite: A bent-pipe satellite that redirects communications between gateways and terminals using a large number of spot beams. (Usually the spot beams are configured to jointly provide wide area coverage using a cellular spot beam pattern.)
- Gateways: Each gateway provides a connection between the satellite system and the terrestrial global communications network (the Internet). Each gateway communicates with its associated terminals via the satellite. Gateways are located in fixed pre-determined locations; these locations are selected to provide cost-effective network connectivity to wired infrastructure and

to minimize weather impact. Each gateway includes a relatively large parabolic antenna; the gateway equipment is customized to suit the demands of its locations.

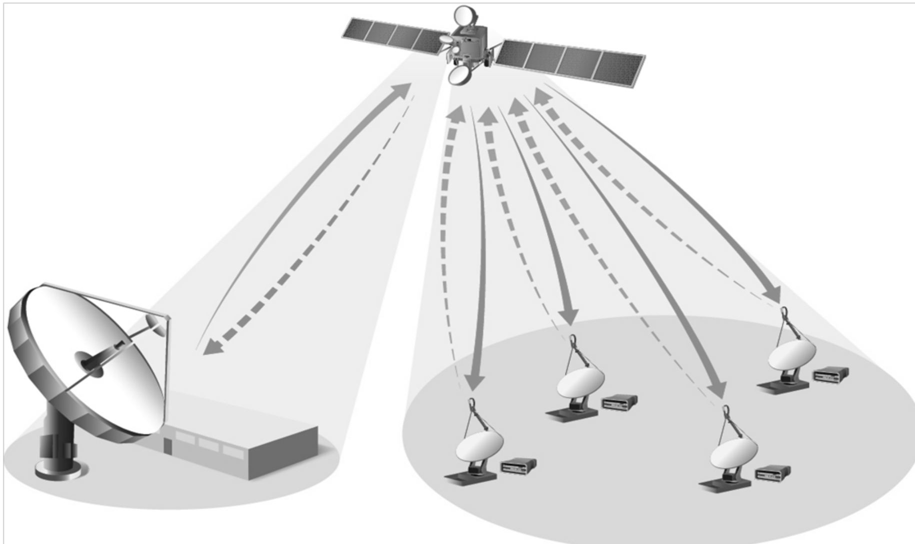

Figure 2 Cross-Strapped Topology

The various communication links within the satellite system are:

- Uplink: The uplink is the communications from the ground to the satellite. The uplink frequency for Ka-band is approximately 30 GHz.
- Downlink: The downlink is the communications link from the satellite to the ground. The downlink frequency for Ka-band is approximately 20 GHz.
- Forward link: The forward link is the overall communications link from the gateway to the terminal. It consists of the gateway uplink and the terminal downlink. The forward link is generally engineered so that the terminal downlink dominates performance. (Since the gateway services many terminals, it is generally cost effective to make the gateway antenna large enough to provide extra margin on the gateway uplink.)
- Reverse link: The reverse link is the overall communications link from the terminal to the gateway. It consists of the terminal uplink and the gateway downlink. The reverse link is also generally engineered so that the terminal uplink dominates performance.

Weather Effects

The primary atmospheric region affecting Ka-band communications is the troposphere, which extends from the surface to an elevation of approximately 15 km. Virtually all precipitation occurs within the troposphere, as it contains about 99% of the water vapor in the atmosphere.

The other atmospheric region of interest is the ionosphere, which extends from about 70 km above the surface to 1000 km, where scintillation occurs. Scintillation is a perturbation in the amplitude and phase of an electromagnetic signal caused by variations in the dielectric parameters of the atmosphere. Scintillation effects occur in the region of the ionosphere 400 km above the surface of the earth, though Ka-band scintillation also occurs in the troposphere.

The most important weather effect for our purposes is rain, which includes wet snow and other moist precipitation. (Dry snow has a minimal effect on Ka-band propagation.) Rain events can last for an extended period of time, but the most significant attenuation due to rain occurs during relatively short periods of very intense rainfall. These intense rain fades are highly localized, so terminals in the same general region often will not experience similar rain fades simultaneously. The depth of rain fades vary significantly with carrier frequency. In general, the higher the carrier frequency is, the deeper the fades get.

The international engineering and scientific community has spent years collecting data on rain and other weather effects and devising statistical models that reflect the observed behavior. The depth of rain fade is generally measured as a function of availability. Availability is a long-term statistical concept; it indicates the probability at which the specified parameter (in our case, attenuation due to rain) will not exceed a stated value. For example, if the availability is 99.5% and the stated attenuation is 5 dB, this means that in the long term we expect attenuation to exceed 5 dB 0.5% of the time. Most of the time, the attenuation will be much less than this amount.

The expected rain attenuation for the continental United States (CONUS) with 99.5% availability for 20 GHz (the downlink frequency) is shown in Figure 3 and for 30 GHz (the uplink frequency) is shown in Figure 4. The data in these figures was derived using the International Telecommunications Union (ITU) statistical model as specified in ITU-R 618-10. These figures show that weather effects are most significant in the Gulf Coast and Florida regions, and that attenuation in the downlink frequency band (20 GHz), in the range of 1 to 6 dB, are smaller than in the uplink frequency band (30 MHz), in the range of 2 to 12 dB.

We show an example of a typical rain fade as a function of time in Figure 5. The figure shows rain rate in inches per hour and the resulting forward link attenuation in dB during an intense rain shower. The attenuation data was collected in June 2011 in the United Kingdom using the KA-SAT HCS satellite and a ViaSat SurfBeam 2 Pro Portable terminal. Weather information was collected from a local weather station co-located with the terminal. The rain rate exceeded 1.0 inch per hour for several minutes, resulting in up to 3 dB of attenuation. The attenuation correlates only loosely with the rain intensity, probably partly because the signal path goes up from the ground diagonally in a direction different from the direction of rainfall.

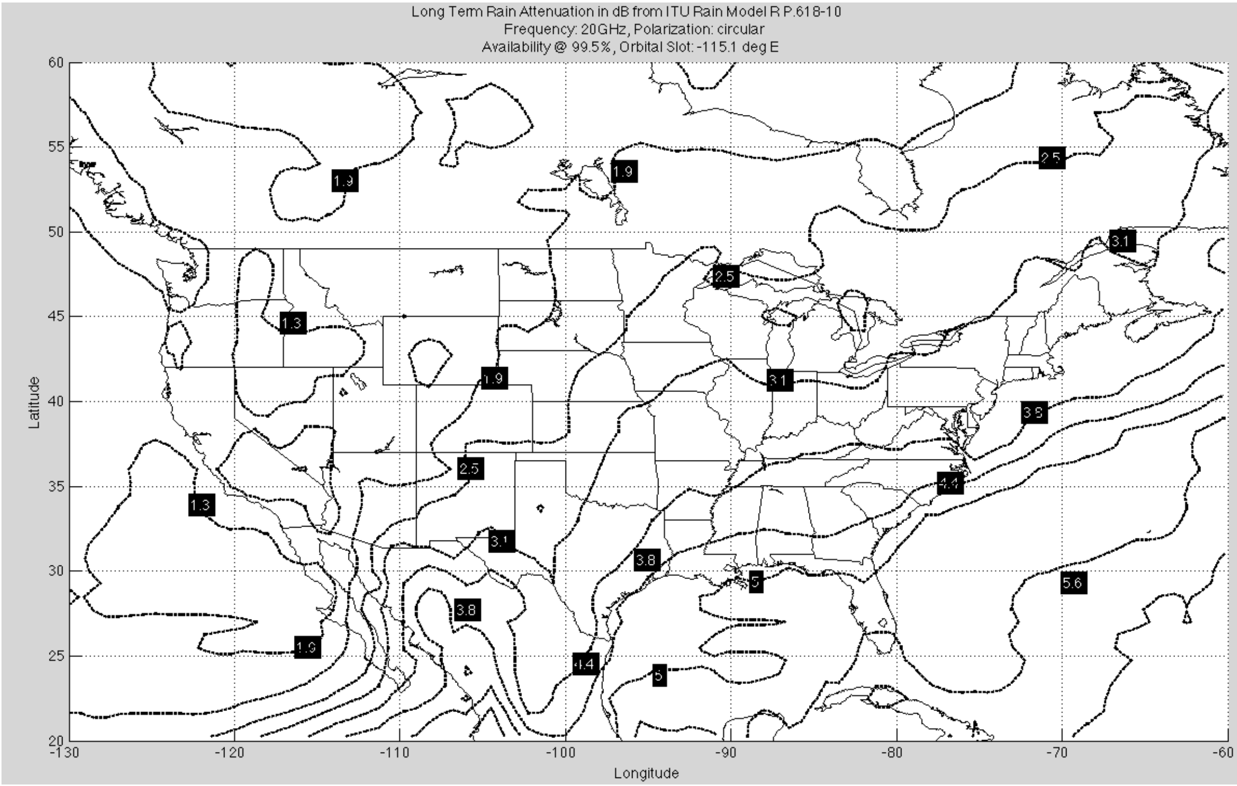

Figure 3 CONUS Rain Attenuation at 20 GHz with 99.5% Availability

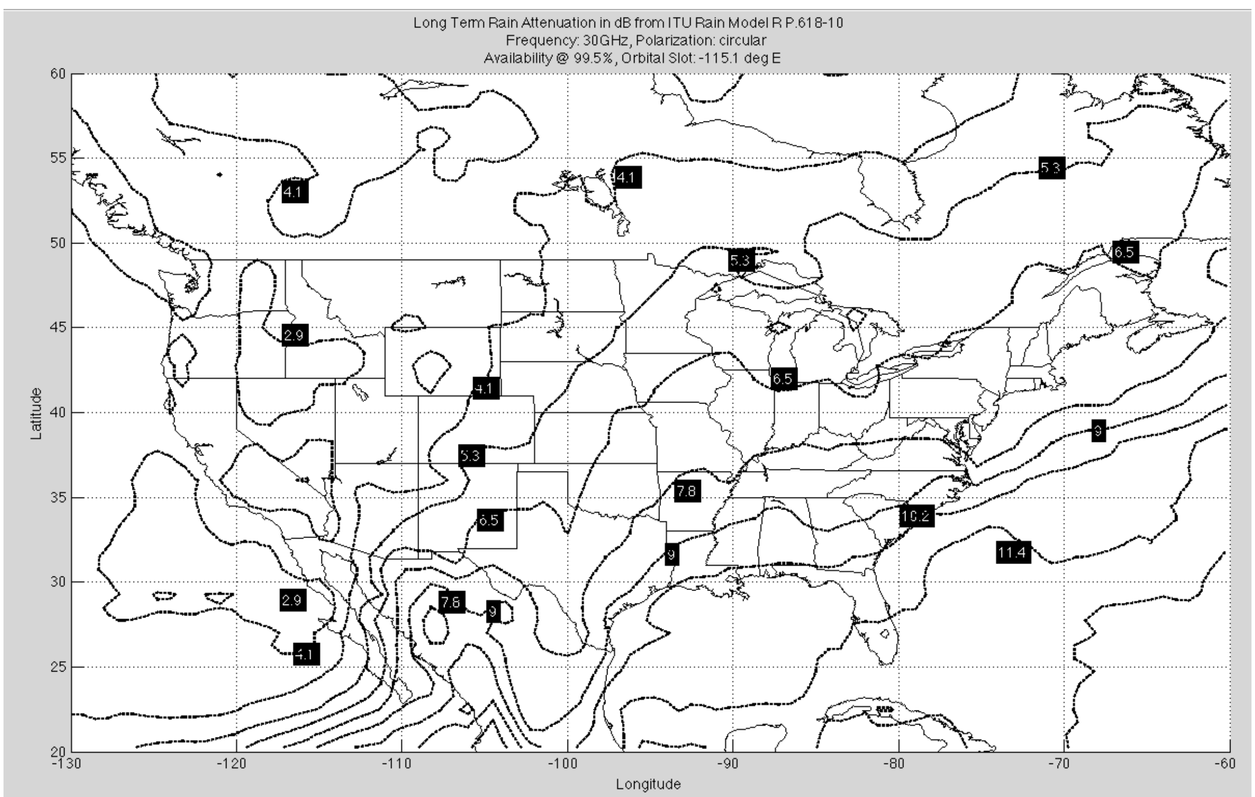

Figure 4 CONUS Rain Attenuation at 30 GHz with 99.5% Availability

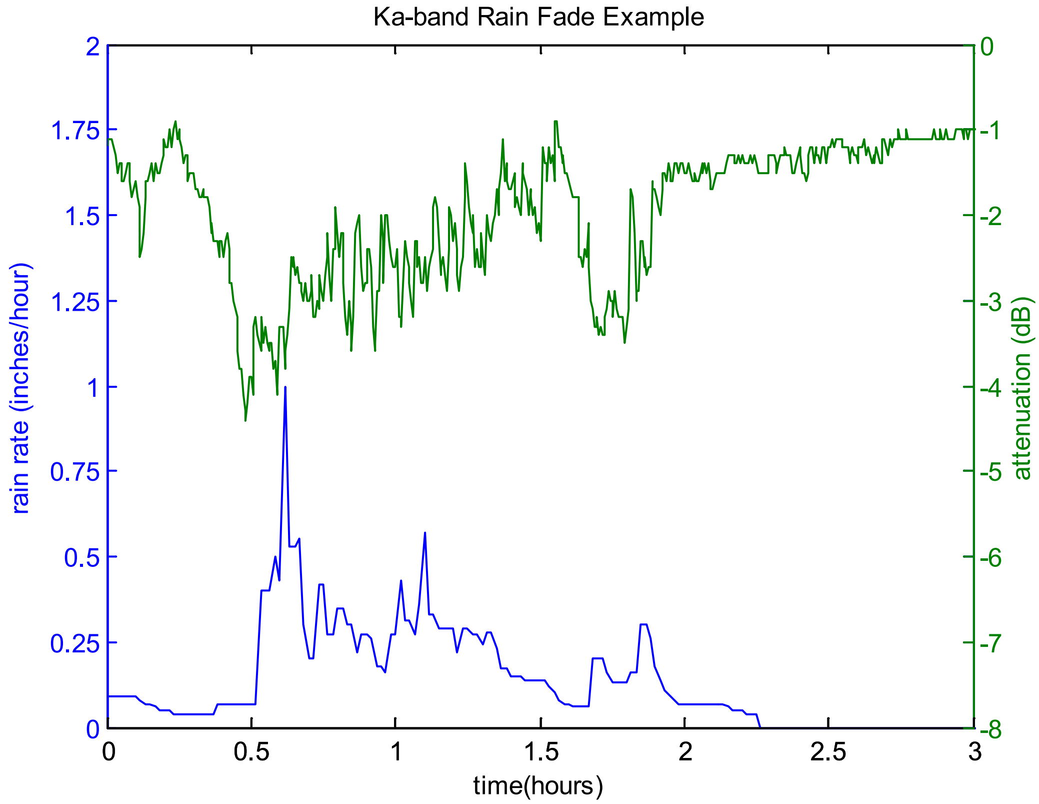

Figure 5 Rain Fade Example

In addition to rain, other weather effects include:

- Gaseous attenuation: This is caused by gases in the atmosphere absorbing electromagnetic radiation. In general, gaseous attenuation is highly frequency dependent, but the attenuation is approximately equal at 20 GHz and 30 GHz (though the attenuation is higher between these frequencies). Gaseous attenuation varies from 0.2 dB to 0.7 dB over CONUS as estimated with ITU-R models with 99.5% availability.
- Cloud attenuation: Various types of rain, fog, or ice clouds in the troposphere cause attenuation. Using ITU-R models with 99.5% availability, peak attenuation varies from 0.1 to 0.8 dB at 20 GHz and varies from 0.3 to 1.7 dB at 30 GHz.
- Scintillation: Scintillation is a variation in signal amplitude caused by variations in the refractive index primarily in the ionosphere. As estimated with ITU models, peak attenuation due to scintillation varies from 0.2 to 0.5 dB at 20 GHz and from 0.2 to 0.7 dB at 30 GHz, as estimated using ITU-R models with 99.5% availability.

Computing the overall attenuation due to rain, gaseous attenuation, cloud attenuation, and scintillation is not simply a matter of combining the separate losses, but is somewhat more complicated. With 99.5% availability, At 20 GHz the overall attenuation ranges from 2 to 7 dB and at 30 GHz it ranges from 4 to 14 dB. Most of the time the overall weather attenuation will be much smaller than this, a few tenths of a dB or less. Examples of weather attenuation are shown in Table 1.

Availability (%)	Freq (GHz)	Location	Rain(dB)	Gas (dB)	Cloud (dB)	Scin (dB)	overall
99.5	30	Central Florida	11.4	0.6	1.7	0.5	13.7
99.5	20	Central Florida	5.3	0.7	0.8	0.4	6.8
99.5	30	South Illinois	7.8	0.4	1.4	0.4	9.6
99.5	20	South Illinois	3.7	0.4	0.6	0.3	4.7
99.5	30	NW New Mexico	3.9	0.2	0.3	0.2	4.4
99.5	20	NW New Mexico	1.7	0.2	0.1	0.2	2.0
99.5	30	NW Oregon	4.1	0.4	0.7	0.3	5.2
99.5	20	NW Oregon	1.9	0.4	0.3	0.3	2.6

Table 1 Example Overall Weather Attenuation

Since Ku-band satellite systems have been operating for many years and users are comfortable with the reliability of these systems, it is interesting to compare the weather effects of Ka-band with those of Ku-band. Ku-band satellite uplink frequencies are approximately 14 GHz and downlink frequencies are approximately 12 GHz. Typical Ku-band weather effects are shown in Table 2. Attenuation effects are much smaller than at Ka-band, especially on uplink. On the other hand, Ka-band HCS satellites will be somewhat hotter than Ku-band satellites, and Ka-band antenna gains will be 4 to 6 dB higher than Ku-band antennas of comparable size. This increased gain in Ka-band immediately provides a degree of rain fade mitigation, however in some areas weather effects do present a larger challenge to overcome.

Availability (%)	Freq (GHz)	Location	Rain(dB)	Gas (dB)	Cloud (dB)	Scin (dB)	overall
99.5	14	Central Florida	2.3	0.2	0.4	0.3	2.9
99.5	12	Central Florida	1.6	0.1	0.3	0.3	2.0
99.5	14	South Illinois	1.6	0.1	0.3	0.2	2.0
99.5	12	South Illinois	1.1	0.1	0.2	0.2	1.4
99.5	14	NW New Mexico	0.7	0.1	0.1	0.1	0.9
99.5	12	NW New Mexico	0.5	0.1	0	0.1	0.6
99.5	14	NW Oregon	0.7	0.1	0.1	0.2	0.9
99.5	12	NW Oregon	0.4	0.1	0	0.1	0.5

Table 2 Example Ku-band Weather Attenuation

Mitigation of Weather Effects in Terminal Locations

The effects of weather in terminal locations are generally more significant than the effects of weather in gateway locations, as the forward link performance is dominated by the terminal downlink while the reverse link performance is dominated by the terminal uplink. This is because the gateway economics allow its antenna to be large enough such that the link performance is dominated by the behavior of the terminal side of the link in all but the worst weather conditions, but the terminal equipment antenna is limited by both cost and size constraints. Also, the gateway location can often be chosen to avoid regions with the worst weather conditions but the terminals must be located where service is needed, so that the terminal can be anywhere in the region of coverage. However, there are various methods available to mitigate the weather effects in individual terminals. We'll explore these mitigation techniques now.

Many rain events will result in short term fades lasting for several seconds. These fades can be mitigated using various network protocols to retransmit missing data or to compensate for missing information. The Internet itself is inherently lossy, so Internet applications already tolerate some degree of loss. Streaming applications (such as video) can mitigate losses by buffering data; this allows them to continue emptying the buffer while waiting for missing data to be resent. Real-time applications (such as voice calls or video conferencing) may suffer from some short term loss of data, but this can often be overcome by the correct choice of transmission layer protocols. Where necessary, other low layer protocols can mitigate short term fades.

Longer term fades, lasting for several seconds to several minutes, require more active mitigation to maintain an adequate quality of service. The mitigation techniques for HCS include adaptive power control and adaptive coding and modulation.

Adaptive power control is mainly applicable to the reverse link. The terminal increases transmit power to compensate for fades in the uplink. Practical reverse uplink power control is limited to a correcting for a few dB of variation since by design power amplifier in the terminal is optimized for general HCS employment, but other constraints like regulatory conditions may limit the amount of power available. (On the forward link, power control to compensate for individual terminal fades is less practical since the gateway transmits via the satellite to many terminals; there are also issues with altering the power transmitted from the satellite.) Since weather fades on the uplink are larger than on the downlink, adaptive uplink power control is useful for mitigating fades, even if the mitigation is only about 3 dB or so.

Adaptive modulation methods play a significant role in compensating for weather induced fades. Explaining how these work will be a little complicated; we'll start by explaining the concept of a modcode point and then we'll describe how adaptive modulation can compensate for fades. By doing so, we expect to show how Ka-band HCS systems can compensate for the higher depth of fades found at Ka-band.

A modcode is a combination of modulation type and forward error correction code rate used to send information. As an example, a subset of modcode points defined in the DVB-S2 satellite communications standard for forward link communications is shown in Table 3. The table shows the modulation type, code rate, normalized data rate (the actual data rate will depend on the amount of bandwidth allocated to the modulated signal), and the signal-to-noise ratio required for that modcode to be received reliably. It also shows the data rate step—the percent change in data rate between the current modcode and the next higher modcode—and the SNR step—the extra SNR required to operate at the next step. By using the listed modulations, the modulation type can be adjusted to change the data rate by a factor of 7 as the signal-to-noise ratio changes by 15 dB. (A similar modcode set is defined for use on the reverse link.)

Modulation	Code Rate	Normalized Data Rate	Required SNR (dB)	Data Rate Step	SNR Step (dB)
QPSK	1/4	0.5	-2.1	134%	1.2
QPSK	1/3	0.7	-0.8	120%	0.8
QPSK	2/5	0.8	0.0	125%	1.3
QPSK	1/2	1.0	1.3	120%	1.2
QPSK	3/5	1.2	2.5	111%	1.0
QPSK	2/3	1.3	3.5	112%	1.0
QPSK	3/4	1.5	4.5	107%	0.6
QPSK	4/5	1.6	5.0	104%	0.4
QPSK	5/6	1.7	5.5	107%	1.0
QPSK	8/9	1.8	6.5	112%	0.4
8PSK	2/3	2.0	6.9	112%	1.4
8PSK	3/4	2.2	8.2	111%	1.5
8PSK	5/6	2.5	9.7	120%	0.8
16APSK	3/4	3.0	10.5	107%	0.9
16APSK	4/5	3.2	11.4	104%	0.6
16APSK	5/6	3.3	12.0	107%	1.2
16APSK	8/9	3.5	13.2	n/a	n/a

Table 3 DVB-S2 Forward Link Modcodes

The possible techniques for determining which modcode point to use include:

- CCM (Constant Coding and Modulation)

- VCM (Variable Coding and Modulation)
- ACM (Adaptive Coding and Modulation)

In CCM, commonly used in conventional Ku-band satellite systems, all terminals use the same modcode point all the time for all services. This is a legacy approach from one-way satellite broadcast systems, where all terminals receive the same signal and since there is no return link, there is no way to adapt the modcode. The modcode point is chosen to be robust against expected fades. In effect, the data rate on the network is matched to the needs of the weakest terminal. Most of the time—when there is no fade—the system will be operating at a lower data rate than it could otherwise support.

CCM operation in the presence of a fade is shown in Figure 6. In the example, the SNR (signal-to-noise ratio) before the fade starts is 10 dB. The SNR drops during the fade event and eventually recovers. The selected CCM modcode (QPSK rate ¾) delivers a normalized data rate of 1.5 bits/Hz and has an SNR threshold of 4 dB. The terminal experiencing the fade will experience a brief outage during the deepest part of the fade, and then it will recover service as the fade lessens.

CCM is simple to implement and works well in systems that don't experience large variations in signal level. Since many Ku-band systems (which don't generally experience deep weather-induced fades) use CCM, user experiences based on it may lead to skepticism about how well Ka-band satellite systems will work, given their deeper rain fades.

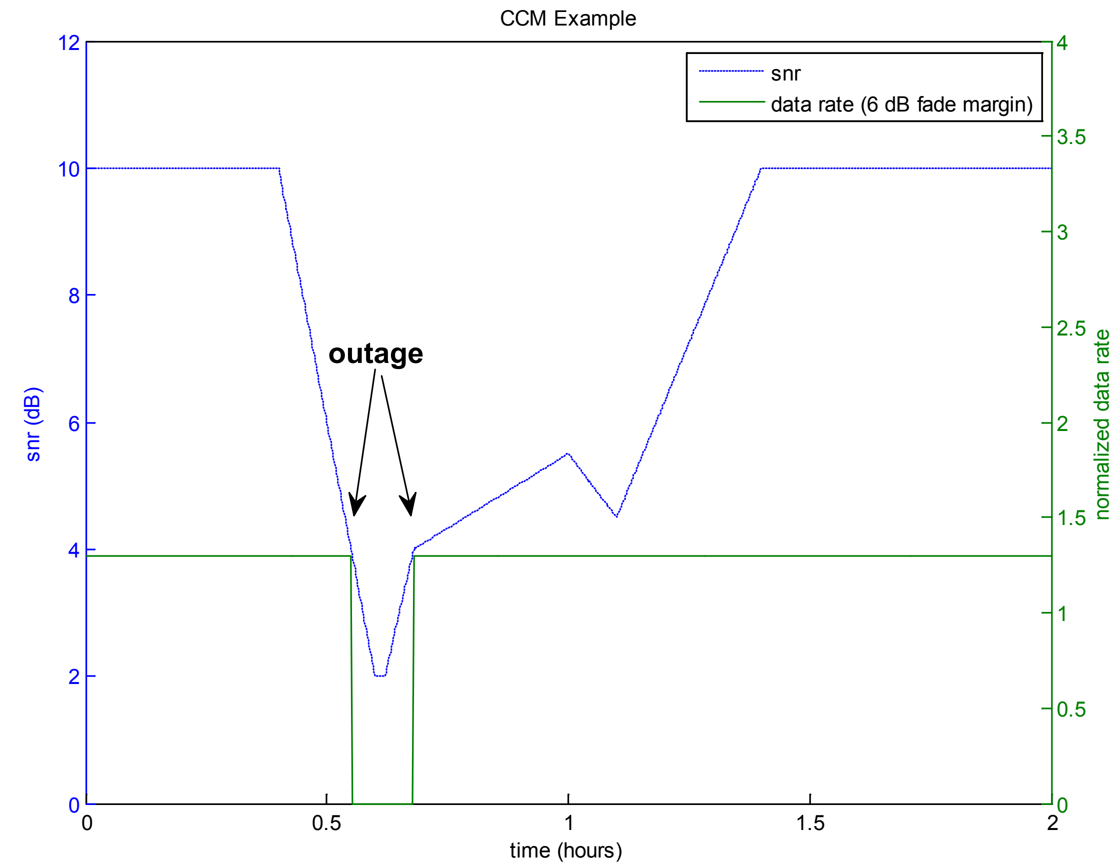

Figure 6 CCM Example

In VCM, different services (and different terminals or terminal types) may use different modcode points, but the modcode selected for a given service (or a given terminal or terminal type) will remain constant at all times. The modcode point selected for each service is determined by weighing the data rate requirements against the QoS (quality-of service) required. Some services may demand higher data rates and be able to tolerate longer and more frequent outages than other services.

VCM can mitigate weather effects by allocating more fade margin—and thus accepting lower data rate—to terminals subject to more extreme weather effects while allocating a higher data rate—and thus accepting lower fade margin—to terminals subject to less extreme weather effects. In this way, VCM avoids a limitation of CCM, where all terminals must suffer a lower data rate to give a subset of these terminals appropriate fade margin. A disadvantage of VCM is that each terminal must accept a lower data rate than the link could otherwise support in return for suitable weather margin. VCM has been used with success in Ku-band, but in Ka-band, with its larger fade margins, the disadvantage mentioned above becomes more significant.

VCM operation is illustrated in Figure 7. Service 1 uses a modcode that can tolerate 6 dB fades, but delivers a lower data rate, while service 2 used a modcode that offers a higher data, but can tolerate smaller fades. Most of the time service 2 (maybe more than 99% of the time) will offer higher speed, but it is less robust to fade.

VCM is not much more complicated to implement than CCM, and it offers the network means to achieve higher throughput for services that can tolerate more and longer outages, but it still forces the operators and users of satellite networks to accept compromises.

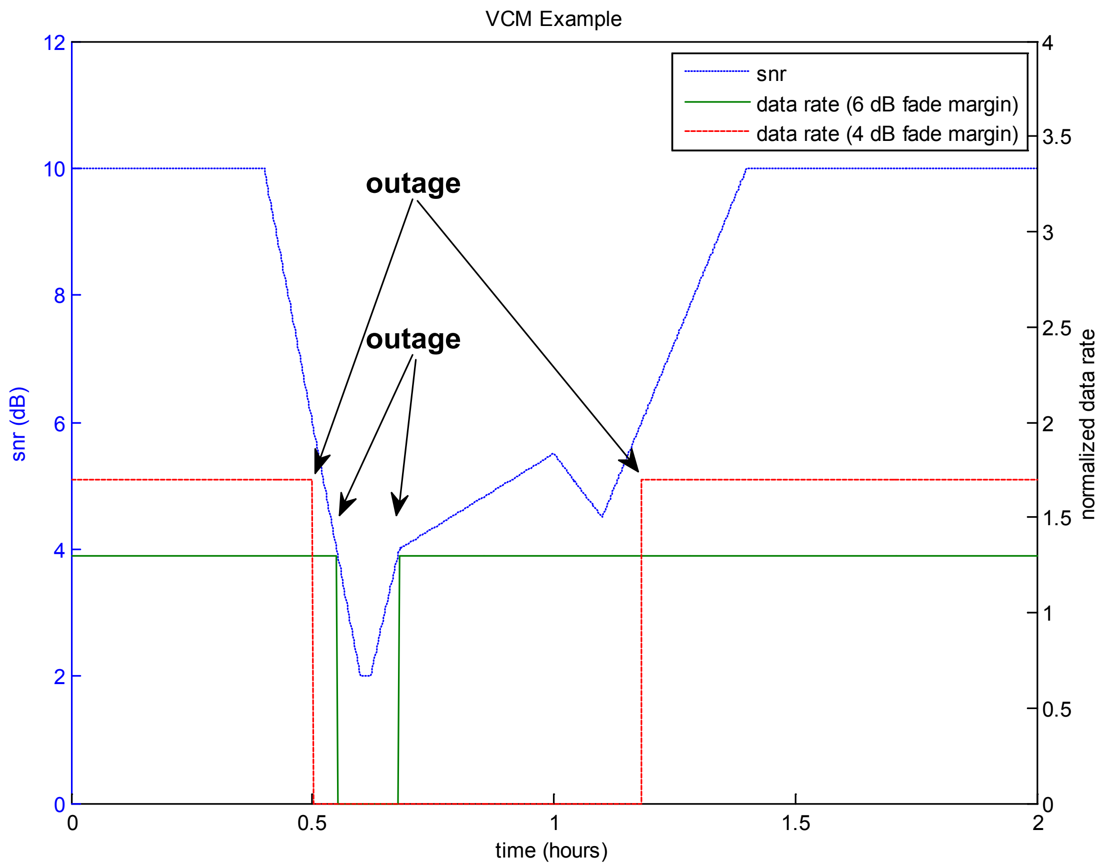

Figure 7 VCM Example

In ACM, the modcode for each terminal is adaptively tuned to meet the current requirements of the terminal. As channel conditions change, such as during a weather induced fade, the modcode adjusts to compensate for it. Terminals in the same beam are likely to use different modcodes during a weather event, because weather induced fades tend to be highly localized. The goal of adaptation is to give each terminal the highest possible data rate that the link will support (while preserving some operating margin to accommodate short term fluctuations).

An example of ACM operation is shown in Figure 8. Before the fade starts, the terminal operates at a high data rate. As the fade progresses, the data rate falls and rises as the modcode adapts to meet the current requirements of the channel.

Changing the modcode changes the instantaneous data rate of the terminal, but it need not change the overall data rate experienced by the user. The amount of time the satellite system allocates to a given user's messages can be adjusted to compensate for reduction in data rate, keeping overall data throughput constant as shown in Figure 9.

ACM is more complicated to implement than VCM or CCM, but it is a powerful tool for mitigating the large weather induced fades experienced in Ka-band. A sufficiently large set of modcode points can accommodate very deep fades. For example, the modcodes shown in Table 3 can accommodate more than 15 dB variation. When coupled with adaptive power control, ACM can compensate for even the large fades experienced in Ka-band.

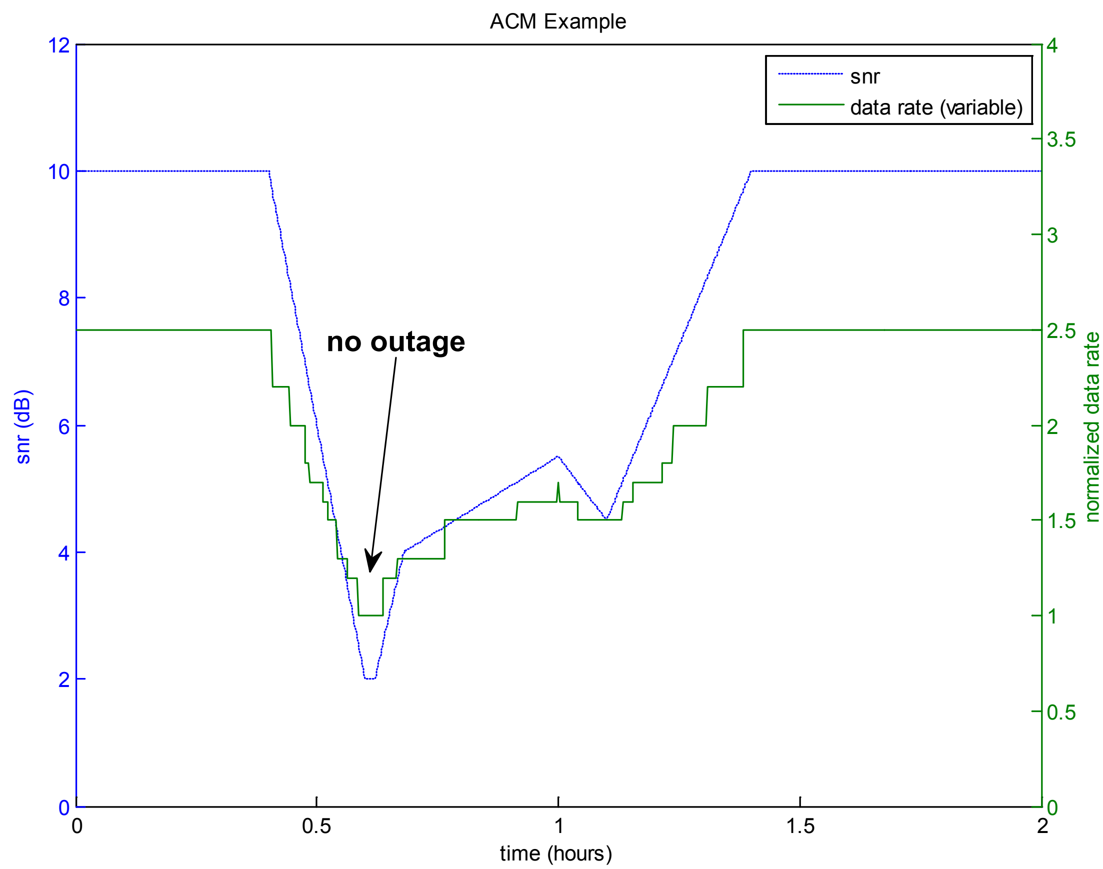

Figure 8 ACM Example

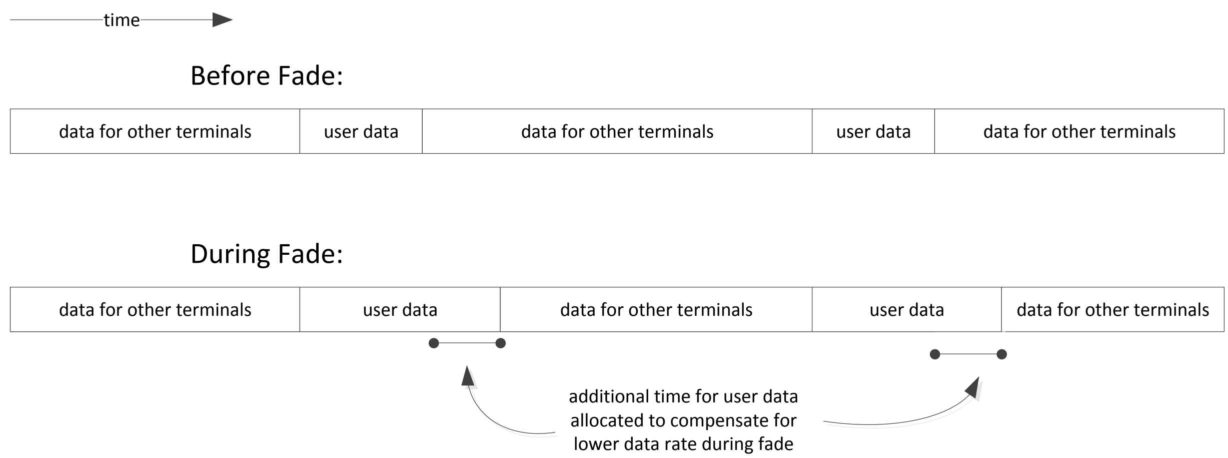

Figure 9 Time Compensation Example

Mitigation of Weather Effects in Gateway Locations

Weather effects can also occur at gateway locations. A deep fade in a gateway location could cause outages to all the terminals serviced by that gateway. However, there are powerful tools available to mitigate effects on gateways.

The most powerful tool for gateways is planning. In the HCS architecture, gateways may be located outside of the spot beams of the terminals they are servicing. This leaves a lot of flexibility in determining the location as gateways can be placed in areas that do not experience deep fades due to weather. Each gateway is customized to meet the demands of its selected location. Specifically, the size of the antenna at the gateway can be matched to the demands of its location.

It is also possible to deploy redundant gateways in separate locations to serve the same terminals. If weather conditions threaten one gateway, a backup gateway can be brought online to compensate for it. ViaSat has developed methods that allow this transition of responsibilities while maintaining active communications links.

In the event of weather induced fades, a gateway can use adaptive power control and adaptive modulation to compensate for fades in a manner similar to that described in the previous section.

Example of Ka-band Systems

While HCS satellite systems are relatively new, mitigation of Ka-band weather effects is not. ViaSat has been continuously providing Ka-band consumer Internet service in the continental United States since 2005. This service currently supports 400,000 home and business customers nationwide, using the

WildBlue-1, Anik-F2, and ViaSat-1 satellites. This satellite system has demonstrated robust coverage in the presence of weather-induced impairments over its operational history by using techniques such as those described in this whitepaper.

Conclusions

There is no doubt that weather effects in Ka-band present a more significant challenge than at lower frequency bands. However, HCS combined with a more technologically advanced ground segment are able to overcome these challenges. The mitigation techniques described here, including adaptive power control and adaptive modulation and coding as well as gateway site planning, are powerful tools that can effectively mitigate these fades.