Equalisation and Iterative Reception for Spectrally Efficient CPM in Multipath Environments

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***Abstract*—Modern spectrally efficient continuous phase modulation (CPM) waveforms offer attractive properties for narrowband tactical communications operating in VHF/UHF 30-400MHz bands. These waveforms exhibit robustness to a significant amount of intersymbol interference, due to multipath propagation, when iterative receivers are used for demodulation and decoding. However, certain propagation characteristics encountered in mountainous or coastal terrains may represent exceptionally challenging multipath environments. In these scenarios, the use of simple types of channel equalisation schemes, with an iterative CPM receiver, is demonstrated to alleviate the detrimental impact of multipath propagation. The combined effect of equalisation and iterative demodulation and decoding is investigated as a method to operate under these conditions.**

I. Introduction

Continuous phase modulation has been shown to provide excellent spectral efficiencies for narrowband tactical communication systems in the UHF/VHF bands [1]. Typically, the radio propagation characteristics at these frequencies results in channels that are relatively benign with multipath delay spreads of only a few microseconds [2], [3]. In this case, it has been shown that to achieve relatively high spectrally efficiencies, iterative detection for serial concatenated partial response CPM can be employed to effectively alleviate the effects of intersymbol interference (ISI) [1]. In this respect, the receiver simply ignores the channel induced ISI resulting in a marginal degradation in terms of error rate performance. In this paper, we consider long distance links whereby the transmitter and receiver are subject to relatively harsh multipath propagation, induced by mountainous or coastal environs. In these conditions, channel delay spreads tend to be sparse with relatively strong (in relation to the dominant component) signal components arriving at discrete time delays of the order of 10's of microseconds [4], [5], [6] for long distance links. Of course, in these particular scenarios, waveforms that are more robust to noise and interference would be deployed, to limit the impact of the ISI. This, in turn, leads to choices of waveforms with relatively low spectral efficiencies. To this end, we examine the effects of channel models with relatively large multipath delay spreads and the resultant performance of receivers employing iterative detection and a relatively simple channel equalisation scheme.

Optimal detection of CPM in multipath channels can be achieved by a receiver employing joint detection, based on maximum likelihood techniques, taking into account the memory of both the CPM waveform and the delay spread of the channel [7]. However, the complexity of these techniques grows exponentially with the memory values, rendering these schemes unsuitable when the channel power delay profiles are both sparse and relatively long in duration. To avoid these problems, suboptimum schemes can be considered that employ either separate equalisation and decoding [8], [7] or some form of iterative equalisation and decoding scheme [9]. In this work, we examine the inclusion of a relatively simple fractionally spaced linear equaliser prior to iterative detection. In addition, we consider the effects of the channel on burst packet communications whereby offsets in the phase, timing and frequency are present. In Section II we describe the signal model including a description of the burst packet structure. Section III details the receiver processing including the equalisation scheme. Finally, Sections IV and V contain the simulation results and conclusions.

II. Signal Model

For the work presented herein, we consider the physical layer specifications for a terrestrial narrowband communications waveform. The physical layer consists of a packet based burst transmission system supporting a time division multiple access (TDMA) or carrier sense multiple access (CSMA) medium access control (MAC), formed by the serial concatenation of a convolutional encoder and CPM for the payload section. To enable

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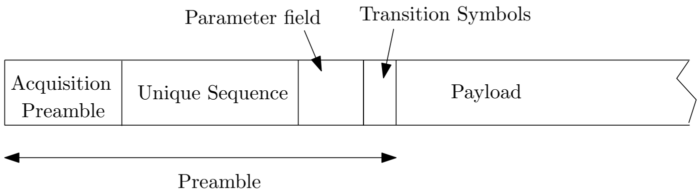

Figure 1. Physical layer packet structure for the NBWF.

reliable synchronisation and parameter estimation the payload portion of the burst packet is preceded by a preamble. The preamble consists of an acquisition preamble used to attain coarse frame timing, frequency and phase estimates; a unique sequence for symbol timing and equaliser training and a parameter field to identify the payload portion, see Figure 1. Transition symbols are also included in the preamble to return the modulator to a known phase state and ensure phase continuity and spectral containment for the CPM waveform.

For the burst packet, the transmitted CPM waveform can be expressed as

$$s(t, \boldsymbol{\alpha}) = \sqrt{\frac{2E}{T}} e^{j\phi(t,\boldsymbol{\alpha})} \tag{1}$$

where E is the energy per symbol and T is the symbol duration. $\phi(t, \boldsymbol{\alpha})$ is the information contained in the phase and defined in the interval $kT \leq t \leq (k+1)T$ as

$$\phi(t, \boldsymbol{\alpha}) = 2\pi h \sum_{i=0}^{k} \alpha_i q(t - iT) \tag{2}$$

where $q(t)$ is the phase-smoothing response function, h is the modulation index and α_i are the transmitted symbols taken from the M_c-ary alphabet $\alpha_i \in \{\pm1, \pm3, ..., \pm(M_c - 1)\}$.

III. Receiver

Figure 1 shows the packet structure for the physical layer, including the preamble section. To initialise the coefficients for the equalisation, we use the unique sequence as the known preamble, formulating the problem as follows. Assuming the CPM signal is strictly band-limited to bandwidth W, we can express the received signal as

$$r(t) = \int_{-\infty}^{\infty} s(t - \tau, \boldsymbol{\alpha}) f(t;\tau) d\tau + w(t) \tag{3}$$

where $w(t)$ denotes a zero mean complex Gaussian noise process with power spectral density N_0 W/Hz. The time-variant frequency selective fading channel can be written as

$$f(t;\tau) = \sum_{l=0}^{L_c-1} f_l(t)\delta(\tau - lT_s) \tag{4}$$

where T_s is the sampling period satisfying $T_s \leq 1/W$ and is related to the symbol duration $T = T_s N_s$ where N_s is an integer number of samples per symbol. L_c is the number of channel taps defined in terms of T_s and $f_l(t)$ is the time-variant channel coefficient for the l^{th} channel tap. By properly selecting the oversampling rate and adjusting the channel coefficients, equation (4) represents a discrete time multipath fading channel model. Assuming that the received signal is sampled at time $t = nT_s$ and that the channel is slowly fading such that $f_l(t) = f_l$, as is the case for VHF [3], we can filter the received signal with a fractionally spaced linear filter, c_q, and write the output as

$$y_n = \sum_{q=0}^{Q-1} r_{n-q} c_q. \tag{5}$$

If we express (5) using matrix notation, after some simple algebra, we find the coefficients for the equaliser via the minimum mean square error (MMSE) solution as

$$\boldsymbol{c} = \boldsymbol{R}_{rr}^{-1} \boldsymbol{R}_{ry} \tag{6}$$

where $\boldsymbol{R}_{rr} = \boldsymbol{r}^H \boldsymbol{r}$ is the autocorrelation matrix of the input signal and $\boldsymbol{R}_{ry} = \boldsymbol{r}^H \boldsymbol{y}$ is the cross-correlation vector, where $(.)^H$ represents the Hermitian transpose. For our receiver, we use the unique sequence as a reference signal and thus substitute $\boldsymbol{s}_d$ for $\boldsymbol{y}$ in (6), where $\boldsymbol{s}_d$ is the deterministic sequence of samples corresponding to the unique sequence of the transmitted preamble. Once equalisation has been performed, the payload section is then processed by an iterative detector employing either coherent or noncoherent CPM detection in tandem with a suitable soft input soft output maximum *a priori* detector.

The development above outlines the receiver signal processing to mitigate the channel induced ISI. However one or two key assumptions have been made regarding the received signal. First the formulation assumes that the local oscillator is perfectly synchronised to the transmitter. Second, the symbol timing is known perfectly. In practice, these unknown parameters would have to be estimated and possibly tracked from the preamble sequence. In this case, the received signal has the form

$$x(t) = Ce^{j(\omega_o t + \phi_o)} r(t + \tau_p) \tag{7}$$

where C is the amplitude, ω_o and ϕ_o are the unknown frequency and phase offsets and τ_p is the unknown timing error.

TABLE I
CPM PARAMETERS

Mode	Symbol Rate	L	M_c	h	Code Rate
N1	30ksym/sec	2	2	$1/2$	2/3
N2	42ksym/sec	2	2	$1/4$	3/4

For the simulation results provided, we demonstrate the error rate performance for receivers employing both coherent and noncoherent detection and perfect synchronisation. This is followed, with results that consider inaccuracies in the parameter estimation including any residual phase, frequency or timing offsets.

IV. SIMULATION RESULTS

The structure of the burst packet transmission for the simulation results is as follows. The packet duration is 25ms with a preamble overhead of approximately 5.3ms at a baud rate of 30ksym/sec. The preamble consists of 45 symbols for the acquisition, 63 symbols for the unique sequence, 3 transition symbols and 48 symbols in the parameter field. The preamble is generated with binary CPM and parameters of $h = 1/2$, a modulation memory $L = 2$ and a rectangular phase pulse. The remaining packet duration is assigned to payload data, with the parameters as defined in Table I and rectangular phase pulse shapes for both modes under consideration. For these modes, the code rates are generated from a rate $1/3$ binary convolutional encoder based on the octal generator $[13, 15, 17]$. To examine the role of the linear equaliser in mitigating the ISI, it is instructive to consider a two path channel model with the power in the second path set at 3dB less than the main path and with various relative delays. Figure 2 shows the error rate performance of the receiver employing coherent detection plotted against the energy per bit to noise power spectral density (E_b/N_o), with and without equalisation. The result is for mode N1 and 8 passes through the iterative detector. Clearly for delays of 14μsec, equivalent to a multipath component arriving at approximately $0.4T$, the receiver requires 7dB more energy per information bit to attain an error rate performance compatible with an AWGN channel at 10^{-4} error rate. However, enabling the linear equaliser results in a reduction of the required transmit energy by approximately 3.5dB at 10^{-4} error rate. Moreover, for delays greater than 14μsec the equalised receiver significantly reduces the energy requirements of the transmitter, compared to the non-equalised receiver, enabling communications to continue. A similar trend can be observed

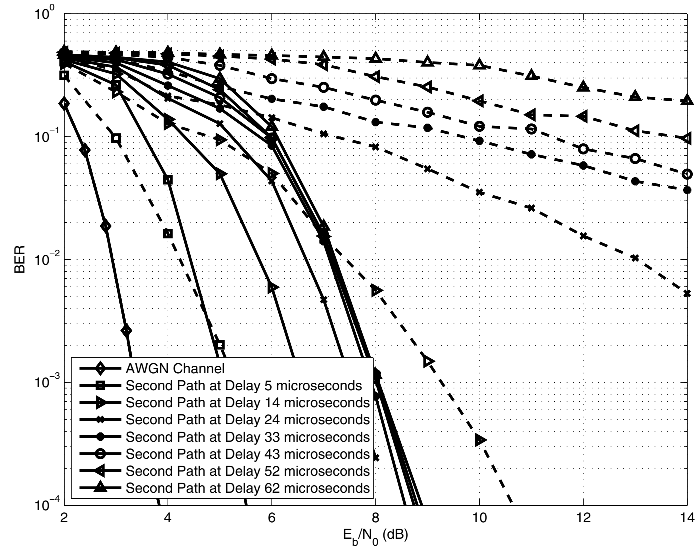

Figure 2. Bit error rate performance for various delays of the second path without equalisation (dashed) and with equalisation (solid). Results are shown for coherent detection with 8 iterations in the receiver and mode N1.

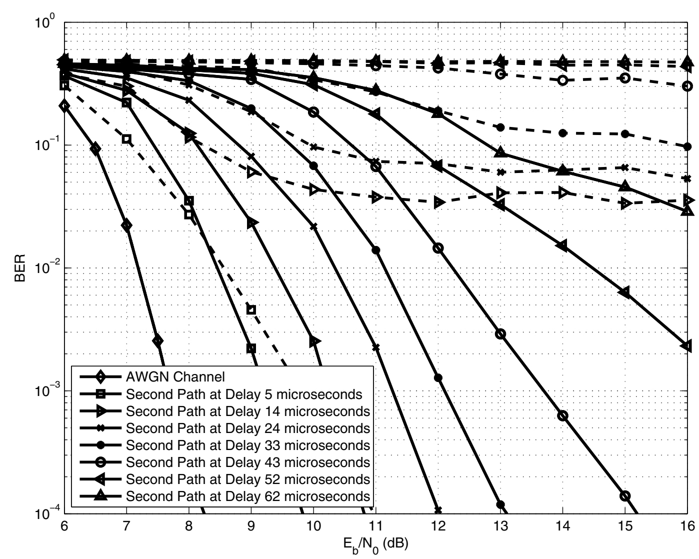

Figure 3. Bit error rate performance for various delays of the second path without equalisation (dashed) and with equalisation (solid). Results are shown for coherent detection with 8 iterations in the receiver and mode N2.

for mode N2 as shown in Figure 3. In this case, error floors occur for the non equalised receiver for delays of 14μsec and greater and demonstrates the benefits of channel equalisation techniques when encountering relatively harsh multipath environments.

Figures 4 and 5 now show the bit error rate performance using a noncoherent detector. In this case, equalisation of the waveform for mode N1 (Figure 4)

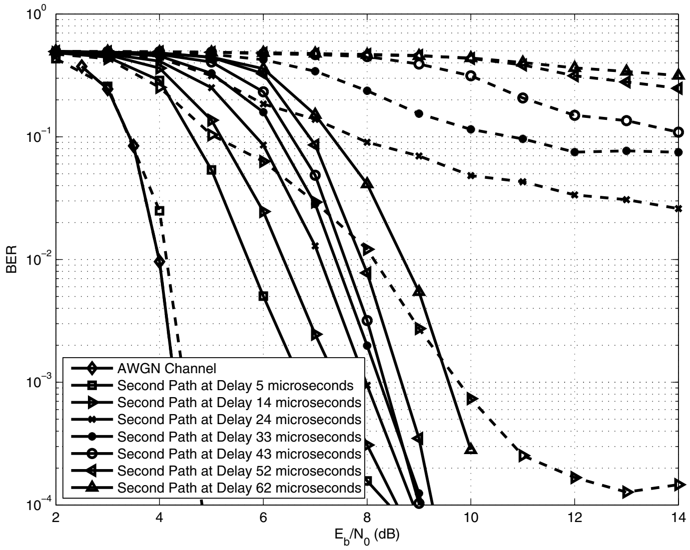

Figure 4. Bit error rate performance for various delays of the second path without equalisation (dashed) and with equalisation (solid). Results are shown for noncoherent detection with 8 iterations in the receiver and mode N1.

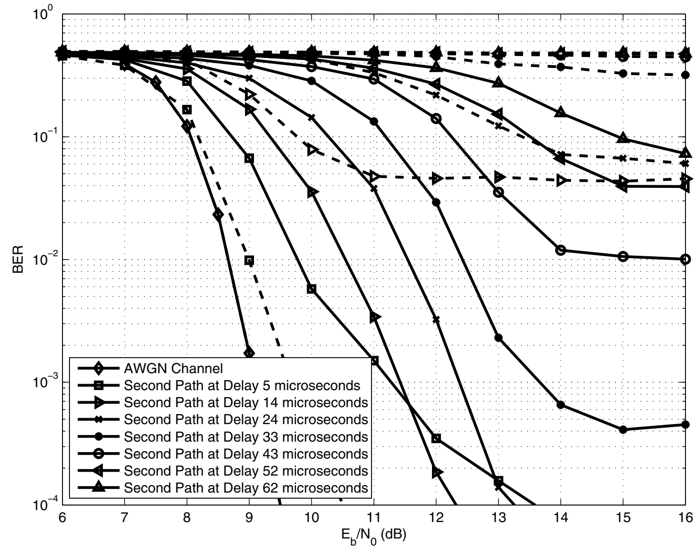

Figure 5. Bit error rate performance for various delays of the second path without equalisation (dashed) and with equalisation (solid). Results are shown for noncoherent detection with 8 iterations in the receiver and mode N2.

is effective at reducing the error floors for all of the delays simulated. It is interesting to observe, that for multipath components arriving within 5μsec the use of an equaliser is not always necessary, resulting in additional noise added to the signal. The choice whether or not to use explicit equalisation should therefore be based on the propagation environment, with adaptive schemes employed to turn the equalisation on and off.

In contrast, for mode N2, delays of 43μsec (approximately $1.3T$) and greater, result in an irreducible error floor irrespective of the equaliser. In this scenario, it is hypothesised that other mitigation techniques are required to reduce the error floors in the receiver performance.

A. Synchronisation

Figures 2 - 5 give an indication of the performance for coherent and noncoherent detection in multipath conditions. However, the results are somewhat ideal as the transmitter and receiver are perfectly synchronised. Furthermore, the inclusion of the iterative processing for the simulation results makes it difficult to understand the individual contributions of the equaliser and iterative processing. In the following, we demonstrate the error rate performance when the transmitted preamble (depicted in Figure 1) is used to estimate frequency, phase and timing offsets with compensation prior to the equalisation processing. In addition, the results compare the bit error rate for one pass through the iterative detector i.e. a conventional CPM receiver and multiple passes. In this scenario, we consider only noncoherent detection following the equaliser due to its inherent robustness to remnant frequency and phase offsets. The algorithms used to estimate the unknown synchronisation parameters are detailed in [11] to which the reader is referred for a more thorough analysis.

Figure 6 shows the bit error rate curves for one pass through the noncoherent receiver with and without channel equalisation and receiver synchronisation enabled. It is clear, for delays greater than 33μsec, the receiver encounters a floor in the bit error rate performance when the multipath is not equalised. Enabling the linear equaliser removes the error floors and therefore can be used to mitigate the channel ISI. The loss in error rate performance, compared to the curve for additive white Gaussian noise (AWGN), for a delay in the second path of 5μsec approximately $0.15T$ is attributed to the approximation errors in estimating the equaliser coefficients. Figure 7 then shows the effects of both channel equalisation and iterative detection and the benefits of combining the two techniques. Comparing Figures 6 and 7, if there is no equalisation and with a delay component arriving at 5μsec the iterative receiver improves the bit error rate performance by approximately 3dB at 10^{-4} error rates and approximately 7dB at 10^{-4} for delays of 14μsec. For delays greater than 14μsec, linear equalisation in combination with the iterative receiver

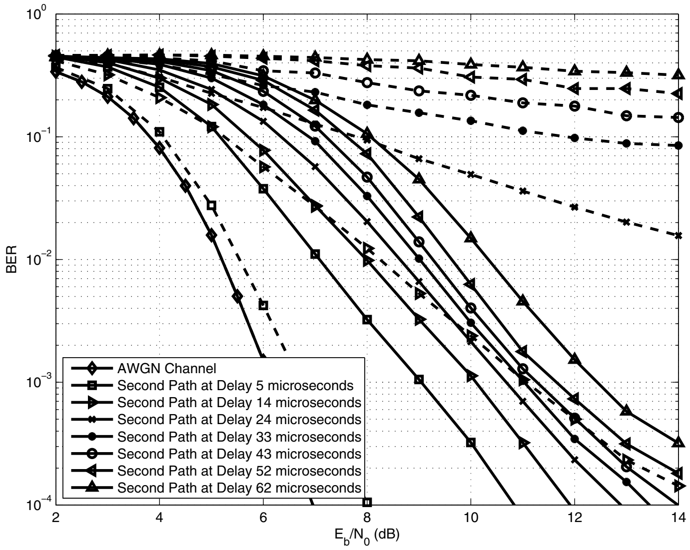

Figure 6. Bit error rate performance for various delays of the second path without equalisation (dashed) and with equalisation (solid). Results are shown for noncoherent detection with 1 iteration in the receiver and mode N1.

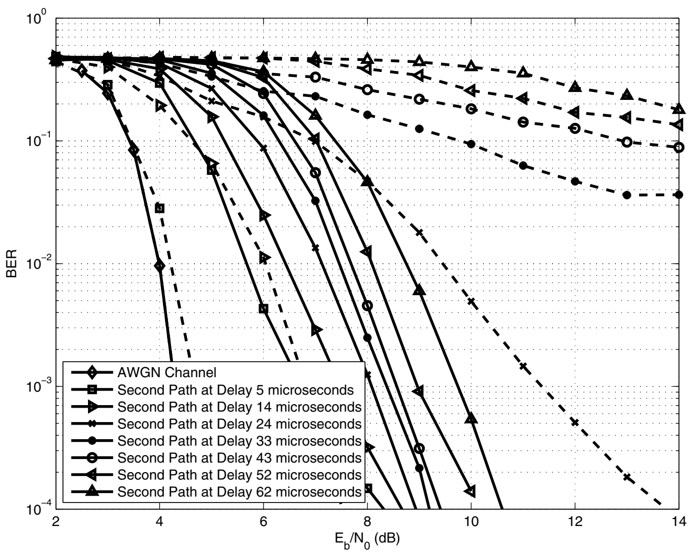

Figure 7. Bit error rate performance for various delays of the second path without equalisation (dashed) and with equalisation (solid). Results are shown for noncoherent detection with 8 iterations in the receiver and mode N2.

effectively combats the multipath albeit with an increase in the required energy per bit to attain the same error rate performance. In fact, the loss in error rate performance for a delay of approximately 62μsec is approximately 6.5dB at 10^{-4} error rate when compared to the curve for AWGN. The latter result demonstrates that these types of waveforms can be deployed in relative harsh multipath environments whilst suffering a marginal loss in signal to noise ratio as opposed to irreducible error floors.

TABLE II
EXAMPLE POWER DELAY PROFILE FOR MOUNTAINOUS CONDITIONS

Power (dB)	-15	-3.6	-3.2	-1.5	-0.5	0	-2.9	-2.5
delay (μsec)	0	2.1	4.2	12.5	14.6	16.7	21	23

Figures 9 and 10 depict a similar trend for one and eight iterations and with mode N2. In this case, however, the error floor for a second path delay of 14μsec is not removed by iterations alone and it requires the combined effect of equalisation and iterative detection to improve the error rate performance. In either case, the techniques described are useful in mitigating relatively severe ISI.

B. Mountainous Channel Model

To obtain a more realistic indicator of error rate performance for the iterative receiver combined with a linear equaliser, the channel models under consideration are taken from [12], which describes a propagation tool for tracing paths in various topographical regions. The model is based on a carrier frequency of 60MHz and covers an area of mountainous terrain near Garmisch-Partenkirchen in Germany. The power delay profile for one realisation of the channel model is listed in Table II. Figure 8 shows the performance of the receiver in terms of bit error rate for modes N1 and N2. The performance is compared to the case of an AWGN channel and shows that the equaliser and iterative detector operate jointly to reduce the channel ISI. Due to the number of scatterers in the multipath environment depicted in Table II. It is hypothesised that the MMSE equaliser is able to make a fairly good estimate of the frequency selective pass band channel inverse, reflected in the bit error rate performance curves.

V. CONCLUSIONS

This paper has investigated the effects of relatively harsh multipath propagation on the error rate performance of CPM using the physical layer of a narrowband tactical terrestrial waveform. It is shown that the combination of a simple equalisation scheme and iterative detection enables the successful operation of transmission modes for challenging multipath environments. Therefore, equalisation and iterative detection are two techniques that work in synergy to address the ISI caused by severe multipath in slow fading channels.

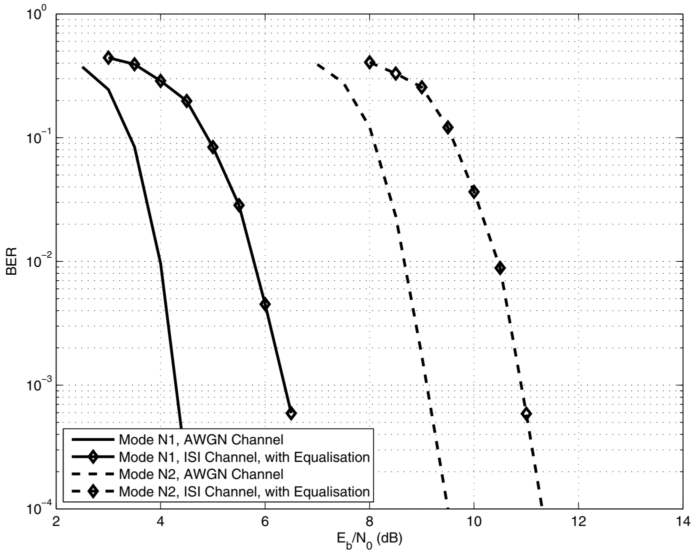

Figure 8. Bit error rate performance comparing the equalised modes and an AWGN channel.

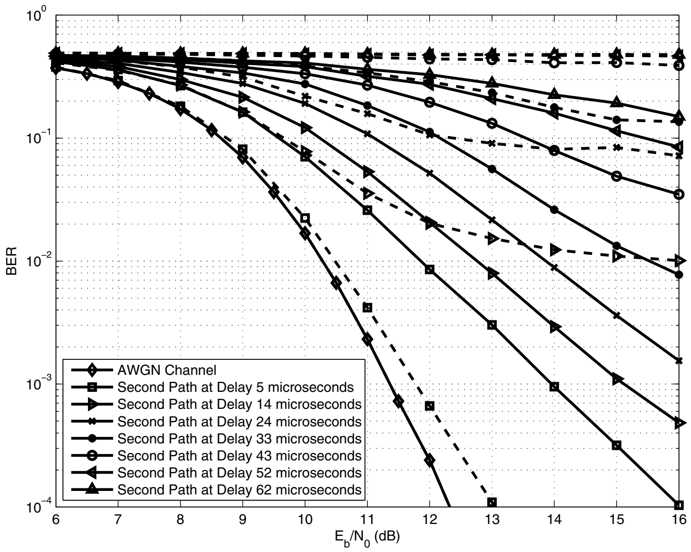

Figure 9. Bit error rate performance for various delays of the second path without equalisation (dashed) and with equalisation (solid). Results are shown for noncoherent detection with 1 iteration in the receiver and mode N1.

ACKNOWLEDGEMENTS

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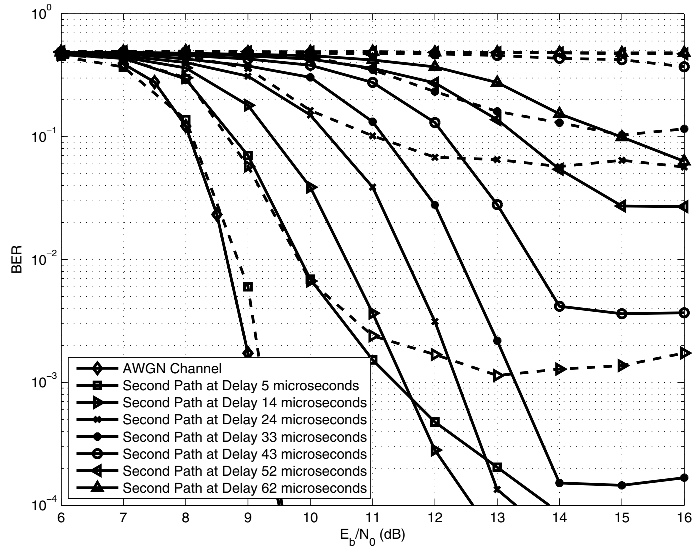

Figure 10. Bit error rate performance for various delays of the second path without equalisation (dashed) and with equalisation (solid). Results are shown for noncoherent detection with 8 iterations in the receiver and mode N2.

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