Channel Loading Effects on Power Limited Wireless Transmitters Utilizing Discrete Multitone Modulation

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Abstract—A method is presented for optimizing the throughput of a radio channel limited by intermodulation distortion induced in transmission of discrete multitone (*DMT)* signals. The DMT concept is presented, and the carrier-to-interference ratios as a function of the amount of channel loading are computed for different power levels. These values, obtained using 2 different methods - the NPR approach and the MMSE Gain method - are shown to be in good agreement. The degradation in C/I for a fully loaded channel with respect to the two-tone case is also computed.

I. Introduction.

As the value of radio spectrum continues to escalate, designers face more and more pressure to increase the data throughput of existing channels. Channel imperfections, such as noise, multipath fading, and Doppler shifts limit the effectiveness of such high efficiency modulation formats such *as quadrature amplitude modulation* (QAM). Various attempts have been made to alleviate these effects by more advanced techniques. *Direct sequence spread spectrum* has been employed as a means to avoid narrowband fades [1]. As shown in Figure 1, spreading the available energy per bit across a wide bandwidth insures a relatively high average *carrier-to-noise ratio* (*C/N*) due to the low probability of a fade affecting the entire band. The downside of this technique is that energy is wasted in the sections of the band that are faded below the detection threshold. *Discrete multitone modulation* (DMT) has been proposed as a method to improve the efficiency of the energy distribution within a faded channel [2,3]. The concept of DMT is also illustrated in Figure 1. The channel is divided into *N* subchannels, with an average *C/*N given by:

$$\overline{C/N} = \Gamma\left\{\left[\prod_{i=1}^{N}\left(1+\frac{(C/N)_i}{\Gamma}\right)\right]^{1/N} - 1\right\} \quad (1)$$

This reduces to the geometric mean of the subchannel carrier-to-noise ratios when C/N >> Γ. The gap Γ represents how far our system is from achieving capacity as defined by Shannon's limit [2]. Assuming a subchannel is assigned a carrier only if its carrier-to-noise ratio were above a given threshold, with the total power remaining unchanged, the improvement in C/N obtained from the Discrete Multitone approach is approximately given by

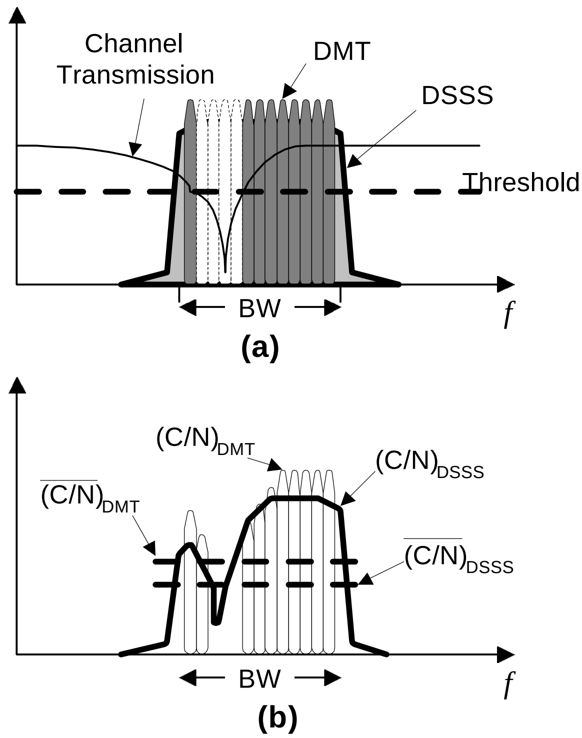

Figure 1: Direct sequence spread spectrum (DSSS) compared to discrete multitone (DMT). a) DSSS power spectrum is flat across band, while DMT spectrum is distributed only in unfaded portions. b) Net result is an improvement in C/N for DMT.

$$\overline{C/N}_{imp} = \left[\prod_{i=1}^{N_{on}}\left(1+\frac{(C/N)_i}{\Gamma}\right)\right]^{N_{on}/N} \quad (2)$$

where N_{on} is the number of channels turned on, usually obtained using a waterfill algorithm [3]. The waterfill

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0-7803-4603-6/97/$5.00 (c) IEEE

algorithm assigns more bits to subchannels with higher SNR and fewer bits to subchannels with lower SNR while subchannels with SNR's below a certain threshold are completely turned off.

The benefits of *DMT* considering only noise limited channels were treated thoroughly in [3]. In fixed point-to-point or point-to-multipoint networks, channel parameters change slowly, allowing minimal feedback within the system. The improvements obtained under such conditions are comparable to wired networks. In wireless networks, the effect of the DMT transmit system must also be considered. Intermodulation distortion has a major impact on the transmit system by introducing interference in each of the subchannels. Output Backoff (OBO) may be used to alleviate this problem; the determination of adequate OBO levels was discussed in [4]. However, the analysis was restricted to the case of random phase modulation only. This paper addresses the case of QAM, whereby both amplitude and phase assume discrete states assigned by the symbol constellation. Furthermore, this paper treats random assignment of subcarrier frequencies. This is also an extension of that presented in [4], where the C/I was calculated for an empty channel surrounded by various combinations of filled chnnels.

II. Multitone Intermodulation Distortion.

Consider the multicarrier transmit system shown in Figure 2. An *automatic leveling loop* is employed to keep the average transmit power constant regardless of the number of carriers turned on. In this way, the power per carrier varies inversely with the number of subchannels utilized.

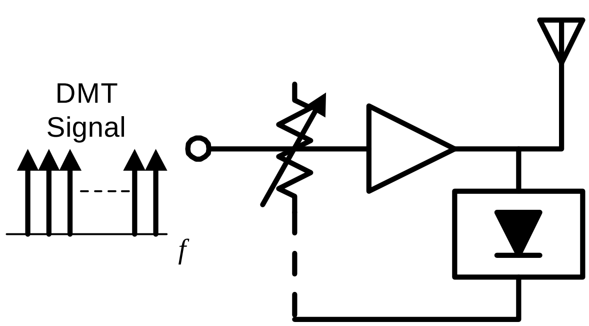

Figure 2: DMT transmission system. Average transmit power is held constant regardless of the number of subchannels utilized.

If only a single carrier is used, the only *IMD* that is generated is due to the individual components of the modulated signal. The output spectrum will contain both inband and out-of band *IMD*, as shown in Figure 3a. The inband *IMD* will manifest itself in the measured *error vector magnitude* (*EVM*), while the out-of-band *IMD* will produce *adjacent channel power* (*ACP*) interference [5]. Now consider the converse situation where all but one channel is used, shown in Figure 3b. The *IMD* produced in the empty channel, which is also present in the occupied channels, is referred to as the *noise power ratio* (*NPR*).

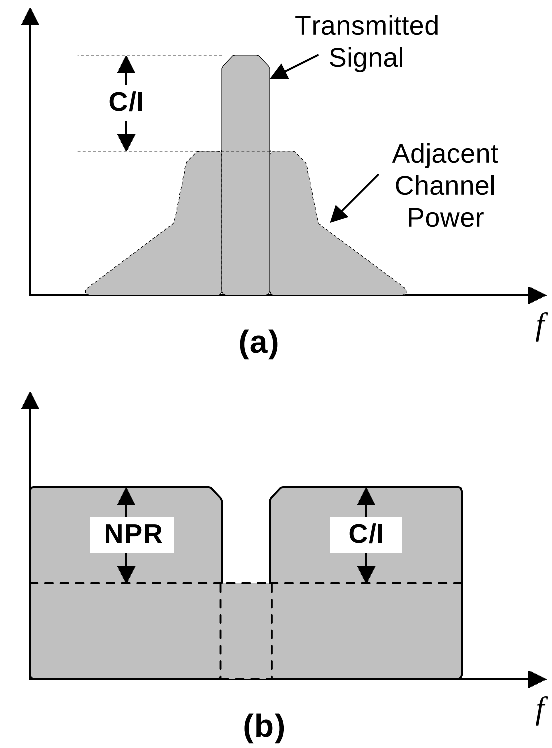

Figure 3: a) Single carrier modulated signal producing *IMD*. Inband *IMD* results in *error vector magnitude.* b) Multicarrier signal producing *IMD. Noise power ratio* is *C/I.*

III. Analysis and Simulation Tehnique.

It is not clear from inspection whether one would expect the *C/I* to be higher with a single modulated signal transmitted at a power of *P* than *N* modulated carriers, each having a power of *P/N.* Our approach to determine which is the better case was to use the behavioral modeling approach discussed in [6]. The gain compression and phase deviation characteristics of the PM2105, a two-stage GaAsFET power amplifier operating at 1900 MHz and 5 V DC supply [7], shown in Figure 4, were used to compute the *C/I* within each channel occupied by a quadrature amplitude modulated signal. 256 subchannels were used in the simulation.

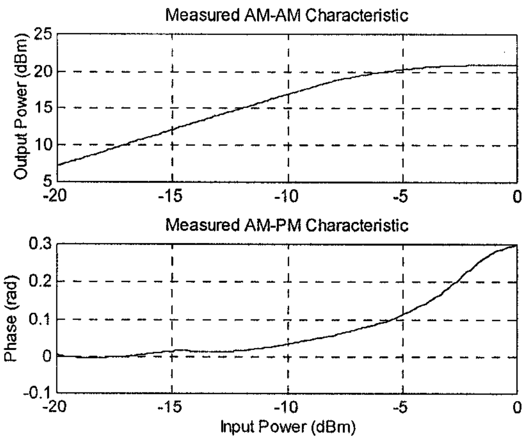

Figure 4: Gain Compression and Phase Deviation characteristics used in the channel loading simulations.

The carrier-to-interference ratio was computed using two different approaches. The NPR approach consists of measuring the interference in the empty subchannels; assuming the interference level is flat, the total interference in all the subchannels can then be obtained as well as the carrier to interference ratio [8]. The algorithm used in shown in Figure 5.

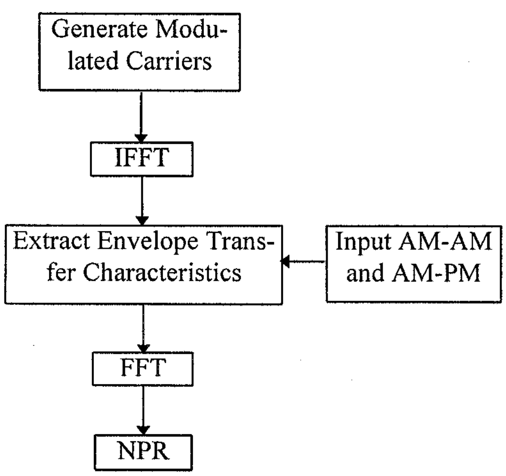

Figure 5: Carrier-to-interference calculation using the NPR approach.

The second approach used was to minimize the mean square error (MMSE) between the output envelope and a linearly amplified version of the input envelope. Once the linear gain, α_{min}, that minimizes the mean square error was determined, the interference was computed as the difference between the actual output envelope and the output obtained from feeding the input envelope through a linear power amplifier with gain α_{min}. A block diagram detailing this approach is shown in Figure 6.

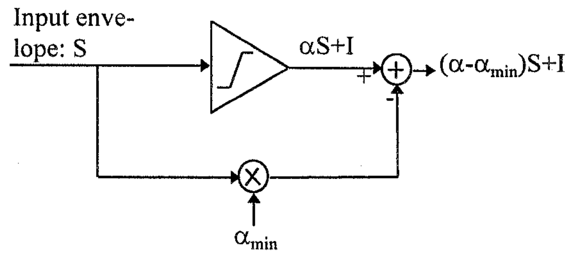

Figure 6: Carrier-to-interference calculation using the MMSE Gain approach.

IV. Simulation Results.

The *C/I* as a function of the number of occupied subchannels in shown in Figure 7 for different power levels with respect to the output power at 1 dB compression gain, (P1dB). At a given power level, as the number of used subchannels increases, the carrier-to-interference ratio flattens out above 30 filled channels. The difference between the C/I for 2 carriers and the asymptotic limit for a large number of carriers is close to 8 dB as shown in Figure 7. A similar result is obtained by manipulating the equations derived in [4]. Figure 8 illustrates the difference in the behavior of 16-QAM modulated carriers and unmodulated carriers. As can be seen, the unmodulated 2-tone C/I for a total power level of 3 dB below P1dB is about 28 dB. However, as the number of unmodulated carriers increases, the C/I degrades radically. With QAM modulated carriers, the effect is much less severe.

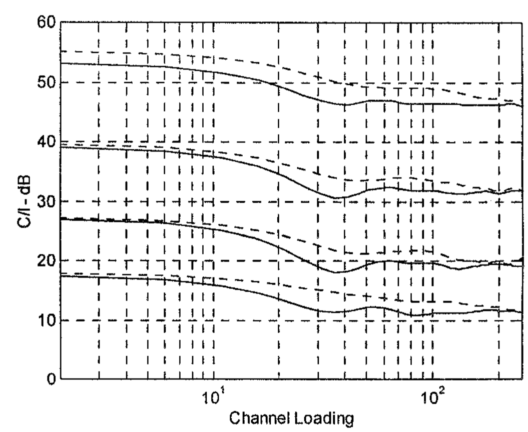

Figure 7: C/I versus number of channels occupied for QAM modulated carriers with P/P1dB= -13.5, -3, 0, 2.5 dB. Solid: MMSE Gain Method - Dash: NPR Method

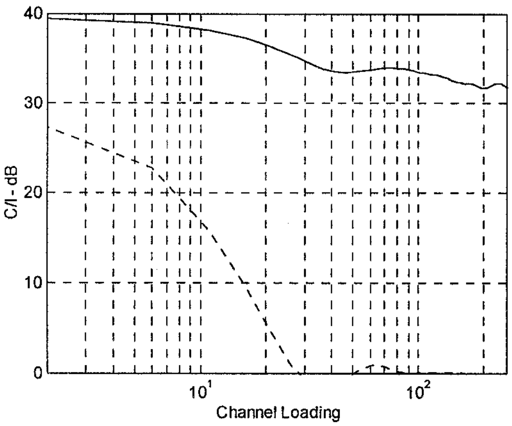

Figure 8: C/I versus number of channels occupied for 16-QAM modulated carriers (solid) and unmodulated carriers (dash). P/P1dB = -3 dB.

Thus, in order to optimize throughput, the channel should be fully loaded. Using only the best 10 % of the subchannels will increase the carrier-to-interference ratio by as much as 8 dB; however the throughput will be significantly reduced. Assigning bits to the subchannels obtained from the waterfill algorithm will maximize the data rate while maintaining constant the C/I levels. Furthermore, as the power level increases, so do the intermodulation levels. Consequently, the carrier-to-interference degrades as seen in Figure 9.

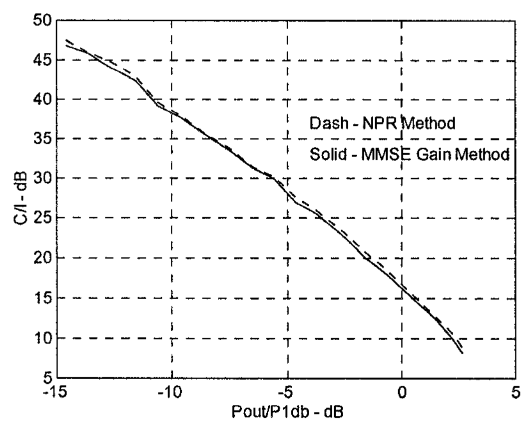

Figure 9: C/I versus power level for QAM modulated carriers. The degradation is approximately 2 dB for every dB of input power increase (i.e. the IMD is dominated by third order effects).

V. Conclusions.

Carrier to Interference levels for QAM modulated carriers and unmodulated carriers were computed as a function of the amount of channel loading for different power levels. Two methods were used: the Noise Power ratio (NPR) approach and the Minimum Mean Square Error (MMSE) approach, and the values obtained from both methods were found to be in good agreement. We showed that C/I levels degrade approximately 8 dB from 2 carriers to an asymptotic limit for a large number of carriers. Furthermore, the C/I for modulated carriers is dominated by third-order effects, and differs significantly from that of unmodulated carriers

VI. Acknowledgments.

The authors gratefully acknowledge the help of Jose Tellado-Mourello in the development of the MMSE Gain algorithm.

VII. References.

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