# A SURVEY OF FADING MODELS FOR MOBILE RADIO CHANNEL CHARACTERIZATION

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**Abstract** - Future 3G and 4G mobile communication systems will be required to support wide range of data rates and quality of service matrix. For the efficient design of data link and transport protocols system designer needs knowledge of the statistical properties of physical layer. Studies have shown that without proper characterization of the channel, blind application of existing protocols and transmission policy may results in disastrous performance unless proper measures are not being taken. Channel characterization also helps in allocation of resources, selection of transmission policy and protocols. A feasible measure is to have an accurate and thoroughly reproducible optimum channel model which can mimic the mobile radio channel in diversities of fading error environments. Objective of channel model is to supply proper outputs for designing of upper layer protocol in such a fashion as if it were running on the actual physical layer. The model should fit very well to the measured data and should easily handle analytically. Various approaches for characterization of fading mobile channels have appeared in literature over last five decades. This article surveys the fading channel models for proper characterization of the radio channel and provides approaches to classify the existing channel models. The paper also presents the contribution made by these channel models with their assumptions, suitability, applications, shortcomings and further improvement issues. In present environment Markov Models are best suited for characterization of the fading radio channel. In these models radio channel is presented in terms of fading states and modeled as stochastic process. A proper constructed channel model may be valuable means to enhance the reliability and capacity of future mobile radio channel.

***Keyword*** *– Markov Channel Model, Error probability, State, Fading statistics, Transmission policy*.

## I. INTRODUCTION

Considerable efforts have been made in the last few decades to propose and investigate various channel models. The Accurate channel model is valuable tool for the wireless fading channel characterization. The traditional simplest channel model is Additive White Gaussian Noise (AWGN) model in which received signal is assumed to be affected only by constant attenuation and delay [1]. Digital transmission over mobile radio channel often needs a more elaborate model. In such cases it is necessary to account for other propagation vagaries referred to as fading which affects the envelope of the received signal. Based on the fading statistics the fading channel is known as fast, slow, flat, stationary and non stationary channel. Characterization complexity of such models further increases due to involvement of large number of factors such as physical location of receiver, speed of vehicle, carrier frequency and modulation technique. Earlier, channel models are developed based on Probability Density Function (PDF) of envelope of the received signal. However, using these analytical models it is difficult to calculate system performance parameters. For example there is no closed form expression for simple characteristics associated with the model such as PDF of fade duration and PDF of number of fades inside the fixed time interval. For error performance analysis of fading channel, the continuous PDF is typically used. It involves complex integration, which is very difficult to analyze while designing upper layer protocols [2].

For 3G and 4G communication systems, the noisy channel may possess certain time varying memory content that causes channel quality to vary with time, depending on previous channel conditions. These phenomena may cause unexpected degradation to the transmission because most subsystems are designed under assumption of memory less channel [3]. When the channel quality is time varying the use of received SNR is used to measure it. The time varying memory can be exploited to find out the previous channel conditions in prediction of upcoming channel quality that can be used to improve the performance of communication system.

One of the important families of channel models that have been used to characterize the error sequence in channel with memory is Finite State Channel (FSC) models [4]. The FSC model is statistically described by probabilistic function in term of Markov chain. Fig 1 shows the basic block diagram of Discrete Markov Channel Model.

In this class of discrete channel model fading environment is first estimated and created using simulation or from the measured data set. Envelope of the received signal strength is identified and in to number of states. Each partition is known as a state, which may be associated with a particular channel quality. Transitions among states indicate the time varying characteristics of channel. The number of states and probability of state transitions reflect the channel characteristics. This can be represented by the state transition matrix P as shown below

$$P = \begin{matrix} P_{11}\ P_{12}\ldots\ldots\ldots\ldots P_{1n} \\ P_{21}P_{22}\ldots\ldots\ldots\ldots P_{2}n \\ \\ P_{n1}\ P_{n2}\ldots\ldots\ldots\ldots\ldots P_{nn} \end{matrix} \qquad (1)$$

Where $P_{ij}$ indicates that the row position of the matrix is the state from which the transition occurs and column position of the matrix is the state to which the transition occurs clearly

$$\Sigma P_{ij} = 1 \qquad (2)$$

i varies from 1 to N.

Short distance single channel can be modeled as first order two state Markov processes, which is simple in nature [8, 9, 10, 11]. If model is build for long distances for slow fading, more states need to be chosen to represent the physical system. Model parameters are then derived and optimization techniques are applied. This helps in channel statistics computation and selection of best fit model. The required computational efforts increase rapidly with number of states and quickly become computationally impractical even for the moderate number of states. For the fast and times varying channel finite 'N' state model of higher order are required. Proposed 3G and 4G wireless systems are expected to operate at 2 Mbps and 100 Mbps respectively and higher vehicular speed. Hence they will not be operating under the simple fading environment. Small distance and short term analysis is therefore not sufficient. Therefore investigating performance analysis of such systems and construction of the channel model becomes more complex. On the other hand accuracy of the model is required to statistically represent the physical channel. In this survey paper, developments in the area of fading channel models to mimic the statistical behavior of wireless channel and the underlying radio propagation are being reviewed. It is observed that the major efforts in this area are to develop models with tradeoff between complexity and accuracy in different fading environment. The paper is organized as follows. Motivation for channel modeling for its characterization is presented in section 2. The classification of channel models as Analytical and Statistical model are well described in Section 3 and Section 4 respectively. Then more advanced channel Models as variable State and Variable order Discrete Markov Models developed within wireless standards are reviewed in Section 5. Finally, paper is concluded in Section 6.

## II. MOTIVATION

Channel Model can effectively demonstrate the channel behavior based on its fading statistics. Purpose of modeling is to compute and estimate the various first and higher order fading channel statistical parameters. These channel parameters are derived from the model for performance evaluation and design of wireless communication system. Some of these parameters are Level Crossing rates (lcr), Outage time, and outage probability, distribution of lcr and Sojourn time. Outage time is the time duration for which channel suffers with outage. Outage probability shows the probability of outage. Other interesting parameter is lcr which gives the number of fades below a certain level during fixed time interval. The probability distribution of lcr further describes the fading rate of the channel. The contribution of analytical approximation using level crossing rate is important for real time application and is given by equation 3.

$$LCR = \sqrt{2\pi}.\ f_d \rho . e^{-\rho 2} \qquad (3)$$

$\rho$ is calculated using relation $R/R_{rms}$. $R_{rms}$ is the threshold level of received envelope and R is level at which crossing is to be found. It is time dependent and also affected by speed of mobile radio vehicle. Its value ranges from 0.01 to 1. The average fade duration is defined as the average time the fading envelope remains below a specified level after crossing that threshold level [7]. It can be expressed as

$$AFD = \left(e^{-\rho 2} - 1\right) \ / \sqrt{2\pi}.\ f_d \rho \qquad (4)$$

The duration of a signal fade determines the probable number of signaling bits that will be lost during the fade. This can be used to calculate BER. Sojourn time is described in terms of number of time steps for which channel remains in same state. Its distribution demonstrates the rate of change of fading. Channel model can be further used for estimating the probability of rare event like deep fades, probability of channel recovery from deep fading and critical outage time over which channel can survive. The majority of previous work of modeling channel with memory is carried out under certain assumptions. These are listed as follows-

**2.1 Assumptions -**

1. The fading process is assumed stationary. Models based on Markov processes necessitate that the error statistics remain constant over time [39].
2. Model is assumed to be constructed with one of the fading channel condition like slow, flat or fast. For the next generation practical situation these static channel conditions are not enough for designing and analysis.
3. The proposed models are based on the condition where all states are equiprobable [39].
4. The proposed models are with specific transmission schemes. Modeling assumes ideal channel coding and modulation technique.

Under these assumptions it is possible to have multiple models representing the same fading channel. The Challenge of selecting best-fit model remains to be investigated. There is couple of challenging issues to be addressed in making best fit Channel model as an accurate and useful tool for the wireless fading channel representation. These are mentioned as below.

**2.2 Challenging issues** -

1. The exact fading envelope of the channel or its SNR distribution is indefinite practically. Thus, the model is constructed under the assumption of fading distribution. Some of these are Rayleigh, Rician, Lognormal and Nakagami which are theoretically motivated from multipath point of view [8]. The PDF selection is one of the issues to be investigated.
2. the most popular first order Markov Model may not provide accurate characterization of channel in various environments. As the error process is not stationary, variation in fading due to Doppler spread and phase delay may cause fading channel to be non stationary. Thus various techniques need to be explored to apply for designing channel model for such channels.
3. The number of parameters which are computed to characterize the channel should be such that it simplifies the model performance and protocol design. The proper selection of channel parameters and transmission schemes are current research motivation in the area for fading channel characterization. These parameters must have technological interpretation. Best fit model selection issue is to be well thought-out by appropriately balancing the complexity and accuracy of the model.

## III. ANALYTICAL MODEL

Wireless Channel Error modeling schemes have been surveyed and classified in this section. These models have been developed to approximate the pathloss behavior of fading channels. A variety of channel models have been reported in the last few decades. This is pictorially depicted in Fig 2. Based on the approaches, the channel models are classified as Analytical and Statistical models. Analytical models are based on the concepts developed of received Field strength measurements, their Correlation and Distribution. In this section Analytical Models are described. These Models are basically propagation models and can be classified in various ways. In wireless communication the mechanism of radio propagation can be represented by the impulse response of the channel between the position of transmitter and receiver [42]. Time invariant channels are described by channel impulse response. It requires generation of multiple independent random processes [22]. These types of analytical models are based on received field strength like Finite scatter Model and maximum entropy model for MIMO channel and Jakes Model for fading channel [40, 41].

To represent fading channel Analytical models are also proposed in terms of Probability Density Function (PDF) to analyze the error performance. Probability Density Function of continuous channel is used, which has difficult analysis since these models involve complex integration [8, 19, and 21]. However, for the set of independent complex Gaussian process, each process should be with identical Power Spectral Density (PSD) or autocorrelation function based models like Kronecker Model. It is also assumed that Cross correlation function between them should be zero.

Construction of Analytical models requires sufficient set of measured data. This need accurate equipments for measurements and requires time to collect data. Mobile system is continuously evolving and hence assumptions and conditions at the time of measurmentmay are different from actual usage of the channel.

## IV. STATISTICAL MODEL

In order to simplify the fading channel modeling and to reduce the analytical complexity a Discrete Markov Model (DMM) is often adopted specially to fulfill the need of 3G & 4G Networks. Statistical models are then developed which are simpler to construct and estimate fading statistics. Binary Symmetric Channel (BSC) memory less channel is the simplest one which was used as a starting point for development of discrete channel models [11, 12, 13, 15, 16, 20 21, 22]. A mobile radio channel is defined in terms of noise interference and other disturbances, represented by continuous waveforms. The channel performs the stochastic or random mapping of channel input to channel output. Motivation for replacing the continuous channel model by discrete channel model increases the speed of simulation and reduces complexity. The Descrete Channel Model is an abstraction of physical channel in which channel is completely characterize by small set of parameters. The basic Markov model parameters are, Set of states, stochastic matrix T, transition probabilities, steady state vector of Transition Matrix, error probability matrix, Mean bit error rate and Initial state probability distribution. These models describe the error generation process probabilistically and are computationally more efficiently than continuous channel model. Wireless fading channel modeling with discrete Markov models has been examined in the past. This part of the paper presents brief review on the previous work mentioning various approaches taken and contributions made to construct DMM.

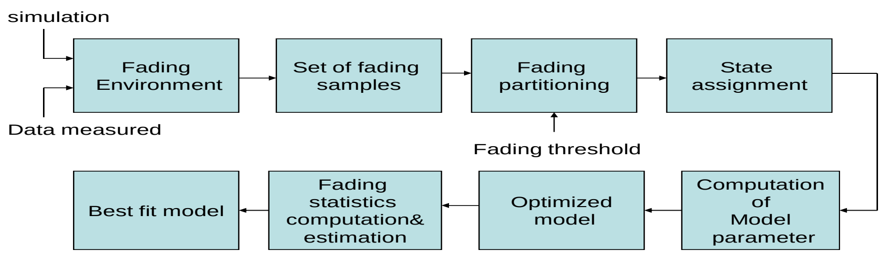


Fig. 1 - Block Diagram of Channel Model

In these models, fading channel is represented with finite number of states. Each state corresponds to a specific signal quality representing constant bit error probability. Fig.1 and Fig. 2 show the basic block schematic and classification of channel model. The very first model was given by Gilbert Elliott. In Gilbert Channel Model probability of error in good state is assumed as zero while in Gilbert Elliott channel model probability of error is assumed as non-zero. Modeling a radio communication channel as a two state Gilbert Elliott channel model is not adequate when channel suffers with time and location dependent fading as in the case with wireless channel. Channel may become frequency selective if Bandwidth of signal is greater than bandwidth of the channel. Burst error channel model is then represented by Fritchman model. In this model (N-1) states are considered as good states and one state is considered as bad state. The channel transfer function is time variant. A straightforward solution is to form a channel model with more than two states, interest in wideband systems made it necessary to incorporate frequency selectivity. Since then more sophisticated models for fading channel have been proposed. This leads to finite state Markov channel models. Fig. 3a, 3b demonstrates State diagram of two state Gilbert Elliott channel model and Fritchman burst error channel model.

### 4.1 First order Finite State Markov Chain (FSMC) Model

The DMM can be constructed as first order and higher order Finite State Markov Chain (FSMC) Model. These models are further classified as N state and variable state Markov Chain model. Attempts were made in (9, 11, 12, and 13) on the use of the first order Markov model to characterize fading channel. Most channels have slow time variable parameters and may be considered stable over a short period of time interval, This time duration may be bit time for slow fading and even packet time for fast fading [8] such a channel is modeled as a stationary channel. Multiple M stationary channel models can thus represent a non-stationary channel and the resultant model is referred as quasi-stationary model. In such cases selection of states is based on Bit Error Rate (BER) probability [9] associated with each state. Further, Wang and Mayor [10] created FSMC model with more than two states for Rayleigh channel based on SNR partitioning. Binary Symmetric channel (BSC) is associated with each state and transitions with Markovian property are assumed between states. Long range prediction of fading mobile radio channels has also appeared in literature [11].

In [12] it is shown that First Order Markov Chain model provides a mathematically tractable solution for time varying channels and uses only the received SNR of the symbol immediately preceding the current one for defining the states of the systems. Residual error exists due to intrinsic nature of physical channel even after channel code is being used. The statistics of residual error is studied in [14] for evaluating the performance of the system when block transmission is performed over the burst channel. In [16], Zang and Kassam pointed out that fading speed of the channel decides the SNR and its partitions to specify the states. They further presented the relationship between a physical channel and its finite state Markov model

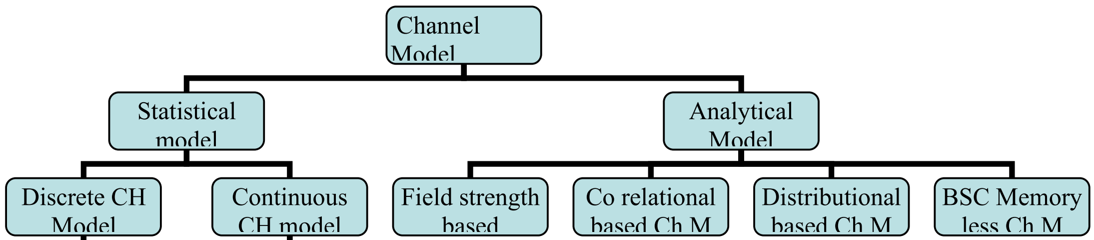
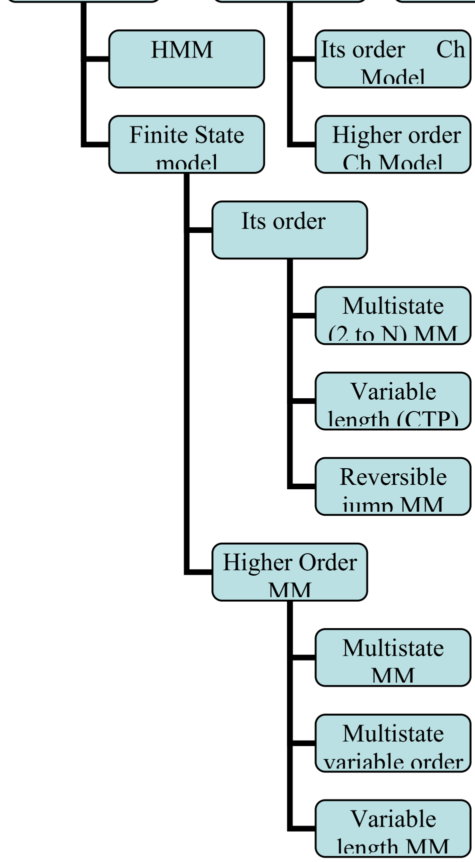


Fig. 2 - Classification of Channel Model

for packet transmission and simulation is done to compute initial statistics. It is also proposed in [16] that state time duration may be variable. The application of the first order Markov model to protocol design and performance analysis was considered in [14, 15, and 19]. This includes design of forward error control codes and throughout analysis ARQ schemes. However, the computational complexity of the model also increases exponentially with number of states and subsequent performance analysis becomes more complex.

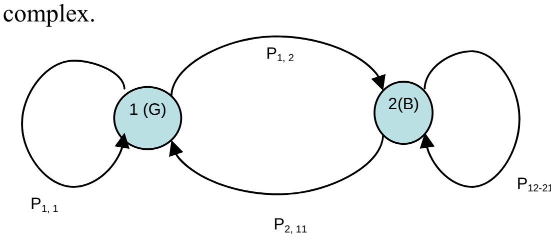


Fig. 3 a – Gilbert Elliot Channel Model

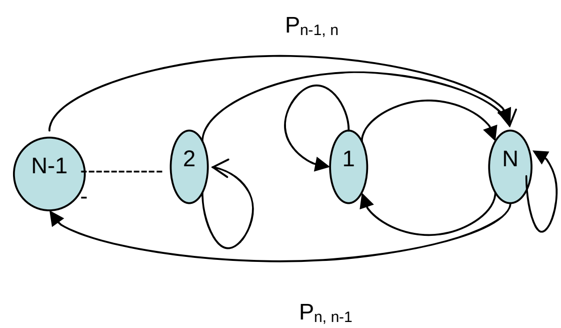


Fig. 3 b - Fritchman model for burst channel with N-1 Good state and single error state

**4.2 Finite Order Finite length Markov Model**

In the first order model only the transitions to two adjacent states are allowed where the states are ordered according to the decreasing values of bit error probability First order models are suitable for very slow fading [19] in such cases $f_dT$ is approximately taken equal to 0.007. In practical $f_dT$ ranges from zero to 0.4 there, Bi variate Rayleigh distribution is considered. This takes only adjacent samples correlation into account.

A model based on finite state Markov chain is feasible for slow channel parameters variations. The initial state distribution is also considered because the depth of fade at which channel observation starts is also crucial. This is true especially when one makes short term observations on physical channels.

In [20] two states Markov chain is discussed as Block Markov Model (BMM) and is presented as a channel characterization tool. In yet another approach slow fading channel is studied based on block error and Markov Model channel state. Block error process in a WCDMA cellular System is then presented and channel state and Block Markov Model were compared in [27]. Markov models that characterize the packet error processes on Rayleigh fading channel are considered using various binary modulation schemes. It is observed that the models available in the literature so far consider only the fading process ignoring the underlying modulation schemes used [28]. The new model is introduced for a Markov system in which repair time or outage time is sufficiently short. System availability as a measure of reliability is also examined in [29]. A sampling scheme is studied and discussed in [30] for the Rayleigh fading channel that accumulates sufficient information to successfully model the channel-state transitions "into" and "out" of the fade state". The threshold characterizing the boundaries between the fade and nonfade states is obtained as a function of the fraction of channel errors and the average SNR. The concept of a Block-Fading Gaussian Channel (BFAWGN), where the channel state over a block of possibly *N* symbols remains constant but varies from one block to another according to random process, is presented in [31].

The quantized fading channel theoretically requires infinite order model for exact description. However such models are practicality not feasible and possible as they exhibit a sufficiently large degree of complexity and memory requirements. To tradeoff between complexity and memory new approaches are proposed. For example variable order and variable states FSMC is currently being investigated. The FSMC model is completely described by specifying the transmission schemes. Improved FSMC description and as a method to build higher order model Context Tree Pruning (CTP) algorithm is being proposed in [17]. However, in the previous literature presented, the objective of a transmission policy was not considered. CTP is applied to the discrediting fading. Based on the channel conditions and respective transition probabilities context length is defined. CT models determine fading state evolution and not the quantities directly related to the fading state itself. Babich and Lombardi [3] used contingency table to determine the order of Markov chain. Narrow band Rayleigh and Rician statistics are used to compute transition probabilities. CTP algorithm is proposed as a method to buildup higher order model. The range of fading rates and threshold values are considered in building models. The state space size and structure are decided accordingly. Fig. 4 and 5 demonstrates State diagram of Finite N states first order and second order channel models.

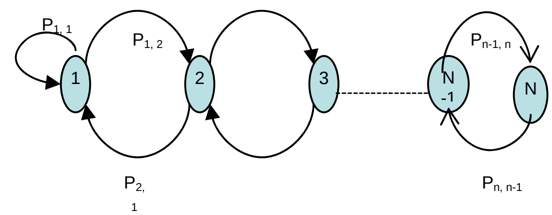


Fig. 4 - N State First Order Markov Model

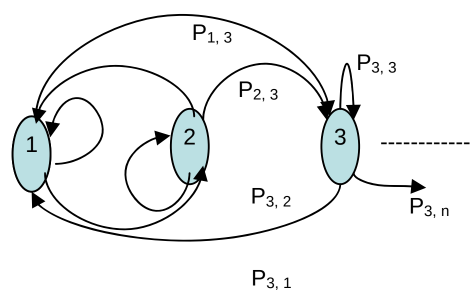


Fig. 5 - Second Order Finite State Model

## V. VARIABLE ORDER VARIABLE LENGTH MARKOV CHANNEL MODEL

Future wireless systems will be characterized by high mobility and varying physical environments. Designing of such systems will include optimization and performance assessment of communication systems that can be modeled as Markov channels with unknown memory [17]. As the presently investigated finite state and first order models are not sufficient to investigate the performance of 3G and 4G upcoming network, there have been some attempts to use higher order Markov models and Hidden Markov Model (HMM) [11, 15]. HMM was adopted to represent fading channels in Bursty error environment. Error process is specified by a probability transition matrix, initial probability matrix vector and the state dependent probability of error matrix .There are many methods for estimating the HMM parameters. The model parameters are computed on the basis of observed output sequence. Baum Welch algorithm is proposed to estimate HMM parameters [11, 15]. For modeling slowly varying fading channel, HMM approximates as a Birth Death process. The estimation becomes computationally intensive when observation output sequence contains long string of identical symbols.

Several studies [11, 14, 16, 19, and 21] have shown multistate MC as a channel model to assess the effect of fading [11, 14]. Reversible jump Markov chain is then studied which assumes blind estimation of sequence of states is taken. In contrast to traditional multistate model, no prior assumptions are considered on expected propagation condition, environment and the form of associated probability distribution. This method Can be applied to any data set regardless of environment. In this paper number of states varies during estimation process [(37]. A channel model with variable length Markov chain is proposed in [38]. The paper proposes a general class of markov chains whose structure has a variable order and parsimonious description of transition probabilities. The model based on Kullback Leibler (KL) distance of fading samples. Optimization techniques are applied for obtaining fading and simulation parameters. For minimizing the receiver computational complexity FSMC model with minimum number of states and memory order is desired. Concept of subset is therefore used in [39]. Substates are obtained by partitioning fading channel gain (Amplitude, Phase or both) into number of non overlapping intervals. The proposed analysis can be used to design receiver with minimum number of FSMC states and negligible information loss. Flat fading channel is considered with single amplitude state and number of substates based on fading channel gain phase. The proposed model is only for first or second order memory. This is used to compute the Information rate. Each model can be considered best among models with a degree of complexity.

## VI. CONCLUSION

The existing channel models are not adaptable to next generation mobile networks. These present models need to be accurate enough to meet challenges of estimating channel parameters related to fast fading and continuous time variable channel. The paper presents the evolution of fading channel models from AWGN model to advanced variable order variable state Markov Chain Model. Applications, limitations and underlying assumptions of each of the models are also discussed and objective comparison has been presented. Various issues related to channel modeling are elaborated which are still to be investigated for more optimized characterization of fading channel.

It is observed that Discrete Channel Models are best suited to next generation mobile networks. These are based on states. These states represent the channel fading condition. The choice of the particular model leads to state definitions and transition probabilities for approximating Markov chain. For the proper selection of a particular model the designer must afford a measure of fidelity and make own choice of what is acceptable compromise between fidelity and complexity. Although higher order, variable order, variable state Markov models and HMMs were used to enhance the modeling accuracy and suitability. The optimum representation in terms of optimal order and the optimal number of states is an issue of investigation. Another chellenge for future research is to determine optimum number substates, memory order and to find out lower bounds on Capacity, Reliability, and Survivability and Information rates in a communication system with fading channel environment. BER evolution of FSMC based receiver is another topic of investigation. Further improvement in channel models can be in the direction of state selection and its merging. This approach referred as “State breathing technique”, which will make adaptive creation of variable state group size as per channel fading conditions and performance requirements. This may be valuable means to enhance the reliability and capacity of future mobile radio channel.

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