Cascade Fading Channel Models for Wireless Communication-A Survey

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ABSTRACT
Statistical theory plays an important role in channel modelling which in turn can be applied in design and performance evaluation of various communication systems. The design and analysis of cascade fading models have been an active area of interest in recent years due to its application in numerous real world scenarios such as keyhole channel and multihop communication system. These cascade fading models are developed by the product of independent but not necessarily identically distributed random variables. Many researchers are currently working in this area and new cascade fading models have been suggested recently in the literature. Due to ever-increasing demand and ubiquitous access of personal communication services, wireless systems are required to operate in increasingly hostile environments so there is a need of better models for wireless communication. So in order to find the gap areas in the literature pertaining to cascaded models, an exhaustive survey has been done here in this paper. This effort will surely help the researchers working in this area, to be able to identify the most appropriate fading channel model for an efficient wireless communication system design.

Keywords
Cascade fading, keyholes, relay terminals, multihop, multiple input and multiple output (MIMO).

1. INTRODUCTION
Wireless is the fastest growing area in communication system. Radio signals propagation through wireless channels is a complicated phenomenon characterized by various effects including path loss, multipath fading and shadowing. Except path loss which is distant dependent the other two parameters can be statistically described by various fading models. As the expectations for the performance and reliability of wireless systems have increased, the importance of accurate channel modelling in system design, evaluation has also increased. Along with the complexity of the channel model comes the complexity of the analytical solution that helps to assess the performance. Recently cascade fading models have gained significance as they are useful in modeling wide range of fading conditions. Depending upon the radio propagation environment and communication scenarios various multipath fading models are available in literature [1]. These models are categorized as short term fading , long term fading and composite models. Several short term fading models include Rayleigh, Rician, Weibull, Nakagammi-m, and gamma . For long term fading condition lognormal distribution is widely accepted [1]. Various composite channel models have also been proposed which are often formed by combining distributions for fast fading with log normal for shadowing like Rayleigh-lognormal, Rician -lognormal, Nakagammi –lognormal etc . Mostly, such models assume that there is little or no multiple scattering in the channel. Rather in general, the signal leaving the transmitter reaches the receiver after multiple scattering. Thus the most suitable way to model such realistic fading conditions when multiple scattering exist is through cascaded approach. The practical applications of cascaded fading models include modelling of wireless signal propagating through **relay terminals** and **keyholes**.

In multihop environment, several low power relay stations (nodes) are deployed between the transmitter (source) and receiver (destination) extending the range of wireless network. Such systems provide network connectivity where traditional network architecture fails or might be impossible due to local constraints. These nodes can be non-regenerative (amplify and forward), DF (decode and forward) or DAF(decode amplify and forward. However if the source and destination terminals are separated and surrounded by many stationary and moving object such that the signal transmitted by source terminal can propagate through electromagnetically small keyhole among obstacle where each keyhole behaves as a source terminal to next keyhole and hence the overall propagation channel can be considered as cascaded fading channel .The main utility of modelling of keyhole phenomenon is in multiple input and multiple output systems (MIMO). A physical interpretation of these models can be given by considering the received signals generated by the product of large number of rays reflected via N statistically independent scatters. Hence considering the merits of cascading models several researches is available in literature in recent past which is surveyed in next section.

The rest of the paper is organized as follows. Section II presents the system and channel model, in section III various performance measures are discussed , a tabulated comparison of various existing cascade fading models is done in section IV. Various research gaps and open issues are discussed in section V before the paper is finally concluded in section VI.

2. SYSTEM AND CHANNEL MODEL
Consider the signal transmission over cascaded fading channels in presence of Additive White Gaussian Noise. The baseband representation of the received signal is given as Z = sY+N ; where s is transmitted baseband signal which can take different values from modulation alphabets such as M-quadrature amplitude modulation (MQAM) and M-phase shift keying (MPSK) ,N is Additive White Gaussian Noise and Y represents slow , flat frequency channel's –faded envelope constructed as the product of $N \geq 1$ independent but not necessarily identically distributed (n.i.d.) random variables R_i; $1 \leq i \leq N$.

$$Y = \prod_{i=1}^{N} R_i \qquad (1)$$

The received instantaneous SNR per symbol "γ" of the cascaded channel can be represented as the product of N powers i.e.

$$\gamma = \prod_{i=1}^{N} \gamma_i = \frac{E_s}{N_0} Y^2 \qquad (2)$$

$$\Rightarrow \qquad \gamma = \frac{E_s}{N_0} \prod_{i=1}^{N} R_i^2$$

where E_s is the transmitted symbol's average energy and N_0 is one sided AWGN power spectral density.

The corresponding average SNR $\overline{\gamma}$ is

$$\overline{\gamma} = \frac{E_s}{N_0} E\left(\prod_{i=1}^{N} R_i^2\right) \qquad (3)$$

As all R_i are independent hence R_i^2 are also independent. The expression (3) reduces to.

$$\overline{\gamma} = \frac{E_s}{N_0} \prod_{i=1}^{N} E(R_i^2)$$

The n^{th} order moment of γ is given as

$$E(\gamma^n) = \left(\frac{E_s}{N_0}\right)^n \prod_{i=1}^{N} (E(R_i^2)^n) \qquad (4)$$

Using these moments we can find out various performance metrics in various cascaded channels

3. PERFORMANCE METRICS

Under this section we will review first order and second order statistics that helps to evaluate the performance of any statistical model.

3.1 First order statistics

3.1.1 Amount of fading (A.F)

The amount of fading provides a quantitative measure of fading present in wireless channel.

$$AF = \frac{E(\gamma^2) - (E(\gamma))^2}{(E(\gamma))^2}$$

But as it does not provide the complete characteristics of channel or impairments caused by the existence of fading or shadowing in the channel, so to provide a better quantitative measure we need to look at error rates and outage probability.

3.1.2 Error rates

The error rate performance provides us with a means to see how much additional SNR is required to maintain the specific error rate as fading condition changes. The average end-to-end SNR is a useful performance measure serving as it is an excellent indicator of the overall system's fidelity. The average error probability in cascaded channels is represented as [1]:

$$p_e(\overline{\gamma}) = \int_0^\infty p_e(\gamma) f(\gamma) d\gamma$$

Where $\overline{\gamma}$ *is* average SNR and f (γ) is the density function of instantaneous SNR

As error rates goes down the excess SNR required to mitigate the presence of fading in the channel increases so this "excess SNR" provide more quantitative information on fading rather than amount of fading.

3. 1.3 Outage probability

For uninterrupted and reliable wireless communication the received power should be greater than the minimum power (threshold value). Hence it is very important to calculate the outage probability when the received power goes below certain threshold value. The outage probability is defined as the probability that the instantaneous SNR falls below a certain threshold γ_{th} , i.e.

$$P_{out}(\gamma_{th}) = P\,(\text{SNR} < \gamma_{th})$$

3.1.4 Ergodic capacity/average channel capacity

Channel capacity provides a measure of the amount of information that can be reliably transmitted over a communications channel. For a transmitted signal of bandwidth BW over AWGN channel, the channel capacity C is given as [1].

$$C = BW \log_2(1 + \gamma)$$

The ergodic capacity can be obtained by averaging channel capacity over the PDF of γ. i.e

$$\frac{E(C)}{BW} = \frac{1}{Ln\ 2} \int_0^\infty \ln(1+\gamma) f(\gamma) d\gamma$$

3.2 Second order statistics

The measures we reviewed above, namely error probability, outage probability are quantitative measures of the fading channel based on first order statistics as the only information they required was the pdf of the SNR. However, the second order statistics, which require the joint pdf of the SNR, will provide additional information on the fading channel. Two such measures are level crossing rates (LCR) and the average fade duration (AFD).

3.2.1 Level crossing rate (LCR)

The level crossing rate (LCR) $N_A(a)$ is defined as the expected rate at which the envelope crosses a specified signal level A i.e. the number of times/unit duration the envelope crosses the threshold in the negative direction. The expression for LCR is given as [1]

$$N_A(A) = \int_0^\infty \acute{a}\, f(A,\acute{a}) d\acute{a}$$

Where f(A,á) is the joint pdf of a and á at A.

3.2.2 Average fade duration (AFD)

It is defined as the average duration of time the amplitude /envelope stays below the threshold once it goes below. It provides a measure of the time that the wireless system remains in outage. It takes into account the relative motion of the transmitter/receiver. The average fade duration (AFD) is defined as

$$T(a) = \frac{F(A)}{N(A)}$$

where numerator $F(A)$ is the probability that "a" is less than the fixed value A which is just CDF or the outage Probability .Hence average fade duration can be termed as the ratio of outage probability to LCR.

The next section surveys various existing models on the basis of above mentioned statistics.

4. COMPARISON OF VARIOUS CASCADED MODELS

On the basis of first and second order statistics a comparison is given below in Table 1. The expressions for amount of fading, n^{th} order moment of instantaneous SNR are given and various constraints and utilities of these models are also discussed.

Table 1.

Channel	Statistics	Amount of Fading	n^{th}order moments of instantaneous	Bounds/ Constraints	Scope /Applications
Casaded Nakagami-m	In [5] expression for MGF, PDF, and CDF are given in terms of Meijer-G- function. In [10] pade approximation technique is used for evaluation of MGF. Expression of outage probability is obtained in[11]	$\prod_{i=1}^{N}(1+\frac{1}{m_i})-1$	$\bar{\gamma}^n\prod_{i=1}^{N}\frac{\Gamma(n+m_i)}{\Gamma(m_i)m_i^n}$	$m_i \le ½$ 0< AF ≤3^N - 1. It fails to account for fading conditions greater than 3^N - 1.So as N increases AF increases.	1.It approx. lognormal distribution for small value of N [5] 2. Used for the evaluation of the end-to-end outage probability of multihop wireless communication systems with CSI-assisted relays.[11]
Cascaded Weibull	Expressions for MGF, PDF, and CDF for double weibull and n weibull model are obtained in [12],[4]. In [10] pade approximation technique is used for evaluation of MGF.	$\prod_{i=1}^{N}\frac{\Gamma\left(1+\frac{4}{c_i}\right)}{\Gamma(1+\frac{2}{c_i})}-1$	$\bar{\gamma}^n\prod_{i=1}^{N}\frac{\Gamma\left(1+\frac{2n}{c_i}\right)}{\Gamma(1+\frac{2}{c_i})^n}$	More than 30 multipliers are required to accurately approximate lognormal. Variability is more in in cascaded weibull as compared to cascaded nakagami .	It can approximate lognormal channel with long term fading conditions [3] It is useful in Performance Evaluation of Space–Time Block Codes [12]
Cascaded Generalized K	Expressions for MGF, PDF, CDF ergodic capacity are obtained in [6] .Error rate, outage probability, average channel capacity are evaluated in [9].	$\prod_{i=1}^{N}\left(1+\frac{1}{m_1}\right)\left(1+\frac{1}{v_i}\right)-1$	$\bar{\gamma}^n\prod_{i=1}^{N}\frac{\Gamma(n+v_i)\Gamma(n+m_i)}{\Gamma(m_i)\Gamma(v_i)v_i^n m_i^n}$	For m_i=1 then it becomes k distribution. For limiting case of v_i; $i.e\ as\ v_i \to \infty$ it reduces to nakagami – model.	This distribution proved to be useful in evaluating the performance of nakagami lognormal channel. .It is used to analyze the performance of STBC over MIMO keyhole fading channel [6].
Cascaded Generalized – Nakagami	In [2] expressions for MGF,PDF,CDF are given in terms of Fox-H function and Outage probability ,error rates and channel capacity are also evaluated.	$\prod_{i=1}^{N}\frac{\Gamma(m_i+\frac{2}{v_i})\Gamma(m_i)}{\Gamma(m_i+\frac{1}{v_i})^2}-1$	$\bar{\gamma}^n\prod_{i=1}^{N}\frac{\Gamma(m_i)^{n-1}\Gamma\left(\frac{n}{v_i}+m_i\right)}{\Gamma(\frac{1}{v_i}+m_i)^n}$	$m_i \ge ½$ For v_i =1 then it reduces to cascaded nakgami- m model	It is used to model signal propagation through keyholes and to model the fading statistics in multihop transmission over non regenerative relays [2].
Cascaded Rayleigh	Expressions for diversity order and effective diversity order [7].Expressions for second order statistics are obtained in [8],[13].	2^N-1	$\bar{\gamma}^n\Gamma^N(1+n)$	It is single parameter distribution. It is inadequate to model all fading conditions. The envelope is uniformly distributed in [0, 2π].	Used to model multipath fading in mobile to mobile communication especially in IVC systems. Used in pilot symbol assisted co-operative systems [14]

5. OPEN ISSUES

Various existing models are surveyed on the basis of first and second order statistics. The closed form expressions of MGF, PDF, CDF of most of the models available in literature are expressed either using Meijer –G function or Fox-H function. The applicability of Fox –H function is limited as it involves intricate algorithms to solve and even there is no guarantee that it will give stable results. The data available here can be used to model fading statistics for heterogeneous composite multihop {AF (amplify and forward),DF(decode and forward), DAF (decode amplify and forward)} and keyhole channels .Even the error rates which are calculated only in case of coherent BPSK i.e. in Gaussian channel could be extended to other modems as well. Also instead of exploring new distributions, a closer match to actual scenario should be obtained.

6. CONCLUSION

Cascaded fading models are proved to be useful to model the conditions that cover wide range fading scenarios that would not have been possible with single, double or composite models. It includes those as well and even retains the ability to model all types of fading. It has also been used as an analytic tool for studying the performance of ECG diversity receivers. A generalized survey is done and this has not only facilitated us with present state of models but has also given us the gap areas which act as guide for researchers working in this area. It is expected that this overview will be helpful to students and educators who are engaged in study of wireless systems.

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