A UNIFIED MLSE DETECTION TECHNIQUE FOR TDMA DIGITAL CELLULAR RADIO

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ABSTRACT

A unified maximum-likelihood sequence estimation (MLSE) detection technique is proposed for TDMA digital cellular radio. In this technique, the probabilistic likelihood metrics are calculated from the joint conditional probabilities of all received sample sequences including complex-valued, oversampled, and/or multi-channel diversity sequences provided that the sample statistics are independent. Based on the calculated metrics, the well-known Viterbi algorithm is used to decide on the maximum-likelihood sequence. The same unified approach can be used to analyze the probability of error for MLSE detection. As an application, a receiver employing the proposed detection technique is constructed and its performance is analyzed and simulated according to the North American digital cellular standard. Simulation results verify the effectiveness of the proposed technique.

I. INTRODUCTION

Since the inception of the maximum-likelihood sequence estimation (MLSE) technique about two decades ago [1-2], it has been widely used in digital communication and other areas to detect signals corrupted by intersymbol interference (ISI) and noise. The optimal receiver proposed by Forney [1] consists of a whitened matched filter, a sampler with a sampling rate $1/T$, and the Viterbi algorithm. The early efforts for applying the MLSE technique to a landline telephone modem include the utilization of a prefilter or an adaptive equalizer to reshape and/or truncate the channel impulse response to a reasonable length. Then the complexity of the MLSE algorithm can be greatly reduced [3]. In these applications, the telephone channel characteristics are well understood and hence can be accurately modeled. Therefore, one can design an MLSE receiver with moderate complexity to achieve superior performance.

The terrestrial cellular radio transmission environment, on the other hand, is more difficult to handle. The channel is typically of time-dispersion, frequency selective fading, and fast time-variation. For this type of transmission medium, it may be difficult to include a *meaningful* matched filter in a receiver to compensate phase distortion incurred on the transmitted waveform. Further, for narrow-band and low- or medium-rate signal transmission, delay spread of the channel may be comparable to a symbol period or just a fraction of it. This is actually the case for the North American digital cellular standard proposed by the Telecommunications Industry Association (TIA) [4]. Under this condition, if no matched filter can be realized in a receiver, the received signal sequence sampled at symbol intervals may not be adequate for proper estimation of the transmitted sequence. Hence, the full potential of MLSE detection may not be achieved. In addition, multi-channel diversity may be used in a cellular radio system to mitigate fading. Under these circumstances, how to design a receiver to achieve the potential of MLSE detection and to take advantage of diversity reception remains a problem.

In this paper, we summarize some previously reported results [5-6] and propose a unified MLSE detection technique suitable for TDMA digital cellular radio. We start by considering an optimal MLSE receiver structure for detecting the DQPSK modulated, complex-valued symbol sequence. Then a $T/2$ fractionally-spaced MLSE (FS-MLSE) receiver [5] is presented. Afterwards, the receiver structure for multi-channel diversity is derived, which includes the symbol-spaced MLSE (SS-MLSE) algorithm and the FS-MLSE algorithm. Due to short delay spread of the channel considered, the computational complexity of the receiver is very reasonable. Hence, good receiver performance will be the main objective of this study.

The organization of this paper is as follows. Section II describes in general the unified MLSE detection technique, where various receiver structures are described. Section III presents the specific design considerations for the North American digital cellular radio. Then in Section IV, we extend the unified technique to the analysis of the probability of error for MLSE detection. In Section V, simulation results are presented to verify the effectiveness of the proposed technique. Finally, in Section V, concluding remarks for this study are given.

II. A UNIFIED MLSE DETECTION TECHNIQUE

2.1 An SS-MLSE Receiver

A simplified cellular radio communication up-link is illustrated in Fig. 1. It consists of a modulator, a transmitter filter, an up-link converter, a cellular radio channel and a zero-mean additive white Gaussian noise source. The corresponding MLSE receiver in the down-link is depicted in Fig. 2. It consists of a whitened matched filter, a sampler sampled at kT, a receiver filter used to reject out-of-band spectral components and noise, and an MLSE detector. An equivalent discrete-time transceiver is shown in Fig. 3, where a finite-tap transversal filter is used to model the overall channel impulse response.

It is known that [1] if a matched filter is used in the receiver, the output sequence $\{y_k\}$ forms a set of sufficient statistics for estimation of the transmitted sequence. Since the noise spectrum within the signal bandwidth is flat, the equivalent sampled noise sequence $\{\eta_k\}$ will still be considered additive white. The samples in $\{v_k\}$ are then statistically independent and the joint probability density function $p(\mathbf{v}_K|\mathbf{x}_K)$ can be expressed as [7]

$$p(\mathbf{v}_K|\mathbf{x}_K) = \prod_{k=1}^{K} p(v_k|x_k, x_{k-1}, \ldots, x_{k-L}) \tag{1}$$

where $\mathbf{v}_K = (v_1, v_2, \ldots, v_K)$, is the observed sequence, and $\mathbf{x}_K = (x_1, x_2, \ldots, x_K)$, is one of the possibly transmitted sequences, and L is the channel memory length.

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For the observed sequence $\mathbf{v}_K$, each $p(\mathbf{v}_K|\mathbf{x}_\kappa)$ has to be calculated and $max\, p(\mathbf{v}_K|\mathbf{x}_\kappa)$ is found. The sequence $\mathbf{x}_K$ corresponding to $max\, p(\mathbf{v}_K|\mathbf{x}_\kappa)$ is then chosen as the transmitted sequence. In implementing the MLSE detector by using the Viterbi algorithm, the logarithm of $p(\mathbf{v}_K|\mathbf{x}_\kappa)$ is used as likelihood metric. Further, it is calculated in a recursive manner, that is,

$$\ln[p(\mathbf{v}_k|\mathbf{x}_k)=\ln[p(v_k|x_k,x_{k-1},\ldots,x_{k-L})]+\ln[p(\mathbf{v}_{k-1}|\mathbf{x}_{k-1})] \quad (2)$$

where $\ln[p(v_k|x_k,x_{k-1},\ldots,x_{k-L})]$ is the incremental metric for the newly observed symbol and $\ln[p(\mathbf{v}_{k-1}|\mathbf{x}_{k-1})]$ is the metric calculated in the previous iteration.

For DQPSK modulated signal, both $\{v_k\}$ and $\{x_k\}$ are complex, so is the white Gaussian noise, that is, $\eta_k=\eta_{kr}+j\eta_{ki}$. In this case, we have

$$\ln[p(v_k|x_k,x_{k-1},\ldots,x_{k-L})]\propto-(\Delta\mu_{kr}+\Delta\mu_{ki})$$
$$=-\left(\left|v_{kI}-\mathrm{Re}\left(\sum_{n=0}^{L}\hat{f}_n x_{k-n}\right)\right|^2+\left|v_{kQ}-\mathrm{Im}\left(\sum_{n=0}^{L}\hat{f}_n x_{k-n}\right)\right|^2\right) \quad (3)$$

where v_{kI} and v_{kQ} are the inphase and quadrature components of v_k, respectively, $\{\hat{f}_n\}$ is the complex channel impulse response. In practice, $\{\hat{f}_n\}$ has to be estimated by using an adaptive channel estimator.

2.2 An FS-MLSE Receiver

If no attempts are made to implement a matched filter in a cellular radio receiver, an FS-MLSE technique can be used to improve receiver performance [5]. In an FS-MLSE receiver, the observed sequence has to be oversampled. For the sake of simplicity, we consider the case of oversampling by 2.

Let us consider again the DQPSK modulated signal where the complex samples in the oversampled sequence are statistically independent. In this case, the likelihood metric for the observed intermediate sample $v_{k-1/2}$ is given by

$$\ln[p(v_{k-1/2}|x_k,x_{k-1},\ldots,x_{k-L})]\propto-(\Delta\mu_{(k-1/2)r}+\Delta\mu_{(k-1/2)i})$$
$$=-\left(\left|v_{(k-1/2)\mathrm{I}}-\mathrm{Re}\left(\sum_{n=0}^{2L}\hat{f}_n x_{k-1/2-n/2}\right)\right|^2+\left|v_{(k-1/2)\mathrm{Q}}-\mathrm{Im}\left(\sum_{n=0}^{2L}\hat{f}_n x_{k-1/2-n/2}\right)\right|^2\right) \quad (4a)$$

where $\{\hat{f}_n\}$ represents the $T/2$ fractionally-spaced channel impulse response and $(x_{k-1/2},x_{k-1},\ldots,x_{k-1/2-L})$ is the sequence interpolated from $(x_k,x_{k-1},\ldots,x_{k-L})$. The metric for the observed sample v_k is

$$\ln[p(v_k|x_k,x_{k-1},\ldots,x_{k-L})]\propto-(\Delta\mu_{kr}+\Delta\mu_{ki})$$
$$=-\left(\left|v_{kI}-\mathrm{Re}\left(\sum_{n=0}^{2L}\hat{f}_n x_{k-n/2}\right)\right|^2+\left|v_{kQ}-\mathrm{Im}\left(\sum_{n=0}^{2L}\hat{f}_n x_{k-n/2}\right)\right|^2\right). \quad (4b)$$

The likelihood metric for the two observed samples $v_{k-1/2}$ and v_k within one symbol period is given by

$$\ln[p(v_{k-1/2},v_k|x_k,x_{k-1},\ldots,x_{k-L})]\propto$$
$$-[(\Delta\mu_{(k-1/2)r}+\Delta\mu_{(k-1/2)i})+(\Delta\mu_{kr}+\Delta\mu_{ki})]. \quad (5)$$

Hence, an incremental likelihood metric can be calculated by using (5) in conjunction with (4a) and (4b).

Again, the $T/2$ fractionally-spaced channel impulse response $\{\hat{f}_n\}$ has to be estimated before it can be used in metric calculations.

2.3 An SS-MLSE Receiver with Multi-Channel Diversity

An equivalent multi-channel diversity receiver is shown in Fig. 4. In this receiver, all receiving channels are assumed to have uncorrelated characteristics. If a matched filter is used in each receiving channel, the SS-MLSE algorithm can be used to optimally estimate the transmitted sequence. In the case of DQPSK modulation, the incremental metric is given by

$$\sum_{m=1}^{M}\ln[p(v_k^m|x_k,x_{k-1},\ldots,x_{k-L})]\propto-\sum_{m=1}^{M}(\Delta\mu_{kr}^m+\Delta\mu_{ki}^m)$$
$$=-\sum_{m=1}^{M}\left(\left|v_{kI}^m-\mathrm{Re}\left(\sum_{n=0}^{L}\hat{f}_n^m x_{k-n}\right)\right|^2+\left|v_{kQ}^m-\mathrm{Im}\left(\sum_{n=0}^{L}\hat{f}_n^m x_{k-n}\right)\right|^2\right) \quad (6)$$

where the superscript m denotes the m^{th} diversity channel, and M is the total number of diversity channels contained in the receiver.

By calculating each incremental metric according to (6), estimation of the transmitted sequence can be carried out in much the same way as that for single channel MLSE detection.

2.4. An FS-MLSE Receiver with Multi-Channel Diversity

Without implementing matched filters, the FS-MLSE algorithm can be used in a multi-channel receiver to estimate the transmitted sequence. In this case, the incremental metric has the form of

$$\sum_{m=1}^{M}\ln[p(v_{k-1/2}^m,v_k^m|x_k,x_{k-1},\ldots,x_{k-L})]\propto$$
$$-\sum_{m=1}^{M}[(\Delta\mu_{(k-1/2)r}^m+\Delta\mu_{(k-1/2)i}^m)+(\Delta\mu_{kr}^m+\Delta\mu_{ki}^m)] \quad (7)$$

where

$$-(\Delta\mu_{(k-1/2)r}^m+\Delta\mu_{(k-1/2)i}^m)$$
$$=-\left(\left|v_{(k-1/2)\mathrm{I}}^m-\mathrm{Re}\left(\sum_{n=0}^{2L}\hat{f}_n^m x_{k-1/2-n/2}\right)\right|^2+\left|v_{(k-1/2)\mathrm{Q}}^m-\mathrm{Im}\left(\sum_{n=0}^{2L}\hat{f}_n^m x_{k-1/2-n/2}\right)\right|^2\right) \quad (8a)$$

and

$$-(\Delta\mu_{kr}^m+\Delta\mu_{ki}^m)$$
$$=-\left(\left|v_{kI}^m-\mathrm{Re}\left(\sum_{n=0}^{2L}\hat{f}_n^m x_{k-n/2}\right)\right|^2+\left|v_{kQ}^m-\mathrm{Im}\left(\sum_{n=0}^{2L}\hat{f}_n^m x_{k-n/2}\right)\right|^2\right). \quad (8b)$$

2.5 A Unified MLSE Receiver

In general, the observed sequences in a receiver could be complex-valued and multiple oversampled. They could also be received from multiple diversity and multiple channels. In this case, if the samples in all sequences are statistically independent, we can detect the transmitted sequence based on the following recursive equation

$$\sum_m\sum_l\cdots\sum_i\ln[p(\mathbf{v}_{ki\ldots l}^m|\mathbf{x}_k)$$
$$=\sum_m\sum_l\cdots\sum_i\ln[p(v_{ki\ldots l}^m|x_k,x_{k-1},\ldots,x_{k-L})]+\sum_m\sum_l\cdots\sum_i\ln[p(\mathbf{v}_{(k-1)i\ldots l}^m|\mathbf{x}_{k-1})] \quad (9)$$

where the first summation could be taken over the likelihood metrics of the real and imaginary samples, the second summation could be taken over the metrics of multiple oversampled samples, the third summation could be taken over the metrics of multi-channel samples, and so on.

In a practical implementation by using the Viterbi algorithm, however, some simplifications can be done. Essentially, the unified algorithm will search through the trellis in the same manner as the conventional MLSE algorithm. Also, the number of path metrics to be updated and stored will be the same as those in the conventional algorithm. The only difference lies in the calculation of incremental likelihood metrics. Since now the observed sequences could be multi-dimensional, a multiple summation is required to calculate an incremental metric in addition to calculating each individual Euclidean distance. For any specific receiver falling into one of the categories described in Sections 2.1-2.4, the appropriate equation can be used to calculate the incremental metric and then to detect the transmitted sequence.

III. SPECIFIC DESIGN CONSIDERATIONS

The unified MLSE detection technique described in Section II can be directly applied to the North American TDMA digital cellular radio.

For the receiver using an SS-MLSE algorithm, a lowpass filter with time-invariant parameters may be used before the sampler to fill partially the role of a matched filter. Such a filter may be able to compensate phase distortion caused by the cellular radio channel to some degree. However, due to fast variations of the channel, the usefulness of such a filter for phase equalization may be very limited.

For the receiver using an FS-MLSE detector, no matched filter may be required. The calculation of likelihood metrics, however, involves intermediate samples. An interpolation process is required to obtain intermediate samples from a possibly transmitted symbol sequence. The same interpolation process is needed to provide intermediate samples (from decisions of a training pattern or decisions made by the Viterbi algorithm) for the fractionally-spaced channel estimator. For the North American digital cellular radio, a square-root raised cosine filter with a rolloff factor of 0.35 is required in the transmitter and another identical filter may be used in the receiver. Hence, the above-mentioned two interpolation processes may be implemented by convolving the zero-inserted symbol sequence with the $T/2$ fractionally-spaced raised cosine filter [5].

Further, due to the use of the $T/2$ fractionally-spaced square-root raised cosine filter in the receiver, each observed intermediate sample may be correlated to its adjacent symbol sample. When the incremental metric is calculated, this correlation may have to be taken into consideration.

For the multi-channel diversity receiver, since all diversity channels are either uncorrelated or with low correlation, the impulse response of each channel has to be estimated by its own channel estimator. Overall, there are M channel estimators required in each receiver.

IV ANALYSIS OF ERROR PROBABILITIES

The method used to calculate the sequence error probability for conventional MLSE detection has been developed in [1]. With some modifications, the same method can be applied to analyze the error probability of the detection schemes described above. In particular, one of the subevents which cause a portion of the sequence being incorrectly detected is that over the duration of incorrect detection, the sum of the accumulated metrics of the estimated sequence exceeds the sum of the accumulated metrics of the correct path. With the likelihood metrics defined in Section II, the probability of occurrence of this subevent can be readily derived in the same unified manner. This will not be further pursued here.

V. SIMULATION RESULTS

Simulations have been carried out to verify the effectiveness of the proposed unified detection technique. In these simulations, the major aspects of the North American digital cellular standard are followed. Specifically, the modulation scheme is $\pi/4$-shifted DQPSK with a transmission rate 48.6 kb/s. The slot length is 6.67 ms, of which 162 symbols are included. A two-ray Rayleigh fading channel model is used where the two rays have equal power, independent fading characteristics, and a delay spread of $T/4$, $T/2$, and T (T equals to 41.2 µs). In all simulations, discrete-time channel models are used and no matched filter is included in the receiver. Further, on each receiving channel, an adaptive channel estimator is used to estimate the channel impulse response.

Fig. 5 shows the bit-error-rate (BER) results of the MLSE receivers described in Sections II and III. Here, two-channel diversity MLSE receivers are considered along with those single channel receivers. The vehicle speed is 50 km/h and the delay spread between the two fading rays is $T/4$. It is apparent that under the current channel condition, the FS-MLSE algorithm significantly outperforms the SS-MLSE algorithm. The main reason behind this may attribute to the fact that the FS-MLSE plays an equivalent role of combined matched filter and the SS-MLSE detector. The loss due to channel estimation errors is greatly reduced by using the FS-MLSE algorithm. For the two-channel MLSE receivers, diversity reception provides a significant gain over the single channel receivers. The two-channel FS-MLSE receiver exhibits superior performance to the two-channel SS-MLSE receiver when signal-to-noise ratio is high.

In Fig. 6, the BER simulation results are presented for the channel with a vehicle speed of 100 km/h and a delay spread of T. In this case, although the FS-MLSE algorithm still exhibits superior performance to the SS-MLSE algorithm, the gap between the two vanishes over a certain SNR range. This is because that for the second ray to be delayed exactly by one symbol period, the detection using the SS-MLSE algorithm suffers no great loss due to channel estimation errors than that using the FS-MLSE algorithm.

VI. CONCLUDING REMARKS

In this paper, we have proposed a unified maximum-likelihood sequence estimation technique. Under the assumption that the sample statistics are independent, we have described in detail how to optimally estimate a variety of received sample sequences, including complex-valued, oversampled, and/or multi-channel diversity sequences, in a unified manner.

Also considered in this paper are the issues related to applying the proposed technique to the North American digital cellular radio as well as how to extend the unified approach to analyze the probability of error for MLSE detection. Then simulation results have been presented to show the usefulness of the proposed technique. Although the primary focus of this study is on TDMA digital cellular radio, the proposed unified technique can also be applied to other digital communication systems.

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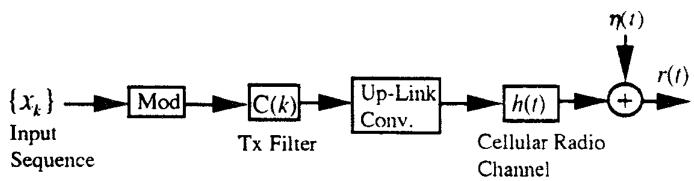

Fig. 1 A Cellular Radio Communication Up-Link

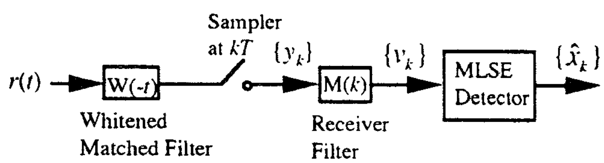

Fig. 2 The MLSE Receiver Corresponding to Fig. 1

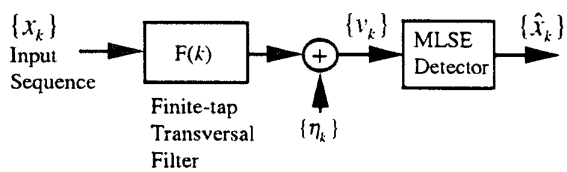

Fig. 3 Equivalent Cellular Radio Transceiver

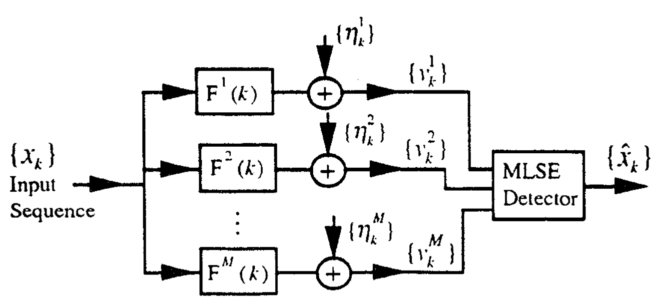

Fig. 4 Equivalent Multi-Channel Diversity Receiver

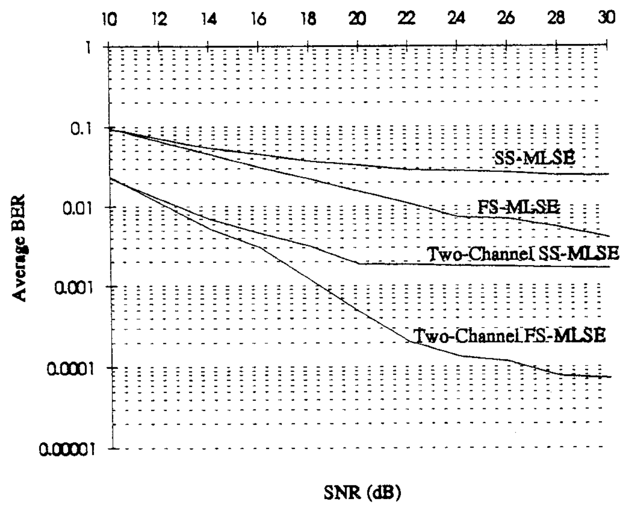

Fig. 5 BER Simulation Results of the MLSE Techniques (50 km/h, Delay Spread = T/4)

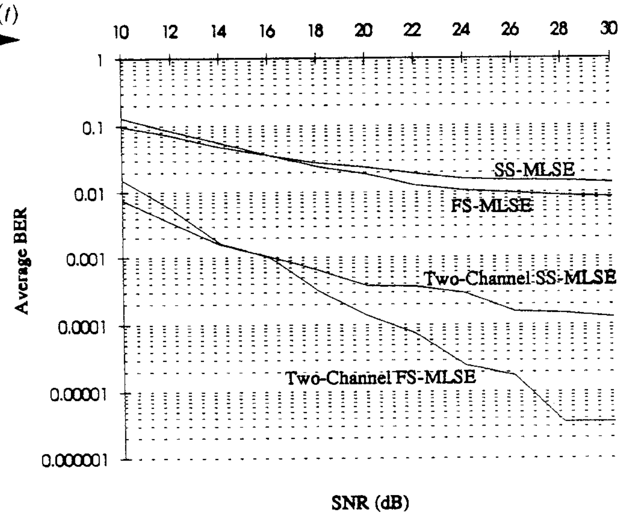

Fig. 6 BER Simulation Results of the MLSE Techniques (100 km/h, Delay Spread = T)