A Novel Method of Noise Thresholding Based on Ricean K-factor

S. Mashayekhi, *Member, IEEE*, H. Noori, Z. Vali, and D. G. Michelson, *Member, IEEE*

***Abstract*—Estimating the channel parameters such as Ricean K-factor and delay spread are challenging in temporal and spatial domain measurements due to the difficulty of selecting proper noise threshold. Depends on the channel situation, isolating the direct signal from the scattered components can become difficult such that additional steps may be required to verify if LOS component exist in the Doppler delay spectrum. This issue is more problematic in high frequencies in where the delay spread value reaches a maximum value far before the threshold used for delay spread calculation reaches the noise floor. Most of the existing noise threshold determination algorithms are complicated to implement, requiring rigorous impulse response inspection or are based on assumptions which may not be valid in the environment which measurements are taken. In this paper using the equivalence of the Rician fading distributions observed in the delay, spatial and frequency domains, we propose a bisection algorithm for estimating the noise threshold in measurement-based estimates of the channel impulse responses. This allows more accurate estimation of channel parameters such as K-factor and delay spread. Comparing the accuracy of the channel parameter estimates using the proposed and conventional methods of calculating noise threshold verifies the advantages of the proposed algorithm.**

***Index Terms*—Ricean channel, communication channels, parameter estimation, multipath channels, fading channels**

I. Introduction

Estimating the channel parameters, especially the Ricean K-factor, is challenging in temporal and spatial domain measurements due to the difficulty of selecting proper noise threshold value to extract LOS and multipath components out of noisy channel impulse response (CIR). It has been shown that noise threshold have negligible effect on the estimation of path loss whereas the mean excess delay and RMS delay spread can be affected [15]. Moreover, choosing different threshold level doesn't have linear effect on predicted channel parameters such as delay spread but has random discrepancy [16]. Not only isolating the direct signal from the scattered components is difficult, sometimes additional steps are required to verify if LOS component exist in the Doppler delay spectrum (e.g., using GPS location of mobile and geographical map of the measurement site to verify LOS/NLOS records). The ultimate consequence of the noise is causing the false detection and masking the weak rays in the responses especially when channel SNR is low. This issue is more problematic in high frequencies in where the delay spread value reaches a maximum value far before the threshold used for delay spread calculation reaches the noise floor [17]. Effect of thresholding on channel parameter estimation has been shown in many studies [16], [18]. For example the impact on RMS delay spread was studies in [16] using three selected threshold values on measured data concluding that different threshold values can make large effects on estimated channel parameters. Or it was shown in [18] that 9dB change of threshold value, can affect the predicted RMS delay spread value by a factor of two.

The problem of finding proper noise threshold value to separate multipath components and noise from time domain impulse response has gone under several studies [2], [3], [17], [19]. In [17] specific percentage of detected MPCs is chosen such that the sum of the power of the selected paths reaches a desired ratio of total power. In [19], the lowest 25% of the delay profile amplitude points are sorted, and then the highest and the lowest 25% of these low amplitude points are removed (median filtering). The remaining low amplitude points are averaged to yield a power level that is the dynamic range noise floor. In [3], the noise level introduced by side-lobes of the windowing function which was used to obtain the time domain impulse response was assumed much higher than measurement noise floor. As a result, the side-lobe level of the rectangular window was selected as noise threshold. In [2], the noise threshold was argued to be selected as a function of noise level since only thermal noise was considered. Similar method was used in [15], [20]. Beside these methods, many authors also have considered specific dB value below the peak of the CIR (15-30 dB) as noise cut off [21], [22] or a varying threshold decision which depends on the dynamical noise floor and the peak value of CIR [23], [24]. However, most of the above mentioned algorithms are complicated to implement, requiring rigorous impulse response inspection or are based on assumptions which may not be valid in the environment which measurements are taken. Therefore a better-standardized technique is needed for interpretation and presentation of measured channel impulse response data. This problem is addressed in our work along with a proposed solution to estimate the noise threshold more accurately.

The reminder of this paper is organized as follows: in section II we will show the equivalence of the Ricean fading distributions observed in the delay, spatial and frequency domains and demonstrate the advantages of estimating the Ricean K-factor from frequency response data. And using these insights, we will propose an algorithm to estimate the noise threshold. Section III describes the simulation details to calculate proper noise threshold and section IV presents the simulation results to compare the proposed method with other methods of estimating noise threshold level and s*ection V summarizes the paper*.

II. Concept

randomness of only phases in LTI channel and both phases and amplitudes in LTV channels), the Central Limit Theorem again applies here and results in a complex Gaussian process. As a result the frequency domain data's amplitude will follow Ricean distribution. Therefore calculation of K-factor from frequency domain amplitude will be physically meaningful. The following section argues that not only the amplitudes follow Ricean distributions in different domains, but also the first order statistics of these distributions are equal.

Rapid changes in the relative phases of multipath components may occur with shifts in frequency, position of the receiver, or the position of the scatterers, over time. Regardless of the type of shift that occurs, the relative energy in the direct and scattered components is identical so the Ricean K-factor that describes the fading distribution is also identical. As a consequence, we will see the same first-order distribution whether we vary the frequency, the position of the receiver or the position of the scatterers over time; only the sequences will be different. In next section we show the problem with estimating K factor from delay domain data (we will call it *delay domain K-factor*) and show that noise threshold selection is the main challenge which can lead to biased calculations and using the equivalence of K-factors in both domains, we show the merits of using frequency domain data instead for calculating the K-factor.

Exponential decaying power delay profile with a spike has been observed and modeled in many typical propagation channels [14], [30]. PDP of such channel is expressed as

$$PDP(\tau) = p_0\delta(\tau) + p_1 e^{-\alpha\tau}u(\tau)\,, \qquad (0.1)$$

where p_0 and p_1 are amplitudes, α is exponential slope, $\delta(.)$ and $u(.)$ are Dirac and step function, respectively.
According to the definition of delay domain K-factor,

$$K = \frac{p_0}{\int_0^{\tau_N} PDP(\tau)d\tau}\ , \qquad (0.2)$$

where $\boldsymbol{\tau}_N$ is the delay instant when the applied noise threshold (the absolute value in dB) intersects the PDP. *i.e.*,

$$p_1 e^{-\alpha\tau} = N_{Th} \Rightarrow \tau_N = -\frac{1}{\alpha}\ln\frac{N_{Th}}{p_1}\ . \qquad (0.3)$$

In the case of a noise-free scenario, the upper bound of the integration in (0.2) becomes infinite. Using (0.1) and (0.2) K-factors can be calculated as (in linear units)

$$K_{NoiseFree} = \frac{p_0}{p_1}\alpha\ , \qquad (0.4)$$

$$K_{Noise} = K_{NoiseFree}\frac{p_1}{p_1 - N_{Th}}\ , \qquad (0.5)$$

where K_{Noise} is the calculated K-factor when PDP is thresholded By N_{Th}. Using (0.4) and (0.5) one can show the relative error of calculated K-factors in dB due to noise thresholding as

$$\text{Relative Error} = \frac{\Delta K}{K_{NoiseFree}} = \frac{K_{Noisefree}(dB) + 10\log_{10}(\frac{p_1}{p_1 - N_{Th}}) - K_{Noisefree}(dB)}{10\log_{10}(\frac{p_0}{p_1}\alpha)}\ , \qquad (0.6)$$

$$\text{Relative Error} = \frac{\Delta K}{K_{NoiseFree}} = \frac{\log\frac{p_1}{p_1 - N_{th}}}{\log\frac{p_0}{p_1}\alpha},\quad 0 \le N_{Th} < p_1$$

(0.7)domain, a bisection algorithm is proposed as following.
Given the frequency scalar response, K-factor can be estimated using MoM or Ricean fitting approach. Using IFFT, the CIR can be obtained which is noisy and based on different threshold value the profile shape will vary. By varying the noise threshold in steps of 1dB for example, and obtaining delay domain K-factor at each step, the plot or table of noise threshold versus K-factor can be created. Then the proper noise threshold will correspond to the value for which the delay domain K-factor is closest to the value calculated in frequency domain. The flowchart in Figure 1 summarizes these steps.

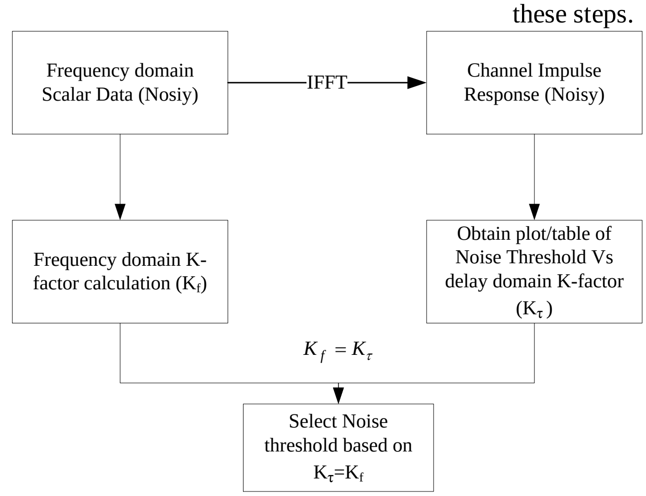

Figure 1 Flowchart of proposed bisection noise threshold detection algorithm

III. Simulation Methodology

In order to realize Ricean channel impulse responses we used the *ricianchan* object of the MATLAB [34]. With the assumption of a LTI channel, the function requires sampling period, the paths delays and average path gains as input parameter. Without loss of generality, for the purpose of this paper, we chose a typical channel with 25MHz channel bandwidth and a CIR with 12 multipath components of fixed arrival times. The average path gains were calculated as input of the ricianchan based on the exponential decaying function and desired K-factor [14]. Every time after the *ricianchan* was called, the response of the channel to the input signal of a Delta Dirac function was obtained using *filter* function and sampling period of 10ns. This created a Ricean CIR which we were interested in and we call it a *channel realization*. The noise was considered as additive white Gaussian and was added using *awgn* function of MATLAB based on the specific SNR value provided at the input of the function. The frequency domain transfer function was then obtained by Fourier transform. For calculating K-factor in delay domain (2.4) was used whereas in frequency domain MoM algorithm described in [4] was used.

IV. Results

As argued, K-factor calculated in both delay and frequency domains should be equivalent. Here we also show this fact using simulation results. Figure 2 is the results of 3600 noise-free channel realizations and then calculating both frequency and delay domain K-factor and plotting the scatter plots in dB units. It is seen that the K-factor in both domains are well fitted on the linear line therefore there is equivalence relation. The K-factor estimation method in frequency domain loses precision at very low K-factors, *i.e.*, K ≤ 5dB. At the same time, the fading distribution does not change much over that range of K, so that imprecision in estimating the K is not impactful.

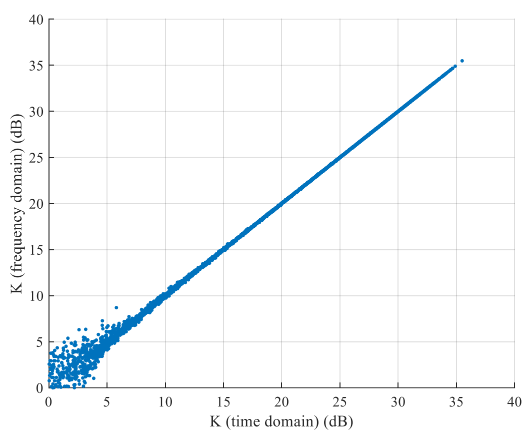

Figure 2 Scatter plot of Ricean K-factor in delay and frequency domains

The Ricean channel was realized several times with the channel parameters described in previous section. Here, for an example, we used SNR=5dB and selected three channels with very close delay domain K-factor of 5dB to present. Figure 3 and Figure 4 first of all show the general pattern of the relative error in calculated K and RMS delay spread versus selected noise threshold. In very low noise threshold values, because of presence of noise, the error is high. As the threshold increases, some portion of noise is masked out and in specific threshold the error becomes very small, *i.e.*, close to zero. Increasing the noise threshold above this value causes some of the MPCs to be masked out as well and error increases until all MPCs are masked out by noise threshold. Second of all, it shows that the proper noise threshold in which the error is minimum, is not always a fixed value necessarily even for channels with close a SNR and K-factor values. This emphasizes getting advantage of frequency domain data instead which is less susceptible to noise for calculating K-factor and as we will see later, for selecting the proper noise threshold.

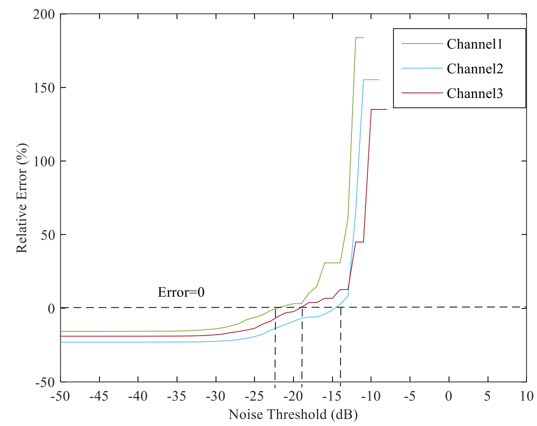

Figure 3. Sensitivity of delay domain K-factor to noise threshold.

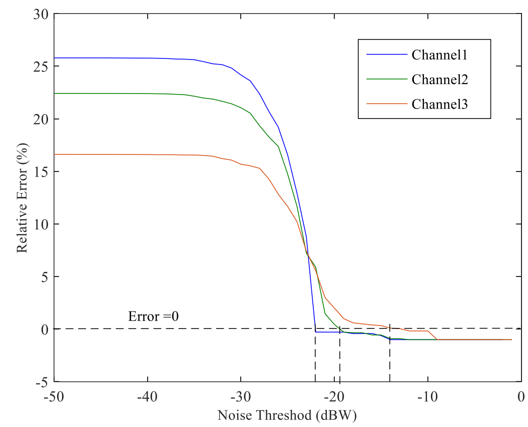

Figure 4. Sensitivity of RMS delay spread to noise threshold.

Unlike the delay domain calculations which correct value of Ricean K-factor depends on the applied noise thresholding, in frequency domain due to spread of the noise spectrum over all frequency points with an even impact, calculations will suffer less when SNR decreases. **Error! Reference source not found.** shows the result of relative error between calculated K-factors from noisy and corresponding noise-free frequency amplitude responses. The simulations are repeated for SNR values from 5dB to 30dB (These values are the practical SNRs values exist in a typical measurement), and for channels generated with *K*=5dB to 35dB with 2dB step sizes. The largest and smallest error in the plot corresponds to *K*=5 and *K*=35dB, respectively. The results show that even for channels with SNR and K-factor as low as 5dB the error of Ricean K factor calculated in frequency domain is small and less than 15%. This shows the merits of calculating K-factor in frequency domain instead of delay domain which we already showed how sensitive it is to the noise threshold. This is the basis for our proposed noise threshold detection algorithm which results are presented in next section.