Joint Antenna Diversity and Combined Soft Output MAP Equalization/Decoding of TCM on Frequency-Selective Fading Mobile Radio Channels

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***Abstract* - A Monte Carlo simulation study of a combined FDMA/TDMA Slow Frequency-Hopping Trellis Coded adaptive receiver for frequency-selective multipath Rayleigh fading mobile radio channels is presented in this paper. The receiver structure comprises state-dependent decision feeedback MLSE soft-output MAP equalizer, block deinterleaver and TCM decoder in one unit. Antenna diversity is considered leading to a joint diversity and combined equalization/decoding scheme. Furthermore, Cyclic Slow Frequency Hopping is used to attain intrinsic frequency diversity to perform a near ideal channel interleaving with a short processing delay. The dynamic behavior of the mobile radio channel has been simulated by means of a selective equal-energy two-ray Rayleigh model, with a variable delay, τ, between the two rays. Bit error rate (BER) is obtained as a function of signal-to-noise ratio (SNR) and with τ, Doppler spread, number of frequencies in the frequency-hopping pattern, number of states considered by the state-dependent decision feedback algorithm and TDMA frame length as parameters.**

I. INTRODUCTION

The continuing growth of mobile telephone traffic and the requirements of integration with the digital communications facilities have spurred the research and development of new high-capacity digital mobile radio systems. The UHF land mobile radio communication channel can be effectively modelled as a frequency-selective time-variant multipath fading channel [1], [2]. For data rates on the order of the coherence bandwidth of the channel, or larger, frequency selectivity causes intersymbol interference (ISI), time variation calls for an adaptive receiver and multipath fading results in a very low SNR when channel exhibits a deep fade.

It is well known that the optimum receiver for a signal impaired by ISI and additive white noise is a whitened matched filter (WMF) followed by a symbol rate sampler and a maximum likelihood sequence estimator (MLSE) [3]. MLSE can be implemented with a probabilistic symbol-by-symbol MAP algorithm [1], [3] or with the Viterbi algorithm (VA) [1], [4]. However, these algorithms become prohibitively complex for channels with a long overall channel impulse response and large data symbol alphabets. Suboptimal reduced computation detection algorithms such as decision feedback equalizer [5], reduced state maximum likelihood sequence estimation [6], [7], M-algorithm MLSE equalizers [8], and others, have therefore been developed and investigated.

Trellis coded modulation (TCM), although originally developed for telephone channels [9], has received also considerable interest in the field of mobile radio [10]-[14]. The primary advantage of TCM over modulation schemes using traditional error correcting coding is its ability to achieve increased power efficiency without the customary expansion of bandwidth introduced by the coding process. Furthermore, when combined with interleaving of sufficient depth, TCM is known to provide some form of time diversity that can be used to improve the reliability of a multipath-fading channel over conventional uncoded modulation. In addition to using coding, multipath fading can be also combated by using antenna diversity reception where the receiver is provided with multiple independently faded replicas of the same information. Diversity is effective because it diminishes the probability of simultaneously having two or more independently faded channels in a deep fade [2], [14].

Joint equalization/decoding on a super trellis as proposed in [15], [16] is not feasible for multipath-fading channels due to the use of the interleaving/deinterleaving process to break up the memory of the channel, which is in contrast to the equalization task where the channel memory is exploited. In this paper we study the probabilistic symbol-by-symbol MAP algorithm as discussed in [3] and extended for soft output by [17], [18]. In the case of coded transmission the soft output (or reliability information) can be passed through the deinterleaver easily and may be exploited by the decoder, thus obtaining an additional soft decision coding gain. The implementation complexity of the MAP algorithm which grows exponentially with the length of the channel impulse response is reduced by making use of a receiver structure that comprises reduced state MLSE with state dependent decision feedback [6], block deinterleaver and TCM decoder in one unit. Furthermore, we consider the

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use of antenna diversity, leading to a joint diversity and combined MAP equalization/decoding scheme. A combined FDMA/TDMA cyclic slow frequency hopping scheme, similar to that adopted by pan-European GSM or DECT systems, is assumed. Known training symbols of each TDMA time slot are exploited in the decoding process and cyclic slow frequency hopping is used to attain intrinsic frequency diversity to perform a near ideal channel interleaving with a short processing delay. In order to assess the performance of this scheme Monte-Carlo simulations of the system have been carried out where the dynamic behavior of the mobile radio channel has been simulated by means of a selective equal-energy two-ray Rayleigh model, with a variable delay, τ, between the two rays. Bit error rate (BER) is obtained as a function of signal-to-noise ratio (SNR) and with τ, Doppler spread, number of frequencies in the frequency-hopping pattern, number of states in the reduced state MLSE and TDMA frame length as parameters.

II. SYSTEM MODEL

In the transmitter, input bits (representing data or digitally encoded speech) are fed into a trellis encoder. The complex-valued output symbol stream is next block interleaved (buffer matrix with N_R rows and N_C columns) to *randomize* the distribution of symbols that could be affected by amplitude fades of duration greater than one symbol period and to make full use of trellis code properties. Both the base and the mobile stations transmit a sequence of message bursts, located in the assigned TDMA time slots. The transmitted burst structure includes a preamble of N_T training symbols, a block interleaver row of N_C information symbols and a guard time. The preamble, known at the receiver, allows an estimate of the channel impulse response (CIR) and a proper initialization of the receiver parameters, on a burst-by-burst basis. Once filtered by the shaping filter, $h_T(t)$, these symbols provide the complex baseband transmitted signal $s(t)$. Finally, to make use of the FH intrinsic frequency diversity, the N_R formed slots are modulated according to the assigned frequency-hopping pattern. By setting the frequency-hopping separation sufficiently large, a null correlation among the different frequency channels can be assured [2].

Since K-diversity reception is used in the system, the channel is modeled as K independent dispersive fading channels corrupted by additive white Gaussian noise. At the receiver side, each of the K diversity branches consists of an FH linear demodulator followed by a matched filter, used to get the maximum signal-to-noise power ratio at the sampling instant, and a noise whitening filter, employed to whiten the colored noise coming out of the matched filter and to make the overall channel impulse response of the channel *minimum phase* or nearly so (this can be controlled by adapting whitening matched filter (WMF) coefficients to channel variations). Complex-valued symbol streams at the output of the K whitening matched filters are fed to the diversity combiner. Finally, diversity combined symbols are processed in the combined soft-output MAP equalizer/decoder.

A. Optimal diversity combiner

Let us assume, in general, that we are receiving a signal transmitted onto the j-th hopping frequency ($j=1,2,\ldots,N_R$). Also, let $\mathbf{S}_k$, $\mathbf{R}_{j,k}$ and $\mathbf{N}_{j,k}$ be the k-component row vectors whose i-th components are s_i, $r_{j,i}$ and $n_{j,i}$, respectively, for $i=1,2,\ldots,k$. $\mathbf{S}_k$ represents the block interleaved transmitted sequence, $\mathbf{R}_{j,k}$ the received sequence and $\mathbf{N}_{j,k}$ the sequence of complex zero-mean additive Gaussian noise components with single-sided power spectrum density equal to N_0. The complex-valued sample at the output of the whitening matched filter, at time $t=iT$, can be expressed as

$$r_{j,i} = \sum_{k=0}^{g-1} s^{\Delta}_{i-k}\, y_{j,i,k} + n_i \qquad (1)$$

where the superscript Δ is a "wild card" for "T" and "D" (training or data) and the sequence of complex values given by the vector

$$Y_{j,i} = \left[y_{j,i,0} \quad y_{j,i,1} \quad \cdots \quad y_{j,i,g-1} \right] \qquad (2)$$

represents the causal equivalent sampled impulse response at time $t=iT$ of the linear baseband channel, being the cascade of the channel impulse response $\mathbf{H}_{j,i}$ (formed by the modulator pulse shaping and j-th mobile radio-link propagation selective distortions) and the corresponding WMF $\mathbf{W}_{j,i}$. Optimal diversity combining is performed by adding the K weighted WMF output signals $r_{j,i}$,

$$r_i = \sum_{j=1}^{K} p_{j,i}\, r_{j,i} \qquad (3)$$

where the combining weights can be determined from the instantaneous channel energies $(E_h)_{j,i} = \|\mathbf{H}_{j,i}\|^2$ as

$$p_{j,i} = \frac{(E_h)_{j,i}}{(E_h)_i} \qquad (4)$$

with

$$(E_h)_i = \sum_{k=1}^{K} (E_h)_{k,i} \,. \qquad (5)$$

Therefore, expression (3) can be rewritten as

$$r_i = \sum_{k=0}^{g-1} s^{\Delta}_{i-k}\, f_{i,k} + \eta_i \qquad (6)$$

where η_i is a sample of a complex zero-mean additive Gaussian noise with single-sided power spectrum density equal to $N_0/(E_h)_i$ and the sequence of complex values given by the vector $F_i = [\, f_{i,0} \; f_{i,1} \; \dots \; f_{i,g-1} \,]$ represents the sampled equivalent channel impulse response of the combined signal and is equal to the weighted sum of all diversity channel impulse responses.

B. Combined Soft-Output MAP Equalization and Decoding

Symbols s_i are transmitted in finite blocks of length $N=N_T+N_C$. MAP equalization means to compute the MAP probabilities $P(s_i|R_N)$, $N_T+1 \le i \le N$, given the observations $R_N=\{r_1, \dots, r_i, \dots, r_N\}$. If the data symbols are taken from an alphabet of size M then, for each position i in the frame, the soft-output MAP equalizer outputs a vector $\mathbf{P}(s_i|R_N)$ of M probabilities. These vectors are stored into the block deinterleaver in successive rows and read out in columns for trellis decoding.

Let μ_i denote an ISI state at time i. There are M^g states where g denotes the length of the channel impulse response. g may be shortened to L by state-dependent decision feedback [6]. Then, by applying Bayes theorem, the MAP probabilities can be expressed as

$$P(s_{i-1}|\boldsymbol{R}_N) = \frac{\sum_{\mu_i \in \Omega(s_{i-1})} P(\mu_i, \boldsymbol{R}_N)}{\sum_{\mu_i \in \Omega_0} P(\mu_i, \boldsymbol{R}_N)} \qquad (7)$$

where Ω_0 denotes the set of all states and $\Omega(s_{i-1})$ the set of all states for which the transmitted symbol is s_{i-1}. The term $P(\mu_i, \mathbf{R}_N)$ can be factorized and solved by a forward and a backward recursion [4, Appendix]

$$P(\mu_i, \boldsymbol{R}_N) = \left(\sum_{\mu_{i-1}} P(\mu_{i-1}, r_0, \dots, r_{i-2}) e^{-\lambda(\xi_{i-1})} \right) \cdot \left(\sum_{\mu_{i+1}} P(r_{i+1}, \dots, r_N | \mu_{i+1}) e^{-\lambda(\xi_i)} \right) \qquad (8)$$

where

$$e^{-\lambda(\xi_i)} \sim \exp\left(-\frac{(E_h)_i}{N_0} \left| r_i - \sum_{h=0}^{L} \tilde{s}_{i-h} f_{i,h} - \sum_{h=L+1}^{g-1} \hat{s}_{i-h} f_{i,h} \right|^2 \right) \qquad (9)$$

is the exponentiated metric increment for a trellis transition branch $\xi_i \triangleq (\mu_i \rightarrow \mu_{i+1})$, $\tilde{s}_{i-h}$ are the (trial) symbols according to the transitions ξ_i and $\hat{s}_{i-h}$ are, in the conventional reduced-state soft-output MAP equalizer, previous symbols along the path history [6]. However, if the most significant taps of the channel impulse response are not represented in the state description (channels with severe frequency selectivity), the loss due to conventional state-dependent decision feedback may become too large. To solve this problem we propose to use a receiver structure that comprises reduced state MLSE with-state dependent decision feedback [6], block deinterleaver and TCM decoder in one unit. That is, instead of using previous symbols along the path history as the symbols for the decision feedback mechanism, we will, by tailoring the block interleaver/deinterleaver matrix size in a proper way, use the final decisions of the trellis decoder for this purpose. These final decisions are highly reliable, then the decision feedback mechanism will be very efficient. Nevertheless, computation of MAP probabilities is affected by previous decisions and thus, the system will be subject to error propagation. Training and tail symbols will be used to define the states from which the trellis starts and in which the trellis ends, respectively.

III. SIMULATION RESULTS AND CONCLUSIONS

Computer simulation programs have been set up in order to evaluate the bit error rate (BER) performance of joint antenna diversity and combined DFE/decoding of TCM on frequency-selective fading mobile radio channels. The dynamic behavior of the channel has been simulated by means of a simple two-ray model, with a variable delay τ between the two rays. Both the direct and delayed signal components have been independently Rayleigh faded, with equal average power, and frequency shifted according to a Doppler power spectrum related to the given vehicle speed [2]. Pulse shaping has been a square-root raised-cosine with roll-off parameter equal to 0.5. The ideal equivalent channel impulse response has been taken for calculating the instantaneous channel energy, adjusting the whitened matched filter coefficients and computing the MAP probabilities on a burst-by-burst basis. The minimum mean square error (MMSE) criterion has been adopted to calculate the whitening filter coefficients and the overall channel impulse response. Interleaving and deinterleaving matrices of 20 rows and a variable number of columns have been assumed. In order to investigate multi-level quadrature amplitude modulation (MQAM) schemes, the selected trellis code has been the rate (2x1/2), 2x16 states, 2x4PAM (16QAM) code, designed by M.L. Moher and J.H. Lodge [13]. This code offers a time diversity order equal to 5, which is the maximum time diversity of all trellis codes having the 16QAM symbol constellation.

Simulation results assuming an ideal training process are presented in Figs. 1-6. The effectiveness of the proposed receiver in fighting long echo delays is compared with that of the conventional reduced-state soft-output MAP equalizer in Figs. 1 and 2, where BER versus τ/T is reported for K equal to one and two and with E_b/N_0 as parameter. These results have been obtained assuming a normalized Doppler spread $f_dT=4.0 \cdot 10^{-4}$, a reduced-state MAP algorithm with 16 states, a frequency hopping pattern with 20 frequencies and a TDMA time slot with 30 data symbols. As it can be seen, for $\tau/T>1$ the proposed combined equalization/decoding scheme outperforms the conventional MAP equalizer. This is due to that for $L=1$ (reduced-state MAP algorithm with 16 states) the final decisions of the trellis decoder have an important influence over the feedback mechanism whenever $\tau/T>1$.

Fig. 3 shows the bit error rate of the combined equalization/decoding scheme for K equal to one and two, for a two-ray model with a normalized delay between the two rays $\tau/T=0.5$, a frequency hopping pattern with 20 frequencies, a TDMA time slot with 30 data symbols, a reduced-state MAP algorithm with 16 states and with the signal to noise ratio and normalized Doppler spread f_dT as parameters. Normalized fading rates of $2.0\cdot10^{-4}$, $4.0\cdot10^{-4}$ and $8.0\cdot10^{-4}$ have been considered. It can be seen that the system performance deteriorates as the normalized fading rate increases and an average bit error floor is clearly shown for fast Rayleigh fading. Nevertheless, comparing the irreducible error probability obtained without diversity with that obtained with two antenna diversity, we can conclude that space diversity applies to the irreducible error floor as well.

The performance improvement that can be obtained by increasing the number of states in the reduced-state soft-output MAP algorithm is investigated in Fig. 4, where BER versus τ/T is reported for a system with 16 and 256 states. These results have been obtained assuming a normalized Doppler spread $f_dT=4.0\cdot10^{-4}$, an E_b/N_0 value of 9dB, a frequency hopping pattern with 20 frequencies and a TDMA time slot with 30 data symbols.

In Figs. 5 and 6 the effects resulting from the unavailability of sufficient number of frequencies in the frequency hopping pattern are shown. It can be seen that for a frequency hopping pattern with fifteen frequencies, the results practically coincide with those obtained for a pattern of twenty frequencies. Even with only ten hopping frequencies, this degradation does not exceed 1.5dB for average bit error rates in the range of interest. It is worthy to point out that, with a normalized Doppler spread $f_dT=4.0\cdot10^{-4}$, the case of a frequency hopping pattern with only one frequency corresponds approximately to a transmission system without interleaving.

In summary, the simulation results demonstrate the robust performance of the joint antenna diversity and combined reduced-state soft-output MAP equalization/decoding of trellis coded modulation on frequency selective fading mobile radio channels. In the future, further simulations must be performed in order to assess the performance of the system using a real channel impulse response estimator. Furthermore, bit error rate (BER) has to be obtained as a function of signal-to-noise ratio (SNR) and with decoding decision delay, TDMA frame length, correlation coefficient between the diversity branches, ... as parameters.

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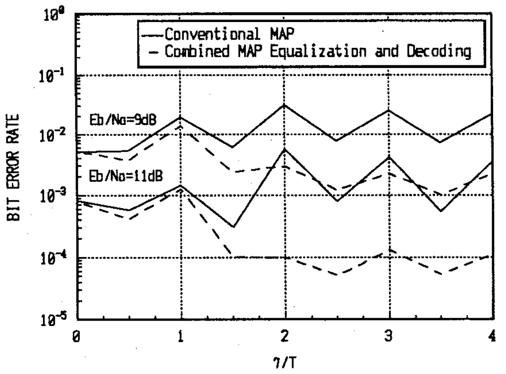

Fig. 1. BER performance for K=1 as a function of τ/T and with E_b/N_o and MAP structure as parameters. (f_dT=4.0 10^{-4}, 20 hopping frequencies)

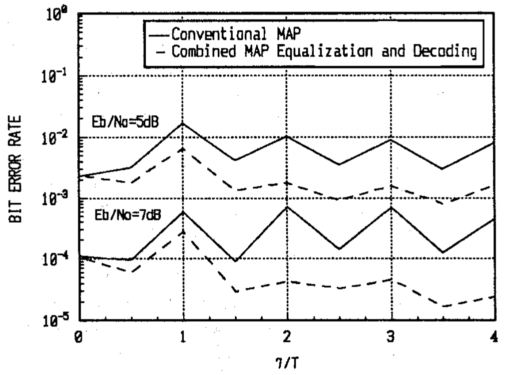

Fig. 2. BER performance for K=2 as a function of τ/T and with E_b/N_o and MAP structure as parameters. (f_dT=4.0 10^{-4}, 20 hopping frequencies)

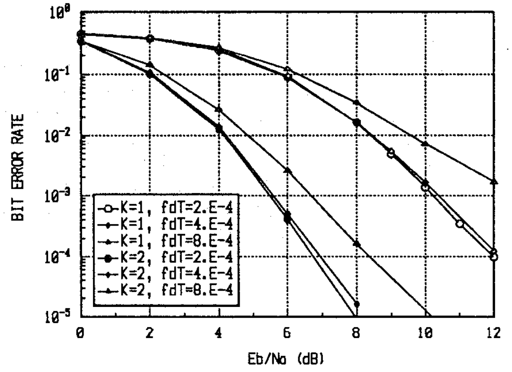

Fig. 3. BER performance for K equal to one and two with f_dT as parameter. (τ/T=.5, MAP 16 states, 20 hopping frequencies)

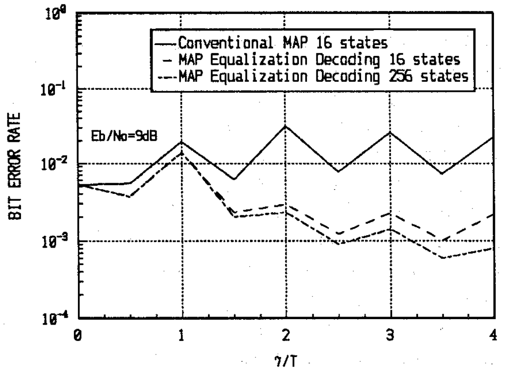

Fig. 4. BER performance for K=1 as a function of τ/T and with the number of states as parameter. (f_dT=4.0 10^{-4}, 20 hopping frequencies)

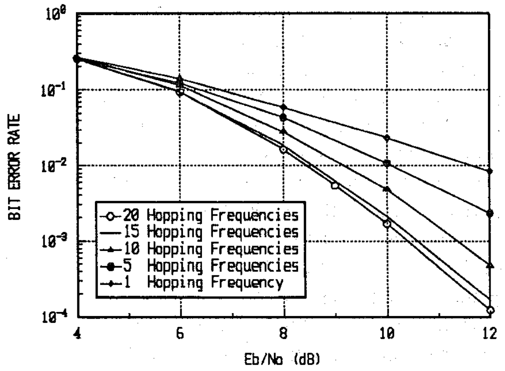

Fig. 5. BER performance for K=1 with de number of hopping frequencies as parameter. (τ/T=.5, f_dT=4.0 10^{-4}, MAP 16 states)

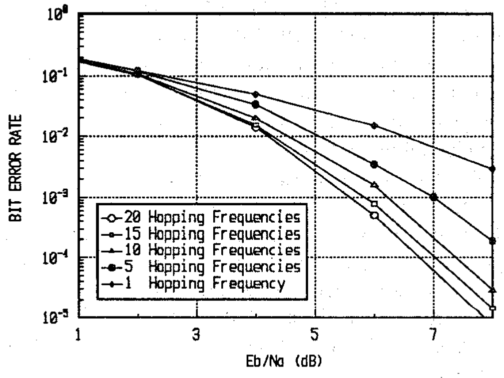

Fig. 6. BER performance for K=2 with de number of hopping frequencies as parameter. (τ/T=.5, f_dT=4.0 10^{-4}, MAP 16 states)