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Large-Scale Parameter Estimation in Channel Sounding with Limited Dynamic Range

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Abstract—In this paper, we examine large-scale parameter (LSP) estimates for spatio-temporal mobile radio channels in the case when the measurement dynamic range is too poor to derive the LSPs for all the measurement locations. Conventionally the LSPs are derived with, e.g., 20 dB dynamic range from the strongest detected multipath component (MPC), but such a measurement dynamic range cannot be guaranteed in all measurements as some of them suffer from large path loss (PL) and/or variation due to shadow fading (SF). We will show that the LSPs, specifically PL, SF, delay spread (DS), and angular spread (AS), can be considered as incomplete data. Incomplete data can be described either by a maximum or a minimum value (or both) when the measurements are with poor dynamic range. We show that the incomplete data should be taken into account in deriving the LSP statistics using the maximum likelihood estimation (MLE) rather than omitted as “outage”. Outdoor-to-indoor (O2I) measurements at the 14-14.5 GHz range are used as an example.

Index Terms—channel models, incomplete data, maximum likelihood estimation, measurement, modeling, outdoor-to-indoor propagation, radiowave propagation, short-range communications.

I. INTRODUCTION

Channel measurements occasionally suffer from limited measurement dynamic range that prevents weak multipaths from being observed, and hence, obscures the “true” channel parameters. Even with the best of channel sounders, there are measurement scenarios, such as non-line of sight or outdoor-to-indoor (O2I), where the path loss (PL) and/or shadow fading (SF) are so large that in some measurement locations the received signal is very weak when compared to the measurement noise level. Conventionally, the channel large-scale parameters (LSPs) are derived from the received signal components that fall within, e.g., 20 dB from the strongest received signal. Measurement locations with less than the desired dynamic range are considered “outage” and are not taken into account in the analysis of the channel parameters, e.g., [1]. Therefore, the outages i) are wasting valuable measurement data, ii) limits the link distance range of the sounder, and iii) potentially distorts the parameters distributions due to the biased sampling concentrating only on, e.g., short link distances.

Incomplete data can be analyzed with maximum likelihood estimation (MLE) [2]–[4]. Incomplete data are censored, grouped, or truncated data of the original. For the censored data, the exact numerical value of the parameter is not known but either a minimum or a maximum value is known, i.e., data

are counted, but not measured. Grouped data point has both minimum and maximum but the exact values between those are not known. Data can be truncated when samples above or below a certain range are immeasurable. A dataset can be a combination of samples for which the values are known and of any type of incomplete data. In the analysis of measured propagation channel data, incomplete data has been taken into account in truncated cluster (or path) power decay [5]–[7], censored polarization components [7]–[9], and censored PL [10]–[12]. The censored PL in [10]–[12] only considers a case when there is no signal in some measurement locations. To the best of the authors’ knowledge, the incomplete data of LSPs due to limited measurement dynamic range, including PL, SF, delay spread (DS), and angular spread (AS), has not been reported in literature.

In this paper, LSPs are examined in O2I scenario at 14 – 14.5 GHz band. In this measurement campaign 20% of the measured links have less than 20 dB measurement dynamic range. We will examine the properties of these “outage” data points. We find that these LSPs are, or can be approximated as, censored or grouped incomplete data and thus can be still be used for LSP estimates using MLE. The parameter statistics are derived for PL, SF, DS, and AS by properly taking into account the incomplete data using MLE. For comparison, the statistics are also derived with ordinary least squares (OLS) without the “outage” data points as well as with the “outage” data, i.e., by assuming that the parameters with less than 20 dB dynamic range can be used as such. It is shown that if the limited dynamic range is not taken into account using MLE the parameters can be significantly affected. For example, the OLS with outage overestimates the PL-slope α by 21% and σ_{SF} by 2.1 dB. The OLS underestimates mean and standard deviations of DS and AS up to 20%. These examples show that the *incomplete data*, when present, *must* be properly taken into account in order to derive reliable and unbiased LSP statistics needed for channel models.

The measurement site, measured links, channel sounder, measurement dynamic range, and the post-processing methods for incomplete data sets are introduced in Sec. II. The LSPs are analyzed in Sec. III and conclusions are presented in Sec. IV. The equations for MLE with incomplete data are presented in Appendix.

II. CHANNEL SOUNDING

The O2I measurement campaign was conducted in an office building in Espoo, Finland. The outdoor antenna height was 4.8 m. The indoor antenna height was about 1.6 m on the second floor, resulting in approximately the same total antenna height. A total of 69 indoor locations were measured from two outdoor locations, i.e., a total of 138 measurements. The two outdoor locations represent two base station (BS) locations: BS1 and BS2. The indoor locations are in two rooms and in the corridor. The link distance range is from 18 m to 50 m.

The measurements are performed with a VNA-based sounder at 14 – 14.5 GHz band, e.g., [13], [14]. The transmitter (Tx) antenna is a 2 dBi omnidirectional antenna and it is located outdoors. The indoor receiver (Rx) antenna is a 19 dBi sectoral horn antenna with about 10° azimuth and 40° elevation beamwidth. The directive Rx antenna is rotated on azimuth from 0° to 360°, with 5°-steps, to capture the angular properties of the channel. A back-to-back calibration was performed prior to the measurement by connecting the Tx and Rx antenna cables by a 20-dB attenuator. The derivations of the LSPs start with power angular delay profile (PADP). Antenna gain compensation is performed for all paths based on the broadside gains of the Tx and Rx antennas of 21 dB. Multipath components (MPCs) are detected as local maximums from the PADP above the noise threshold. The noise threshold is defined 3 dB above the highest peak of noise at very long delays. The LSPs are derived from the detected MPCs. The i^{th} MPC is characterized by its power p_i , delay τ_i , and direction of arrival (DoA) azimuth angle at the Rx ϕ_i .

The measurement dynamic range is defined as the difference between the strongest detected path and the noise threshold. A cumulative distribution function (CDF) of the measurement dynamic range is presented in Fig. 1. With a VNA-based sounder the noise level and measurement time, i.e., the number of measured links, is always a compromise. The measurement was planned using an O2I low-loss PL model for old buildings [15] so that the measurement dynamic range is expected to be at least 20 dB in a majority of locations. The measurement dynamic range is less than 20 dB in 20% of the measurement locations. In this work, when the measurement dynamic range is more than 20 dB the LSPs are calculated only using the top 20 dB of the channel. These LSPs are denoted as PL_{20} , SF_{20} , DS_{20} , and AS_{20} , representing path loss, shadow fading, delay and Rx azimuth angular spreads, respectively. In the case of measurement locations with less than 20 dB dynamic range the M -dB dynamic range result is used to define a minimum or maximum value of the LSP in those locations as will be shown in Sec. III. M is the difference between the strongest detected path and the noise threshold. These LSPs with limited dynamic range are denoted as PL_M , SF_M , DS_M , and AS_M .

Table I presents the parameter estimates. Three different parameter sets are presented. The first one is the MLE that takes into account all the data points including the incomplete data, i.e., PL_M , SF_M , DS_M , and AS_M . The second one is the

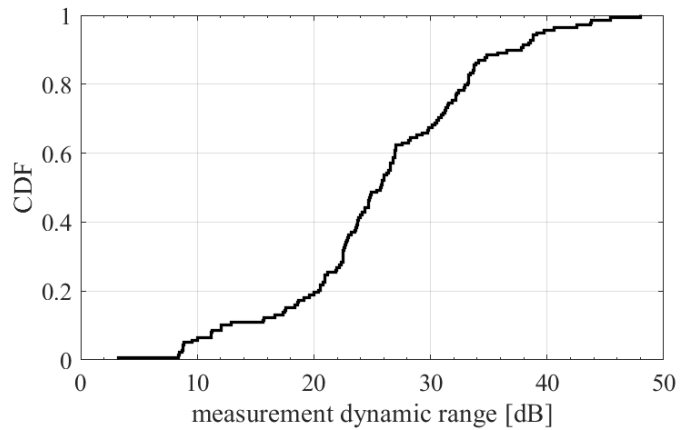


Fig. 1. Cumulative distribution function (CDF) of the measurement dynamic range across the 138 links. 20% of locations have less than 20 dB measurement dynamic range.

TABLE I
COMPARISON OF DIFFERENT PARAMETER ESTIMATIONS: MLE, OLS WITHOUT OUTAGE DATA WITH $M < 20$ dB, AND OLS WITH THE OUTAGE VALUES.

		MLE	OLS w/o out.	OLS with out.
Path loss [dB], $\overline{PL} = 10\alpha \log_{10}(d/1m) + \beta$	α	2.16	2.16	2.62
	β	78.4	78.4	73.6
SF [dB]	σ_{SF}	4.26	4.31	6.40
SF = $\overline{PL} - PL$				
DS	μ_{gDS}	-7.34	-7.46	-7.41
	σ_{gDS}	0.52	0.47	0.46
AS	μ_{gAS}	1.69	1.64	1.67
	σ_{gAS}	0.27	0.27	0.26
DS [ns]	μ_{DS}	75.6	59.1	64.6
	σ_{DS}	70.9	59.1	64.6
AS [°]	μ_{AS}	55.1	48.6	53.0
	σ_{AS}	21.7	17.8	19.6

OLS estimates omitting the “outage” data. The third set of parameter estimates are derived using OLS with the “outage” data included, i.e., assuming $PL_{20} \approx PL_M$, $SF_{20} \approx SF_M$, $DS_{20} \approx DS_M$, and $AS_{20} \approx AS_M$. The parameter estimates with OLS are occasionally similar or different from the ones derived with MLE depending on the particular properties of the distributions in this dataset. The parameters with MLE can be seen as the reference since only the MLE takes into account all the data points including those with the limited measurement dynamic range in the “outage” locations.

III. IMPACT OF OUTAGE DATA ON CHANNEL MODELING

A. Path Loss and Shadow Fading

Path loss is inverse of a sum of the MPC gains. The observable received power is limited by the dynamic range and only MPCs stronger than the noise level can be measured. For consistency with the definition for DS and AS, also PL and SF are calculated using the 20 dB-limit. PL is calculated

from the sum of MPC powers as

$$PL = 10 \cdot \log_{10} \left(1 / \sum_{i=1} p_i^2 \right), \quad (1)$$

where p_i is the power of the i^{th} MPC. SF is defined as the difference between the expected path loss \overline{PL} and PL

$$SF = \overline{PL} - PL. \quad (2)$$

The expected path loss \overline{PL} is obtained by fitting a PL model to the PL data. For simplicity, in this work we use a simple and commonly used PL model

$$\overline{PL} = 10 \cdot \alpha \cdot \log_{10}(d/1\text{m}) + \beta, \quad (3)$$

where parameters α and β are free parameters and d is the link distance.

With a larger dynamic range there are more detectable paths and PL with (1) is lower (or same as a very small change in dynamic range may not have any effect on the number of detectable paths). In other words, PL is monotonically decreasing function as the number of detectable paths decreases, and naturally, the number of detectable paths increases as the dynamic range is higher. Therefore the 20-dB PL is always less than, or equal to, the PL calculated with less than 20-dB dynamic range, i.e.,

$$PL_{20} \leq PL_M, \quad (4)$$

where $M < 20$. According to (2), SF in locations with less than 20-dB dynamic range follows

$$SF_{20} \geq SF_M. \quad (5)$$

The measured PL, as a function of the link distance, is presented in Fig. 2. PL calculated with the 20-dB dynamic range is marked with circles, while those with less than 20-dB dynamic range is marked with triangles. According to (4), the 20-dB-value is below the values shown by the triangles. A PL model (3) is fitted to the data using the MLE as presented in Appendix. Then the shadow fading statistics can then be estimated. The parameter estimates are presented in Table I. The MLE and OLS with outage give similar result but the OLS with outage overestimates the PL-slope α by 21% and σ_{SF} by 2.1 dB.

B. Delay and Angular Spreads

Delay spread is defined as the square-root of the second central moment of the power delay profile [16]. Unlike PL, DS is not necessarily a monotonically increasing or decreasing function of the dynamic range. Nevertheless, in practice, it can be approximated that

$$DS_{20} \geq DS_M, \quad (6)$$

where $M < 20$. Let us examine this approximation by comparing DS_{20} and DS_{10} for all the links that do have a dynamic range greater than 20 dB to calculate DS_{20} . As can be expected, in most case DS_{20} is clearly larger than DS_{10} . Out of the 110 links with dynamic range over 20 dB, only

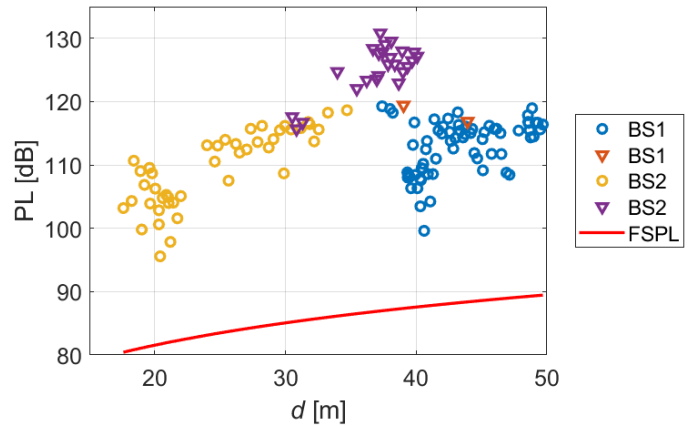


Fig. 2. Measured PL from the base stations BS1 and BS2: with 20 dB dynamic range (circles) and censored samples with less than 20 dB dynamic range (triangles). The 20-dB PL, i.e., PL_{20} , is below (or equal to) the triangle. Free space path loss (FSPL) at the center frequency is shown.

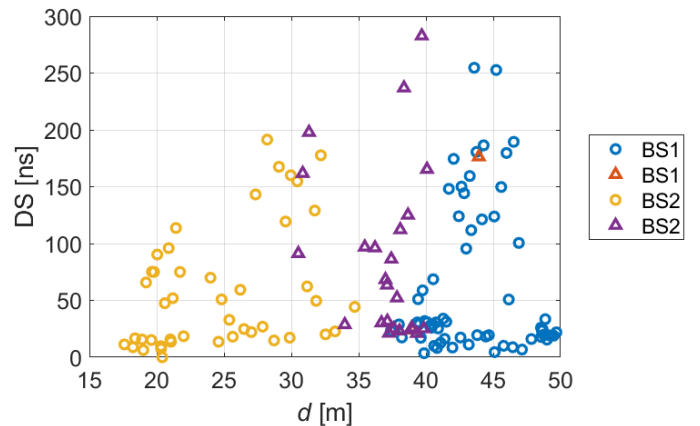


Fig. 3. Measured DS from the base stations BS1 and BS2: with 20 dB dynamic range (circles) and with less than 20 dB dynamic range (triangles). DS with 20-dB dynamic range is (most likely) more than (or equal to) the M -dB DS, i.e., above the upward pointing triangle.

10 have $DS_{20} < DS_{10}$ in contrary to (6). Even in the most extreme example $DS_{10} = 197$ ns and $DS_{20} = 175$ ns. These observations justify the approximation (6).

The mean and standard deviation of DS (and the log-normal distribution $\log_{10}(DS/1\text{s})$) is calculated with MLE as presented in Appendix. The parameter estimates are presented in Table I. OLS with and without outage underestimates the mean and standard deviation as compared to the MLE. The OLS without outage underestimates the mean μ_{DS} by as much as 22%.

The definition of AS is similar to the delay spread. In this work we use azimuth angular spread definition from [17]¹, which has a maximum value of about 104° for a uniform power azimuth angular spectrum. Similarly as DS, AS is not a monotonically increasing or decreasing function with increas-

¹Direction spread defined in [16] is an alternative definition. It is a dimensionless quantity between 0 and 1.

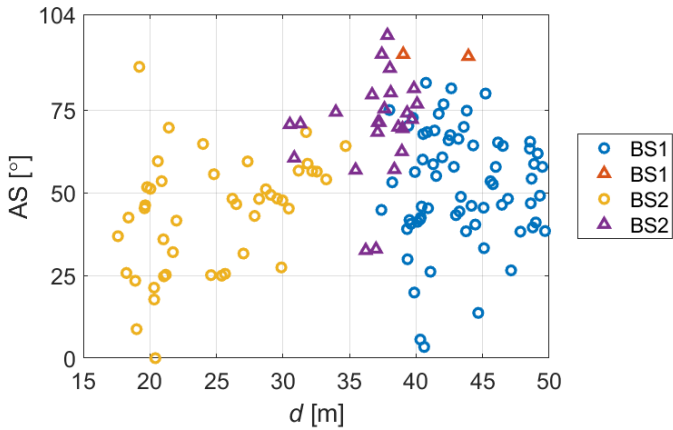


Fig. 4. Measured AS from the base stations BS1 and BS2: with 20 dB dynamic range (circles) and with less than 20 dB dynamic range (triangles). For the latter case, the 20-dB AS is (most likely) between the upward pointing triangle and theoretical maximum of 104° .

ing dynamic range. Nevertheless, it can be *approximated* that

$$104^\circ \geq AS_{20} \geq AS_M. \quad (7)$$

Again, the 10- and 20-dB-values are compared for all the links that do have good enough dynamic range to calculate the desired 20-dB-value. There are only two examples out of 110 where $AS_{20} < AS_{10}$ and the difference is less than 2%. These observations justify the approximation (7). The mean and standard deviation of AS and $\log_{10}(AS/1^\circ)$ is calculated with MLE as presented in Table I; see Appendix for formulation of the MLE. The OLS underestimates both μ_{AS} and σ_{AS} as some of the large observed values are either underestimated or not used at all. The OLS without outage underestimates μ_{AS} by 12% σ_{AS} by as much as 18%. On the other hand, MLE and OLS give quite similar parameter statistics for $\log_{10}(AS/1^\circ)$.

IV. CONCLUSION

We examined a common problem in channel modeling based on measurements with a limited dynamic range that is usually referred to as “outage”. It usually happens that in measurements the dynamic range is insufficient to estimate the LSPs for statistical analysis in a reliable manner. We show that the “outage” data can be used for calculating the LSP statistics if 1) the measured data with less than the desired 20 dB dynamic range is shown to be *incomplete data*, and 2) maximum likelihood estimation is used to take into account the incomplete data. Outdoor-to-indoor measurement data set at 14 – 14.5 GHz is used as an example. It is shown that PL, SF, DS, and azimuth AS are incomplete data, and therefore, also the “outage” data can be taken into account and failing to do so results in unreliable biased sampling that may affect the parameter statistics needed for channel models.

In this paper, we have limited the analysis to the parameters available in this O2I measurement data. Other LSPs include elevation angular spread (ES), which was not measured as

the horn was rotated only in the azimuth direction, and K-Factor, which is applicable only in line-of-sight scenario. Nevertheless, it seems likely, based on the presented analysis, that also these parameters are incomplete data in the case of limited measurement dynamic range. Future work includes the analysis of ES and K-factor.

APPENDIX

Log-likelihood function for sample n with a known value x_n is

$$L_n(\mu, \sigma) = -\ln(\sigma) + \ln \phi\left(\frac{x_n - \mu}{\sigma}\right), \quad (8)$$

where $\phi(\cdot)$ is probability density function (PDF). Log-likelihood function for a *censored* sample j with known minimum value $x_j > x_{j,\min}$ is

$$L_j(\mu, \sigma) = \ln \left[1 - \Phi\left(\frac{x_{j,\min} - \mu}{\sigma}\right) \right], \quad (9)$$

where $\Phi(\cdot)$ is cumulative distribution function (CDF). Log-likelihood function for a *censored* sample k with known maximum values $x_k < x_{k,\max}$ is

$$L_k(\mu, \sigma) = \ln \left[\Phi\left(\frac{x_{k,\max} - \mu}{\sigma}\right) \right]. \quad (10)$$

Log-likelihood function for a *grouped* sample l known to be $x_{l,\min} < x_l < x_{l,\max}$ is

$$L_l(\mu, \sigma) = \ln \left[\Phi\left(\frac{x_{l,\max} - \mu}{\sigma}\right) - \Phi\left(\frac{x_{l,\min} - \mu}{\sigma}\right) \right]. \quad (11)$$

The total log-likelihood function is

$$L(\mu, \sigma) = \sum_{n=1}^N L_n(\mu, \sigma) + \sum_{j=1}^J L_j(\mu, \sigma) + \sum_{k=1}^K L_k(\mu, \sigma) + \sum_{l=1}^L L_l(\mu, \sigma). \quad (12)$$

The parameter estimates are derived as

$$[\hat{\mu}, \hat{\sigma}] = \underset{\mu, \sigma}{\operatorname{argmin}} \{-L(\mu, \sigma)\}. \quad (13)$$

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