Stabilized Precoder for Indoor Radio Communications

M. P. Sellars, *Member, IEEE*, S. D. Greaves, *Member, IEEE*, I. J. Wassell, *Member, IEEE*, J. Porter, and W. J. Fitzgerald

***Abstract*—A low complexity, stabilized precoder for broadband indoor radio is presented, which uses radial root reduction for stability, and so avoids the use of a modulo operator. Simulations show that the stabilized precoder has comparable performance to Tomlinson–Harashima (TH) precoding with perfect automatic gain control (AGC), and is immune to AGC fluctuations which degrade the performance of TH precoding.**

***Index Terms*—Automatic gain control (AGC), equalization, indoor radio, precoder.**

I. Introduction

TOMLINSON–HARASHIMA (TH) precoding [1] has been proposed for use in time-division-duplex (TDD) indoor radio networks, where multipath interference is a major obstacle to high-speed transmission [2]. The challenge of precoding is to keep the precoder stable even when equalizing a nonminimum-phase channel [3]. TH precoding uses a modulo operator to ensure stability of the precoder feedback (FB) filter, and this causes increased sensitivity to automatic gain control (AGC) errors [2], [4].

II. System Model

For precoding on the uplink, the converged feedforward (FF) and feedback (FB) filter taps from the downlink DFE are loaded directly into the precoder FF and FB filters respectively [3]. The precoder FB filter has transfer function $1/D(z)$ where $D(z) = B(z) + 1$ and $B(z)$ represents the FB filter taps. Provided that the downlink equalizer has fully converged, the zeros of $D(z)$ consist of [5]: 1) Stable zeros (zeros well inside the unit circle in the z-plane) and 2) Critical zeros (zeros on or close to the unit circle). These critical zeros cause instability, and so some form of precoder stabilization is necessary. The FF filter has transfer function $C(z)$, with all zeros inside the unit circle. The overall precoder transfer function $A(z) = (C(z)/D(z)) = (C(z)/(1 + B(z))) = (1/H(z))$, where $H(z)$ is the channel transfer function.

III. Stabilized Precoder

Instead of a modulo operator for stability, the Stabilized Precoder in Fig. 1 uses a hard limiter, which limits the signal $y(k)$ input to the feedforward (FF) filter. The transmitted power is similar to that of the TH precoder, [6], since the hard limiter restricts the peak range of $y(k)$. The FF filter (normalized to unity power gain) tends to smooth out fluctuations in $y(k)$, [6], so that the peak transmit power is similar to the average power bound in [7].

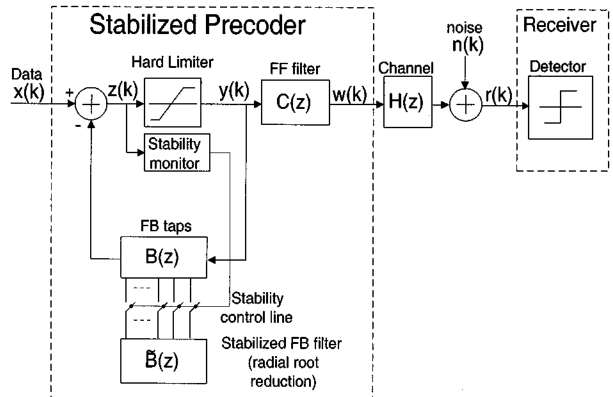

Fig. 1. Stabilized precoder.

The output of the summer $z(k)$ is monitored by a stability monitor block (a threshold detector was used), which detects the onset of a large amplitude signal and transfers a new set of coefficients $\tilde{\boldsymbol{B}} = [\tilde{b}_1, \tilde{b}_2, \cdots, \tilde{b}_p]$ into the FB filter in place of the original coefficients $\boldsymbol{B} = [b_1, b_2, \cdots, b_p]$. These new coefficients have zeros which have been pulled further inside the unit circle to ensure stability. The new set $\tilde{\boldsymbol{B}}$ may be calculated from the DFE FB taps using radial scaling of the roots. This is a trade-off between equalization accuracy and stability. However, since the critical zeros of the FB filter are always located either inside, or in close proximity to, the unit circle [5], only a small amount of radial reduction is required, (discussed later in more detail). Radial scaling of all zeros by $1/\gamma$ is efficiently implemented by multiplying each tap coefficient b_k by a scalar constant $1/\gamma^k$ [8]. The new FB filter transfer function is $1/\tilde{D}(z)$ where:

$$\tilde{D}(z) = D(\gamma z) = [\gamma^p\, d_0 + \gamma^{p-1}\, d_1 z^{-1} + \cdots + d_p z^{-p}] \quad (1)$$

The new set of FB taps is

$$\tilde{B}(z) = \left[\frac{1}{\gamma}\, b_1 z^{-1} + \cdots + \frac{1}{\gamma^{p-1}}\, b_{p-1} z^{-(p-1)} + \frac{1}{\gamma^p}\, b_p z^{-p}\right] \quad (2)$$

IV. Simulations

A set of 1000 indoor radio channels was generated using standard indoor channels in [9, Ch. 6], with average RMS delay

Manuscript received February 22, 2000. The associate editor coordinating the review of this letter and approving it for publication was Prof. A. Haimovich.

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Publisher Item Identifier S 1089-7798(00)07661-4.

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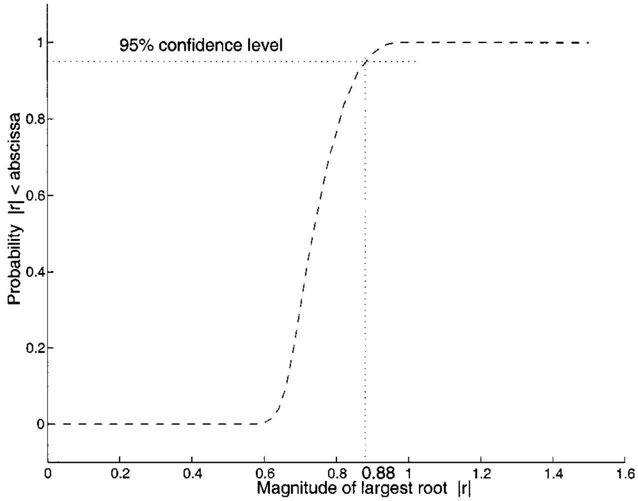
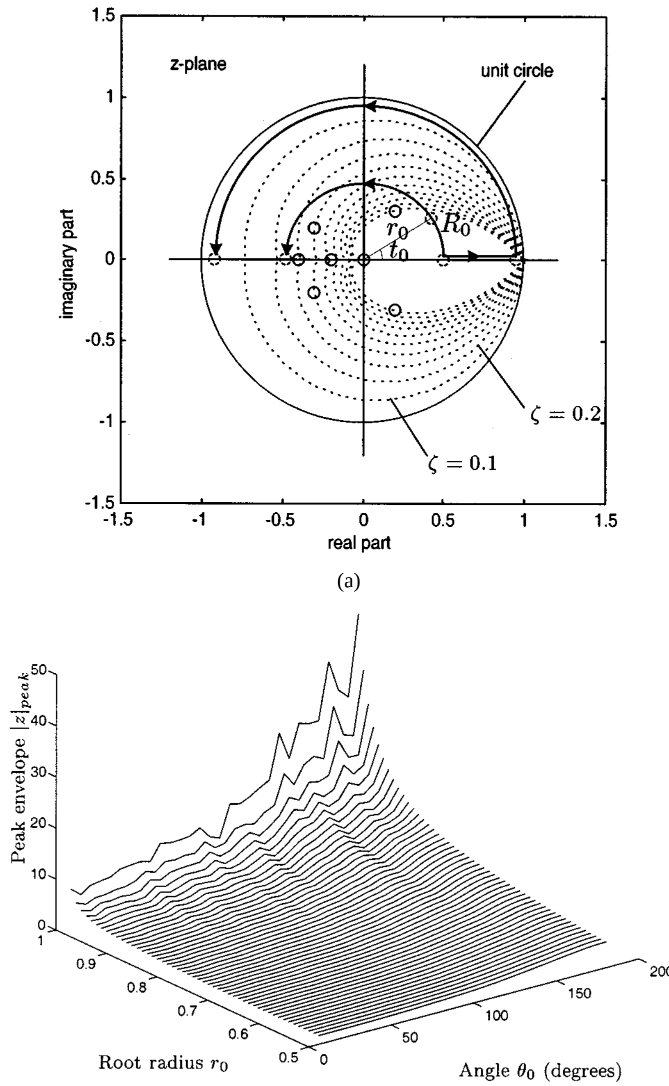


Fig. 2. Cumulative distribution of largest root of precoder FB filter.

spread $D_{\mathrm{RMS}} = 55$ ns (indoor channels may be considered static over a data burst [6]). It is important to verify that the converged FB taps of the downlink equalizer do result in roots of $D(z)$ lying inside, or near to, the unit circle. We examine the magnitude of the largest root $|r|$ of $D(z)$. Fig. 2 shows the cumulative distribution of $|r|$ averaged over all channels, with $\mathrm{SNR} = 20$ db. It is seen that 95% of all channel realizations result in $D(z)$ with $|r| \leq 0.88$.

A discrete-time system is bounded-input bounded output (BIBO) stable if all of its roots lie within the unit circle of the z-plane [10, Ch. 13]. Even if the FB filter is BIBO stable, it is possible for the output to have a large oscillatory response, determined by the damping factor ζ. To investigate the effect of ζ, a simplified precoder with no hard limiter was used, so that $y(k) = z(k)$. The FB filter $D(z)$ had 6 fixed roots inside the unit circle as shown in Fig. 3, and one root R_0 where $R_0 = r_0 e^{j\theta_0}$. The root radius r_0 was varied from 0.50–0.99, and the angle θ_0 varied from 0 degrees to 180 degrees. In Fig. 3(a), the positions of the root R_0 are marked by the arrows and dashed circles. For each position of root R_0 the peak value $|z|_{peak}$ of the signal $z(k) = y(k)$ is plotted in Fig. 3(b). It is seen that $|z|_{peak}$ depends both on the radius r_0 of the largest root, and also on the angle θ_0.

Since the output $z(k)$ of the precoder FB filter may become large, a hard limiter is needed to limit $z(k)$. In the TH precoder, the modulo operator guarantees that $z(k)$ will always lie within a fixed range. If the modulo operator is not present, then a hard limiter is necessary (or else saturation will effectively cause hard limiting in fixed-point arithmetic implementations). Fig. 2 shows that for almost all channels, the roots of $D(z)$ all lie within the unit circle, so the precoder FB filter is almost always BIBO stable. The usefulness of the Stabilized Precoder lies in reducing overshoot and oscillations in the FB filter impulse response, by reducing the magnitude of those roots which have low damping factor, (but are already inside the unit circle). The curves of constant damping factor ζ in the z-plane are logarithmic spirals. This makes it difficult to determine exactly which roots are the cause of excessive oscillation, and by exactly how much they should be reduced to keep the output $z(k)$



(b)

Fig. 3. (a) Roots of $D(z)$ in the z-plane, showing the range of root R_0 (b) Peak value of signal $z(k)$ at FB filter output.

within a given range. There are often multiple roots with large magnitudes and varying values of damping factor ζ, and so it is difficult to determine which particular roots need to be reduced. For this reason, an *ad-hoc* approach with very low complexity has been adopted, whereby the Stabilized Precoder simply radially scales all the roots by a factor $1/\gamma$ if the FB filter output exceeds a certain threshold. Extensive simulations have shown that a range of $0.90 \leq (1/\gamma) \leq 0.96$ gives reasonable results. If $1/\gamma$ is too small, then root reduction introduces residual ISI due to imperfect equalization. If $1/\gamma$ is too close to unity, root reduction has little effect. A similar *ad-hoc* method was used in [11] to stabilize adaptive autoregressive (AR) filters.

Fig. 4 shows the SER (symbol error rates) averaged over 20 000 bursts of 2000 QPSK symbols, at a bit rate of 25 Mbps. Perfect automatic gain control (AGC) was used, so the results for the TH precoder are best-case figures. The Stabilized Precoder used a radial scaling factor $(1/\gamma) = 0.96$, achieving error rate performance comparable with the TH precoder. The SER curves flatten out at high SNR, as in [12].

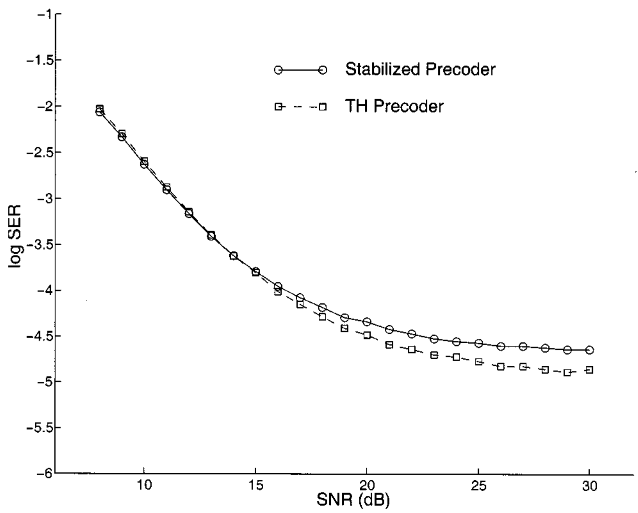


Fig. 4. Symbol error rates (SER) for the stabilized precoder and TH precoder.

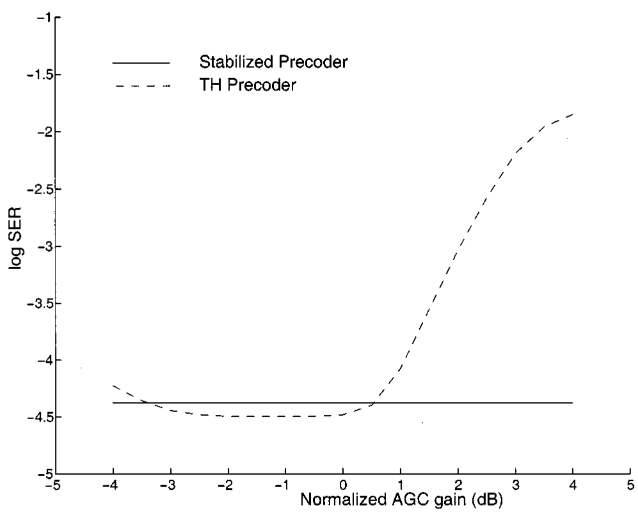


Fig. 5. Symbol error rates (SER) vs. Normalized AGC gain.

To investigate the effect of AGC error [2], [13], a single-tap FIR filter (single complex multiplier) was used to achieve gain and phase synchronization of the received precoded signal. A short training sequence was used to adjust the complex tap coefficient, after which the complex tap value was fixed, and a small offset ΔG was added to the gain of the received signal [2]. Normalized AGC gain (dB) $= 20\log((G+\Delta G)/G)$ where $G =$ ideal AGC gain, $\Delta G =$ error in AGC gain. Fig. 5 shows the variation of SER with normalized AGC gain for the TH Precoder and Stabilized Precoder, $\mathrm{SNR} = 20$ dB, averaged over 20 000 bursts. As the normalized AGC error increases, so the performance of the TH precoder degrades: this problem is addressed in [4]. The Stabilized Precoder is insensitive to AGC error because it avoids modulo operators.

V. Conclusion

TH precoders are sensitive to AGC errors at the receiver, and this makes them unsuitable for use in radio communication systems. The Stabilized Precoder achieves error rates comparable to the TH precoder, but is immune to AGC fluctuation.

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