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OFDM for Data Communication Over Mobile Radio FM Channels—Part I: Analysis and Experimental Results

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***Abstract*—This paper describes the performance of OFDM/FM modulation for digital communication over Rayleigh-fading mobile radio channels. The use of orthogonal frequency division multiplexing (OFDM) over mobile radio channels was proposed by Cimini [1]. OFDM transmits blocks of bits in parallel and reduces the bit error rate (BER) by averaging the effects of fading over the bits in the block. OFDM/FM is a modulation technique in which the OFDM baseband signal is used to modulate an FM transmitter. OFDM/FM can be implemented simply and inexpensively by retrofitting existing FM communication systems.**

Expressions are derived for the BER and word error rate (WER) within a block when each subchannel is QAM-modulated. Several numerical methods are developed to evaluate the overall BER and WER. An experimental OFDM/FM system was implemented and tested using unmodified VHF FM radio equipment and a fading channel simulator. The BER and WER results obtained from the hardware measurements agree closely with the numerical results.

I. INTRODUCTION

THE demand for data communication over mobile radio channels has increased steadily over the last few years and will likely continue to grow [2], [3]. A common application is found in mobile data terminals (MDT's) used for emergency, law and order, public utility, and a host of commercial services such as courier, dispatch, and inventory control. MDT's allow remote mobile users direct access to computerized databases, resulting in greater productivity. Another benefit is the more efficient use of the allocated (and increasingly scarce) radio spectrum. Features such as the transmission of graphical information or the use of encryption for secure communication can also be readily implemented.

The design of a VHF/UHF mobile radio data communication system presents a challenging problem [4]. In most areas *multipath propagation* causes a moving receiver to experience severe and rapid fluctuations of received signal strength. In a commonly used and proven model [4], [5], it is assumed that there is no line-of-sight path from the transmitter to the receiver; rather, the received signal is made up of a large number of component waves scattered by buildings and other objects near the mobile. Under certain conditions, it can be shown that over short distances the amplitude of the received signal can be well approximated by a Rayleigh distribution. During a deep fade the received signal strength may be reduced to an unacceptably low level. If a conventional serial modulation scheme is used, the bits "hit" by such a fade will be lost.

Recently, Cimini [1] proposed the use of an orthogonal frequency division multiplexing (OFDM) scheme in which the bits in a block (packet) are transmitted in parallel, each at a low baud rate. The intent of the scheme is to spread out the effect of the fade over many bits. Rather than have a few adjacent bits completely destroyed by a fade, the hope is that all the bits will only be slightly affected. Another technique [6] uses a chirp filter to spread individual signaling pulses over time.

The OFDM signal is generated using digital signal processing (DSP) techniques at baseband and this signal must then modulate an RF carrier. In Cimini's [1] proposal the signal is translated directly to the RF frequency, resulting in a system that we call OFDM/SSB. Frequency modulation (FM) can also be used, resulting in our proposed OFDM/FM system. An OFDM/FM system has the advantage that it can use existing unmodified FM radio equipment and can therefore be implemented more quickly and at lower cost than an OFDM/SSB system which requires precise and relatively complex coherent reception.

The following section briefly describes the Rayleigh fading channel and OFDM/FM. A simple model for the OFDM channel is introduced and used to derive the bit and word error rates for OFDM/FM in Section III. Section IV describes several numerical methods that can be used to evaluate the performance of OFDM/FM while Section V describes experimental measurements on an OFDM/FM system and compares the experimental and numerical results.

II. PRELIMINARIES

A. VHF/UHF Mobile Radio Channel

The channel model used in this paper is a nonfrequency-selective (flat) Rayleigh fading model in which additive white Gaussian noise is the major noise source. Field measurements [7]–[12] have shown that the flat fading assumption is reasonable for narrow-band (under 20 kHz bandwidth) signals.

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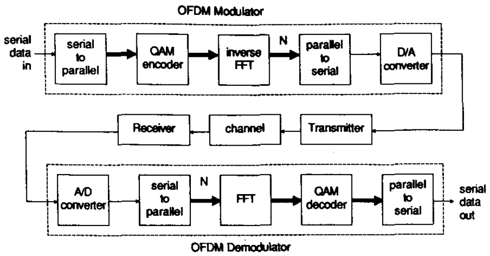

Fig. 1. An implementation of an OFDM system.

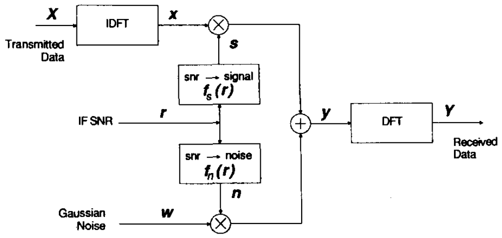

Fig. 2. The equivalent baseband channel model.

B. Orthogonal Frequency Division Multiplexing

Description: OFDM uses frequency division multiplexing with subcarrier frequencies spaced at the symbol (baud) rate. That is, if the block duration is T, the subcarrier frequencies are at $1/T, 2/T, 3/T, \cdots$. This frequency spacing makes the subcarriers orthogonal over one symbol interval [13]–[17]. Modulation is done by using several bits (typically two to five) to set the amplitude and phase of each subcarrier. An OFDM modulator can be efficiently implemented by using an inverse discrete Fourier transform (DFT) to convert the complex phase/amplitude data for each subcarrier into a sampled OFDM signal. Similarly, demodulation can be performed with a DFT which extracts the phase and amplitude of each subcarrier from the sampled OFDM signal.

Because OFDM can be used to efficiently multiplex many bits into one block (symbol), the baud (symbol) rate can be greatly reduced compared to conventional serial modulation methods. The symbol rate is typically reduced by hundreds or thousands of times.

Previously, OFDM modems have been used for data transmission over telephone channels [17]–[21]. OFDM-like multicarrier modems have also been used on HF (3 to 30 MHz) radio channels [22]–[26].

The DFT extracts the phase and amplitude information for $N/2$ (complex) subchannels from the N (real) samples in the block. Some subchannels may not be usable because the signal-to-noise ratio (SNR) at that frequency may be too low. If the fraction of subchannels that are usable is ρ and M bits can be transmitted on each subchannel, then the number of bits per block is $N_b = \rho MN/2$. The block duration is $T = N/f_s$ where f_s is the sampling rate. The bit rate is therefore $R = N_b/T = f_s\rho M/2$.

Implementation: Fig. 1 shows a block diagram of an OFDM implementation. The modulator collects a block of bits from the data source, encodes them into complex (QAM) data values, and converts the data to signal samples using an inverse FFT. The digital-to-analog (D/A) converter produces the analog baseband OFDM signal.

This baseband signal modulates an RF transmitter. The modulated signal is transmitted over the fading channel. A receiver recovers the baseband signal from the received RF signal which may have been corrupted by fading and additive noise.

The demodulator collects a block of samples from the analog-to-digital (A/D) converter, converts the samples to complex data values using an FFT, and decodes the complex data values back into bits.

III. OFDM Bit Error Rate Analysis

In this section, a simple and general model for the mobile radio channel, the *equivalent baseband channel* (EBC) model, is described and then used to obtain an expression for the bit error rate (BER) of OFDM. The assumption that errors occur independently is used to determine the word error rate (WER). The final subsection describes how the EBC model can be applied to the OFDM/FM channel.

A. The Equivalent Baseband Channel Model

The model used to predict the performance of OFDM over mobile radio channels must include all significant effects and yet be kept simple enough for analysis and efficient numerical work. Towards this end, the EBC model converts the effects of fading at IF (or RF) into equivalent effects at baseband. Two effects are considered: time-varying channel gain (fading), and additive noise.

Fig. 2 is a diagram of the EBC model. The received samples, $y = \{y_0, y_1, \cdots, y_{N-1}\}$, are the sum of the received data and noise samples. The received data samples are the transmitted data samples x scaled by the channel gain vector s. The received noise samples are zero-mean Gaussian random variables scaled by the channel noise gain vector n.

Both s and n are functions of r, the IF signal-to-noise ratio (SNR) vector. We assume that the IF noise level is fixed so that r is proportional to the IF signal level. The functions $s = f_s(r)$ and $n = f_n(r)$, define what we call the SN curves of the receiver. The SN curves can be obtained either from analysis of ideal receiver performance [4] or from measurements (Section V).

The model assumes that the receiver SN curves are memoryless. This allows the average signal and noise powers to be obtained by averaging the instantaneous signal and noise powers. Such a quasi-static approximation is valid when the Doppler rate is less than the baseband bandwidth [27], [28], as is the case with land mobile radio applications.

B. BER Analysis

An expression for the BER of a given OFDM block transmitted over the equivalent baseband channel is derived in this section. The notation a indicates a vector $\{a_0, a_1, \cdots, a_{N-1}\}$ and $\langle a \rangle$ denotes the time average of the variable a over N

samples, i.e., $\langle a\rangle = 1/N(a_0 + a_1 + \cdots + a_{N-1})$. The word *sample* is used for quantities in the time domain, while the term *value* is used for quantities in the frequency domain.

Mean and Variance of the Received Value: In Appendix A, the ensemble average of the m-th received data value Y_m over the set of all possible transmitted data vectors with the m-th data value fixed at $X_m = D(D = \pm 1 \pm j)$ and over all possible noise vectors w is found conditioned on a given fixed signal level vector r (and the corresponding s and n) as

$$E[Y_m|X_m = D, X_{-m} = D^*, r] \approx D\langle s\rangle. \tag{1}$$

The conditional variance (given the same conditions as for the mean) of a received data value Y_m, is found to be

$$\operatorname{var}(Y_m|X_m = D, X_{-m} = D^*, r) \approx 2\Big(\langle s^2\rangle - \langle s\rangle^2 + \langle n^2\rangle\Big). \tag{2}$$

Bit Error Rate Within a Block: Since the interference (between subchannels) on each subchannel is caused by a large number of independent subchannels, the central limit theorem indicates that the distribution of this interference should be approximately Gaussian. This is confirmed by measurements of the interference distribution in the experimental OFDM/FM system described in Section V. Since the effect of the channel noise is also Gaussian (because of the linearity of the DFT) and independent of the interchannel interference (because r is fixed), the sum of the noise and interference will also be Gaussian and their powers will add.

Using signal-space arguments [29] it is then possible to obtain the BER within a block for the QAM encoding described in Section IV-C as

$$\begin{aligned} \mathrm{BER}_{\mathrm{block}}(\alpha,\beta,\gamma) &= \frac{1}{2}\operatorname{erfc}\left(\frac{\alpha}{\sqrt{2(\beta-\alpha^2+\gamma)}}\right)\\ &= Q\left(\frac{\alpha}{\sqrt{(\beta-\alpha^2+\gamma)}}\right) \end{aligned} \tag{3}$$

where $\alpha = \langle s\rangle$, $\beta = \langle s^2\rangle$, and $\gamma = \langle n^2\rangle$.

Evaluating the Overall BER: The overall BER can be obtained by using the joint distribution of α, β, and γ, i.e.,

$$\mathrm{BER} = \int_0^\infty \int_0^\infty \int_0^\infty \mathrm{BER}_{\mathrm{block}}(\alpha,\beta,\gamma)p(\alpha,\beta,\gamma)\,d\gamma\,d\beta\,d\alpha. \tag{4}$$

To obtain estimates of the overall BER, the joint distribution of α, β, and γ is required. Unfortunately, no closed-form expression is available for this joint distribution, $p(\alpha,\beta,\gamma)$. In Section IV, a Monte–Carlo numerical integration procedure is described that can be used to evaluate this expression.

C. WER Analysis

In many data communication systems, any error within a related group of bits (a *word*) invalidates all of the bits. In such systems the performance measure of interest is the word error rate (WER). The assumption of random bit errors would simplify the prediction of the error rate of words contained within an OFDM block. Experimental results (see Section V) showed that the independent error assumption is a good approximation for the system that was studied.

In order to predict the WER it will be assumed that the bit errors are independent. Such an assumption would *not* be valid for a conventional serial modulation scheme on a fading channel. With this assumption, the block WER can be expressed easily in terms of the block BER, namely,

$$\mathrm{WER}_{\mathrm{block}} = 1 - (1 - \mathrm{BER}_{\mathrm{block}})^{N_w} \tag{5}$$

where N_w is the number of bits per word.

D. Modeling the OFDM/FM Channel

Baseband Noise Distribution: Although the probability distribution of the FM discriminator output noise depends on the SNR [30], the noise values after the DFT demodulator can be assumed to be Gaussian because the DFT sum makes any noise distribution approximately Gaussian.

Baseband Noise Spectrum: The spectrum of the discriminator noise output also depends on the IF SNR. The distribution of the noise power among the subchannels thus depends on the IF SNR. The distribution of the noise among the different subchannels will vary from block to block because fading causes the IF SNR to vary. To simplify the analysis, however, it was assumed that the blocks were sufficiently long so that the distribution of noise power among the subchannels was almost the same for all blocks. It was also assumed that differences in subchannel SNR's due to the uneven spectral distribution of the noise were corrected by changing the allocation of power among the subchannels in the transmitted baseband signal. The noise spectrum was therefore assumed to be independent of the IF SNR. The validity of this assumption was later verified experimentally.

Experimental measurements of the noise powers in the different subchannels in the presence of fading showed that subchannels at lower frequencies had more noise. This caused subchannels at lower frequencies to have higher error rates. Measurements of the error rates in the different subchannels showed that the error rates could be made approximately equal by using a -10 dB per decade preemphasis at the transmitter in addition to the built-in $+20$ dB per decade standard pre-emphasis.

Random FM Noise: The spectrum of the "random FM" noise at the discriminator output is independent of the SNR and decreases as $(1/f)$ for frequencies above the Doppler rate [27]. The effect of random FM at a given Doppler rate can be included in the model by modifying the 'N' portion of the SN curves. However, this was not necessary since the level of the random FM noise was not significant at any of the Doppler rates measured as shown by the measurements described in Section V-F.

Clipping Noise: Clipping in the FM transmitter was modeled as an additional source of additive white Gaussian noise. Although the clipping is not independent of the signal level, it should normally form a relatively small portion of the total

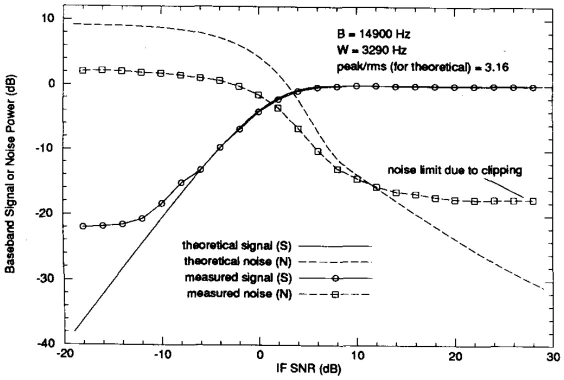

Fig. 3. Theoretical and measured SN curves.

noise power. For example, in the experimental measurements the modulating signal level was set so that clipping distortion had no measurable effect on the BER.

Squelch: Squelch can be incorporated into the SN curves by setting the values of s and n to zero when the IF SNR level falls below the squelch threshold. This assumes an ideal squelch circuit that has no hysteresis or delay.

FM Receiver SN Curves: Fig. 3 shows typical measured and theoretical FM receiver SN curves. This example shows the nonlinear SN curves of an FM discriminator. The measured curves show the effect of baseband SNR limiting due to clipping. The maximum baseband SNR ("limiting baseband SNR") is about 18 dB. A similar effect would be produced by random FM.

IV. EVALUATION OF ERROR RATES

This section describes three methods to evaluate the BER and WER performance of OFDM. These are 1) a computation for very short or very long block lengths, 2) a Monte–Carlo integration, and 3) a baseband signal processing simulation. The results obtained using these methods will be compared to experimental results in Section V.

A. BER for Very Short and Very Long Blocks

When the block duration is very short relative to the average fade duration, the received signal level will be constant during the block. Thus, $\langle s \rangle = s$, $\langle s^2 \rangle = s^2$, and $\langle n^2 \rangle = n^2$. The bit error rate for each block, $\mathrm{BER}_{\mathrm{block}}$, as a function of the IF SNR can be averaged over the Rayleigh signal level distribution to obtain the average overall BER. That is,

$$\mathrm{BER}_{\text{short block}} = \int_0^\infty \mathrm{BER}_{\mathrm{block}}\big(s(r), s^2(r), n^2(r)\big)p(r)\,dr. \tag{6}$$

Note that since the signal level is constant over the block $\langle s \rangle^2 = \langle s^2 \rangle$ and (3) simplifies to

$$\mathrm{BER}_{\mathrm{block}}(\alpha, \beta, \gamma) = Q\left(\frac{\alpha}{\sqrt{\gamma}}\right) = Q\left(\frac{s(r)}{n(r)}\right). \tag{7}$$

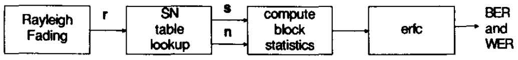

Fig. 4. The numerical integration method.

When the block is very long, each block will have the same statistics and therefore each block will have the same BER. The overall BER will be the block BER for the average block statistics. That is, if

$$\overline{\alpha} = \int_0^\infty s(r)p(r)\,dr, \qquad \overline{\beta} = \int_0^\infty s^2(r)p(r)\,dr,$$
$$\text{and } \overline{\gamma} = \int_0^\infty n^2(r)p(r)\,dr, \tag{8}$$

then

$$\mathrm{BER}_{\text{long block}} = \mathrm{BER}_{\mathrm{block}}\big(\overline{\alpha}, \overline{\beta}, \overline{\gamma}\big). \tag{9}$$

B. Monte–Carlo Integration

The second method uses a Monte–Carlo numerical integration technique to evaluate the BER given by (4). The method involves generating random fading waveforms and then using their α, β, and γ statistics to compute the expected overall BER.

Fig. 4 shows the steps in this procedure. A Monte–Carlo procedure is used in which signal level vectors r are chosen at random from a waveform which is Rayleigh distributed with the appropriate Doppler rate. From each r the values of α, β, and γ and the resulting $\mathrm{BER}_{\mathrm{block}}$ are calculated. The arithmetic mean of these $\mathrm{BER}_{\mathrm{block}}$ values gives the overall BER.

This method can be used to evaluate the BER for any channel that can be accurately described by the EBC model. It is faster than the more detailed simulation described in the following section because it does not involve generating random data or noise or computing DFT's.

C. Software Simulation of the Equivalent Baseband Channel

The OFDM system can be studied in more detail by generating a sampled baseband OFDM waveform and passing it through an equivalent baseband channel. This method involves performing most of the baseband signal processing for an OFDM system. It allows testing of signal processing procedures that cannot be included in the EBC model or whose effect is too complex to analyze. However, this approach is considerably slower[1] than the Monte–Carlo integration method.

Fig. 5 shows the steps involved in the baseband simulation. A block of bits from a pseudo-random bit sequence (PRBS) generator is QAM-encoded into a block of complex values. The inverse FFT generates the baseband OFDM signal by converting each block of $N/2$ complex values into N samples. The Rayleigh-fading generator produces the signal envelope. The SN lookup table and the channel simulator implement the

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[1] A typical simulation (about 3 million samples for each of four SNR's and three block sizes) required about 8.5 h CPU time on a Sun 3/50 compared to about 1.5 h for the numerical integration procedure.

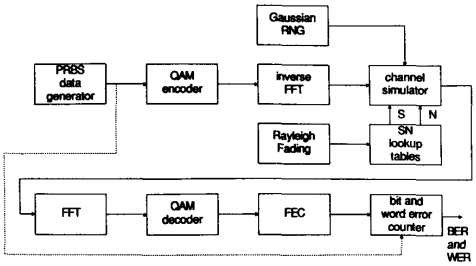

Fig. 5. Simulation using the equivalent baseband channel.

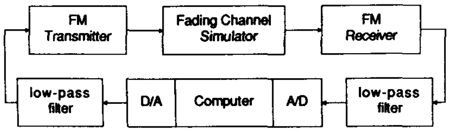

Fig. 6. Block diagram of experimental setup.

equivalent baseband channel (shown in Fig. 2) and combine the baseband signal and Gaussian noise. The FFT demodulates the OFDM signal and the QAM decoder recovers the binary data. The final step in the simulation is to compare the transmitted and received bit sequences and to compute the BER and WER.

The QAM data encoding is done by using two bits per subchannel: one bit for the imaginary (quadrature) component and one bit for the real (in-phase) component. A 0 b is converted to a value of −1, and a 1 b to a +1. Unused subchannels are set to zero. The decoding is done by comparing the received values to a threshold of zero.

A more detailed simulation that includes the IF stages of the receiver could be used to study other effects but would require significantly more computation.

V. EXPERIMENT

This section describes a laboratory experiment used to demonstrate the feasibility of OFDM/FM using unmodified commercial VHF FM radio equipment. The performance of this experimental system is compared to results obtained using the methods of Section IV.

A. Experimental Hardware

Fig. 6 shows a block diagram of the experimental setup. The various components used are described below. The transmitter and receiver were placed in cast aluminum boxes and their power supply leads were passed through EMI filters to provide RF shielding. An 11 dB 50 ohm attenuator was mounted inside the transmitter shielding box to reduce the RF output level to 12.5 dBm.

Transmitter: The transmitter was an Icom model IC-2AT narrow-band FM transceiver designed for operation in the 144 to 148 MHz amateur band. Its specifications are similar to those of commercial land mobile radio equipment [31]. The audio processing circuitry contains a +20 dB per decade preemphasis network, a limiter (peak clipping) circuit and a low-pass filter. The frequency deviation was measured to be 5 kHz.

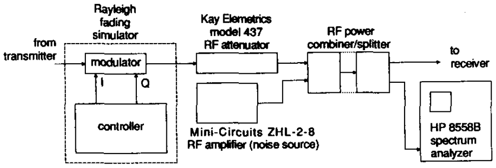

Fig. 7. Fading channel simulator.

Channel Simulator: Fig. 7 shows the channel simulator. The simulator consists of a Rayleigh-fading simulator [32], an RF attenuator, a noise source, and a combiner/splitter.

The signal and noise levels were measured at RF. To ensure that the IF SNR and the RF SNR were equal, the receiver's internal noise was masked by adding noise to the RF signal. The level of noise added ensured that the noise added by the receiver had a small (<0.5 dB) effect on the IF SNR.

Receiver: The FM receiver was another Icom model IC-2AT transceiver. The receiver IF filter bandwidth specification is ±7.5 kHz at −6 dB and ±15 kHz at −60 dB. The receiver uses a Motorola MC3357 "Low Power Narrow-Band FM IF" IC for most of the IF and AF signal processing functions. The FM detector is a quadrature-type discriminator [33], [34]. The squelch level was set to minimum so that the receiver audio output was always on.

Computer: An IBM PC/AT-compatible computer was used for all of the digital signal processing tasks as well as test data generation and BER and WER measurement. All of the signal processing computations were done using IEEE-standard 32 b floating point numbers.

A/D and D/A Board: The analog interface circuit was designed and built for this project. It contains a 10 b A/D converter, a 12 b D/A converter, a sample-and-hold amplifier, buffer amplifiers, and a timing circuit.

Reconstruction and Antialiasing Filters: A Krohn–Hite model 3342 filter was used to reconstruct the analog waveform from the D/A output samples. The reconstruction filter used one eighth-order Butterworth low-pass section with a −3 dB frequency of 4 kHz and a one eighth-order Butterworth high-pass section with a −3 dB frequency of 100 Hz. The high-pass section was used to provide AC coupling to the transmitter.

A second Krohn–Hite model 3342 filter was used to low-pass filter the receiver AF output signal to avoid aliasing. This anti-aliasing filter used two cascaded eighth-order Butterworth low-pass sections with −3 dB frequencies of 4 kHz.

Audio Attenuator: An audio attenuator was used to reduce the D/A output (approximately 140 mV rms) to a level suitable for modulating the transmitter (approximately 6 mV rms). The attenuator circuit included a low-pass filter to reduce RF leakage and a switch to turn the transmitter on and off.

B. Experimental Software

The simulation program used in Section IV was modified to make BER and WER measurements over the experimental channel. Instead of using a subroutine that simulates the

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