our OA, but the frequency spacing Δf_2 between P_1 and P_2 should exceed 20 GHz to avoid a complicated NDFWM spectrum. A disadvantage of the method is the necessity of an optical filter. For future applications we consider some modifications and extensions of the frequency conversion technique described here. Firstly, P_1 and P_2 need not be copropagating waves with the same polarisation. This may offer some advantages with respect to gain saturation of the OA and channel filtering. Secondly, S_{in} may be converted simultaneously to several frequencies within the bandwidth of the OA. The different converted channels can independently turned on and off with the powers of the different pump waves P_2.

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EXPERIMENTAL EVALUATION OF TRELLIS DECODING PERFORMANCE ON LINEAR BLOCK CODES IN DIGITAL MOBILE RADIO

Indexing terms: Digital communication systems, Codes and coding, Mobile radio systems, Decoding

Word error rate (WER) performance with soft decision decoding of linear block codes using a trellis is investigated in a Rayleigh fading channel. The signal envelopes corresponding to each bit in a received block are sampled and used for estimating the reliability of the bit. The WER performance is evaluated via laboratory experiments using Hamming (7, 4) code. A great improvement in WER performance can be achieved over conventionally-used minimum distance decoding.

Introduction: In land mobile radio, the digital signal transmission performance is severely degraded owing to multipath Rayleigh fading.[1] Error control coding, in which random error correcting block codes, such as BCH codes, have been widely used, is an effective technique for reducing fading effects.[2] It is well known that soft decision decoding can achieve better performance than conventional minimum distance decoding.[3–5] This is because soft decision decoding uses not only the algebraic redundancy of the code but also the channel measurement information (CMI) for estimating reliability of received bits, while minimum distance decoding uses only the redundancy. However, most soft decision decoding algorithms are complex, and are applicable only to restricted classes of codes. Wolf[5] has shown that the well known Viterbi algorithm, in which the decoding complexity is greatly reduced, can be applied to decoding of linear block codes using a trellis.

This letter presents a method for applying trellis decoding of linear block codes to a Rayleigh fading channel. The received signal envelopes corresponding to each bit of the code are sampled and used as the CMI. The metric values corresponding to each node of the trellis are derived from the CMI. The word error rate (WER) performance of trellis decoding and minimum distance decoding with 1 bit error correction for Hamming (7, 4) code are investigated via laboratory experiments. These decoding algorithms are applied to 16 kbit/s signal transmission using GMSK modulation and frequency detection. The experimental results show that the WER performance is greatly improved over minimum distance decoding in an experimentally-simulated Rayleigh fading channel when the trellis decoding is used.

Trellis decoding using received signal envelopes: Consider an (N, K) linear block code. Let the ith column vector of the parity check matrix be denoted as $\boldsymbol{h}_i$ $(i = 1 \sim N)$. For a codeword $\boldsymbol{X}_j = (X_{j1}, \ldots, X_{jN})$, in which X_{ji} is an element of a Grois field GF (q), the node $\boldsymbol{S}_k$ is defined as

$$\boldsymbol{S}_k = \sum_{i=1}^{k} X_{ji} \boldsymbol{h}_i \tag{1}$$

where $k = 1 \sim N$ and $\boldsymbol{S}_0 = (0\ 0 \ldots 0)^t$. The series $\boldsymbol{S}_1, \boldsymbol{S}_2, \ldots, \boldsymbol{S}_N$ is the locus of the codeword $\boldsymbol{X}_j$. The set of all loci described by the series for all codewords constitutes a trellis. A trellis for Hamming (7, 4) code is shown in Fig. 1.

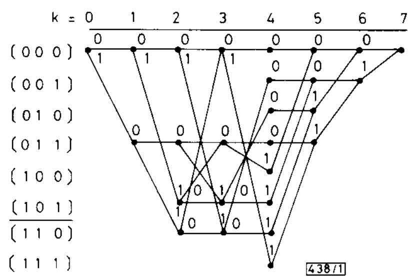

Fig. 1 *Trellis for Hamming (7, 4) code*

The metric value of the kth node for the codeword $\boldsymbol{X}_j$ is given by

$$L_k(X_j) = \sum_{i=1}^{k} \log f_i \tag{2}$$

where $k = 1 \sim N$, and f_i is the likelihood ratio of the hard decision result of the $\boldsymbol{X}_j$s ith bit. The f_i value is given by

$$f_i = \begin{cases} p_i/(1 - p_i) \ldots Y_i \neq X_{ji} \\ (1 - p_i)/p_i \ldots Y_i = X_{ji} \end{cases} \tag{3}$$

where p_i is the error probability of the ith bit and Y_i is the decision result for the bit. The sampled value of the received signal envelope is used as the CMI to estimate the bit error probability. For example, the bit error probability p_i for noncoherent FSK is estimated by $p_i = (1/2) \cdot \exp(-\gamma_i/2)$, where $\gamma_i = R_i^2/2$ is the signal/noise power ratio (SNR) with R_i the envelope sample of the ith bit and N_0 the average in-band noise power.

The Viterbi algorithm can be applied to the trellis. When the kth node of the codeword $\boldsymbol{X}_i$ is the same as that of $\boldsymbol{X}_j$, the metric values of these codewords, $L_k(\boldsymbol{X}_i)$ and $L_k(\boldsymbol{X}_j)$, are compared, and the codeword with smaller value is discarded. In all the nodes which have two entering branches, the codeword of greater metric value is selected. In the nth node, the most likely of the codewords is selected and delivered as the output of decoding.

Laboratory experiment results: The trellis decoding algorithm was applied to 16 kbit/s signal transmission using a GMSK modulation and frequency-detection system. Laboratory experiments were conducted for the Hamming (7, 4) code. A 16 kbit/s bit stream of the coded data was interleaved, differentially encoded, and fed to the IF stage GMSK-modulator. The differential encoding was necessary to apply a 1/2-bit offset decision rule[6] in the receiver to avoid causing error propagation. A Gaussian lowpass filter with a 3 dB bandwidth of 8 kHz was used for premodulation band limitation. The fading GMSK signal was generated by a Rayleigh fading simulator operating on a 90 MHz band. The maximum Doppler frequency f_D of the fading simulator was set at 120 Hz, corresponding to a typical vehicle speed of 64 km/h for the RF frequency of a 2 GHz band. The bit interleaving degree M_i was set at 64, where the envelope samples in a received block are considered statistically independent. A limiter-discriminator type receiver and 1/2-bit offset decision were used.*

An approximately Gaussian ceramic filter with a centre frequency of 455 kHz and a 3 dB bandwidth of 12 kHz was adopted for the predetection bandpass filter. The frequency discriminator output was lowpass-filtered by another Gaussian filter with 3 dB bandwidth of 8 kHz for postdetection noise reduction. The filter output was fed to a 1/2-bit offset decision circuit, and the data stream regenerated.

The logarithmically-compressed IF signal was envelope-detected. The envelope detector output was lowpass-filtered by a four-pole Butterworth filter with a 3 dB bandwidth of 1 kHz. The filter output was sampled and then value-limited in the $0 \sim 20$ dB range using an n bit A/D convertor with resolution n of $0 \sim 6$. A great amount of $(n + 1)$-bit data segments consisting of regenerated data and the envelope sample were stored for later processing. The trellis decoding algorithm was performed using the stored data.

The experimental WERs against the A/D-convertor resolution n is shown in Fig. 2 for $M_i = 64$, when the channel bit error rate (BER) was $1 \cdot 4 \times 10^{-2}$. The WER performance improvement levels off when $n \geq 3$. The experimental WERs against the channel BERs are shown in Fig. 3 for trellis decoding and minimum distance decoding with 1 bit error correction for $M_i = 64$ and $n = 3$. A great improvement in WER performance is obtained over minimum distance decoding when trellis decoding is used. The BER of (N, K) block code

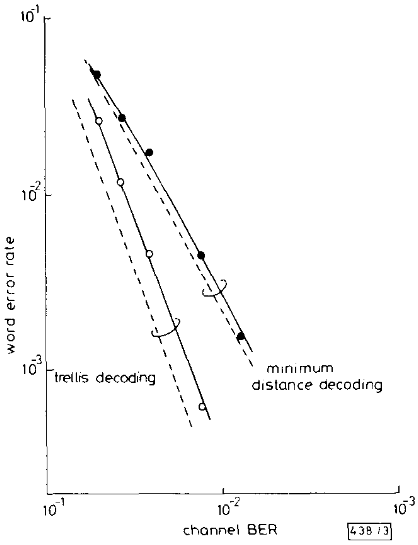

Fig. 3 *WER against channel bit error rate*
Hamming (7, 4) code; $f_D = 120$ Hz; $M_i = 64$; 3 bit A/D conversion
– – – – Simulation
●●● Minimum distance decoding
○○○ Trellis decoding

after decoding is estimated from the WER by the following:[7] BER after decoding $\approx$ WER $\times 2^{K-1}/(2^K - 1)$. The BER after the trellis decoding for the Hamming (7, 4) code is about 1×10^{-3} while that after minimum distance decoding is about 5×10^{-3}, when the channel BER is 2×10^{-2}. The computer simulation results of WER are also plotted in the Figure. A little degradation from the simulation results is observed in the experimental WERs. Further study will clarify the reason for this degradation.

Conclusion: WER performance with trellis decoding of linear block codes was investigated in a Rayleigh fading channel. The Hamming (7, 4) code was used for the WER performance evaluation via laboratory experiments. The trellis decoding algorithm was applied to a 16 kbit/s signal transmission using GMSK modulation and a frequency detection system. A great improvement in WER performance was obtained over conventional minimum distance decoding when the bit interleaving degree = 64 and the maximum Doppler frequency = 120 Hz.

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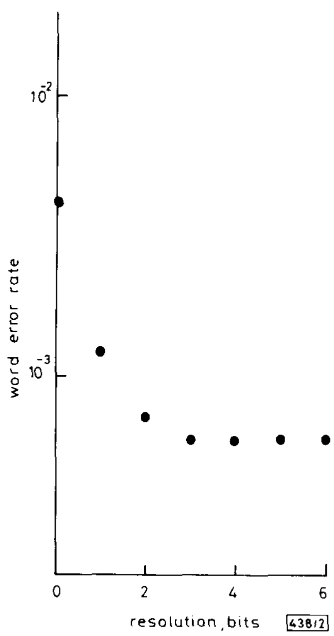

Fig. 2 *Experimental WER against resolution of n-bit A/D conversion*
Hamming (7, 4) code; $f_D = 120$ Hz; $M_i = 64$; BER $= 1 \cdot 4 \times 10^{-2}$

* Limiter-discriminator detection is widely used for FSK signal reception. The BER for FSK with a limiter-discriminator can be approximated by (1/2) exp $(-\alpha\gamma)$, in which parameter α is experimentally obtained. Hence, this algorithm can be applied.

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