Three-Site Diversity at Ka-Band Satellite Links in Norway: Gain, Fade Duration and the Impact of Switching Schemes

Martin Rytir, Michael Cheffena, Per Arne Grotthing, Lars E. Bråten and Terje Tjelta

***Abstract*—Analysis of two years of measurements from a three-site satellite beacon diversity experiment in Norway is presented. The operating frequency was 19.68 GHz, elevation angles were between 21.7° and 22°, and site separations 23, 29.7 and 50.1 km. Due to spatial decorrelation of rain, combined attenuation at these sites occurs much less frequently than at a single site. All three two-site combinations and a three-site combination were investigated.**

Measured values for diversity gain at 0.01% exceedance level were 8.8, 10.7 and 12.1 dB for the two-site pairs and 12.5 dB for three-sites, given a single site attenuation level between 13 and 16 dB. Comparison of the measured data showed excellent agreement with current ITU-R models. Fade duration statistics for single-site and for the combinations are analyzed and it is shown that the statistics for the diversity combinations can be modelled using a double-lognormal function as is the case for single-site statistics.

Analysis of the effects of a non-ideal switch-over scheme showed that using moderate switch-over threshold levels and time delays, the number of switch-overs can be significantly reduced while most of the diversity gain and reduction in number of fades is retained.

***Index Terms*—Spatial diversity, radiowave propagation, satellite**

I. Introduction

SATELLITE telecommunication links that utilize centimeter and millimeter waves are susceptible to tropospheric impairments. High intensity rain causes significant attenuation on the link and can lead to reduced capacity or even complete loss of communication. Besides constant power margins, numerous Fade Mitigation Techniques (FMTs) can be utilized. The transmission power at both ends of the uplink and downlink can be continuously adjusted to maintain the required signal levels. While effective, there are limits to these techniques due to the available power that become even more important when using small-sized aperture terminals. Adaptive Coding and Modulation (ACM) changes the coding and/or modulation of the transmitted signal so that it is less susceptible to attenuation at the expense of throughput. For gateway stations or communication hubs this reduction can affect many users at the same time. Similarly, services that require high data rates might quickly become unavailable on small terminals.

Rain at locations some distance away from each other is less correlated. Two links towards the same satellite that are separated by at least a few tens of kilometers will generally not experience the same attenuation levels simultaneously. By using two or more links that are connected to each other in a diversity scheme even severe attenuation can be avoided [1], [2].

The ITU-R model [3], as well as multiple measurements [4-9] shows that at Ka-band frequencies site separations of a few tens of kilometers can lead to significant reduction of the attenuation. However, both the ITU-R model and majority of the measurements deal only with first order statistics based on ideal selection-combining diversity. The second-order statistics, which are important for implementation of additional FMTs are usually not investigated, with a notable exception found in [10]. In a selection-combining scheme the link with lowest attenuation at any given moment is always selected. This represents the best results achievable without combining the signals as is done in an Equal Gain Combining (EGC) and Maximum Ration Combining (MRC) schemes. While easily applicable for downlink reception the frequent switch-over may cause issues for uplink operation, depending on the system used [2]. Only a few studies have been performed on the impact of switching schemes on satellite links. Theoretical modelling was done in [11] and impact on measured statistics was shown in [12].

In this paper two years of measured data at 20 GHz, from three sites in the south of Norway are analyzed. The simultaneous measurements at the three sites provide three pairs of two-site combinations as well as a three-site scheme for diversity analysis. Due to the site location at 60° N the elevation angle towards a geostationary satellite will be relatively low and is 22° for the measurements analyzed in this paper. The elevation angle is significantly lower compared with those for the majority of diversity experiments done previously. The low elevation angle clearly gives an increased path length through the atmosphere, which is likely to affect

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the diversity performance. One year diversity measurement results from two of the sites as well as one year of results from the three-site combination have been published previously [8], [9].

The rest of the paper is organized as follows. Section II describes the measurement location and setup as well the data processing. In Section III, the measured precipitation and attenuation for both single site and diversity combinations are presented and compared with models. In Section IV, measured fade durations and a new fade duration model for diversity links based on a single-site model is introduced. Section V investigates the effect of non-ideal diversity schemes on the attenuation statistics as well as on the fade duration, inter-switch durations and number of switch-overs. Impact on system design for a real system that uses site diversity is discussed in Section VI followed by conclusions in Section VII.

II. Experiment Setup

A horizontally polarized beacon transmitted at 19.68 GHz from Eutelsat Ka-Sat GEO satellite at 9° East was received at three geographically separated measurement stations.

A. *Measurement Location*

As can be seen in Fig. 1, the stations are located in the south of Norway, close to Oslo. The distances between the station pairs are 23, 29.7 and 50.1 km with Nittedal Teleport located between the two other sites. Two of the stations are at the same height above mean sea level (AMSL) while Kjeller is slightly lower. The elevation angle towards Ka-Sat is almost identical as well ranging from 21.7 to 22°. The stations are located approximately in line with the main weather (precipitation) direction found by a detailed study of spatial rain rate correlation in the area [13].

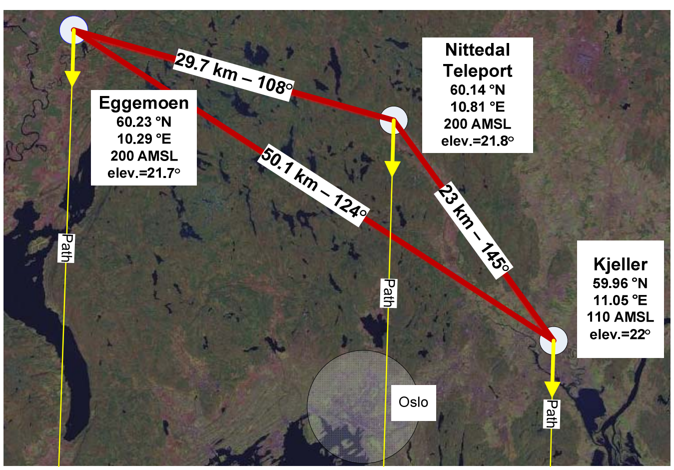

Fig. 1. The three measurement sites in the South of Norway.

B. *Measurement Terminals*

Parabolic antennas with 1.2 m diameter are in use at Kjeller and Nittedal, while a 1.8 m antenna is used at Eggemoen. For each station a plastic cover shields the feedhorn from accumulation of rain and snow, while a passive dehydrator is used to keep the waveguide dry. The beacon signal is converted to L-band using temperature stabilized Low Noise Block downconverter (LNB) and fed to an Agilent CXA or EXA spectrum analyzer (SA) with 30 Hz Resolution Bandwidth. PCs control the SAs and record the beacon signal level at a rate of approximately 10 samples per second. The clear-sky carrier to noise ratio is 37 dB at Kjeller and 42 dB at Nittedal and Eggemoen, due to different antenna feeds.

Vaisala WXT 520 compact weather stations are placed at each site to record meteorological parameters including rain rate. In addition at Eggemoen and Nittedal, Lambrech 1518H3 tipping buckets are in use for independent rain rate records. At Kjeller a Vaisala PWD22 Present Weather Detector is operating providing additional information about the precipitation. The meteorological measurements operate during both summer and winter seasons. All the sites and recording instruments are synchronized using Network Time Protocol (NTP). Further details about the measurement setup can be found in [14].

C. *Data Processing*

As a first step during data processing, invalid measurements are removed by an automatic procedure that checks for frequency instability and then controlled by a manual visual inspection of the time series plots. Attenuation events are identified and the 0 dB level is set based on interpolation of the signal before and after an event. Outside of attenuation events the measured data are filtered using a 6^{th} order Butterworth high-pass filter with a cut-off frequency of 12 mHz to remove slow-varying attenuation caused by gas attenuation, antenna de-pointing and gain changes due to temperature. The resulting timeseries consists therefore of excess attenuation and scintillation.

Periods with missing beacon data at any of the three sites are removed from the time series and the resulting data are resampled to a common time vector at 10 samples per second. The concurrent availability of the three beacon measurements during the two years of measurement (October 2013 – September 2015) was 81%. The longest missing segment was during winter 2014 (7.3%), in addition a few (1-2 weeks) segments were missing in June, August and September 2015.

III. Precipitation and Attenuation

A. *Precipitation*

To get an idea of the climatic conditions during the two years of measurement the precipitation values measured at the three sites are shown and compared with prediction methods in Fig 2. In this figure all rain data have been used and further more scaled to one year assuming zero precipitation during outage periods. Only data from the WXT 520 weather stations are plotted as this is the only sensor type common for all three sites. At Nittedal and Eggemoen the data were compared with those collected using the tipping-bucket sensors and showed good correlation. The availability of weather data measurements was between 88 % and 91% for the three sites.

There are significant differences between the sites with Nittedal recording the highest rain intensity values and Kjeller the lowest. The measured values exceeded for 0.01% of time are 24.0 mm/h for Kjeller, 30.7 for Eggemoen and 34.0 for Nittedal. The ITU-R values are around 28 mm/h for all sites

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[15]. Norwegian maps (NWM) give 20 mm for Eggemoen and

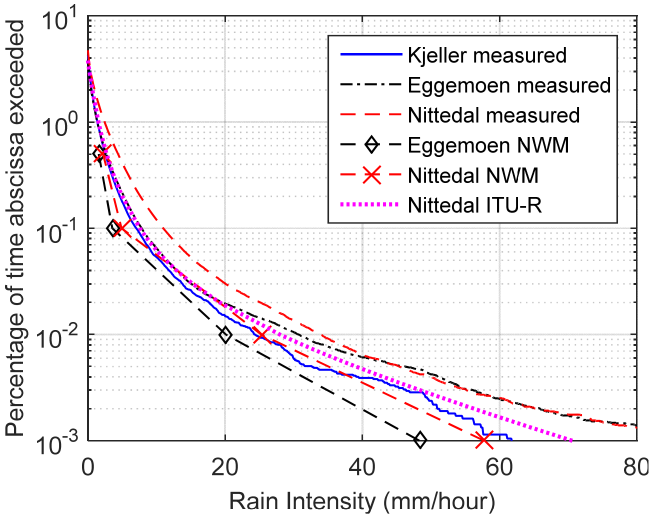

Fig. 2. Measured rain intensity at the three sites compared with ITU-R and Norwegian map (NWM) values. ITU-R values for all sites are nearly identical therfore only one is shown. Norwegian map values for Kjeller are nearly identical to values for Nittedal so they are also omitted

25 mm for Nittedal and Kjeller [16].

B. Attenuation

The measured attenuation (excess and scintillation) for all locations, as well as attenuation for all diversity combinations is shown in Fig. 3. Single site-attenuation curves are similar for all three sites with slightly higher attenuation recorded at Kjeller and slightly lower at Eggemoen. This is in contrast to the precipitation measurement published in the previous section. However, it should be noted that the precipitation measurements are point measurements and are of limited use in describing the precipitation conditions along a slant path with low elevation angle. At 22° elevation angle the path length below rain height of 2.5 km is over 6.5 km [3].

The diversity scheme used is ideal selection diversity (SC) where at each sample the site with lowest attenuation value is used. Significantly reduced attenuation is achieved for all of the diversity combinations. The two combinations with shortest separation distance (KJ-NIT and NIT-EGG) show very similar attenuation values while the combination with largest separation distance (KJ-EGG) is clearly better. There is very little to be gained by adding additional station (Nittedal) between two existing ones (KJ-EGG).

C. Diversity Gain and Comparison with Models

One of the two site combinations is compared with ITU-R models for rain attenuation [3] and for diversity using the model from § 2.2.4.1 of [3] in Fig. 4. The ITU-R prediction models use rain rate and probability of rain as given by the ITU-R maps. Both the single site prediction and the diversity model fit quite well for the 2 years of measurement. For comparison of diversity prediction it is more useful to plot the equipropable diversity gain, defined as the difference (in dB) between the attenuation for a single terminal and the joint (diversity) attenuation at a fixed probability [17]. In Fig. 4 the measured gain is therefore the difference between the solid blue line (for Kjeller) or the dash-dot black line (for Eggemoen) and the dotted line. Likewise the gain predicted by the ITU-R model is the difference between the dashed and dash-dot green lines. The diversity gain for each station is plotted in Figs. 5 to 6 and shows very good agreement with the model. Adding a third station only has benefits in the cases

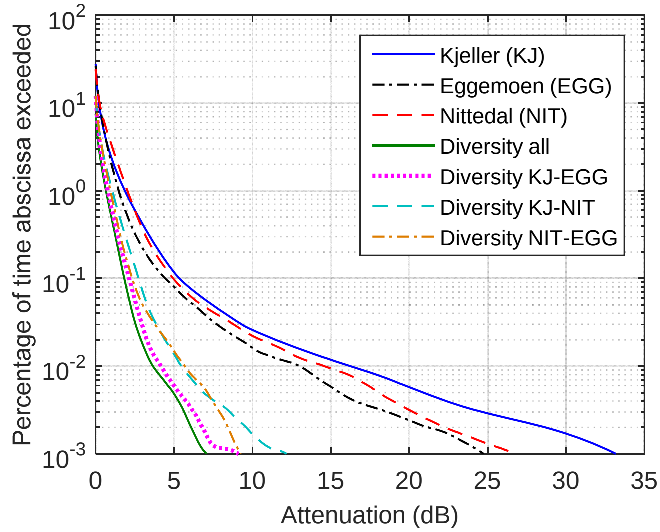

Fig.3. Measured attenuation and selection diversity for all sites.

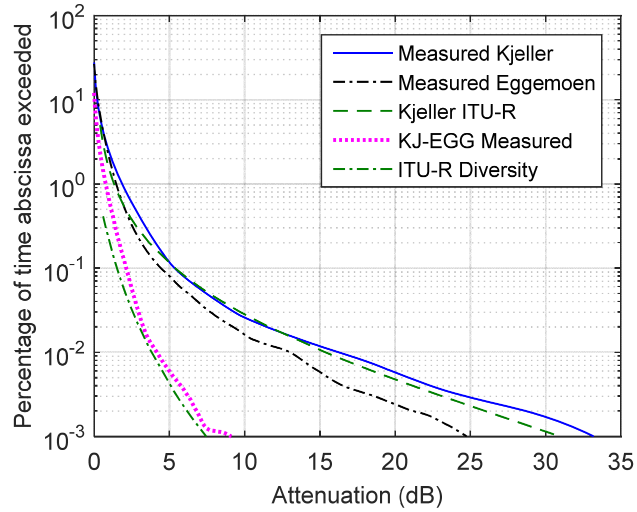

Fig.4. Single site and diversity attenuation for Kjeller and Eggemoen compared with ITU-R models. ITU-R single site prediction for Eggemoen is identical to Kjeller and is therefore omitted.

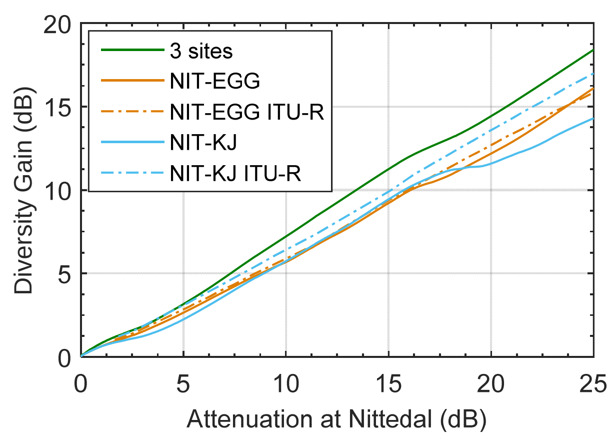

Fig.5. Measured and predicted equi-probable diversity gain for Nittedal.

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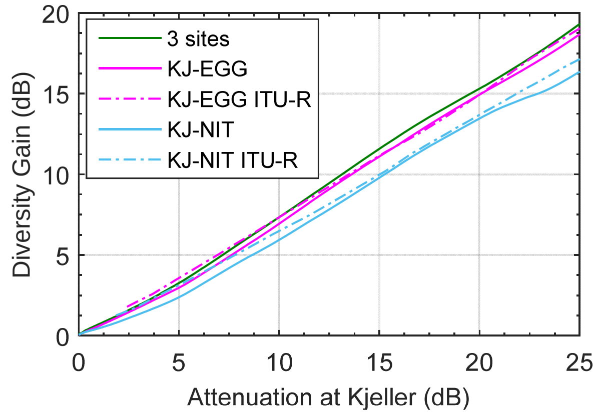

Fig.6. Measured and predicted equi-probable diversity gain for Kjeller.

where the station increases the longest separation distance.

IV. Fade Duration

While diversity significantly reduces attenuation on the combined link it cannot remove it entirely, which is especially true for configurations with shorter site separation. Therefore additional FMTs are still likely to be employed on the link. Proper design of these requires not only first but also second order statistics (such as fade duration) of the diversity link.

Fade duration is defined as the time interval between two successive crossings of the same attenuation threshold. It provides important information with regard to e.g., outage probability as well as the time durations the system needs to be able to compensate for.

A. Measured Fade Duration

Fade duration statistics for two years for two of the 2-site combinations are shown in Figs. 7 and 8. The third combination (NIT-EGG) is very similar to NIT-KJ and is omitted for brevity. The number of fades is significantly reduced, especially for the higher fading levels (5 dB and more). As an example the number of 5 dB fades longer than 10s at Kjeller was 363, while for KJ-EGG it was 19. The diversity combination with the highest separation distance (KJ-EGG) experiences larger reduction in number of fades than those with lower separation distance. The three-site combination in Fig. 9 shows some reduction in number of deep fades compared with the KJ-EGG combination, but the effect is limited. Note that for fade levels of 8 and 10 dB, the number of events is low and a single long event (>300s) at the KJ-EGG combination covers the period during which the 3-site combination experiences numerous shorter events. Therefore, the KJ-EGG curves for 8 and 10 dB levels end below the 3-site curves.

B. Fade Duration Modelling

A prediction model is required in order to design practical satellite communication links. Different models for predicting the fade duration statistics of satellite links exist in the literature. The models usually utilize two functions to describe the short and long durations caused by atmospheric turbulence and by the space-time variations of rain, respectively. A power-law and lognormal functions were used in [18], a

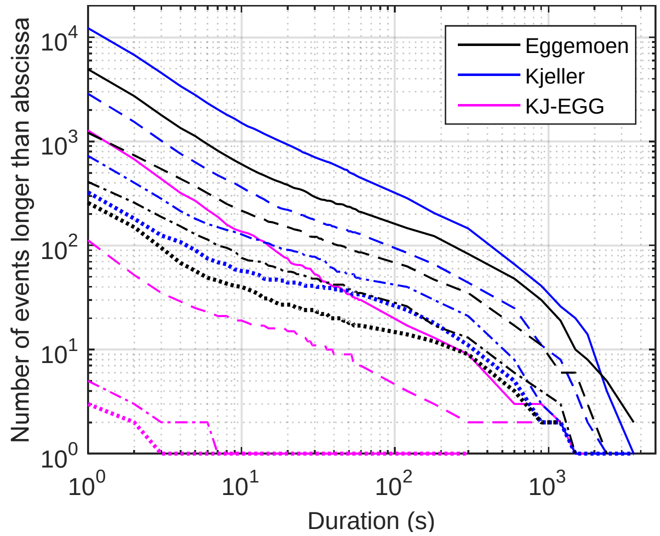

Fig.7. Fade duration for Eggemoen and Kjeller and their selection diversity combination for 3 (-), 5 (--), 8 (-.) and 10 (..) dB fade levels for 2 years.

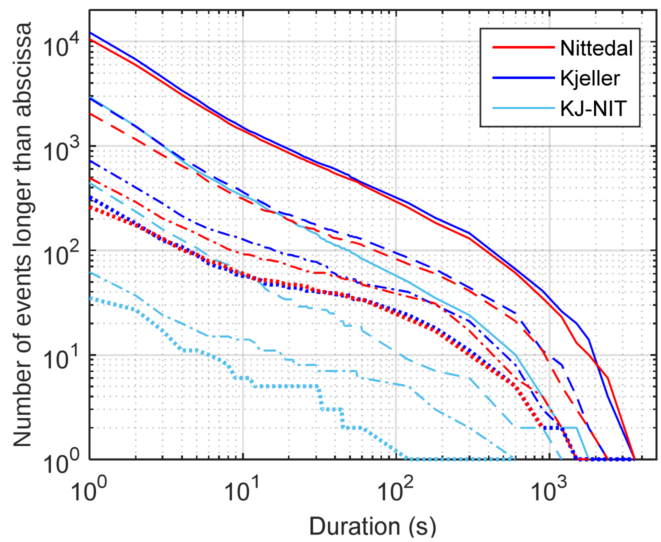

Fig.8. Fade duration for Nittedal and Kjeller and their selection diversity combination for 3 (-), 5 (--), 8 (-.) and 10 (..) dB fade levels for 2 years.

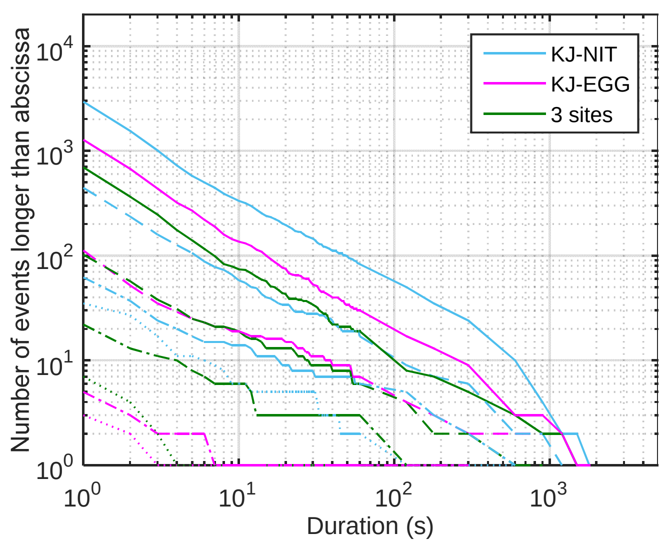

Fig.9. Fade duration for Kjeller-Nittedal and Kjeller-Eggemoen combinations compared with 3-site diversity for 3 (-), 5 (--), 8 (-.) and 10 (..) dB fade levels for 2 years.

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double exponential function was utilized in [19], and a double lognormal distribution was used in [20] and [21]. However, no model currently exists for describing the joint fade duration statistics of diversity links.

In the model used in [20] and [21] the probability of fade duration t longer than T s, given that the attenuation a is greater than A dB is given by

$$P(t \geq T|a > A) = \alpha \cdot \frac{Q\left(\frac{ln(T/m_s)}{\sigma_s}\right)}{Q\left(\frac{ln(T_{min}/m_s)}{\sigma_s}\right)} + (1-\alpha) \cdot \frac{Q\left(\frac{ln(T/m_r)}{\sigma_r}\right)}{Q\left(\frac{ln(T_{min}/m_r)}{\sigma_r}\right)}, \quad (1)$$

where Q is the standard complementary cumulative distribution function for a normally distributed variable, defined as

$$Q(z) = \frac{1}{\sqrt{2\pi}} \int_z^\infty exp\left(-\frac{1}{2}x^2\right)dx. \quad (2)$$

Parameters m_s and σ_s are the mean and standard deviation of the first lognormal function that describes fade durations due to atmospheric turbulence. Parameters m_r and σ_r are the mean and standard deviation of the second lognormal function that describes fade durations due to the space-time variations of rain. Parameter α defines the fractions of fades associated with each lognormal function, and T_{min} is the minimum duration period.

Fig. 10 shows a comparison of the modelled fade durations as given by the model in (1) using the coefficients given in [21]. The parameters used are those given for locations below 50° of latitude. The modified parameters for locations above 50° did not give good fit; this is probably caused by the limited number of measurements used to obtain them in [21]. The values for 3 dB fade level show very good agreement with the measurements while at the higher fading levels the predicted number of fades is higher than measured. However, the shape of the distribution agrees very well with the model.

A model with the same structure as in (1) was fitted to the measured joint fade duration statistics of the diversity links to investigate the applicability of such a model for link diversity. The results for the Kjeller – Nittedal diversity link are shown in Figure 11. We can clearly observe that a double lognormal model fits well the measured joint fade duration statistics of the diversity link. Similar results were also observed for the other two combinations.

From the large spread of fitted model parameters for all combinations in Table I it is clear that a larger set of measurement data is needed to infer a set of model parameters applicable for a wide range of scenarios. However, observing that the fade duration distribution for a diversity combination has similar shape as the distribution for single site (see Figs. 7 and 8), we can define fade duration improvement ratio for a given fade level A as

$$IM_{FD}(T,A) = \frac{NF_S(T,A)}{NF_D(T,A)} \quad (3)$$

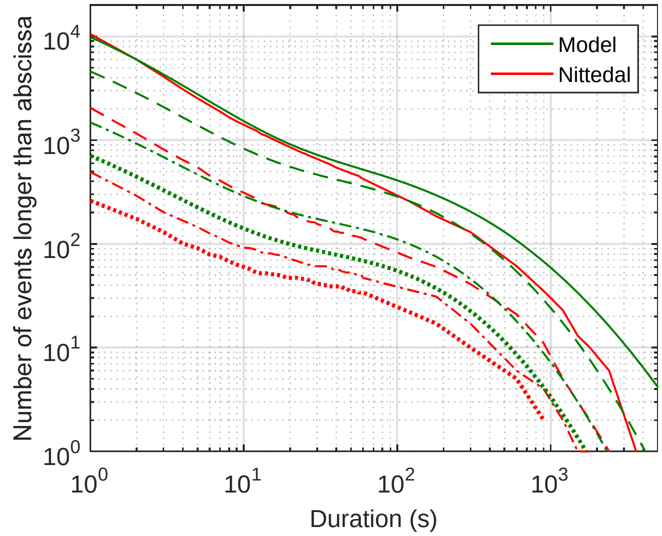

Fig.10. Double-lognormal model [21] for fade durations for Nittedal for 3 (-), 5 (--), 8 (-.) and 10 (..) dB fade levels for 2 years.

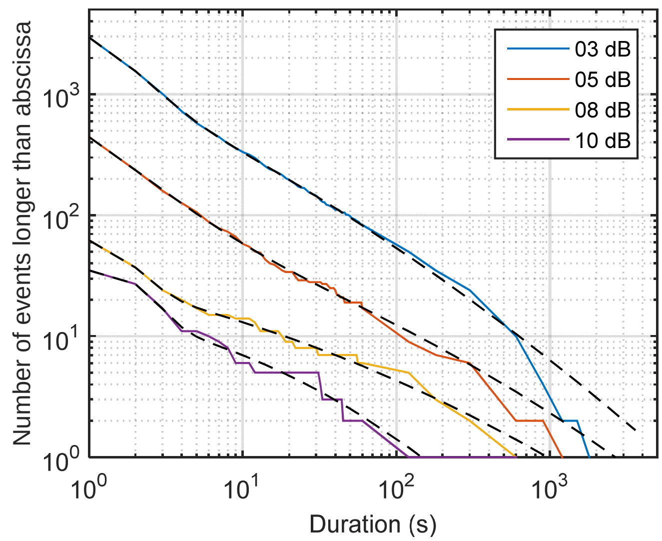

Fig.11. Double-lognormal fit (--) for fade durations for the KJ – NIT combination for 2 years.

where $NF_S(T)$ is the number of fades longer than T for single site and $NF_D(T)$ is the number of fades longer than T for a diversity combination. For the combinations measured in this paper the ratio was close to constant for all fade lengths shorter than 300s and with a fade level of less than 5 dB. The measured values of IM_{FD} at the 3 and 5 dB fade levels were 5 and 7.5 for NIT-KJ (23 km), 8.4 and 7 for NIT-EGG (29.7 km) and 14 and 20.6 for KJ-EGG (50.1 km). Note that the number of fades at Eggemoen was much lower than on the other two sites, which affects the results.

V. IMPACT OF SELECTION COMBINING SCHEMES

The ideal selection diversity investigated in Sections III and IV gives theoretically best achievable results. Since this scheme always selects the site with strongest signal it either needs to have both stations operational at the same time, which is not always possible or desired, or it needs instant switch-over between these two with no adverse effects. If the links are affected by strong scintillation effects the number of

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switch-overs can be quite high. While instant switch-over might be achievable in some systems, often it will impose some penalty, for example short breaks in the transmission or need for additional guard intervals [2]. It is therefore interesting to investigate how the first and second order diversity statistics are affected by some switch-over algorithms.

TABLE I
MODEL COEFFICIENTS

	Thr.	α	m_s	σ_s	m_r	σ_r
KJ-NIT	3	0.478	-0.002	3.764	1.038	0.784
	5	0.142	6.004	2.608	-0.003	2.532
	8	24.232	0.192	2.644	0.299	2.503
	10	0.522	-1.012	2.626	2.329	0.312
KJ-EGG	3	0.624	7×10^{-6}	4.328	1.023	0.800
	5	2.169	3.69×10^{-4}	3.645	2.450	1.242
	8	78.711	1.455	2.498	1.641	2.442
	10	73.449	-3.658	2.193	3.987	2.132
NIT-EGG	3	0.053	-130	1.417	0.087	0.019
	5	0.106	28.455	2.083	0.030	2.256
	8	0.403	-4.423	2.412	1.576	0.583
	10	12.336	3.901	0.951	4.288	0.886
3 site	3	1.063	-1.5×10^{-10}	5.288	9.784	0.550
	5	1.374	5.7×10^{-7}	4.847	4.569	1.033
	8	22.244	3.6×10^{-12}	9.313	5.56×10^{-9}	8.214
	10	12.430	-5.521	0.997	-6.123	0.906
NIT (model)	3	0.939	0.348	1.754	169.6	1.375
	5	0.911	0.348	1.754	169.6	1.136
	8	0.895	0.348	1.753	169.6	1.056
	10	0.891	0.348	1.753	169.6	1.035

NIT model values are as given in [20], for locations below 50° latitude.

A. Two site combination - Example

For the two site combinations three different switch-over methods were investigated:

1) *Threshold (TH) + Time (TM)*
Switch-over between the sites is executed, if attenuation at the current site exceeds a set threshold for a chosen number of seconds. If both sites are above attenuation threshold the site with lower attenuation is chosen. The time delay is added to avoid frequent switching when the attenuation is very close to the threshold.

2) *Threshold + Instant*
A different station is chosen immediately after a given threshold is exceeded. Once above the threshold the site with minimum attenuation is always selected. This scheme is meant to represent close to ideal selection diversity for a given threshold.

3) *Threshold + Time + Fade-slope (FS)*
After crossing the threshold level a switch-over occurs when the current fade-slope exceeds a given value. If that does not happen the switch-over occurs latest after a chosen number of seconds (just like in 1)). This scheme aims to enable faster switch-over at the start of high attenuation events compared with scheme 1), while avoiding switches due to noise-induced variations. Fade slope is calculated as a difference between mean level in the last 2 second period compared with the mean of the preceding 2 seconds.

Numerous values for the threshold, time and fade slope settings were tested. In Figs. 12 to 19 an example of their impact on the KJ-EGG two-site diversity combination is shown. In Fig. 12 it can be seen that the diversity attenuation closely matches the ideal selection combining scheme for the lower thresholds. For the higher thresholds there is some increase in attenuation levels but the values for a given probability are still much lower than single site levels. The different tested switch-over schemes have limited impact on the attenuation statistics; this is especially true for the 3 and 5 dB thresholds.

The different switching methods have, however, significant impact on the number of switch-overs, especially for the lower thresholds. As an example, in Fig. 13 the number of switch-overs at the 3 dB threshold is reduced from 4231 to 291 by changing the switching method. Fig. 14 shows the number of inter-switch periods (time spend at one station before switching to the other) of a given duration for the different threshold and switching methods. In the case of the instant switching method, the majority of switch-overs are very closely spaced, with short periods spend at each site. The methods that utilize Time delays and/or Fade slope avoid this problem and therefore reduce both the total number of switch-overs and the number of short periods at each site. See Section VI for more detailed explanation.

The impact a switching method has on the fade durations of the KJ-EGG combination is shown in Fig. 15. In cases where the switch-over threshold is much higher than the fade level, the fade duration statistic is close to the single-site case. For

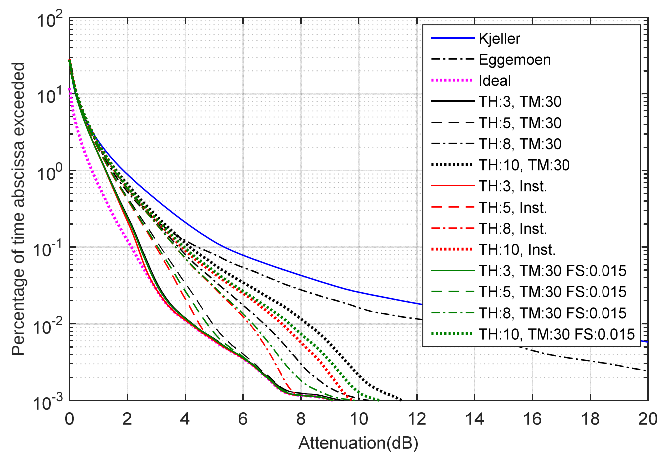

Fig.12. Attenuation for the different combining schemes for KJ-EGG combination.

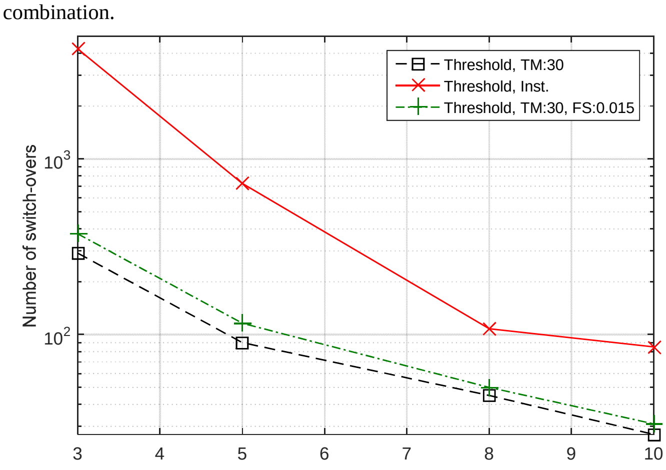

Fig.13. Number of switch-overs for the KJ-EGG combination, using different switching schemes. Note that the numbers are for two years of measurement.

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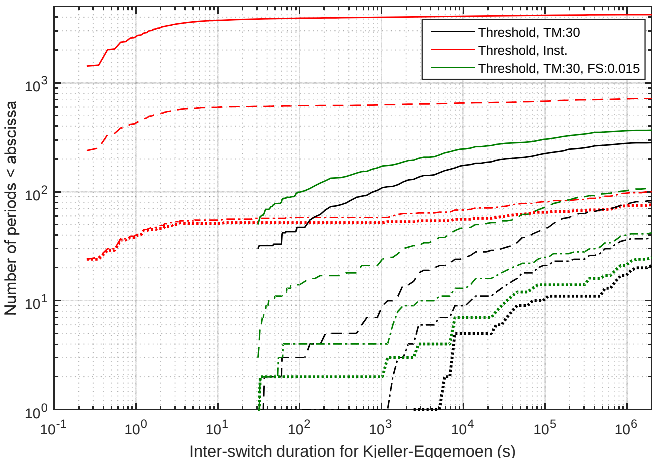

Fig.14. Inter-switch duration for KJ-EGG combination for 2 years, using the different switching schemes for 3 (-), 5 (--), 8 (-.) and 10 (..) dB switching thresholds.

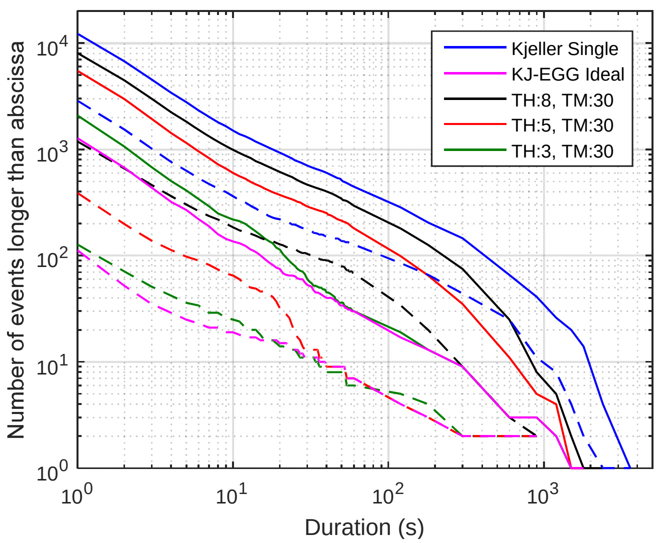

Fig.15. Fade duration the KJ-EGG combination for 3 (-) and 5 (--) dB fade levels using ideal switching and Threshold+Time scheme for 2 years..

equal switch-over threshold and fade level values the 30s Time Limit used in this case clearly reduces the number of longer fades, however, the number of fades shorter than 30 s is also significantly reduced (see Fig. 7 for comparison). For thresholds much lower than the fade level the fade durations are nearly identical to the ideal switch-over case.

B. Three site combination

The effects of a switch-over scheme on the 3 site combination are shown in Figs. 16 to 19. The scheme used was similar to threshold + time used in the previous section. A switch-over was initiated if the attenuation level was above certain threshold over a given period of time; the station with least attenuation at that instant was put in use instead.

From Fig. 16 it is clear that the attenuation statistics are nearly identical to the two site KJ-EGG combination for all but the highest switch-over thresholds. The number of switch-overs is also similar with the 3 site combination, experiencing slightly larger number of switch-overs at lower thresholds.

Inter-switch duration statistics in Fig. 18 show that for 5, 8 and 10 dB switching thresholds the 3 site combination experiences more short periods at one station before a switch-over is made again. This extra switching results in some

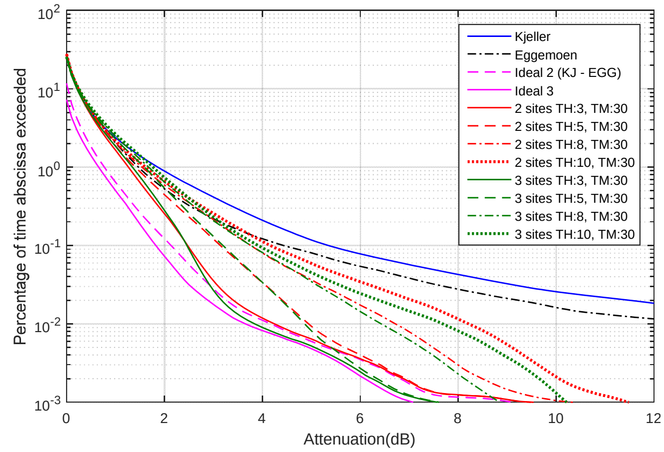

Fig.16. Attenuation for the 3-site combination using different thresholds compared with KJ-EGG combination.

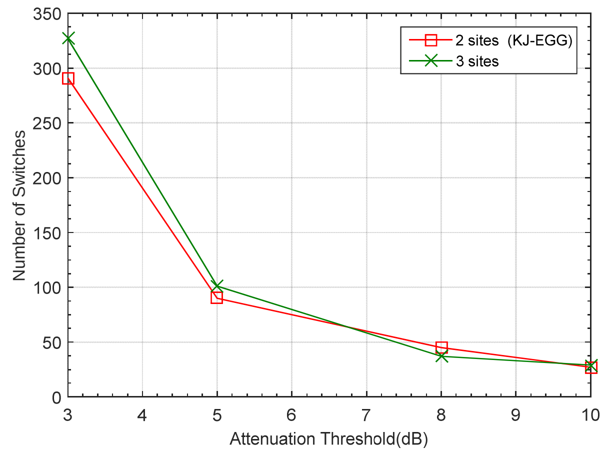

Fig. 17. Number of switches for the 3-site combination compared with KJ-EGG for different thresholds.

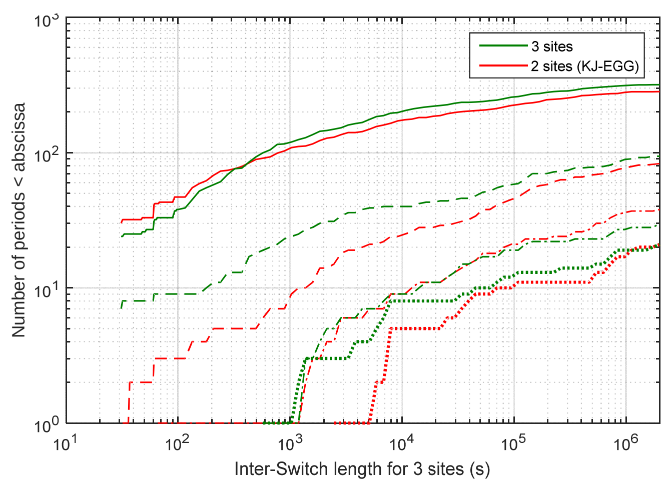

Fig.18. Inter-switch duration for the 3-site combination KJ-EGG for 3 (-), 5 (--), 8 (-.) and 10 (..) dB switching thresholds.

reduction in the number and duration of fades as shown in Fig. 19, but the effect compared with the KJ-EGG combination is again minimal.

VI. Discussion

In [22] it was pointed out that there was no available commercial system for seamless switch-over in a diversity setup at that time. While a TDMA system can be designed to

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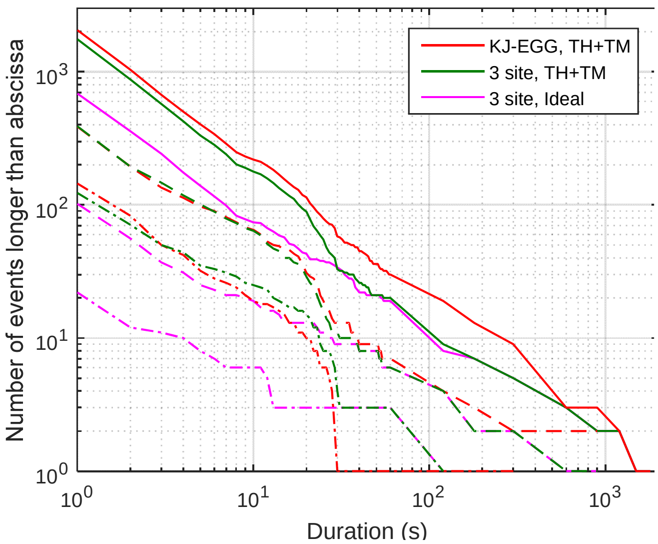

Fig.19. Fade duration for the 3-site combination for 3 (-), 5 (--) and 8 (-.) dB fade levels using ideal switching and Threshold+Time switching schemes for 2 years. Only combinations with same switching thresholds as the corresponding fade level are shown.

execute a switch-over during pre-defined intervals without adverse effects, the results analyzed in this paper show that by using moderate thresholds and time delays it is possible to drastically reduce the number of switch-over operations and thereby reducing the need for such a system. This is true as long as there is enough margin available to overcome very short duration attenuation events (less than a few seconds), which are typically caused by scintillation and are also affected by the signal to noise ratio of the measurement.

For an example, as can be seen in Figs. 12 and 13, a system based on the Kjeller-Eggemoen combination with a margin of 5 dB ideal diversity scheme reduces the outage time from 0.08 % of an average year (420.5 min) to 0.006 % (31.5 min), however at a cost of some 4 million switch-overs per year. Large number of the fast switch-overs occurs when the mean attenuation at both sites is comparable. Addition of a threshold value reduces this to only periods where attenuation at both sites is above the threshold value. A scheme that executes a switch-over only after a threshold of 5 dB is exceeded at one of the stations reduced the number of switch-overs to 363 with no effect on the outage time. Adding a 30 second delay before a switch-over is started, reduces the number of switch-overs further to 45 at the cost of increasing the outage time to 0.009% (47 min). From Fig. 14 we can see that out of the 363 switch-overs for the instant switch-over scheme, some 200 are separated by less than 1 second and can, depending on the coding/interleaving used, cause problems to some services. These short switch-overs, caused mostly by scintillation are removed by the addition of a switch-over delay which ensures that switch-over is done first when attenuation at one site is consistently higher than the other.

The short switch-overs could also be avoided by using averaged/filtered attenuation data. However, this requires additional margin for the effects of scintillation whose amplitude changes significantly even during the course of a single day. In the shown approach this margin is included in the threshold itself and continuously traded between scintillation and rain/cloud attenuation.

When using a single set of modems a further reduction of the adverse effects of switch-over is possible by carefully adjusting the electrical path length so that it is equal for both antenna sites. In a TDMA system a switch-over will then ideally lead to a loss of a single frame. With a typical frame length of 400 ms the 45 switch-overs will then cause only 18 additional seconds of outage.

VII. Conclusions

In this paper, we have presented results from two years of a three-site diversity beacon measurement at 19.68 GHz in the south of Norway. The sites were separated by 23, 29.7 and 50.1 km, and positioned approximately on a straight line in an area where spatial correlation of rain has previously been extensively studied [13].

Rain-rate measurements during these two years were comparable with long-term values from ITU-R. Single-site attenuation measurements at all sites show good agreement with ITU-R models, with slightly higher attenuation levels recorded at Kjeller compared with the other two sites. The measured attenuation exceeded for 0.1 % of time was on the order of 5 dB and for 0.01 % of time on the other of 15 dB, with high attenuation events occurring only during the May-September period.

Employing the sites in a diversity combination leads to significantly reduced attenuation levels. Even for the shortest separation distance (23 km) the rain attenuation is decorrelated sufficiently to avoid nearly all high-attenuation events. Addition of a third station between two existing ones gives close to no additional improvement. For all combinations, the measured diversity gain shows excellent agreement with the ITU-R model for the two years of measurements. Due to yearly variations, this does not guarantee equally good fit for long-term statistics, especially since the concurrent availability of all 3 measurements was 81%.

Fade duration statistics for each site as well as for the 2- and 3- site diversity combinations were presented. Significant reduction in the number of fades of all fade lengths and at all fade levels was measured for all combinations. For fade duration statistics the addition of a third station leads to a reduction in fade numbers at some fade levels.

Both the single-site and diversity fade duration statistics can be modelled using a double-lognormal distribution. The single-site model utilizing the coefficients found by fitting a large number of measurements in [21] shows good agreement for the lower fade depths while predicting significantly higher number of deep fades. The ratio between the number of fades for single site and a diversity combination was found to be approximately constant for the lower fade depths at short to medium durations. Further data from different locations are needed to develop reliable model parameters. However, the authors are aware of only one different dataset [10]. The ITU-R SG3 database does not collect second order statistics for diversity combinations.

Impact of non-ideal diversity switch-over scheme both on attenuation and fade duration statistics was investigated. A simple switch-over scheme based on an attenuation threshold and a timer had minimal negative effect on the diversity attenuation statistics while drastically reducing the number of

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switch-overs between the stations. Fade duration statistics for such a scheme were also only marginally worse than those for perfect ideal switch-over. Three-site diversity did not offer significant improvement over the two-site combination with largest separation distance in this scheme.

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