E-band terrestrial radio – propagation and availability aspects

László Csurgai-Horváth and István Frigyes

Abstract— **This paper is focusing on the E-band terrestrial radio channel, especially on availability calculations and on the relationship between fade duration statistics and availability. This frequency band is applied in high speed data transmission links between endpoints at a distance of few kilometres. There is a high demand for such connections with high reliability features; mobile backhaul networks are good example for that. The main propagation impairment causing bursty drop-outs on the transmission links is rain. Based on our long term measurements we will show the availability characteristics of the E-band radio and propose a new method for availability calculations. We investigate the relationship between fade duration statistics and the availability as well.**

Index Terms— **E-band propagation, rain fading, path attenuation, availability, fade duration**

I. INTRODUCTION

THIS paper derives the availability characteristics of millimetre-band radio links established by E-band devices with high transmission speed, exceeding the Gbit/s rate. The demand for such connections is high and even increasing because the new broadband services like high-speed internet, multimedia services, etc. require higher and higher bandwidth and data transmission speed. However, rain as the main reason of channel degradation severely influences the quality of service and may cause unavailable periods during the transmission. Therefore in our paper we concentrate on the rain attenuation on terrestrial E-band radio connections, furthermore on its first and second order statistics. Based on long-term measurements we derive some of the channel's propagation and availability characteristics.

A comprehensive description of atmospheric effects that are significantly influencing the millimetre-band propagation channel can be found in [1]. Several calculation methods are detailed in this book, while the related ITU-R recommendations and standardized computation procedures are defined in [2]-[5]. In the beginning of our paper we summarize our latest results on terrestrial E-band propagation measurements and compare them with the related ITU-R path attenuation models.

In our paper one of the question that we focused on is the availability, thus the operation of the investigated E-band link at low input signal levels –near to the fade margin- is particularly interesting. The dynamic range of our measurement system is limited by the nature of the applied equipment. Therefore in order to increase the dynamic range and ensure to study the operation even during the deep fade events we apply some signal processing techniques [12] to reduce the noise floor and extend the observed measurement range. After data processing we approximate the upper tail of the measured attenuation distribution with an exponential function that serves to create a final closed form to estimate the required antenna diameter for a specific probability margin of interruption.

As the main scope of our interest is availability calculation, we apply the above mentioned dynamic range extension method to estimate the attenuation statistics in this frequency band. As the data processing technique and the first model constitution was already published in [8], besides the refinement of this model and using a longer measured dataset for higher precision, we are focusing on system availability calculations and prove the correctness of the relationship between interruption probability margin and the antenna diameter.

A second important question is in this paper the connection between fade duration statistics and the availability of the radio link. According to its definition, fade duration is the amount of time that the signal envelope stays below a specific level [5]. The distribution of fade duration at specific levels –especially around the fade margin- serves as an alternative method to calculate the availability of the radio system. It will be shown that the attenuation distribution and the fade duration statistics results similar values for the probability of interruption. Nevertheless, fade duration statistics comprise additional information about the nature of fading events. Therefore it can be used to indicate the number of bits or blocks that are affected by a fade event. This information is well applicable during the design of coding schemes for wireless channels [6].

This paper is organized in five sections. The introduction is followed by the description of the measurement environment, the discussion of the data processing method, comparing with

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the ITU-R recommendations and introducing the improved model for attenuation statistics. Section III derives the relationship between availability and attenuation statistics. In Section IV we study how fade duration statistics can be applied to estimate the availability. The paper ends with some concluding remarks.

II. E-Band Measurements and Statistics

Our measurements were performed on an experimental 72.56 GHz radio link [11], serving as part of the backhaul network of Telenor Hungary connecting a base station with the corresponding base station controller. The measured endpoint of the radio link was located in a dense built-in city area (Budapest) at the top of a building at a height of 102 m. The exact geographical position is N47.48° latitude and E19.06° longitude. Further technical parameters can be found in Table I.

TABLE I.
THE E-BAND LINK PARAMETERS

Frequency	72.56 GHz
Path length/Effective path length (d/d_{eff})	2.3/2.08 km
Transmit power	16 dBm
Antenna gain	44 dBi
Antenna diameter	31cm
Receive sensitivity	-61 dBm
Polarization	horizontal
Receiver noise figure (NF)	7 dB
Bandwidth at 1000Mbps (B)	1400 MHz
Minimum signal-to-noise ratio for BER<10^{-3} (C/N)	12 dB
Campaign period	05.2009-11.2012

During a 43 month measurement campaign we recorded the level of received power with 1 sample/sec rate. The median value of the received power level was -42.66 dBm; we applied this as clear sky level during the relating calculations. In Fig. 1 a weekly time series with typical rain attenuation events can be seen.

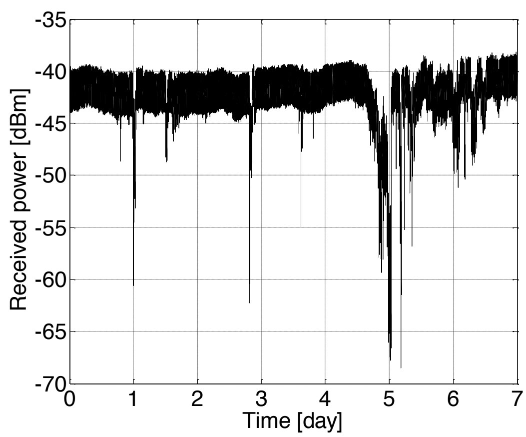

Fig. 1. One week received power time series with rain events

Considering the system maintenance periods, valid data was recorded in 84.2% time of the whole campaign. As the system was dedicated only for this measurement, there was no real data transfer on the radio link. This explains the relatively high outage rate caused by different other tests that we performed.

The clear sky level is the function of the transmitted power, transmitter and receiver antenna parameters and receiver gain. We considered these parameters as constant during the measurement campaign. The clear sky value is characterizing the actual measurement system and serves as a reference level for attenuation calculations.

The atmospheric scintillation and the constant but not negligible noise of some system elements (amplifiers, downconverters, etc.) cause a continuous, high-speed low-level variation of the received power. This variation will be removed by an appropriate filtering as it is detailed in Section IV. The reason of the observable high attenuation peaks is rain; other effects like interference, shadowing, multipath propagation is negligible due to the careful link design and the lack of interfering radio sources in this frequency band.

Generally a terrestrial radio link like the investigated one operates trouble-free as long as the attenuation is less than the fade margin of the system. The quality of the radio connection only decreases when the attenuation is high enough to reduce the received power level near to the receiver sensitivity. Therefore it is especially important to know the high-attenuation statistics of the received power time series. In order to increase the accuracy of the low-level signal measurement, we applied the noise subtraction method to reduce the noise floor and extend the dynamic range of our measurements [12].

The details of this method were presented in [8] therefore only by referring to this paper we apply its results. With (1) we can calculate the actual attenuation A_{actual} after the noise subtraction:

$$A_{actual} = \frac{A_{measured}}{1 - A_{measured}(N / P_{median})}, \tag{1}$$

where $A_{measured}$ denotes the measured attenuation, P_{median} is the clear-sky level, N is the noise power.

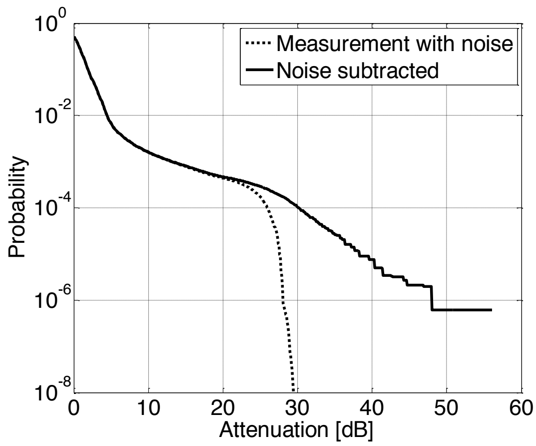

Fig. 2. Measured attenuation CCDF and its value after noise subtraction

Fig. 2 depicts the measured attenuation CCDF and the result of noise subtraction by using (1). The value of N/P_{median} can be determined from the vertical tangent of the measured data CCDF (Complementary Cumulative Distribution Function) at the highest observable attenuation. The noise subtraction significantly increases the dynamics in the high attenuation range that is very important for the forthcoming availability calculations.

To estimate the long-term statistics of rain attenuation, the recommendation ITU-R-P 530 [2] can be applied for E-band as well. We compared the ITU model-based rain attenuation CCDF with our measurements after noise subtraction (Fig. 3). As in the range of high attenuation, the two curves are rather different from each other, in [8] we proposed the following exponential approximation of the attenuation probability in the *A=33-45dB* range:

$$\begin{aligned} &\text{if } 33dB < A < 45dB: \\ &p_A = a \cdot \exp(-d_{eff} b \cdot A) \\ &a = 0.2991 \\ &b = 0.1281 \end{aligned} \tag{2}$$

In (2) a and b are empirical parameters, while d_{eff} denotes the effective path length [2]. Effective path length is the corrected value of the real path length and it is the function of frequency and the actual climatic zone. The validity of (2) is fairly high if we consider the long (43 months) measurement period, and accurately estimates the probability of the E-band attenuation in the higher range.

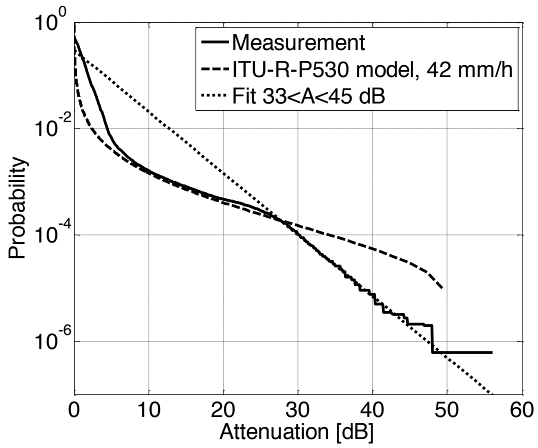

Fig. 3. Measured attenuation CCDF, the ITU-R approximation and the proposed exponential fit

For the ITU-R calculations the rain zone *K* [3] was applied with $R_{0.01}$*=42mm/h*, as this is recommended for the measurement location (Budapest).

III. ATTENUATION CHARACTERISTICS AND AVAILABILITY

The ITU-R F.1703 recommendation defines the availability objectives for the backhaul network [4]. In [9] the availability ratio is defined as *AR=0.9995 (99.95%)*. This value is significantly lower than the value required by different mobile operators (usually 0.99998). Based on our measurements firstly we determine the availability of the investigated E-band radio link.

The minimum required input signal for nominal operation can be determined from the physical link parameters (see Table I.). The value of the receiver threshold *Th* is the following [7]:

$$\begin{aligned} Th &= kT_0 + NF + 10\log B + C/N = \\ &= -174 + 7 + 91.46 + 12 = -63.54dBm \end{aligned} \tag{3}$$

This value yields the first estimation of the link availability. The difference between the threshold *Th* and the nominal received power (-42.66 dBm) is 20.88 dB. This value can be considered as the upper attenuation limit of the error-free operation. The distribution of attenuation after noise subtraction (see Fig. 2) is $4.06 \cdot 10^{-4}$ at 20.88 dB, resulting 99.9594 % link availability.

A different approach to calculate the availability is using the physical system parameters (path length, carrier frequency and system gain). In the following we will do such calculations and prove the method by comparing the result with our long-term measurement data.

For a given radio link the antenna is the most flexible component, therefore in [8] we constructed a practical equation to express the minimum required antenna gain G_A if we know the path length d, the carrier frequency f_C, and the system gain G_S. The main input parameter of the calculation is the p_m probability margin of interruption. The system gain can be expressed as the difference of the transmit power and the receiver threshold:

$$G_S = P_T - Th = 16dBm + 63.54dBm = 79.54dB \tag{4}$$

Applying (1) the final form to determine the minimal antenna gain for the required p_m interruption probability margin is (for details see [8]):

$$G_A^{dB} \geq \left(\begin{aligned} &32.44^{\text{dB}} + 20\log d^{km} + 20\log f^{MHz} + \\ &+ 0.3d^{km} - \frac{1}{bd_{eff}^{km}} \ln \frac{p_m}{a} - G_S^{dB} \end{aligned} \right) / 2 \tag{5}$$

By parameterizing the above equation with $p_m=4.06 \cdot 10^{-4}$, for the investigated link we get G_A*=41.4dB*. If we compare the antenna gain given by the manufacturer [11] (*44dB*), the precision of (5) is apparent.

IV. FADE DURATION STATISTICS AND AVAILABILITY

In this section we will derive the relationship between fade duration statistics and link availability. The distribution of fade duration is often called as second-order statistics of the attenuation process. According to its definition, fade duration is always considered at a specific attenuation threshold and it is the time interval between two crossings of the signal level above the threshold [5].

Fade duration statistics is an additional tool of radio link design engineers because it describes a different aspect of the propagation channel. The attenuation statistics informs us about the probability that the fading depth exceeds a specified level, but the length of the individual fade events and thus the possible outage periods cannot be determined with examining only the attenuation distribution. This can be demonstrated with the identical attenuation statistics for two different radio connections: one with several short fade events and another with less but longer fade events. This kind of channels may result different operational characteristics, therefore solely the attenuation distribution is not enough to describe them.

Fade duration can be characterized for example with the statistics of number the fade events longer than a specific duration. This kind of statistics can be seen in Fig. 4 for the investigated E-band link, depicting the most relevant (≥20dB) threshold ranges in point of view the availability. Before calculating the fade duration, the effect of scintillation (fast, low level fluctuation) should be removed from the measured time series, as proposed in [5]. According to the recommendation a low-pass filter can be applied with 3 dB cut-off frequency at 0.02 Hz to eliminate the scintillation and other rapid variations of rain attenuation. If scintillation and rapid variations of the attenuation process are not filtered out, the signal will exhibit stronger fluctuations and the fade duration statistics will be significantly different. During data processing we applied a 20 sec moving average filter that performs the recommended filtering process.

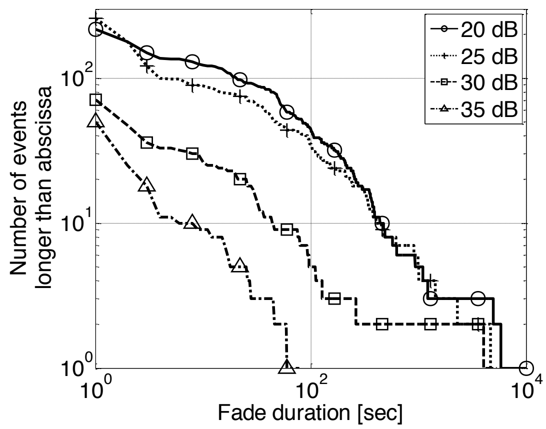

Fig. 4. Fade duration statistics based on 43 month measurements

In the previous sections it was shown how the long term attenuation statistics and the physical system parameters can be applied to estimate the availability for E-band radio.

While the system gain determines the maximal attenuation that can be allowed for a specific error probability, the fade duration statistics helps to determine the length of the unavailability periods and it may lead to different channel characterization aspects.

A. Availability and measured fade duration statistics

Rain with moderate intensity usually does not affect the quality of the radio connection if the attenuation stays below the fade margin. Therefore the length of deep fades becomes particularly interesting if a system operates near to the fade margin. Fade duration statistics is applicable to extract relevant data about the timing characteristics of the fading process and the behaviour of the individual fade events can be even better observed. In the following the statistics of the measured fading length will be shown at this threshold an above it, respectively.

We have seen in Section III that the attenuation threshold of the error-free operation is 20.88 dB, so the closest integer value, 21 dB will be also included in the following calculations. In Table II, the number of the fade events with a specific/or longer duration at different thresholds is given. The total number of recorded samples was $93.84 \cdot 10^6$ for the whole measurement campaign.

TABLE II.
DETAILED FADE DURATION DATA (STATISTICS OF 43 MONTH)

Duration [s]	10	100	1000
Number of events at 20dB	123	44	5
Number of events at 21dB	108	43	5
Number of events at 25dB	88	35	4
Number of events at 30dB	26	5	2
Number of events at 35dB	9	0	0

The total duration of the fade events at specific thresholds are summarized in Table III, considering the whole measurement campaign. In the table one can find also the durations projected to a 1 year period as well.

TABLE III.
TOTAL FADE DURATION

Threshold [dB]	43 month duration [s]	Projected to 1 year [s]
20	43107	12030
21	40410	11277
25	26112	7287
30	10209	2849
35	366	102

To evaluate these results we can find the p_m probability margin by dividing the 1 year fade duration at 21 dB with the total duration of year:

$$p_m = \frac{fd^{[21dB]}}{d^{[\text{year}]}} = \frac{11277s}{24 \cdot 3600 \cdot 365s} = 3.58 \cdot 10^{-4}, \qquad (6)$$

that is 99.9642% availability. It is very close to 99.9594% link availability that was calculated from the attenuation statistics. It is not surprising that the fade duration statistics provides the same availability rate as the attenuation statistics.

The main difference and the relevance of fade duration statistics can be derived from Fig. 4. There are numerous long duration fade events even at high attenuation that may cause the radio channel unavailable for a period that is longer that the duration which is tolerable by the system. This is the main reason why fade duration statistics is important: a deep fading may interrupt the operation of the link for significant period; however its impact to the yearly attenuation statistics could be negligible.

In such cases to improve the availability of the radio link, one of the possible solutions is to increase the transmit power or the antenna size. Increasing the transmit power have several side-effects: besides the increased power consumption it increases the probability of unwanted interference as well. Larger antennas affect the system costs and several mechanical problems may also arise. Besides these obvious but not always feasible solutions, various coding techniques are available. In the following section the effects of block coding and their relationship with the length of fade events will be shortly discussed.

B. Block coding and fade duration

The propagation channel often produces burst errors instead of independent ones due to the behaviour of the fade events. This is one of the main reasons why fade duration statistics may help to select the right modulation scheme, error correction method or interleaving structure. These aspects will be briefly discussed in the following.

Forward Error Correction (FEC) adds redundant information to the source data in order to improve the capacity of the radio channel. One of the major forms of FEC is block coding that is often applied to channels with burst impairments [10].

The RF interface of the investigated E-band device operates with BFSK modulation mode and utilizes an RS(204,188) FEC [11]. Considering 1 Gbps data rate and the redundancy of the FEC, the bit time $T_b=0.92\ ns$ and the block time is *188 ns*. By comparing this time with the much higher durations of fade events, it is obvious that the difference between them is several orders of magnitude.

At this high data rate even a more complex code like low-density parity-check (LDPC) block code or LDPC convolutional code [13] transfers several blocks during the rain fade events. This means that the error correction capability of these codes cannot completely mitigate the effect of the rain fading. The coding gain of LDPC is around 2-3 dB [14] compared it with convolutional code. On the other hand, attenuation during rain events could be significantly higher than this level. Considering this assumption, LDPC coding enhances the system performance when the radio link operates near to the system threshold. Another benefit is that the error correction expands the connectivity range of the individual links therefore it reduces the installation costs as larger coverage area can be achieved with less equipment.

As a conclusion, block coding at the physical layer may eliminate the effects of fast fading, scintillation or white Gaussian noise but it is not responsible to combat again slow fading. One of the solutions is the introduction of coding at higher level: at the transport, network or application layer where the transmission structure is longer than the duration of fade events (several seconds or minutes), or the protocol ensures retransmission in case of an error. If a feedback channel exists and channel state information (CSI) is available, with automatic repeat request (ARQ) or by using adaptive power control (APC), further improvement can be achieved to eliminate the effect of the slow and deep fading. This technique is the dynamic FEC, nevertheless this is out of the scope of our study.

V. CONCLUSIONS

In this paper a 43-month duration E-band terrestrial radio-wave propagation measurement was analysed and investigated from point of view the RF link availability. We have shown the rate of the availability based on the measured attenuation statistics and we applied a new model by using the physical system parameters for the calculations and an approximation of the availability with using the fade duration statistics. It was shown that the attenuation statistics does not completely characterize the channel with rain fading. Therefore one of the known second-order statistics, fade duration distribution was calculated and investigated. This is an important statistics that informs us about the length of the fade events and provides additional information for radio link designers. A further application of second order statistics is to support the implementation of advanced fade mitigation techniques like block coding or adaptive transmission control.

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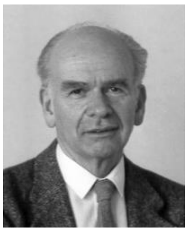

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