Availability of Wireless Fading Channel under Outage State with Tolerance Time

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***Abstract* – Analytical models are often developed to characterize probabilistic behavior of wireless channels using Finite State Markov (FSM) model approach. The paper presents Outage Tolerant FSM (OTFSM) channel model based on maximum acceptable 'Tolerance time'. These are the short outage times, a wireless channel can tolerate without compromising telecommunication system quality in terms of acceptable Bit Error Rate (BER). The model is used to estimate channel availability and its further improvement with tolerance time. The rationale of the tolerance time threshold with error correction capability is also discussed. Constant and arbitrary distributed tolerance time is considered in model development and is applied over wireless channel. Further fading parameters of the wireless channel such as Average Fade Duration (AFD), frequency of outage and probability of outage are derived in terms of tolerance time. The case study demonstrates the improvement in channel availability by eight to ten percent with tolerance times of approximately one forth of estimated AFD. The proposed methodology will help in efficient characterization of the fading channel which can be used in deciding error correction codes to alleviate the multipath effects and to evaluate performance of the wireless system including higher order protocols.**

Keywords – Channel availability, Fading statistics, FSM model, Tolerance time, Channel coding, Weibull distribution function.

I. INTRODUCTION

Fading channel characterization plays an important role in deciding physical layer parameters such as modulation and coding techniques and for performance evaluation of the system including higher layer protocols [1, 2, 3]. The fundamental technique used to characterize a fading channel is to construct the suitable stochastic model and to analyze it. In order to simplify the fading channel modeling and to reduce the analytical complexity various approaches based on Finites State Markov [FSM] model have been presented in the past [4, 5, 6, 7]. These approaches were also applied to estimate fading parameters such as AFD, frequency of outage and probability of outage of the wireless channel. Further channel models were developed with more than two states based on partitioning of received signal to interference ratio (SIR), appeared in literature [8, 9, 10, 11].

In a wireless communication system, channel bandwidth and transmitted power constitute two primary communication resources. Availability of equipments and other practical constraint like battery limit the power level in transmitted signal. Further limitations of physical medium and electronic components used to implement transmitter and receiver put upper limit on the channel bandwidth. Moreover different applications have different requirements in terms of data rate, range and mobility. In present days complex telecommunication system, spectral efficiency is the key design parameter to meet the challenges and to fulfill the requirements of emerging mobile networks [2, 3]. ITU also has announced for better spectrum efficiency as the goal for 3G IMT 2000 system. Channel availability estimation and techniques for its improvement may help in achieving such desired goals. The paper presents estimation of channel availability and its improvement using Outage Tolerant FSM (OTFSM) channel model based on concept of 'Tolerance time'. These are the short outage times, a wireless channel can tolerate without compromising telecommunication system quality in terms of acceptable bit error rate (BER). In wireless communication when received signal falls below than the threshold level, outage starts and channel becomes unavailable. Techniques such as channel coding, interleaver and diversity are applied to mitigate the fading effects [12, 14, 15]. The motivation for introducing the 'tolerance time' is to reduce the frequency and immediate need of using these techniques during outage time. From this perspective, the channel can be finely forced to operate during these tolerable outage times. Investigations are also made to analyze the effect of tolerance time on fading parameters of wireless channel, channel coder and interleaver. Paper is arranged in following sections. In Section II, a brief survey of existing channel models with their assumptions and limitations is presented. The new model with the concept of 'Tolerance time' is introduced in Section III. Methodology to estimate the channel availability and fading parameters of wireless channel with and without 'Tolerance time' is developed in Section IV. The case study and results are presented in Section V with conclusion in Section VI.

II. THE EXISTING CHANNEL MODELS

Channel modeling is often done to investigate influences of noise and signal transmission perturbations on the performance of a wireless system. An ideal Additive White Gaussian Noise (AWGN) channel model [1] is often used for communication system analysis as it provides upper bound on system performance such as channel capacity. However, in wireless communication systems the channel is subjected to various impairments in addition to additive noise thus results in large and small scale fading [2, 3]. Wireless channels suffer with time and location dependent fading resulting in fluctuation of received signal power. Simple AWGN model is, therefore, no longer valid and there is a need for more and suitable channel model. Traditional Radio channel models are usually large scale fading models based on Maxwell's equations in free space propagation. These models were developed and evaluated while considering specific channel condition which leads to an empirical characterization of channel which lacks generalization. [3].

Analytical models representing fast fading channels are proposed in terms of Probability Density Function (PDF) of received signal envelope. However it is difficult to analysis PDF of continuous channel since these models involve complex integration [3, 6, 8]. In order to simplify the fading channel modeling and to reduce its analytical complexity a FSM model is often adopted specially to fulfill the need of 3G and 4G Networks. The FSM model is an abstraction of physical channel in which channel is completely characterized by small set of parameters.

Binary Symmetric Channel (BSC) is the simplest one among discrete Markov models. Gilbert [4] and Gilbert Elliott [5] channel models were proposed in 1960 and 1963 respectively, which are based on FSM channel modeling. Various approaches for characterization of fading radio channels as FSM have appeared in literature over last five decades [8, 9, 10, 11, 12]. All these channel models are based on identification of suitable probability density function (pdf) of received signal. In mobile communication system, wireless channel suffers with multipath propagation and therefore the received envelope is approximated according to certain pdf like Rayleigh, Rician and Nakagami, which are theoretically motivated from multipath point of view. The complete range of received signal strength normalized to its rms value is divided in finite number of non overlapping intervals. Each interval of received signal envelope amplitude represents a particular state corresponds to different channel quality. Fading is said to be occurred and channel is said to be in outage state whenever the received signal falls below than the specified SIR threshold. Rest of the time channel will be in satisfactory state. The channel model is further classified as finite 'N' state and variable state FSM model [7, 8]. Most of the wireless channels have slow time varying signal strength parameter and may be considered stable over a short period of time interval. Wang and Mayor [8] proposed FSM channel model with more than two states based on SIR partitioning for Rayleigh channel. Binary Symmetric Channel (BSC) is associated with each state and transitions with Markov property are assumed between states. Deterministic channel modeling and long range prediction of fast fading mobile radio channels has also appeared in literature [6]. The statistics of residual error is studied by Zorzi [9], in which block of data transmission is considered over the burst channel. Zang and Kassam [10] pointed out that SNR and number of partitions depends on fading speed of the channel. Babich et al. [11] proposed a technique to improve FSM description and as a method to build higher order model with Context Tree Pruning (CTP) algorithm.

Stochastic channel models are proposed to compute and estimate first and higher order fading channel statistic like frequency of outage, (frequency of transitions from and to outage states), AFD (average time during which channel experiences fade), average satisfactory time between two outages and outage probability, (probability of channel being in fading) [12]. The state interval cannot be made too large; otherwise variance of received signal strength will not be distinguished [7]. In [13, 17] the minimum duration of outage was discussed using specific fade duration distribution (FDD) function.

It is revealed from literature survey that a major contribution to channel characterization is based on FSM channel modeling and evaluation of traditional fading parameters [18]. It has been observed that the Markov model approach was not applied for estimation of channel availability and its improvement. However in recent years Mobile systems are emerging as 3G and 4G networks. For such systems the different frequency components contained in the transmitted bandwidth experience hostile channel environment and operate at high data rate up to 2Mbps. Hence, there is a need to reform the existing FSM models and to evaluate additional channel characterization parameters such as tolerable outage time and channel availability.

This paper presents development of OTFSM channel model based on tolerance time and estimation of channel availability using the same.

III. THE PROPOSED CHANNEL MODEL

In the proposed model concept of combined states is considered. The state space 'S' consists of 'n' states, each state corresponds to non overlapping interval of received signal strength. Further 'S' is partitioned in to two disjoint subsets S_1 and S_2 where

$$S_1 = \{1, 2 \ldots \ldots, k\} \tag{1}$$

$$S_2 = \{k+1, k\ k+2, \ldots \ldots, n\} \tag{2}$$

Where states '1' to 'k' are considered as satisfactory states and 'k+1' to 'n' are the outage states. Transitions 'q_{ij}' indicate transition from one of the satisfactory state ' $i \in S1$' 'to one of the outage state '$j \in 2$' vice versa is 'q_{ji}'. Let 'P_s' is the probability that the channel is in one of satisfactory states and 'P_o' is the probability that the channel will be in one of outage states. These quantities are computed using frequency duration analysis, as follows [16]

$$P_s = \sum_{i}^{k} P_i \qquad 1 \le i \le k \tag{3}$$

$$P_o = \sum_{k+1}^{n} P_j \qquad k+1 \le j \le n \tag{4}$$

'P_i' is steady state probability of being in state 'i' and 'P_j' is steady state probability of being in state 'j'.
Frequency of transitions from subset 'S1' to subset 'S2' is denoted by 'f' and computed as follows [16] -

$$f_{out} = \sum_{i=1}^{k} P_i \sum_{j=k+1}^{n} q_{ij} \tag{5}$$

The transition frequency includes all transitions that leave 'S1' and enter 'S2', but ignores all transition that occurs among states in a subset. Let 'T_{out}' is the random variable indicates the fading interval. Then '$\overline{T_{out}}$' is the AFD for which channel will be in outage and is evaluated as follows

$$\overline{T_{out}} = \frac{P_o}{f} \tag{6}$$

Let 'T_s' is the random variable indicates the satisfactory interval. Average satisfactory time ($\overline{T_s}$) between two outage can be computed as

$$\overline{T_s} = \frac{P_s}{f} \tag{7}$$

Above fading parameters are used to evaluate channel availability and fading parameters with tolerance time.

A. *Formulation of tolerance time*

In this section concept of 'Tolerance time' is introduced. GSM system employed with convolution channel code and interleaver for case study purpose [15]. Let the convolution code used in the system be of code rate 'r', and hamming distance of 'd_{free}', then the length of the burst error can be corrected by such codes defined as error correction capability 'E_c' in terms of number of bits is given as [2,3]

$$E_c = \frac{1}{2}(d_{free} - 1) \tag{8}$$

If 'T_b' is the bit duration, the transmission corresponding to error correction time 'Tc' is given by

$$Tc = T_b \times E_c \tag{9}$$

Further, if interleaver of length 'd' is used, then Tc is defined as

$$Tc = T_b \times d \times E_c \tag{10}$$

Table 1 indicates the 'Tc' for the various code rate and interleaver depth with constraint length = 9.

TABLE 1 – CHANNEL CORRECTION TIME FOR VARIOUS CODE RATE AND INTERLEAVER DEPTH

Convolution Coder		Tc , Channel correction time		
d_{free}	*Rate*	*Without Interleaver*	*With Interleaver depth*	
			d = 5	d = 9
12	½	18 μsec	90 μsec	162 μsec
24	¼	39.6 μsec	198 μsec	356 μsec

Let denote maximum tolerance time as 't_{tol}' and some value of tolerance time is denoted as 'τ'. When tolerance time is considered, the states which fall under tolerable outages will be considered as satisfactory states. This results in OTFSM channel model. Value of the tolerance time can be selected according to past outage statistic, error correction time and acceptable BER. In terms of threshold value of the tolerance time, two cases may be considered
Case 1 - Constant tolerance time of value 't_{tol}'.
Case 2- Variable tolerance time distributed according to some distribution function.
Let take range of 'τ' from 'τ_1' to 'τ_2' with

$$\tau_1 < \tau < \tau_2 \tag{11}$$

$$\text{For } \tau = 0, \tag{12}$$

OTFSM model would behave same as the original model.

$$\text{For } \tau = \infty, \tag{13}$$

OTFSM will never be in fading. Tolerance time may be considered as non-negative random variable with certain distribution like Weibull, Beta or Exponential with distribution function F(τ). In the paper Weibull distribution function with parameters α and β is considered, given as

$$F(\tau) = 1 - e^{-\beta \tau^{\alpha}} \tag{14}$$

For α = β =1, It will be negative exponential distribution function.

IV. METHODOLOGY TO ESTIMATE CHANNEL AVAILABILITY

For the proposed study constant and arbitrary distributed tolerance time are considered and therefore FSM model evolved as OTFSM model. If outage time is greater than 't –**T_C**', but less than τ , the channel is supposed to be in satisfactory state, otherwise in outage state for the OTFSM model.

Table 2 indicates the channel availability at different observation time.

TABLE 2 - CHANNEL AVAILABILITY AT DIFFERENT OBSERVATION TIME FOR THE EXISTING / OTFSM CHANNEL MODEL

Channel model	$t < T_c$	$T_c < t < t_{tol}$	$t > t_{tol}$
FSM model state/Availability	Satisfactory/ Available	Outage/ Unavailable	Outage/ Unavailable
OTFSM model state/Availability	Satisfactory/ Available	Satisfactory /Available	Outage/ Unavailable

Following part of the section presents the methodology to estimate channel availability (the probability that the channel is operating satisfactorily at time't') while accounting for the constant and arbitrary distributed tolerance time.

A. Case 1: Constant tolerance time

Let '$X(t)$' represents the stochastic process describes existing channel model without tolerance time and '$Y(t)$' represents OTFSM channel model that includes tolerance time. $V(t)$ and $\bar{V}(t)$ are considered as instantaneous availability of existing and OTFSM channel model respectively. Probability (at time t' channel is in satisfactory state) is denoted by the summation of the probability that the stochastic process '$X(t)$ and $Y(t)$' are in satisfactory state and the probability that '$X(t)$' is in outage but '$Y(t)$' is in satisfactory state, given as follows [14]

$$\bar{V}(t) = P(Y(t) = 1, X(t) = 1) + Y(t) = 1, X(t) = 0) \tag{15}$$

$Y(t) = 1,\ X(t) = 1)$ is the channel availability for the existing channel model and represented as :) .

Channel availability for the OTFSM channel model $\bar{V}(t)$ can be shown as below

$$\bar{V}(t) = V(t) + P(Y(t) = 1, X(t) = 0) \tag{16}$$

For the first order two state Markov process channel availability is computed as follows [14]

$$V(t) = \frac{\mu}{\mu+\lambda} + \frac{\lambda}{\mu+\lambda} e^{-(\lambda+\mu)t} \tag{17}$$

'λ' and 'μ' are the rate to arrive and departure from the outage state. The computation is required which denote the probability that the channel is in satisfactory state and surviving while it is in fading. This is shown as follows

$$P(Y(t) = 1, X(t) = 0) = \int_0^{\infty} \int_0^{\min(t,\tau)} V(t - Tc)\lambda\, P(Tc < t < \tau)\, dTc\ dF(\tau) \tag{18}$$

When tolerance time is denoted as a random variable 'τ' with distribution function of F(τ), "(18)" indicates the probability of transition of the existing model from satisfactory state to outage state in time $(t - Tc)$ to $(t - Tc + t_{tol})$ and the outage time is greater than '$t - Tc$' but less than 't_{tol}'. For constant tolerance time it is derived as follows -

$$= \int_0^{\min(t,t_{tol})} (\text{Rate at which channel visit state '1'} * \text{channel remain available at } (t - Tc)\text{time}) * P(Tc < t < t_{tol})\, dTc \tag{19}$$

Value of $V(t - Tc)$ is substituted from equation "(17)" therefore

$$P(Y(t) = 1, X(t) = 0) = \int_0^{\min(t,t_{tol})} (1/\mu + \lambda[\mu + \lambda e^{(\lambda+\mu)\bar{}(t-Tc)}]\, \lambda (e^{-(t-Tc)\mu} - e^{\mu T})) \, dTc \tag{20}$$

When $T_c < t < t_{tol}$, the existing channel model will be in outage state while OTFSM model will be considered in satisfactory state. It involves complex integration process hence derived as

$$P(Y(t) = 1, X(t) = 0) = \frac{\lambda}{\lambda+\mu} [(1 - e^{-(\lambda+\mu)t}) - e^{\mu t_{tol}} (\mu t + \frac{\lambda}{\mu+\lambda}(1 - e^{-(\lambda+\mu)t})] \tag{21}$$

Channel availability for the OTFSM model is summation of "(17)" and "(21)", given as

$$\bar{V}(t) = V(t) + P(P(Y(t) = 1, X(t) = 0) \tag{22}$$

As 't' tends to infinity, channel steady state availability can be expressed as follows

$$\bar{V} = V + \lim_{t\to\infty} P(P(Y(t) = 1, X(t) = 0) \tag{23}$$

$$\bar{V} = V + \frac{\lambda}{\lambda+\mu} [(1 - (1 + \mu t_{tol})e^{-\mu t}) \tag{24}$$

Channel instantaneous and steady state unavailability can be expressed as -

$$(1 - V(t)) \text{ and } (1 - \bar{V}(t)) \tag{25}$$

B. Case 2: Variable tolerance time

When tolerance time is denoted as a random variable 'τ' with distribution function of F(τ) ,

$P\ (Y(t) = 1, X(t) = 0\ )$ can be written [14] as follows

$$= \int_0^{\infty} \int_0^{\min(t,\tau)} V(t - Tc)\lambda . P\ (Tc < t < \tau) dTc \ \ dF(\tau) \tag{26}$$

Then we can get steady state system availability as

$$\bar{V} = V + \frac{\lambda}{\lambda + \mu} \int_0^{\infty} [\,(1 - (1 + \mu\tau)e^{-\mu\tau})\,] dF(\tau)$$

$$= V + \frac{\lambda}{\lambda+\mu} \int_0^{\infty} (1 - e^{-\mu t} dF(\tau) + (\mu\tau e^{-\mu t})\, dF(\tau)\,)$$

$$= V + \frac{\lambda}{\lambda+\mu}\ (\ 1\text{-}\ f^*(\ \mu) + \mu\ d(f^*(\ \mu)/d\mu) \tag{27}$$

Where $f^*(\ \mu) = \int_0^{\infty} e^{-\mu t} dF(\tau)$ (28)

$f^*(\ \mu)$ is Laplace Stieltjes Transform (LTS).

For Weibull distributed tolerance time with $F(\tau) = 1 - e^{-\beta\tau^{\alpha}}$, let $\alpha = 1$, $\beta = 1$, "(28)" can be evaluated as

$$f^*(\ \mu) = \frac{1}{1+\mu} \tag{29}$$

and using "(29)", channel steady state availability for OTFSM model "(27)"can be rewritten as

$$\bar{V} = V + \frac{\lambda}{\lambda+\mu}\, [\,(1 - \frac{1}{1+\mu} - \frac{\mu}{(1+\mu)^2}) \tag{30}$$

C. *Effect of tolerance time on fading statistics*

Probability that outage time is less then time't' is denoted as $P\ (t_{out} \le t)$, hence

$$P\ (t_{out} \ge \tau) = (1 - F(\tau)\ ) \tag{31}$$

Let denote 't_{out}' and '$\overline{T_{out}}$' are the instantaneous outage time and AFD without tolerance time .

pdf of instantaneous outage time is shown as below-

$$f_{\overline{T_{out}}}\ (\tau) = \frac{d\,P\,(t_{out} \ge \tau)}{d\tau} \tag{32}$$

If outage time is Weibull distributed then

$$P\ (t_{out} \ge \tau) = 1\text{-}\ (1\text{-}\ e^{-\lambda\tau^{\alpha}}) = e^{-\lambda\tau^{\alpha}} \tag{33}$$

Let denote t'_{out} and $\overline{T'_{out}}$ are the instantaneous outage time and AFD of fading channel modeled as OTFSM .

- ***Density function of outage time of OTFSM***

$$f_{T'_{out}}\ (t'_{out}) = \frac{f_{\overline{T_{out}}}\ (t'_{out})}{P(t_{out}\ \ge\ t_{tol})} \tag{34}$$

Using "31", "32" for any $F(\tau)$, "34" can be computed and used to evaluate AFD of OTFSM model.

- $\overline{T'_{out}}$ **(AFD of OTFSM model)**

$$\overline{T'_{out}} = \int_{t_{tol}}^{\infty} t'_{out}\ f_{\overline{T_{out}}}\ t'_{out}\ dt'_{out} \tag{35}$$

Using "34", $\overline{T'_{out}}$ can be computed.

- f'_{out} **(Frequency of outage of OTFSM model)**

= Level crossing rate. Pr (Crossing is an outage)

Using "5", "31", f'_{out} can be given as

$$= f_{out}\ \ (\ Pr\ (t_{out}\ \ge\ t_{tol})) \tag{36}$$

Substituting from "(33)"

$$= f_{out}\, e^{(-t_{tol}/\overline{T_{out}})^{\alpha}} \tag{37}$$

Let ratio of tolerance time to AFD is termed as Tolerant Factor (TF) and denoted by 'υ'. Equation "(37)" can be rewritten as

$$f'_{out} = f_{out}\ e^{(-\upsilon)^{\alpha}} \tag{39}$$

Using Equation "(33)", the probability of outage time greater then tolerance time can be rewritten as

$$R_{tol} = P\ (t_{out} \ge t_{tol})\ = e^{-\upsilon^{\alpha}} \tag{40}$$

Figure 1 shows the probability of outage time greater then tolerance time with variation in tolerant factor, 'υ'.

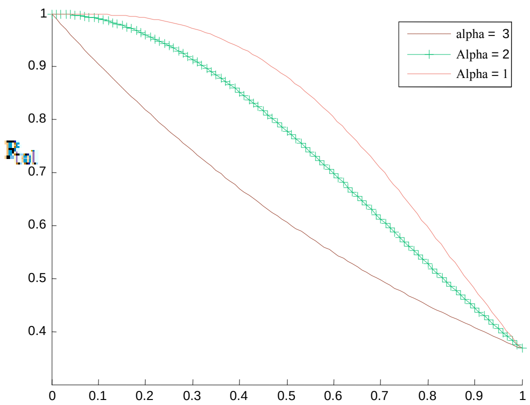

Figure - 1 Probability of outage time greater then tolerance time with variation in Tolerant Factor , 'υ' .

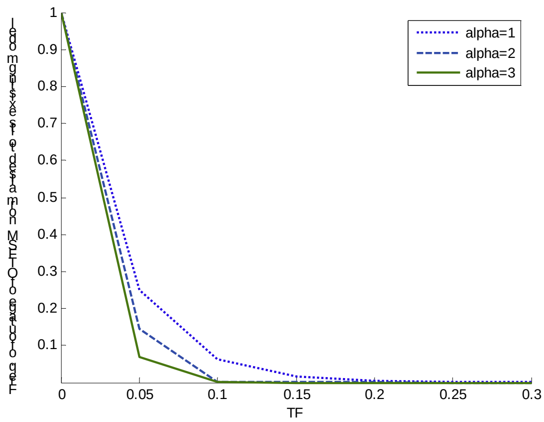

Figure 2 - The variation in normalized frequency of outage of OTFSM with TF.

Figure 2 demonstrates the variation in frequency of outage of OTFSM model normalized to its frequency of outage of existing model, with respect to TF.

The comparison of frequency of outage with different values of 'α' is shown in the plots. It is observed that the frequency of outage decreases faster with smaller TF.

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V. CASE STUDY AND RESULTS

Rayleigh channel is simulated using MATLAB. AFD is calculated using "(6)" and 'λ' and 'μ' are derived from simulation results with fade depth of = 10 dB. Two different values of 'μ' of 26 and 128 transition per unit time and two values of tolerance time according to AFD are considered for case study purpose.

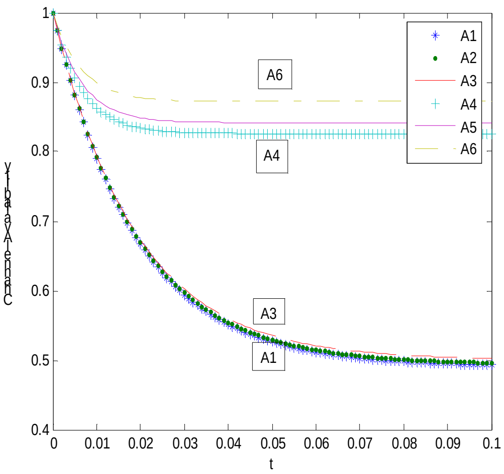

Figure 3 – Channel availability of OTFSM model and existing model with 'μ' = 26 and 128 tr. /time

In figure 3 the plots A1 to A3 and A4 to A6 indicate the variation in channel availability with lower and higher departure rates respectively. Plots A2, A3 and A5, A6 show the variation in channel availability of OTFSM model with tolerance time of 0.00195 sec and 0.0039 sec. A1 and A4 show the variation in channel availability of existing model. It can be demonstrated that the channel availability improves using OTFSM model by eight to ten percent and with increase in departure rate 'μ'.

VI. CONCLUSION

Concept of channel availability and tolerable outage time were not discussed in past using FSM channel model approach. This paper first discusses existing channel models with their assumption and limitations. Development of outage tolerant FSM channel model is presented to evaluate channel availability. Concept of tolerance time is introduced as a technique to improve channel availability. Fading parameters such as frequency of outage and probability of outage time greater than tolerance time are also evaluated using Weibull distributed tolerance time. It has been shown that tolerance time has large impact on channel availability and fading parameters of the wireless channel. Results may be used to decide physical layer parameters of the wireless channel and its performance evaluation including higher layer protocols.

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