

Characterization of Error Sequences in UHF Digital Mobile Radio Channels

Assia Semmar, Michel Lecours, *Senior Member, IEEE*, Jean-Yves Chouinard, *Member, IEEE*, and John Ahern, *Member, IEEE*

Abstract—A statistical characterization of transmission errors for digital mobile radio links at 910 MHz in different types of urban areas is presented. Error sequences for messages of 2 s duration at a nominal rate of 20 kb/s for BPSK demodulated transmissions have been obtained and characterized by Fritchman's channel model including one error state and two to four error-free states. In the data analyzed no trend has been observed in the Fritchman parameter in function of the type of area or of vehicle speed. Typical Fritchman parameter values have been established, however, in function of average channel error rate, for low and intermediate error rate channels, in the order of 10^{-3} and 10^{-2} , and for higher error rate channels. Results are also presented for a limited sample of QPSK demodulated 40 kb/s transmissions.

I. INTRODUCTION

TO optimize the design of digital mobile radio systems requires knowledge of the transmission channel properties. The objective of the present paper is to characterize transmission errors in digital mobile radio links in urban areas by Fritchman's digital channel model [1]–[3]. Such a description can be used to determine or simulate the typical characteristics of digital transmission channels, taking into account the real conditions met in practice such as mean error rates, error burst and error-free interval distributions [4], [5]. It can also be applied to the design of error control coding schemes [6]–[8].

With this objective of characterizing digital mobile radio links, a series of experimental measurements have been taken with BPSK modulated signals at a nominal rate of 20 kb/s (19.531250 kHz) at a frequency of 910 MHz. An important feature of the transmission system was the use of highly stable reference oscillators at transmitter and receiver, providing close to perfect bit clock timing and carrier stability, so that the received carrier phase was essentially affected only by Doppler shift and channel effects. From the sampling at every baud of the in-phase and quadrature component of the mobile unit circulating in different types of urban areas at a range of up to 6 km from the base station and at speeds between 20 and 100 km/h, error sequences corresponding to differentially decoded BPSK demodulated transmissions of 2 s duration have been determined and analyzed. The same has been done, using QPSK demodulation, with a limited sample of representative received signal records.

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A. Semmar, M. Lecours, and J. Ahern are with the Electrical Engineering Department, Laval University, PQ, Canada 61K 7P4.

J.-Y. Chouinard is with the Electrical Engineering Department, University of Ottawa, Ottawa, ON, Canada K1N 6N5.

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In the next section of this paper, the experimental system will be described. The following sections will deal with the characterization of error sequences for BPSK using Fritchman's digital channel model, and typical Fritchman's parameters will be established for low and intermediate error rate channels (in the order of 10^{-3} and 10^{-2} error rates) and for higher error rate channels. In the last section, some results applicable to QPSK will be presented.

II. EXPERIMENTAL SYSTEM

The experimental system consists of a base station transmitter, and of a mobile unit equipped with a receiving and data acquisition system. As illustrated in Fig. 1, the fixed base station transmits a binary phase modulated signal at a frequency of 910 MHz through a 6-W amplifier feeding a 3-dB gain vertical monopole. A frequency synthesizer (HP-8663A) is driven by a 5 MHz quartz reference oscillator, this quartz oscillator having a short term stability in the order of 10^{-12} . The output of the same 5 MHz oscillator, after division by 256, provides a 19.531250 kHz clock to a pseudorandom sequence generator to produce the binary data stream.

The transmitting site was located at a height of 20 m atop the fifth floor of the engineering building at Laval University. This site commands a good view of the general Quebec city region, which houses a population of about 600 000, and toward the center of town which is at a distance of 4–6 km. This permitted measurements to be taken with the mobile unit moving in a varied environment such as fairly open expressways, commercial and suburban areas, the relatively dense area of the city center, and also some narrow streets of the old town.

Fig. 2 presents the block diagram of the receiving and data acquisition system housed in the mobile unit. A highly stable 5 MHz reference oscillator is also used at the receiver to drive a frequency synthesizer which will provide the receiver local oscillator signal at 910.455 kHz, to pilot two frequency synthesizers providing the IF in-phase and quadrature references at 455 kHz and to provide, after frequency division by 256 and appropriate delay adjustment, the 19.531250 kHz bit clock timing of the receiver.

The incoming 910 MHz signal at the receiver first goes through a test receiver (HP-8902A) whose local oscillator at 910.455 MHz is provided by a frequency synthesizer (HP-8673C), which is itself driven by the 5 MHz reference oscillator. The 455 kHz signal at the receiver output (as modified by the Doppler shift and the various channel effects)

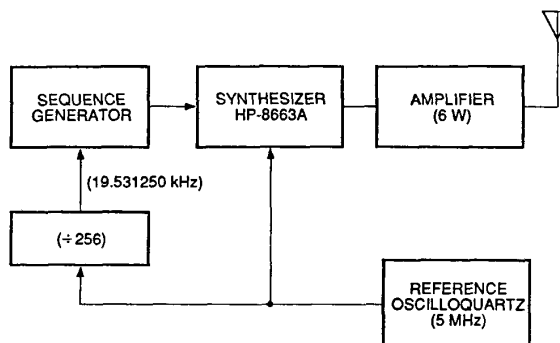


Fig. 1. Transmission system.

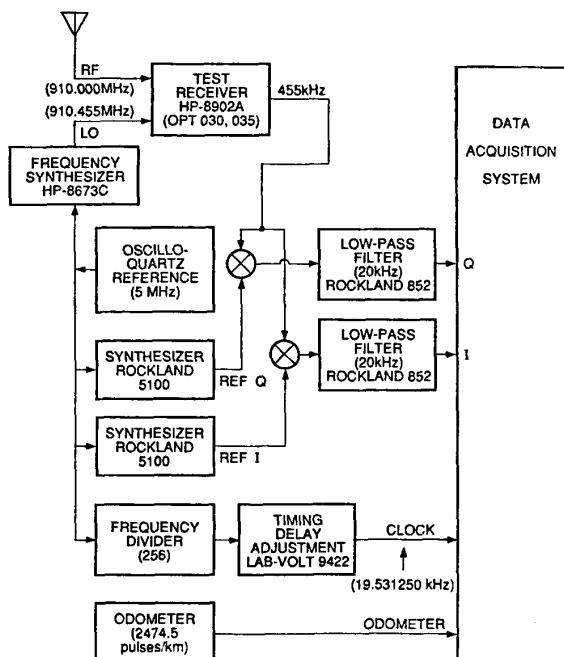


Fig. 2. Reception and data acquisition system.

is mixed with the two 455 kHz reference signals, which are 90° out of phase with each other, and are synthesized under the control of the 5 MHz reference oscillator. The in-phase and the quadrature reference signals are thus produced. The mixer outputs, once low-pass filtered, provide the base-band I and Q signals: these are sampled simultaneously at every symbol and recorded with a 12 b resolution in a microcomputer memory; record lengths of 40960 samples could be recorded, corresponding to a transmission duration of about 2 s. Odometer pulses are also sampled.

The received signal amplitude and phase are computed from the classical relationships:

$$A = \sqrt{I^2 + Q^2} \quad (1)$$

$$\Phi = \tan^{-1} \left(\frac{Q}{I} \right). \quad (2)$$

The use of frequency references with a short-term frequency stability of 10^{-12} at both transmitter and receiver,

together with a procedure at the start of each measurement period to adjust the receiving system in the mobile unit, while stationary, to be in phase—except for a small constant phase difference—with the phase of the incoming signal, permitted the observation and measurement of Doppler phase shift and channel phase effects.

An example is given in Figs. 3(a)–3(d) for a recording of a received BPSK signal at 20 kb/s (DATA 46) covering a distance of 1 m on a street in an urban area, 2.5 km from the transmitter site and oriented transversally to the direction of signal incidence. The number of samples shown on the horizontal axis indicates a time duration of some 0.2 s, and each dot on the curves corresponds to a received bit.

Figs. 3(a) and 3(b) show the I and the Q signals recorded: the linear vertical scale is arbitrary and the two curves correspond to the two BPSK states (0° and 180° or $+1$ and -1). Fig. 3(c) shows the signal amplitude computed from the I and Q samples, while Fig. 3(d) displays the phase (modulo 360°): note that the phase curves of Fig. 3(d) also come in pairs, corresponding to the two BPSK states, as was the case on Figs. 3(a) and 3(b) for the I and Q signals.

As shown by the phase curves of Fig. 3(d), the overall phase variation follows a certain slope, corresponding to the Doppler frequency and there are more or less abrupt variations due to channel phase effects [9], [10] which are obviously related to the signal fades shown in Fig. 3(c).

From the number of cycles covered by the phase recording, the Doppler frequency can be computed. The recording from which Fig. 3 was extracted, for instance, showed an average Doppler frequency of 15 Hz; this relatively low value is consistent with the vehicle speed of 19 km/h and the street orientation which was transversal to the normal direction of signal incidence.

The measurement procedure at the receiving station in the mobile unit involved a number of steps including the setting of the sampling clock so that the samples were taken in the center of the symbol period, always with the very high short-term stability offered by the reference oscillator. Moreover, after each sampling run, a part of the data in the computer memory was unmodulated and displayed on the microcomputer screen in order to check its validity before being downloaded to a disk file. There was then a definite advantage to have a relatively short data sequence so that the operator could easily check the integrity of the recording, and short sequences, 7 and 31 b long, have been used for the measurements. Such short data sequences, however, do not have long stretches of "ones" (1) and "zeros" (0), and hence, it would not have been valid to use such sequences to test a bit clock recovery circuit. However, for error rate measurements in a system which can essentially be considered as memoryless from one bit to the next, as is the case here, the results are not modified by the choice of the data sequence.

III. ERROR SEQUENCE CHARACTERIZATION

A number of models have been proposed to characterize the error sequence generation process in real communication channels [1]–[4]. Gilbert [1] originally proposed a model

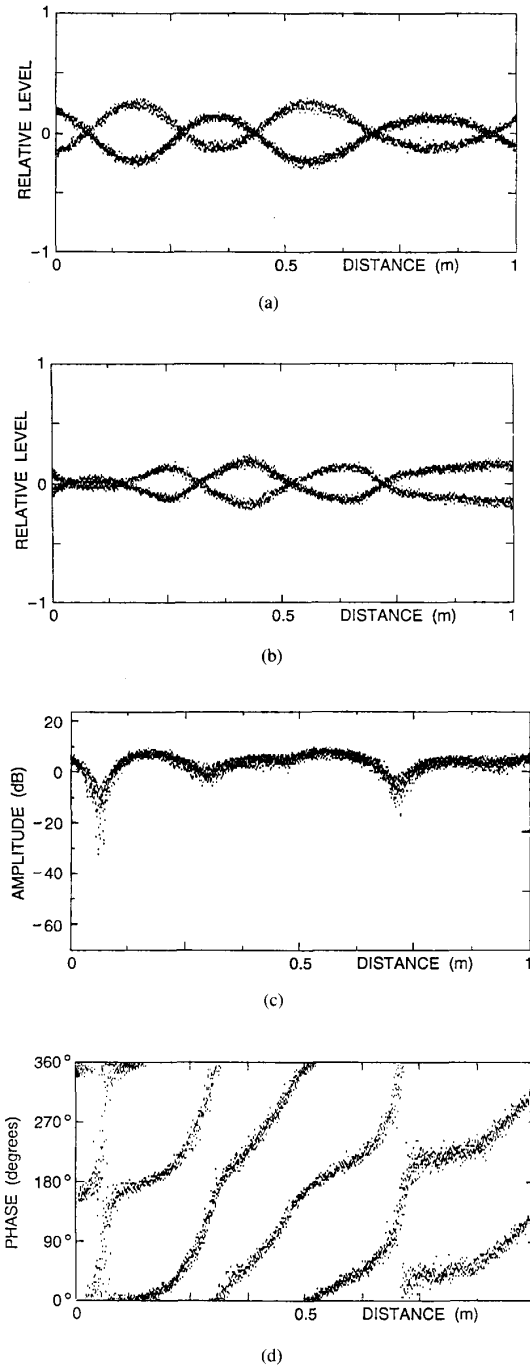


Fig. 3. Example of a received BPSK modulated signal. (a) In-phase component I . (b) Quadrature component Q . (c) Amplitude $\sqrt{I^2 + Q^2}$. (d) Phase $\tan^{-1}(Q/I)$.

based on a two-state Markov chain. The first state is an error-free binary symmetrical channel (BSC) while the second state represents a BSC having a nonzero crossover probability. The burst generation process is determined by the transition probabilities of the Markov chain. Gilbert's

model was generalized by Fritchman [2], who verified its applicability to the description of various digital channels. The model was extended to an N -state Markov chain. The N states of the Markov chain are partitioned in two groups, a first group A consisting of k error-free states and a second group B consisting of $(N - k)$ error states. In this paper, the error sequence analysis is based on Fritchman's model.

For a binary error sequence where the absence or the presence of an error is indicated by a "0" or a "1," respectively, the experimental error-free interval length distribution $P(0^m | 1)$ is determined by computing the ratio of the intervals (or series of consecutive "zeros") for which the length equals or exceeds m , to the total number of intervals encountered within an observed error sequence. Similarly, we evaluate the error burst length distribution $P(1^m | 0)$ by considering, this time, the proportion in the error sequence of the consecutive series of "ones" equal to or greater than the burst length m .

An N -state Markov chain, with k error-free states and $(N - k)$ error states, corresponds to error-free interval and error burst distributions resulting from the summation of k and $(N - k)$ exponentials, respectively.

We consider the simplified version of Fritchman's model in which transitions between different states are allowed only from a state belonging to one of the two groups, that is A or B , to a state from the other group. Within a group, the only possible transitions are from and to the same state. For this particular case of Fritchman's model, the error-free interval length distribution $P(0^m | 1)$ is expressed as

$$P(0^m | 1) = \sum_{i=1}^k \alpha_i \beta_i^m \quad (3)$$

and the error burst length distribution $P(1^m | 0)$ is equal to

$$P(1^m | 0) = \sum_{i=k+1}^N \alpha_i \beta_i^m \quad (4)$$

where the values α_i and β_i are Fritchman's model parameters.

The error generation process is determined by the transition probabilities $P_{i,j}$ from a state i , at a given instant, to the subsequent state j . For the simplified model, the probability $P(0^m | 1)$ of obtaining an interval length greater than or equal to m bits can be related to the transition probabilities [2]:

$$P(0^m | 1) = \sum_{i=1}^k \frac{P_{N,i}}{P_{i,i}} \cdot (P_{i,i})^m \quad (5)$$

For $i = 1$ to k and $N - k = 1$ which is the case illustrated in Fig. 4, the transition probabilities are related to Fritchman's parameters by

$$P_{i,i} = \beta_i \quad (6a)$$

$$P_{i,N} = 1 - \beta_i \quad (6b)$$

$$P_{N,i} = \alpha_i \beta_i \quad (6c)$$

$$P_{N,N} = 1 - \sum_{i=1}^k \alpha_i \beta_i \quad (6d)$$

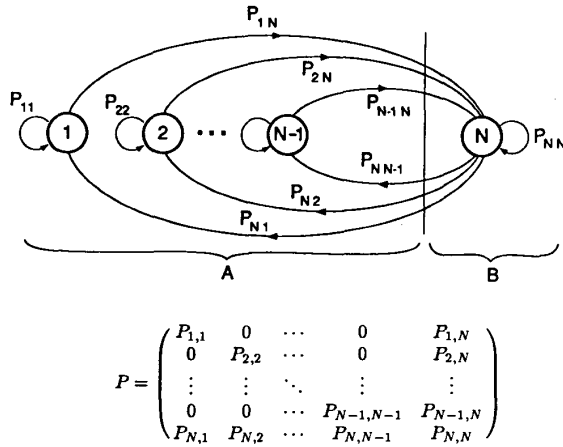


Fig. 4. Fritchman's simplified model with $k = N - 1$.

In many cases [1], [2], [5], it has been found that the error burst distribution is well described by a single exponential. A single error state, as in Fig. 4, is then sufficient. We have used a least-square linear regression to determine the corresponding Fritchman parameters. This is illustrated, for a typical data file, in Fig. 5 where the staircase function is the measured error burst distribution and the straight line is the result of the least square linear regression. The corresponding exponential equation for $P(1^m|0)$ is indicated in the lower left-hand corner of the figure. The mean square error for the data file illustrated in Fig. 5 is 1.14×10^{-2} which is somewhat better than the median mean square error value of 5×10^{-2} for all data files.

As for the interval length distribution, Fritchman [2], Chouinard [5], and others have found that a model with $k = 2$ or 3 exponential functions is generally sufficient. In our case, we have, for the high error rate sequences, used a model with up to four exponential functions. To determine Fritchman's parameters, different methods are available. We have used the Gauss-Newton method [11], which performs well and converges rapidly. This is illustrated for a typical data file in Fig. 6 where the function with irregular steps is the experimental error-free length distribution and where the smooth curve represents the distribution given by the model, in this case, a $k = 3$ exponential functions model, once the Gauss-Newton optimization process has been completed. One initiates the optimization process by determining the number of straight line segments required to represent the distribution and by determining initial approximate values for the slope of these segments and hence for the Fritchman parameters. After a few iterations, the algorithm converges towards the final parameter values. In the case of Fig. 6, the residual mean square error was 2.5×10^{-2} which is close to the median value of 10^{-2} for all files.

In the lower left-hand corner of Fig. 6, the equation for the error-free length distribution $P(0^m|1)$, which corresponds to a sum of three exponentials, is given as well as the corresponding Fritchman parameters. In the upper right-hand corner, the corresponding state diagram with the $P_{i,j}$ transition probabilities is illustrated: these can be computed, using (6d),

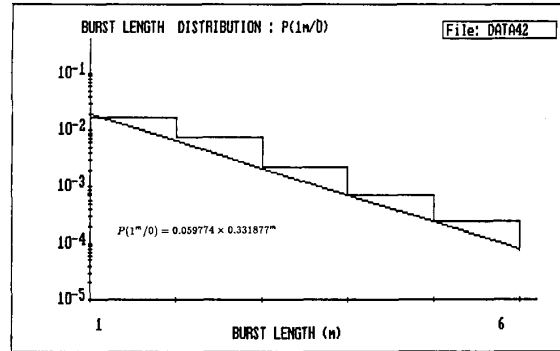


Fig. 5. Error burst length distribution $P(1^m|0)$ and corresponding least squares curve (file: DATA 42).

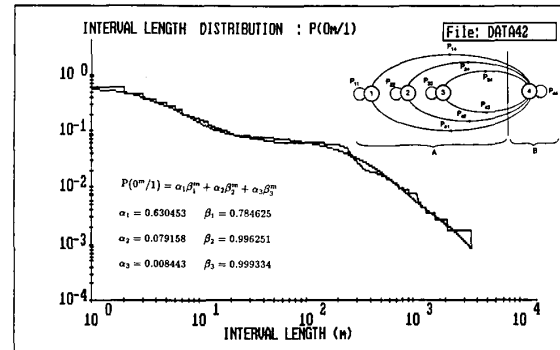


Fig. 6. Error-free interval length distribution $P(0^m|1)$ and obtained Fritchman's model curve for $k = 3$ (File: DATA 42).

from the Fritchman parameter values, as will be discussed further in the next section.

IV. RESULTS FOR BPSK DEMODULATION

In order to permit an interpretation of the characteristics of the recorded data, the data files have been divided in three classes, by order of increasing error rate, computed as the ratio of the error count to the total number of bits (40960), and classified so that the first class of four files groups sequences with low error rates (i.e., $\text{BER} < 10^{-2}$), the second class of 20 files groups files with intermediate error rates ($10^{-2} \leq \text{BER} < 10^{-1}$), and the third class includes 11 files with high error rates ($\text{BER} \geq 10^{-1}$). The results for the measured error rate distributions will first be presented, after which Fritchman's model parameters will be discussed.

A. Error Burst Distributions

With the burst rate defined as the ratio of the number of bursts of a given length to the total number of bursts, Fig. 7 gives the error burst distribution for each class of channels as defined above (low, intermediate, and high error rate channels). For the error sequences measured, the longest error burst observed had a length of 13.

On average, from the observation of the measured data or from the burst rate distributions of Fig. 7, it can be concluded that more than two thirds of all errors are produced when the burst length L is larger than 1, which is a clear

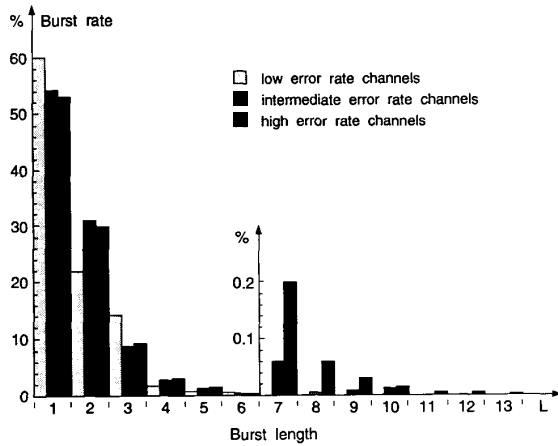


Fig. 7. Error burst distribution for low, intermediate and high error rate channels. (change of scale for $L \geq 7$).

indication of the existence of an error burst channel. The length L of these error bursts is, however, relatively short, less than 1% of all bursts having a length L of 6 or more. As should be expected, Fig. 7 shows that the higher the error rate, the higher the probability of longer bursts.

From a quantitative point of view it may be interesting to note that if, as noted above, about one third of all errors are single errors, another third are double errors (bursts of length 2) and that the total number of errors contained in bursts larger than 2 also represents about one third of the total number of errors, this number decreasing sharply as L increases.

B. Error-Free Interval Distribution

Let us recall that, for the error-sequences analyzed here, the digital mobile radio channel has been modeled by an N -state Markov chain partitioned in two groups, an A group consisting of k error-free states and a B group, including a single error state. The number of states k varies from 2 to 4. From our previous discussion on the simplified version of the Fritchman model, transitions between states are allowed only between the single state of group B and the states of group A and vice-versa; within a group, the only possible transitions are from and to the same state.

Table I presents the minimum, mean, and maximum values of the Fritchman parameters (α_i, β_i), as well as their standard deviation for low, intermediate, and high error rate channels. Let us recall that the low error channels include four data files with bit error rates lower than 10^{-2} . These have been modeled with good precision by a three-state Fritchman channel (one error state, two error-free states). The high error rate channels include 11 files with bit error rates larger or equal to 10^{-1} and these have been modeled by a four-state Fritchman channel (one error state, three error-free states). The intermediate error rate channels include 20 files, 15 of which could be modeled by a three-state Fritchman channel and the rest by a four-state Fritchman channel.

In this and subsequent tables, the convention has been

TABLE I
MINIMUM, MEAN, MAXIMUM VALUES AND STANDARD DEVIATION OF THE FRITCHMAN PARAMETERS FOR THE BPSK DEMODULATED SEQUENCES

Error Rate	Fritchman Parameters																							
	α_1			α_2			α_3			β_1			β_2			β_3								
	min	mean	max	s.d.	min	mean	max	s.d.	min	mean	max	s.d.	min	mean	max	s.d.	min	mean	max	s.d.				
Low	0.551	0.719	1.	0.213	0.096	0.158	0.314	0.105	—	—	—	—	0.418	0.664	0.857	0.182	0.998	0.998	0.999	$3 \cdot 10^{-4}$				
Intermediate	0.566	0.634	0.886	0.081	0.025	0.079	0.161	0.039	—	—	—	—	0.634	0.780	0.862	0.069	0.991	0.996	0.999	0.002				
Intermediate (4 states)	0.595	0.636	0.676	0.029	0.075	0.119	0.186	0.045	0.001	0.011	0.027	0.010	0.579	0.728	0.784	0.084	0.886	0.964	0.996	0.048				
High	0.316	0.579	0.729	0.132	0.119	0.239	0.479	0.114	0.011	0.025	0.047	0.014	0.483	0.589	0.665	0.053	0.832	0.883	0.923	0.029				
																					0.970	0.987	0.996	0.007

adopted that the least persistent error-free state is always named state 1: this state corresponds to the Fritchman parameters (α_1, β_1) and is related to the transition probabilities to and from state 1 ($P_{1,1}, P_{1,N}, P_{N,1}$). State 2, which corresponds to Fritchman parameters (α_2, β_2) and is related to the transition probabilities to and from state 2, is a more persistent error-free state than state 1. And when state 3 is an error-free state, as for the high error rate channels, then the convention that we have adopted is that it is more persistent than state 2. In other words, an error-free state 1 corresponds to short error-free intervals, while an error-free state 2 (and eventually an error-free state 3) corresponds to longer error-free intervals. The highest numbered state N is, by convention, always the error state.

For $N = 3$ and $k = 2$, the transition probability matrix between these two groups is expressed as

$$P = \begin{bmatrix} P_{11} & 0 & P_{13} \\ 0 & P_{22} & P_{23} \\ P_{31} & P_{32} & P_{33} \end{bmatrix} \quad (7)$$

with

$$\begin{aligned} P_{11} &= \beta_1 & P_{22} &= \beta_2 \\ P_{13} &= 1 - \beta_1 & P_{23} &= 1 - \beta_2 \\ P_{31} &= \alpha_1 \beta_1 & P_{32} &= \alpha_2 \beta_2 \\ P_{33} &= 1 - \alpha_1 \beta_1 - \alpha_2 \beta_2. \end{aligned}$$

In the case of the four-state Fritchman model, the transition probability matrix is written as

$$P = \begin{bmatrix} P_{11} & 0 & 0 & P_{14} \\ 0 & P_{22} & 0 & P_{24} \\ 0 & 0 & P_{33} & P_{34} \\ P_{41} & P_{42} & P_{43} & P_{44} \end{bmatrix} \quad (8)$$

with, from (6a) to (6d)

$$\begin{aligned} P_{11} &= \beta_1 & P_{22} &= \beta_2 & P_{33} &= \beta_3 \\ P_{14} &= 1 - \beta_1 & P_{24} &= 1 - \beta_2 & P_{34} &= 1 - \beta_3 \\ P_{41} &= \alpha_1 \beta_1 & P_{42} &= \alpha_2 \beta_2 & P_{43} &= \alpha_3 \beta_3 \\ P_{44} &= 1 - \alpha_1 \beta_1 - \alpha_2 \beta_2 - \alpha_3 \beta_3. \end{aligned}$$

Table II gives the transition probabilities $P_{i,j}$ between the Markov chain states, calculated per (7) and (8) from the mean values of Fritchman's parameters given in Table I. In order to use the same table format for the three-state and the four-state models, $P_{i,N}$ and $P_{N,j}$ are used to denote the transition probabilities to and from the error state N , which is always the highest numbered state in the N -state model.

In order to give some physical interpretation to these transition probabilities let us suppose that the channel is initially in state k , which is the most persistent error-free state:

- Probability $P_{k,k}$ to stay in state k is the largest among the transition probabilities and its value is close to unity. For a Markov chain with a specific number of states, the detailed results [12] show that $P_{k,k}$ has a tendency to increase as the

error rate decreases, thus promoting the creation of longer error-free intervals; consequently, probability $P_{k,N}$ of moving to the error state tends to increase with the channel error rate.

- Once at the error state N , Table II shows that the value of $P_{N,N}$ is close to 0.4 for low, intermediate as well as for high error rate channels: Specifically, the set of recorded data files [12] gives an average value of $P_{N,N}$ of 0.4222, with a standard deviation of 0.0318, the lowest and highest values being 0.3076 and 0.4879, respectively. Those relatively high values of $P_{N,N}$ cause the generation of error bursts.

V. RESULTS FOR QPSK DEMODULATION

In order to obtain results applicable to QPSK, four typical data files were selected and submitted to QPSK differential decoding and demodulation. This corresponded to a transmission rate of 20 000 bauds or 40 000 b/s. Since the data was binary phase modulated, the transmitter itself used only two out of the four QPSK states.

The results for the burst count and mean burst rate as well as for the transition probabilities between states are given in Tables III and IV. These can be compared to Tables V and VI which correspond to the DBPSK demodulation of the same sequence.

One first notes that, to properly model these channels, longer Markov chains are required than in the case of BPSK demodulation. Also, relative to BPSK demodulation, the following comments can be made:

The number of bits in error has increased by a factor of 3 to 4, or if one prefers, the number of symbols in error has increased by a factor of close to 2; this is the result of the smaller decision zones in QPSK.

The proportion of single error bits has increased and, consequently, the proportion of long error bursts has decreased: this appears simply due to the fact that a symbol error is QPSK rarely results in both corresponding bits being in error and, hence, the probability of long bit error bursts is reduced.

An increase in the proportion of medium length error-free intervals, in the range of 100–2000 b, has been noticed, which is consistent with the above comments.

VI. CONCLUSION

In conclusion, the nonuniform time-distributed behavior of error sequences in a UHF digital mobile radio channel is well described by Fritchman's error generation model. However, the actual distributions of the error bursts and of the error-free intervals are all factors that have to be considered when establishing a realistic error burst channel model. From the measured error sequences, typical Fritchman parameter values have been estimated for different bit error rates. It has been observed that a three-state Markov chain, consisting of two error-free states and one error state, is adequate to characterize the error distribution for low error rate channels ($\text{BER} < 10^{-2}$) and most of the intermediate error channels ($10^{-2} \leq \text{BER} < 10^{-1}$), while a four-state Markov chain with three error-free states is required for the remaining intermediate error rate channels as well as the high error rate

TABLE II
TRANSITION PROBABILITIES BETWEEN THE MARKOV CHAIN STATES COMPUTED FROM THE MEAN VALUES OF THE FRITCHMAN PARAMETERS FOR THE BPSK DEMODULATED SEQUENCES (TABLE I) (SUBSCRIPT N REFERS TO THE ERROR STATE, AND IS EQUAL TO THE HIGHEST NUMBERED STATE IN THE N -STATE MODEL)

Error Rate	Transition Probabilities Between States									
	$P_{1,1}$	$P_{1,N}$	$P_{2,2}$	$P_{2,N}$	$P_{3,3}$	$P_{3,N}$	$P_{N,1}$	$P_{N,2}$	$P_{N,3}$	$P_{N,N}$
Low ($N = 3$)	0.664	0.336	0.998	0.002	—	—	0.477	0.158	—	0.365
Intermediate ($N = 3$)	0.780	0.220	0.996	0.004	—	—	0.495	0.079	—	0.427
Intermediate ($N = 4$)	0.728	0.272	0.964	0.036	0.998	0.002	0.463	0.115	0.011	0.411
High ($N = 4$)	0.589	0.411	0.883	0.117	0.987	0.013	0.341	0.211	0.025	0.423

TABLE III
BURST COUNT AND MEAN RATE OF DIFFERENT BURST LENGTHS L FOR THE DQPSK DEMODULATED SEQUENCES

File	Errors	Burst Count and Mean Burst Rate									
		$L = 1$	$L = 2$	$L = 3$	$L = 4$	$L = 5$					
Data 110	713	365	0.71	127	0.25	11	0.02	10	0.02	1	0.002
Data 46	3111	1507	0.69	470	0.21	111	0.05	46	0.02	17	0.01
Data 42	3992	1894	0.69	620	0.22	120	0.04	61	0.02	26	0.01
Data 48	14905	6494	0.66	2220	0.22	570	0.05	294	0.03	134	0.01

TABLE IV
TRANSITION PROBABILITIES BETWEEN THE MARKOV CHAIN STATES FOR THE DQPSK DEMODULATED SEQUENCES ($N = 3$ for DATA 110, $N = 4$ for DATA 46 and DATA 42, and $N = 5$ for DATA 48)

File	Transition Probabilities Between States													
	$P_{1,1}$	$P_{1,N}$	$P_{2,2}$	$P_{2,N}$	$P_{3,3}$	$P_{3,N}$	$P_{4,4}$	$P_{4,N}$	$P_{N,1}$	$P_{N,2}$	$P_{N,3}$	$P_{N,4}$	$P_{N,N}$	
Data 110	0.8104	0.1895	0.9989	0.0010	—	—	—	—	0.5839	0.1169	—	—	0.2991	
Data 46	0.7596	0.2403	0.9649	0.0350	0.9991	0.0009	—	—	0.4902	0.1789	0.0164	—	0.3143	
Data 42	0.6996	0.3003	0.9375	0.0624	0.9973	0.0026	—	—	0.4229	0.2375	0.0361	—	0.3033	
Data 48	0.6500	0.3499	0.8826	0.1173	0.9626	0.0373	0.9938	0.0061	0.4152	0.2150	0.0327	0.0036	0.3334	

TABLE V
BURST COUNT AND MEAN RATE FOR DIFFERENT BURST LENGTHS L FOR A SAMPLE OF DBPSK DEMODULATED SEQUENCES

File	Errors	Burst Count and Mean Burst Rate									
		$L = 1$	$L = 2$	$L = 3$	$L = 4$	$L = 5$					
Data 110	164	72	0.64	32	0.28	9	0.08	—	—	—	—
Data 46	837	302	0.57	185	0.35	29	0.05	14	0.03	3	0.01
Data 42	1117	367	0.54	224	0.32	61	0.08	18	0.02	7	0.01
Data 48	5030	1759	0.56	1002	0.32	203	0.06	86	0.02	33	0.01

TABLE VI
TRANSITION PROBABILITIES BETWEEN THE MARKOV CHAIN STATES FOR A SAMPLE OF DBPSK DEMODULATED SEQUENCES ($N = 3$ for DATA 110 and DATA 46, $N = 4$ for DATA 42 and DATA 48)

File	Transition Probabilities Between States									
	$P_{1,1}$	$P_{1,N}$	$P_{2,2}$	$P_{2,N}$	$P_{3,3}$	$P_{3,N}$	$P_{N,1}$	$P_{N,2}$	$P_{N,3}$	$P_{N,N}$
Data 110	0.6855	0.3145	0.9987	0.0013	—	—	0.3780	0.3144	—	0.3076
Data 46	0.8630	0.1370	0.9993	0.0007	—	—	0.5248	0.0311	—	0.4441
Data 42	0.7846	0.2154	0.9963	0.0037	0.9993	0.0007	0.4947	0.0789	0.0084	0.4180
Data 48	0.5938	0.4062	0.8837	0.1163	0.9891	0.0109	0.2825	0.2932	0.0393	0.3849

channels ($\text{BER} \geq 10^{-1}$). A similar behavior is observed for the QPSK demodulated data.

The question of establishing trends or relationships between such parameters as type of urban area, vehicle speed, or dominating Doppler frequency and the values of the Fritchman parameters or of the transition probabilities is of interest for the design of error control coding schemes. To fully assess the performances of error control codes for a

wide variety of digital mobile radio channels, further experimental error distribution measurements are required. Alternatively, a simulation following the approach used by Fukasawa *et al.* [7], [8], taking into account carrier to noise ratio and coding rate, can be considered.

Error burst patterns typical of those encountered in real UHF digital mobile communication channels can be easily simulated [13] for the design and the performance analysis of

efficient error control coding schemes. Error sequences, much longer than the original error sequences can also be generated for long-run testing purposes. It is important to point out that the experimental system used, with its stable reference oscillators at the transmitter and the receiver, ensured carrier recovery and bit clock timing. The transmission system was then freed from loss of synchronization problems, which would have to be taken into account in practical system design.

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engineering career at RTM in Morocco.

Assia Semmar received the degree in telecommunications engineering from the National Institute of Post and Telecommunications (INPT), Rabat, Morocco, in 1985, and received the M.Sc. degree in electrical engineering from Laval University, Quebec, Canada, in 1991, studying under a scholarship from the Canadian International Development Agency.

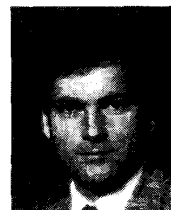
From 1985 to 1988, she worked for the Morocco Radio and Television (RTM) as a video and maintenance engineer. She is now pursuing her



Michel Lecours (S'62-M'67-SM'84) graduated from l'École Polytechnique, Montreal, in 1963 and received the Ph.D. degree in electronics and communications from the Imperial College, London, England, in 1967.

Since 1967, he has been a Professor in the Electrical Engineering Department at Laval University, the head of the Electrical Engineering Department from 1975 to 1977, and the Vice-Dean of the faculty of science and engineering from 1977 to 1985. He also worked in transmission system engineering at Bell Northern Research in Ottawa, and more recently, he was a visiting research scientist in the Digital Mobile Radio Section at the Electrical Communication Laboratories of NTT in Japan.

In the field of technology transfer, he has collaborated with Lab-Volt (Quebec) Ltd. to the development of telecommunication training equipment, for which a Canada Award for Excellence was obtained in 1986. He was also awarded, in 1987, the Annual Merit Award from the Ecole Polytechnique of the Montreal Alumni Association. In 1991, he became a Fellow of the Engineering Institute of Canada.



Jean-Yves Chouinard (S'82-S'83-M'83-M'87) received the B. Sc.A., M.Sc., and Ph.D. degrees in electrical engineering from Laval University, Quebec, Canada, in 1979, 1984, and 1987, respectively.

From 1979 to 1981, he was with Northern Telecom in Montreal, Quebec, Canada. He worked as a postdoctoral fellow at the Space and Radio Communication Division of CNET, Issy-les-Moulineaux, France, from 1987 to 1988. Since 1988, he has been an assistant professor at the electrical engineering department of the University of Ottawa, Ontario, Canada. His research interests are mobile radio propagation, in-door wireless communications, mobile-satellite personal communications, digital channel modeling, and modulation and error control coding techniques.



John Ahern (S'77-M'79-S'80-M'81) received the B. Sc.A. and M.Sc. degrees in electrical engineering from Laval University, Quebec, Canada, in 1980 and 1984, respectively.

From 1983 to 1990 he was involved in the design of several measurement systems for research into propagation and noise at VHF, UHF and microwave frequencies. During this period he also acted as a consultant to several companies, including Lab-Volt Ltd. where he was on the design team that won a Canada Award for Excellence in 1986 and World-Didac Gold awards in 1986 and 1990. He is presently Director of Engineering at Comlab Inc. and is a registered professional engineer in the Province of Quebec.