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maximally decimated multirate filterbanks. Unlike the existing precoding methods, such as the TH and trellis precodings, the new precoding

- i) may be independent of the ISI channel;
- ii) is linear and does not have to implement any modulo operation;
- iii) gives the ideal FIR equalization at the receiver for any FIR ISI channel including spectral-null channels;
- iv) expands the transmission bandwidth in a minimum amount.

The precoding is built on nonmaximally decimated multirate filterbanks. Based on multirate filterbank theory, we present a necessary and sufficient condition on an FIR ISI transfer function in terms of its zero set such that there is a linear FIR $N \times K$ precoder so that an ideal FIR equalizer exists, where the integers K and N are arbitrarily fixed. The condition is easy to check. As a consequence of the condition, for any given FIR ISI transfer function (not identically 0), there always exist such linear FIR precoders. Moreover, for almost all given FIR ISI transfer functions, there exist linear FIR precoders with size $N \times (N-1)$, i.e., the bandwidth is expanded by $1/N$. In addition to the conditions on the ISI transfer functions, a method for the design of the linear FIR precoders and the ideal FIR equalizers is also given. Numerical examples are presented to illustrate the theory.

I. INTRODUCTION

INTERSYMBOL interference (ISI) is a common problem in telecommunication systems, such as terrestrial television broadcasting, digital data communication systems, and cellular mobile communication systems. The main reasons for the ISI are because of high-speed transmission and multipath fading. There have been considerable studies for these problems, such as [1]–[29] and [33]–[40]. These studies can be primarily split into three categories:

- i) post equalization, such as least-mean-squared (LMS) equalizer and decision feedback equalization (DFE), for example, [1]–[3], [18]–[29], and [36]–[39];
- ii) multicarrier modulation to increase transmission symbol length, for example, [4]–[6];

and Forney [9], [10], matched spectral null pre
in partial response channels [12], and other pre
schemes, for example, [13]–[17] and [40].

The basic idea for DFE is that once an information s
has been detected, the ISI that it causes on future symbo
be estimated and subtracted out prior to symbol detectio
usually consists of a feedforward filter and feedback
The feedback filter is driven by decisions of the output
detector, and its coefficients are adjusted to cancel the
the current symbol that results from past detected symbo
coefficient adjustment may be done via a linear equaliz
LMS algorithms. The convergence of these iterative algo
are dependent of the channel characteristics. When a cha
spectral null or frequency selective fading, these algorith
very slow and, therefore, become computationally exp
The performance of the existing linear equalizers signif
degrades over frequency selective fading channels. Al
DFE has better performance than the existing linear equ
when the frequency fading is in the middle of a pas
it does not offer much improvement in other fading
For more details, see, for example, [3] and [35]. I
equalization techniques, there are many research resul
for example, [18]–[29] and [36]–[39] on blind equali
where channel characteristics are assumed unknown. I
equalization techniques, there are approximately three
of results:

- i) high-order statistics techniques;
- ii) second-order cyclostationary statistics techniqu
oversampling;
- iii) antenna array (smart antenna) multireceiver tech

where there is a considerable amount of overlaps betw
and iii).

A block diagram for TH precoding is shown in Fig. 1,
the basic idea is to equalize the signal before transm
With TH precoding there are two drawbacks: i) The tran
needs to know the channel characteristics, and ii) the pre
is not reliable when the ISI channel $H(z)$ has spectral
frequency selective fading characteristics, which is b
the pre-equalizer mod$[1/H(z), M]$ oscillates in a dr
way when $H(z)$ is close to zero. The trellis precoding s
proposed by Eyuboglu and Forney [9] whitens the noise
equalizer output. This scheme combines precoding and

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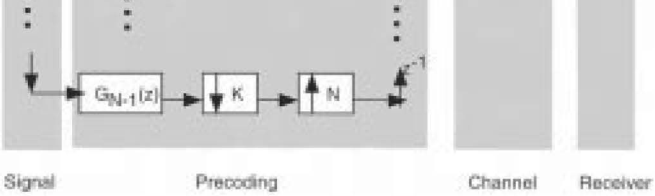

Fig. 2. Nonmaximally decimated multirate filterbank in a communication channel with ISI.

shaping. There are also similar drawbacks about this approach.

i) The transmitter also needs to know the ISI channel characteristics.
ii) The trellis shaping depends on the ISI channel.
iii) The trellis precoding technique may not be suitable for spectral-null channels either.

In the matched spectral null precoding scheme [12] in partial response channels, certain error control codes are chosen to match the spectral nulls of partial response channels in order to lose less signal information through the channel. This approach is mainly for magnetic recording systems.

We now propose a multirate filterbank as a precoder before transmission (shown in Fig. 2), where $\downarrow K$ indicates downsampling by K, and $\uparrow N$ indicates upsampling by N, i.e., inserting $N-1$ zeros between two adjacent samples, and $H(z)$ is the ISI transfer function. Later, we will see a multirate filterbank decoder for the receiver to eliminate the ISI. If input signal $x[n]$ in Fig. 2 can be completely recovered from the received signal $\hat{x}[n]$ through an FIR linear system, we call that the system in Fig. 2 has perfect reconstruction (PR) or an FIR ideal linear equalizer. In what follows, we use "precoder" and "multirate filterbank" interchangeably.

With the precoder proposed in Fig. 2, there are three questions to be answered:

i) What is the condition on $H(z)$ such that there exists a multirate filterbank with N channels and decimation by K in Fig. 2 so that $x[n]$ can be recovered from $\hat{x}[n]$ through an FIR linear system?
ii) If the condition on $H(z)$ in the first question is satisfied, how does one design a multirate filterbank in Fig. 2 to eliminate the ISI?
iii) If both of these two problems are solved, how does the receiver recover the input signal $x[n]$ from the received $\hat{x}[n]$?

$G_{N-1}(z) = 0$, the precoding scheme in Fi
equivalent to the fractionally spaced equalizer studi
example, [36]–[39], where the receiver needs to sa
signal N times faster than the baud sampling. When
the precoding concept has appeared in [39] by Tsatsa
Giannakis, where the precoder $G_l(z) = c_l, l = 0, 1, \cdots$
for N constants c_l was used. As we can see, the c
$K = 1$ is a very special case in our precoding schem
moreover, our new precoding scheme in Fig. 2 provide
potential precoders $G_l(z), l = 0, 1, \cdots, N-1$ rathe
only constants c_l, which allows one to search the optim
with respect to an individual channel.

When $K \geq N$ and there are N interference channels
of a single channel $H(z)$ in Fig. 2, a detailed analys
given by Nguyen [31]. When $K > N$, as mentio
[31], PR is impossible, but partial alias cancellation filte
were proposed in [31]. The applications discussed in [
in wide-band radio communications, where only part
signal frequencies is of interest to the user. In this
we are interested in applications in the ISI channels w
systems in Fig. 2 and, therefore, the case of $K <$
also implies that unlike the existing precoding techniqu
new precoding expands the transmission bandwidth, w
what we lose for the new precoding method, and fortu
we will show that the bandwidth expansion can be a
as possible in theory.

An intuitive way to reduce the ISI generated from a l
$H(z)$ is to smoothly interpolate $x[n]$ with a large
number of interpolations between samples of $x[n]$
the interpolated one has the lowpass property. Howev
drawbacks about this approach may occur. One is
usually requires a large amount of increasing of da
(number of interpolations between samples). The o
that a good frequency band structure for a nonlowpas
as bandpass, filter $H(z)$ is required for PR. In this
we want to solve the above three problems systema
Given two integers $0 < K < N$, we present a nec
and sufficient condition (see Theorem 1) on an FI
$H(z)$ such that there exists an FIR nonmaximally dec
multirate filterbank with N channels and decimation b
that $x[n]$ can be recovered from $\hat{x}[n]$ in Fig. 2 with
synthesis bank. The condition we found is basically very
In fact, it can be proved that for any given FIR filter
not identically 0, there always exists an FIR nonmax
decimated multirate filterbank in Fig. 2 for recoverin

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