PERFORMANCE OF A SPREAD SPECTRUM OFDM SYSTEM IN A DISPERSIVE FADING CHANNEL WITH INTERFERENCE

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ABSTRACT

This paper investigates the use of frequency domain equalization techniques to suppress narrowband interference and combine multiple paths in both direct sequence spread spectrum (DS-SS) and orthogonal frequency division multiplexing (OFDM) spread spectrum (OFDM-SS) systems. The similarities between the two signaling formats are highlighted and it is shown that the same receiver structures can be used for both. Two and four ray channels are considered, including those with delay spreads in excess of the symbol interval, along with tone jamming. The results show that all the equalizers that were evaluated are able to suppress the tone interference while combining the energy in the multiple paths. Additionally, in order to maintain good performance, decision feedback and multiple layers of forward taps are necessary when the delay spread is in excess of a symbol interval.

1. INTRODUCTION

One of the features of Direct Sequence Spread Spectrum (DS-SS) signaling is that it is resistant to multipath propagation effects and interference. The interference resistance arises from the fact that the interference is spread in the receiver as the DS-SS signal is being despread. The ability to tolerate multipath is a result of the impulse-like autocorrelation function of the spreading sequences which, within limits, allows a correlation receiver to isolate a particular path. The main constraint is that the particular path be *resolvable* from the other paths, meaning that the other paths must be delayed by at least one chip interval from the path that you want to demodulate. Any paths which are closer will produce either constructive or destructive interference with the desired path, depending on the relative carrier phases.

While a simple correlation receiver is relatively tolerant of multiple received paths, a RAKE receiver can take *advantage* of multipath propagation by isolating and coherently summing the energy in the individual resolvable paths, producing an improvement in bit-error-rate (BER) performance. The RAKE requires knowledge of the channel response to perform the coherent combining operation and requires that all the paths be resolvable to take full advantage of the additional energy. The equalizers discussed in this paper perform RAKE-like combining of multipath energy.

Orthogonal frequency division multiplexing (OFDM) [1, 2] has received considerable attention as a method to efficiently utilize channels with non-flat frequency responses and/or non-white noise. In its most common form, a high rate data stream is divided up among the many carriers in the sys-

tem in a manner which optimizes the capacity of the overall channel. OFDM can also be used as a spread spectrum modulation (OFDM-SS) [3, 4, 5] wherein spectral spreading is accomplished by putting the *same data* on all the carriers, producing a spreading factor equal to the number of carriers. At the receiver, the energy from all the carriers is coherently combined to produce the decision variable. Multiple users can be supported in the same channel through Code Division Multiple Access (CDMA) [6]. In this case each user has a unique signature sequence which determines the set of carrier phases. To receive a particular signal, the receiver needs to know the signature sequence for that user in order to align the carrier phases for the coherent combining operation. Figure 1 is a block diagram of an OFDM-SS transmitter/receiver pair. As shown in the figure, carrier generation is usually performed efficiently using an inverse Fast Fourier Transform (FFT) while demodulation is performed using a forward FFT.
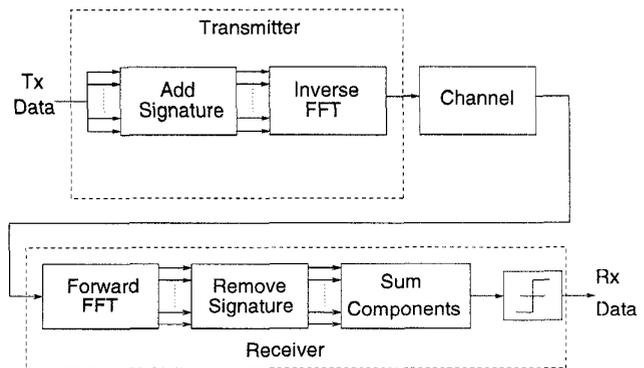

Figure 1. Block Diagram of an OFDM Spread Spectrum System

Spread Spectrum OFDM has many of the same properties as DS-SS. In essence, the primary difference between the two systems is that DS-SS uses a binary spreading *code*, consisting of a sequence of 1's and -1's, while the OFDM-SS system uses a spreading *waveform*, consisting of a series of samples which have non-discrete amplitude values. Indeed, an OFDM-SS modulator can be constructed by storing the spreading waveform and using it to modulate the data in a manner similar to that used with a spreading sequence in DS-SS. The spreading waveform is clearly broadband like the DS-SS spreading sequence and, likewise, has an impulse-like autocorrelation function. Consequently, the OFDM signal is also tolerant of multipath and interference.

Many times, OFDM systems employ *guard times* between

the symbols to avoid the introduction of inter-symbol interference by the multipath channel and to simplify the equalization problem [7]. This guard time must be larger than the expected delay spread and can significantly reduce the channel throughput. The focus of this paper is improving the performance of both the OFDM-SS and DS-SS systems in the presence of multipath and interference *without the use of guard times*. The clear similarities between the signaling formats allows the same receiver structures to be used for both. Since the OFDM receiver inherently includes a FFT, frequency domain techniques are the primary focus. Frequency domain excision [8, 9] has been used successfully to suppress interference in both DS-SS and OFDM-SS systems. Since the goal is to both take advantage of the multiple paths produced by the channel and suppress interference, frequency domain equalization [10, 11] will be considered here in place of excision.

The next section describes three equalizers that will be studied, while Section 3. discusses the channel model and system parameters used in the simulation. Section 4. presents the simulation results and Section 5. provides some conclusions.

2. FREQUENCY DOMAIN EQUALIZERS

All of the equalizer structures that will be considered are similar in that they operate in a decision-directed mode and adapt to minimize the mean-square error between the decisions and the decision variable. The iterative LMS algorithm can be used to adjust the equalizer tap weights to perform this minimization. Since they are decision directed, each of the equalizers requires a training sequence upon start-up to ensure convergence.

The simplest of the equalizer structures is shown in Figure 2. Since it has only one layer of forward taps, this equalizer will be referred to as 1DLMS. It is assumed that the
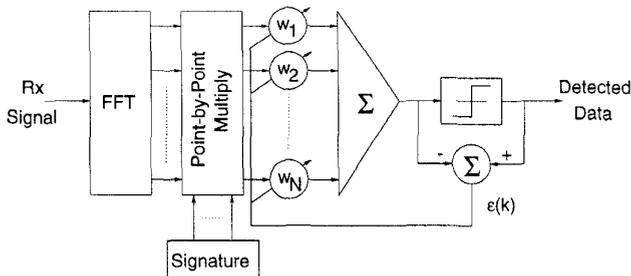

Figure 2. Block Diagram of a Frequency Domain Equalizer for DS-SS and OFDM-SS (1DLMS).

block processing of the FFT is time-aligned with the symbols of the OFDM-SS signal in the shortest path. The output of the FFT is point-by-point multiplied by the complex conjugate of the signature sequence and then processed by a set of variable tap weights. The weighted values are then summed to produce the decision variable. For binary signaling, the decision is made by comparing the summed value with a threshold of zero. Higher-order signaling formats require a multiple-threshold decision device. The decision variable is then compared to the output of the decision device to produce an error signal which, in turn, is used to adjust the tap weights via the LMS algorithm.

This same structure has previously been used in a DS-SS system to suppress narrowband interference [12, 13, 14]. In

this case, the complex conjugate of the signature sequence is replaced by the complex conjugate of the FFT of the spreading sequence. This paper will demonstrate that this same structure can simultaneously combine multiple delayed paths like a RAKE receiver and suppress tone interference. It has also been shown that the point-by-point multiply can be *eliminated*, since the tap weights will converge to provide the despreading operation in addition to the other functions. As in the OFDM-SS case, the time segments processed by the FFT must be time-aligned with the symbols of the received signal.

The equalizer of Figure 2 is limited in a number of ways. First, it is only able to collect the portion of the energy in a delayed copy of a particular symbol that overlaps in time with that same symbol in the primary path. In other words, the portion of the delayed symbol energy that falls into the next symbol interval cannot be used to improve performance. Second, the delayed symbol energy falling into the next symbol interval acts as interference to that next symbol, potentially causing performance loss. Due to the impulse-like autocorrelation function of the spreading code (DS-SS) or spreading waveform (OFDM-SS), this loss tends to be small except when a delayed path has a relative delay equal to an integer number of symbol intervals. As a result of these two limitations, the equalizer becomes less effective as the delay spread grows larger and is best-suited for delay spreads that are less than a symbol interval. With the desire for higher data rates, it cannot always be assumed that the delay spread will not exceed the symbol interval. A way to improve the equalizer performance with large delay spreads is to include a *decision feedback* stage [11]. Figure 3 shows the block diagram of a decision feedback equalizer (DFE), which will be denoted as 1DLMS+DF.
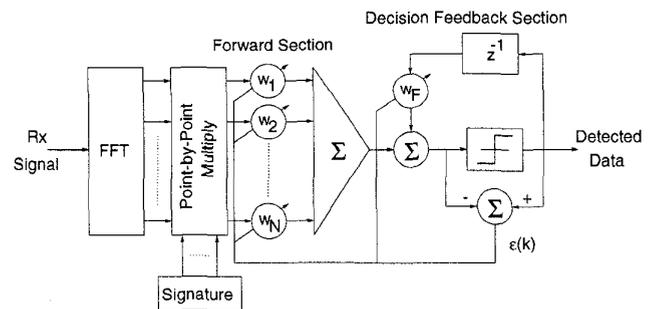

Figure 3. Block Diagram of a Frequency Domain Equalizer with Decision Feedback for DS-SS and OFDM-SS (1DLMS+DF).

In this equalizer, the past decision is weighted, using the tap weight denoted by w_F, and summed, making it possible for the equalizer to suppress the interference caused by the previous symbol, yielding an improvement in performance. If paths with delay relative the primary path in excess of a full symbol interval are present, adding additional feedback elements will yield further improvement. This structure does not, however, allow the energy that falls into a subsequent symbol interval to be used constructively. For this to happen, a second set of forward taps must be added, as shown in Figure 4 (2DLMS+DF). Now, the equalizer will be able to use some part of this additional energy, thereby significantly improving performance for large delay spreads.
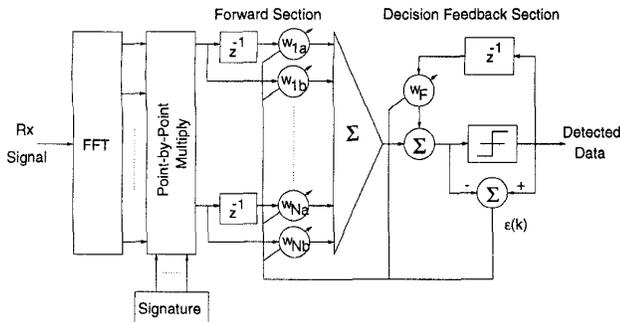
Figure 4. Block Diagram of a Frequency Domain Equalizer with Decision Feedback and Two Levels of Forward Taps for DS-SS and OFDM-SS (2DLMS+DF).

3. SIMULATION MODELS

The impulse response of an L-path time varying frequency selective fading channel at time t and delay τ can be expressed as

$$h(\tau, t) = \sum_{l=0}^{L-1} a_l(t) \exp[-j\theta_l(t)]\delta(\tau - \tau_l), \qquad (1)$$

where $a_l(t)$, $\theta_l(t)$ and τ_l are the amplitude, phase and delay of the lth path, respectively. The number of resolvable paths is limited to the delay spread, i.e. the maximum τ_l, divided by the chip duration. The delay spread, however, can be longer than the symbol duration.

For this paper, we have assumed that the channel model does not change with time and we have used 2 path and 4 path models. The mean received signal power for all models has been normalized to one. Additive white Gaussian noise (AWGN) and, in some instances, tone jamming, is added to the faded signal to obtain the desired energy-per-bit to noise power spectral density ratio, E_b/N_o, and jammer-to-signal power ratio, (JSR), values. For both the 2 path and 4 path channel models, the power is divided equally among the paths and the delay between the paths can be varied in chip increments.

DS-SS and OFDM-SS modulators, a channel model with the channel described above, and receivers including each of the three equalizers have been implemented in the form of a simulation. All sampling is performed at the chip rate. Monte Carlo simulations were performed for both signaling formats under varying channel conditions and with each of the equalizers. The OFDM-SS signal consisted of 64 carriers and a signature sequence of all 1's was used. DS-SS signal used an augmented m-sequence of length 64 as the spreading code. The FFT in the receiver has 64 bins and perfect symbol synchronization is assumed, i.e. the blocks of the data processed by the FFT are time aligned with the symbol intervals of the non-delayed path. Similarly, all processing is performed at baseband, effectively assuming perfect carrier synchronization. Random data is sent by the transmitter and binary signaling is used. A minimum of 100 bit errors were recorded for each of the data points and sufficient time was allowed for the equalizers to converge before data collection began. Finally, the actual transmitted data bits are used in the equalizers in place of the data bit decisions, thereby avoiding any error propagation effects. Clearly, in an actual

receiver the use of decisions will introduce some performance loss.

4. RESULTS

4.1. Multipath Alone

Figure 5 shows the performance of the three receiver structures for OFDM-SS signaling and a 2-ray channel model with a delay spread of 10 chips. In this case a "chip" corresponds
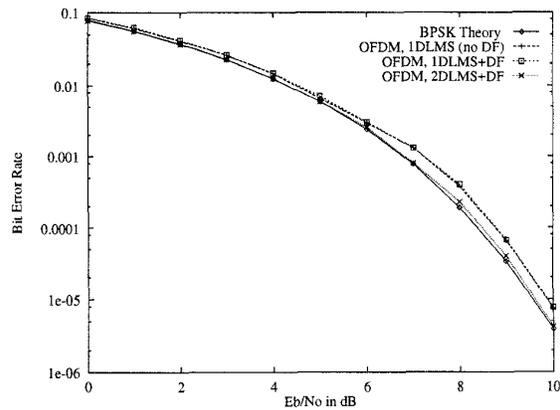

Figure 5. BER vs. E_b/N_o for a 2-Ray Channel with a delay spread of 10 chips, AWGN and OFDM-SS Signaling.

to a sample. Since the delay spread is moderate, a large fraction of the "extra" energy in the second path can be utilized by both the 1DLMS and 1DLMS+DF equalizers, producing BER within about 0.5 dB of the theoretical BPSK performance in AWGN alone. The amount of interference caused by the energy from the previous data bit falling into the current bit interval is small due to the impulse-like autocorrelation function of the signal and this results in the performance being relatively unchanged by the addition of the decision feedback stage. The 2DLMS+DF can utilize the additional energy in the delayed path which falls into the next data bit interval and, consequently, achieves the better performance than the other equalizers, showing negligible degradation from the theoretical BPSK performance in AWGN.

Figure 6 shows the performance when the delay spread is increased to 64 chips, i.e. a full data bit interval. In a sense, this delay spread represents a worst-case situation since the delayed signal is not resolvable from the direct path. The job of the equalizer, then, is not just to gain an advantage from the presence of the second path but, more importantly, to suppress the large level of interference caused by this second path. The results in the figure show that decision feedback is necessary to accomplish this interference cancellation. The performance of the 1DLMS equalizer is very poor, having a BER of approximately 0.25. The addition of a decision feedback stage (1DLMS+DF) provides a large performance improvement while the addition of a second forward stage along with decision feedback (2DLMS+DF) provides even greater improvement. The 1DLMS+DF receiver shows a performance that is approximately 3 dB away from the BPSK because it is unable to use any of the energy in the delayed path and this energy is included in the E_b/N_o calculation. The performance of the 2DLMS+DF is approximately 1.0 dB better than that of the 1DLMS+DF due to the fact that
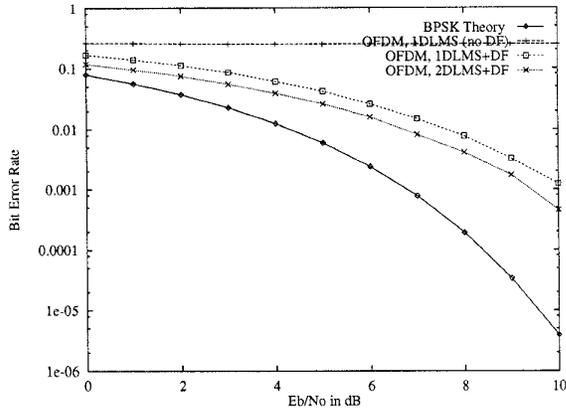
Figure 6. BER vs. E_b/N_o for a 2-Ray Channel with a delay spread of 64 chips, AWGN and OFDM-SS Signaling.

it is able to use a fraction of the energy that falls into the next bit interval.

Figure 7 shows how the performance of each of the equalizers varies as a function of delay spread when E_b/N_o
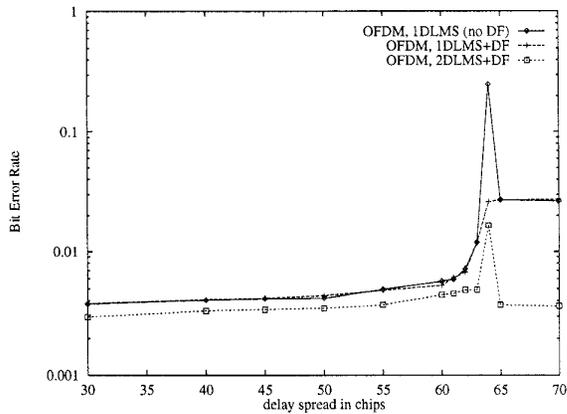

Figure 7. BER vs. Delay Spread for a 2-Ray Channel with $E_b/N_o = 6$ dB and OFDM-SS Signaling.

is fixed at 6 dB. The channel is a 2-ray model. The figure shows that the primary advantage provided by including the decision feedback stage is the ability to maintain acceptable performance when the delay spread is a full symbol interval. The performance of the 1DLMS and DLMS+DF are nearly identical at other delay spread values. The 2DLMS+DF consistently outperforms the other equalizers, particularly at delay spread values that exceed the symbol interval. Note that the BER of both the 1DLMS and 1DLMS+DF equalizers remains high as the delay spread increases above a symbol interval. The performance loss is approximately 3dB and occurs because the energy in the second path is completely lost. In contrast, the BER of the 2DLSM+DF is nearly the same for delay spreads above and below the symbol interval.

Figure 8 shows the BER as a function of E_b/N_o for a 4-ray channel. The power is equally divided among the rays and the rays are equally spaced in time. The curves show that the performance of the 2DLMS+DF equalizer remains good with the additional paths, though some loss is incurred with
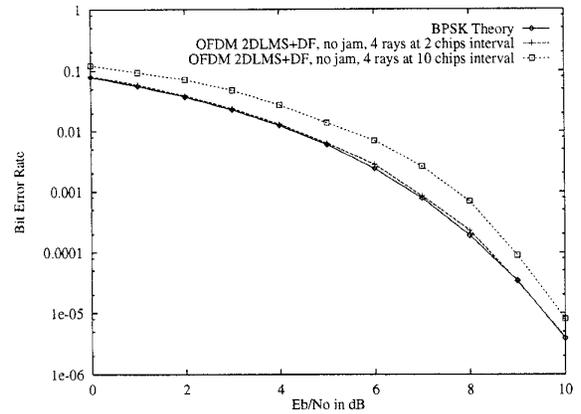

Figure 8. BER vs. E_b/N_o for the 2DLMS+DF Equalizer and a 4-Ray Channel.

As was discussed earlier, the equalizer structures can be used for both DS-SS and OFDM-SS. Figure 9 compares the performance of the 2DLMS-DF equalizer for each of the sig-
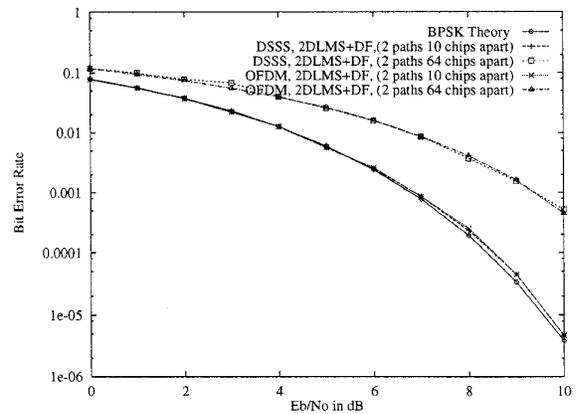

Figure 9. BER vs. E_b/N_o for the 2DLMS+DF Equalizer and a 2-Ray Channel for both DS-SS and OFDM-SS Signaling.

naling formats under the same channel conditions. Clearly, the performance is identical for both the DS-SS and OFDM-SS signal for the two-ray channel with delay spreads of 10 chips and 64 chips. This equivalence in performance has been observed in general, meaning that the results presented here for OFDM-SS can be readily applied to DS-SS systems as well.

4.2. Interference and Multipath

The equalizers are effective at removing narrowband interference as well as combining multiple paths. Figure 10 shows the performance of the three structures in the presence of a tone jammer with JSR = 20 dB and a frequency of 0.135 times the chip rate. It is clear that all three equalizers are able to suppress the interference. The use of decision feedback and a second layer of forward taps does not provide any advantage with the jammer alone.

Figure 11 shows the performance of the equalizers with a two-ray multipath channel with delay spread of 10 chips and
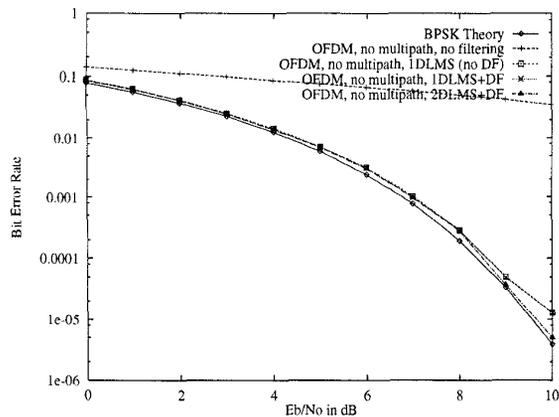
Figure 10. BER vs. E_b/N_o for the Equalizers with Tone Jamming, JSR=20 dB, frequency=0.135 times the chip rate.

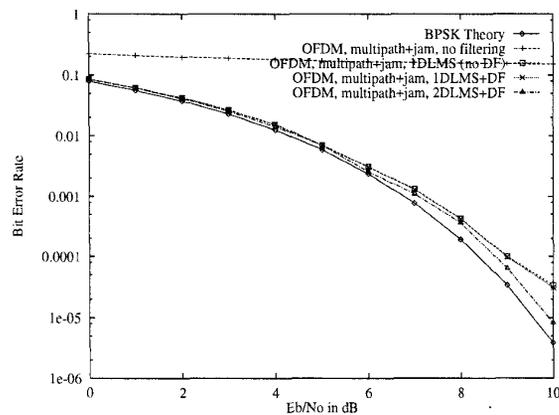the tone jammer. The equalizers all suppress the interference

Figure 11. BER vs. E_b/N_o for the Equalizers with a 2-Ray Channel (Delay = 10 chips) and Tone Jamming (JSR=20 dB, frequency=0.135 times the chip rate).

and take advantage of the second ray. The performance is very close to that shown in Figure 5 which considers the same multipath channel without the interference. Clearly, the equalizers can perform both the interference suppression and multipath combining operations simultaneously.

5. CONCLUSIONS

This paper has investigated the performance of frequency domain equalizers for both suppressing narrowband interference and combining multiple paths in DS-SS and OFDM-SS receivers. The results show that decision feedback is needed to maintain reasonable performance when a path is delayed by a full symbol interval and that excellent performance can be obtained for delay spreads over a symbol interval if two layers of forward taps and a decision feedback section is used. Performance results are identical for both the DS-SS and OFDM-SS signals.

REFERENCES

[1] S. B. Weinstein and P. M. Ebert. Data transmission by frequency-division multiplexing using the discrete fourier transform. *IEEE Transactions on Communication Technology*, (5), October 1971.

[2] H. Sari, G. Karam, and I. Jeanclaude. Transmission techniques for digital terrestrial tv broadcasting. *IEEE Communications Magazine*, 33(2), Feburary 1995.

[3] G. K. Kaleh. Frequency-diversity spread-spectrum communication system to counter bandlimited gaussian interference. *IEEE Transactions on Communications*, 44(7):886–893, July 1996.

[4] G. J. Saulnier, V. A. A. Whyte, and M. J. Medley. OFDM spread spectrum communications using lapped transforms and interference excision. In *IEEE International Conference on Communications Conference Record*, pages 944–948, 1997.

[5] G. J. Saulnier, M. Mettke, and M. J. Medley. Performance of an OFDM spread spectrum communication system using lapped transforms. In *Conference Record of the IEEE Military Communications Conference*, 1997.

[6] B. Fettweis, A. S. Bahai, and K. Anvari. On multi-carrier code division multiple access (MC-CDMA) modem design. In *Proceedings of the IEEE Vehicular Technology Conference*, pages 1670–1674, 1994.

[7] G. Santella. Ofdm with guard interval and sub-channel equalization in a 2- resolution transmission scheme for digital television broadcasting. In *Conference Record,ICC/SUPERCOMM'94*, pages 374–380, May 1994.

[8] L. B. Milstein and P. K. Das. An analysis of a real-time transform domain filtering digital communication system - Part I: Narrowband interference rejection. *IEEE Transactions on Communications*, COM-28(6):816–824, June 1980.

[9] L. B. Milstein and P. K. Das. An analysis of a real-time transform domain filtering digital communications system - Part II: Wideband interference rejection. *IEEE Transactions on Communications*, COM-31:21–27, June 1983.

[10] Hongnian Xing and P. Jarske. Frequency domain equalization for the multicarrier spread spectrum system in multipath fading channel. In *1996 International Conference on Communication Technology Proceedings*, pages 603–606, May 1996.

[11] M. Itami, H. Takano, H. Ohta, and K. Itoh. A method of equalization of ofdm signal with inter-symbol and inter-channel interferences. In *Proceedings of ICCS '94*, pages 109–113, November 1994.

[12] M. J. Medley, G. J. Saulnier, and P. Das. Narrowband interference suppression using wavelet transform domain wiener filtering. In *Proceeding of the IEEE International Conference on Telecommunications*, 1996.

[13] M. J. Medley, G. J. Saulnier, and P. Das. Interference suppression using transform domain LMS adaptive filtering. In *Proceedings of the 1996 IEEE Digital Signal Processing Workshop*, 1996.

[14] M. J. Medley and G. J. Saulnier. Transform domain LMS convergence in tone interference. In *Conference Record of the IEEE Military Communications Conference*, 1997.