REAL-TIME FADE MITIGATION USING RADIOMETRIC MEASUREMENTS FOR FUTURE KA-BAND SERVICES AT DLR.

Yunir Gataullin

German Space Operations Center, DLR, Münchner Str. 20, 82234, Wessling,
Phone: +49(0)815328-3150, Email: yunir.gataullin@dlr.de

Abstract

Due to the congestion of popular C- and Ku-band frequencies, the satellite communication systems are rapidly moving toward the higher frequencies. Most of the commercial communication satellites in the near future will operate Ka-band transponders. One of the inevitable part of such systems are ground stations which support In-Orbit-testing and the traffic routine for the satellites. The main problem at Ka-band link planning is the link availability reduction due to rain fade and scintillation, which effects in a link margin reduction. The only efficient way to deal with this problem is to use Fade Mitigation Techniques (FMT) which allows adaptable margins to be used. This paper discusses the possibility of implementing an open loop FMT for future DLR's Ka-band Ground Station based on the long-term fading models, radiometric and beacon measurements. The real-time fade prediction and mitigation problem is discussed and the solutions for long- and short-term fade variations are presented.

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1. Introduction

German Space Operations Center plans to provide new Ka-band services with its 13-meter Ka-band antenna which is currently being developed and will presumably be used for future space missions such as SmallGEO, Heinrich Herz, Lunar Exploration Orbiter, DEOS and several others. It is well known that the radio signals of frequencies above 10 GHz all suffer from various limiting effects such as rain attenuation, scintillation and depolarization, which affect the satellite links significantly. These time varying random weather events, like rain and clouds, increase the moisture in the atmosphere and consequently a noise temperature and the attenuation. The major attenuation contribution at Ka-band frequencies is a rain fade, which seriously affects the link availability. To deal with this problem in a long term, there are various rain attenuation models, which have been developed by different authors. Most of these models are able to predict the stochastic fluctuation of the rain attenuation based on the long-term statistics, which are successfully used within the systems where a large fixed link margin is employed. However, the technology limitations combined with the cost efficiency requirements (e.g. power and bandwidth) do not allow using static margin systems, and push towards the implementation of adaptive control schemes, called Fade Mitigation Techniques, in general. The new FMT systems with a link margins adaptable to the rapidly changing weather conditions are presently being developed and some of them are already in use. In order to implement such system, it is necessary to measure and predict the short-term variations of the rain attenuation, which cannot be obtained by existing long-term statistical models within required precision limits. Many papers have been written on prediction algorithms using various theories and models. This work is not an intention to elaborate a new prediction algorithm, but an attempt to design an FMT technique, to employ the observation- and estimation-based prediction algorithms in real-time satcom applications and to test it, in order to select one convenient FMT for future Ka-band operations at DLR.

There are three basic categories of FMT's used to adapt system resources to the atmospheric and rain attenuation fluctuations in a real-time manner [1]:

- Power Control
- Adaptive Waveform
- Diversity

The adaptive waveform techniques include adaptive coding, adaptive modulation and adaptive data rate reduction. These techniques can be used for services that can tolerate a reduction of the information rate such as video, voice or data transmission. However, they require complex signal processing and delays due to exchange of signalling between transmitter and receiver. Diversity techniques are only useful in the case of big hubs especially for backhaul services. In case of site diversity, one requires additional antenna, related infrastructure and re-routing strategy, which is not cost efficient. From this perspective, power control techniques are very suitable, relatively simple and cheaper technique to implement. The closed loop power control system might be useful for low orbiting satellites, but is not effective technique to be used for GEO applications due to the prohibitive long delays of the signal, which lead in the enormous prediction errors in real-time applications. In this study, therefore Uplink Power Control (ULPC) with the open-loop fade detection technique is described. This countermeasure is an adaptive power control, in which the transmitted power is increased to compensate for fading due to rain on the propagation path. ULPC is one of the most flexible techniques, which mainly affects the terminal without influencing multiple access schemes [2]. In the case of transparent satellite transponders, ULPC can prevent from reduction of satellite EIRP caused by the decreased uplink power level that would occur in the absence of ULPC [3]. This advantage can be utilized during In-Orbit testing of SmallGEO satellite.

The rest of this paper is organized as follows: Section 2 describes long-term Ka-band statistics and link availability in Weilheim ground station. The influence of atmospheric noise is considered in section 3. Section 4 describes the fade detection logic. The prediction algorithms used in the technique are presented in the section 5. Section 6 provides the conclusion and future work.

2. Long-term rain attenuation statistics and link availability in Weilheim

The ITU's long-term rain attenuation statistics have been analized to determine the amount of rain fading for different availabilities in Weilheim. Link availability is essentially the percentage of time that the available rain fade margin is not exceeded. For the 99.9% availability performance the attenuation can easily exceed 15 dB. This can lead to huge and unpractical antenna designs if the fixed rain margin is employed. Figure 2.1 illustrates the results of rain attenuation prediction for different rain availabilities at 30 GHz at Weilheim region for the rainfall rate of about 40mm/h [4].

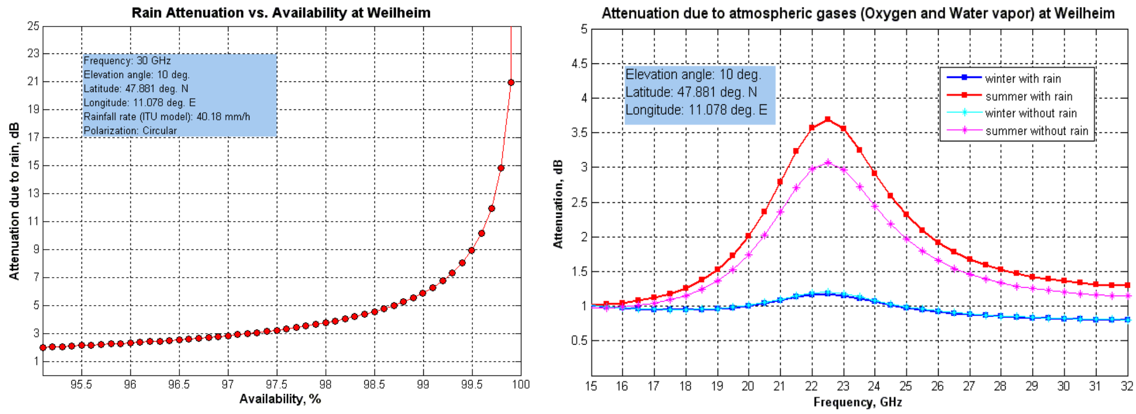

Fig. 2.1 **Left:** Rain attenuation vs. availability at Weilheim Ground Station at frequency 30 GHz. **Right:** Season dependent gaseous attenuation (with and without rain) vs. Frequency at Weilheim Ground Station [4]

As seen from the Fig. 2.1, rain attenuation is an important factor to keep in mind when designing the Ka-band link. For the availability of 97% we have about 3dB rain attenuation, which goes upward with increased availability. As availability requirements becomes very demanding, the amount of rain fading becomes prohibitive or inefficient for any satellite links which use a fixed margin concept [4].

The results of the total attenuation due to atmospheric effects for frequencies 26/30 GHz and elevation angle 10° are summarized for availability 95% in the Table 2.1.

Table 2.1 Total attenuation due to atmospheric effects at Weilheim [4]

Atmospheric effect	at 26 GHz	at 30 GHz
Attenuation due to rain, dB	1.4	1.95
Attenuation due to atmospheric gases, dB	1.92	1.35
Attenuation due to clouds and fog, dB	0.8	1.1
Attenuation due to scintillation, dB[1]	1.0	1.0
Total attenuation, dB[2]	3.66	3.98

Even though these results are obtained for a long-term prediction, they provide an idea of attenuation level which can affect the Ka-band link in this region. These high values, which are increasing with availability requirements lead to the consideration of a Fade Mitigation Techniques, which allow a real-time adaptive methods to be used for Ka-band satcom services. This is described in the next sections.

[1] The scintillation loss was not estimated in this work and the typical value found in the literature was used instead.
[2] A general method for calculating total attenuation is provided by ITU-R 618-8.

3. Atmospheric noise and Ka-band link margin analysis

The FMT technique based on detection, prediction and decision algorithms was described by [5]. The open-loop fade detection based on the real-time measurements is presented as an uplink power control (ULPC) technique for future DLR missions. The measurements will be performed by means of onsite radiometer which is time synchronized with the Ka-band ground station. In order to understand the adaptive methods, it is necessary to introduce the attenuation sources and the way they impair the link.

The standard link equation that relates the transmission power and required carrier-to-noise ratio is given by [4],

$$\frac{C}{N} = \frac{P_t \cdot G_t \cdot G_r}{L_{FS} \cdot L_p \cdot L_{atm} \cdot T_{sys} \cdot k} \tag{1}$$

Where: P_t – transmitted power, G_t – transmitting antenna gain, G_r – receiving antenna gain, L_{FS} – free space path loss, L_{atm} – loss due to atmospheric absorbtion, L_p – spacecraft and ground antenna pointing loss, T_{sys} – system noise temperature, k – Boltzmann's constant

In the equation (1), ground station/satellite antenna gains and free space loss are the a priori known values. Since the T_{sys} and L_{atm} are weather dependent variables, the only variable that can be adapted to compensate the losses due to rain noise and attenuation (while maintaining the constant rate and modulation) is the uplink power[3].

Both L_{atm} and T_{sys} are affected by atmospheric noise temperature. The atmospheric loss L_{atm} is related to atmospheric noise temperature T_{atm} through the following approximation [6]:

$$L_{atm} \approx \begin{cases} \dfrac{275}{275 - T_{atm}}, & T_{atm} < 275 \\ \infty, & otherwise \end{cases} \tag{2}$$

The system noise temperature, T_{sys}, reflects the noisiness level of the system and includes equipment noise temperature, atmospheric noise temperature and cosmic background noise. That is given by [6],

$$T_{sys} = T_{eq} + T_{atm} + \frac{2.7}{L_{atm}} \tag{3}$$

From the equation (3), (2) and (1) one can conclude that the atmospheric noise temperature measured by radiometer will suggest the link margin which can be controlled by transmitted power. However, some errors will still remain in the measurements during rainy periods due to rain scattering and scintillation effects. In order to maintain the C/N at the satellite repeater within required limits, it is necessary to adapt the transmit power on the ground station to rapidly changing noise temperature, attenuation and scintillation fluctuations. The variable system link margin shall be approximately equal to a rain fade and scintillation fade (ideal case) at all times. One should also keep in mind that the absorption loss of the atmosphere depends on the length of the path the signal travels through the atmosphere, therefore noise temperature and rain attenuation are strongly dependent on the elevation angle. For LEO satellites the fade variations with the elevation angle are much higher compared to that of the satellites located on GEO or MEO orbits. This implies that if the attenuation is known for any elevation angle θ_0, the following equation can be used to account for elevation change and determine the attenuation at elevation θ [6]:

$$L_{atm}(\theta) = \left[L_{atm}(\theta_0)\right]^{\sin\theta_0 / \sin\theta} \tag{4}$$

[3] There are other FMT's that consider adaptive waveform techniques, which are beyond this article scope.

4. Open-loop rain fade detection

Fading due to rain in a Ka-band link is well described as slowly varying, log-normally distributed process. Its dynamics can be modelled as a first-order auto-regressive process, as supported by experimental data. This model gives rise to an optimal estimator that can be used in adaptive power control, for example, ULPC. The open loop fade detection concept relies on the estimation of the uplink impairment from the measurements of propagation conditions. The following detection methods can be used in parallel for Ka-band fade mitigation at DLR ground station:

- Sky brightness temperature measurements collected by radiometer
- Fade measurements obtained by Ka-band satellite beacons
- Rain rate measurements obtained by means of disdrometer and radar
- Temperature, pressure, humidity and rain intensity measurements using meteorological station.

A single detection source may not be accurate enough due to errors in the measurement. For example, in case of the observations of a beacon signal transmitted by the satellite repeaters, the measurements do not always provide reliable attenuation observations due to onboard instrumental drifts (unless a special "research" beacon transmitter is used onboard the satellite, e.g. ITALSAT/OLYMPUS Ka-band beacons) [10]. Radiometric measurements on the other hand are usually have a limited dynamic range and are therefore blind to rain scattering (approximately 20% of total attenuation) and tropospheric scintillation [7]. Therefore it is useful to compare and test several rain attenuation measurements and estimation sources in parallel. This may not be very cost-effective in case if no additional hardware is available, but is reasonable for testing and research purposes prior to the beginning of Ka-band operations. In addition to the active radiometric and satellite beacon measurement, the statistical attenuation estimation models can be used as inputs in order to assess system performance and to compare different available prediction and estimation methods. The FMT system proposed for Ka-band ground station in Weilheim is illustrated on Fig. 4.1.

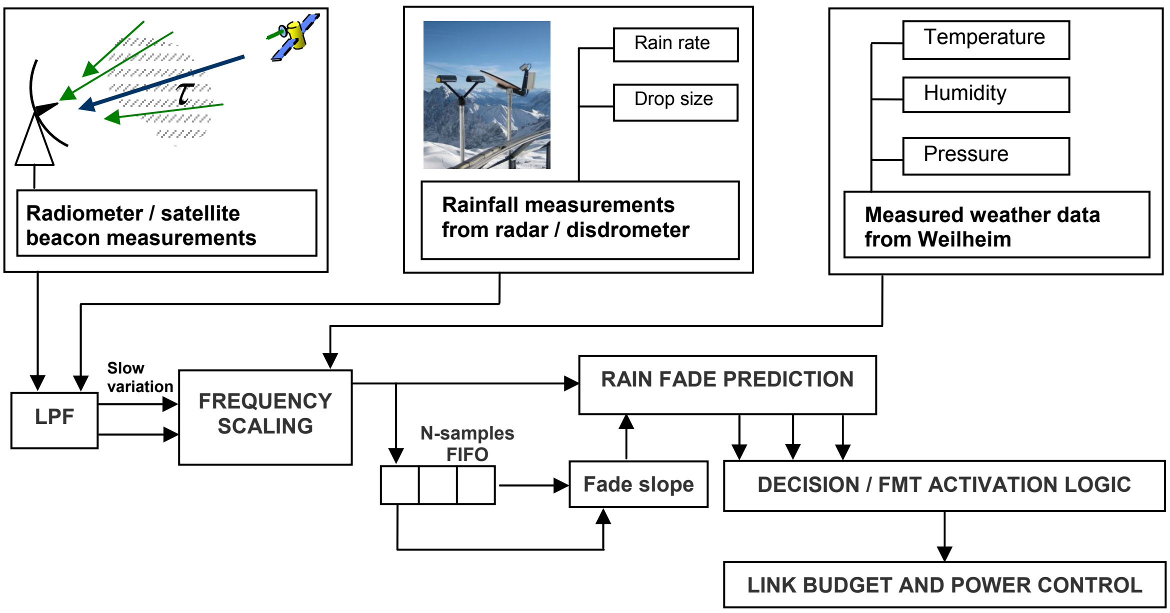

Fig. 4.1 Fade detection, processing, prediction and FMT decision

In order to have a good estimate of the fading level, it is necessary to separate the slow varying component (attenuation) and the fast varying component (scintillation). Scintillation is a short-term random amplitude fading and phase change that can occur due to changes in the density of the atmosphere. This fast-varying component has to be removed by means of scintillation filters because this component is difficult to predict (and needs to be predicted separately), which is seen from the autocorrelation functions which decrease very rapidly with time. This fast-varying attenuation component can be removed by subtracting it from the total attenuation measurement. On a decibel scale, the slow attenuation component, x is given by

$$x = y - \overline{y}, \tag{5}$$

where the fast varying component $\overline{y}$ is identified with the aid of *one-second averaging* of the received signal y. This is realized using low-pass filtering. If no scintillation predictor is foreseen, the system shall have a build-in fixed margin of about 1 dB to compensate for scintillation losses.

5. Short-term fade prediction and decision logic

When the fade is detected and the scintillation is removed, the frequency scaling is required in case if fading was measured on frequency different from the uplink frequency. This introduces additional error source, which is the dominant error component of the estimated channel loss for ULPC. To achieve better performance the radiometer will need to operate on the uplink frequency band and the ULPC activation thresholds and margins should be designed taking into account the dependence of the scaling error on the attenuation. The radiometer detections may also introduce additional processing times and errors. These radiometrically obtained data can then be used as the inputs into the fade prediction models which are described by various authors and are still being improved.

The satellite beacon measurements can be obtained from the downlink telemetry beacon which is then scaled to the uplink frequency attenuation and the prediction algorithms are applied using the attenuation sample of time t_0 and the previous attenuation samples at time t_{0-n}. The time interval Δt between the obtain samples, as well as the number of previous samples has an influence on the prediction accuracy. The smaller is the Δt , the better is the prediction accuracy. In case of radiometric measurements, the integration time of the radiometer may have certain limitations, and might therefore, reduce the overall prediction accuracy. These prediction algorithms have been studied by Van de Kamp, where the Markov process is used to construct the rain attenuation model [8]. Simple solution of a fade slope interpolation has been shown by Castanet and Grémont. Using this method, one can obtain the attenuation prediction in the short-term future:

$$A(t + \delta t) = A(t) + \delta t * \frac{A(t) - A(t - \Delta t)}{\Delta t} \tag{6}$$

Where $A(t)$ *is the attenuation at present time,* $A(t - \Delta t)$ *is the attenuation at previous time step*

The [6] has compared the influence of number of previous attenuation samples on the prediction error and found that the best performance is achieved with one or two samples. He also suggested the following rule to be used for power increase added to the initial transmitter power changes adaptively according to the received signal attenuation α . When the required power increase for signal attenuation α is denoted as $\Delta(\alpha)$, the average power increase $E[\Delta]$ is given by the following equation:

$$E[\Delta] = \int_0^\infty \Delta(\alpha) P_\alpha(\alpha) d\alpha, \tag{7}$$

Where $P_\alpha(\alpha)$ *is the probability density function of attenuation* α *.*

The probability density function of the typical attenuation values suggests an implementation of the uplink power increase/decrease in stepwise change of about 0.5 dB. The performance of other existing prediction models will be tested during the real time operations.

6. Conclusion and future work

Presented fade mitigation technique describes a mechanism which can enhance power efficiency and the IOT performance of the Ka-band ground station at DLR. The advantages and limitations of radiometric, beacon-based and other rain fade detection/estimation techniques as a fade countermeasure which can be used at any Ka-band ground station are also described. It becomes obvious, that if the proper prediction and estimation techniques are used, the Ka-band facilities with adaptive power-control technique can use the advantage of the increased link availability.

The testing of the above described FMT can be first undertaken as the new Ka-band ground station becomes available at DLR. The test results and comparison of several detection sources will be analyzed in future as attenuation data becomes available. Scintillation and scattering are still being limiting factors at Ka-band even during a good weather conditions, but could be mitigated using small fixed link margins. Potential system interference due to the uplink power increase along with the adaptive waveform techniques is to be analyzed in the next study.

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