Regular paper

An adaptive hidden Markov model for indoor OFDM based wireless systems

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Abstract—Detailed physical layer simulation of orthogonal frequency division multiplexing (OFDM) systems requires programs that execute too slowly due to long coherence time of the indoor mobile channel. Evaluation of higher layers of such systems is simplified if suitable models for reproduction of channel errors statistics are available. An adaptive hidden Markov model (HMM) for indoor OFDM based systems that accurately reproduces error statistics of the real system with less computational effort than the exact simulation is presented in this paper. The standard HMM methodology has been modified in order to reproduce the periodicity in the error positions of the OFDM systems. The proposed model is validated by comparison of three statistical parameters: number of errors, length of the errors run and length of the error—free intervals in a frame of bits.

Keywords—hidden Markov model, OFDM, multicarrier transmission.

1. Introduction

Orthogonal frequency division multiplexing (OFDM) is a special case of multicarrier transmission, where a single stream is transmitted over a number of lower rate subcarriers. In this way, several modulated orthogonal carriers with overlapping spectra are transmitted in parallel. The parallel approach has the advantage of spreading out a frequency selective fade over many symbols. It has been proposed as the modulation type for several broadband indoor wireless systems in order to combat frequency selective fading. ETSI-BRAN has selected this type of transmission for HIPERLAN/2 [1] while OFDM has been chosen for the IEEE 802.11a [2] and the recently approved IEEE 802.11g standards in the 5.2 GHz and 2.4 GHz frequency ranges respectively. OFDM proposals have been also presented for the 4G wireless systems [3].

One of the indoor radio channel characteristics is that the impulse response is slowly changing in comparison with system bit rate. Therefore, long time consuming programs are needed to simulate all the possible channel conditions, which make the real time emulation of OFDM systems virtually impossible and hampers simulation of higher layers. One method to overcome this problem is to model the physical layer using a HMM [4].

The HMMs are useful tools for modelling stochastic random processes that are general enough to approximate various statistical data, which explain their popularity in many applications such as speech recognition, image analysis, control theory, biology, communications theory, queuing theory, etc. In several works, channels with memory as well as the error sequences in digital communication systems are modelled using HMMs [5–9].

In an indoor OFDM based wireless communication system, the bit errors appear on the subcarrier where the notch of the frequency selective fading is centered, and, due to the slow varying nature of the indoor channel, the fading affects the same subcarrier for duration of several OFDM symbols. Therefore, a periodicity equal to the number of bits in an OFDM symbol is observed in the position of the errors after demodulation.

In this paper, an adaptive HMM suitable for characterization of indoor OFDM based systems is proposed. The merit of the adapted HMM is ensured by applying the model to the uplink of a typical indoor physical layer based on OFDM. The paper is organized as follows: Section 2 presents HMM basics and Section 3 describes in detail the proposed HMM. In Section 4 a typical OFDM physical layer is analyzed, while Section 5 presents some simulation results. Finally, conclusions are presented in Section 6.

2. Hidden Markov model basics

The HMM is an extension of the Markov model concept which includes the case where the observation is a probabilistic function of the state rather than deterministic one. The resultant model is a double stochastic process which is not observable. An HMM can be characterised by the following parameters [4]:

- **N**, the number of states in the model. The individual states are defined as $S = \{S_1, S_2, \ldots, S_N\}$ and the state at instant t as q_t.

- **D**, the number of the different observation symbols per state. The observation symbols correspond to the physical output of the system being modelled. The individual symbols are defined as $V = = \{v_1, v_2, \ldots, v_D\}$.

- $\mathbf{A} = \{a_{ij} 1 \leq i, j \leq N\}$, the state transition probability matrix, where

$$a_{ij} = P\left[q_{t+1} = S_j \,|\, q_t = S_i\right]. \qquad (1)$$

- $\mathbf{B} = \{b_j(k)\ 1 \le j \le N,\ 1 \le k \le D\}$, the observation symbol probability matrix, where

$$b_j(k) = P\big[v_k \text{ at } t \,|\, q_t = S_j\big]\,. \qquad (2)$$

- The initial state distribution vector $\pi = \{\pi_i\}$, $1 \le i \le N$, where π_i is the probability for the initial state to be S_i, that is

$$\pi_i = P\big[q_1 = S_i\big]\,. \qquad (3)$$

Giving appropriate values to the parameters N, D, A, B, and π, one can use the HMM as a generator to produce the observation sequence $O = \{O_1, O_2, \ldots, O_T\}$, where O_T is one of the symbols of V, and T is the number of observations in the sequence. From the above it is concluded that an HMM requires both model parameters (N and D), the observed symbols and three probability measures (A, B and π) to be specified. For convenience, the following notation is used to indicate the complete set of model parameters:

$$\lambda = (\text{A, B, } \pi)\,.$$

3. The description HMM adopted

In order to use a HMM in communication systems it is necessary to divide the received data into constant length packets, where each one is characterised by the number of errors it contains. The HMM reproduces the correlation between consecutive packets by forcing the current state to depend on the state of the previous packet. In our context, a reasonable choice is to identify a packet of the HMM with a coded packet plus medium access control (MAC) headers.

A HMM consists of a Markov chain that has a number of states, each state representing a range of number of errors within the packet. Choosing the correct number of states is of critical importance to obtain an accurate model. A small number of states obligates the HMM to group together very distinct observations, while with too many states the training simulation may not provide enough distinct events to estimate the parameters of each state correctly. By using the statistical information from exact physical layer off-line simulations for a specified number of states, the range of numbers of errors in every state and the probability of each state are tentatively defined. It is noted that the states should be as equiprobable as possible. Next, also by the exact simulation, the "transition matrix" filled with the probabilities of passing from one state to another is obtained. This matrix is used as the input to the HMM program that generates a sequence of errors statistically similar to the real one.

When running the HMM, the exact number of errors to place in a received packet is determined by sampling a random variable with a mean equal to the mean number of errors of the current state. In a conventional HMM, the errors are distributed inside the packet with uniform statistics [10]. This is not adequate for an indoor OFDM based physical layer because, as already mentioned, the errors appear in periodic clusters. Our method includes obtaining, from the training simulation, the probability density function (p.d.f.) of the error positions in the real packets, conditioned by the fact that the notch of fading is centered on one of the subcarriers. This is repeated for every subcarrier. Then, when running the model, the errors are distributed inside the packet, in the adequate carrier, according to the previously stored p.d.f.'s.

To check the performance of the proposed model, some validation tests are carried out, consisting of analysing the errors introduced by the HMM within the packets and comparing them with the training simulation. The validation is based on the comparison of p.d.f. of the following three statistical parameters:

- number of errors in a frame of bits,
- length of error runs in a frame of bits,
- length of error—free intervals in a frame of bits.

In case when large deviation in the validation test is obtained after choosing the number of states N, the initial number of states is increased and the procedure is repeated.

Once the given physical layer is well trained, the statistical information generated by the off-line simulation is no longer needed. Therefore, the HMM parameters are sufficient to reproduce the error distribution of the physical layer in future cases.

4. Physical layer description

A typical indoor physical layer based on OFDM is used in the simulations (Fig. 1). It provides a 20 Mbit/s (uncoded) wireless link occupying a bandwidth of 25 MHz and a carrier frequency of 5.2 GHz. OFDM with 16 subcarriers and QPSK modulation on each one has been selected. An inverse fast Fourrier transformation (IFFT) and an oversampling factor of 4 are used to generate the time domain samples transmitted during one OFDM symbol. Oversampling is necessary to avoid aliasing in the generated signal spectrum.

A cyclic prefix is added by copying some samples from the end of each OFDM symbol to the beginning in order to protect the symbol from the echoes of the channel. The use of a time domain raised cosine (roll-off = 0.5) windowing of each OFDM symbol is necessary to reduce the adjacent channel interference. The raised cosine window lasts for 15.6% of the OFDM symbol at the beginning and at the end of each symbol. Thus the total symbol is made up of the windowing time, a FFT period of 1.28 μs and a 160 ns guard time (cyclic period). After modulation the signal is up-converted to the RF channel band. Before being transmitted, the signal passes through a nonlinear amplifier. To limit the distortion due to the power amplifier without reducing too much its efficiency, a 3 dB back-off is applied.

A three-ray, time-varying radio channel with a delay spread of 100 ns in a picocellular environment has been chosen for

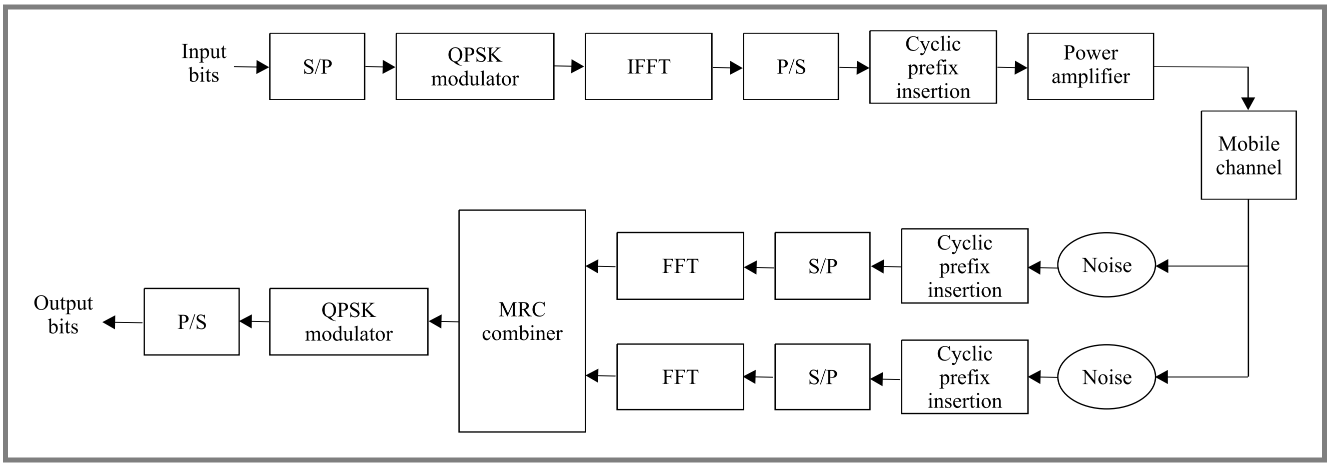

Fig. 1. Block diagram of a typical OFDM physical layer.

simulation while, complex-valued additive white Gaussian noise (AWGN) model is assumed.

At the receiving end, the signal is demodulated coherently and the bits are detected using minimum distance criterion. To estimate the transfer function of the channel a pilot sequence of 10 known OFDM symbols are transmitted with ideal back-off once every 1000 OFDM symbols. Since the indoor channel is slowly time variant, the pilot sequence is known a priory by the receiver. In this way, two antennas spatial diversity with two independent receivers whose outputs are combined using maximal ratio combining (MRC) is applied while, ideal time and frequency synchronism are assumed.

5. Simulation results

Off-line simulations of the physical layer for the up-link assuming mobile terminal speed of 1 m/s have been carried out. In order to take all possible values of the channel, the simulation time must be 100 times the coherence time. This means that at least $3 \cdot 10^6$ FFT blocks are simulated for every E_b/N_0 value.

Figure 2 shows the mean bit-error-rate (BER) versus the mean E_b/N_0 values. The simulation with linear amplifier and ideal channel estimation and the theoretical curve are compared in order to demonstrate the correct operation of the simulation tool.

Validation results of the HMM for a packet length of 512 bits are presented in this section. Every packet contains the data payload, the error correction and detection bits and all necessary medium access control headers.

Validation results for a mean E_b/N_0 value of 10 dB, corresponding to a mean BER value of $6 \cdot 10^{-2}$, are analysed first. Figure 3 allows to compare the length of the error-free intervals obtained by a HMM with 16 states and the real system. It can be seen how the proposed HMM correctly reproduces the periodicity of error positions in the real sequence. In Fig. 4 the p.d.f. of the number of errors, for different numbers of states in the HMM is shown. It is obvious that a HMM with 8 states gives better accuracy than one with 4 states only. Increasing the number of states to 16 does not give significant performance improvement.

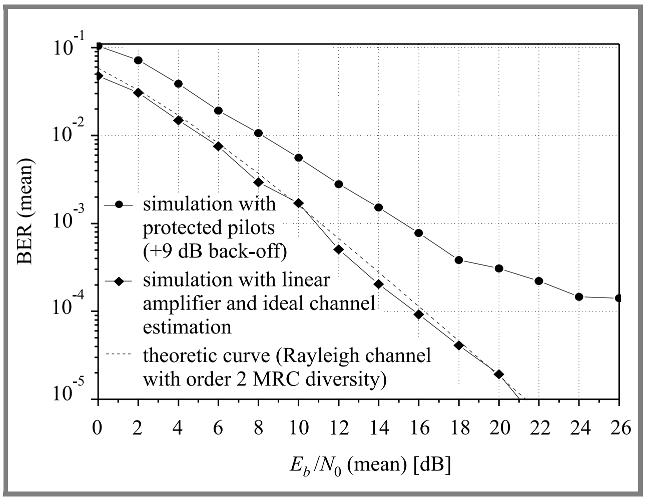

Fig. 2. Mean E_b/N_0 versus BER characteristics.

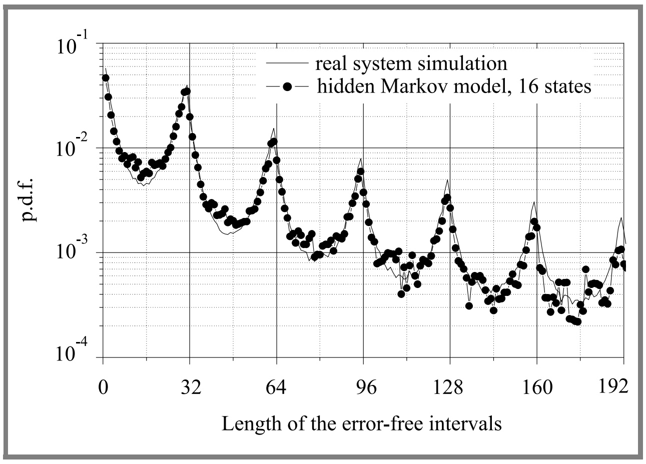

Fig. 3. Probability density function (p.d.f.) of the length of the error-free intervals for a mean E_b/N_0 of 10 dB.

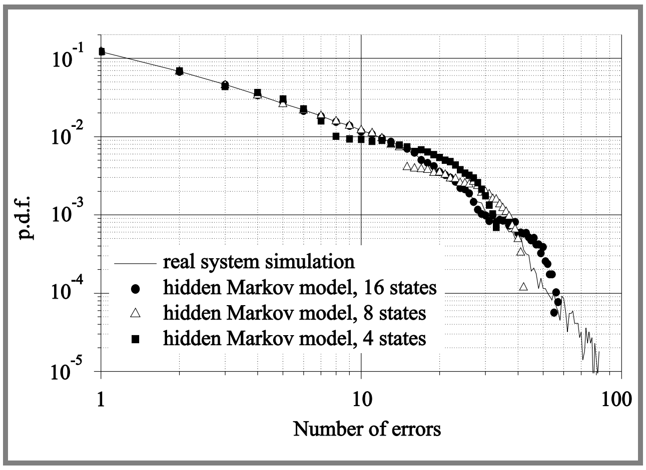

Fig. 4. Probability density function (p.d.f.) of the number of errors for a mean E_b/N_0 of 10 dB.

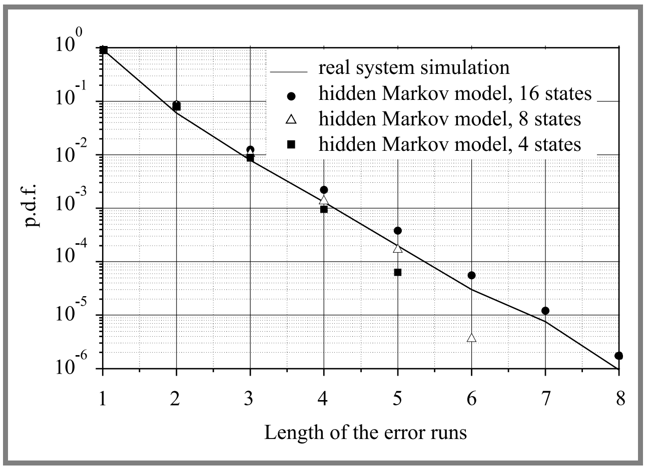

Fig. 5. Probability density function (p.d.f.) of the length of the error runs for a mean E_b/N_0 of 10 dB.

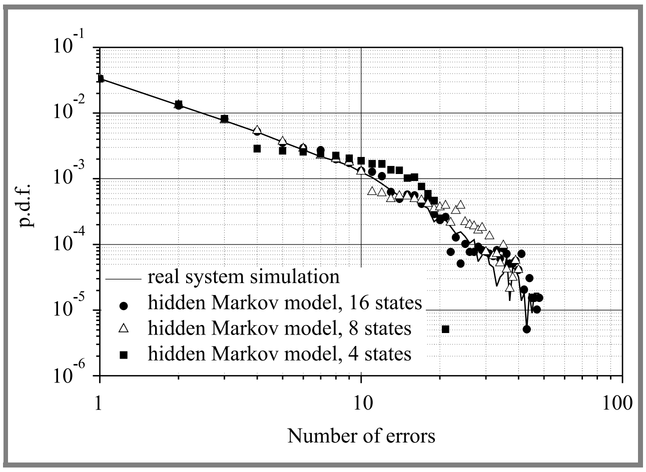

Fig. 6. Probability density function (p.d.f.) of the number of errors for a mean E_b/N_0 of 18 dB.

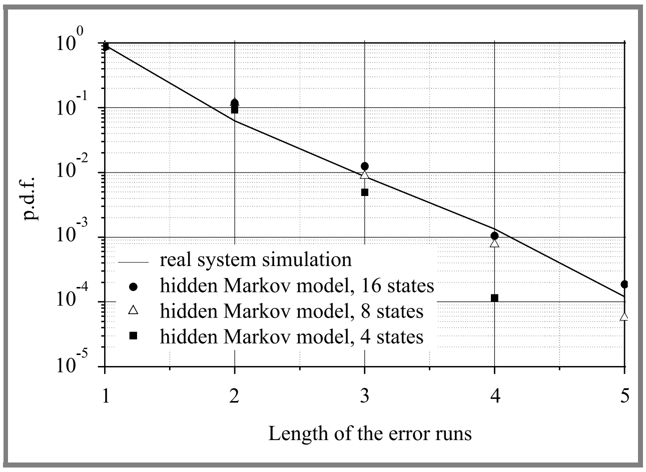

Fig. 7. Probability density function (p.d.f.) of the length of the error runs for a mean E_b/N_0 of 18 dB.

Finally, Fig. 5 compares the p.d.f. of the error runs length. As we can see, 16 states are preferable because the error runs are better reproduced than with 8 or 4 states. Consequently, the use of 16 states is suggested for this E_b/N_0 value.

It has to be noted that when increasing the number of states more parameters have to be saved, increasing simulation time. Thus, it is sometimes better to have a less accurate, but faster HMM. This fact can be seen in Figs. 6 and 7, where the p.d.f. of the error runs and the number of errors in a packet are presented for a mean E_b/N_0 value of 18 dB, corresponding to a mean BER of $3 \cdot 10^{-4}$. It is evident in these figures that using a HMM with 16 states gives no significant improvement of HMM accuracy. Thus, use of 8 states is preferable because simulation runs faster.

It is concluded from the above results that the proposed HMM reproduces the error distribution of the examined OFDM based physical layer with a good accuracy. In case of any modification to the physical layer parameters or the indoor propagation channel model the procedure described in Section 3 must be repeated, producing another set of HMM parameters. Therefore, a database of HMM parameters for the up and downlink for different radio channel models can be created. This database could be the basis for evaluation of an OFDM based real time emulator.

6. Conclusion

In this paper an adaptive HMM for indoor OFDM based physical layers have been presented. In such physical layers the fading is centered on one of the subcarriers. Due to slow nature of the indoor channel the fading remains on the same carrier for several OFDM blocks, producing a periodicity in the errors position. The merit of the proposed model is its ability to reproduce this periodicity easily, saving only some parameters.

The efficiency of the HMM has been verified by applying it to a typical indoor OFDM system. Off-line simulations for the uplink have been carried out in order to obtain the statistics of the real sequences.

In order to train the HMM, three statistical parameters have been analyzed; the probability of the number of errors, the length of the errors run and the length of the error free intervals in a packet. From the results presented it can be concluded that the proposed HMM can approach the error distribution of an indoor OFDM physical layer with good accuracy.

Therefore, the proposed HMM is a method that reduces substantially the computational effort and allows real time emulation of indoor OFDM systems and fast simulation of higher layers protocols and algorithms on a realistic physical layer. As a consequence, a good model capable to characterize OFDM based indoor wireless communication systems can be obtained.

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