Narrowband Interference Rejection in OFDM via Carrier Interferometry Spreading Codes

Zhiqiang Wu⁺, *Member, IEEE*, Carl R. Nassar⁺⁺, *Senior Member, IEEE* and Xiaoyao Xie⁺⁺⁺, *Member, IEEE*

⁺Dept of ECE, West Virginia University Institute of Technology, Montgomery, WV 25136

⁺⁺Dept of ECE, Colorado State University

⁺⁺⁺Guizhou University, Guiyang, P.R. China

Abstract

OFDM (Orthogonal Frequency Division Multiplexing) has gained a great deal of attention of late and is considered a strong candidate for many next generation wireless communication systems. However, OFDM (in its current implementation) does not demonstrate robustness to narrowband interference. In our earlier work, we showed how Carrier Interferometry (CI) spreading codes may be applied to spread OFDM symbols over all N subcarriers – this allows OFDM to exploit frequency diversity and improve performance (without loss in throughput). In this paper, we show that, by spreading OFDM symbols over all N subcarriers via CI spreading codes, the resulting CI/OFDM system is also capable of suppressing narrowband interference. Simulation results over AWGN and multi-path fading channels confirm CI/OFDM's robustness in the presence of narrowband interference.

I Introduction

Orthogonal Frequency Division Multiplexing (OFDM) has a bright future – it promises to emerge as the technology of choice in many next generation wireless communication systems [1][2]. Already, OFDM has been adopted as the standard for Wireless Local Area Network (WLAN) systems (IEEE 802.11a [3], IEEE 802.11g [4], and Hyper-LAN II [5]).

In OFDM, a high-rate incoming signal is serial-to-parallel converted to N low-rate data streams, and each is sent over one of N orthogonal subcarriers [1][2]. Because each symbol stream is transmitted over one narrowband subcarrier, each symbol stream experiences a flat fade. This enables a simple OFDM receiver structure.

However, OFDM is not without its drawbacks. One important drawback in OFDM, which has not gained much attention, is its sensitivity to narrowband interference. Since each OFDM symbol is transmitted over a unique subcarrier, one or more information symbols are likely to be lost when corresponding subcarriers experience a narrowband interference. As a direct consequence, the BER performance of OFDM system degrades rapidly in the presence of narrowband interference. Coded OFDM (COFDM) (e.g., [2][3]) can be used to account for this problem; however, this solution can significantly reduce the throughput of OFDM systems.

In our earlier work of [6][7], we proposed a novel OFDM architecture capable of exploiting frequency diversity to improve BER performance (without any throughput loss). The novel OFDM system, referred to as CI/OFDM (Carrier Interferometry OFDM), spreads each of the N low-rate symbol streams across all N subcarriers using orthogonal Carrier Interferometry (CI) spreading codes. A performance

analysis of the proposed CI/OFDM system shows that, at a bit error rate (BER) of 10^{-3} , CI/OFDM gains approximately 10 dB relative to OFDM for BPSK modulation (and 5 dB gains are observed for the 64QAM constellation).

In this paper, we extend the proposed CI/OFDM architecture and demonstrate its ability to suppress narrowband interference. For example, the authors derive a novel CI/OFDM receiver employing Minimized Mean Square Error Combining (MMSEC) (for both AWGN and fading channels), where the receiver is now optimized in the presence of narrowband interference. The authors then show that CI/OFDM's spreading of each low-rate symbol stream, coupled with the optimized receiver, is able to counter the impact of narrowband interferers. That is, the CI/OFDM system developed in this work is very robust to narrowband interference. Performance analysis and simulation results performed over AWGN channels and frequency-selective fading channels confirm the anti-interference capability of CI/OFDM.

Section II introduces the CI/OFDM transmitter. Section III presents the CI/OFDM receiver structure and its MMSE combining schemes, optimized in the presence of narrowband interference. Section IV presents the emulated performance results over AWGN and frequency-selective fading channels, demonstrating the significant anti-interference capability of CI/OFDM.

II CI/OFDM Transmitter Structures

Figure 1 illustrates both the traditional OFDM transmitter (Figure 1(a)) and the novel CI/OFDM transmitter (Figure 1(b), (c)). In both OFDM and CI/OFDM, the input data stream is first serial to parallel converted. In CI/OFDM, *each* information symbol is then modulated onto *all* of the N carriers (Figure 1(c)). To ensure the separability of information symbols at the receiver side, the transmitter applies a unique orthogonal spreading code to each information symbol (where spreading is applied in the frequency domain, i.e., across carriers (Figure 1 (c))). Specifically, orthogonal Carrier Interferometry (CI) codes, first proposed for MC-CDMA systems (CI/MC-CDMA [8][9]), are applied, as they ensure the orthogonality among all transmitted information symbols. These spreading codes correspond to the application of (to the k^{th} symbol)

$$c^{(k)}(t) = \sum_{i=0}^{N-1} \beta_i^{(k)} e^{j2\pi\Delta f i t} \cdot g(t) \quad (1)$$

where (1) Δf is the carrier separation ($\Delta f = 1/T_s$ to ensure carrier orthogonality); (2) $g(t)$ is a rectangular pulse

shape of duration T_s (where T_s is OFDM symbol length); and (3) $\{\beta_i^{(k)}, i = 0, 1, \dots, N-1\}$ refers to k^{th} symbol's spreading sequence characterized by

$$\{\beta_0^{(k)}, \beta_1^{(k)}, \dots, \beta_{N-1}^{(k)}\} = \left\{ e^{j\frac{2\pi}{N} \cdot k \cdot 0}, e^{j\frac{2\pi}{N} \cdot k \cdot 1}, \dots, e^{j\frac{2\pi}{N} \cdot k \cdot (N-1)} \right\} \quad (2)$$

It is important to note that CI spreading codes defined in equation (1) and (2) are a group of orthogonal spreading codes, i.e.,

$$\text{Re} \left[\frac{\int c^{(k)}(t) c^{(l)}(t) dt}{\int c^{(k)}(t) c^{(k)}(t) dt} \right] = \text{Re} \left[\frac{1}{N} \cdot \sum_{i=0}^{N-1} e^{j(\frac{2\pi}{N} \cdot k \cdot i - \frac{2\pi}{N} \cdot l \cdot i)} \right] \\ = \delta_{k,l} = \begin{cases} 1 & k = l \\ 0 & k \neq l \end{cases} \quad (3)$$

(a) OFDM Transmitter

(b) CI/OFDM Transmitter

(c) CI/OFDM Transmitter for the k^{th} symbol

Fig. 1. (a) OFDM Transmitter, (b) CI/OFDM Transmitter, (c) Detailing the Spreading Operation in CI/OFDM

The transmitted signal for the k^{th} symbol in CI/OFDM system is thus

$$s^{(k)}(t) = \text{Re} \left[A \cdot s^{(k)} \cdot c^{(k)}(t) \cdot e^{j2\pi f_c t} \right] \quad (4)$$

$$s^{(k)}(t) = \text{Re} \left[\sum_{i=0}^{N-1} A \cdot s^{(k)} \cdot e^{j(2\pi \cdot i \cdot \Delta f t)} \cdot e^{j\frac{2\pi}{N} \cdot k \cdot i} \cdot e^{j2\pi f_c t} \cdot g(t) \right] \quad (5)$$

In equation (5), A is a constant that ensures bit energy of unity, $s^{(k)}$ is the k^{th} information symbol and f_c is the carrier frequency. For ease in presentation, we assume

BPSK modulation in this presentation, i.e., $s^{(k)} \in \{-1, +1\}$

The total transmitted signal for the entire CI/OFDM symbol (considering all N transmit symbols) corresponds to

$$S(t) = \text{Re} \left[\sum_{k=0}^{N-1} \sum_{i=0}^{N-1} A \cdot s^{(k)} \cdot e^{j(2\pi \cdot i \cdot \Delta f t)} \cdot e^{j\frac{2\pi}{N} \cdot k \cdot i} \cdot e^{j2\pi f_c t} \cdot g(t) \right] \quad (6)$$

III CI/OFDM Receiver Structure and MMSE Combining

After transmission over a frequency-selective fading channel, and assuming the presence of a narrowband interference, the received CI/OFDM signal corresponds to

$$r(t) = \sum_{k=0}^{N-1} \sum_{i=0}^{N-1} A \cdot \alpha_i \cdot s^{(k)} \cdot \cos[2\pi f_c t + 2\pi \cdot i \cdot \Delta f t + \frac{2\pi}{N} \cdot k \cdot i + \phi_i] \\ + I(t) + n(t) \quad (7)$$

where (1) α_i and ϕ_i are the fading gain and phase offset, respectively, introduced into the i^{th} carrier by the frequency selective Rayleigh fading channel, and (2) $n(t)$ is additive white Gaussian noise (AWGN). Also in equation (7), $I(t)$ represents a narrowband interference. We assume (1) $I(t)$ interferes with M ($M \ll N$) subcarriers, namely subcarriers $(m, m+1, \dots, m+M-1)$ in the CI/OFDM transmission (see Figure 2) and (2) $I(t)$ can be characterized statistically using a Gaussian random process.

Fig. 2. Narrowband Interference for CI/OFDM

The receiver structure for the k^{th} symbol in CI/OFDM is illustrated conceptually in Figure 3. Here, the received signal is decomposed into its N carrier components and recombined to minimize the interference from (a) other symbols (inter-symbol interference), (b) the narrowband jammer, and (c)

the noise. A hard decision device follows to create the symbol estimate $\hat{s}^{(k)}$. In practice, the frequency decomposition is better implemented (i.e., implemented at a reduced cost) by application of a single FFT. In what follows, we detail the receiver operation.

Fig. 3. Receiver for CI/OFDM

Referring to Figure 3, frequency decomposition leads to N decision statistics for the k^{th} symbol:

$$\vec{r}^{(k)} = (r_0^{(k)}, r_1^{(k)}, \dots, r_{N-1}^{(k)}) \quad (9)$$

where

$$r_i^{(k)} = \begin{cases} A\alpha_i s_i^{(k)} + \sum_{\substack{l=0 \\ l \neq k}}^{N-1} A\alpha_l s^{(l)} \cos\left(\frac{2\pi}{N} \cdot k \cdot i - \frac{2\pi}{N} \cdot l \cdot i\right) + I + n_i & i \in \{m, m+1, \dots, m+M-1\} \\ A\alpha_i s_i^{(k)} + \sum_{\substack{l=0 \\ l \neq k}}^{N-1} A\alpha_l s^{(l)} \cos\left(\frac{2\pi}{N} \cdot k \cdot i - \frac{2\pi}{N} \cdot l \cdot i\right) + n_i & \text{else} \end{cases} \quad (10)$$

In equation (10), whenever $i \in \{m, m+1, \dots, m+M-1\}$ (i.e., when the i^{th} carrier is degraded by the narrowband interference), the decision variable includes four terms: the first term represents the desired signal on the i^{th} carrier, the second term represents inter-symbol interference from the remaining $N-1$ symbols, the third term (a zero mean Gaussian random variable with variance σ_I^2) represents the contribution of narrowband interference, and the fourth term (a zero mean Gaussian random variable with variance $N_0/2$) represents the contribution of additive Gaussian noise.

A carefully designed cross-carrier combiner is employed next to (1) counter the impact of narrowband interference, I , and (2) counteract the presence of both the inter-symbol

interference and the noise. The general form of the combiner is

$$R^{(k)} = \sum_{i=0}^{N-1} W_i \cdot r_i^{(k)} \quad (11)$$

We propose the design of weights W_i based on Minimized Mean Square Error Combining (MMSEC) to exploit the frequency diversity available in a frequency-selective fading channel and jointly minimize (1) narrowband interference I , (2) inter-symbol interference and (3) additive noise.

It is easy to show that the i^{th} combining weight, derived via the MMSE criteria, corresponds to

$$W_i = \frac{A\alpha_i}{E[(r_i^{(k)})^2]} = \begin{cases} \frac{A\alpha_i}{NA^2 P_i \alpha_i^2 + \sigma_I^2 + \frac{N_0}{2}} & i \in \{m, m+1, \dots, m+M-1\} \\ \frac{A\alpha_i}{NA^2 P_i \alpha_i^2 + \frac{N_0}{2}} & \text{else} \end{cases} \quad (12)$$

where

$$P_i = E\left[\cos^2\left(\frac{2\pi}{N} i \cdot (k-l)\right)\right] = \begin{cases} 1 & i = 0, N/2 \\ 1/2 & \text{else} \end{cases} \quad (13)$$

It is important to note that, when the narrowband interference has very high power (e.g., 10dB higher than the signal power), i.e., $\sigma_I^2 \gg NA^2 \alpha_i^2$, the combining weights in equation (12) are very well approximated by

$$W_i = \begin{cases} 0 & i \in \{m, m+1, \dots, m+M-1\} \\ \frac{A\alpha_i}{NA^2 P_i \alpha_i^2 + \frac{N_0}{2}} & \text{else} \end{cases} \quad (14)$$

In other words, in the presence of very high power narrowband jammer, the CI/OFDM receiver simply ignores those subcarriers impacted by narrowband interference: It only combines carriers not corrupted. The combining of equation (14) is also an excellent approximation whenever (1) an estimate of the narrowband interference power σ_I^2 is not available or (2) the presence of narrowband interference leads to inaccurate estimate of fading gain (α_i 's). In the next section we demonstrate the proposed CI/OFDM system's robustness to the narrowband interference.

IV Channel Model and Simulation Results

In this section, we test the performance of the CI/OFDM system (proposed in Sections II and III) in the presence of narrowband interference. We compare these performance results with those of traditional OFDM in the presence of an identical interference. Here, simulations are performed over (1) an AWGN channel and (2) a frequency-selective Rayleigh fading channel. Both CI/OFDM and OFDM systems employ $N=32$ carriers to transmit 32 data bearing symbols.

To model realistic wireless environments, the Rayleigh fading channel employed in our simulation demonstrates frequency selectivity over the entire bandwidth, BW, but flat fading over each of the N carriers. Specifically, we assumed a channel model with coherence bandwidth, $(\Delta f)_c$, characterized by

$$(\Delta f)_c / BW = 0.25 \quad (15)$$

As a result, the α_i 's in the 32 carriers are correlated according to

$$\rho_{i,j} = \frac{1}{1 + ((f_i - f_j) / (\Delta f)_c)^2} \quad (16)$$

where $\rho_{i,j}$ denotes the correlation between the i^{th} carrier and the j^{th} carrier, and $(f_i - f_j)$ is the frequency separation between these two carriers. Generation of correlated fades, for purposes of simulation, has been discussed in [11].

Figures 4 and 5 illustrate the simulation results in an AWGN channel. Specifically, Figure 4 illustrates the bit error rate (BER) versus signal to noise ratio (SNR) results for OFDM in the presence of narrowband interference and Figure 5 plots the same axis for CI/OFDM. In both figures, four cases are considered: (1) no narrowband interference is presented; (2) the narrowband interference corrupts only 1 subcarrier; (3) the narrowband interference corrupts 2 subcarriers and (4) the narrowband interference corrupts 4 subcarriers. The narrowband interference is assumed to have much higher power than the transmit OFDM and CI/OFDM signal in the same band, i.e., subcarriers experiencing narrowband interference are completely lost and the combiner of equation (14) is employed. It is evident from these figures that (1) OFDM suffers dramatic performance degradation due to narrowband interference, as a high error floor is observed whenever narrowband interference is present; (2) CI/OFDM offers a graceful performance degradation in the presence of narrowband interference and no error floor is observed. This is the direct consequence of CI/OFDM's inherent spreading of information over the entire bandwidth. In OFDM systems, whenever one or more carriers experience a high power narrowband interference, the information on those carriers is lost, creating the high BER floor of Figure 4. In CI/OFDM systems, however, there is no

information *only* on corrupted carriers - instead, each information symbol is spread over all N carriers (by employing CI spreading codes). Thus, CI/OFDM systems tolerate narrowband interference, demonstrating the graceful degradations we observe of Figure 5.

Fig. 4. Simulation Results for OFDM with Narrowband Interference in AWGN Channel

Fig. 5. Simulation Results for CI/OFDM with Narrowband Interference in AWGN Channel

Figures 6, 7, 8 and 9 illustrate the simulation results in a frequency selective fading channel. Specifically, Figure 6 illustrates the bit error rate (BER) versus signal to noise ratio (SNR) results for OFDM in the presence of narrowband interference, Figure 7 plots the same axis for CI/OFDM, and Figure 8 compares OFDM and CI/OFDM performances. Figure 9 compares OFDM and CI/OFDM's performances versus number of corrupted carriers. From Figures 6 and 7, it is clear that (1) CI/OFDM significantly outperforms OFDM by exploiting frequency diversity (in CI/OFDM, a $BER=10^{-3}$ is observed at 15dB, whereas OFDM requires 24dB); (2) the performance of OFDM degrades dramatically whenever narrowband interference is present and (3) CI/OFDM offers a graceful performance degradation in a narrowband-interference channel. Figure 8 illustrates CI/OFDM's extremely large performance gain relative to OFDM in the presence of narrowband interference. These

results confirm CI/OFDM's capability in terms of suppressing narrowband interference.

To further illustrate the advantage of CI/OFDM over OFDM with narrowband interference, we also simulated the performance of both systems with channel coding. Rate $\frac{1}{2}$ constraint length 7 convolution code is employed for both OFDM and CI/OFDM. Figure 10 shows the performance of OFDM system with channel coding under narrowband interference, while Figure 11 illustrates CI/OFDM. It is obvious from these figures that CI/COFDM strongly outperforms OFDM system in all scenarios.

Fig. 6. Simulation Results for OFDM with Narrowband Interference in Frequency Selective Fading Channel

Fig. 7. Simulation Results for CI/OFDM with Narrowband Interference in Frequency Selective Fading Channel

Fig. 8. OFDM vs CI/OFDM with Narrowband Interference

Fig. 9. Simulation Results for CI/OFDM with Increasing Numbers of Carriers Experiencing Narrowband Interference

Fig. 10. Simulation Results for COFDM with Narrowband Interference in Frequency Selective Fading Channel

Fig. 11. Simulation Results for CI/COFDM with Narrowband Interference in Frequency Selective Fading Channel

V Conclusions

In this paper, we present CI/OFDM as a powerful technology with important application to channels experiencing narrowband interference. By spreading all information symbols over all N subcarriers with CI spreading codes, CI/OFDM not only exploits frequency diversity (improving BER performance), but also suppresses narrowband interference. Simulation results over AWGN and frequency selective fading channels confirm that CI/OFDM offers a much more graceful performance degradation whenever narrowband interference is present. This is a direct consequence of CI/OFDM's inherent spreading of information over the entire bandwidth.

REFERENCES

- [1] F. V. Nee and R. Prasad, *OFDM for Wireless Multimedia Communications*, Artech House, Boston, 2000
- [2] B. Le Floch, M. Alard, and C. Berrou, "Coded orthogonal frequency division multiplex," *Proceedings of the IEEE*, Vol. 83, no. 6, pp 982-996, June 1995.
- [3] IEEE 802.11, "Draft supplement to standard for telecommunications and information exchange between systems – LAN/MSN specific requirements – Part 11: wireless MAC and PHY specifications: High speed physical layer in the 5 GHz band," P802.11a/D6.0, May 1999.
- [4] IEEE P802.11 - TASK GROUP G - Project IEEE 802.11g Standard for Higher Rate (20+ Mbps) Extensions in the 2.4GHz Band
- [5] ETSI, "Broadband Radio Access Networks (BRAN); HIPERLAN Type 2 Technical Specification Part 1 – Physical Layer," DTS/BRAN030003-1, Oct. 1999.
- [6] D. Wiegandt, Z. Wu and C. R. Nassar, "High performance OFDM via carrier interferometry", *IEEE Transactions on Communications*, vol. 51, no. 7, pp. 1123-1134, July 2003.
- [7] D. Wiegandt and C. R. Nassar, "High-throughput, high-performance OFDM via pseudo-orthogonal carrier interferometry coding", *IEEE PIMRC 2001*
- [8] B. Natarajan, C.R. Nassar, S. Shattil, Marco Michelini, Zhiqiang Wu, "High-Performance MC-CDMA via Carrier Interferometry Codes", *IEEE Transactions on Vehicular Technology*, vol. 50, no. 6, November 2001.
- [9] C.R. Nassar, M. Michelini, B. Natarajan, and S. Shattil, "Introduction of carrier interference to spread spectrum multiple access," presented at the *1999 IEEE Emerging Technologies Symposium on Emerging Technologies in Wireless Communications and Systems*, Richardson, TX, April 12-13, 1999.
- [10] S. Hara and R. Prasad, "Overview of multi-carrier CDMA", *IEEE Communications Magazine*, vol. 35, no. 12, Dec. 1997, pp. 126-133
- [11] B. Natarajan, C.R. Nassar and V. Chandrasekhar, "Generation of Correlated Rayleigh Fading envelopes for

spread spectrum applications", *IEEE Communication Letters*, Vol. 4. No.1. Jan, 2000, pp. 9-11