A Generic Radio Channel Emulator to Evaluate Higher Layer Protocols in a CDMA System

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ABSTRACT Currently, we are involved in a standardisation process to specify the next mobile system generation. A Wideband Code Division Multiple Access (WCDMA) system is considered in most of the region versions. It would be very useful to count on a radio channel emulator which allows to evaluate higher layers protocols within this context. This paper presents a radio channel emulator developed for a Code Division Multiple Access (CDMA) based system. Its versatility and low complexity have been exposed, and the validation process to check the model accuracy has also been shown for this system as an example.

I. INTRODUCTION

Mobile communications and data communications on the Internet are the two fastest growing markets in telecommunications. One of the main important target in third generation mobile systems is the combination of Internet technology with mobile connectivity. Meeting the problems this combination poses, and developing packages of services, terminals and applications which will delight users will be one of the key challenges to the mobile supply community over the next decade.

The main trouble in mobile systems is the radio access, so it is important to investigate the impact of this access in the protocols used in packet mode services. At this aim, a radio channel emulator has been developed for a Code Division Multiple Access (CDMA) access scheme based system.[1]

Due to the random nature of the mobile radio channel, the performance of the physical layer shall be statistically characterised. For the case of logical channels, which require full integrity of the message, the statistical behaviour of the physical layer is given by the Packet Error Rate (PER).

In the case of logical channels, which do not require full integrity of the message, the statistical behaviour of the physical layer is given in terms of the Bit Error Rate (BER). However, at difference of the PER case, for those channels it is not enough to consider that the BER value characterises the behaviour of the physical layer.

[1]This research was supported by a grant of the *Comissionat per a Universitats i Recerca* from the *Generalitat de Catalunya* and by CICYT project TIC98 –0684.

0-7803-6465-5/00 $10.00 © 2000 IEEE

Certainly, at difference of the PER case where the error correction procedures are based on Automatic Repeat Request (ARQ) techniques, for the BER case powerful error correction techniques, based on the use of Forward Error Correction (FEC), must be taken into account.

In that context, it is well known that the performance of the decoding techniques highly depend on the bursty nature of the errors in the received data packet. On the other hand, due to the specific nature of the mobile radio–channel, the errors on the received signal tend to appears in burst. Therefore, it is not enough to characterise the physical layer by means of the BER but a mechanism to emulate the burst nature of the error must be also included. This property together with the possibility to work in real time, are the main reasons to model the transport chain by means of a Hidden Markov Model (HMM) and to use this technique to process the BER data. A statistical system behaviour is needed to train the HMM. To that end, off–line simulations have been made.

The simulation model implements every transmission chain element, which can be considered quite accurate to a real system. So it has been used to derive the channel behaviour, mainly in terms of error distribution. On the other hand, the emulation model considers the system as a black box (see **figure 1**), and intends to reproduce its input/output behaviour without requiring a knowledge of the internal structure and processes that yield these results. The use of emulation models implies a loss of accuracy with respect to simulation models, but is adequate to operate in real time. In some cases, this loss of accuracy has been proved to be negligible. Certainly, the main advantage of using HMM in the emulator is the huge reduction in time, resources and effort with regard to a real simulation of the system.

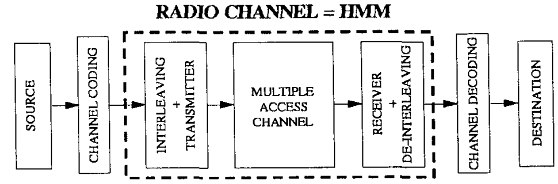

Figure 1. Emulated Transmission Chain

Since there exist a large variety of mobile propagation environments, it is necessary to emulate several channels in order to validate the system behaviour in different propagation environments. Several testing scenarios have been defined to show this diversity. For every testing scenario the Markov model is properly trained through adequate off–line simulations.

In the next section, the basic principles on which the Hidden Markov Model (HMM) is based are explained. After this, the validation process to check the model accuracy for a CDMA system is shown through an example. The applicability of the emulator are also detailed. Some conclusions on the work done are finally presented.

II. HIDDEN MARKOV MODEL BASICS

The Hidden Markov Model is a signal stochastic model [1] [2]. The basic theory was published in several papers by Baum and his colleagues in the late 60 and early 70. However, it did not become popular until the last fifteen years.

To understand the principles of the Hidden Markov Model, it is first necessary to have some knowledge of the Markov Chains.

A.– Markov Chains

Let us consider a system described each time instant by a state within the set of N different states, $S_1, S_2, ..., S_N$. At discrete times, the system experiences a change of state according to a set of probabilities associated to this state. Let us define the time instants associated to state changes as t=1,2,..., and the current state at instant t as q_t.

A full probabilistic description of such a kind of system requires to specify the current state at instant t and previous states. For a first–order Markov discrete chain, this description is simply given by the current state and the previous one:

$$P\left[q_t = S_j \middle| q_{t-1} = S_i, q_{t-2} = S_k, \ldots\right] = P\left[q_t = S_j \middle| q_{t-1} = S_i\right] \quad \textbf{(1)}$$

Only the processes in which the right side of equation (1) is independent of time are usually considered. Therefore, the set of state transition probabilities a_{ij} can be defined as:

$$a_{ij} = P\left[q_t = S_j \middle| q_{t-1} = S_i\right], \qquad 1 \le i, j \le N$$
$$\sum_{j=1}^{N} a_{ij} = 1 \qquad \textbf{(2)}$$

where $a_{ij} \geq 0$ since they must follow standard stochastic restrictions.

B.– Hidden Markov Models

The Hidden Markov Model (HMM) is an observable model in which the observation is a probabilistic function of the state. The resultant model is a doubly embedded stochastic process with a subjacent stochastic process, which is not observable (it is hidden) and can only be seen through another set of stochastic processes that produce the observation sequence.

An HMM is characterised by:

- N, the number of states of the model. Although the states are hidden, for many applications there is a physical meaning related to the state o the set of states of the model. The states are usually interconnected among them, so each state can be reached from any other. The individual states are defined as $S = \{S_1, S_2, ..., S_N\}$ and the current state at instant t as q_t.
- M, the number of different observation symbols per state. The observation symbols correspond to the physical output of the system being modeled. The individual symbols are defined as $V = \{v_1, v_2... v_M\}$.
- The transition probability distribution between states, $A = \{a_{ij}\}$, where:
$$a_{ij} = P\left[q_{t+1} = S_j \middle| q_t = S_i\right], \qquad 1 \le i, j \le N \quad \textbf{(3)}$$
- The observation symbol probability distribution in state j, $B = \{b_j(k)\}$, where
$$b_j(k) = P\left[v_k \text{ at } t \middle| q_t = S_j\right], \qquad \begin{array}{c} 1 \le j \le N \\ 1 \le k \le M \end{array} \quad \textbf{(4)}$$
- The initial distribution of states, $\pi = \{\pi_i\}$, where:
$$\pi_i = P\left[q_1 = S_i\right], \qquad 1 \le i \le N \quad \textbf{(5)}$$

Giving appropriate values to the parameters N, M, A, B and π, the HMM can be used as a generator to produce the observation sequence $O = \{O_1, O_2, ..., O_T\}$, where O_t is one of the symbols of V, and T is the number of observations in the sequence. The procedure is as follows:

1. Choose an initial state $q_1 = S_i$ according to the initial state distribution π.
2. Set t = 1.
3. Choose $O_t = v_k$ according to the symbol probability distribution at state S_i, i.e., $b_i(k)$.
4. Go to a new state $q_{t+1} = S_j$ according to the transition probability distribution of state S_i, i.e., a_{ij}.
5. Set t = t+1, and go back to 3 if t<T. If t=T, the procedure is finalised.

This procedure can be used as an observation generator, and also as a model by which a given observation sequence is generated by a so–designed HMM.

A complete specification of an HMM requires the two model parameters (N and M), the observed symbols and the three probability measures (A, B and π) to be specified. For convenience, to indicate the complete set of model parameters the following short notation is used:

$$\lambda = (A, B, \pi) \tag{6}$$

C. – Soft Decision

An ergodic HMM allows to model the errors introduced by the channel, but does not consider the presence of soft decision information. To handle this kind of information, the procedure adopted is as follows [3].

To emulate soft decision information, two different types of matrices are considered: one contains the mean of a given set of soft decision values within a burst, and the other contains the instantaneous probability of a soft decision value.

The main objective is to store the probability density function of the soft decision information in order to reproduce it in the HMM–based emulation. To precisely do this, two kind of probability density function are stored.

First, within the soft decision mean matrix, the probability density function of the soft decision mean in a burst is stored for every state (each row corresponds to the probability density function).

Secondly, two matrices are stored for every state: one corresponding to correct bits and the other corresponding to erroneous bits. Each one of those matrices contains the probability density function for a given soft decision mean value of either correct or erroneous bits within a burst.

The procedure followed to reproduce these probability density functions consists in selecting a decision soft mean value for a given burst and, according to this value, selecting the soft decision level corresponding to each bit within the burst.

To select the mean value, it is necessary to know the current HMM state, which depends on the number of errors within a block. After selecting the mean, from the soft decision matrix for correct and erroneous bits corresponding to the current state, a soft decision level is chosen for every bit within the block.

III. VALIDATION

The validation process has been splitted into two different parts: the validation of errors introduced by the channel and the validation of the soft decision information associated to every bit. This has been done for an access scheme, based on a CDMA technique.

The validation procedure consists in analysing the modeled channel metric and comparing it with the metric of the simulations employed to train the HMM. To do the validations, the Markov chain was employed to emulate the transmission of 10 millions bits, since the results obtained with 100 millions bits were nearly the same. Between 5 and 10 millions the differences in the results were not negligible. Moreover, the time needed to emulate 10 millions bits was considered reasonable (about 3 minutes on a 166 MHz PC Pentium).

The validation of errors is the first step for a complete validation of the model. It consists in analysing the errors introduced by the HMM within the frame and comparing them with those of the real channel simulation. This analysis is done by means of the metric generated by the channel and the simulation metric.

To analyse the errors, the following statistics are computed:

- Histogram of number of errors per block or frame.
- Histogram of the length of error bursts.
- Histogram of free error intervals.

An example of the histograms obtained for the CDMA–based system validation is illustrated in **figures 2** and **3**. The shown values correspond to a given point in a simulated trajectory for a 16 Kbps speech service within a high traffic macrocell environment.

In this example, two emulation models with number of states N=16 and N=8 have been analysed and compared.

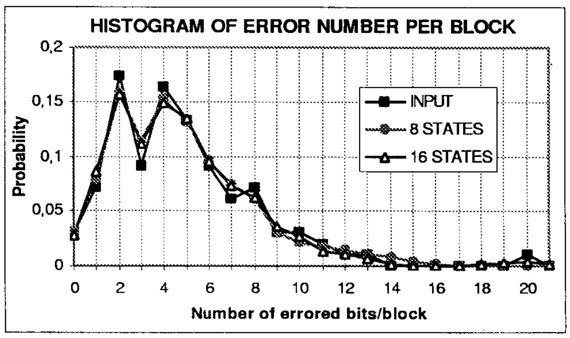

Figure 2. Histogram of error number per block.

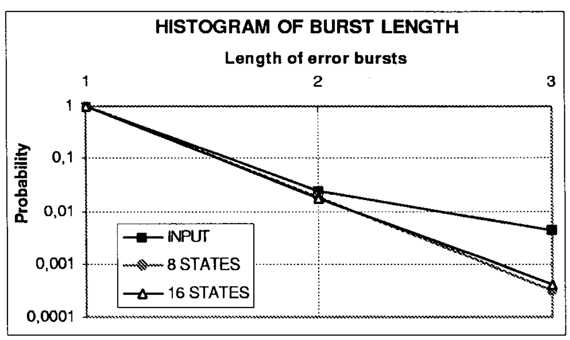

Figure 3. Histogram of burst length.

These two figures show the precision of the HMM for the considered system when employed to emulate the errors introduced by the mobile channel. An important number of cases have been analysed to validate the HMM–based emulator used as error generator and the results obtained have been also precise enough.

The last step to completely validate the model is the validation process for the soft decision information.

In order to do this, the following statistics are computed and compared to those of the simulations of the real channel:

- Histogram of the block soft decision mean.
- Histogram of dispersions around means with non–zero probability.
  The dispersion of the soft decision level is computed according to the following expression:
  $$\sigma^2 = \frac{1}{K}\sum_{i=1}^{K}\left|x^i_{SD} - x_{MSD}\right|^2 \qquad (7)$$
  where K is the number of bits per block, x^i_{SD} is the soft decision level of bit i–th, and x_{MSD} is the soft decision mean of the whole block.
- Histogram of soft decision levels for every non–zero mean.

The validation of the soft decision information has also been done. The figures shown next (from **figure 4** to **8**) represent an example of validation for this system. The results have been obtained for the same environment considered in figures 1 and 2.

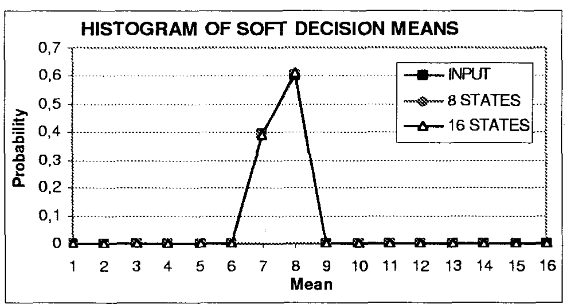

Figure 4. Histogram of soft decision means.

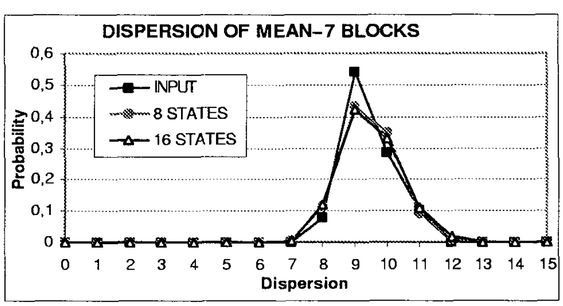

Figure 5. Dispersion of mean–7 blocks.

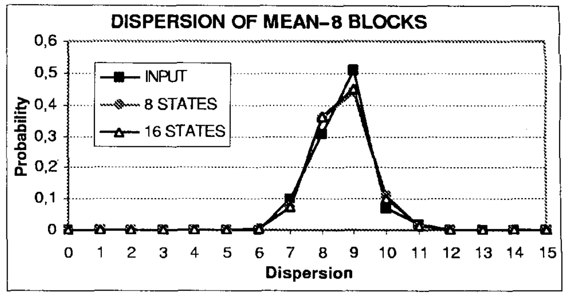

Figure 6. Dispersion of mean–8 blocks.

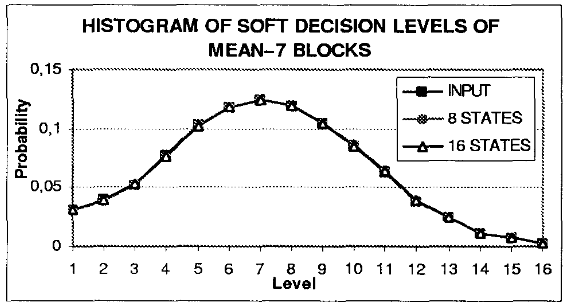

Figure 7. Histogram of soft decision levels of mean–7 blocks.

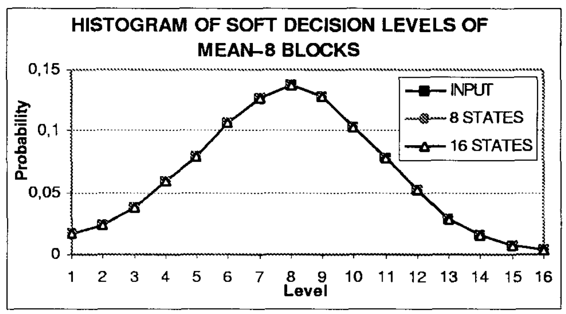

Figure 8. Histogram of soft decision levels of mean–8 blocks.

This example shows the precision of the HMM for a CDMA– based system when employed to emulate the soft decision provided to the decoder output.

An important number of cases have been analysed to validate the HMM–based emulator used to generate soft decision information and the results obtained have been also good enough.

IV. EMULATOR APPLICABILITY

The designed Hidden Markov Model can be easily handled regarding to its size and can be considered quite fast concerning emulation. It is applicable to any study which requires sending data through a digital mobile communication channel. It allows the emulation of a great number of channels with different propagation conditions, provided that it is trained with the adequate parameters.

This emulator is part of a more complex demonstrator developed within the Rainbow project [4]. For the Rainbow demonstrator, a database containing around 7000 files has been created. These files contain the appropriate parameters to emulate different propagation environments. Such parameters have been obtained by generation of the HMM from actual channel simulations. The simulations have been run considering a given trajectory in a given environment. Microcell and macrocell environments have been assumed.

A new simulation is needed when any of the following characteristics is changed:

- Environment (macro, micro, picocell)
- Traffic (high, medium, low)
- Link direction (uplink, downlink)
- service (speech or the different type of data)
- mode (different rates of the same service)
- server (best server or worst BTS server)
- diversity (with or without)

The database structure has been organised as a tree according to each of these characteristics. The files of the database contain the needed parameters to train the HMM. These parameters are:

- Number of bits per block, K.
  The HMM must know this value, as it needs to know the length of transmitted blocks to emulate the channel behaviour.
- Number of states, N.
  The HMM must have this value to know how many states have been created. This value should be provided before the state information.
- Number of soft decision levels, S.
- State transition matrix.
  This is one of the most important parameters of the model, as it contains the hop probabilities between the different states of the chain.
- Soft decision mean matrix.
  This matrix is needed when the model considers soft decision information to be provided to the decoder.
- For each state:
  - Minimum error.
  - Maximum error.
  - Error mean.
  - State probability
  - Soft decision matrix for correct bits.
  - Soft decision matrix for error bits.

To use the emulator it is only necessary to choose the adequate HMM parameter file to train the HMM based emulator, and decide if a Hard or a Soft decision channel is required. Then, the bits can pass through the emulator as they pass through the real radio channel. If a Soft decision channel has been selected, each output bit will consist of a binary value plus a soft decision level. Otherwise, only binary value is delivered in a Hard decision channel.

V. CONCLUSIONS

In this paper, the Hidden Markov Model (HMM) used to emulate the radio channel in a CDMA access scheme, and its validation, have been presented. The model needs to be trained with off-line simulation statistics in order to emulate a particular system within a given environment. It is a versatile tool since only by changing the simulation statistics, different systems can be emulated.

The validation of the model has been done in two phases making use of statistical measures. First, the generation of the errors introduced by the channel is proved in comparison to the simulation statistics. After this, the generation of soft decision information is also validated by comparing the values obtained from the emulator and from the simulation. This has been done for a CDMA-based system and an example has been presented.

The validation procedure has shown the accuracy of the model used to emulate different radio channel schemes. The main advantage of using HMM-based emulations instead of simulations of the radio system is that the first ones allow operation in real time with a moderate implementation complexity. This results in an important reduction in time, resources and effort with regard to real simulations.

This is why it can become a powerful tool to test higher layer protocols within the current standardisation process for the third generation mobile systems. In this sense, the emulator presented in this paper can be updated to model a WCDMA system as the one considered by the international standardisation organisms.

ACKNOWLEDGEMENTS

This work was part of the Rainbow project (AC015), partially funded by the European Commission under the Advanced Communications Technologies and Services (ACTS) framework.

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