Site Diversity Experiment in Q-Band Satellite Communications in Slovenia and Hungary

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***Abstract*—To enable throughput rates in the terabit-per-second range, future satellite communications will have to utilize a large amount of available bandwidth in the Q-band and above. At these high frequencies, the signal is severely degraded and attenuated by tropospheric phenomena, especially rainfall, which reduces the availability of satellite communication links and degrades the quality of service. Site diversity is an efficient technique used to mitigate rain attenuation. In this letter, we evaluate the performance of the large-scale site diversity system consisting of ground stations in Ljubljana and Budapest based on long-term satellite signal measurement campaigns by Alphasat at 39.402 GHz. The measured attenuation time series are statistically analyzed and presented for a period of one year and compared with three representative prediction models.**

***Index Terms*—Measurements, Q-band, rain attenuation, satellite, site diversity, statistics.**

I. Introduction

IN SATELLITE communications, frequencies in the Q-band and above have recently been explored because they provide a large amount of available bandwidth required for high throughput communications deployment. However, as frequency increases, the effects of atmospheric phenomena on the degradation of propagating electromagnetic waves on Earth-satellite links become more severe. Among the atmospheric phenomena, rainfall is the dominant factor, causing high attenuation and consequently reducing the availability of the satellite communication link and degrading the quality of the service. Therefore, uplink power control (UPC) and adaptive coding and modulation (ACM) are commonly used as propagation impairment mitigation techniques (PIMTs) against rain attenuation [1]. However, UPC has the disadvantage that requires a powerful high power amplifier to support the power increases, while ACM requires cross-layer information exchange to maintain throughput constant when necessary. A more effective PIMT for mitigating rain attenuation is site diversity, requiring two or more spatially separated ground stations connected by terrestrial links. Considering that rainfall intensity is known to be inversely correlated with distance between pairs of stations, rain attenuation can be effectively mitigated by selecting the Earth station with the highest signal level at a given time.

Propagation measurement campaigns provide the experimental environment and data for developing and evaluating channel models needed to characterize ground segment requirements such as fade margins and geographic locations of ground receivers in a site diversity system. In the past, most satellite propagation measurement campaigns for site diversity experiments have been conducted at the Ka-band by various research groups [2], [3], [4], [5], [6]. Site diversity experiments are rare in the Q-band. One important experiment exists from an early ITALSAT propagation campaign [7], while the more recent experiment was conducted between ground stations located in Graz and Budapest from the Alphasat satellite [8]. In this letter, we investigate the large-scale site diversity performance between two ground stations located in Ljubljana, Slovenia, and Budapest, Hungary measuring the copolar beacon signal from the Alphasat satellite at the frequency of 39.402 GHz. In particular, we provide a detail statistical analysis of the measured joint distribution of rain attenuation over one-year period and comparison to three representative models.

The rest of the letter is organized as follows. Section II briefly introduces the site diversity experiment, while Section III explains data processing with some illustrative examples of attenuation time series. Section IV describes the statistical analysis of joint rain attenuation in dual site diversity. Final remarks and conclusions are given in Section V.

II. Site Diversity Experiment Setup

The two-site large scale diversity experiment was conducted with two receivers, located in Ljubljana and Budapest and measuring beacon signals from the Alphasat satellite at Q-band frequency. The Alphasat satellite is in geosynchronous orbit at 25° East and carries the Aldo Paraboni payload for scientific research measurements in Ka- and Q-bands operated by ESA [9]. The Q-band beacon operates at a frequency of 39.402 GHz in 45° tilted linear polarization. The ground distance between the stations is 383 km as shown in Fig. 1. Table I summarizes the coordinates of the ground stations and the main link parameters. Both receivers were developed and installed in 2015, one at

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Fig. 1. Geometry of the site diversity experiment.

TABLE I
LINK PARAMETERS OF EXPERIMENT SETUP

Receiver Location	Latitude [°N]	Longitude [°E]	Altitude [m]	Elevation [°]	Azimuth [°]
Ljubljana	46.04	14.48	292	36	165.5
Budapest	47.48	19.06	120	35.14	172.13

the Jozef Stefan Institute (JSI) in Ljubljana and the other at the Budapest University of Technology and Economics (BME).

The ground receiver in Ljubljana developed by JSI utilized the same 1.2 m parabolic antenna for the measurement of the co-polar beacon signals in Ka-band (19.7 GHz) and Q-band (39.4 GHz), as well as the cross-polar signals induced by the depolarization of the copolar signals as they propagate through the atmosphere [10]. The ground receiver in Budapest was developed by BME and uses the 1.8 m Cassegrain parabolic antenna [8], [11]. To reduce the elevation and azimuth variations of the geosynchronous satellite, both receivers were equipped with a tracking system with 0.005° pointing resolution. Since this letter is focused on the performance of site diversity in the Q-band, only measurements of the copolar Q-band signal are considered. The one-year period data from May 16, 2017, to May 15, 2018 with the greatest availability of concurrent data of 94%, during the total measurement campaign are considered.

III. PROPAGATION DATA PROCESSING

The received signal was sampled in ground stations with the sampling rate of 6.1 Sps (sample per second) in Ljubljana and 1 Sps in Budapest and the obtained time series are stored throughout both measurement campaigns for further processing and analysis. Furthermore, due to the higher sampling rate at the ground station in Ljubljana, the data are subsampled to 1 Sps to synchronize with the data from the station in Budapest. The rain attenuation time series were then extracted from the raw copolar signal data time series. For the site diversity study, the joint attenuation time series were calculated, which represent the minimum values of attenuation time series between two sites at the same synchronized time [12], [13]. In this letter, we have investigated the ideal selection scheme in site diversity that provides the best achievable results by considering the instantaneous switchover between stations and selecting the Earth-satellite link with the least signal degradation due to rain.

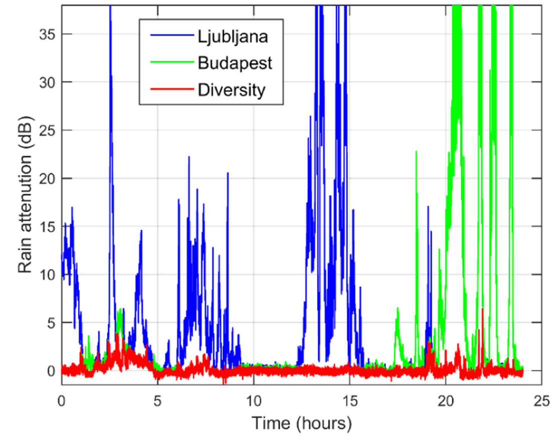

Fig. 2. Rain attenuation at 39.402 GHz on September 16, 2017.

The number of switchovers can be quite high with negative impact on the technical deployment of site diversity. Therefore, real site diversity systems usually employ switching algorithms that significantly reduce the number of switches, but as a result, the diversity gain is also reduced depending on the switching scheme selected.

Fig. 2 shows an example of rain attenuation measured separately at Ljubljana and Budapest on September 16, 2017, and the joint rain attenuation of the site diversity system. By 16:00, the ground station in Ljubljana experienced several heavy rain events that caused huge signal attention exceeding 38 dB, while during the same period almost clear sky prevailed in Budapest with only a few light rain events. In the late afternoon, after 17:00, the situation changed and while there was huge signal attenuation due to rain experienced in Budapest, the station in Ljubljana recorded only a few slightly increased rain attenuation events in the evening. By selecting the satellite communication link with the lowest attenuation at any time, the rain attenuation in the ideal site diversity system, is almost completely mitigated, reaching a maximum of only about 7 dB for a relatively short time.

Another example, depicted in Fig. 3, shows the time series during several hours on September 2, 2017.

On this day heavy rain occurred simultaneously in the afternoon at both sites, resulting in higher rain attenuation in the site diversity system, exceeding 23 dB, compared to the previous case. Thus, it is evident that during the summer, short time heavy rainfall can occur in the investigated locations simultaneously even at the stations in the large-scale site diversity system that is several hundred kilometers apart. This shows that site diversity alone is not capable of completely mitigating rain attenuation in every configuration.

IV. RAIN ATTENUATION STATISTICAL ANALYSIS

For the site diversity experiment, we statistically analyzed the rain attenuation time series for the one-year period. The

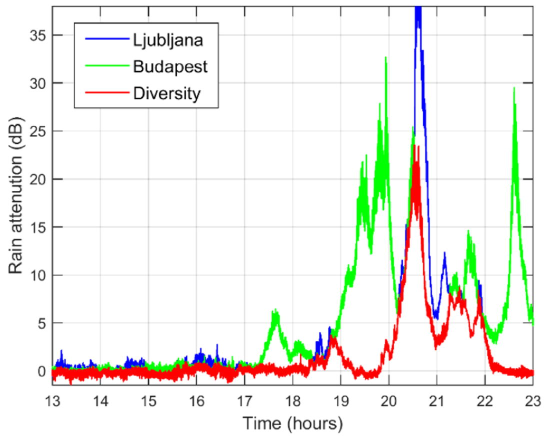

Fig. 3. Rain attenuation time series at 39.402 GHz during several hours on September 2, 2017.

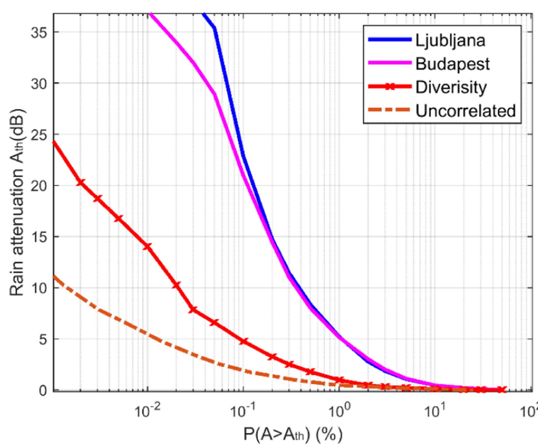

Fig. 4. Annual CCDFs of rain attenuation for single sites Ljubljana, Budapest and joint rain attenuation for site diversity.

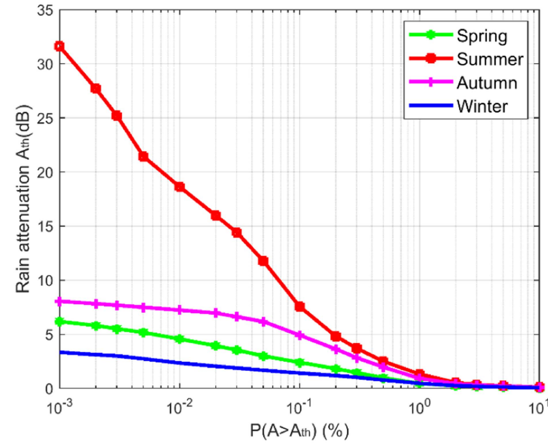

Fig. 5. Seasonal CCDFs of joint rain attenuation for site diversity.

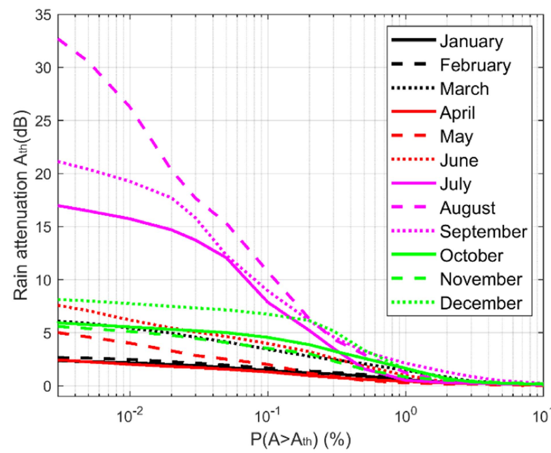

Fig. 6. Monthly CCDFs of joint rain attenuation for site diversity.

results are presented as complementary cumulative distribution functions (CCDFs) of joint rain attenuation. Fig. 4 shows the annual CCDFs of rain attenuation separately for each site and for the joint rain attenuation for the site diversity experiment. The site diversity system significantly mitigates the rain attenuation of the Earth-satellite system. For example, the attenuation exceedance for 0.1% of the time (approx. 525.6 minutes per year) of about 22 dB at each single site is reduced to 5 dB in the site diversity system. For attenuation exceedance for 0001% of the time, both sites are in saturation (reaching the noise level), while the attenuation for the site diversity system is 24 dB. With an additional mitigation technique, the attenuation of 24 dB can be further reduced to ensure good quality of service and high availability of the link at 0.001% of the time, which is unlikely to be achieved at these frequencies without using site diversity. For the reference, the theoretical uncorrelated joint CCDF is also depicted, obtained by multiplying the two single-site probabilities of exceedance at each rain attenuation threshold.

Site diversity performance was also examined separately for each season and the corresponding CCDFs are shown in Fig. 5. The season with quite high joint attenuation in site diversity system is summer. Compared to summer, significantly lower rain attenuation was observed in spring, autumn, and winter.

To provide better insight into site diversity performance, CCDFs for each month are shown in Fig. 6. Exceeded joint rain attenuation in the site diversity experiment was the largest during the summer months, especially for low percentages of time, with the highest attenuation in August, followed by September and July. Attenuation in the other months was relatively insignificant for nearly all values of exceedance probability.

To indicate the performance of the proposed technique, Fig. 7 depicts the annual and seasonal diversity gains at each individual ground station of the site diversity system as follows [14]:

$$G\left(A_{single}\right) = A_{single}\left(P\right) - A_{diversity}\left(P\right) \quad (1)$$

where A_{single} and $A_{diversity}$ are the attenuation values at a given ground station for the single-site and site-diversity system, respectively, that are exceeded for the same time percentage P. The benefits of site diversity for rain attenuation mitigation for each single site during the year and each season is clearly illustrated in terms of diversity gain, which increases almost linearly with attenuation.

In autumn, the diversity gain is smaller compared to other seasons for almost any attenuation, most likely because of

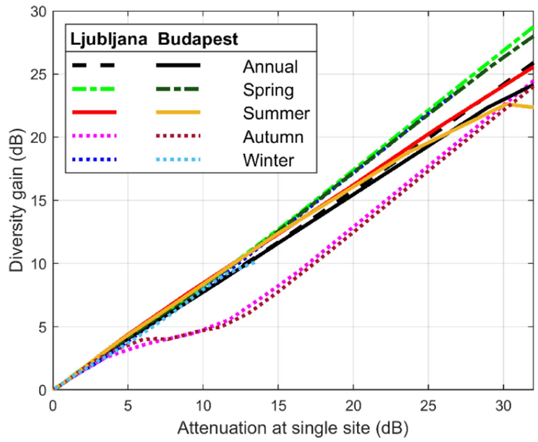

Fig. 7. Annual and seasonal diversity gains obtained at each site.

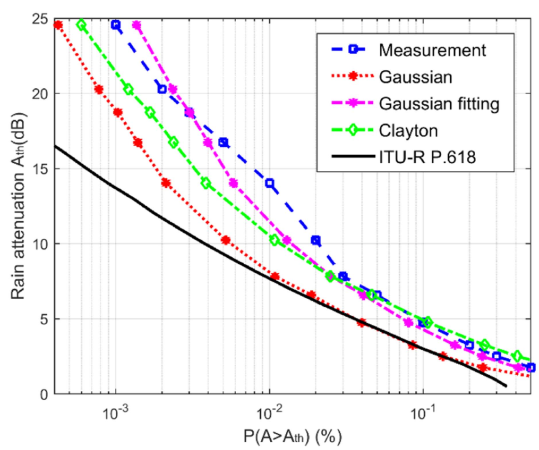

Fig. 8. ITU-R and Gaussian copula prediction of outage probability due to rain attenuation in the Q-band site diversity system with ground stations in Ljubljana and Budapest.

stratiform rainfalls typical for this season. In spring, the gain is the highest for attenuations higher than 15 dB, and reaches the gain of around 27 dB for a single site attenuation of 30 dB. Despite the fact that the CCDF of joint rain attenuation is the highest in summer, as depicted in Fig. 5, the diversity gain in summer is shown to be high.

In Fig. 8, the measured CCDFs of the joint rain attenuation of the site diversity are compared with the prediction obtained by ITU-R Recommendation P.618-§2.2.4.1 [15], Clayton model [16] and Gaussian copula model [17]. For all three models, the measured CCDFs of rain attenuation at both single sites are used as input data. Although the Clayton and Gaussian copula models perform better than the ITU-R model, all models, especially for low probabilities, underestimate the actual measured attenuation CCDF curve. Gaussian copula is a new model that has been shown to be the best among copula-based models for the European site diversity experiments in the extensive analysis for the Ka- and Ku-bands [18]. In this model, the joint CCDF is expressed as follows [17]:

$$P\left[A_1 \geq A_{th}, A_2 \geq A_{th}\right] = 1 - u_1 - u_2 + C(u_1, u_2) \quad (2)$$

where the Gaussian copula function is expressed as

$$C\left(u_1, u_2, \rho\right) = \frac{1}{2\pi\sqrt{1-\rho^2}} \int_{-\infty}^{\Phi^{-1}(u_1)} \int_{-\infty}^{\Phi^{-1}(u_2)} e^{-\frac{t_2^2 - 2\rho t_2 t_1 + t_1^2}{2(1-\rho^2)}} dt_2 dt_1 \quad (3)$$

where Φ is the CDF of the marginal standard Gaussian distribution and u_1, u_2 are single site CDFs and ρ is modeled as

$$\rho = Ae^{-\frac{d}{\alpha}} + (1-A)e^{-\left(\frac{d}{\beta}\right)^2}, \quad d > 0 \quad (4)$$

with constants $A = 0.7447$, $\alpha = 40$, $\beta = 625$, and distance d between the two stations in kilometers.

With the stations at $d = 383$ km apart, $\rho = 0.1754$. To improve the performance of the Gaussian copula model in the Q-band, the expression for the dependence parameter ρ of the Gaussian copula needs to be evaluated by additional experimental measurement data for the Q-band and above.

From the fitting of the experimental data to expression (2) it is proven that a good fit can also be obtained for the Q-band, as shown in Fig. 8. In this case, the value $\rho = 0.3235$ was obtained from the fitting. Our example shows that this and similar experimental measurements in the Q-band are also very important for improving the models; however, modeling is beyond the scope of this letter. The experiment presented here is a good case to evaluate the method, while further site diversity experiments are needed to modify the models for the Q-band.

V. Conclusion

This letter presents a large-scale site diversity experiment based on Q-band Alphasat satellite signal measurements in Ljubljana and Budapest. The investigation is focused on rain attenuation in the site diversity system over a period of one year. The results are presented statistically in terms of CCDFs of the joint attenuation in the site diversity system and show a significant decrease in attenuation compared to the single site ground stations. The advantages of the site diversity system are confirmed by the diversity gains at both ground stations for one year and for each season, which are shown to increase almost linearly with increasing rain attenuation. Although, the diversity gain is high in summer, the joint CCDF of rain attenuation during summer is higher compared to other seasons. This is due to the fact that in summer, the single sites at Q-band are characterized by high rain attenuation and that even in large-scale site diversity, rainfall can occur simultaneously at both sites. In autumn, the diversity gain is smaller compared to other seasons for almost all attenuation thresholds, most likely due to the stratiform rainfalls that characterize this season.

The measurement CCDF fits the Clayton and Gaussian copula prediction models better than the ITU-R model, although neither model performs particularly well. The improved performance of the Gaussian copula model was achieved by modifying the dependence parameter ρ, but it needs to be further tuned by more extensive measurements obtained from the site diversity systems in the Q-band.

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