ResearchGate

See discussions, stats, and author profiles for this publication at: https://www.researchgate.net/publication/221287408

The History of Orthogonal Frequency Division Multiplexing

Conference Paper · January 2008

DOI: 10.1109/GLOCOM.2008.ECP.690 · Source: DBLP

CITATIONS
48

READS
10,479

3 authors, including:

Nickolas LaSorte
NTIA
28 PUBLICATIONS **234** CITATIONS

SEE PROFILE

Hazem Refai
University of Oklahoma
268 PUBLICATIONS **3,499** CITATIONS

SEE PROFILE

All content following this page was uploaded by Nickolas LaSorte on 22 May 2014.

The user has requested enhancement of the downloaded file.

IPR2024-00946
Petitioners' Ex. 1020
Ex.1020.0001

The History of Orthogonal Frequency Division Multiplexing

Nick LaSorte, W. Justin Barnes, Hazem H. Refai, *Member, IEEE*

***Abstract*—This paper depicts the development of Orthogonal Frequency Division Multiplexing from a historical perspective. A summary of major research milestones are noted that contributed to modern-day OFDM. These contributions include the use of discrete Fourier transforms replacing the analog implementation and addition of cyclic extensions to ensure orthogonality among the sub-channels. Also, channel equalization algorithms to suppress inter-symbol interference and inter-carrier interference, channel estimation through the insertion of pilot tones among data blocks, peak-to-average power ratio reduction, and synchronization techniques are discussed.**

I. INTRODUCTION

The total signal bandwidth, in a classical parallel data system, can be divided into N non-overlapping frequency subchannels. Each subchannel is modulated with a separate symbol and then the N subchannels are frequency-multiplexed. The general practice of avoiding spectral overlap of subchannels was applied to eliminate inter-carrier interference (ICI). This is shown in Fig 1 (a). This resulted to insufficient utilization of the existing spectrum. An idea was proposed in the mid-1960s to deal with this wastefulness through the development of frequency division multiplexing (FDM) with overlapping subchannels. The subchannels were arranged so that the sidebands of the individual carriers overlap without causing ICI. This principle is displayed in Fig 1 (b). To achieve this the carriers must be mathematically orthogonal. From this constraint the idea of Orthogonal Frequency Division Multiplexing (OFDM) was born.

OFDM took time to evolve to where it is today, utilized by various standards, such as 802.11 a/g and 802.16 [1-3]. The objective of this paper is to give an overview of the evolution of OFDM. The organization of this paper is as follows. The evolution of FDM to OFDM is discussed and its various military applications are noted in Section II. The birth of OFDM and an early implementation are reviewed in Section III. The establishment of orthogonality to OFDM is discussed in Section IV. Other research contributions that brought OFDM to its modern state are surveyed in Section V. An overview and conclusion of an OFDM system are given in Section VI.

Paper submitted March 31, 2008

N. LaSorte, and W. J. Barnes are graduate students at the University of Oklahoma-Tulsa, Tulsa, OK 74135 (email: nicklasorte@ou.edu, william.j.barners-1@ou.edu).

H. Refai is with the Electrical and Computer Engineering Department, University of Oklahoma-Tulsa, Tulsa, OK 74135 (e-mail: hazem@ou.edu).

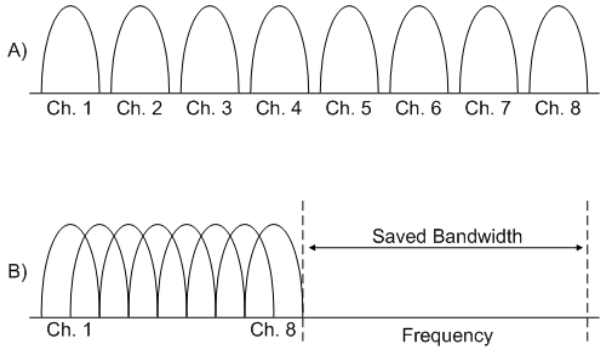

Figure 1: A) The frequency spectrum of eight channels shown utilizing frequency division multiplexing. Parallel transmitters are employed in which guard bands are placed between sub-carriers. B) The frequency spectrum of OFDM is shown where sub-channels are orthogonal to the adjacent channels. The percentage of bandwidth used to transmit the same data is reduced by 50%.

II. FREQUENCY DIVISION MULTIPLEXING

The use of FDM goes back almost a century, where more than one low rate signal, such as a telegraph, was carried over a relatively wide bandwidth channel using a separate carrier frequency for each signal. The carrier frequencies were space adequately such that the signals did not overlap. Guard bands, or empty spectral regions were placed between the signals to ensure that they could be separated with the use of filters at the receiver. This concept is illustrated in Fig 1 (a). The spectral efficiency of the data transmission are consequently lower. Instead of each channel carrying a separate message, the different frequency carriers transmit different bits of a single higher rate message. A serial-to-parallel converter divides the incoming message and outputs to multiple carriers. This is depicted in Fig 2.

Compare a single wideband serial scheme using the same channel to a parallel transmission scheme. The parallel system will be more costly to implement than a single wideband transceiver. Each of the parallel sub-channels can carry a low rate signal, but the spectral efficiency of these schemes is less than that of the single wideband transceiver because of the implementation of the guard bands between the parallel channels. Alternatively, the wideband scheme is more susceptible to inter-symbol interference (ISI) because of the short duration of the transmission period and the higher distortion experienced by the wider frequency band. Before wideband equalization matured in receiver design, the general practice to achieve high data rates over a time and frequency dispersive channel was to employ a parallel transmission scheme, despite the bandwidth inefficiency.

IPR2024-00946
Petitioners' Ex. 1020
Ex.1020.0002

978-1-4244-2324-8/08/$25.00 © 2008 IEEE.

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE "GLOBECOM" 2008 proceedings.
Authorized licensed use limited to: University of Oklahoma Libraries. Downloaded on June 26, 2009 at 10:59 from IEEE Xplore. Restrictions apply.

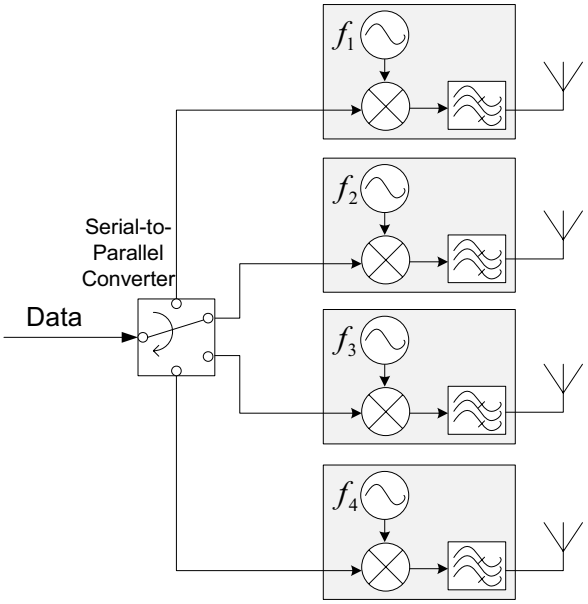

Figure 2: A parallel transmission scheme utilizing FDM is implemented by the use of a serial-to-parallel converter and multiple narrowband transmitters.

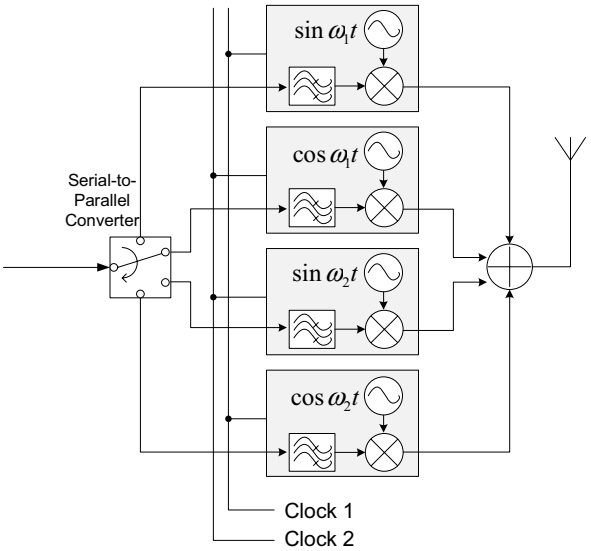

Figure 3: The OFDM scheme, proposed by Chang, implements Fourier transforms to bestow orthogonality amongst the subcarriers. The evolution from the FDM parallel transmission to the first OFDM scheme can be seen by replacing the narrowband transmitters, employed by an FDM scheme, with an analog implementation of Fourier transforms .

An early military application that implemented parallel transmission was the Kineplex system, proposed in 1957 [4]. The Kineplex system was developed by Collins Radio Company for data transmission over a high frequency radio channel subjected to severe multi-path fading. In the Kineplex system, 20 tones are modulated by differential 4-PSK without filtering, which resulted in overlapping channels. However, similar to modern day OFDM, the tones could be spaces at frequency intervals that were capable of separation at the receiver by a bank of filters.

It should also be noted that in 1961, Franco and Lachs proposed a multi-tone, code-multiplexing scheme [5] using a 9-point QAM constellation for each carrier, with correlation detection at the receiver. Sine and cosine waves were used to generate orthogonal signals. This design featured an optimal spectral efficiency and simple coding in the frequency domain.

III. The Birth of OFDM

The first OFDM scheme dates back to 1966 when Robert W. Chang published his pioneering work on the synthesis of band-limited orthogonal signals for multi-channel data transmission [6]. He was then issued a patent in 1970 for his work [7]. He presented a new scheme of transmitting signals simultaneously over a band-limited channel without ICI and ISI. The main idea of OFDM is to divide the frequency selective channel into a number of parallel, frequency flat subchannels. By making the sub-channels narrowband, the individual channels experience almost flat fading, this makes receiver design simple. His solution to constructing orthogonal subchannels is shown in Fig 3.

Chang produced orthogonality between the sub-channels by Fourier transforms, using the summation of sine and cosine. Preservation of orthogonality within each channel permits establishing individual channel data transmission rates equal to the channel bandwidth. This is half the ideal Nyquist rate. However, due to the fact that adjacent channels are synchronized, they can be overlapped by 50 percent, as is shown in Fig 1 (b).

In 1967, Saltzberg [8] analyzed and demonstrated the performance of the efficient parallel data transmission systems, where he concluded that the strategy of designing an efficient parallel system should concentrate on reducing crosstalk between adjacent channels than on perfecting the individual channels themselves. His conclusion has been proven far-sighted today in the digital baseband signal processing to battle ICI. Each sub-channel's orthogonality in the OFDM system can be preserved through the staggered QAM technique. However, the difficulty of sustaining orthogonality with an analog system emerges when a large number of subcarriers are required.

An early OFDM application, AN/GSC-10 (KATHRYN), was a variable data rate modem built for the high-frequency radio [9]. Up to 34 parallel low rate channels using PSK modulation were generated by a frequency multiplexed set of subchannels. Orthogonal frequency assignment was used with channel spacing of 82 Hz to provide a guard time between successive signaling elements.

IV. Orthogonality

The advantage of OFDM is reduced if orthogonality cannot be maintained between the subcarriers. If more subcarriers are required, the modulation, synchronization, and coherent demodulation produce a complicated OFDM circuit requiring additional hardware cost. This leads to an

IPR2024-00946
Petitioners' Ex. 1020
Ex.1020.0003

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE "GLOBECOM" 2008 proceedings.
Authorized licensed use limited to: University of Oklahoma Libraries. Downloaded on June 26, 2009 at 10:59 from IEEE Xplore. Restrictions apply.

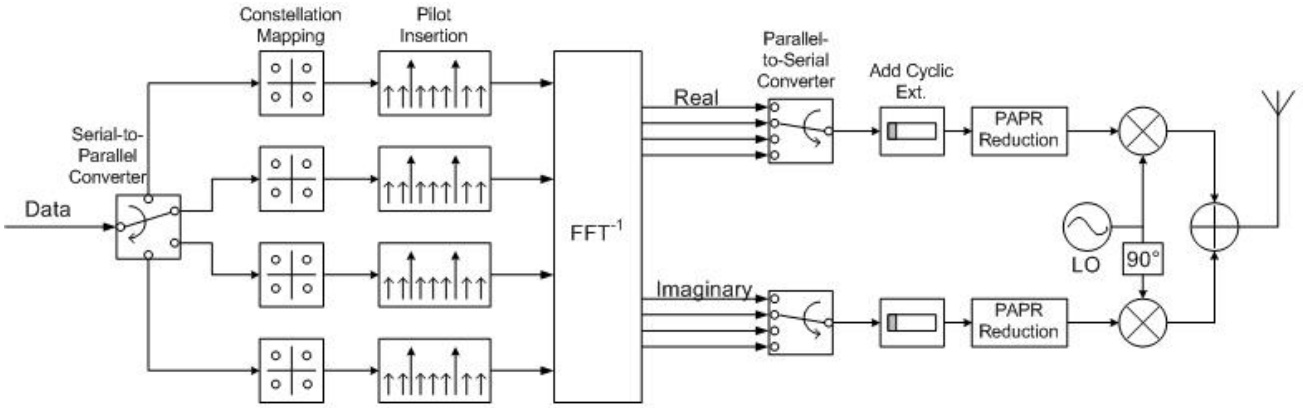

Figure 4: Shown in the block diagram above is a modern day implementation for an OFDM system. Pilot Insertion, FFT, Cyclic Extension, and PAPR Reduction are contributions which are discussed in this paper.

impractical analog implementation of the Fourier transforms using oscillators at the required frequencies. The oscillator drift in analog components led to the initial failure of orthogonality which results in an increased occurrence of ICI.

A. Discrete Fourier Transform

Throughout the development of OFDM technology, there have been a number of remarkable contributions. The first milestone came about in 1971 when Weinstein and Ebert [10] used a discrete Fourier transform (DFT) to perform baseband modulation and demodulation in the receiver. It should be noted that in 1970, the application of the DFT to an FDM system was first proposed by Darlington [11]. This renovation of the original analog multicarrier system to a digitally implemented OFDM eliminates banks of subcarrier oscillators and coherent demodulators and thus reduces the implementation complexity. This evolution makes the modern low-cost OFDM systems plausible today.

DFT-based OFDM can be completely implemented in the digital baseband for efficient processing, eliminating bandpass filtering. All subcarriers still overlap in the frequency domain while the DFT ensures orthogonality. It transforms the data from the frequency domain to the time domain.

When the DFT of a time domain signal is computed, the frequency domain results are a function of the sampling period T and the number of sample points N. The fundamental frequency of the DFT is equal to $\frac{1}{NT}$, where NT is equal to the total sample time. Each frequency represented in the DFT is an integer multiple of the fundamental frequency. The maximum frequency that the DFT can represent a time domain signal sampled at a rate of $\frac{1}{T}$ is $f_{\max} = \frac{1}{2T}$, as given by the Nyquist sampling theorem. This frequency is located in the center of the DFT points. The IDFT performs the inverse operation to the DFT. It takes a signal defined by frequency components and converts them to a time domain signal. The time duration of the IDFT time signal is equal to NT. The Fast Fourier Transform (FFT), a fast algorithm for computing DFT, can further reduce the number of arithmetic operations from N^2 to $N\log N$, where N is the size of the FFT. This contribution to OFDM can be seen in Fig 4.

The ISI and ICI were mitigated by using a guard time between the symbols and raised-cosine windowing in the time domain. Weinstein and Ebert also added a guard interval in the case of multipath channels. Even though the proposed system did not achieve perfect orthogonality among the subcarriers over a time dispersive channel, it was nevertheless an important contribution to OFDM.

B. Cyclic Extension

Another milestone in OFDM came about in 1980, when Peled and Ruiz solved the orthogonality problem by introducing a cyclic extension (CE), more commonly referred to today as cyclic prefix [12]. In their scheme, CE are substituted for the conventional null guards of the OFDM symbol. This effectively converts the linear convolutive channel to simulate a channel performing cyclic convolution ensuring orthogonality over a time dispersive channel and eliminating ISI completely between subcarriers as long as the CE remains longer than the impulse response of the channel. However, the CE induces a loss in effective data rates, but the zero ICI generally compensates for the reduction. The cyclic extension is added to the data stream after the FFT^{-1} is computed. This advancement to the OFDM scheme is shown in Fig 4.

V. Other Contributions

A. Channel Equalization

An important advantage of the OFDM transmission technique as compared to single carrier systems is seen in frequency-selective channels. The signal processing in the receiver is rather simple in this case. The orthogonality of the OFDM sub-carriers is maintained after transmission over the radio channel and the effect of ICI is reduced to a multiplication of each subcarrier by a complex transfer factor. Therefore, equalizing the signal is very simple, whereas equalization may not be feasible in the case of conventional single carrier transmission covering the same bandwidth. In 1980, Hirosaki introduced an equalization algorithm to further suppress ISI and ICI [13], which results from a channel impulse response or timing and frequency errors such as channel distortion, synchronization error, or

IPR2024-00946
Petitioners' Ex. 1020
Ex.1020.0004

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE "GLOBECOM" 2008 proceedings.
Authorized licensed use limited to: University of Oklahoma Libraries. Downloaded on June 26, 2009 at 10:59 from IEEE Xplore. Restrictions apply.

phase error. His implementation was designed for a subchannel-based equalizer for an orthogonally multiplexed QAM system.

B. Channel Estimation

OFDM systems transmit data in blocks. Two straightforward ways of identifying the channel in an OFDM system is to either insert a training sequence between consecutive blocks or to insert pilot tones inside each block. The unknown finite-impulse response of the channel can then be identified in the time domain by the training sequence, or in the frequency domain by the pilot tones.

Pilot symbol-assisted modulation schemes obtain the channel frequency response based on the estimate of the known frequency domain pilot symbols that are interleaved among the transmitted data symbols. The pilot subcarriers assist the sampling of the channel frequency response. The corresponding sampling frequency needs to be higher than the Nyquist frequency required for the alias-free representation of the channel frequency response at the Doppler frequency encountered. This addition to the data can be seen in the block diagram in Fig 4.

Hirosaki's early application of QAM modulation and pilot tones where applied to his high-speed OFDM system in 1981 [14]. In 1985, Cimini introduced a pilot-based method to reduce interference from multipath and co-channels [15]. His analysis and simulation focused on the deployment of OFDM for mobile communication. In 1989, Kalet suggested a subcarrier-selective allocating scheme [16]. He allocated more data through transmission of dependable subcarriers near the center of the transmission frequency band. He concluded that these subcarriers suffered less channel distortion.

C. Peak-to-Average Power Ratio

One of the major drawbacks of multicarrier transmission is the high peak-to-average power ratio (PAPR) of the transmit signal. Therefore, the OFDM receiver's detection efficiency is very sensitive to the nonlinear devices used in its signal processing loop, the digital-to-analog converter and the power amplifier. This may severely impair the system's performance due to induced spectral growth and detection efficiency degradation. The result of induced interference into the OFDM system is an increase in the bit-error rate.

One solution to reduce the PAPR in an OFDM system is through the manipulation of the signal itself. There is a well written overview discussing techniques in dealing with the PAPR for an OFDM system, *written by Han and Lee [17].*

D. Synchronization

An important topic in OFDM transmission systems as well as any wireless transmission scheme is synchronization at the receiver, since time and frequency synchronization errors disturb the orthogonality of the sub-carriers and therefore reduce the SNR considerably. The loss of orthogonality among sub-carriers also cause ISI and ICI. Pilot tones, used in channel estimation, are also effectively used for frequency and time synchronization. Bo Ai *et al* recently published an overview of various synchronization techniques for OFDM [18].

VI. Conclusion

Chang's OFDM is a special case of wideband multicarrier modulation in which multiple symbols are transmitted in parallel using different sub-carriers with overlapping frequency bands that are mutually orthogonal. An equivalent wideband frequency bandwidth is separated into a number of narrowband signals. The time dispersion caused by multipath delay is reduced because the symbol duration of a narrowband signal will be larger than that of a wideband transmission scheme. The overlapping multicarrier techniques can implement the same number of channels as conventional FDM system but with a reduced amount of bandwidth. In conventional FDM, adjacent channels are separated using a guard band. In order to utilize the overlapping technique, crosstalk between adjacent channels must be reduced through orthogonality between sub-carriers.

In OFDM, each subcarrier has an integer number of cycles within a given time interval T, and the number of cycles by which each adjacent subcarrier differs is exactly one. This implementation adds orthogonality to the sub-carriers. The subcarriers are data modulated using phase shift keying or quadrature amplitude modulation. The amplitude spectrum of each modulated subcarrier using either PSK or QAM has a sinc^2 shape. At the peak spectral response of each subcarrier all other subcarrier spectral responses are identically zero.

Following data modulation, symbols are fed through a serial-to-parallel conversion process. Each PSK or QAM symbol is assigned a subcarrier and an inverse DFT, contributed by Weinstein and Ebert in 1971, performed to produce a time domain signal. OFDM deals with multipath delay spread by dividing a wide band signal into N narrowband channels where N is the number of subcarriers. However, if the delay spread is longer than the symbol duration, multipath will affect performance. A guard time is introduced to eliminate ISI caused by delay spread. As a rule, the guard time is usually two to four times larger than the expected delay spread. To reduce ICI, OFDM symbols are cyclically extended into the guard interval, as pointed out by Peled and Ruiz in 1980. This cyclic extension ensures that an OFDM symbol will have an integer number of cycles in the DFT interval as long as the delay is less than the guard time.

At the receiver after the radio frequency and analog-to-digital conversion stage, time and frequency synchronization between the transmitter and receiver is very crucial to the performance of an OFDM link. A wide variety of techniques have been proposed for estimating and adjusting both timing and carrier frequency. Next, a DFT is used to demodulate all subcarriers. To demodulate the subcarriers using PSK or QAM modulations, reference phase and

IPR2024-00946
Petitioners Ex. 1020
Ex.1020.0005

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE "GLOBECOM" 2008 proceedings.
Authorized licensed use limited to: University of Oklahoma Libraries. Downloaded on June 26, 2009 at 10:59 from IEEE Xplore. Restrictions apply.

amplitude of the constellation on each subcarrier are required.

REFERENCES

[1] IEEE Std. 802.11a. Supplement to Part 11; Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: High-speed Physical Layer in the 5 GHZ Band, IEEE Std. 802.11a-1999,1999.

[2] IEEE 802.11g, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications, Amendment 4: Further Higher Data Rate Extension in the 2.4 GHz Band, 2003.

[3] IEEE 802.16 Standard - Local and Metropolitan Area Networks – Part 16, IEEE Std 802.16a-2003.

[4] Dolez, M.L., Heald E.T., Martin D.L., "Binary Data Transmission Techniques for Linear Systems." Proc. I.R.E; May 1957, 45: 656-661.

[5] Franco, G.A., Lachs G., "An Orthogonal Coding Technique for Communications." I.R.E. Int. Conv. Rec.; vol. 8, pp 126-133, 1961.

[6] R.W. Chang. "Synthesis of band-limited orthogonal signals for multichannel data transmission," Bell Systems Tech. Journal, vol. 45, pp.1775–1796, Dec. 1966.

[7] "Orthogonal Frequency Division Multiplexing." U.S. Patent No. 3, 488, 4555, filed November 14, 1966, issued Jan. 6, 1970.

[8] B. R. Saltzberg, "Performance of an efficient parallel data transmission systems," IEEE Transactions on Communications Technology, vol. 9, pp. 723-728, Dec. 1967.

[9] M. S. Zimmerman and A. L. Kirsch, "The AN/GSC-10 (KATHRYN) variable rate data modem for HF radio," IEEE Transactions Communications, vol. 15, pp. 197–205, Apr. 1967.

[10] S. B. Weinstein and P. M. Ebert, "Data transmission by frequency-division multiplexing using the discrete Fourier transform," IEEE Trans. Communications, vol. 19, issue: 5, pp. 628-634, Oct. 1971.

[11] S. Darlington, "On digital single-sideband modulators," IEEE Transactions on Circuit Theory, vol. 17, pp. 409–414, Aug. 1970.

[12] A. Peled and A. Ruiz, "Frequency domain data transmission using reduced computational complexity algorithms," In Proc. IEEE International Conference on Acoustics, Speech, and Signal Processing, volume 5, pp. 964-967, April 1980.

[13] B. Hirosaki, "An analysis of automatic equalizers for orthogonally multiplexed QAM systems," IEEE Transactions on Communications, vol. 28, pp.73-83, Jan.1980.

[14] B. Hirosaki. "An orthogonally multiplexed QAM system using the discrete Fourier transform," IEEE Transactions on Communications, vol. 29, issue 7, pp.982–989, July 1981.

[15] L.J. Cimini, "Analysis and simulation of a digital mobile channel using orthogonal frequency division multiplexing," IEEE Trans. on Communications, vol. COM-33, pp. 665-675, July 1985.

[16] I. Kalet, "The multitone channel," IEEE Transactions on Communications, vol. 37, pp.119-124, February 1989.

[17] S.H. Han, J.H. Lee. "An overview of peak-to-average power ratio reduction techniques for multicarrier transmission," IEEE Wireless Communications, vol. 12, issue 2, pp. 56-65, April 2005.

[18] B. Ai, Z. Yang, C. Pan, J. Ge, Y. Wang, Z. Lu, "On the synchronization techniques for wireless OFDM systems," IEEE Transactions on Broadcasting, vol. 52, issue 2, pp: 236-244, June 2006.

IPR2024-00946
Petitioners' Ex. 1020
Ex.1020.0006

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE "GLOBECOM" 2008 proceedings.
View Authorized licensed use limited to: University of Oklahoma Libraries. Downloaded on June 26, 2009 at 10:59 from IEEE Xplore. Restrictions apply.