Novel Multi-Carrier Implementation of FSK for Bandwidth Efficient, High Performance Wireless Systems

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***Abstract*—In traditional BFSK, two distinct carrier frequencies are used to represent binary '1' and binary '0'. In this paper, we propose transmitting multiple, orthogonal, in-phase sub-carriers around two carrier frequencies to represent the binary information. We demonstrate that this technique is spectrally efficient when compared to traditional BFSK. Performance and data rate benefits are also demonstrated in both non-coherent and novel coherent reception techniques. Moreover, while traditional BFSK is not employed in channels that are frequency selective, we show that with coherent reception, the new FSK scheme can be used in frequency selective channels to exploit frequency diversity benefits.**

I. Introduction

FREQUENCY shift keying (FSK) is a modulation technique of great practical importance. It is commonly used whenever the hardware simplicity of the receiver is of utmost importance[1]. Recently, FSK has gained popularity with its adoption in the Bluetooth standard [2]. Bluetooth technology represents a new universal radio interface that enables electronic devices to communicate via short-range connections [3].

The selection of FSK for personal area networks (such as Bluetooth) was motivated by a number of considerations. Non-coherent FSK receivers can be designed with ease and can be implemented in a cost-effective manner. Since most FSK modulation techniques result in constant envelope, information is carried by the zero crossings of the signal alone. Hence, FSK is robust in systems that have non-linearities due to, e.g., RF amplifier effects [4].

However, FSK also has significant disadvantages. Since the BFSK constellation is orthogonal rather than antipodal, it suffers from a 3 dB penalty in signal to noise ratio (SNR) for a given bit error rate (BER) relative to coherent BPSK. Additionally, the spectral efficiency of FSK can be lower than passband pulse amplitude modulation (PAM) and phase shift keying. Next, since the basic FSK signal is not a linear function of the data, existing linear equalization techniques cannot be used. Hence, compensation for channel distortion like selective fading is more difficult in FSK. This is a major drawback that hinders the widespread use of FSK in wireless systems [1].

In this paper, we propose an enhancement to binary FSK (BFSK) that provides better spectral efficiency and BER performance at high data rates. This technique also makes it easy to employ FSK in frequency selective channels. Specifically, in traditional BFSK, two distinct carrier frequencies are used to represent a binary '1' and binary '0'. In the new system, we use N orthogonal in-phase subcarriers around the two carrier frequencies. The total transmitted signal has an average frequency equal to the traditional BFSK carrier frequency, while the envelope takes on a carrier interferometry pattern. Hence, this novel FSK system is refered to as Carrier Interferometry/FSK (CI/FSK).

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In this paper, we first demonstrate that CI/FSK has spectral efficiency comparable to that of FM (frequency modulation) with a sinc($\cdot$) modulating waveform, and hence can support higher data rates in a given bandwidth relative to BFSK. We then analyze the crest factor [5] of the transmitted signal and prove that the non-constant envelope is not a concern in CI/FSK. In fact, the crest factor of the CI/FSK signal, when considering all bit transmissions, is shown to be equal to that of a single sine wave.

With respect to BER performance, the CI/FSK system with non-coherent detection is shown to provide a 2-3 dB gain (in a flat fading channel) relative to traditional BFSK. Performance benefits are available in CI/FSK even when its data rate is increased beyond that of traditional BFSK. We also introduce a novel coherent receiver that enables the use of CI/FSK in frequency selective channels. Specifically, this receiver separates the multiple subcarrier components of the CI/FSK signal and then recombines them to create the decision variable. The performance results show that CI/FSK provides a very good BER performance by exploiting the available frequency diversity.

The paper is organized as follows: Section II introduces the CI/FSK signal and the transmitter. This section also discusses the bandwidth occupancy of CI/FSK, followed by crest factor analysis. Non-coherent and coherent detection schemes are discussed in Section III. Performance results are provided in Section IV and conclusions follow in Section V.

II. CI/FSK Signaling

A. Frequency Representation

In CI/FSK, two non-overlapping frequency bands with center frequencies $f_c + f_d$ and $f_c - f_d$ are used to convey binary information, similar to BFSK. However, unlike BFSK, the CI/FSK transmitter sends N orthogonal in-phase carriers centered around $f_c + f_d$ (for bit '1') or $f_c - f_d$ (for bit '0'). This is shown in Figure 1. Two key parameters must be carefully defined: Δf, the carrier spacing, and N, the number of carriers. To maintain orthogonality between subcarriers, we select $\Delta f = \frac{1}{NT_b}$, where T_b is the bit duration; This frequency spacing creates overlap between subcarriers (not shown in Figure 1), which in turn enhances bandwidth efficiency (as discussed in subsection C). Next, the parameter N is selected as a value large enough to ensure flat fading over each carrier frequency band (much like OFDM)- in the examples of this paper, we assume $N = 15$ (which suffices for most applications).

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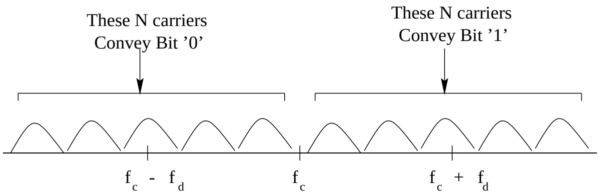

Fig. 1. The CI/FSK signal sent for bit '0' (on left) and bit'1' (on the right). Each signal is the linear combination of N carriers.

B. Time Representation

The CI/FSK signal for the k^{th} bit, $a_k \in \{-1, +1\}$, corresponds to (in the time domain)

$$s_k(t) = A \sum_{i=1}^{N} \cos\left(2\pi f_c t + a_k (2\pi(i - \frac{1}{2})\Delta f)t)\right) \quad 0 \leq t < NT_b \tag{1}$$

where A is a constant that determines symbol energy. Using simple summation rules, the CI/FSK signal can be expressed in time according to

$$s_k(t) = A \frac{\sin\left(\frac{N}{2}\Delta f t\right)}{\sin\left(\frac{1}{2}\Delta f t\right)} \cos\left(2\pi(f_c + a_k \frac{N}{2}\Delta f)t\right) \quad 0 \leq t < NT_b \tag{2}$$

As is evident from (2), the CI/FSK signal does not have a constant envelope. This signal is shown (over time duration NT_b) in the solid line of Figure 2. This CI/FSK signal can be rewritten as

$$s_k(t) = A \cdot E(t) \cos\left(2\pi(f_c + a_k f_d)t\right), \quad 0 \leq t < NT_b \tag{3}$$

where $E(t)$ represents the carrier interferometry envelope pattern and $f_d = \frac{N}{2}\Delta f$.

Next, we consider the transmission of multiple bits from the transmitter. Maintaining consistency with conventional transmission mechanisms, bit $k+1$ is sent as (referring to equation (3))

$$s_{k+1}(t) = A \cdot E(t - T_b) \cos\left(2\pi(f_c + a_{k+1} f_d)t\right). \quad 0 \leq t < NT_b \tag{4}$$

This is shown in the dotted line of Figure 2 over duration 0 to NT_b. Since

$$\int_0^{NT_b} E(t - kT_b)E(t - nT_b)dt = 0 \qquad (n \neq k), \tag{5}$$

bit transmissions maintain the required condition of zero ISI at the transmitter side, i.e., $s_k(t)$ and $s_{k+1}(t)$ are orthogonal at the transmitter side. The total transmitted signal for a block of N bits then corresponds to

$$\begin{aligned} s(t) &= \sum_{k=0}^{N-1} A \cdot E(t - kT_b) \cos\left(2\pi(f_c + a_k f_d)t\right), \\ &= A \sum_{k=0}^{N-1} \sum_{i=1}^{N} \cos\left(2\pi f_c t + a_k (2\pi(i - \frac{1}{2})\Delta f)(t - kT_b))\right), \\ & \quad 0 \leq t < NT_b. \end{aligned} \tag{6}$$

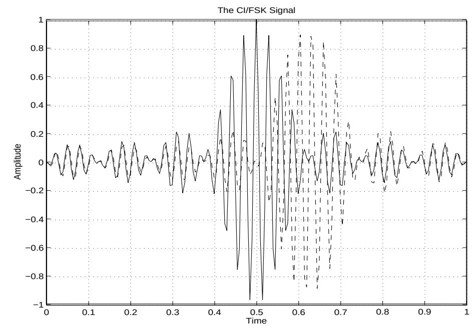

Fig. 2. Solid line is one CI/FSK signal. Dashed line is a time shifted CI/FSK signal (shifted by a multiple of the bit duration T_b)

C. Bandwidth Occupancy

FSK can be understood as frequency modulation (FM) with a carefully selected modulating waveform. The bandwidth of the modulating waveform determines the total bandwidth of transmission.

For traditional BFSK, the modulating waveform is a rectangular pulse. Assuming no overlap in the BFSK spectrum, the minimum bandwidth required to support a data rate of R_b is [6]

$$BW_{BFSK} = 2f_d + 2R_b = \frac{4}{T_b}. \tag{7}$$

In CI/FSK, we space the subcarriers using $\Delta f = \frac{1}{NT_b}$. This allows an overlap among subcarriers while still maintaining (1) subcarrier orthogonality and (2) non-overlapping spectrum for '1' or '0' transmission. The ability to overlap subcarriers enables CI/FSK to achieve greater bandwidth efficiency. Specifically, to support a data rate of R_b, the minimum bandwidth required is

$$BW_{CI/FSK} = 2N\Delta f = \frac{2}{T_b}. \tag{8}$$

In essence, CI/FSK demonstrates the spectral efficiency of FM with a sinc modulating waveform [6], and hence can support higher data rates in a given bandwidth relative to BFSK.

Specifically, in a given bandwidth, CI/FSK supports twice the data rate relative to traditional BFSK. Also, CI/FSK supports a 35% increase in data rate relative to the proposed GFSK in Bluetooth [7].

D. Crest Factor Analysis

One concern regarding the use of CI/FSK is an increased peak-to-average power ratio (PAPR) relative to traditional BFSK. This concern arises because, in the time domain $[0, NT_b]$, the CI/FSK signal envelope for bit k consists of a mainlobe with sidelobe activity (Figure 2). The correspondingly large PAPR threatens to reduce efficiency of the power amplifier, and increase signal dynamic range (requiring power amplifiers with a higher range of linearity).

To measure the signal compactness of the CI/FSK signal, we employ the crest factor (CF): for a multi-carrier signal $u(t)$ [5]

$$CF = \frac{M^+ - M^-}{2E_{eff}} \tag{9}$$

where M^+ is the largest positive and M^- is the most negative value of $u(t)$. Also, $E_{eff} = \|u\|_2$ represents the energy of $u(t)$, i.e., the rms value of $u(t)$. It is clear from (9) that a sine wave has a crest factor of $\sqrt{2}$.

Considering a block of N CI/FSK signals over $[0, NT_b]$ (see equation (6)), the transmitted signal actually consists of a sum of N envelopes. It is easily shown that the sum of all N envelopes results in a single sine wave with frequency $N\Delta f$. This is illustrated in Figure 3. Therefore, the crest factor of the total CI/FSK transmitted signal over $[0, NT_b]$ is $\sqrt{2}$, equal to that in a traditional BFSK signal. That is, even though the CI/FSK signal of Figure 2 appears to have a poor CF, the combined signal (considering the envelopes of all the bits) demonstrate the CF of a sine wave. Hence, CI/FSK does not suffer from PAPR problems that plague other multi-carrier transmission techniques.

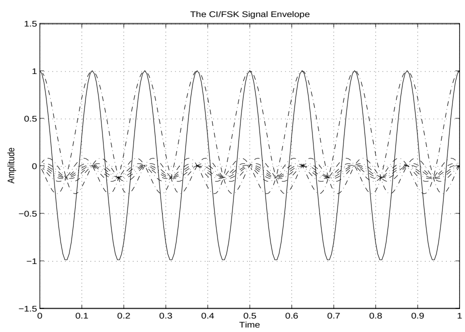

Fig. 3. Combined CI/FSK Envelope (solid line) in a transmission block

III. CI/FSK RECEIVERS

A. Non-Coherent Detection

The non-coherent receiver in CI/FSK is similar to that employed in BFSK and is shown in Figure 4. It consists of two matched filters, matched to the CI/FSK signals corresponding to a binary 1 and 0. A decision is made based on the relative output power of the matched filters. This receiver is easy to implement and is cost efficient.

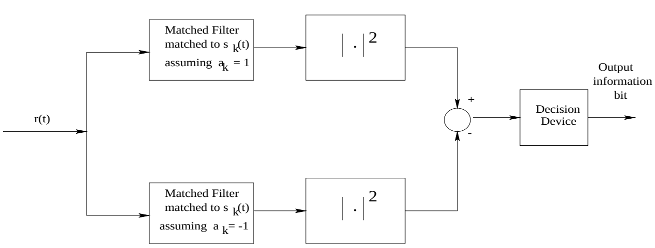

Fig. 4. Non-coherent receiver for detection of CI/FSK symbols

B. Coherent Detection

In traditional BFSK, coherent reception also involves the use of two matched filters, matched to the BFSK signals corresponding to a binary 1 and 0. Here, these filters make use of the phase information of the received signal and the decision variable is obtained by direct comparison of the matched filter output values (instead of their respective powers).

The coherent CI/FSK receiver operates in a different manner. Figure 5 shows the novel coherent receiver for CI/FSK. On the bottom branch of this receiver, the received signal is projected onto all the carriers constituting a binary 1. This is followed by a cross carrier combining. The combining weights are chosen to minimize ISI as well as noise. The outputs of the combiner from the bottom branch is then compared to that of the top branch, and a decision is made based on these values.

Assume the transmitted signal of equation (6) is sent over a frequency selective (multipath) slow fading channel. Here, frequency selectivity corresponds to selectivity over the entire transmit bandwidth, but not over each individual carrier making up the CI/FSK symbol. That is, the i^{th} carrier experiences a unique flat fade characterized by Rayleigh distributed gain α_i and phase distortion ϕ_i. (This is typical of multi-carrier signals - see, e.g., the MC-CDMA and OFDM literature [8][9]). In this case, the received signal corresponds to (assuming ideal phase tracking and removal)

$$r(t) = A \sum_{k=0}^{N-1} \sum_{i=1}^{N} \alpha_i \cos\left(2\pi f_c t + a_k (2\pi (i - \frac{1}{2}) \Delta f)(t - kT_b)\right) + n(t) \quad (10)$$

where $n(t)$ is the additive white Gaussian noise (AWGN). The fades on the N subcarriers corresponding to a binary '1' are correlated with one another, and also with the fades on the N subcarriers corresponding to a binary '0'.

We employ the coherent receiver of Figure 5 to detect the k^{th} bit from the received signal of equation (10). Considering the bottom branch in the receiver of Figure 5, the received signal is first decomposed into its subcarriers, where each subcarrier displays a delay matched to the k^{th} bit. The i^{th} subcarrier component is easily shown to correspond to

$$r_k^i(0) = \alpha_i(0) A \beta_k(0) + \alpha_i(0) A \sum_{j=0, j\neq k}^{N-1} \beta_j(0) \rho_{j,k}^i + \eta_i(0) \quad (11)$$

where $\alpha_i(0)$ represents the fade on the subcarrier with frequency $f_c - (i - \frac{1}{2})\Delta f$ (i.e., $\alpha_i(0)$ matches the α_i of equation (10) if $a_k = -1$, and $\alpha_i(0)$ represents a fade correlated with but different from the α_i of (10) if $a_k = +1$); $\eta_i(0)$ is a Gaussian random variable with mean 0 and variance σ_n^2. Additionally, $\beta_k(0)$ represents the presence of binary data on the bottom branch, i.e., $\beta_k(0) = 1$ if $a_k = -1$ and $\beta_k(0) = 0$ if $a_k = 1$. The second term represents the ISI due to other information bits in $[0, NT_b]$, and $\rho_{j,k}^i = \cos(2\pi i \Delta f(jT_b - kT_b))$ represents the cross correlation between the k^{th} bit and j^{th} bit in the i^{th} carrier.

The r_k^i terms are combined across carriers to create the decision variable $D_k(0)$,

$$D_k(0) = \sum_{i=1}^{N} r_k^i(0) \cdot y_0^i. \quad (12)$$

A similar set of operations performed along the top branch lead to decision variable $D_k(1)$ given by

$$D_k(1) = \sum_{i=1}^{N} r_k^i(1) \cdot y_1^i. \quad (13)$$

The weights y_0^i and y_1^i are determined based on minimum mean squared error criterion. Wiener filter theory analysis yields the following weights:

$$
\begin{aligned}
y_0^i &= \frac{\alpha_i^0}{((\alpha_i^0)^2\sigma_\beta^2\sum_{j=0}^{N-1}(\rho_{j,k}^i)^2+\sigma_n^2)} \\
y_1^i &= \frac{\alpha_i^1}{((\alpha_i^1)^2\sigma_\beta^2\sum_{j=0}^{N-1}(\rho_{j,k}^i)^2+\sigma_n^2)}
\end{aligned} \tag{14}
$$

where $\sigma_\beta^2 = A/4$ represents the variance of the Bernoulli distributed β_k's.

This novel coherent receiver offers key benefits relative to traditional BFSK. In traditional BFSK, equalization in a frequency selective channel is a complex procedure because the FSK signal is not a linear function of the data. However, in CI/FSK, the frequency selectivity in the entire bandwidth is actually resolved by the narrow band subcarriers. This enables the coherent CI/FSK receiver to operate over frequency selective channels, and exploit a frequency diversity benefit (in much the same way as MC-CDMA receivers benefit from frequency diversity gains [10]). This receiver makes CI/FSK better suited to wireless multipath channels (relative to BFSK).

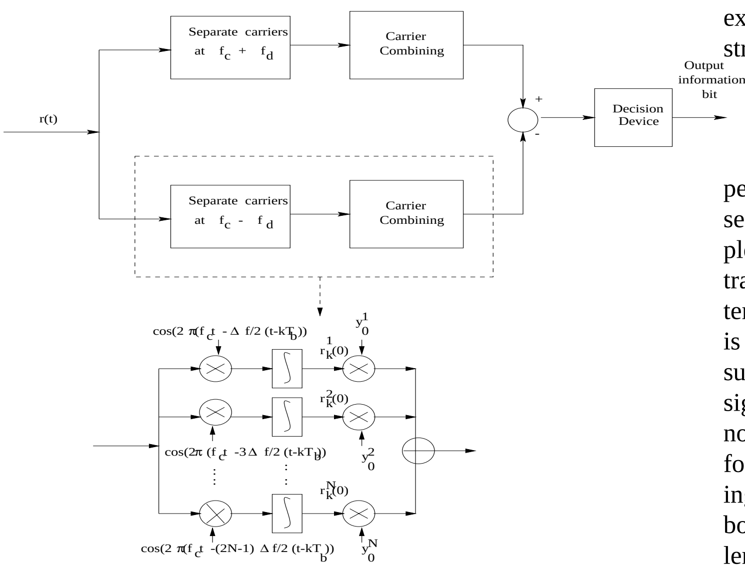

Fig. 5. Coherent Receiver in CI/FSK

IV. Performance Results

Performance results are characterized using BER (bit-error-rate) vs. SNR (signal to noise ratio) curves. The channel model is obtained from the standard UMTS indoor channel models [11]. This model specifies an indoor channel, Channel A, with rms delay spread of 35 ns.

Here, we assume CI/FSK operates with $N = 15$ orthogonal symbols in $[0, 15T_b]$. Figure 6 shows the performance of non-coherent CI/FSK, non-coherent BFSK, and non-coherent GFSK(BT=0.3) in indoor Channel A. In all cases, we hold the bandwidth per binary '0' or binary '1' fixed at 700 kHz (for a total bandwidth of 1.4 MHz). The BFSK system can only transmit 350 kbps in this frequency band (assuming no frequency overlap between the bit 0 and bit 1 frequency bands); BFSK can also support higher data rates by allowing for overlap between bit '0' and bit '1' frequency bands. Figure 6 shows performance curves for BFSK when both 350 kbps are sent, and when 525 kbps are transmitted. We also plot the performance of the more efficient GFSK, which can support 518 kbps in a 700 kHz per binary digit bandwidth. The performance curves verify that gains in throughput due to spectral efficiency of CI/FSK are available without cost in performance relative to BFSK and GFSK. When the BFSK scheme attempts to improve throughput via spectral overlap, its performance is seen to degrade relative to CI/FSK.

Next, Figure 7 represents the BER curves for CI/FSK in frequency selective channels assuming the coherent reception of Figure 5. Specifically, Figure 7 plots CI/FSK performance, demonstrating the improvement in performance with increasing diversity (the degree of diversity, L, is defined as the ratio between the transmission bandwidth per bit ($N\Delta f$) and coherence bandwidth of the channel $(\Delta f)_c$). This curve shows that CI/FSK exploits diversity gains and drives performance away from the poor flat fading results (and toward the excellent AWGN performances). While traditional BFSK is not well suited for use in a frequency selective channel, CI/FSK offers excellent BER performance with a simple receiver, making it a strong candidate for next generation mobile wireless systems.

V. Conclusions

In this paper, we first highlighted the importance of FSK in personal area networks (PANs) such as Bluetooth. We then presented an innovation in FSK in the form of a multi-carrier implementation. Specifically, the new CI/FSK scheme involves transmission of multiple orthogonal carriers around two center frequencies to represent binary information. This scheme is spectrally efficient relative to traditional FSK, enabling it to support increased throughputs. It is also shown that the CI/FSK signal maintains excellent peak to average power ratio. The novel coherent receiver designed for CI/FSK makes it suitable for use in frequency selective channels, with the system benefiting from the available frequency diversity.In short, CI/FSK with both non-coherent and coherent detection demonstrates excellent BER performance at high data rates in frequency selective channels; it demonstrates high spectral efficiency, and it offers a simple means to significantly improve on the existing PAN (Bluetooth) architectures.

VI. References

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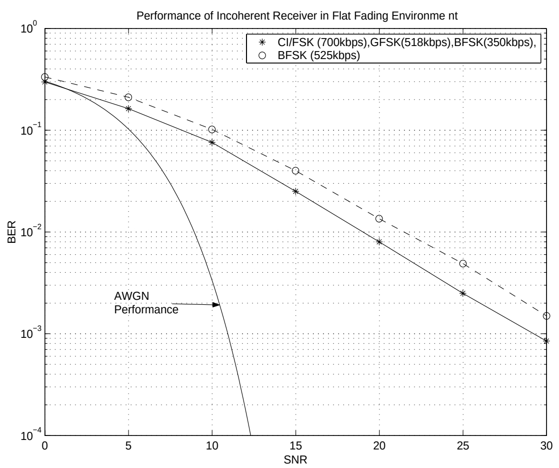

Fig. 6. CI/FSK Performance - Non-Coherent detection

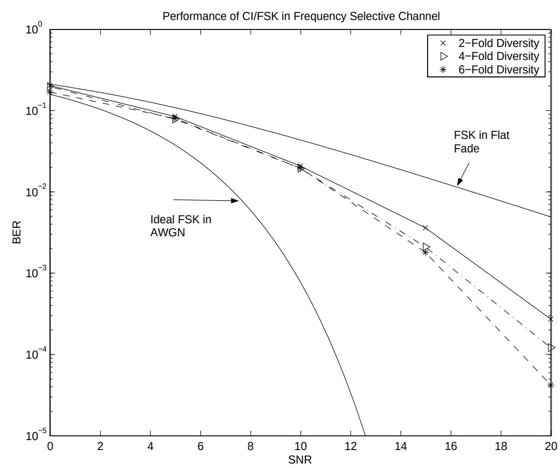

Fig. 7. CI/FSK Performance in frequency selective channels - Coherent detection