Frequency Domain Equalization for Single-Carrier Broadband Wireless Systems

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ABSTRACT

Broadband wireless access systems deployed in residential and business environments are likely to face hostile radio propagation environments, with multipath delay spread extending over tens or hundreds of bit intervals. Orthogonal frequency-division multiplex (OFDM) is a recognized multicarrier solution to combat the effects of such multipath conditions. This article surveys frequency domain equalization (FDE) applied to *single-carrier* (SC) modulation solutions. SC radio modems with frequency domain equalization have similar performance, efficiency, and low signal processing complexity advantages as OFDM, and in addition are less sensitive than OFDM to RF impairments such as power amplifier nonlinearities. We discuss similarities and differences of SC and OFDM systems and coexistence possibilities, and present examples of SC-FDE performance capabilities.

INTRODUCTION

Broadband wireless access technologies, offering bit rates of tens of megabits per second or more to residential and business subscribers, are attractive and economical alternatives to broadband wired access technologies. Air interface standards for such broadband wireless metropolitan area network (MAN) systems in licensed and unlicensed bands below 11 GHz are being developed by the IEEE 802.16 working group and also by the European Telecommunications Standards Institute (ETSI) Broadband Radio Access Network (BRAN) High-Performance MAN (HiperMAN) group. Such systems, installed with minimal labor costs, may operate over non-line-of-sight (NLOS) links, serving residential and small office/home office (SOHO) subscribers. In such environments multipath can be severe. This raises the question of what types of anti-multipath measures are necessary, and consistent with low-cost solutions. Several variations of orthogonal frequency-division multiplexing (OFDM) have been proposed as effective anti-multipath techniques, primarily because of the favorable trade-off they offer between performance in severe multipath and signal processing complexity [1].

This article discusses an alternative approach based on more traditional single-carrier (SC) modulation methods. We show that when combined with *frequency domain equalization* (FDE), this SC approach delivers performance similar to OFDM, with essentially the same overall complexity. In addition, SC modulation uses a single carrier, instead of the many typically used in OFDM, so the peak-to-average transmitted power ratio for SC-modulated signals is smaller. This in turn means that the power amplifier of an SC transmitter requires a smaller linear range to support a given average power (in other words, requires less peak power backoff). As such, this enables the use of a cheaper power amplifier than a comparable OFDM system; and this is a benefit of some importance, since the power amplifier can be one of the more costly components in a consumer broadband wireless transceiver.

MULTIPATH CHANNEL CHARACTERISTICS AND ANTI-MULTIPATH APPROACHES

Broadband cellular wireless access systems in residential neighborhoods must cope with the dominant propagation impairment of multipath, which causes multiple echoes of the transmitted

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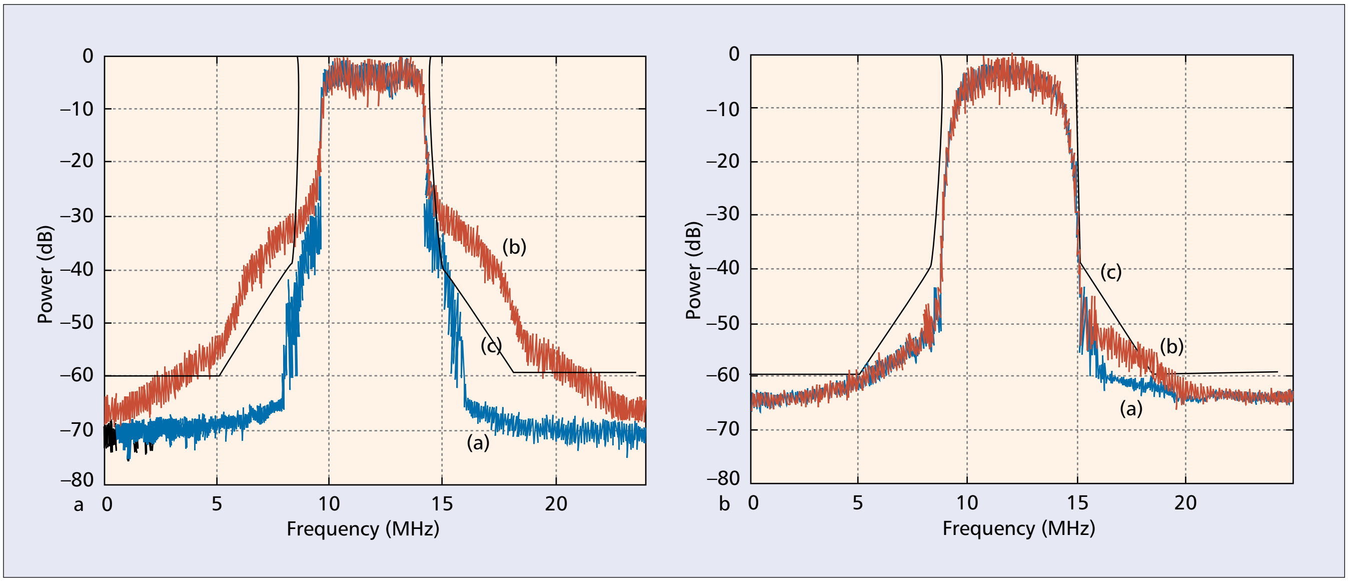


■ **Figure 1.** *a) Power amplifier output power spectra [5] for a QPSK 256-point OFDM system: (a) spectrum with ideal power amplifier (infinite power backoff); (b) spectrum with typical power amplifier with 10 dB power backoff; (c) FCC MMDS spectral mask; b) power amplifier output power spectra [5] for a QPSK SC system: (a) spectrum with ideal power amplifier (infinite power backoff); (b) spectrum with typical power amplifier with 10 dB power backoff; (c) FCC MMDS spectral mask.*

signal to be received with delay spreads of up to tens of microseconds [2]. For bit rates in the range of tens of megabits per second, this translates to intersymbol interference that can span up to 100 or more data symbols. For example, at a 5 MHz symbol rate, a 20 μs multipath delay profile spans 100 data symbols.

For channel responses spanning tens or hundreds of symbols, practical modulation and anti-multipath alternatives are:

- SC modulation with receiver equalization done in the time domain
- OFDM
- SC modulation with receiver equalization in the frequency domain

A brief description of each of these anti-multipath alternatives follows.

Single-Carrier Modulation with Time Domain Equalization at the Receiver

A conventional anti-multipath approach, which was pioneered in voiceband telephone modems and has been applied in many other digital communications systems, is to transmit a single carrier, modulated by data using, for example, quadrature amplitude modulation (QAM), and to use an adaptive equalizer at the receiver to compensate for intersymbol interference (ISI) [3]. Its main components are one or more transversal filters for which the number of adaptive tap coefficients is on the order of the number of data symbols spanned by the multipath. For the above-mentioned 20 μs delay spread example, this would mean a transversal filter with at least 100 taps, and at least several hundred multiplication operations per data symbol. For tens of megasymbols per second and more than about 30–50-symbol ISI, the complexity and required digital processing speed become exorbitant, and this time domain equalization approach becomes unattractive.

OFDM

OFDM transmits multiple modulated subcarriers in parallel [1]. Each occupies only a very narrow bandwidth. Since the channel affects only the amplitude and phase of each subcarrier, equalizing each subcarrier's gain and phase does compensation for frequency selective fading. Generation of the multiple subcarriers is done by performing inverse fast Fourier transform (IFFT) processing at the transmitter on blocks of M data symbols; extraction of the subcarriers at the receiver is done by performing the fast Fourier transform (FFT) operation on blocks of M received samples. Typically, the FFT block length M is at least 4–10 times longer than the maximum impulse response span. One reason for this is to minimize the fraction of overhead due to the insertion of a cyclic prefix at the beginning of each block. The cyclic prefix is a repetition of the last data symbols in a block. Its length in data symbols exceeds the maximum expected delay spread. The cyclic prefix is discarded at the receiver. Its purpose is to:

- Prevent contamination of a block by ISI from the previous block
- Make the received block appear to be periodic with period M

This produces the appearance of circular convolution, which is essential to the proper functioning of the FFT operation.

Time domain equalization typically requires a number of multiplications per symbol that is proportional to the maximum channel impulse response length. OFDM processing requires on the order of $\log_2 M$ multiplications per data symbol, counting both transmitter and receiver operations. Since M is proportional to the maximum expected channel response length, OFDM appears to offer a better performance/complexity trade-off than conventional SC modulation with time domain equalization for large (> about 20 taps) multipath spread [4]. A variation is *adaptive*

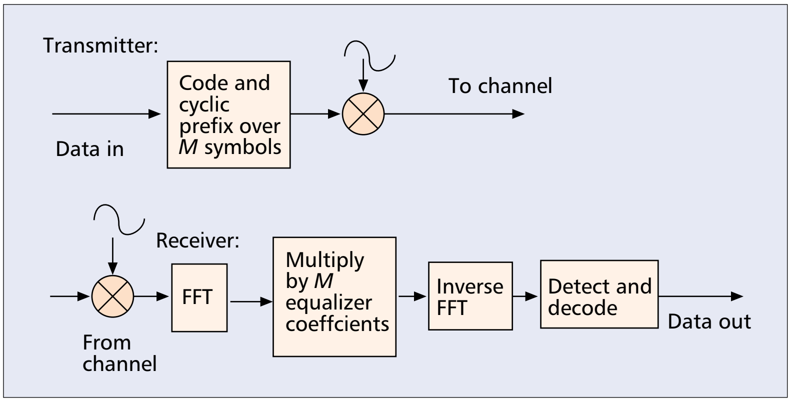


Figure 2. *SC-FDE with linear equalization.*

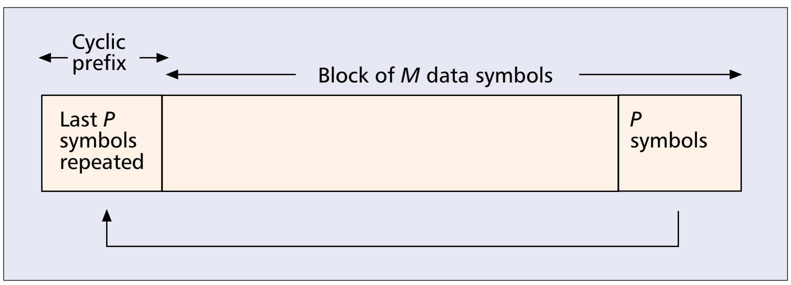


Figure 3. *Block processing in frequency domain equalization.*

OFDM, where the signal constellation on each subchannel depends on channel response at that frequency. It requires feedback from the receiver to the transmitter, and is not commonly employed in radio systems due to complexity and channel time variations. Because of the fixed power and bit rate on each subchannel, some of which might be severely faded by frequency-selective channels, nonadaptive OFDM *must* be coded.

Because the transmitted OFDM signal is a sum of a large number (M) of slowly modulated subcarriers, OFDM has a high peak-to-average power ratio, even if low-level modulation such as quaternary phase shift keying (QPSK) is used on each subcarrier. While there are signal processing methods to reduce this ratio, the transmitter power amplifier in an OFDM system generally must be backed off by several dB more than for an SC system to remain linear over the range of signal envelope peaks that must be faithfully reproduced. Figures 1a and 1b (from [5]) illustrate the spectral regrowth that occurs with 10 dB power backoff at the output of a typical power amplifier for a QPSK OFDM system with 256-point FFT, with 25 percent of the subcarriers not used (Fig. 1a), and for a QPSK SC system with 25 percent excess bandwidth (Fig. 1b). Also shown in these figures is the output power spectrum for an ideal (infinite backoff) power amplifier, and also (with straight lines), the FCC spectral mask for multichannel microwave distribution systems (MMDSs) with 6 MHz bandwidth. Clearly the OFDM system's output power must be backed off more than 10 dB in this example, in order to comply with the FCC mask. This power backoff penalty is especially important for subscribers near the edge of a cell, with large path loss, where lower-level modulation such as binary PSK (BPSK) or QPSK modulation must be used. The increased power backoff required in this situation for OFDM would increase the cost of the power amplifier required for such sites to "reach" the base station. OFDM systems can also exhibit sensitivity to carrier frequency offset and phase noise.

Pilot (known) data is also often incorporated into these data blocks for channel tracking and estimation purposes. What's more, in burst applications, one or more blocks of this size are used for initial receiver training purposes. One other problem associated with OFDM systems involves data packet granularity: the minimum data packet size in an OFDM system is the FFT block length. This problem, which affects the spectral efficiency of short packet transmissions, can be circumvented by using orthogonal frequency-division multiple access (OFDMA), in which the FFT block is shared by multiple users, each using a subset of the subcarriers that constitute an FFT block. The granularity problem is solved in SC systems by simply transmitting short-duration blocks when necessary.

Single-Carrier Modulation with Frequency Domain Adaptive Equalizer Processing at the Receiver

An SC system transmits a single carrier, modulated, for example, with QAM, at a high symbol rate. Frequency domain linear equalization in an SC system is simply the frequency domain analog of what is done by a conventional linear time domain equalizer. For channels with severe delay spread, frequency domain equalization is computationally simpler than corresponding time domain equalization for the same reason OFDM is simpler: because equalization is performed on a block of data at a time, and the operations on this block involve an efficient FFT operation and a simple channel inversion operation. Sari *et al.* [6, 7] pointed out that when combined with FFT processing and the use of a cyclic prefix, an SC system with FDE (SC-FDE) has essentially the same performance and low complexity as an OFDM system. Also notable is that a frequency domain receiver processing SC modulated data shares a number of common signal processing functions with an OFDM receiver. In fact, as we point out in the next section, SC and OFDM modems can easily be configured to coexist, and significant advantages may be obtained through such coexistence.

Figure 2 shows conventional linear equalization, using a transversal filter with M tap coefficients, but with filtering done in the frequency domain. The block length M, suitable for MMDS systems with 6 MHz bandwidths, would be chosen in the range of 64–2048 for both OFDM and SC-FDE systems. There are approximately $\log_2 M$ multiplications per symbol, as in OFDM.

The use of SC modulation and FDE by processing the FFT of the received signal has several attractive features:

- SC modulation has reduced peak-to-average ratio requirements from OFDM, thereby allowing the use of less costly power amplifiers.

- Its performance with FDE is similar to that of OFDM, even for very long channel delay spread.
- Frequency domain receiver processing has a similar complexity reduction advantage to that of OFDM: complexity is proportional to log of multipath spread.
- Coding, while desirable, is not necessary for combating frequency selectivity, as it is in nonadaptive OFDM.
- SC modulation is a well-proven technology in many existing wireless and wireline applications, and its RF system linearity requirements are well known.

A cyclic prefix is appended to each block of M symbols, exactly as in OFDM, as shown in Fig. 3.

As an additional function, the cyclic prefix can be combined with a training sequence for equalizer adaptation.

For either OFDM or SC-FDE broadband wireless systems operating in severe outdoor multipath environments, typical values of M could be 256–1024, and typical values of P could be 64 or 128. Overlap-save or overlap-add signal processing techniques could also be used to avoid the extra overhead of the cyclic prefix.

An inverse FFT returns the equalized signal to the time domain prior to the detection of data symbols. Adaptation of the FDE equalizer's transfer function can be done with least mean square (LMS), root least square (RLS), or least squares minimization (LS) techniques, analogous to adaptation of time domain equalizers [8, 9].

Figure 4 shows a comparison of the complexities of time domain and frequency domain processing (SC or OFDM linear equalizers) as a function of the length of the channel impulse response, measured in symbol intervals. Complexity here is gauged by the number of complex multiplications per transmitted data symbol, including both the filtering operations and LMS adaptation operations (see [9] for a description of the latter). The frequency domain equalizer is assumed to use an FFT block length equal to eight times the channel length.

Decision feedback equalization (DFE) gives better performance for frequency-selective radio channels than linear equalization [3]. In conventional DFE equalizers, symbol-by-symbol data symbol decisions are made, filtered, and immediately fed back to remove their interference effect from subsequently detected symbols. Because of the delay inherent in the block FFT signal processing, this immediate filtered decision feedback cannot be done in a frequency domain DFE, which uses frequency domain filtering of the fed-back signal. A hybrid time-frequency domain DFE approach, which avoids the above-mentioned feedback delay problem, would be to use frequency domain filtering only for the forward filter part of the DFE, and conventional transversal filtering for the feedback part. The transversal feedback filter is relatively simple in any case, since it performs multiplications only on data symbols, and it could be made as short or long as required for adequate performance. Figure 5 illustrates such a hybrid time-frequency domain DFE topology. Once per block, the M FFT output coefficients, $\{R_l\}$, are multiplied by the complex-valued M forward equalizer coefficients $\{W_l\}$(which compensate for the frequency-selective channel's variations of amplitude and phase with frequency). An IFFT is applied to the M weight-equalized complex-valued samples, and the resulting time-domain sequence is passed to a data symbol decision device — or, in the case of a DFE, the estimated ISI due to *previously* detected symbols is computed using B feedback taps $\{f_k\}$, and subtracted off, symbol by symbol. FDE can also be combined with spatial processing to provide interference suppression and diversity [9].

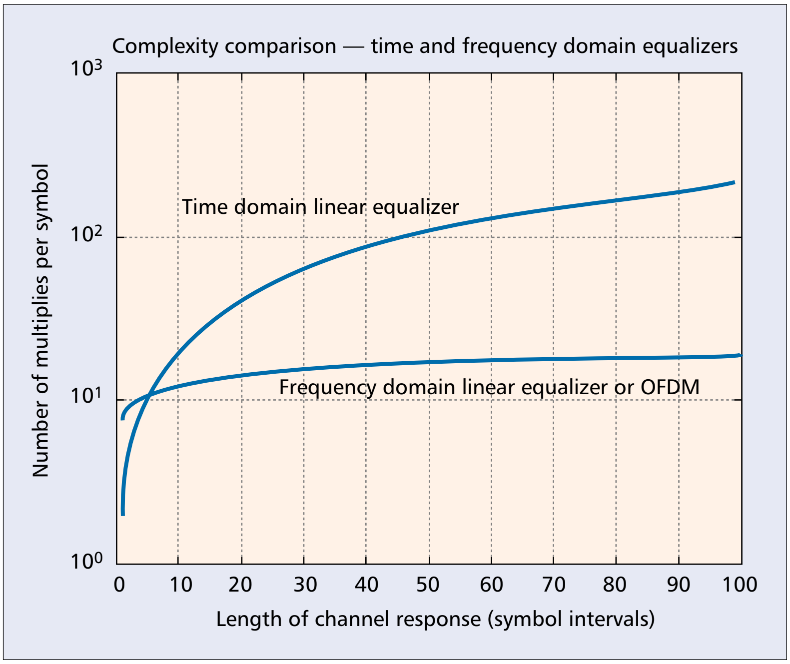


Figure 4. *Complexity comparison of time and frequency domain linear equalizers with LMS adaptation.*

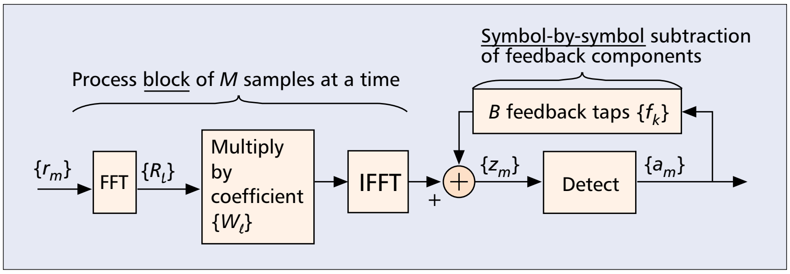
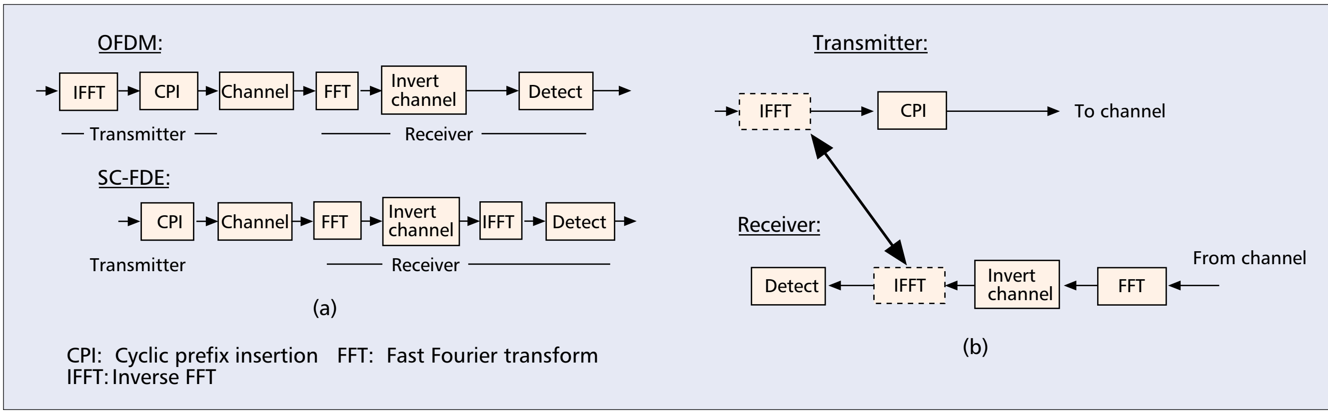


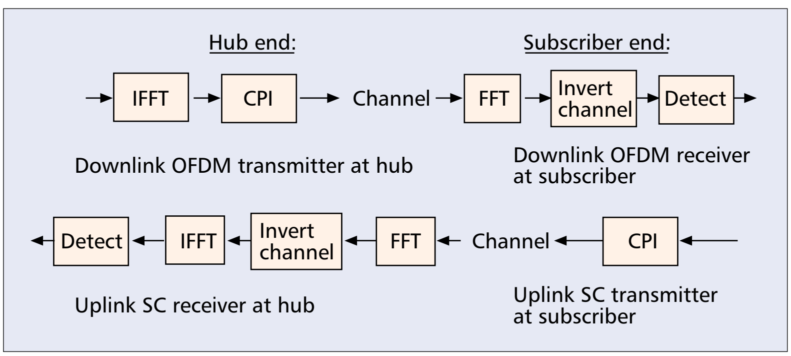
Figure 5. *SC-FDE decision feedback equalizer.*

Coexistence of Single-Carrier and OFDM Systems

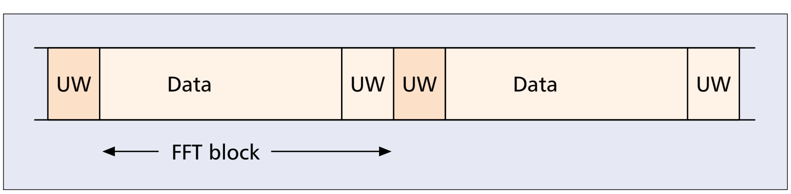
Figure 6a shows block diagrams for OFDM and SC systems with linear FDE. It is evident that the two types of systems differ mainly in the placement of an IFFT operation: in OFDM it is placed at the transmitter to multiplex the data into parallel subcarriers; in SC it is placed in the receiver to convert FDE signals back into time domain symbols. The signal processing complexities of these two systems are essentially the same for equal FFT block lengths.



■ **Figure 6.** *a) OFDM and SC-FDE — signal processing similarities and differences; b) potential interoperability of SC-FDE and OFDM: a "convertible" modem.*



■ **Figure 7.** *Coexistence of SC-FDE and OFDM: uplink/downlink asymmetry.*



■ **Figure 8.** *Continuous downstream transmission showing unique words (UW) used for training shaded.*

A dual-mode system, in which a software radio modem can be reconfigured to handle either SC or OFDM signals, could be implemented by switching the IFFT block between the transmitter and receiver at each end of the link, as suggested in Fig. 6b.

There may actually be an advantage in operating a dual mode system, wherein the base station uses an OFDM transmitter and an SC receiver, and the subscriber modem uses an SC transmitter and an OFDM receiver, as illustrated in Fig. 7. This arrangement — OFDM in the downlink and SC in the uplink —has two potential advantages:

- Concentrating most of the signal processing complexity at the hub or base station. The hub has two IFFTs and one FFT, while the subscriber has just one FFT.
- The subscriber transmitter is SC, and thus inherently more efficient in terms of power consumption due to the reduced power backoff requirements of the SC mode. This may reduce the cost of a subscriber's power amplifier.

Equalizer Training using Least Squares Minimization

The FDE parameters $\{W_l\}$ and $\{f_k\}$ are adapted, or *trained* from the reception of N consecutive training blocks, each consisting of a sequence of P known transmitted training symbols. The length of a training block, P, may be equal to or less than the length of a data block M and is preceded by a cyclic prefix. If it is less than M, P is picked to be at least equal to the maximum expected channel impulse response length in data symbol intervals. If $P < M$, the forward filter parameters derived from training, $\{W_l, l = 0, 1, \ldots, PI\}$ can be *interpolated* to values to be used for blocks of M.

The sequence of P transmitted training symbols is known as a *unique word* (UW). Ideally, its frequency spectrum (FFT) should have equal or nearly equal magnitude for all frequencies. Such an ideal training sequence ensures that each frequency component of the channel is probed uniformly. For unique word lengths P that are powers of two, such as 64 or 256, polyphase Frank-Zadoff sequences [10] or Chu sequences [11] are suitable. If binary-valued sequences are more desirable from a hardware implementation standpoint, length 2^n-1 pseudo-noise (pn) sequences can be modified by adding a small dc value in quadrature, as suggested by Milewski [12]. Each of these types of sequences has the desired property of a constant-magnitude spectrum.

Consider two or more back-to-back unique words, periodically inserted within a data sequence, for synchronization and equalizer training purposes. The first of these back-to-back unique words acts as a cyclic prefix, and absorbs any ISI from previous data. The second and subsequent words form a periodic sequence that have the ideal periodic autocorrelation property described above. An example of the aforesaid description, which may be found in a continuous downstream transmission, is shown in Fig. 8 Note that the payload data blocks of Fig. 8 are preceded and followed by contiguous unique words.

The unique words immediately preceding the data (indicated by shading in Fig. 8) form a periodic sequence of training blocks. Each unique word following the data segment serves as a cyclic prefix for the succeeding unique word and also shields it from ISI from non-training data.

The overhead fraction is $2P/(D+2P)$ if the unique word length is P and the data block length is D. An example of bursty uplink or downlink transmission is shown in Fig. 9. Here, an extra unique word is added as a cyclic prefix, and the total overhead fraction is $3P/(D+3P)$. The efficiency of SC systems can be further improved by using overlap-save frequency domain processing at the receiver, thus eliminating the cyclic prefix overhead.

The use of unique words for equalizer training, as well as interpolation in the frequency domain, is the counterpart of the use of pilot tones and frequency domain interpolation in OFDM systems. Details on training and adaptation processing are found in a white paper on SC-DFE at http://www.sce.carleton.ca/bbw/papers/Ariyavisitakul.pdf.

PERFORMANCE

IDEAL PERFORMANCE

The bit error rate (BER) performance of SC-FDE, using perfect channel knowledge and with training, has been evaluated by simulation using several models of broadband wireless channels with multipath fading. "SUI-5" is one of six channel models adopted by IEEE 802.16a for evaluating broadband wireless systems in 2–11 GHz bands [13]. It has three Rayleigh fading taps at delays of 0, 5 and 10 µs, with relative powers of 0 dB, -5 dB, and -10 dB, respectively. This is a high delay spread model associated with the use of omnidirectional antennas in suburban hilly environments. The channel has a RMS delay spread of 3.05 µs. The fading was modeled as quasi-static (unchanging during an FFT block).

QPSK, 16-QAM, and 64-QAM SC and OFDM systems were simulated against this model for a range of received signal-to-noise ratios, each with 20,000 random channel realizations. For each channel realization, obtained by Monte Carlo simulation, the BER was computed, and then the BER was, in turn, averaged over all channel realizations. BER results were compiled for bit-interleaved convolutionally coded systems with various code rates, obtained by Monte Carlo simulation. Code rates greater than 1/2 were realized by optimally puncturing a standard rate 1/2, constraint length 7 code with octal generator polynomials (133,171). The coded bits were interleaved and mapped into transmitted M-ary QAM data symbols using Gray mapping. The resulting coding scheme is known as *bit-interleaved coded modulation* (BICM), which is known [14] to perform within a dB or two of trellis-coded modulation (TCM) over additive white Gaussian noise channels and to outperform TCM over fast fading channels where the interleaver spans multiple fades. (Therefore, for a coded OFDM block transmitted over a frequency selective fading [multipath] channel, which resembles a fast fading temporal channel, BICM is the most suitable coding scheme).

Each FFT block consists of 512 QAM symbols. Row-column block interleaving was used within each FFT block, where the data bits are written by row, and mapped to QAM symbols by column, each row consisting of 32 bits. The raised cosine rolloff factor used for the SC systems was 10 percent.

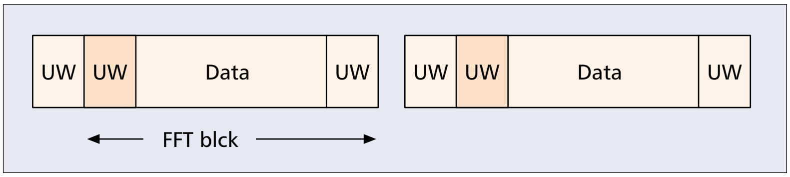


Figure 9. *Bursty transmission with unique words for training shaded.*

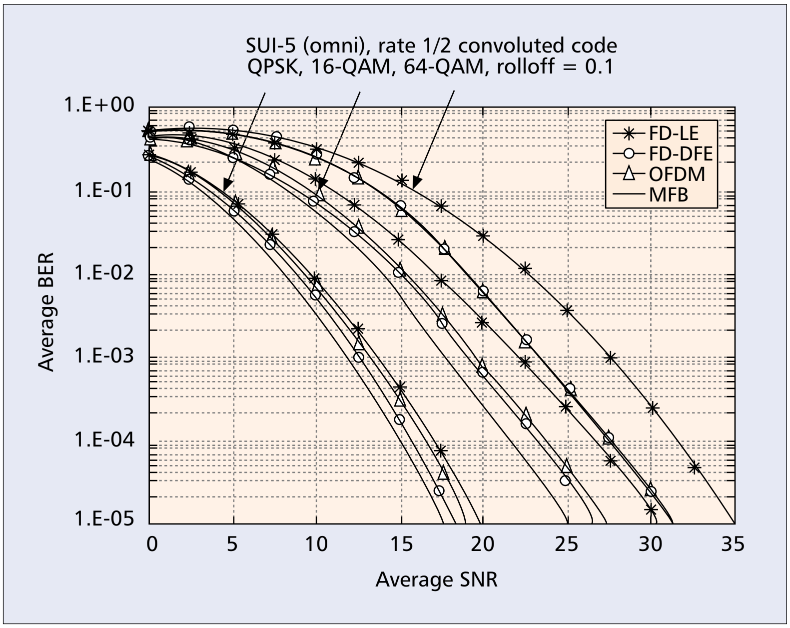


Figure 10. *Performance comparison for systems with perfect channel knowledge on SUI-5 channel for code rate 1/2.*

Figure 10 shows the average bit error probability evaluated over a range of average signal-to-noise ratios (SNRs) using a rate 1/2 code and for the three (4-16-64) QAM constellations, for the following system configurations:

- SC modulation using frequency domain linear equalization (FD-LE)
- OFDM
- SC modulation using ideal frequency domain decision feedback equalization (FD-DFE), assuming (asymptotically) an infinite-length feedback filter and correct feedback (no decision errors)
- For an upper bound comparison, the matched filter bound (MFB) (performance with a matched filter receiver and no ISI)

In these simulations, perfect channel and output SNR estimation was assumed for all systems.

The results of Fig. 10 suggest that for a channel operating at lower average SNRs, where QPSK modulation is appropriate, OFDM, FD-LE and ideal FD-DFE SC systems all perform to within about 1.5–2 dB of one another. The ideal FD-DFE performs to within about 1 dB of the ideal matched filter bound for QPSK. OFDM performed slightly better than FD-LE, and slightly worse than the ideal FD-DFE. For 16-QAM and 64-QAM, there is a somewhat larger spread among the results, but with the same relative rankings. In particular, the spread between the BER performance of FD-LE and that of the other systems becomes larger for higher-level modulations.

Both OFDM and FD-LE suffer from noise

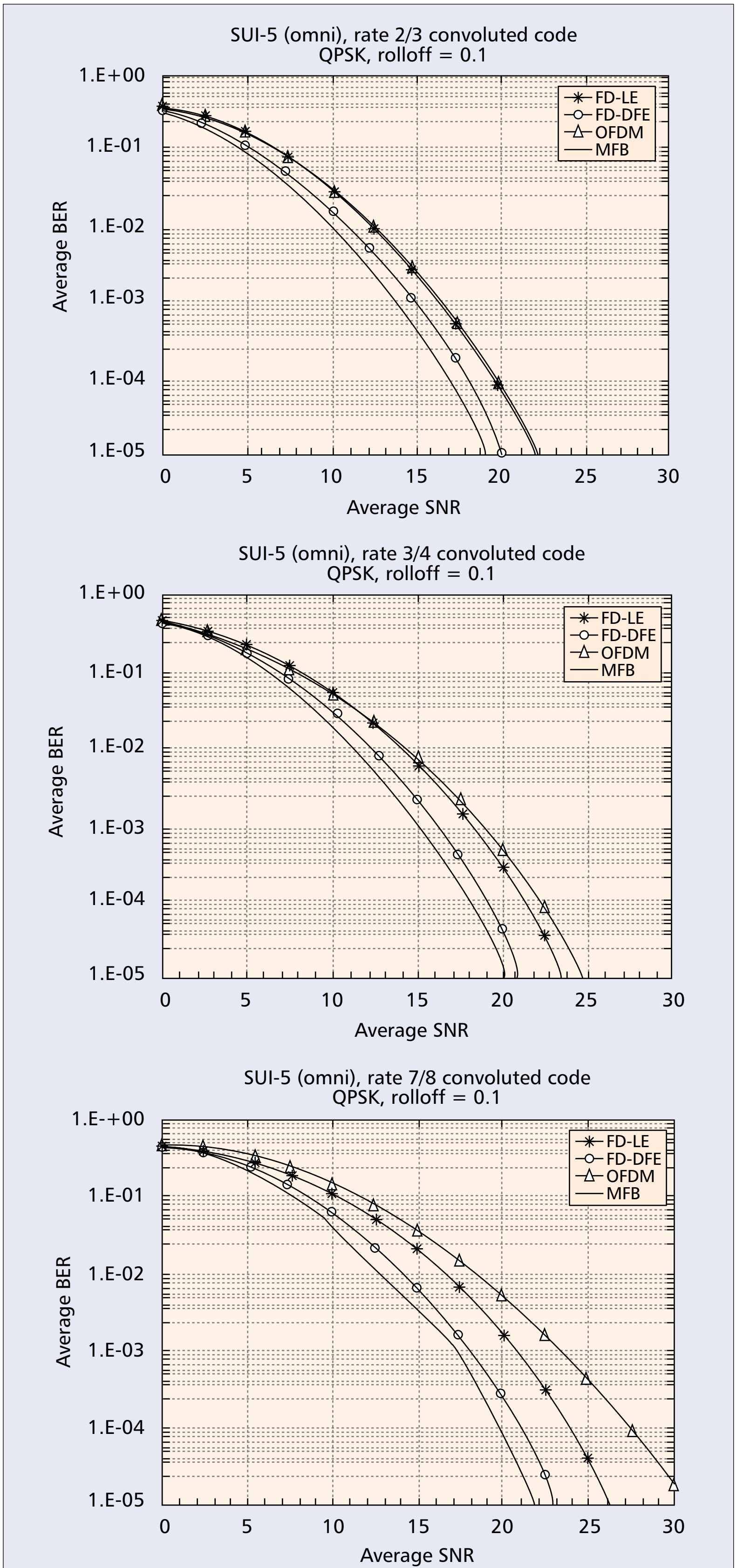


Figure 11. *a) Performance comparison for systems with perfect channel knowledge on SUI-5 channel model for QPSK with code rate 2/3; b) performance comparison for systems with perfect channel knowledge on SUI-5 channel model for QPSK with code rate 3/4; c) performance comparison for systems with perfect channel knowledge on SUI-5 channel model for QPSK with code rate 7/8.*

enhancement in severe frequency selective Rayleigh fading channels such as SUI-5, but their corresponding decoders operate and perform somewhat differently. For the FD-LE, the noise enhancement loss increases with the average input SNR. In other words, when the channel has deep nulls and the SNR is high (typically required for high-level modulation), the linear equalizer will try harder to invert the nulls; as a result, the noise in those null locations is also amplified. In contrast, OFDM can exploit the *independent* (Rayleigh-distributed) *known* (from channel estimation measurements) gain and phase of each subchannel, and combine the useful energy across all subchannels through coding and interleaving. However, the performance of OFDM in frequency selective fading is sensitive to the strength of its forward error correction (FEC) code (which is related to the code rate of the FEC code). The FEC code used by OFDM receivers must be powerful enough (i.e., have enough redundancy) that its correction capability is not overwhelmed by the random occurrence of low SNR bits sampled from subchannels lying in frequency selective null regions. In essence, the frequency selective channel and decoding method serves to puncture the code (i.e., make it weaker): the decoder optimally weights (i.e., derates) extremely low SNR code bits inputs so that they are effectively treated as "don't care" punctured bits. If too many punctures are observed in a particular interval, the effective code rate is very high in that interval, and the FEC is more likely to deliver errors there.

Figure 11a–c shows the performance over the SUI-5 channel using QPSK and higher code rates (2/3. 3/4, and 7/8). Note that for rate 3/4 and 7/8, OFDM actually performs worse than FD-LE. For an *uncoded* system (not shown), the BER performance of OFDM is far inferior to that of the linear and DFE SC systems, since without coding, the Rayleigh fading on each OFDM subchannel presents the appearance of flat Rayleigh fading to the OFDM symbol detector, even when the multipath channel taps themselves do not fade.

PERFORMANCE WITH EQUALIZER TRAINING AND FINITE DFE

Figure 12 shows the simulated performance of an SC FDE, with training, on the SUI-5 channel. 64-QAM symbols with rate 3/4 BICM are used in the data payload. $N = 2$, 4, and 8 Frank-Zadoff sequence unique word training blocks, each of length 64, are used to estimate the forward coefficients of a linear equalizer. The channel estimation procedure uses frequency domain interpolation to extrapolate from 64-training-symbol FFT blocks to the 1024-symbol FFT blocks used for FDE in this example. The performance measure used in Fig. 12 is the probability (over an ensemble of 20,000 SUI-5 channel realizations) that the BER of the rate 3/4, 64-QAM coded system is worse than10^{-6}. Call this probability (that a minimal BER is not maintained) an "outage probability."

Figure 12 also shows that the performance loss relative to perfect channel estimation is on the order of 1–2 dB or less for four training blocks In all cases, the channel is assumed unknown before the use of the training symbols to estimate the channel. What's more, only the training symbols are used to estimate the channel: no decision direction of payload symbols is used to progressively improve the accuracy of the channel estimates. Note that 8 training blocks, each of length 64 symbols, represents a total of one half the length of a single FFT block (1024 symbols) in this example. In a burst environment, one or more of these FFT blocks may compose a single burst.

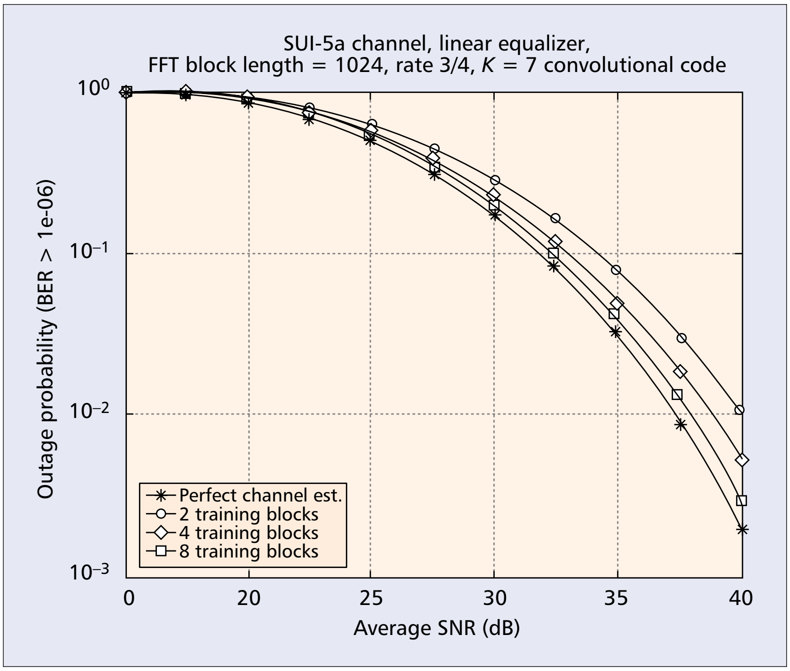
Linear FDE and DFE were also simulated for a channel with an exponential delay spread profile with an average RMS delay spread of 1 μs. Multipath performance in non-LOS suburban environments should be reasonably well bounded by such a model, since measurements reported in [2] suggest a 99 percent worst case RMS delay spread of about 0.3 μs in a non-LOS suburban environment. The time delay of the single feedback tap is set to the delay of the largest-magnitude delayed echo in the channel impulse response. If more feedback taps were to be used, their delays would be set to the second largest, third largest, and so on echo delays. In practice these delays could be estimated during the training period from the IFFT. In this simulation, the effect of decision error propagation in the DFE is not included. A separate investigation of error propagation in the 1-tap DFE revealed an average BER increase corresponding to a degradation of about 1 dB or less.

Again, 20,000 random channel realizations were simulated, each with 16 independently Rayleigh faded taps, spaced at 0.1 μs intervals. The transmitted signal was 16-QAM with a rate 3/4 BICM convolutional code. Figure 13 shows the BER > 10^{-6} outage probability for 4-block training.

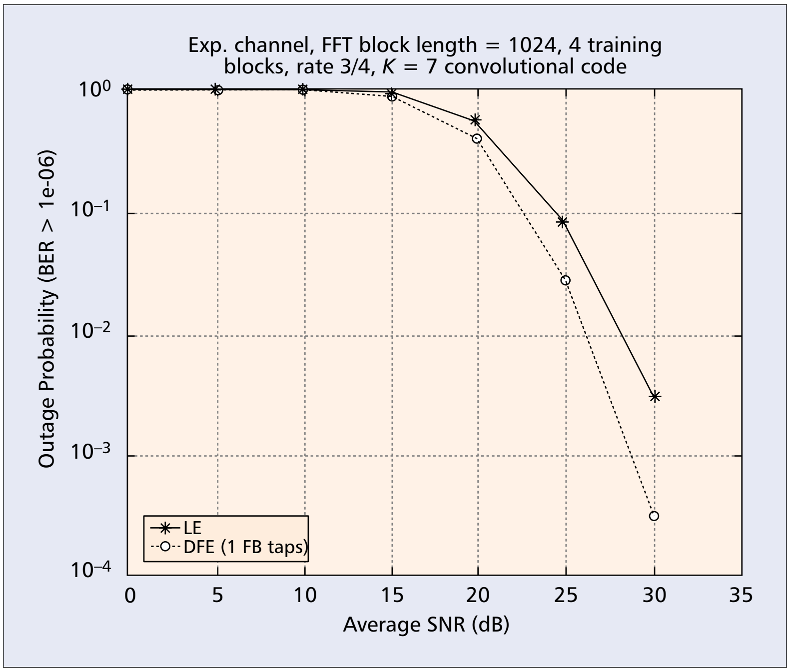
SUMMARY

Fixed wireless access systems providing high data rate access to residential and small business subscribers in non-LOS environments may be subject to severe time dispersion, spanning many bit intervals. For such environments, modulation and equalization strategies based on frequency domain processing should be considered when attempting to achieve adequate anti-multipath performance with reasonable complexity. Frequency domain processing is the basis for OFDM, and it also applies equally well to single-carrier modulation. However, OFDM is very sensitive to power amplifier nonlinearities and frequency offsets. SC modulation, coupled with linear frequency domain equalization at the receiver (SC-FDE), has less sensitivity to transmitter nonlinearities and phase noise than OFDM, and its complexity and performance are similar to those of OFDM. Furthermore, the performance of SC-FDE is enhanced when it is combined with simple sparse time-domain decision feedback equalization.

Also, as we have seen, SC and OFDM systems can potentially coexist for mutual benefit and cost reduction, because of the obvious similarities in their basic frequency domain signal processing functions.



■ **Figure 12.** *Outage probability performance for SC-FDE for SUI-5 Rayleigh fading channel. Training over 2, 4, and 8 64-symbol training blocks.*



■ **Figure 13.** *Outage probability performance for SC-FDE for an exponential delay profile Rayleigh fading channel with RMS delay spread of 1 μs. Training over 4 64-symbol training blocks.*

Lastly, single carrier techniques can easily be combined with multiple-input, multiple-output (MIMO) techniques, in which both transmitting and receiving ends use arrays of antenna elements. MIMO techniques can potentially achieve enormous spectral efficiencies (b/s/Hz), limited only by the number of diversity antenna elements that can be implemented practically [15]. This, in turn, relieves the delay-spread issues, since the desired bit rate is achieved without increasing the symbol rate.

MIMO techniques can potentially achieve enormous spectral efficiencies (bit/s/Hz), limited only by the number of diversity antenna elements that can be practically implemented.

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REFERENCES

[1] L. J. Cimini, Jr., "Analysis and Simulation of a Digital Mobile Channel Using Orthogonal Frequency Division Multipexing," *IEEE Trans. Commun.*, vol. 33, no. 7, July 1985, pp. 665–75.

[2] V. Erceg *et al.*, "A Model for the Multipath Delay Profile of Fixed Wireless Channels," *IEEE JSAC*, vol. 17, no. 3, Mar. 1999, pp. 399–410.

[3] S. U. H. Qureshi, "Adaptive Equalization," *Proc. IEEE*, vol. 73, no. 9, Sept. 1985, pp. 1349–87.

[4] J. T. E. McDonnell and T.A. Wilkinson, "Comparison of Computational Complexity of Adaptive Equalization and OFDM for Indoor Wireless Networks," *Proc. PIMRC '96*, Taipei, Taiwan, pp. 1088–90.

[5] P. Struhsaker and K. Griffin, "Analysis of PHY Waveform Peak to Mean Ratio and Impact on RF Amplification," IEEE 802.16a cont. IEEE 802.16.3c-01/46, Mar. 6, 2001.

[6] H. Sari, G. Karam, and I. Jeanclaude, "Frequency-Domain Equalization of Mobile Radio and Terrestrial Broadcast Channels," *Proc. GLOBECOM '94*, San Francisco, CA, Nov.–Dec. 1994, pp. 1–5.

[7] H. Sari, G. Karam, and I. Jeanclaude, "Transmission Techniques for Digital Terrestrial TV Broadcasting," *IEEE Commun. Mag.*, vol. 33, no. 2, Feb. 1995, pp. 100–109.

[8] S. Haykin, *Adaptive Filter Theory*, 3rd ed., Ch. 10, Prentice-Hall, 1996.

[9] M. V. Clark, "Adaptive Frequency-Domain Equalization and Diversity Combining for Broadband Wireless Communications," *IEEE JSAC*, vol. 16, no. 8, Oct. 1998, pp. 1385–95.

[10] R. L Frank and S.A. Zadoff, "Phase Shift Codes with Good Periodic Correlation Properties," *IRE Trans. Info. Theory*, Oct. 1962, pp. 381–82.

[11] D. C. Chu, "Polyphase Codes with Good Periodic Correlation Properties," *IEEE Trans. Info. Theory*, July 1972, pp. 531–32.

[12] A. Milewski, "Periodic Sequences With Optimal Properties for Channel Estimation and Fast Start-up Equalization," *IBM J. R&D*, Sept. 1983, pp. 426–31.

[13] V. Erceg *et al.*, "Channel Models for Fixed Wireless Applications," IEEE 802.16a cont. IEEE 802.16.3c-01/29r1 Feb. 23, 2001.

[14] X. Li and J. A. Ritcey, "Trellis-Coded Modulation with Bit Interleaving and Iterative Decoding," *IEEE JSAC*, vol. 17, no. 4, Apr. 1999, pp. 715–24.

[15] G. J. Foschini *et al.*, "Simplified Processing for High Spectral Efficiency Wireless Communication Employing Multi-Element Arrays," *IEEE JSAC*, vol. 17, no. 11, Nov. 1999, pp. 1841–52.

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