Detection of sleet attenuation in data series measured on microwave links

Balázs Héder, András Bertók

Budapest University of Technology and Economics,
Broadband Infocommunications and Electromagnetic Theory

balazs@mht.bme.hu

Radio wave propagation on terrestrial high frequency microwave point-to-point links is highly influenced by atmosphere effects, especially by the attenuation of precipitation. Usable models exist for considering rain attenuation, but the statistics of rare sleet events are less known. Our measurements on microwave links makes it possible to model the sleet attenuation. Sleet events can be automatically detected with an algorithm which exploits the important differences between the second order statistics of rain and sleet attenuation time functions. This enables to easily separate and collect sleet events, which is essential for model constitution in the near future.

1. Introduction

High frequency microwave links are frequently used in the core network of mobile cellular systems or in any point-to-point or point-to-multipoint terrestrial or satellite systems, so they can be employed as physical links even in a multilink network [1]; however, because of the applied high carrier frequency (above 10 GHz) the wave propagation is highly influenced by precipitation especially by rain and, due to the high precipitation attenuation, the microwave link can even be terminated. In this frequency band mainly the rain and sleet cause significant attenuation, against which different fade mitigation techniques (FMT) must be applied as countermeasure methods. In order to design suitable FMT e.g. to plan fade margin, information about statistics of expected rain attenuation is highly important. Rain attenuation can be well predicted using the model described in detail in ITU-R recommendation [2], but no usable sleet attenuation model is known in the literature.

Until now no special attention has been paid to modelling attenuation of the rare sleet events which occur especially in winter, although sleet can cause much higher attenuation than rain in case of the same intensity [3,4]. Therefore it is essential to develop a model which can be applied during planning of microwave links.
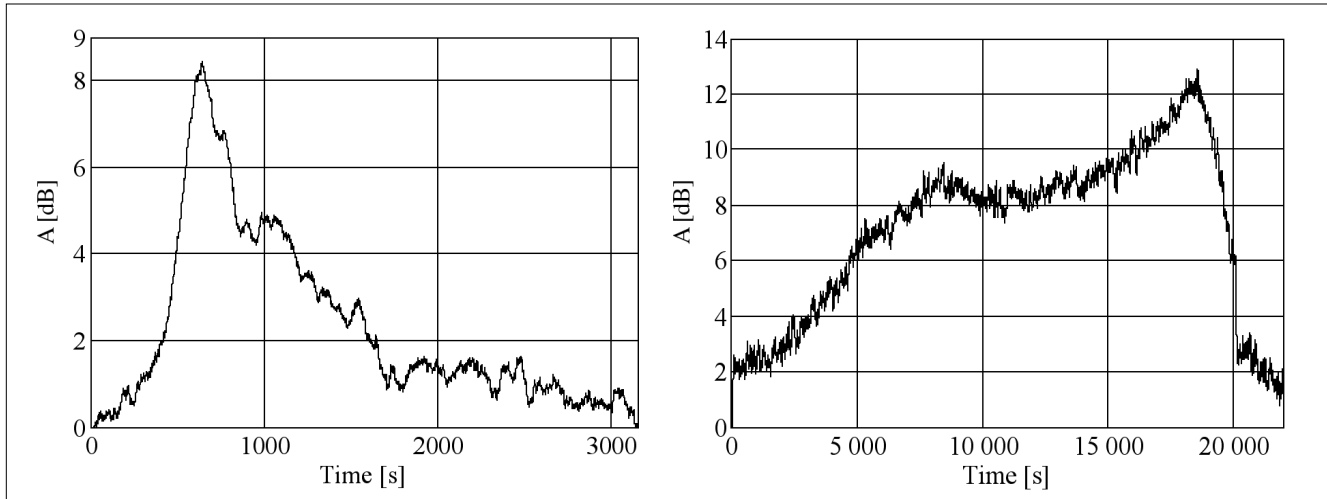
To investigate wave propagation phenomena, a country-wide rain attenuation and weather data measurement system was established in Hungary. A lot of point-to-point millimetre wave links were deployed in star topology for research purposes and meteorological stations were installed at each measuring node [5]. Parameters of links which are investigated in this paper are listed in *Table 1.*

The received IF signal level on microwave links with different parameters and some meteorological parameters, such as rain intensity, temperature, relative humidity etc. measured by the meteorological stations have been being stored since 1997, so sleet attenuation effect could be modelled using our many years measured data, if it would be possible to determine its statistical characteristics by processing appropriately high number of unique events.

It is possible to assort sleet attenuation events from measured data; because time functions of sleet and rain attenuation can be visually distinguished. An usu-

City	Name	freq. [GHz]	length [km]	pol.	k	α
Budapest	HU11	38	1.50	H	0.315	0.955
Miskolc	HU45	38	1.52	V	0.279	0.943
Győr	HU52	38	2.97	V	0.279	0.943
	HU53	23	8.49	V	0.095	1.044
	HU55	38	2.93	V	0.279	0.943
Szeged	HU61	38	3.27	V	0.279	0.943
	HU66	38	2.86	V	0.279	0.943
Budapest	Reference	23	1.00	V	0.095	1.044

Table 1. Parameters of investigated links and of the reference link

(a) Rain attenuation event measured on HU45 link   *(b) Sleet attenuation event measured on HU45 link*
Figure 1. Sleet and rain attenuation as a function of time

al rain event causes lower attenuation than an usual sleet event and the duration of usual rain is smaller than that of usual sleet. Differences between the two types of events can be noticed in *Figure 1*. Both events were measured on HU45 link, so it can be observed that attenuation of sleet is indeed higher than that of rain and the sleet event is much longer than the rain event.

However, sleet events are very rare, therefore collecting appropriately high number of sleet events requires visually browsing a huge amount of measured data, which is exhausting and consumes a lot of time. Automatic detection of sleet events would make this work much faster and easier. After analytically formulating the visually noticeable differences between sleet and rain attenuation events, sleet events can be detected automatically with a suitable algorithm.

2. Data processing

To investigate characteristics of attenuation events the available measured data had to be processed. First the attenuation data series were calculated from the measured received IF signal level data series considering the median level as zero dB attenuation. Rain events with the same intensity cause different attenuation on microwave links with different parameters (Table 1).

The relative rain attenuation γ can be calculated with (1) from the rain intensity R in mm/h and the k and α frequency and polarization dependent variables [2]:

$$\gamma^{[dB/km]} = k \cdot R^{\alpha} \qquad (1)$$

Due to the link parameter dependency on relative rain attenuation, the attenuation time series measured on microwave links with different parameters cannot be compared directly. Therefore the measured attenuation values had to be transformed to a hypothetic reference link which has known parameters. Transformation was performed with (2) which is derived from the

ITU-R P.530 recommendation [6] using (1). Parameters of the reference link are listed in Table 1.

$$A_h = \frac{L_h k_h}{1 + \frac{L_h}{d_{0,h}}} \left(\frac{A_x \left(1 + \frac{L_x}{d_{0,x}} \right)}{L_x k_x} \right)^{\frac{\alpha_h}{\alpha_x}} \qquad (2)$$

The lower index x in (2) is related to the measured link whereas the lower index h is related to the hypothetic reference link; A denotes the attenuation in dB, L is the link length in km and d_0 is the path reduction factor [6]:

$$d_0 = 35 \cdot e^{\left(-0.015 \cdot R_{0.01}\right)} \qquad (3)$$

In (3) the geometrical location dependent $R_{0.01}$ means the rain intensity value in mm/h which is exceeded in 0.01 percent of one year time period on the microwave link. Applying many years of measured data, ITU determined $R_{0.01}$ values for different locations on the Earth; however, the recommended $R_{0.01}$ can be refined using local measurements. Hungary is located in the H and K zones defined by ITU, for which 32 mm/h and 42 mm/h $R_{0.01}$ values are given, respectively [7,8].

By calculating the d_0 values we used interpolated $R_{0.01}$ values based on ITU recommendation and the hypothetic reference link was assumed to be located in Budapest. It must be mentioned that the measured data series contain sleet events as well and (1) cannot be applied for sleet events. However, a fictive rain with a fictive intensity can be considered which would cause the same attenuation event as caused by the sleet. With this remark sleet events can be also transformed by (2) considering $R_{0.01}$. In order to remove the scintillation effect from measured data, a moving average filtering was applied with a window length of one minute. Although the filtering mitigates the maximum measured values, it does not modify the characteristics of the events.

3. Second order statistics of attenuation

Fade duration and fade slope are relevant second order statistics of fading; they are used for the purpose of planning microwave links. Fade slope is the first derivative of fading attenuation time function [9]:

$$\varsigma^{[dB/s]}(t) = \frac{dA(t)}{dt}, \tag{4}$$

where $\zeta(t)$ is the fade slope in dB/s, $A(t)$ denotes the attenuation in dB as a function of t time in seconds. Because the measured attenuation series is discrete in time, the discrete fade slope $\zeta[t_n]$ is determined by (5) where t_n is the nth sampling time instance and Δt is the time interval over which fade slope is calculated.

$$\varsigma^{[dB/s]}[t_n] = \frac{A\left[t_n + \frac{\Delta t}{2}\right] - A\left[t_n - \frac{\Delta t}{2}\right]}{\Delta t} \tag{5}$$

In practice the conditional probability density function $P(\zeta|A_j)$ (CPDF) is usually determined [11,12], which is defined at the attenuation level A_j and derived from $\zeta[t_n,A_j]$ discrete fade slope values calculated around dA environment of A_j:

$$[t_n, A_j] = \tag{6}$$

$$\frac{A\left[t_n + \frac{\Delta t}{2}\right] - A\left[t_n - \frac{\Delta t}{2}\right]}{\Delta t} \bigg| A_j + dA \geq A[t_n] > A_j - dA$$

Fade duration gives the time interval during which the attenuation exceeds a given threshold [9,10].

Let $l_{e,j}$ denote the fade duration in seconds of event e at attenuation level A_j, which is the length of the interval during the e fading event in which the attenuation exceeds the A_j level. Considering the $\lambda(.)$ function, which gives the length of its argument in seconds, $l_{e,j}$ is calculated by (7). Fade duration statistics are usually demonstrated by their probability distribution:

$$l_{e,j} = \lambda\left(e : A > A_j\right) \tag{7}$$

Some differences can be noticed between second order statistics of rain and sleet events. As shown in *Figure 1*, a usual rain event has smaller length than a usual sleet event, therefore their fade duration statistics must be significantly different. At the end of the sleet event attenuation abruptly decreases to around 0 dB. Such behaviour cannot be noticed in case of rain attenuation event.
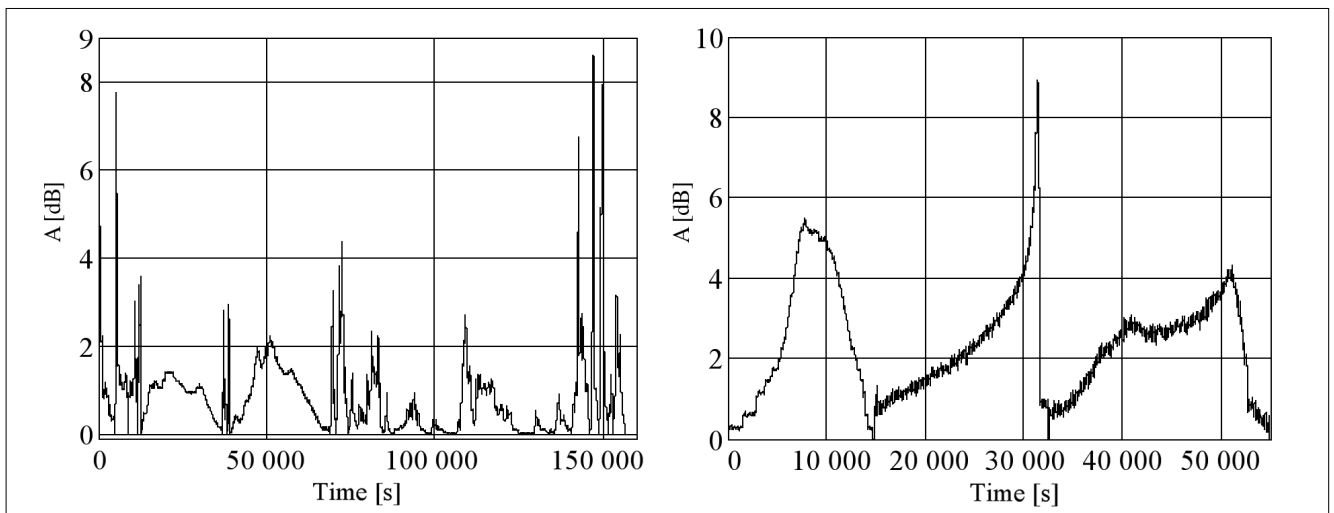
Consequently, fade slope statistics of rain and sleet attenuation must be different as well. Exploiting these differences, sleet and rain events can be recognized in a measured attenuation time series using an appropriate computer program. It must be mentioned that our goal is to detect as many sleet events as possible, therefore the false alarms, when there is a rain event in the measured data, but our algorithm decides for a sleet, are more tolerable in our case than the missed detections, when there is sleet in the measured data and it is decided for a rain event. After running the sleet detection algorithm, the miss-detected rain events can be easily filtered out manually from among the found sleet events.

4. Determining reference statistics

Statistics which are representative of the attenuation events can be calculated from our measured attenuation time series. The event detection algorithm compares the calculated second order statistics of the found event with the pre-calculated reference statistics. In order to derive the reference characteristics, two selections of attenuation events were prepared. One of them contains only some (processed and transformed) rain attenuation events; the other contains only some sleet events *(Figure 2)*. Reference statistics were calculated from these concatenated data series.

Four attenuation levels were defined on the transformed data series where the statistical investigation of fading was performed.

Figure 2. Selected rain and sleet attenuation events
(a) Concatenated rain events   *(b) Concatenated sleet events*

j	A_j [dB]	$E\{l_{r,j}\}$ [s]	$E\{l_{s,j}\}$ [s]	$l_{t,j}$ [s]
1	1	1320	3939	2500
2	1.4	1017	4719	2000
3	2	485	3796	1500
4	2.4	326	2572	1000

Table 2.
Expected values of fade duration
for rain and sleet events
and the duration thresholds

By defining the attenuation levels two conditions have to be satisfied: (i) all the selected events in *Figure 2* have to have values at all the defined attenuation levels in order to get as accurate reference statistics as possible; (ii) the fade slope and fade duration statistics of the selected events have to be different at the defined attenuation levels.

Choosing the empirical attenuation levels A_1=1 dB, A_2=1.4 dB, A_3=2 dB, A_4=2.4 dB these necessary conditions are satisfied. First the reference fade duration statistics had to be calculated. Let $l_{r,j}$ and $l_{s,j}$ denote the length of the *r* rain event and of the *s* sleet event (i.e. the fade duration) at the A_j attenuation level, respectively, and let $E\{l\}$ denote the expected value of the duration.

The calculated expected values of fade duration for rain and sleet events are listed in *Table 2* for different attenuation levels.

Results are in accordance with our expectations: the expected length of rain events is much smaller than that of sleet events. Based on the calculated expected val-

ues a duration threshold $l_{t,j}$ was defined for every investigated attenuation level.

An event length higher than $l_{t,j}$ means that the event might be sleet, a lower length means that the event is probably a rain. By determining the thresholds special attention was paid to that the threshold must be closer to $E\{l_{r,j}\}$ at each attenuation level ensuring the minimal number of missed detections despite of more false alarms:

$$l_{t,j} < \frac{E\{l_{r,j}\} + E\{l_{s,j}\}}{2} \qquad (8)$$

The exact values of $l_{t,j}$ thresholds which are listed in *Table 2* were intuitively determined so that (8) was satisfied.

Reference statistics of the fade slope were also determined from the prepared concatenated time series which are depicted in *Figure 2*. The $P(\zeta|A_j)$ conditional probability density functions of the discrete fade slope at the $A_1...A_4$ attenuation levels were calculated with (6) considering dA=0.02 dB and Δt=2 s. Maximum values and standard deviations of $P(\zeta|A_j)$ highly differ at dis-
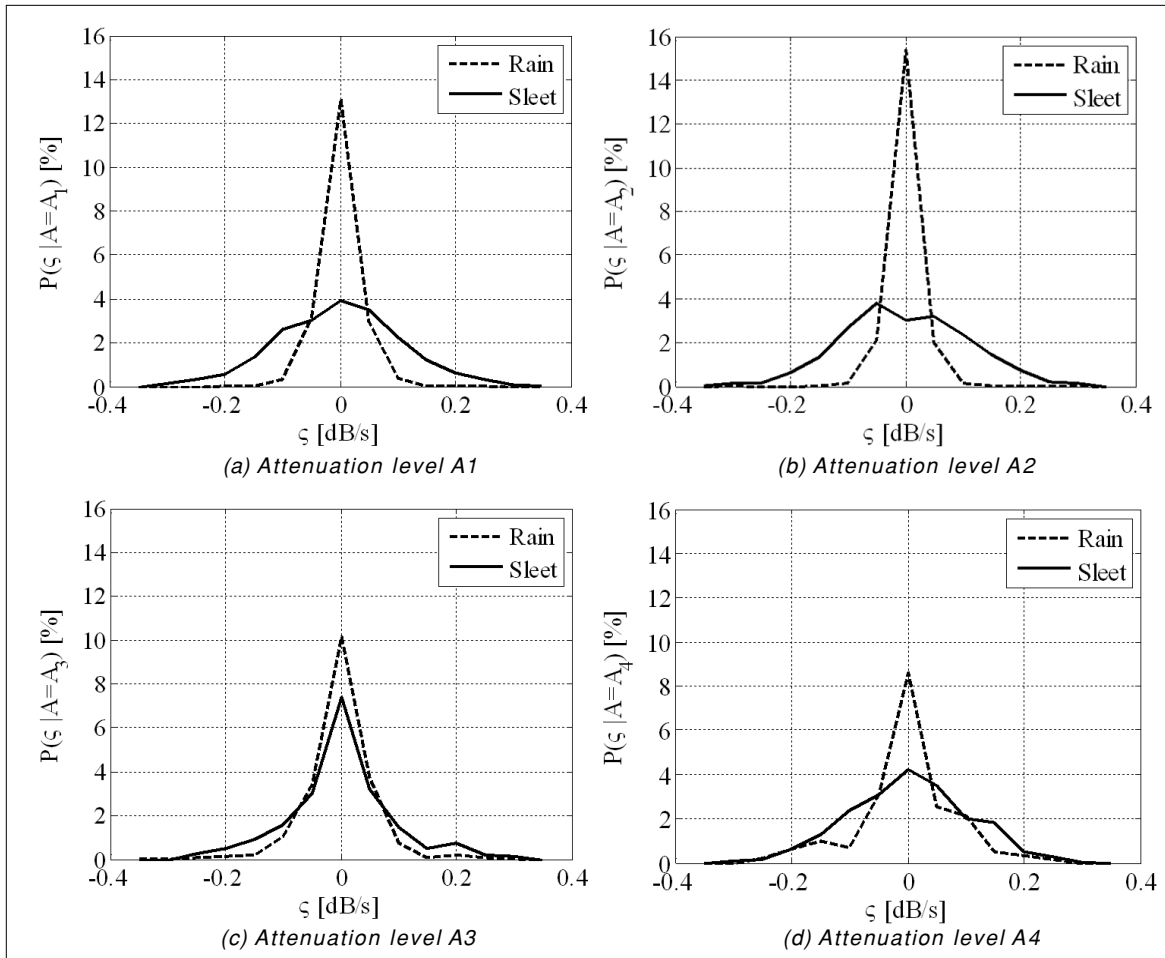

(a) Attenuation level A1

(b) Attenuation level A2

(c) Attenuation level A3

(d) Attenuation level A4

Figure 3.
Conditional
probability
density
functions of
fade slope
for different
attenuation
levels

tinct A_j levels. As shown in *Figure 3*, the calculated CPDFs correspond to the expectations. At each investigated attenuation level the maximum values of fade slope CPDFs that are calculated from the sleet event are smaller than the maximum values of fade slope CPDFs that are calculated from the rain events. Moreover, deviation of fade slope CPDF is higher in case of sleet events due to the rapid decrease of attenuation time function. It must be mentioned that the measured data series has a quantization step of 0.01 dB therefore discrete fade slope calculated with (6) has possible values of $k \cdot 0.05 / 2\,\mathrm{dB/s}, k \in N$. This results in less smooth fade slope CPDF curves as can be seen in Figure 3.

Let $m_{r,j}$ and $m_{s,j}$ denote the maximum of $P(\xi|A_i)$ in case of rain and of sleet event, respectively and let $\sigma_{r,j}$ and $\sigma_{s,j}$ denote the standard deviation of $P(\xi|A_i)$. Let us define $m_{t,j}$ as the CPDF maximum threshold. Higher CPDF maximum than $m_{t,j}$ means that the event might be a rain, otherwise it might be a sleet. Similarly let us define $\sigma_{t,j}$ as the CPDF deviation threshold. A deviation higher than $\sigma_{t,j}$ means that the event might be a sleet, otherwise it might be a rain. To minimize missed detections (9) and (10) must be satisfied by determining the thresholds.

$$m_{t,j} > \frac{m_{r,j} + m_{s,j}}{2} \qquad (9)$$

$$\sigma_{t,j} < \frac{\sigma_{r,j} + \sigma_{s,j}}{2} \qquad (10)$$

The maximum and standard deviation values of fade slope CPDFs which are depicted in *Figure 3* and the applied $m_{t,j}$ and $\sigma_{t,j}$ thresholds are summarized in *Table 3*. The $m_{t,j}$ and $\sigma_{t,j}$ thresholds were intuitively determined so that (9) and (10) were satisfied.

5. Event detection algorithm

The suitable algorithm which can be applied for automatically detecting sleet events in the measured attenuation time series uses the previously determined reference statistics i.e. the $l_{t,j}$, $m_{t,j}$ and $\sigma_{t,j}$ thresholds. The flowchart of the algorithm is depicted in *Figure 4*. First of all the input data series in which we want to find sleets, have to be processed by the data processing method described in Section 2. After that the data series must be transformed to the hypothetic reference link with (2).

The computer program which uses this algorithm sweeps over the processed attenuation data series. In this paper our goal is to detect sleet events in a measured data, and as described in Section 1, sleet events
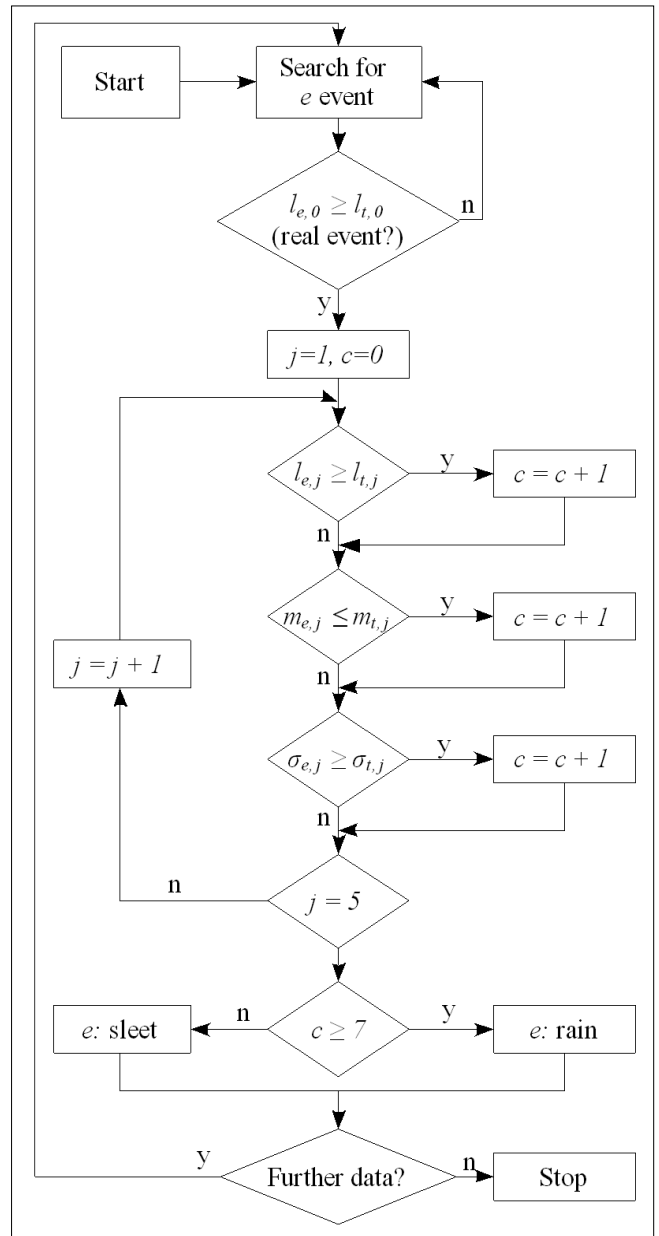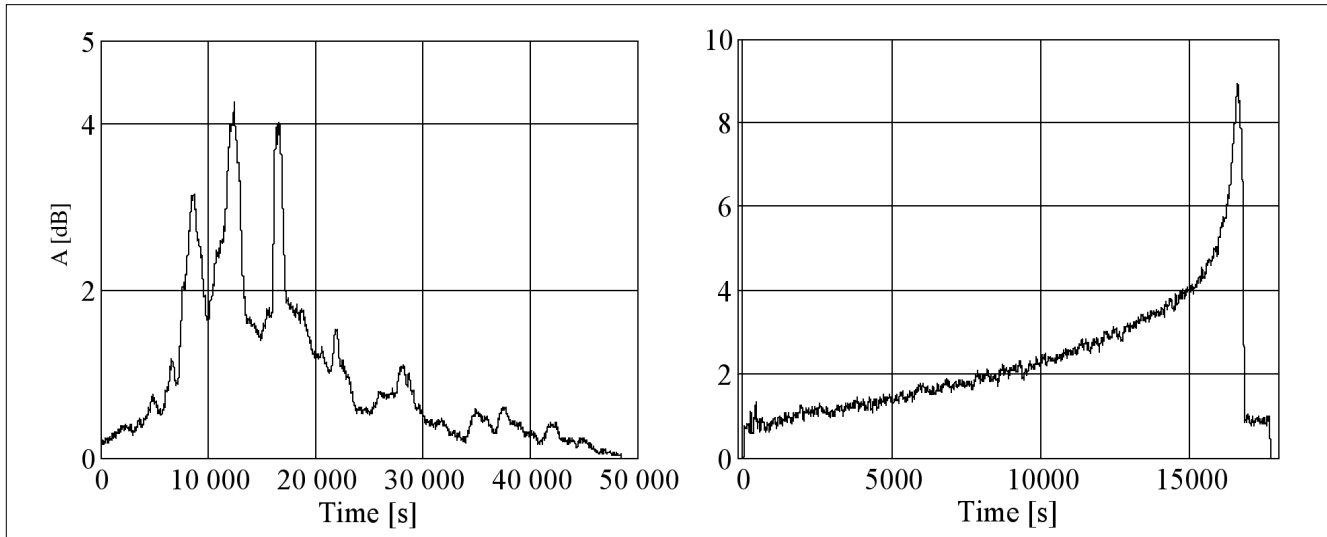

Figure 4. Flowchart of sleet detection algorithm

have quite high duration and cause significant attenuation. Therefore in our case real attenuation events, which are denoted by e are considered as rain or sleet events causing remarkable attenuation and having remarkable duration. So scintillation or very short rain events with very low rain intensity are not considered as real event. Based on the previous remarks, two empirical thresholds were defined, one for attenuation and one for duration, which are denoted with A_0 and $l_{t,0}$, respectively. If the algorithm finds a data series interval

Table 3. Maximum and standard deviation values of fade slope's conditional probability density functions and the defined $m_{t,j}$ and $\sigma_{t,j}$ thresholds	j	A_j [dB]	$m_{r,j}$ [%]	$m_{s,j}$ [%]	$m_{t,j}$ [%]	$\sigma_{r,j}$	$\sigma_{s,j}$	$\sigma_{t,j}$
	1	1	13.1	3.9	9.5	0.0036	0.0109	0.006
	2	1.4	15.4	3.1	9.5	0.0031	0.0113	0.0065
	3	2	10.2	7.4	9	0.0063	0.0093	0.007
	4	2.4	8.6	4.2	7	0.0097	0.0108	0.01

(a) Rain attenuation event measured on HU55 in 2004   (b) Sleet attenuation event measured on HU45 in 2004

Figure 5. Test attenuation events

in which the attenuation exceeds the defined $A_0 = 0.6$ dB level and whose duration of $l_{e,0}$ is longer than $l_{t,0} = 300$ s threshold this attenuation interval is defined to be a real e event. If a real e event is found, the algorithm starts to investigate it in details at the predefined A_j attenuation levels. The calculated $l_{e,j}$, $m_{e,j}$ and $\sigma_{e,j}$ parameters of the e event (i.e. the fade duration and fade slope statistics) are compared with the corresponding thresholds. One comparison at the current attenuation level is called as a test in our terminology. If the e event is assumed to be a sleet based on the current test, a c counter is incremented.

The algorithm examines the satisfaction of total 12 conditions at the 4 mentioned attenuation levels, so if $c \geq 7$ at the end of the event detection, the program decides for sleet, otherwise it decides for rain.

6. Verification results

Because of the quite small amount of the already collected sleet events, the first verification of the presented algorithm was performed on two short measured attenuation data series. One of them contains only one known and typical sleet event; the other contains only one but extraordinarily long (therefore not so typical) rain event. The time functions of the processed and transformed attenuation caused by the two events are depicted in Figure 5.

The rain event was registered in November 2004, whereas the sleet event was measured in January 2004.

The results of the tests are summarized in Table 4, where the black bullet symbol next to the test value means that the event detection passed the current test at the corresponding attenuation level, i.e. the event was recognized correctly. The black circle symbol means that the event detection failed the current test i.e. the event was not recognized. The value of the c counter after the event detection is also represented in Table 4. It can be noticed that although the test rain event seems to be a sleet on the basis of its length, the algorithm decided correctly for rain 8 times and decided incorrectly for sleet only 4 times ($c=4$), which resulted in a correct final detection. The test sleet event complied with all conditions ($c=12$), the program recognized it correctly. In the course of the event detection verification an extremely long rain event was chosen on purpose in order to demonstrate that theoretically in some cases the fade slope statistics are sufficient in themselves to correctly recognize the investigated event.

7. Conclusions

To be able to model sleet attenuation on microwave links it is essential to process as many sleet attenuation events as possible, which requires collecting these events from many years of measured data. Second order sta-

j	A_j [dB]	HU45, sleet						HU55, rain					
		$l_{e,j}$ [s]		$\sigma_{e,j}$		$m_{e,j}$ [%]		$l_{e,j}$ [s]		$\sigma_{e,j}$		$m_{e,j}$ [%]	
1	1	13790	•	0.0114	•	3.7	•	15564	○	0.0029	•	13.6	•
2	1.4	11149	•	0.0113	•	3.1	•	11997	○	0.003	•	12.7	•
3	2	7304	•	0.0113	•	2.6	•	2836	○	0.0037	•	10.4	•
4	2.4	5935	•	0.0111	•	4.2	•	2836	○	0.0036	•	12	•
c		12						4					

Table 4. Test results of sleet and rain detection

tistics of rain and sleet event's attenuation are highly different. With exploiting the differences sleet event can be automatically detected and collected by an appropriate algorithm.

In the work presented, some significant parameters of the event's second order statistics were determined, and then thresholds were defined in order to be able to distinguish the two types of events. The presented algorithm can detect sleet events in an arbitrary measured attenuation data series applying the pre-defined reference statistics. Our method was proven using known rain and sleet attenuation events. In the course of the verification both events were correctly recognized. It has been stated that fade slope statistics alone can be sufficient for detecting sleet events; however, in some cases fade duration statistics can make the recognition easier.

In order that our prepared program can find sleet events in arbitrary measured attenuation data with high reliability, the reference statistics need to be refined with considering as many rain and sleet attenuation events as possible.

Acknowledgement

Authors

BALÁZS HÉDER was born in Budapest, Hungary, in July 1980. He received in 2004 M.Sc. degree from Budapest University of Technology and Economics, in Electric Engineering. From 2004 until 2007 he was Ph.D. student at Budapest University of Technology and Economics, Department of Broadband Infocommunications and Electromagnetic Theory. From 2007 he is research assistant at the same place. He has actively participated to the Satellite Communications Network of Excellence (SatNEx) IST FP6 project. His current research interests include terrestrial microwave point to point and point to multipoint radio systems, especially broadband fixed wireless access systems (BFWA, LMDS), rain attenuation on millimetre band electromagnetic waves, diversity methods, Markov-chain modeling of rain attenuation, B3G systems.

ANDRÁS BERTÓK was born in Keszthely, Hungary, in February 1987. He will receive B.Sc. degree in 2010 from Budapest University of Technology and Economics, in Electric Engineering. He started research terrestrial microwave point to point radio systems, especially rain and sleet attenuation on high frequency electromagnetic waves from 2008 at Budapest University of Technology and Economics, Department of Broadband Infocommunications and Electromagnetic Theory.

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