A Wide-Band Radial Basis Function Decision Feedback Equalizer-Assisted Burst-By-Burst Adaptive Modem

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***Abstract*—The performance of radial basis function-based decision feedback equalized (RBF DFE) burst-by-burst adaptive quadrature amplitude modulation (AQAM) is presented for transmissions over dispersive wide-band mobile channels. This scheme is shown to give a significant improvement in terms of the mean bit error rate (BER) and bits per symbol (BPS) performance compared to that of the individual fixed modulation modes. The structural equivalence of the RBF DFE to the optimal Bayesian equalizer enables it to potentially outperform the conventional Kalman-filtered AQAM DFE scheme.**

***Index Terms*—Adaptive modulation, decision feedback equalization, radial basis function, wide-band modem.**

I. INTRODUCTION

BURST-BY-BURST adaptive quadrature amplitude modulation (AQAM) schemes employ a higher order modulation mode in a transmission burst, when the channel quality is favorable, in order to increase the bits per symbol (BPS) throughput and, conversely, a more robust but lower order modulation mode is utilized in those transmission bursts, where the instantaneous channel quality drops [1], [13]. Stimulated by Webb and Steele [1], in recent years intensive research was conducted toward advancing the state-of-the-art in AQAM [2]–[6]. In this contribution, we propose a novel AQAM scheme for transmissions over wide-band fading channels, which employs a radial basis function decision feedback equalizer (RBF DFE), in order to mitigate the effects of the dispersive wide-band channel. We will show that this RBF-AQAM scheme naturally lends itself also to channel quality estimation.

II. SYSTEM OVERVIEW

The structure of our AQAM RBF DFE is portrayed in Fig. 1. The receiver extracts the AQAM mode signaling bits from its received data burst. Then the received data burst is equalized, the estimated BER of the received burst is evaluated at the output of the RBF DFE and it is used as the AQAM mode-switching criterion. The estimated BER of the received burst is compared to a set of switching thresholds and the modulation mode to be used in the next transmission burst is decided accordingly. The *a posteriori* probabilities $\varsigma_i(k),\ i = 1, \ldots, \mathcal{M}$ of the $\mathcal{M}$-QAM symbols can be evaluated from the output f^i_{RBF} of the ith subnet of the $\mathcal{M}$-QAM RBF equalizer characterized by [7], [9]

$$\begin{aligned} f^i_{\mathrm{RBF}}(\mathbf{v_k}) &= P(\mathbf{v_k} | I_{k-\tau} = \mathcal{I}_i) \cdot P(I_{k-\tau} = \mathcal{I}_i) \\ &= \sum_{j=1}^{n_s^i} w_j^i \varphi(|\mathbf{v}_k - \mathbf{c}_j^i|), \\ &\qquad i = 1, \ldots, \mathcal{M}, \quad j = 1, \ldots, n_s^i \end{aligned} \tag{1}$$

where $\mathbf{c}_j^i$, $\mathbf{w}_j^i$ and $\varphi(\cdot)$ are the RBF's centers, weights, and activation function, respectively. Furthermore, the equalizer's input is $\mathbf{v}_k$ and the dimension of the vectors $\mathbf{v}_k$ and $\mathbf{c}_j^i$ is equivalent to the equalizer's feedforward order m, while n_s^i is the number of channel states. The RBF centers $\mathbf{c}_j^i$ and weights $\mathbf{w}_j^i$ are assigned to $\mathbf{c}_j^i = \mathbf{r}_j^i$, $\mathbf{w}_j^i = p_j^i$, respectively, where $\mathbf{r}_j^i$ is the noiseless channel output vector or the channel state and p_j^i is the probability of occurrence of a specific channel state [7], [9]. The actual number of channel states n_s^i is determined by the design of the algorithm that reduces the number of channel states from the maximum of $\mathcal{M}^{m+L-1}$ [8], where $L+1$ is the channel impulse response (CIR) duration. In this contribution, we use a RBF DFE, which invokes its previous decision for either RBF subset center selection [8] or space translation [10], in order to reduce the number of channel states required in computing the equalizer output and therefore to reduce its computational complexity. We can obtain the *a posteriori* probabilities of the jth bits, $\varsigma_b^j(k)$ from the *a posteriori* probability of each $\mathcal{M}$-ary symbols at signaling instance k. The probability of bit error associated with the decision that the jth bit has the value (either 0 or 1) exhibiting the maximum *a posteriori* probability, $\tilde{\varsigma}_b^j(k)$, is given by $P_b^j(k) = 1 - \tilde{\varsigma}_b^j(k)$. For our AQAM RBF DFE scheme, we are unable to employ the true *average* probability P_b of bit error, which is given by $E\{P_b^j(k)\}$, as the AQAM modem mode-switching criterion, since a prompt near-instantaneous modem mode selection is required for accommodating the channel's fluctuating quality. Hence we invoked the estimated *short term* probability of bit error or BER, $P_{\mathrm{bit,\,ST}}$, which was estimated by averaging $P_b^j(k)$ over a single transmission burst according to

$$P_{\mathrm{bit,\,ST}} = \frac{\sum_{k=1}^{\mathcal{F}} \sum_{j=1}^{\mathrm{BPS}} P_b^j(k)}{\mathcal{F}} \tag{2}$$

where BPS is the number of bits per symbol and $\mathcal{F}$ is the number of AQAM symbols per burst. Thus, we could estimate the channel quality on a burst-by-burst basis, using (2). The short-term BER of (2) is compared to a set of AQAM mode-switching BER values associated with the current modulation mode of the received data burst. The modulation modes

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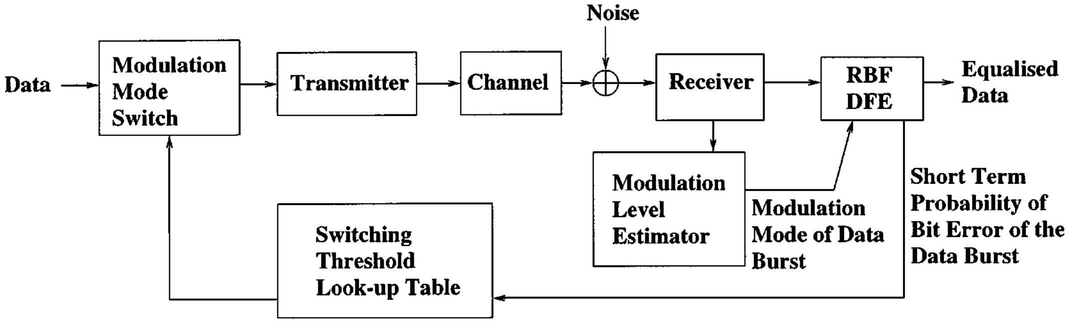

Fig. 1. System schematic of the joint adaptive modulation and RBF equalizer scheme.

TABLE I
MODULATION SWITCHING MECHANISM BASED ON SHORT-TERM BER $P_{\mathrm{bit,ST}}$ AND ITS CORRESPONDING SWITCHING THRESHOLDS $P_i^{\mathcal{M}}$, $i = 2, 4, 16, 64$ CORRESPONDING TO A SPECIFIC CURRENT $\mathcal{M}$-QAM MODE

Modulation Mode	short-term BER range
NO TX	$P_{\mathrm{bit,ST}} \geq P_2^{\mathcal{M}}$
BPSK	$P_2^{\mathcal{M}} > P_{\mathrm{bit,\,ST}} \geq P_4^{\mathcal{M}}$
4-QAM	$P_4^{\mathcal{M}} > P_{\mathrm{bit,\,ST}} \geq P_{16}^{\mathcal{M}}$
16-QAM	$P_{16}^{\mathcal{M}} > P_{\mathrm{bit,\,ST}} \geq P_{64}^{\mathcal{M}}$
64-QAM	$P_{64}^{\mathcal{M}} > P_{\mathrm{bit,\,ST}}$

TABLE II
SIMULATION PARAMETERS

No. data symbols per burst	144
No. training symbols per burst	27
Transmission Frequency	1.9GHz
Transmission Rate	2.6MBd
Vehicular Speed	30 mph
Normalised Doppler Frequency	3.3×10^{-5}
Channel impulse response	$F(z) = 0.707$ $+0.707z^{-1}$

utilized in our system are BPSK, 4-QAM, 16-QAM, 64-QAM, and no transmission (NO TX). Therefore, the modulation mode is switched according to the estimated short-term BER, $P_{\mathrm{bit,ST}}$ of (2), using the regime of Table I.

III. PERFORMANCE STUDY

A. Assumptions

The achievable best-case performance of the RBF DFE AQAM scheme was derived by stipulating the following assumptions. Firstly, perfect CIR estimation or channel state estimation was assumed at the receiver. The RBF's centers were assigned the values of the channel states. Secondly, the CIR was time-invariant for the duration of the transmission burst, but varied from burst to burst, which corresponds to assuming that the channel is slowly varying. Thirdly, we assumed that the receiver had perfect knowledge of the AQAM mode used in its received burst. In reality, modem mode control signaling is employed to convey the modulation mode used to the receiver [2], [5]. Finally, the RBF DFE used in the system neglected error propagation due to erroneous decision feedback, which in practical terms implied a negligibly low probability of symbol errors, hence feeding the correct symbol to the RBF subset center selection or translation process [8], [10].

B. Simulation Model

In our experiments, we used slot-by-slot time division duplex (TDD), where the UL/DL slots followed each other directly. The simulation parameters are listed in Table II. We evaluated the performance of the AQAM RBF DFE for two different systems. The higher integrity scheme had a target BER of 10^{-4}, which can be rendered near-error-free with the aid of channel coding, and hence we referred to this arrangement as a data transmission scheme. By contrast, the lower integrity scheme was designed for maintaining a BER of 10^{-2}, which is adequate for speech transmission. The target BPS throughput values of these schemes were 3 and 4.5, respectively. The BER switching thresholds $P_i^{\mathcal{M}}$, corresponding to $\mathcal{M}$-QAM, can be obtained by estimating the BER degradation/improvement, when the modulation mode is switched from the current $\mathcal{M}$-QAM mode to a higher/lower number of BPS. Explicitly, we obtain this BER degradation/improvement estimate from the RBF DFE's short-term BER according to (2) upon switching from every possible modulation mode to every possible legitimate next AQAM mode, as described in [12].

Comparison With Constituent Fixed Modulation Modes: The BER and BPS performance was evaluated for two different AQAM schemes. In the first scheme (AQAM-NB), the transmitter always transmitted data without transmission blocking. By contrast, in the second transmission blocking assisted scheme (AQAM-B), there were no data transmitted, whenever the estimated short-term BER was higher than the target BER. Hence the AQAM scheme could be "tuned" to a certain required average target BER performance. For a target BER of 10^{-2}, only the AQAM-NB scheme was investigated, since we were aiming for speech transmission, which is sensitive to the latency caused by transmission blocking. Fig. 2 shows that the BER and BPS performance of the AQAM-NB (BER $= 10^{-2}$) scheme was better than that of BPSK and 4-QAM for average SNRs below 8 dB and in the range of 8–15 dB, respectively. Even though the mean BER performance of

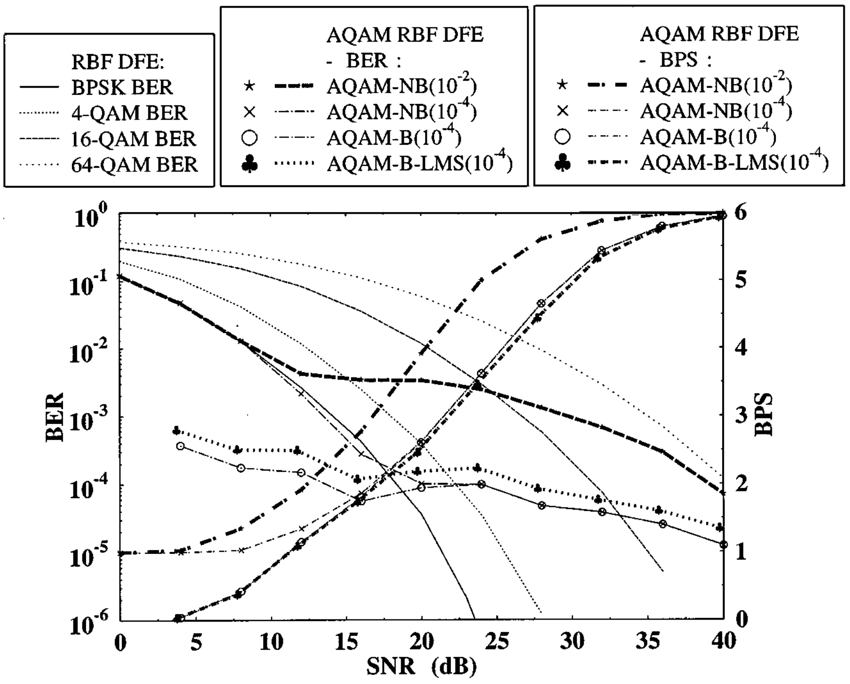

Fig. 2. The BER and BPS performance of the AQAM RBF DFE, showing also the BER performance of the constituent fixed modulation modes, namely BPSK, 4-QAM, 16-QAM, and 64-QAM, over the two-path Rayleigh-fading CIR of Table II. The modem mode switching levels used for the AQAM RBF DFE scheme are listed in Table III. The switching levels are obtained using the method described in [12]. The RBF DFE had a feedforward order of $m = 2$, feedback order of $n = 1$, and decision delay of $\tau = 1$ symbol. The AQAM-NB scheme always transmits data without transmission blocking and the AQAM-B scheme utilizes transmission blocking. The AQAM-B-LMS scheme uses transmission blocking and a LMS CIR estimator with a step-size of 0.2

TABLE III

SWITCHING BER THRESHOLDS $P_i^{\mathcal{M}}$ OF THE JOINT ADAPTIVE MODULATION AND RBF DFE SCHEME FOR THE TARGET BER OF 10^{-2} AND 10^{-4} OVER THE TWO-PATH RAYLEIGH FADING CHANNEL OF TABLE II

	BER of 10^{-2}				BER of 10^{-4}			
	$P_2^{\mathcal{M}}$	$P_4^{\mathcal{M}}$	$P_{16}^{\mathcal{M}}$	$P_{64}^{\mathcal{M}}$	$P_2^{\mathcal{M}}$	$P_4^{\mathcal{M}}$	$P_{16}^{\mathcal{M}}$	$P_{64}^{\mathcal{M}}$
NO TX	9×10^{-3}	5×10^{-5}	0.0	0.0	9×10^{-5}	1×10^{-15}	0.0	0.0
BPSK	10^{-2}	5×10^{-5}	0.0	0.0	10^{-4}	10^{-15}	0.0	0.0
4-QAM	6×10^{-2}	10^{-2}	10^{-12}	0.0	1.5×10^{-2}	10^{-4}	10^{-45}	0.0
16-QAM	2×10^{-1}	10^{-1}	10^{-2}	10^{-8}	1.2×10^{-1}	5×10^{-2}	10^{-4}	10^{-50}
64-QAM	3×10^{-1}	2×10^{-1}	9×10^{-2}	10^{-2}	2.2×10^{-1}	1.5×10^{-1}	3×10^{-2}	10^{-4}

the AQAM-NB (BER $= 10^{-2}$) scheme is equivalent to that of the BPSK scheme at 8 dB and to that of the 4-QAM scheme at 15 dB, the mean BPS throughput of the AQAM-NB (BER $= 10^{-2}$) scheme improved by a factor of 1.35 and 2.6, respectively. However, the AQAM-NB (BER $= 10^{-2}$) scheme could only achieve the target BER of 10^{-2} and BPS of 4.5, if the channel SNR was above 9 dB and 22 dB, respectively. Similar trends were observed for higher integrity transmission, i.e., for the 10^{-4} target BER scheme in Fig. 2. The AQAM-B (BER $= 10^{-4}$) scheme achieved the target mean BER at channel SNRs above 13 dB, while the AQAM-NB (BER $= 10^{-4}$) scheme could only achieve the target BER at average SNRs in excess of 20 dB. Note, however, that the target BPS performance of 4.5 and 3 of the lower and higher integrity schemes, respectively, can only be achieved by the AQAM scheme for channel SNRs in excess of about 22 dB. Fig. 2 shows the performance degradation when the CIR is estimated with the aid of the least mean square (LMS) channel estimator. Observe that the AQAM-B-LMS scheme suffers from a slight BER and BPS performance degradation, since the accuracy of the short-term BER estimation is affected, when the LMS-based CIR estimate is used for evaluating (1). However, the required target BER performance can be still maintained by using a set of slightly more conservative switching thresholds at the cost of a slightly degraded BPS throughput.

Comparison of the RBF DFE and Kalman-Filtered DFE: Let us now embark on a comparative analysis of the best-case performance of the AQAM RBF DFE and the conventional Kalman-filtered AQAM DFE scheme proposed by Wong *et al.* [11] for wide-band channels. The AQAM DFE scheme in [11] used the pseudo-SNR at the output of the DFE as the switching criterion. The parameters of the conventional DFE

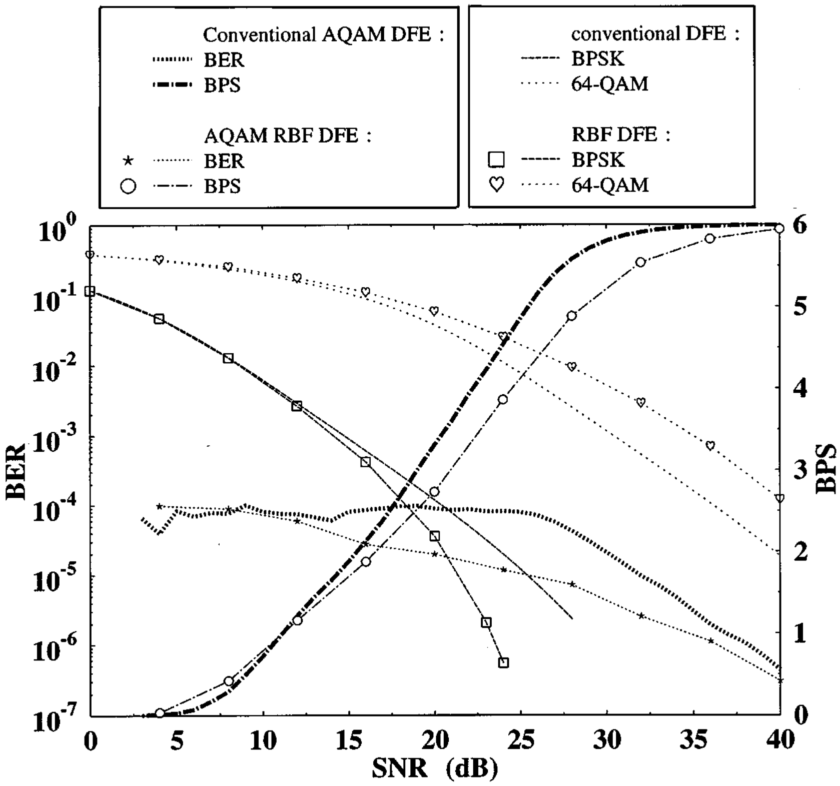

Fig. 3. Simulated best-case performance of the AQAM RBF DFE scheme and the numerical best-case performance of the AQAM conventional DFE scheme for target BER' of 10^{-4} [11] with transmission blocking. The figure shows also the BER performance of the constituent lowest and highest order fixed modulation modes, namely BPSK and 64-QAM. The channel parameters are listed in Table II and the assumptions stated in Section III-A. The modem mode optimized switching levels used for the AQAM conventional DFE scheme [11] are as follows: $f_1 = 8.304\,59$ dB, $f_2 = 10.4541$ dB, $f_3 = 16.8846$ dB, $f_4 = 23.051$ dB. The RBF DFE had a feedforward order of $m = 2$, feedback order of $n = 1$ and decision delay of $\tau = 1$ symbol and the conventional DFE had a feedforward order of $m = 15$, feedback order of $n = 2$, and decision delay of $\tau = 15$ symbols.

were chosen such that it exhibited the best possible performance for our simulation scenario, and hence a further increase of the equalizer's order would not give a significant performance improvement. For our best-case performance comparisons assuming *no channel quality estimation latency*, the channel quality was estimated perfectly prior to transmission and the appropriate AQAM mode was chosen for the data burst to be transmitted, which satisfied the target BER requirement.

According to Fig. 3, the performance of the AQAM-B DFE and AQAM-B RBF DFE is fairly similar for the target BER of 10^{-4} over the average SNR range of 5–12 dB, but the BPS performance of the AQAM-B RBF DFE is better than that of the AQAM-B DFE in that range. In this average SNR range, the lower order modulation modes such as BPSK and 4-QAM dominate. Since the RBF DFE can provide a better BER performance than that of the conventional DFE for the lower order BPSK and 4-QAM modes, the BPS performance of the AQAM-B RBF DFE can be improved, while maintaining a similar BER performance to that of the AQAM-B DFE. As the average SNR increases above 12 dB, the BER performance of the AQAM-B RBF DFE is still better at the expense of a lower BPS performance. In the higher SNR range, the BER performance difference between the AQAM-B DFE and AQAM-B RBF DFE decreases. This is because at higher SNRs the 64-QAM mode prevails, since the 64-QAM BER performance of the conventional DFE was better than that of the RBF DFE. Hence the mean BER improvement of the AQAM-B DFE scheme was expected. The overall results of our simulations show that the AQAM RBF DFE is capable of performing as well as the conventional AQAM DFE. Furthermore, the performance of the AQAM RBF DFE can be improved by increasing both the decision delay τ and the feedforward order m, as argued in [9]. However, the computational complexity of the RBF DFE is dependent on the AQAM mode, since the number of RBF centers increases with the number of modulation levels [9]. This is not so in the context of the Kalman-filtered DFE, where the computational complexity is only dependent on the feedforward and feedback order.

IV. CONCLUSION

Our simulation results showed that the proposed RBF DFE-assisted burst-by-burst AQAM modem outperformed the individual constituent fixed modulation modes in terms of the mean BER and BPS throughput. Our results also showed that the AQAM RBF DFE scheme has the potential of outperforming the conventional AQAM DFE at the expense of a higher computational complexity.

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