High Performance Viterbi Decoder for OFDM Systems

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Abstract—**It is well-known that, for systems that deploy conventional convolutional codes, a Viterbi decoder is the best solution in maximum likelihood sense to decode an information sequence. Typically, a Viterbi decoder uses Euclidean or Hamming distance as a metric. The use of a conventional metric leads to a high performance for systems that are employed for frequency nonselective channels (e.g., additive white Gaussian noise (AWGN), or Rayleigh fading). However, if the system is based on orthogonal frequency division multiplexing (OFDM) and the channel has frequency selective multipath fading, then the performance can be further improved. In this paper we propose a simple modification to the conventional Viterbi metric (Euclidean distance) that improves the performance substantially if the channel is frequency selective. Simulation results on wireless local area network (WLAN) standard IEEE 802.11a show that the performance is improved about 10 dB when the proposed metric is used. Furthermore, the proposed metric gives the same high performance as the conventional Viterbi metric if the channel is AWGN or flat fading.**

I. Introduction

In recent years high speed wireless data communications have found many application areas. OFDM, [1], allowed WLANs to reach up to the rates of 54 Mbps. In 1999, such a WLAN system was standardized as IEEE 802.11a at 5 GHz band [2]. Another OFDM based WLAN system titled as IEEE 802.11g at 2.4 GHz band was standardized in 2003 [3].

These standards and many OFDM based systems deploy conventional convolutional encoders at the transmitter. Typically, a Viterbi decoder is used to decode the information sequence at the receiver. A conventional Viterbi decoder uses Euclidean or Hamming distance as a metric with Euclidean distance (soft decisions) providing about 2 dB gain over Hamming distance (hard decisions). This leads to a high performance if the channel is frequency nonselective (e.g., AWGN or flat fading). In this paper we propose a simple modification to the conventional Viterbi metric (Euclidean distance) that improves the performance of the system significantly over frequency selective multipath fading channels. An estimate of the channel SNR, based on channel and noise estimation, corrects the effects of channel or noise variations with frequency as will be shown. This estimate is used to modify the conventional Viterbi metric in the decoder.

The proposed new method enhances system performance in frequency selective fading channels substantially without any degradation in flat fading channels. The technique is based on interpreting the Viterbi decoder metric in the light of frequency selectivity and is a simple modification to conventional Viterbi decoding. Although variations of this technique have occasionally been used in industry, the technique did not appear in print widely. And, the results to be presented here in terms of its very low complexity implementation employing only a 3-bit representation of the magnitude of the channel estimate and eliminating noise estimation are new. Furthermore, we quantify the gain due to incorporating noise estimation. We provide simulation results for IEEE 802.11a systems. This standard only specifies the encoder and therefore this decoding technique provides the substantial gain while working within the standard. In addition, the technique is beneficial for all OFDM systems.

In Section II we present a brief overview of IEEE 802.11a standard for reader's convenience. The maximum likelihood criterion for a Viterbi decoder, the original and the proposed metrics are introduced in Section III. Detailed simulation results of IEEE 802.11a over frequency nonselective and frequency selective channels are displayed in Section IV. Finally, we end the paper with a brief conclusion in Section V where we restate the important themes presented.

II. Overview of IEEE 802.11a

The OFDM system used in IEEE 802.11a provides a WLAN with data payload communication capabilities of 6, 9, 12, 18, 24, 36, 48, and 54 Mbps. The system uses 52 subcarriers that are modulated using binary or quadrature phase shift keying (BPSK/QPSK), 16-quadrature amplitude modulation (QAM), or 64-QAM. Forward error correction coding (convolutional coding) is used with a coding rate of 1/2, 2/3, or 3/4.

Block diagrams of a typical IEEE 802.11a system are shown in Figure 1. At the transmitter, binary input data is encoded by the industry standard rate 1/2, constraint length 7 code with generator polynomials (133,171). The rate may be increased to 2/3 or 3/4 by puncturing the coded output bits [2]. After interleaving, bits are mapped into complex

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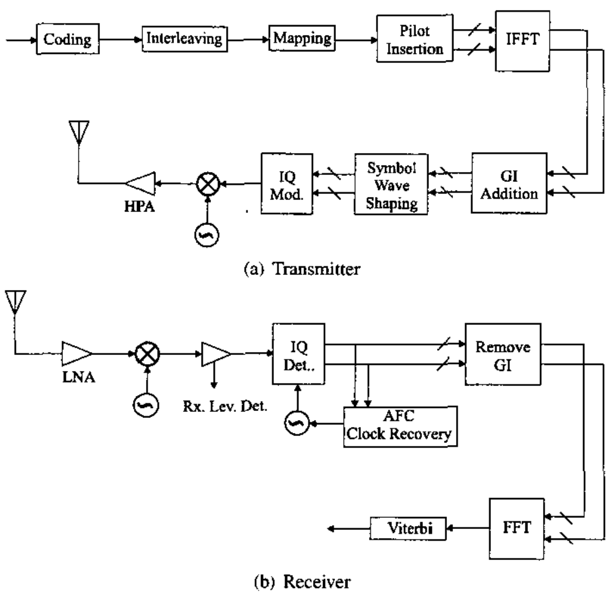


(a) Transmitter

(b) Receiver

Fig. 1. Transmitter and receiver block diagrams for 802.11a OFDM system

numbers according to the modulation scheme that is being used. In order to facilitate coherent reception, four pilot values are added to each of the 48 data values, such that a total of 52 modulation values are reached per OFDM symbol. 52 values are then modulated onto 52 subcarriers by applying and Inverse Fast Fourier Transform (IFFT). A guard interval (cyclic prefix) is added to make the system robust to multipath propagation. Next, windowing is applied to attain a narrower output spectrum. The modulated and windowed digital output signals are converted to analog signals, which are then up-converted to the proper channel in the 5 GHz band, amplified, and transmitted through an antenna.

A typical OFDM receiver basically performs the reverse operations of the transmitter, together with additional training tasks. First, the receiver has to estimate frequency offset and symbol timing, using special training symbols in the preamble. Then, it can do a Fast Fourier Transform (FFT) for every OFDM symbol to recover 52 modulation values of all subcarriers. The training symbols and pilot subcarriers are used to correct for the channel response as well as any remaining phase drift. After taking FFT, a Viterbi decoder can be used to decode the information sequence. A low complexity soft-decision Viterbi decoder for a bit-interleaved system (Figure 1a) can be easily implemented using the results in [4].

Figure 2 shows the packet format of the IEEE 802.11a standard. The preamble is composed of 10 repetitions of a "short training" sequence, and two repetitions of a "long training sequence". At the receiver end, short training sequences are used for Automatic Gain Control (AGC) convergence, diversity selection, timing acquisition, and coarse frequency acquisition in the receiver. Long training sequences are used for channel estimation and frequency acquisition. The SIGNAL field of

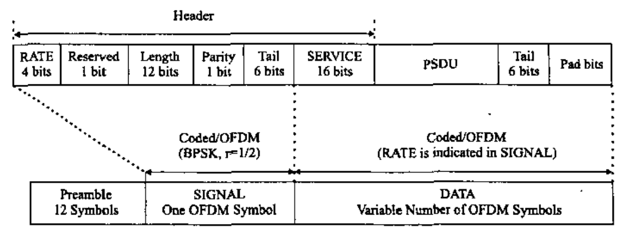


Fig. 2. Packet Format

the packet contains the RATE and the LENGTH of the data transmitted. One OFDM symbol is created with BPSK modulation of the subcarriers using convolutional coding at rate 1/2 for the encoding of the SIGNAL. DATA field of the packet contains the bits to be transmitted within Physical layer convergence protocol Service Data Unit (PSDU). The rate, modulation scheme and the length of the DATA bits are given in the SIGNAL field. The details of the packet format and the transmitter are given in [2].

The summary of the important parameters of the IEEE 802.11a standard are given in Table I.

Information Data Rate	6, 9, 12, 18, 24, 36, 48 and 54 Mbps
Modulation	BPSK OFDM QPSK OFDM 16-QAM OFDM 64-QAM OFDM
Error Correcting Code	K=7 (64 states) convolutional code
Coding Rate	1/2, 2/3, 3/4
Number of Subcarriers	52

TABLE I

MAJOR PARAMETERS OF IEEE 802.11A SYSTEM

III. THE ORIGINAL AND THE MODIFIED VITERBI METRICS

It can be shown [5], [6] that the maximum likelihood criterion for the receiver is

$$\min_Z \left| \frac{\hat{H}Z - X}{\sigma} \right|^2 \tag{1}$$

where

- Z: Transmitted Data
- H: Channel, $\hat{H}$: Channel Estimate
- W: Gaussian noise with variance σ^2
- X: Received Data
- $X = HZ + W$

Then the minimization can be factored as

$$\min_Z \left| \frac{\hat{H}Z - X}{\sigma} \right|^2 = \min_Z \frac{|\hat{H}|^2}{\sigma^2} |Z - \hat{Z}|^2 \tag{2}$$

where $\hat{Z} = \frac{X}{\hat{H}}$.

Let $\bar{Z}$ be the closest point to $\hat{Z}$ in constellation. Then a simple noise estimation $\hat{\sigma}^2$ can be evaluated by

$$\hat{\sigma}^2 = E\left|X - \hat{H}\hat{Z}\right|^2 \tag{3}$$

where the expectation is taken over the OFDM tones. Consider the ratio

$$q = \frac{|\hat{H}|^2}{\hat{\sigma}^2}, \tag{4}$$

then the proposed modified Viterbi metric can be written as

$$c_{modified} = q|Z - \hat{Z}|^2. \tag{5}$$

Note that a conventional Viterbi decoder uses

$$c_{original} = |Z - \hat{Z}|^2 \tag{6}$$

as a metric. When there is no channel or noise variation with frequency, a conventional Viterbi metric yields a satisfactory performance. However, the estimate in equation (4) corrects the effects of channel or noise variations with frequency, and therefore the modified metric (5) shows significant improvement when the channel is a frequency selective multipath fading channel. If there are no variations in the channel with frequency, the modified metric shows the same high performance as the conventional Viterbi metric.

Note that the quantity in equation (4) is an estimate of the SNR in the channel. As such, the modified metric can be considered as incorporating channel quality, channel reliability, or channel state information.

In an IEEE 802.11a system, channel estimation ($\hat{H}$) is already calculated using the long training sequences in the preamble for equalization. In some cases, this estimate is already in polar form and $|\hat{H}|$ is already available. Therefore, implementing the proposed modified metric does not require greater computational complexity. We have established through simulations that one can even simplify the metric further by employing simply the magnitude of the channel estimate rather than the magnitude square and, also, eliminating noise estimation

$$\begin{aligned} q_{simple} &= \frac{|\hat{H}|}{\gamma} \\ c_{simple} &= \frac{|\hat{H}|}{\gamma}|Z - \hat{Z}|^2 \end{aligned} \tag{7}$$

where γ is an experimentally obtained scaling factor.

Simulation results in Section IV show that the simplified metric performs almost as well as the modified metric given in (5). Thus, with a slight change in the conventional Viterbi metric, substantial improvement can be achieved without introducing greater computational complexity.

In addition, the technique does not require a large resolution in expressing q_{simple}. Simulations with 802.11a showed that only 3 bits of resolution is sufficient for the same level of performance as infinite resolution to $|\hat{H}|/\gamma$!

A. Channel Quality Operation and Frequency Selective Channels

Equation (4) corresponds to a measurement of the Signal-to-Noise Ratio (SNR), or the channel quality in the channel. In our implementation, channel quality (4) is scaled and clipped to $[0, 1]$, and is represented by a small number of bits. This corresponds to forcing those sections of the decoder trellis for which the channel SNR is small to have a lower branch metric and contribute less to the path metric. As a result, branches whose channel quality are higher are emphasized in path decision making. This is similar to zero forcing equalization versus mean-squared error equalization where the reciprocal of the channel SNR is a term in the denominator of the optimum equalizer, deemphasizing equalizer output when the channel SNR is low, [6].

Note that for channels without frequency selective fading, the value of (4) is the same for all frequency bins in OFDM and therefore there is no difference in the performance of conventional metric and the modified metric. When there is frequency selectivity in the channel, however, the QAM symbols corresponding to the different OFDM tones are weighted differently, and since this weighting provides the necessary modification to the decoder metric as in (2), optimum decoding performance is achieved.

Sometimes it is questioned whether this operation "undoes" the effect of channel inversion $\hat{Z} = X/\hat{H}$. As can be seen from equation (2), the answer is no. The optimum operation actually corresponds to multiplying the values of transmitted QAM symbols with $\hat{H}$ and comparing them with the received symbols X and the channel quality metric achieves this in a simple way.

IV. Simulation Results

A. Channel Models

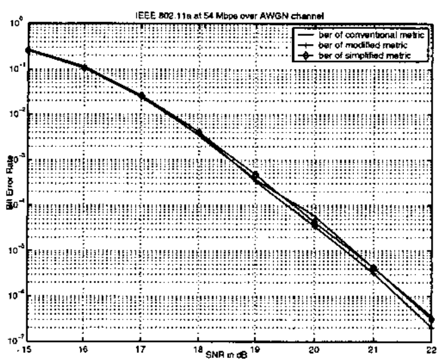
In the simulations below we used four different channel models. In all cases noise (W) is a complex random variable (r.v.) with a white Gaussian distribution.

1) **AWGN:** Flat deterministic (unity) channel with additive white Gaussian noise (AWGN), i.e., frequency response $H = 1$.
2) **Flat Fading:** Random flat channel with AWGN. The frequency response H is a Rayleigh r.v., and it is assumed that H is the same for the whole packet.
3) **Exponential Channel:** Frequency selective multipath channel with AWGN. H corresponds to an FIR filter with root mean square (r.m.s.) delay spread 25 or 75 ns. Each complex component is an independent Gaussian r.v., and the mean envelope has first order exponential decay. WLANs operate mostly over frequency selective multipath channels. Therefore, results for exponential channels are key for their operation.

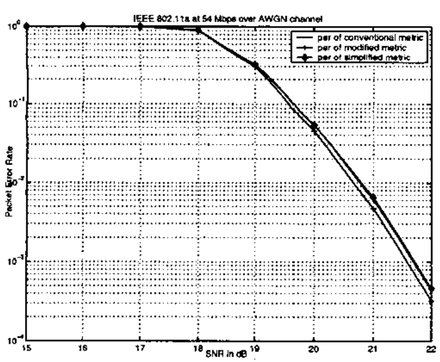
B. Simulation Results at 54 Mbps

We ran simulations on WLAN standard IEEE 802.11a at 54 Mbps transmission mode with 1000 bytes packet length. We compared the performance of the conventional Viterbi metric, the modified and the simplified metrics using a conventional Viterbi decoder at the receiver. The channel quality (q, equation (4)) is divided by a scaling factor β (64 for the figures below) for the modified metric. For the simplified metric, γ in equation (7) is set as one, and the values of q and q_{simple} are kept within zero to one (i.e., q and q_{simple} are clipped at one). We observed that the results do not depend significantly on the value of β, similar results are established for β values of 32 and 128.

For AWGN and flat fading channels the performance of the conventional Viterbi metric matches the performances of the modified and the simplified metrics, see Figures 3 and 4. This is an expected result since there is no channel or noise variation with frequency over AWGN and flat fading channels.



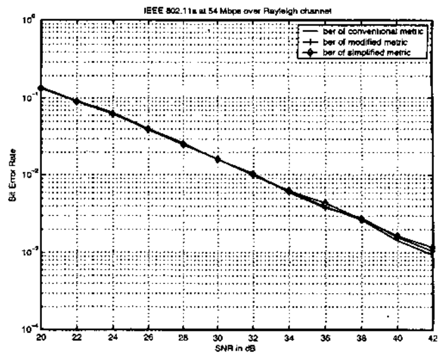
(a) BER vs SNR



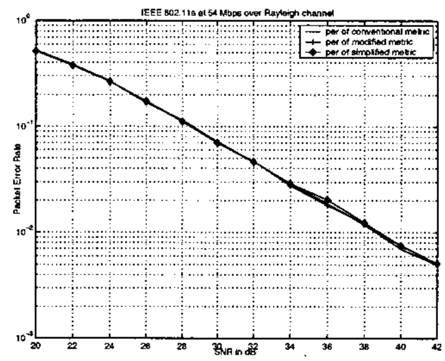
(b) PER vs SNR

Fig. 3. BER and PER vs SNR in dB for 54 Mbps 802.11a system over AWGN channel

Over the frequency selective multipath channels both the modified and the simplified metrics performed substantially better than the original Viterbi metric. For 25 ns exponential channels the improvement of the channel SNR is more than 10 dB for both the modified and the simplified metrics at the Bit Error Rate (BER) value of 10^{-5}, see Figure 5. Similarly, SNR is improved by more than 10 dB for both metrics at the Packet Error Rate (PER) value of 10^{-3}. When the r.m.s. delay spread is 75 ns, the improvement of SNR is about 15 dB at



(a) BER vs SNR



(b) PER vs SNR

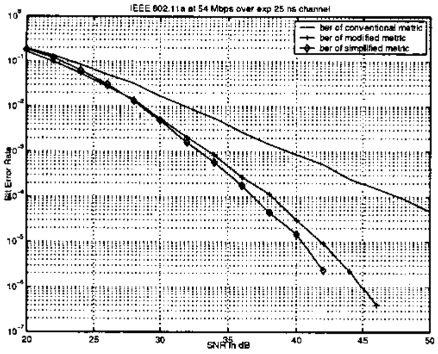
Fig. 4. BER and PER vs SNR in dB for 54 Mbps 802.11a system over flat channel

10^{-5} BER level and even more than 15 dB at 10^{-3} PER level for the modified and the simplified metrics, see Figure 6.

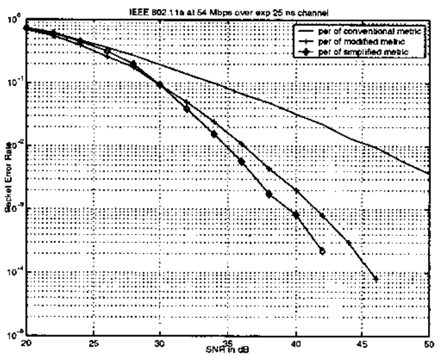
As can be seen from the figures, the results for the modified and the simplified metrics are very close. In fact, the modified metric, (5), shows slightly better performance in low SNR values than the simplified metric, (7). Other way around holds for high SNR values. This is an expected result, since the noise estimation method in equation (3) is relatively simple, and in our simulations the average is over a small number of tones. Better noise estimation methods, or taking the average over larger number of tones, can lead to more accurate estimation of the noise, and therefore could increase the performance of the modified metric.

V. Conclusion

In this paper we proposed a simple modification to the original Viterbi metric for WLAN receivers. The new modified metric corrects the effects of channel or noise variation with frequency. Simulation results illustrated that the modified metric improves the performance of a Viterbi decoder by around 10 dB when the channel is a frequency selective multipath channel. Further analysis showed that even without the noise estimate, using only the magnitude of the channel

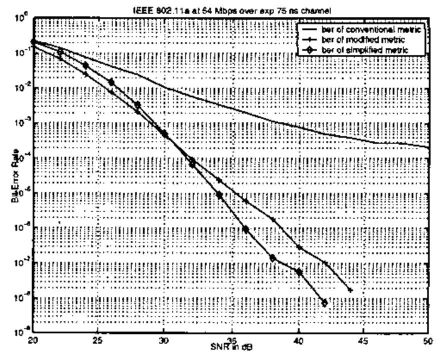


(a) BER vs SNR

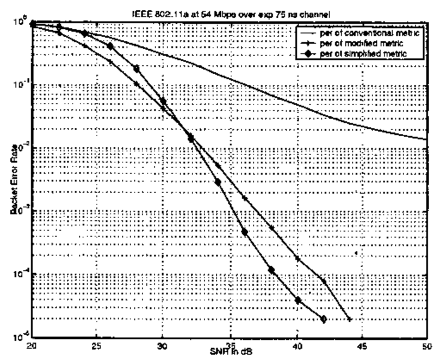


(b) PER vs SNR

Fig. 5. BER and PER vs SNR in dB for 54 Mbps 802.11a system over 25 ns exponential channel



(a) BER vs SNR



(b) PER vs SNR

Fig. 6. BER and PER vs SNR in dB for 54 Mbps 802.11a system over 75 ns exponential channel

estimate leads to a substantial improvement in performance of the receiver.

In a typical IEEE 802.11a receiver the channel estimate is already obtained using special training sequences in the preamble for equalization. Therefore, the implementation of the new metric (modified or simplified) does not introduce any significant computational complexity to the decoder.

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