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Probability Distribution of Rician *K*-Factor in Urban, Suburban and Rural Areas Using Real-World Captured Data

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***Abstract*—The Rician *K*-factor of the vehicle-to-vehicle (V2V) wireless propagation channel is estimated using a moment-based method on the envelope of measured pulse data. The measurements were carried out under vehicle-to-vehicle wireless communication channel condition with car rooftop antenna heights at one end of the link and very low antenna height at the other end. Data captured from typical urban, suburban and rural areas are analyzed and the *K*-factor probability density function is generated for each scenario to give an insight into the V2V channel behavior. For all three areas, the majority of *K* values are found to be within the range of -10 to +10 dB. The *K*-factor distributions are close to normal with mean values of 1.8, 2.6 and 3 dB respectively for urban, suburban and rural area.**

***Index Terms*—Vehicle-to-vehicle (V2V) communication, Probability Distribution Function (PDF), Rician K-factor, radio wave propagation**

I. Introduction

An IMPORTANT requirement for developing a wireless vehicle-to-vehicle communication network is to have an accurate description of the propagation channel. In a multipath wireless communication environment, the received signal comprises a collection of random scatterers of the transmitted signal, each characterized by a different magnitude, phase and angle of arrival. Generally, a deterministic signal component is present, arising from one of two sources: 1) large fixed scatterers in the environment or 2) the line-of-sight (LOS) signal.

The narrowband complex baseband representation of such a channel is modeled by [1]:

$$\mathrm{h(t)} = \sqrt{\frac{\mathrm{K}\Omega}{\mathrm{K+1}}}\mathrm{h_{sp}(t)} + \sqrt{\frac{\Omega}{\mathrm{K+1}}}\mathrm{h_{sc}(t)} \quad (1)$$

where h_{sp}(t) represents a unit-power deterministic specular component and h_{sc}(t) is a unit-power, zero-mean, complex Gaussian wide-sense stationary random process representing the diffuse scatter components. The parameter Ω is the average power of *h(t)*, and *K*, also known as the Rician *K*-factor, is defined as the ratio between the deterministic signal power to that of the variance of the multipath components. Generally as *K* increases, the probability of encountering a deep fade reduces, while if *K* decreases, the dominant path degenerates in amplitude, and when *K* is reduced to 0, the Rician distribution reverts to Rayleigh. The *K* factor, which represents the relative power of the dominant component, is a useful measure of the communication link quality. Therefore, estimation of *K* is of practical importance in a variety of wireless scenarios, including channel characterization, adaptive modulation, and localization applications.

In the literature, a huge amount of research has been carried out developing various methods to estimate the Rician *K*-factor, for example non-coherent techniques using samples of the received fading envelope have been proposed in [2]-[5]. Others use the in-phase and the quadrature (I/Q) components [2], [6]. The method of maximum likelihood (ML) was derived and its statistical behavior was investigated in [7]. However, most of these works were only investigated in simulation. Measurements were carried out to analyze *K*-factors for indoor environment [8] and in the reverberation chambers [9]-[10]. In [11], the maximum likelihood method was used to estimate the *K*-factor in urban areas with high transmitter location. As far as the authors are aware, *K*-factor investigations for the vehicle-to-vehicle channel based on measurement data in real multipath environments are not available elsewhere. Here we provide results for the vehicle-to-vehicle wireless channel with low transmit (Tx) and rooftop receive (Rx) antenna installations.

In this paper, the estimation of the Rician *K*-factor distribution from real world measurements is presented. The measurements were carried out under vehicle-to-vehicle channel conditions with low antenna installation at the transmitter. Results captured from typical urban, suburban and rural scenarios were analyzed using the moment-based method and the probability density function (pdf) of the Rician *K*-factor was generated for each scenario to give an insight into the V2V channel behavior.

II. Moment-based Estimation of K from the Envelope

Research has found that for a random variable signal envelope with a Rician probability density, the *K*-factor can be resolved by using two different moments of the signal [2]. An estimator that depends on the m^{th} and n^{th} moments could be expressed as

$$\widehat{K}_{n,m} := f_{n,m}^{-1}\left(\frac{\hat{\mu}_n^m}{\hat{\mu}_m^n}\right) \quad \text{, with}$$

$$\hat{\mu}_k := \frac{1}{N}\sum_{l=0}^{N-1} R^k(lT_s) \quad (2)$$

where moment estimator μ_k is the k^{th} moment of the signal envelope *R(t)*, T_s is the sample period and *N* is the number of available samples. Two natural choices for (n, m) that have been extensively discussed are (*1*, *2*) and (*2*, *4*). The selection of (*1*, *2*), which involves the lowest order moments, can be calculated from

$$f_{1,2}(K) = \frac{\pi e^{-K}}{4(K+1)}\left[(K+1)I_0\left(\frac{K}{2}\right) + KI_1\left(\frac{K}{2}\right)\right]^2 \quad (3)$$

where I_α is a modified Bessel function of the first kind and order α. It is found that this estimator approaches the performance of the maximum likelihood estimator [12] and the theoretical Cramer-Rao bound [2]. However, resolving *K* involves the complex numerical procedure of inverting (3), which increases the computation complexity. An alternative choice of (*2*, *4*) for (*n*, *m*) involving finding the roots of a second-order polynomial, which can be done in closed form [2], is shown in (4) and this approach of *K* estimation is adapted in this work.

$$K_{2,4} = \frac{-2\hat{\mu}_2^2 + \hat{\mu}_4 - \hat{\mu}_2\sqrt{2\hat{\mu}_2^2 - \hat{\mu}_4}}{\hat{\mu}_2^2 - \hat{\mu}_4} \quad (4)$$

Our *K*-factor estimation algorithm was tested on synthetic random distributions and found to provide a reliable estimate of *K*.

III. Measurement Setup

A. Antenna Setup

A multiple-input, single-output (MISO) wireless measurement system was set up for channel measurement in typical urban, suburban and rural areas. Quarter wavelength whip monopole antennas were used in this study. The measurement system operates at the TETRA frequency (430 MHz) with a narrowband modulation scheme. In order to emulate a V2V wireless channel, both the transmitter antenna and the receiver antenna array were deployed on vehicles. In all of our measurements a single transmitter antenna was deployed 50 cm above road level to observe the ground effect on a very low antenna installation. On the receiver side, three whip monopole antennas were fixed on the car roof in an equilateral triangle shape, spaced 25 cm apart to create multiple receiving channels, as shown in Fig.1. The height above road level of the receiver antennas is about 1.5 meters. During the test, the transmitter vehicle was parked at a fixed point, and the receiver vehicle was driven at steady speed, subject to traffic conditions, around the selected routes for each environment whilst the channel I/Q components data (which contain envelope and phase information of the channel) were recorded. Two GPS antennas were also deployed on the two vehicles respectively to get the real time location information.

B. Data Capture

During the measurement, a narrow band signal pulse was fed to the transmitter antenna. Signal pulses were captured every 1 second with sampling rate of 48k Sa/s. The transmitted pulse has an overall length of 341 ms, which corresponds to 16368 samples per pulse. Pulse data were distinguished from noise by using a peak finder following an FFT, however some noise with large peaks were occasionally picked up in the pulse data. These pulses normally have much shorter length compare to a good signal pulse. Therefore, pulses with length shorter than 16000 samples in the captured data were discarded during the K-factor estimation and treated as false pulses.

Due to the nature of the transmitted signal, for each complete signal pulse, 8000 samples were analyzed for *K* estimation. These 8000 samples have duration of 0.17 s and at typical driving speeds they correspond roughly to a 2 m movement in the city centre and 5 m on the motorway. Within this period, we assume the dominant component is time-invariant. Calculations based on too-short duration signals sometimes generate complex *K* values, so signals received on all three channels were linked together to be processed for *K* evaluation.

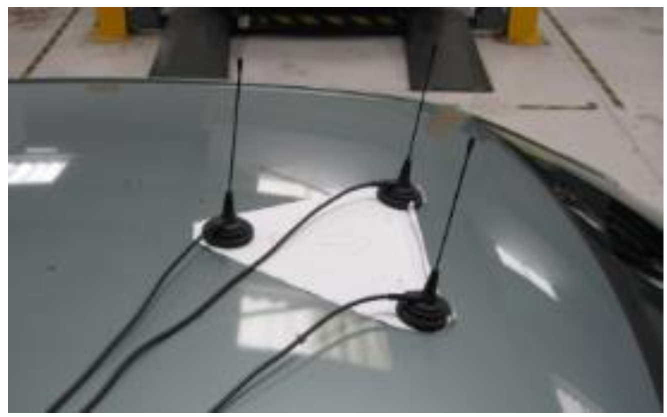

Fig.1. Measurement antenna setup (receiver)

IV. Results Analysis

The captured I/Q components data in our channel measurement contain both voltage envelope and phase information. In order to derive the magnitude of the signal envelope from the I/Q data, first of all, a calibration process was performed based on a lookup table method. During the calibration process, three receiver antennas were replaced by a signal generator as shown in Fig.2. All the rest of the data capturing system was kept the same. Based on the system sensitivity range, the output power level of the signal generator was adjusted across the range -130 dBm to -30 dBm in 1 dB steps, and the I/Q data were recorded and analyzed to create a lookup table. This procedure eliminates cable losses and LNA non-linearity from the channel measurements.

The next step was to curve-fit the recorded I/Q voltage level and the input signal generator power level in the lookup table to find proper curve fitting coefficients for all three channels. If a good curve fitting function can be found, the captured real world I/Q data can be easily fitted to the curve and the magnitude of the signal envelope can be produced. The curve fitting process was divided into three segments in this case, the lower and higher end of the curves were fitted using 3rd order polynomial and the middle part was fitted by a straight line. The original calibration curves for three channels are plotted in Fig.3 in solid lines. The fitted curves for three channels are plotted in Fig. 3 in dashed lines to compare with the original curve. It is evident that the error is minor. Please note that for any input power level greater than -40 dBm, the received signal tends to saturate, and no curve fitting can be made for this range. The (very occasional, 1% of data) saturated signals during the measurement indicate a very short distance from the transmitter to the receiver, it is reasonable to assume that there is a strong LOS signal so a large *K* value (*k*=50) was inserted into the *K* calculation instead of using the moment equation.

Finally, the real world I/Q data for three channels in each good signal pulse was calibrated using the curve-fitting coefficients. Equation (4) was then used to calculate the *K*-factor based on the second- and fourth-order moment of the envelope of the calibrated signal. The *K*-factor distributions for three environments were analyzed individually and the results are explained in the following sections.

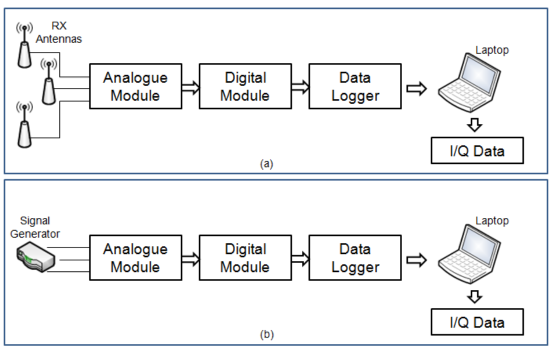

Fig. 2. Data acquisition and calibration system block diagram

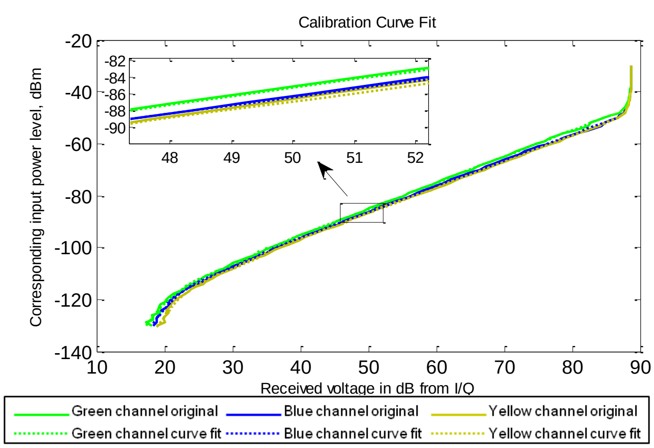

Fig. 3. Calibration curve fit

V. Measured K-factor Distributions

A. Leeds City Center (Urban Area)

Measurement data for an urban area was collected around the city centre in Leeds, U.K. This is a built up area with average building heights about 15 m and long narrow straight streets about 10 m wide. A few circuits around several routes were completed to provide a comprehensive database. Leeds city centre street view and one of the drive routes are shown in Fig.4. The vehicle with the transmitter antenna was parked at the position marked by a green label in the picture, and the driving route is shown with blue lines with the end point marked in red dot.

Statistics for the data collected from Leeds city center are listed in Table I. The estimated pulse numbers were predicted from the binary file size of the captured data. Incomplete pulses are those having a pulse width less than 16000 samples. Saturated pulses are those having received signal level equal to the receiver's maximum. Complex *K* value pulses are the pulses which generate a complex value using Equation (4), the reason for this phenomenon will be described in the following section. The *K*-factor evaluation using equation (4) was implemented in MATLAB. The calculated *K*-factor distribution for the good pulses is plotted in Fig.5. It can be seen that the calculated *K* values are within the range of -12 to +15 dB with the majority of *K* values within the range of -7 to +10 dB. The distribution fitting tool in MATLAB was used to find the closest best-fit model for the *K* distribution. It was found that in this case two models are suitable for the distribution: logistic and normal.

(a) (b)

Fig. 4. (a) Urban area street view; (b) an example drive route

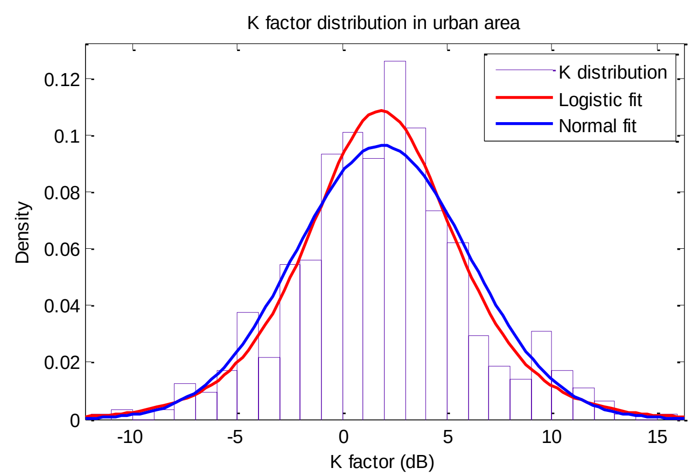

Fig. 5. *K*-factor distribution for urban area

The logistic distribution has the density function:

$$y = \frac{e^{-\frac{x-\mu}{\sigma}}}{\sigma\left(1+e^{-\frac{x-\mu}{\sigma}}\right)^2} \quad (5)$$

with location parameter μ and scale parameter $\sigma > 0$, for all real x. The distribution has been used for various growth models, and is used in logistic regression. It has longer tails and a higher kurtosis than the normal distribution.

The normal distribution pdf is:

$$y = f(x|\mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(x-\mu)^2}{2\sigma^2}} \quad (6)$$

with the mean value of μ and the standard deviation σ. From Fig. 5 we can see that in this case the logistic fit matches our *K* distribution quite well and it has a mean value of 1.85, standard deviation of 4.15. The Normal fit has a mean value of 1.88 and standard deviation of 4.13.

Table I shows that there are a certain number of *K* values that have complex values for the urban scenario. If we observe the signal behavior of the pulses that have complex *K* values, two main behaviors were found: 1) multi-mode behavior, and 2) lognormal behavior. Possible reasons that could cause multi-mode signal behavior are:

1) Distribution under-sampling. If the vehicle is moving slowly, only a short distance is travelled within the pulse duration. The range of different phase combinations of the multipath components is too small to produce a representative distribution of amplitudes.
2) Local scattering. There could be local scatterers close to the receiver that interrupt the Rician behaviour. These random scatterers could be tree branches, lamp post, local traffic moving in different directions, etc.
3) Undulating road surface. The convex or concave road surface could cause the effective antenna height change with distance. This is more sensitive at low antenna heights.

Lognormal behavior would arise where a number of independent random processes combine multiplicatively. This might correspond to rapid changes in the field as the vehicle moves in or out of shadowed regions. Moreover, the undulating road surface and scattering of signals from random scatterers could also initiate lognormal signal behavior within one pulse.

B. *Garforth (Suburban Area)*

Garforth is a typical British suburban area with mostly two story residential houses and gardens. The average building height is less than eight meters. The area is slightly hilly with vehicles randomly parked along single carriageway roads. The measurement area fell within a maximum range of approximately 1 km around the parked transmitter. Typical street view and the Garforth drive route map are shown in Fig. 6.

(a) (b)

Fig. 6. (a) Suburban area street view; (b) an example drive route

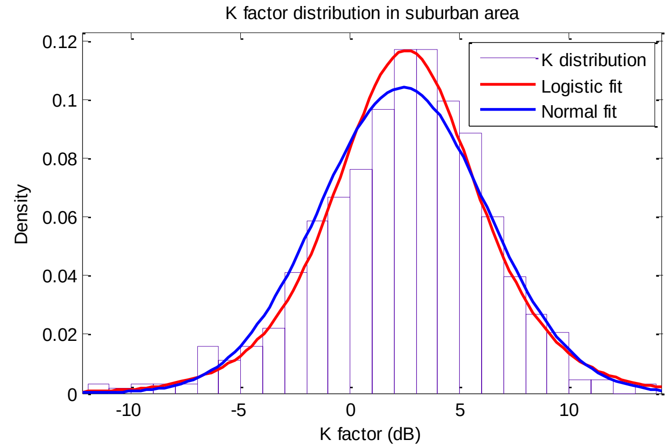

Fig. 7. *K*-factor distribution for suburban area

The data statistics in this area are listed in Table I, from which we can see that the real captured pulse numbers are much higher than the estimated pulse numbers. However these extra pulses are mainly incomplete pulses which indicate that the noise level during the data capturing is high and some of the noises were accidently picked up as signal during the measurement, these pulses are removed from our final data analysis. (There were fewer such instances in the urban scenario, since the range was shorter and signal-to-noise ratio was thus better). Compared to the urban area, the calculated complex *K*-value pulse numbers from this suburban area are much reduced. The saturated pulses are collected when the receiver vehicle was driving away from the transmitter in very close vicinity. The distribution of calculated Rician *K*-factor is plotted in Fig. 7 with two suitable curves fitted. For this suburban area we can see the majority of *K* fall within the range of -3 dB to +8 dB. The logistic curve gives the best fit with a mean value of 2.6, standard deviation 3.88. The normal distribution gives a mean value of 2.41, standard deviation 3.84 and this is higher than the mean *K* value in the urban area.

TABLE I
MEASUREMENT DATA STATISTICS

	Urban Area	Suburban Area	Rural/Open Area
Estimated pulses	875	650	740
Captured pulses	731	926	915
Incomplete pulses	4	279	467
Saturated pulses	4	11	0
Complex K value pulses	82	3	6

C. *Scunthorpe (Rural & Open Area)*

An open area motorway with flat empty fields on each side was chosen in this research to study the rural area channel behavior. In this measurement, the transmitter vehicle was parked beside a minor road which is very close to a motorway, and the receiver vehicle was driven a full circuit on the motorway between two junctions. The maximum distance from the transmitter to the receiver in this test is about 8 km. Although there are a few bridges on the motorway and random trees along the road side, there is fairly good line of sight from the transmitter to the receiver. The open area drive route is shown in Fig. 8 and statistics of the data are listed in Table I.

Since the driving distance in this area was further than our reception distance, the number of good signal pulses actually captured was fewer than estimated from the binary file size. In this measurement, there were no saturated pulses and the number of complex *K* value pulse was just six. The *K*-factor distribution for the “good” signal pulses is shown in Fig. 9. Referring to the figure, the estimated *K*-factor values range from -15 dB to +12 dB. However, most *K*-factor values fall between 2 to 7 dB, which might be expected in an open or rural area where there is a good line of sight. Both logistic and normal distributions provide a good fit to the data, the logistic fit being slightly better. For the logistic fit, the mean value for the distribution is found to be around 3 with standard deviation of 3.88. The normal distribution has a mean value of 2.63 dB with standard deviation of 3.82.

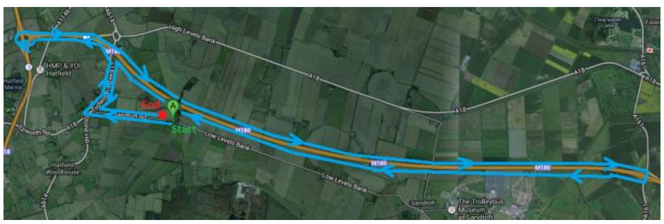

Fig. 8. Rural open area drive route

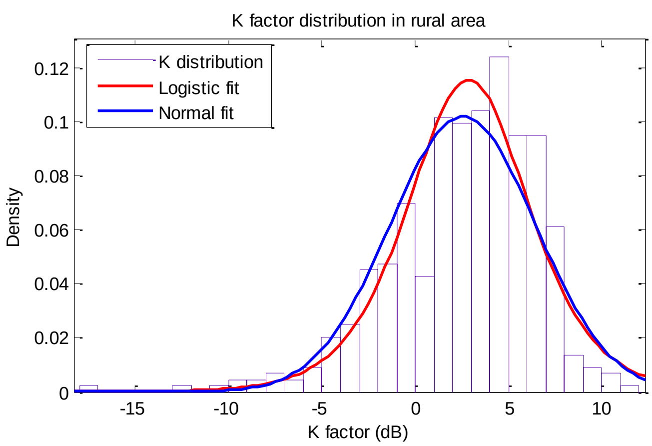

Fig. 9. *K*-factor distribution for rural open area

VI. Conclusion

The Rician *K*-factor of the vehicle-to-vehicle wireless propagation channel was estimated using a moment-based method on the envelope of measured pulse data. The measurements were carried out under vehicle-to-vehicle wireless communication channel condition with car rooftop antenna heights at the receiver end of the link and very low antenna height at the transmitter. Data captured from typical urban, suburban and rural areas were analyzed and the *K*-factor probability density functions were generated. For three areas, the *K*-factor distributions are close to a normal distribution with mean values of 1.8, 2.6 and 3 dB respectively for urban, suburban and rural area, however, the logistic distribution provides a somewhat better fit with very similar mean and standard deviation. The majority of *K* values are found to be within the range of -10 to 10dB for these three scenarios.

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