

Dual Switched Predictive DIR MLSD Receiver for Dynamic Channels

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A linear prefilter can be used to reduce the required complexity of a maximum likelihood sequence detector Viterbi algorithm (MLSD-VA) by shortening the overall channel and prefilter impulse response in dynamic communication systems. The combination of channel and prefilter should have the effect of producing a desired impulse response (DIR) at the detector. Falconer and Magee (1973) showed that for a finite length DIR there are a limited number of possible DIRs that are optimal. For a DIR of length two symbols, there are only two optimal DIRs, for a length three DIR there exists a range of possibly optimal DIRs. In this paper, we present a novel receiver architecture in which we use two equalisers and two Viterbi detectors. Each equaliser has a different target DIR. A selection device chooses between the output of the two VAs. It is demonstrated that, using the two optimal length two DIRs can be preferable to both switched triple DIR system and adaptive DIR strategies. It is also demonstrated in this paper that there exists a range of environments where adaptive DIR MLSD-VA receivers fail, however the proposed dual switched DIR MLSD-VA is successful in these environments. The efficacy of the switched dual DIR MLSD-VA is also shown using doubly selective fading channels.

Keywords and phrases: maximum-likelihood sequence detection, fading channels, equalisation.

1. INTRODUCTION

The detection of a signal transmitted through a communication channel that contains intersymbol interference (ISI) and additive Gaussian noise has been widely studied for a broad range of channel models. Maximum likelihood sequence detection (MLSD) implemented using the Viterbi algorithm, proposed by Forney [1], is an optimal equalisation method to combat ISI. The computational complexity of the Viterbi algorithm (VA) grows exponentially with the length of the channel impulse response (CIR). One technique [2] that has been used to reduce the complexity of the VA is to use a prefilter to truncate the CIR. The cascade of the prefilter and the channel produces an equivalent channel impulse response (ECIR) at the input to the VA, which is close to the adaptive desired impulse response (DIR) being used by the VA. The DIR is shorter than the CIR and hence the complexity of the VA is reduced. In [3], different length DIRs were investigated using the mean square error (MSE) criterion. In [4], the optimal DIR using the effective signal-to-noise ratio (SNR) criterion was determined. In both cases, it was shown

that for the case of a length two DIR there exist just two optimal DIRs. If the power of the DIRs is constrained to one, then the two optimal DIRs are $(1/\sqrt{2}, 1/\sqrt{2})$ and $(1/\sqrt{2}, -1/\sqrt{2})$. In [4], optimal length three DIRs were shown to have a partial response of type $(\alpha, 2\alpha, \alpha)$.

In a dynamic multipath fading channel environment, adaptive channel estimation has been used with MLSD-VA to track the channel variation. Adaptive MLSD-VA refers to using MLSD-VA along with adaptive channel estimation. The adaptive MLSD using a single channel estimator has been investigated for fading channels in [5, 6, 7]. Per-survivor processing (PSP), proposed in [8, 9], when applied to adaptive MLSD, uses the same number of channel estimators as states in the trellis of the VA.

In a dynamic channel environment, the adaptive length-two DIR tracks the channel between the two optimal DIRs. As channel activity dictates the optimal DIR at any given instant, the adaptive length-two DIR MLSD-VA can be required to change target DIR. This can result in a period of gross misadjustment as the adaptive DIR changes from one optimal DIR to the other optimal DIR. It has been

shown using simulation that the adaptive DIR MLSD-VA system may perform badly during this transition. This leads to the idea of using both of the optimal DIRs in a receiver structure.

It has been shown [10, 11] that rather than using a single adaptive prefilter together with an adaptive DIR, it is preferable to simultaneously operate two adaptive prefilters, each attempting to equalise the channel to one of the possible optimum DIRs. Each equaliser is followed by its own VA and hence at every symbol interval two decisions are produced. The final decision is made by a device that selects the symbol corresponding to the smaller of the two VA metrics. We refer to this type of equaliser as switched dual DIR Viterbi equalisation. The main advantage of such a system is that, as the channel conditions vary there is no period of gross equaliser misadjustment.

In the case of length-three and higher DIRs, it was shown in [4] that the optimal DIRs were of a partial response type. This implies that a large number of optimal DIRs exist for these higher order DIRs. Therefore, it seems plausible that a satisfactory switched DIR equaliser, where the DIR is of length three or greater, can be constructed using a finite number of adaptive prefilters each attempting to equalise to a fixed partial response type DIR. The final symbol decision again is based on selecting the symbol produced by the VA having the smallest metric.

The adaptive DIR MLSD-VA and the switched DIR MLSD-VA will be examined using two different types of channels. A channel consisting of a time varying deterministic channel and AWGN (additive white Gaussian noise) will be used to examine the tracking ability of both systems in difficult operating conditions. It will be shown that the adaptive system fails in a range of environments where the proposed dual switched system is successful. The adaptive and switched systems will be investigated using frequency selective Rayleigh fading channels to obtain bit error rates (BER). The BER will show that the dual switched DIR systems outperform the triple switched systems and comparable adaptive systems.

The paper is organised as follows. In Section 2, a brief description of the mathematical background that results in the optimal DIR is outlined and the basis for a switched DIR MLSD-VA is explained. In Section 3, the predictive switched DIR MLSD-VA is presented as a possible solution to the delay associated with the VA. Simulation results are presented in Section 4, which demonstrate the efficacy of the proposed switched dual DIR MLSD-VA. Finally, in Section 5, conclusions are drawn.

2. OPTIMAL DIRs

It is well known that the transmitter filter, the band-limited channel containing additive white noise, the matched filter, the symbol rate sampler, and the whitening filter can be represented as an equivalent discrete time white noise filter with white Gaussian noise added at the output of the filter. The received signal at the output of the equivalent white noise filter is

$$r(T) = \sum_{l=-K}^K c_l(T)a(T-l) + n(T), \quad (1)$$

where the equivalent white noise filter, sequence of information symbols, and sequence of uncorrelated noise samples are represented, respectively, by $\{c_l(T)\}_{l=-K}^K$, $\{a(lT)\}_{l=-\infty}^{\infty}$, and $\{n(lT)\}_{l=-\infty}^{\infty}$. The error signal used to update the prefilter can be expressed as

$$e(T-D) = \sum_{l=-N}^N p_l(T-D)r(T-D-l) - \sum_{l=0}^L q_l(T)\hat{a}(T-D-l), \quad (2)$$

where the vectors $\mathbf{P}^T = (p_{-N}(T), \dots, p_0(T), \dots, p_N(T))$ and $\mathbf{Q}^T = (q_0(T), \dots, q_L(T))$ represent the tap coefficients of the prefilter and DIR, respectively, and D is the delay in the update error associated with the VA. In a manner similar to that of [3], the error can be minimised to reduce the noise variance seen at the input to the VA. The complete derivation can be found in [12]. Minimising the error in this manner allows for the error to be expressed in a quadratic form

$$E_0 = \mathbf{Q}^T \mathbf{B} \mathbf{Q}, \quad (3)$$

where \mathbf{B} is a square matrix of dimension $(L+1)$; \mathbf{B} can be shown to be a positive definite symmetric Toeplitz matrix. Minimisation of E_0 , with an appropriate energy constraint on \mathbf{Q} , is accomplished by making \mathbf{Q} that normalised eigenvector of \mathbf{B} corresponding to its minimum eigenvalue. In the case of $L=1$, \mathbf{B} is a 2×2 matrix with values b_0 (the diagonal entries) and b_1 (the off diagonal entries). The eigenvalues associated with \mathbf{B} are $b_0 + b_1$ and $b_0 - b_1$ corresponding to just two optimal eigenvectors, either $(1/\sqrt{2}, 1/\sqrt{2})$ or $(1/\sqrt{2}, -1/\sqrt{2})$, when $|\mathbf{Q}|^2 = 1$. Therefore, the eigenvalues $b_0 + b_1$ and $b_0 - b_1$ have associated eigenspaces containing the optimal eigenvectors. The value of b_1 determines which of the eigenvalues is the minimum eigenvalue at any given time instant. A case of interest arises when $b_1 = 0$. When this occurs, \mathbf{B} becomes $b_0 \mathbf{I}$ (\mathbf{I} is the identity matrix) resulting in all 1×2 vectors with $|\mathbf{Q}|^2 = 1$ being optimal. This is a highly undesirable state of operation. In practical implementations the receiver is unable to determine the exact channel state, due to factors including delay in the receiver, additive noise, and round off error, producing inaccuracy in determining \mathbf{B} . Therefore, there exists a region between the two eigenspaces, each containing a single optimal eigenvector, where all 1×2 vectors (with $|\mathbf{Q}|^2 = 1$) are optimal. To remove the possibility of the receiver operating in this undesirable region, prompted the development of the switched dual DIR receiver.

In the case of $L=2$, the optimal eigenvectors can be either (a, b, a) or $(a, 0, -a)$. In [13] a length-three DIR with $|\mathbf{Q}|^2 = 1.5$ was used as an example. Eigenvectors that comply with these constraints are $(0.5, 1, 0.5)$, $(0.5, -1, 0.5)$, and $(\sqrt{1.5}/2, 0, -\sqrt{1.5}/2)$. These DIRs are used in the switched triple DIR MLSD-VA receiver. In [4], the optimal DIR was

where $M_j(n)$ is the metric of state j at time step n given the transition from state k to j , $I_{j,k}(n)$ is the incremental metric from state k to state j at time step n , and λ is the forgetting factor. This improves the responsiveness of the receiver to channel variations.

4. SIMULATION RESULTS

The predictive DIR MLSD-VA was tested using two types of channels, the swept notch channel and the doubly selective fading channel. To examine the tracking and switching capabilities of the proposed system in the predictive architecture, a channel, consisting of the deterministic swept notch channel (SNC) and AWGN, was used. BER were obtained for several different systems using the predictive DIR MLSD-VA architecture with time varying frequency selective fading channels.

4.1. Tracking properties of predictive DIR MLSD-VA systems

The SNC is a three-tap dynamic channel consisting of two zeros with a trajectory within the unit disc in the z -plane. This channel requires that the prefilter performs, in the case of length-two DIRs, its three tasks

- (i) channel shortening,
- (ii) prediction,
- (iii) reduction of distortion.

One of the zeros of the SNC moves in a clockwise direction while the other moves in a counterclockwise direction. This results in the two zeros coinciding as they cross the real axis. Therefore, the SNC changes from being a high-pass to a low-pass channel (or vice versa) as the zeros pass through the imaginary axis. This property of the SNC makes it particularly suitable in examining the tracking and switching properties of the predictive dual switched system as the two optimal DIRs represent high and low-pass channels.

The following examples show some scenarios where the adaptive predictive DIR MLSD-VA failed and the switched dual DIR MLSD-VA was successful.

Figure 2 shows the update-error (2) for the dual switched and adaptive predictive DIR MLSD-VA systems for a channel consisting of the SNC and AWGN. In this case, the SNC was implemented with the zeros having a circular trajectory of radius 0.88. The zeros were rotated around the unit disc at a constant rate $\pi/(5 \times 10^4)$ radians per symbol interval. The SNR was 10 dB. Figure 2 shows the update-error powers for the adaptive and dual switched systems for 10^5 symbols. The systems were trained for the first 5×10^3 symbols. The SNC started at π radians and therefore the channel had a low-pass characteristic. The zeros passed through the imaginary axis after 2.5×10^3 symbol instants and the channel starts to change to a high-pass channel. As the channel is low-pass initially, the $(1/\sqrt{2}, \alpha/\sqrt{2})$ DIR is optimal and as shown in Figure 2, the update-error for the prefilter, using $(1/\sqrt{2}, \alpha/\sqrt{2})$ as a target ECIR, has the smallest error of the dual switched system. The adaptive system

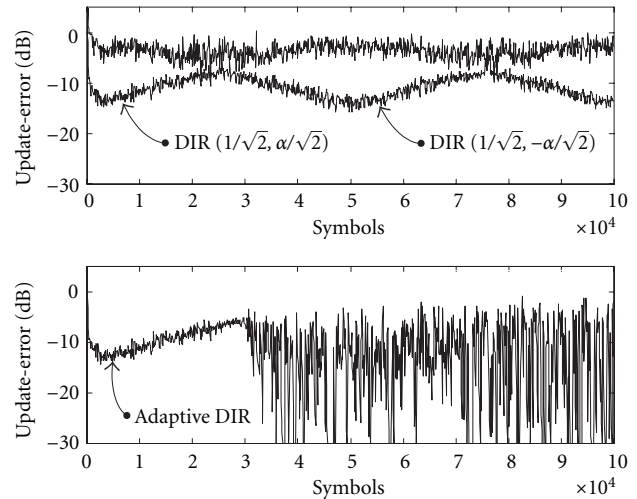


FIGURE 2: Update-error powers of dual switched and adaptive receivers in SNC and high AWGN power environment. Parameters: radius = 0.88, $d\theta/dt = \pi/(5 \times 10^4)$, SNR = 10 dB.

converges to this DIR as shown by the adaptive update-error in Figure 2.

The update-error power for the prefilter using $(1/\sqrt{2}, -\alpha/\sqrt{2})$ is initially much larger than that of the other prefilter but as the channel approaches the transition from low-pass to high-pass, the update-error powers. As the zeros approach the imaginary axis, the update-error signals become quite noisy. The high additive noise power reduces the ability of the prefilters to have an accurate ECIR as the channel changes from low to high pass. After the transition at the 2.5×10^4 th symbol instant, Figure 2 shows that the update-error power for the $(1/\sqrt{2}, -\alpha/\sqrt{2})$ DIR branch of the switched dual system is considerably less noisy and has a smaller magnitude indicating that $(1/\sqrt{2}, -\alpha/\sqrt{2})$ is the optimal DIR in this environment. The update-error power of the $(1/\sqrt{2}, -\alpha/\sqrt{2})$ DIR branch of the system continues to decrease as the channel becomes more high pass until the 5×10^4 th symbol instant, when the two zeros coincide as they cross the real axis. Then the update-error power starts to increase as the channel moves to the transition to a low-pass channel.

Figure 2 shows that the adaptive system performs poorly in this high AWGN power environment. The update-error of the adaptive system indicates that the adaptive system trained to the $(1/\sqrt{2}, \alpha/\sqrt{2})$ DIR successfully. The adaptive system tracks the channel as it approaches the transition from low-pass to high-pass, however it fails to track the channel after transition as shown in Figure 2 by the large oscillations in the update-error power. These oscillations in the update-error power are the result of the ECIR having collapsed to become quite small in magnitude. Figure 2 is an example of the robustness of the dual switched DIR MLSD-VA operating successfully in a robust dynamic environment, where the adaptive DIR MLSD-VA failed.

Figure 3 shows the update-error powers for the dual switched and adaptive DIR MLSD-VA for a dynamic chan-

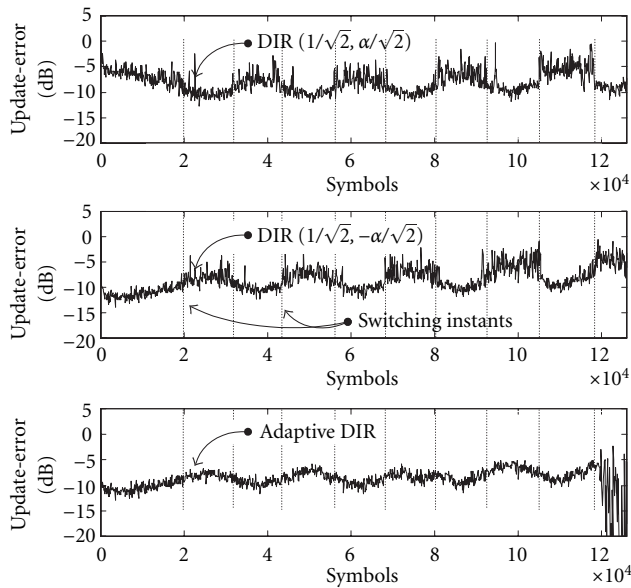


FIGURE 3: Update-error powers of dual switched and adaptive receivers for a SNC with increasing trajectory. Parameters: initial radius = 0.4, final radius = 0.912, $d\theta/dt = \pi/(4 \times 10^4)$, SNR = 9.5 dB.

nel. The deterministic channel that was used to obtain Figure 3 consists of an SNC whose zeros have a trajectory such that the channel has increasing ISI. Increased ISI is achieved by increasing the radius of the trajectory of the zeros. Also, the trajectory of the zeros was such that the channel remained in the vicinity of the boundary between a high-pass and a low-pass channel. This allowed for the examination of the behaviour of the switched dual system and the adaptive system in an environment where the channel was near the boundary of the two optimal DIRs.

The dual switched and adaptive systems were trained for the first 5×10^3 symbols. As can be seen from Figure 3, the channel passed through the boundary between the optimal DIRs nine times. The two update-error powers of the dual switched system indicate the repeated transition of the channel through the imaginary axis in the z -plane. However, Figure 3 shows that the update-error power of the adaptive system is very similar to that of the update-error power of the prefilter with $(1/\sqrt{2}, -\alpha/\sqrt{2})$ as DIR. This indicates that the adaptive system was unable to detect the channel transition due to the high noise power (SNR = 9.5 dB). The adaptive system was initially able to track the channel as the channel ISI was low (initial radius = 0.4), however as the ISI increased, Figure 3 shows that the adaptive system failed after the 1.2×10^5 th symbol instant (indicated by the large oscillations in the adaptive update-error power), yet the dual switched system continued to track successfully. Figure 3 illustrates an example of an environment where ISI resulted in the failure of the adaptive system yet the dual switched system was successful.

Figure 4 shows the update-error power for the dual switched DIR MLSD-VA and the adaptive DIR MLSD-VA

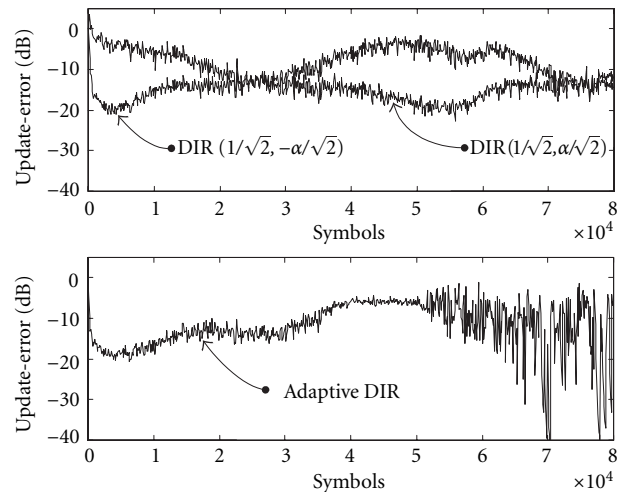


FIGURE 4: Update-error powers of dual switched and adaptive receivers for a SNC with constant trajectory. Parameters: radius = 0.85, $d\theta/dt = \pi/(5 \times 10^4)$, SNR = 20 dB.

systems operating in a channel consisting of the deterministic SNC and AWGN. The zeros of the SNC were moved in a circular trajectory. In this case, the channel was slowly time varying and had a low noise power. Figure 4 shows that the dual switched DIR MLSD-VA successfully tracked the channel, however, the adaptive system fails to track the channel resulting in failure of the adaptive system. This was termed a catastrophic error mode in adaptive predictive DIR MLSD-VA in [19].

The ability of the proposed predictive switched dual DIR MLSD-VA to track a dynamic channel was investigated using the SNC. Figures 2, 3, and 4 show examples of environments where the proposed dual system was successful in tracking the dynamic channel and the adaptive system failed. A more rigorous examination of the performance of the fixed and adaptive DIR MLSD-VA can be obtained from BER.

4.2. BER for predictive DIR MLSD-VA systems

BER were obtained for the receivers using a BPSK transmission system. These were obtained for four different configurations of the predictive receiver:

- (i) system 1 is the dual switched DIR MLSD-VA;
- (ii) system 2 is the length two adaptive DIR MLSD-VA;
- (iii) system 3 is the triple switched DIR MLSD-VA;
- (iv) system 4 is the length three adaptive DIR MLSD-VA.

The four systems were used so that comparison between channel shortening to length-two DIRs (as in the case of systems 1 and 2) and channel shortening to length three DIRs (in the cases of systems 3 and 4) could be made. The fixed DIRs used in system 3 are listed in Section 2.

The channel model used consisted of time and frequency selective channels with continuous power delay profiles (PDPs) as proposed by Hoehner [20] that explicitly

account for outdoor mobile channel characteristics at 1 GHz. Hoeher suggested that the equivalent baseband model can be written as

$$c(t; \tau) = \frac{1}{\sqrt{P}} \sum_{v=1}^P \exp [j(2\pi f_{D,v}t + \theta_v)] \cdot \delta(\tau - \tau_v), \quad (8)$$

where P is the number of elementary echo paths and $\delta(\cdot)$ is Dirac's delta function. Impulse responses can easily be obtained from (8) by independently obtaining the following:

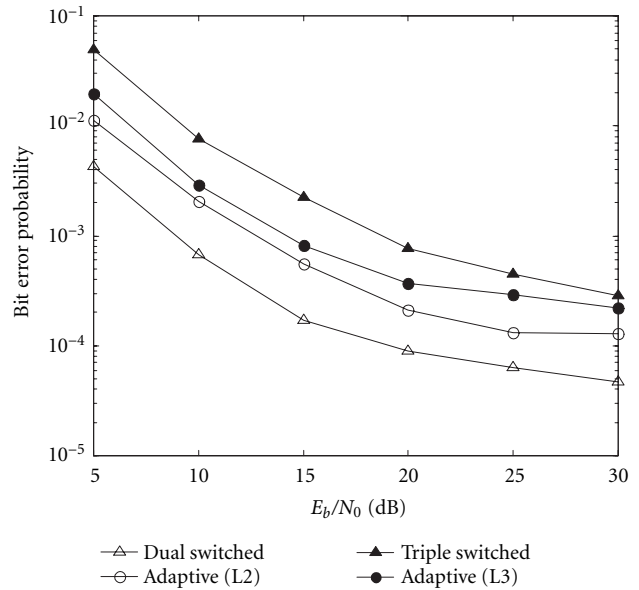
- (a) P Doppler frequencies $f_{D,v}$ from a random variable with Jakes probability density function in $(-f_{D,max}, f_{D,max})$;
- (b) P initial phases θ_v from a uniformly distributed random variable in $[0, 2\pi)$;
- (c) P echo delay times τ_v .

The echo delay times were exponentially distributed thus allowing the length of the power delay profile (PDP) to be determined by altering the decay value of the exponential distribution. Only Rayleigh fading is considered throughout this paper.

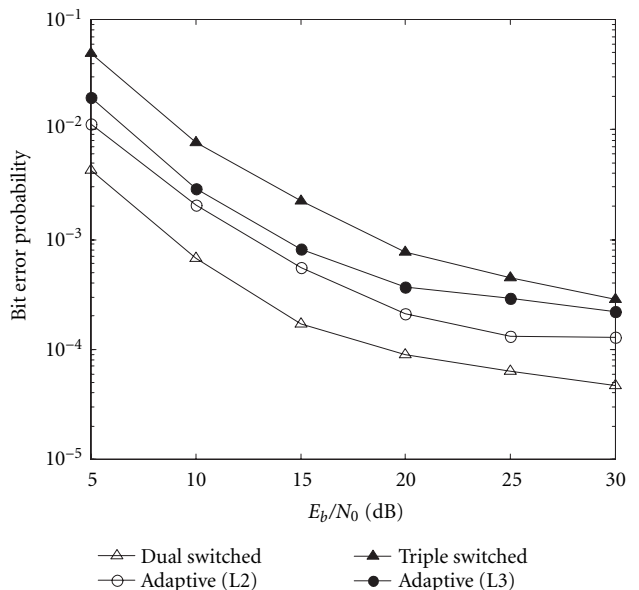
To test the relative abilities of the four systems to successfully shorten a CIR, the four systems were compared using samples of $c(t, \tau)$ that had two different mean echo delay times (impulse response durations). Motivated by the fact that systems 1 and 2 have DIRs of length $2T$ and systems 3 and 4 have DIRs of length $3T$, we used channels with mean echo delay times of $5T$ and $7T$. The four systems were also tested using $f_{D,max} = 1$ Hz, 3 Hz, 12 Hz, and 25 Hz with each of the two different echo delay times. In order to ensure (1) meaningful measurements of BER and (2) a satisfactory approximation of the channel by a sample impulse response of $c(t, \tau)$, we used a large observation period. The channel was faded for each bit. Let B_i denote the i th burst containing 1.5×10^5 bits with values from $\{-1, 1\}$. The first 3×10^4 bits of each burst were used for training. For each BER diagram, a total of 1.3×10^5 bursts were transmitted. A signalling rate of 7.5 MBd was used. It is important to note that the results would be significantly improved with the use of coding and interleaving.

Figures 5 and 6 show BER for the four systems being investigated. The mean echo delay time (MEDT) of the channels used to obtain the results in Figures 5 and 6 was $5T$. Figures 5a and 5b show that system 3 is the least suitable of the systems in a slowly time varying channel. Figures 6a and 6b show that as the maximum Doppler spread increases, system 2 becomes the least successful of the four systems. Figure 6a shows that at high SNR and $f_{D,max} = 12$ Hz, the performance of systems 2 and 4 become almost identical. It can be seen from Figures 5 and 6 that as $f_{D,max}$ increases the most suitable adaptive DIR changes from length $2T$ to length $3T$. System 1 performs considerably better than any of the other systems as the Doppler spread increases.

Figures 7 and 8 show the BER for the four systems being investigated for channels with mean echo delay times of $7T$ for a range of maximum Doppler spreads. As expected, the performance of each of the systems has decreased in com-



(a) Maximum Doppler frequency = 1 Hz.

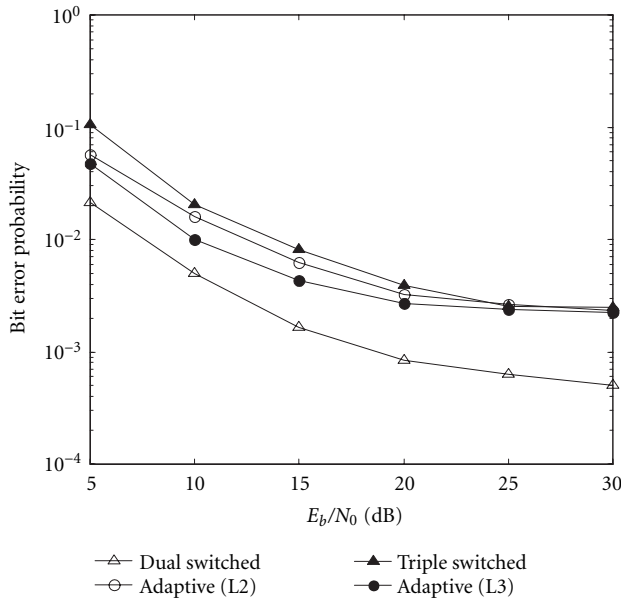


(b) Maximum Doppler frequency = 3 Hz.

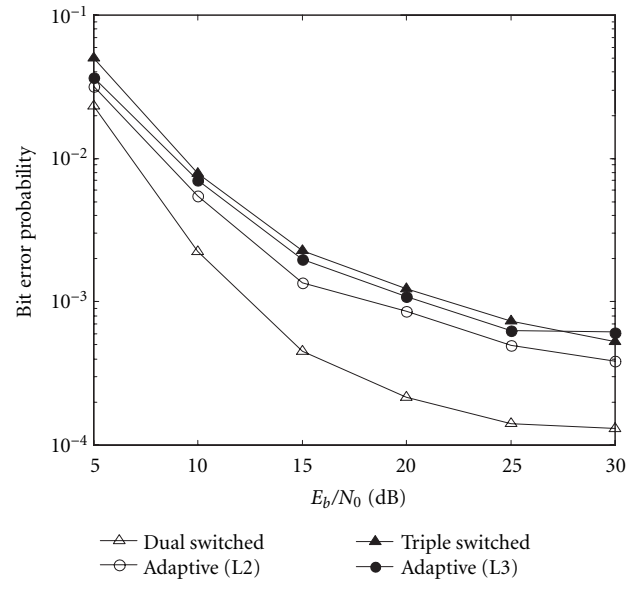
FIGURE 5: BER of DIR MLSD-VA, MEDT = $5T$.

parison to the BER for channels with mean echo delay times of $5T$.

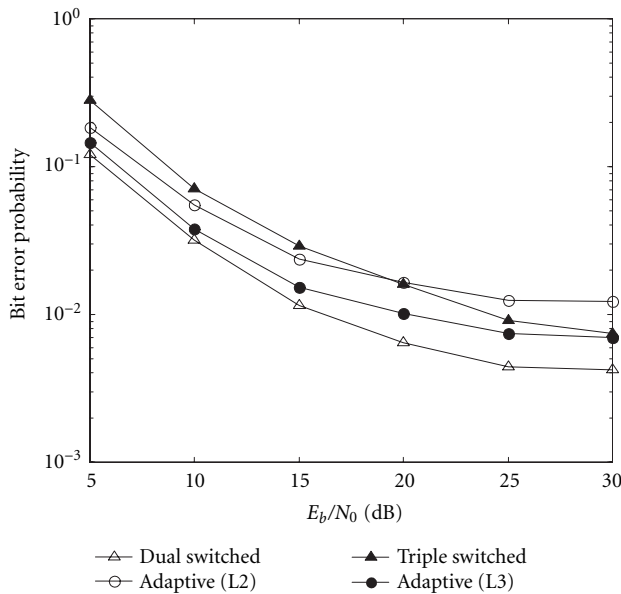
Figures 7a and 7b show that for slowly time varying channels, the adaptive DIR system of length $2T$ (adaptive $2T$ DIR) is again more suitable than the adaptive $3T$ DIR. This indicates that in slowly time varying environments requiring channel shortening, the adaptive $2T$ DIR is able to successfully converge to either of the two optimal DIRs. All the BER indicate that system 3 performs poorly in low SNR



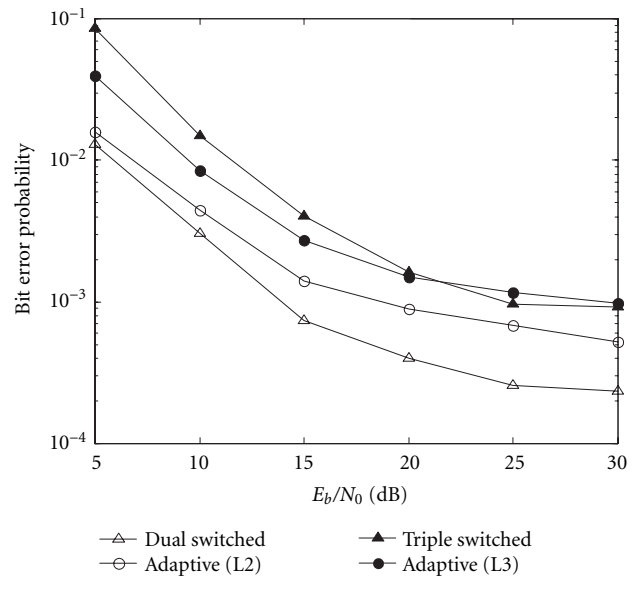
(a) Maximum Doppler frequency = 12 Hz.



(a) Maximum Doppler frequency = 1 Hz.



(b) Maximum Doppler frequency = 25 Hz.



(b) Maximum Doppler frequency = 3 Hz.

FIGURE 6: BER of DIR MLSD-VA, MEDT = 5T.

FIGURE 7: BER of DIR MLSD-VA, MEDT = 7T.

channels. The only observable merit in using system 3 is shown in Figures 7 and 8 in high SNR environments. System 1 is again shown to offer the best performance of the four systems under consideration in these difficult operating conditions.

The length-two adaptive DIR MLSD-VA has a VA implementation cost C , the dual switched system has a VA cost $2C$, the length-three adaptive system also has a VA cost of $2C$, and the triple switched system has a VA cost of $6C$. The BER

show that the dual switched DIR system offers the best performance for the VA cost.

A surprising result is that the dual switched system outperforms the triple switched system that has three times the VA cost. However, the result can be explained by noting that with the length two system all optimum DIRs are implemented, whereas with the length-three DIR triple switched system, only three DIRs out of an infinite number of possibilities are covered.

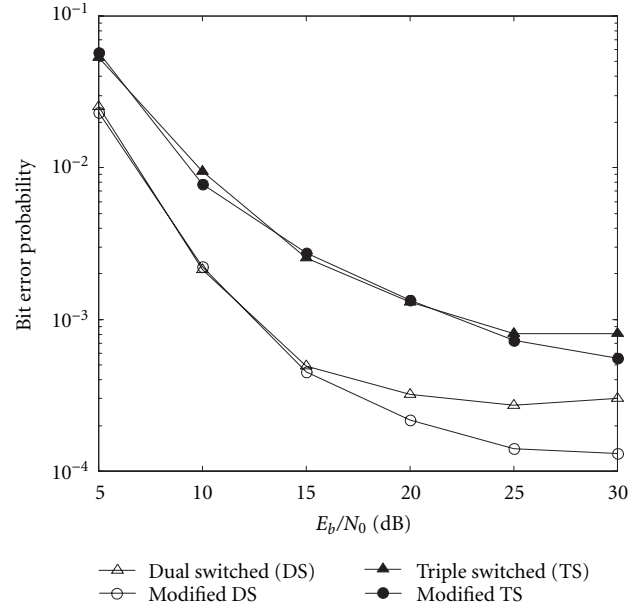
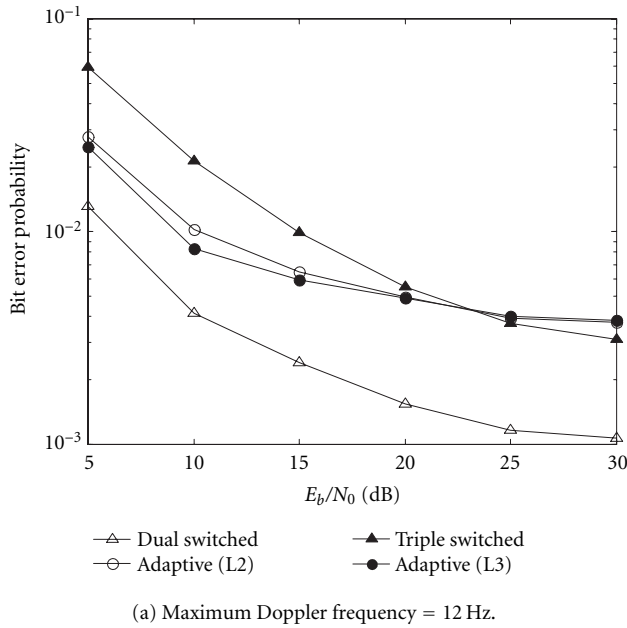


FIGURE A.1: BER for modified and original DIR systems with $MEDT = 7T$. Maximum Doppler frequency = 1 Hz.

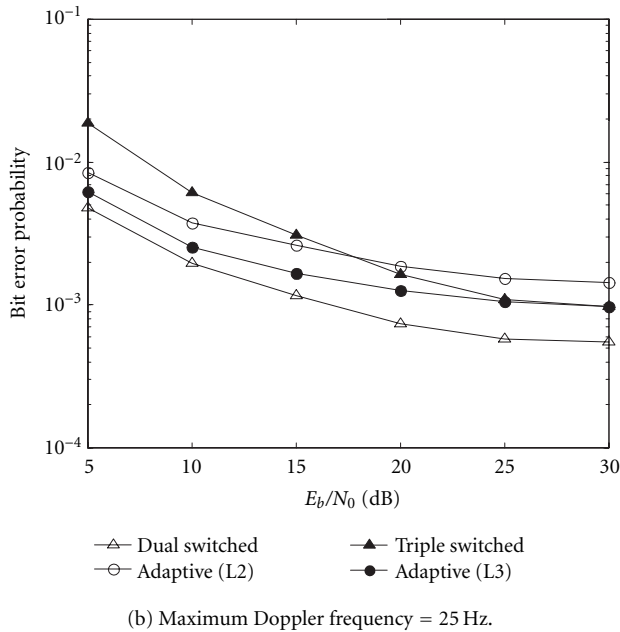


FIGURE 8: BER of DIR MLSD-VA, $MEDT = 7T$.

5. CONCLUSIONS

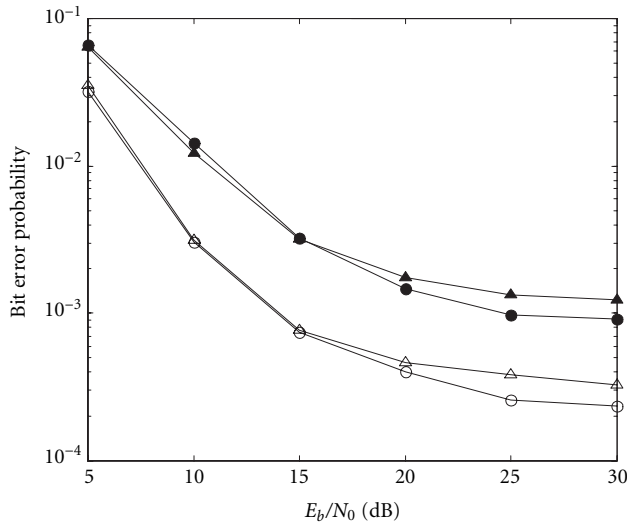
The performance of switched DIR systems to reduce the complexity of an MLSD-VA required for a range of dynamic channels has been investigated. It is readily seen from the results that the switched dual DIR MLSD-VA exhibits superior performance in each of the dynamic environments when compared with similar adaptive 2T DIR systems. For doubly selective multipath radio channels where the adaptive 3T

DIR system is more suitable than the adaptive 2T DIR system, BER curves show that the dual switched DIR system for the same VA implementation cost offers a considerable improvement in performance.

The behaviour of switched dual DIR MLSD-VA and adaptive 2T DIR systems have been studied using several different channel models. It has been shown that there exists a range of dynamic environments where the adaptive DIR system fails because of either ISI or high noise power. It was shown that in these dynamic environments, the dual switched DIR MLSD-VA was successful in tracking the channel behaviour.

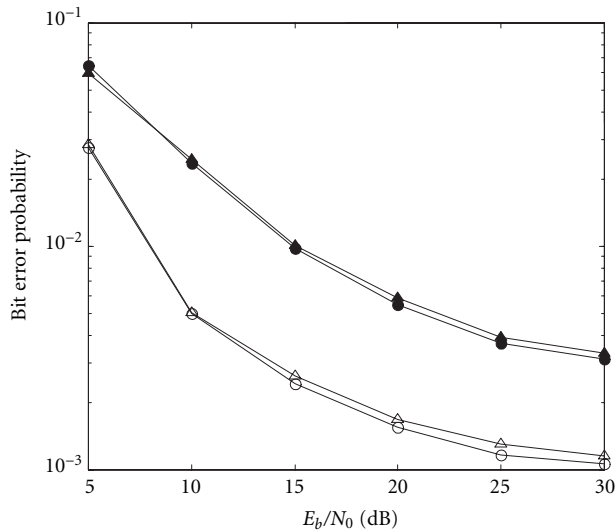
APPENDIX

BER are presented in Figures A.1 and A.2, which indicate the efficacy of using the modified DIRs [14] for the dual switched DIR MLSD-VA system in comparison to the original DIRs suggested by Falconer and Magee [3] and Fredricsson [4]. The BERs shown in Figures A.1 and A.2 were obtained using time varying frequency selective Rayleigh fading channels as described previously. The channels had a mean PDP of length $7T$ and a range of maximum Doppler spreads. The results show that in slowly time varying channels the effect of the catastrophic error that results from the use of the original DIRs reduces the effectiveness of the switched DIR MLSD-VA systems considerably. As the maximum Doppler spread increases, the effect of the catastrophic error mode decreases as can be seen in Figure A.2b.



—△— Dual switched (DS) —▲— Triple switched (TS)
 —○— Modified DS —●— Modified TS

(a) Maximum Doppler frequency = 3 Hz.



—△— Dual switched (DS) —▲— Triple switched (TS)
 —○— Modified DS —●— Modified TS

(b) Maximum Doppler frequency = 12 Hz.

FIGURE A.2: BER for modified and original DIR systems with MEDT = 7T.

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