Varinder Pal Sahni / International Journal of Engineering Research and Applications (IJERA) ISSN: 2248-9622 www.ijera.com
Vol. 3, Issue 4, Jul-Aug 2013, pp.1412-1418

# Review: HYBRID OFDM/CDMA/SFH APPROACH FOR WIRELESS SENSOR NETWORKS

**Varinder Pal Sahni**
Department of Electronics and Communication,ICL Group of colleges,Ambala

## ABSTRACT

**The realization of wireless communication providing high speed, high capacity and high quality information exchange between two portable terminals that might be located anywhere in the world is still the communication challenge. For the development of future wireless communication systems, an extremely spectrum-efficient transmission technology is required. In this study authors propose a signal scheme called Hybrid CDMA-SFH which combines OFDM with CDMA and SFH to generate a system functionally superior to MC-CDMA systems. This study explores various merits and demerits of the proposed system and compares it to the other multicarrier access schemes. The CDMA component provides the inherent advantage of DS-CDMA systems incorporating a spreading signal based on PN code sequence, by providing user discrimination based on coding at the same carrier frequency and simultaneously. The OFDM component provides resistance to multipath effects making it unnecessary to use RAKE receivers for CDMA and thus avoid hardware complexity. The SFH component provides resistance to the "near-far" problem inherent in CDMA. Therefore, this system retains the greatest advantage of CDMA viz., multiple accesses without the disadvantages of "near-far" problems and complexity of RAKE receivers. Hence authors should look for OFDM because of its robustness to multipath and sophistication of synchronisation and because of the possibility of using coherent signal processing in spite of frequency hopping and at the same time the multiuser capability of CDMA systems.**

***Keywords*****-**CDMA,Hybrid CDMA-SFH, MIMO CDMA, RAKE

## I. INTRODUCTION

High Data Rate transmission over mobile or wireless channels is required by many applications. However, the symbol duration reduces with the increase of the data rate, and dispersive fading of the wireless channels will cause more severe intersymbol interference (ISI) if single-carrier modulation, such as in time-division multiple access (TDMA) or Global System for Mobile Communications (GSM), is still used. From [1], to reduce the effect of ISI, the symbol duration must be much larger than the delay spread of wireless channels. In orthogonal frequency-division multiplexing (OFDM), the entire channel is divided into many narrow-band subchannelswhich are transmitted in parallel to maintain high-data Multi-carrier system has been fuelled by large demand on frequency allocation, resulting in a crowded spectrum as well as large number of users requiring simultaneous access. Existing wireless systems may be utilized single frequency, single antenna and pulse for carrier transmission and reception. Problems of such system is that in case of failure the total system will become non operational. A distributed system in terms of multi-carrier, multi-antenna and coded pulse can provide a more suitable communication a more suitable communication and sensor gives rise to multicarrier based hybrid CDMA-SFH technology is the ultimate solution.Recently, communication systems employing multiple antennas (MIMO technology) at the physical layer and code division multiple access (CDMA) as a multiple access technique at the MAC layer, which are known as MIMO-CDMA/MC-CDMA systems, has received remarkable research interest. In fact, the combination of the capacity enhancements arising from the utilization of spatial multiplexing in MIMO with the robustness of spread spectrum and Slow Frequency Hopped (SFH) communications is considered as a promising candidate for next generation wireless systems. CDMA protocols do not achieve their multiple access property by a division of the transmissions of different users in either time or frequency and it is already getting too crowded in these domains, but instead makes a division by assigning each user a different code. This code is used to transform a user's signal to a wideband signal (spread spectrum signal). If a receiver receives multiple wideband signals, it will use the code assigned to a particular user to transform the wideband signal received from that user back to the original signal. All other code words will appear as noise due to decorrelation. However, CDMA systems suffer from the "near-far" problem. Therefore, an elaborate power control scheme is provided by each base station by rapidly sampling the Radio Signal Strength Indicator (RSSI) levels of each mobile and then sending a power change command over the forward link. The second problem in CDMA systems is that the signals travel by different paths to the receiver. It is, therefore, preferred to use a RAKE receiver to utilise maximum ratio combining

techniques to take advantage of all the multipath delays, in order to get a strong signal. These RAKE receivers are extremely complex. In order to combat the "near-far" problem, DS-CDMA was combined with SFH systems. This hybrid technique consists of a direct sequence modulated signal whose centre frequency is made to hop periodically in a pseudorandom fashion. This ensures that, even within the same cell, no two mobiles are operating at the same frequency. There was, however, an industrial demand for very high bit rates, irrespective of the type of access scheme used.This gave rise to OFDM systems. In such systems very high data rates are converted to very low parallel data rates using a series-to parallel converter. This ensures flat fading for all the sub-carriers i.e. a wideband signal becomes a packet of narrowband signals. This will automatically combat multipath effects removing the need for equalisers and RAKE receivers. A variant of this approach was earlier introduced as Multicarrier -CDMA or MC-CDMA. This proposal envisages interfacing a DS-CDMA system with a system of orthogonal coding (not OFDM) using only W alsh coding. We shall briefly examine the advantages and disadvantages of the prevailing systems before proceeding to examine the new proposal. It is pointed out that the advantages/ disadvantages listed are not comprehensive, but only those relevant to this study. It can be seen in Table 1, that each multiple access approach has its advantages and disadvantages. It is especially to be noted that MCDMA achieves the same result as OFDM, but it does not depend upon IFFT for modulation and as compared to MC-CDMAthis system called Hybrid CDMA-SFH approach. This has essentially been developed for the 60 GHz
But it is equally applicable at any other frequency if necessary bandwidth is available. This study proposes a comprehensive approach maximising the merits and minimising the demerits of the individual schemes.

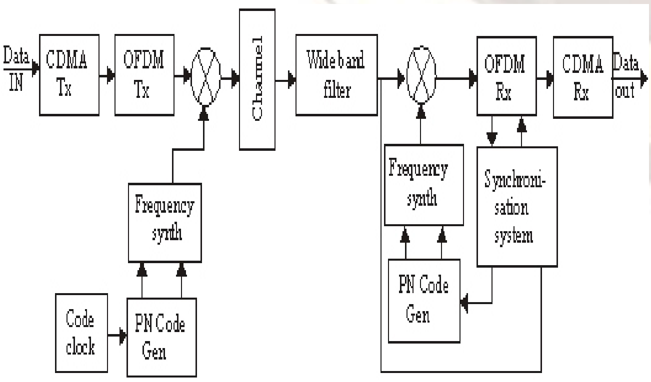


Fig.1.Overall system schematic structure of hybrid CDMA SFH system

## II. TYPES OF MULTIPLE CARRIER SCHEMES

### 2.1.1 OFDM

Advantages

- Saving of large bandwidth,spectral efficiency and mitigation of ISI
- Can be adapted to different transmission environments and available resources.
- Robust against multiple effects and narrowband interference
- Capable of single frequency operation

Disadvantages

- Sensitive to frequency offset and phase noise.
- Synchronization problems
- Large Peak to average power ratios.

2.1.2 MIMO

Advantages

- Increased coverage,capacity,data rate spectral efficiency and reduced power consumption
- It doesnot increase bandwidth
- Solve toughest problems like speed and range

Disadvantages

- Cannot achieve zero ISI and hence cannot be utilized alone.
- Dependent on antenna configuration and scattering environment
- Reciever complexity increase with increasing number of transmit antennas and transmission rate.
- Co-channel interference (CCI) which can also significantly decrease the capacity of wireless and personal communications systems.

2.1.3 MIMO-OFDM

Advantages

- Higher spectral efficiency without increasing the total transmission power or bandwidth of the communication system.
- Improved link reliability,beam forming, and adequate signal processing techniques at both ends of the system by using interference cancellation techniques.
- Avoids inter-symbol-interference and Co - Channel In terference (CCI).
- Reduced equalizer complexity and improve frequency diversity due to delay spread.
- Simplifies the implementation of MIMO without loss of capacity

Disadvantages

- less robust against jam ming Effects
- channel parameter estimation problem.
- Problems due to ‘‘near far’’ effect.

2.1.4 DS-CDMA

Advantages

- Can address multiple users simultaneously and at same frequency
- Resistivity to fading/multipath effect (quality) Interference and antijamming effect

Disadvantages

- Complex Time Domain RAKE receivers
- Synchronization within fraction of chip time becomes difficult.

2.1.5 SFH-CDMA

Advantages

- Reduces ''ne ar-far'' effect.
- Synchronization w ithin fraction of hop time is easier.
- No need for contiguous band widths

Disadvantages

- Coherent demodulation difficult because of phase relationship during hops.

2.1.6 MC-CDMA

Advantages

- Higher number of users as full bandwidth utilized unlike in DS-CDMA
- Effectively combines all the signal energ y in frequency domain , unlike CDMA
- Double the p rocessing gain of DS-CDMA

Disadvantages

- Peak-to-average ratio problem.
- Synchronization problems.
- Overcrowding of the spectrum as each bit is spread across the a vailable bandwidth

2.1.7 OFDM-SFH

Advantages

- Anti multipath capability
- Multiple access due to FH requires very wide bandwidths depending upon the number of users.

Disadvantages

- Peak to average ratio problem
- Synchronisation problems

## III. MATERIALS AND METHODS

The overall schematic structure of hybrid CDMA SFH concept is shown in figure 1. The schematic is self explanatory. However there are few salient points to be noted.

### 3.1 Bandwidth and other considerations

There is a multimedia requirement of high bit rates, typically 155 Mbps, which need wide bandwidths of around 100 MHz or higher. At 60 GHz, different channel conditions are not so severe because larger bandwidths are available.For the successful operation it is assume that there is no carrier offset for perfect OFDM synchronisation. The CDMA systems till now pertain to voice channels with a band spread factor of 128 for a data rate which is at the most 9600 bps. This is necessary due to the adverse transmission conditions and also due to the traffic at that frequency (around 850 MHz). Therefore, a band spread factor of 128 is unnecessary. More likely, a band spread factor of 10 or less will prove sufficient. This, however, has to be verified by extensive simulations. For the band spread factor of 10 the required bandwidth is set at1GHz for a 100 MHz data rate.In such a case the proposal shown in Fig. 2 is a better approach. In this case, band slots of subcarriers hoped within the bandwidth of the OFDM system.If the band spread factor is very less than 10,then this approach adopt the Fig. 3 for hop across multiples of the basic bandwidth. This approach is easier to implement. There is no need for such a design at such frequencies. But we can expect a steep rise in the number of users when high data rates become realisable, especially in case of video-telephones. It is the CDMA aspect (code diversity) which really generate a lot of users.The frequency hopping has been introduced to obtain frequency diversityand also to reduce the "nearfar" problem. This limits the

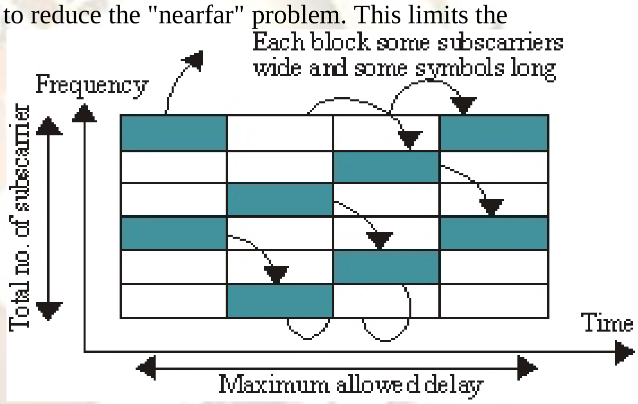


Fig. 2: Characteristics of the allocation design in a multi-userOFDM system

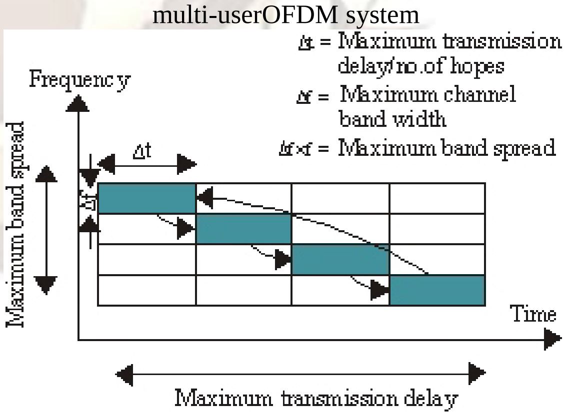


Fig. 3: Behaviour of the maximum band spread with maximumtransmission delay when band spread factor is less than 10

number of users in order to avoid "collisions". The CDMA aspect makes up for this limitation by introducing a larger number of users due to code diversity. Interleaving and error correction coding may be dispensed with if the need so arises i.e. if the channel is not severe. In case, in the foreseeable future, the channel does pose problems, we can increase the spread factor of the CDMA transmission and/or introduce FEC and interleaving. The OFDM aspect is required, because it eliminates the need for RAKE receivers and allows us to use coherent modulation in spite of frequency hopping which makes coherent signal processing difficult. It also helps reduce the burden of synchronisation related to CDMA systems. In this connection, it is pointed out that MC-CDMA also uses OFDM techniques with RAKE receivers. But in this signal processing ,the development is based on without RAKE receivers. Hence, this method is named as Hybrid CDMA-SFH approach and not MC-CDMA.

### 3.2 Error correction coding

In the CDMA transmitter section, there are two levels of coding viz. Convolution encoding and Walsh encoding. The latter is an orthogonal coverage, since PN sequences by themselves are insufficient to ensure channel isolation. This orthogonal coverage should not be confused with the orthogonal subcarrier in OFDM transmitter. The Walsh coding ensures orthogonality between users. The OFDM orthogonality ensures that the sub-carriers for each data frame are orthogonal. The convolution encoding ensures robustness of data as discussed above.

### 2.2 Modulation

Normally, in DS-CDMA systems, the matched filter in the receivers operates on the RF signal to achieve channel isolation based on the specific PN sequence for that channel. The signal is thereafter demodulated. In our case, the CDMA sequence after Walsh coding, does not get converted to RF via QPSK, DPSK or any other type of modulation, but instead is fed as an input to the OFDM transmitter. In the OFDM transmitter, it gets modulated as M-QAM or any other type of modulation.

### 3.3 CDMA receiver

In the CDMA receiver, the OFDM receiver gives it a sequence after M-QAM demodulation.Thereafter, in CDMA signal processing, there is a digitalcorrelator which ensures channel isolation. The output ofthe correlator is then fed to a Viterbi decoder. The outputfrom this decoder is the required data sequence. RAKEreceivers are not required in this case at the matched filterlevel.

### 3.4 Synchronisation

Stringent synchronisation is still required as the PN sequences too need to be perfectly synchronised. However, in such cases, the burden of synchronisation is transferred to the OFDM system. The OFDM system has a more sophisticated synchronization system (Jankiraman and Prasad, 1999; Magnus *et al*., 1996) than the CDMA. As in this case, the OFDM system utilises the cyclic prefixes for synchronisation. Hence, the PN sequences emerging from the OFDM system and moving on to the CDMA system are synchronised more accurately than in case of a pure CDMA system. It is known that synchronisation is one of the limiting factors in CDMA systems for acquiring high data rates. It isexpected that in our proposed system, such criticalproblems will be efectively reduced.

### 3.5 Bit error probabilities

The proposed system is basicallyan OFDM-FH system. This is because the transmission and reception is carried out by the OFDM-FH system. The CDMA system generates the data stream but in a more complicated manner. Hence, the same analysisapplies to this system as for OFDM-FH systems, fordetermining bit error probabilities.

### 3.6 Trade-off between OFDM and CDMA

The OFDM-FHsystem by itself does not work for multimedia operations.This is because multimedia requires very high data rates, typically of the order of 155 Mbps. This requires large bandwidth of typically 100 MHz. By using FH among users, traffic reduces drastically, being limited by the bandwidth available. By adding CDMA in this situation further enhances the number of users since CDMA supports a large number of users working at the same frequency and bandwidth. Hopping is used to obtain frequency diversity with a view to reducing the "near-far" effect. Hence, there is a trade-off.

### 3.7 CDMA signal processing

It may argue that the presentdata rate of 1.2288 MHz in voice channels is inadequatefor multimedia applications. However, in order to supporta large number of users, use of CDMA technique is very vital. Hence, efforts must be made to increase data ratesusing better PLLs for synchronisation and high speed digital electronics. It is pointed out that in this proposal, the entire CDMA signal processing is carried out in the digital domain both for both transmitter and the receiver. Matched filtering is neither carried out at the RF level for the CDMA systems nor is there any operation of transmission or reception at the R F level for the same. This is a big advantage as signal processing is easier in the digital domain as compared to the other.

## IV. PERFORMANCE EVALUATION OF HYBRID-MULTICARRIER ACCESS SCHEMES

### 4.1 Comparison of DSCDMA and DS- CDMA-SFH (DSSFH) Systems

It is assumed that there are K active users,each having a transmitter-receiver pair. Each useremploys a channel Encoder. Let bk(t) denote the modulating sequence of the Kth user, which randomlytakes values from the Set {+1, -1} with equal probability.The coded bit duration is indicated by T and thetransmitted power by $P_T$given by:-

$$h_k(t) = \sum_{i=1}^{L} h_{ki}\,\delta(t-\tau_{ki})\exp(j\varnothing_{ki}) \tag{1}$$

For each path, the gain $h_{ki}$ is Rayleigh distributed, the delay $\tau_{ki}$ is uniformly distributed over (0, 2π). The average power for each path and each user is $E[h^2_{ki}] = \sigma_0/2$. The receiver introduces AWGN n(t) with two sided power spectral density N0/2.

4.1.1 DS-CDMA

The average SNR is given by the approximation

$$SNR = \gamma = \left[\left(\frac{2E_b}{N_0}\right)^{-1} + \frac{LK-1}{N}\times\frac{1}{3}\right]^{-\frac{1}{2}} \tag{2}$$

This is the SN R per bit. The constant 1/3 is due to the rectangular chip pulse. This equation is valid for binary Direct Sequence (DS) systems. In case of MRC with diversity of order M, given that the received signal is Rayleigh distributed, the bit error probability Pb at the decoder input is given by (John, 1995).

$$P_b = \frac{1}{2^{(2M-1)}(M-1)!(1+\gamma)^M} \sum_{m=0}^{M-1} C_m (M-1+m)!\left(\frac{\gamma}{\gamma+1}\right)^m \tag{3}$$

Where,

$$C_m = \frac{1}{m!}\sum_{n=0}^{M-m-1}\binom{2M-1}{n} \tag{4}$$

At the output of the (n,k) block decoder, the probability of bit error is given by (John, 1995):

$$P_e = \sum_{j=t+1}^{n}\binom{n}{j} P_b^j (1-P_b)^{n-j} \tag{5}$$

where*t* denotes the error correction capability of the code.

4.1.2 DS-CDMA-SFH

The general derivation for this system is similar, except that the system uses Binary Frequency Shift Keying(BFSK) modulation followed by noncoherent demodulation, because, of the nature of slow frequency hopping. The considered system is asynchronous as this is the more realistic case. Even when synchronism can be achieved between individual user clocks, radio signals will not arrive synchronously to each user due to propagation delays.However, if two users transmit simultaneously in the same frequency band, a collision or "hit" occurs. The probability of bit error for BFSK is given by (John, 1995):

$$P_b = \frac{1}{2^{(2M-1)}}\exp\left(-\frac{\gamma}{2}\right)\sum_{k=0}^{M-1} C_k\left(\frac{\gamma}{2}\right)^k \tag{6}$$

where,

$$C_k = \frac{1}{k!}\sum_{n=0}^{M-1-k}\binom{2M-1}{n} \tag{7}$$

However, if two users transmit simultaneously in the same frequency band, a collision or "hit" occurs. In this case, we assume the probability of error as 0.5. Hence, the overall probability of bit error for frequency hopped BFSK signal is:-

$$P_b = P_b(1-P_{hit}) + \frac{1}{2}P_{hit} \tag{8}$$

where$P_{hit}$ is the probability of hit, if there are *q* possible hopping channels, there is a 1/q probability that a given interfering user will be present in the desired user's slot. Hence, for K-1 interfering users, the probability that at least one is present in the desired frequency slot is given by:-

$$P_{hit} = 1-\left\{1-\frac{1}{q}\left(1+\frac{1}{N_b}\right)\right\}^{k-1} \tag{9}$$

where$N_b$ is the number of bits/hop, for slow hopping it is equal to 1 hop/bit. At the output of the (n, k) block decoder; the probability of bit error is given by (John, 1995) given by:-

$$P = \sum_{j=t+1}^{n}\binom{n}{j} P_b^j (1-P_b)^{n-j} \tag{10}$$

where, t denotes the error correction capability of thecode.

## V. CONCLUSIONS AND FUTURE SCOPE

This section provides the performance comparison of the DS CDMA and DS-SFH systems taking diversity. This research discusses concept of integrating CDMA with OFDM-FH with a view to reducing the main drawbacks of CDMA "near-far" effect and complex RAKE receivers. Hence, we can definitely conclude that OFDM - FH is a better choice. The bit error probability for the OFDM-FH system appears to be extremely low.The performance of OFDM-FH is explained using 16 QAM as the coherent modulation technique and RS code. It is noted that the curve for bit error without RS coding and with 16 QAM, is inferior to the one with RS coding. The former is similar to the onederived by Proakis (John, 1995) for 16 QAM modulation.This result can be obtained with RS coding. In reality, due to residual "near-far" effect, RS coding will help to improve the system performance, but the OFDMFH result will not be so exceptional. Furthermore, both the curves of system performance can be zero for SNRs in excess of 10 dB. This is, because, if we take a large *T*, Eq. (9) reduces to $P_{hit}$= (K-1)/q. For large SNR, the $P_b$ (Eq. (6) and (8)) tends to ½×(K-1)/q. For large *q* this value tends to zero i.e. multiple access interference limited. It can also be seen that Reed-Solomon coding performs better as compared to BCH coding. A q value of 20 hops appears to be an optimum value. This is, because, the chances of collisions and consequent errors appear to be less with a *T* of 20. However, a larger spread of *T* is preferred. Also,for ideal cases maximum number of user is 10. Users in excess of this number will cause collision and consequent poor bit error capability. However, this is where the advantage of our approach pays off. Then pass the burden of the additional users to the CDMA system. This means that OFDM-FH operates 10 users simultaneously, but in actuality there will be many more, being limited only by the capability of the respective CDMA systemsThis approach will be studied in future which essentially applies to the downlink. It is, however, can also be applicable in the uplink provided synchronization problems are addressed in the OFDM systems. This is driven by a need to maintain orthogonality between mobile receivers. This is essentially an OFDM problem area and does not in any way restrict our suggested approach. This approach yields the greatest advantage of CDMA viz large number of users without the drawbacks of CDMA like power control, multipath effects etc. The suggested system can make this approach a promising solution for multimedia applications. It is recommended that efforts will be made to increase the bit rates of CDMA systems for multimedia, but this proposed work is independent of data rate and can handle data rates as high as 155 Mbps due to OFDM. Also,It will be proposed to conduct further simulations using this approach, leading to a formal proposal for a fourth generation system for wideband multimedia communication

## REFERENCES

[1] I. F. Akyildizn et al, "Wireless sensor networks: a survey," Computer Networks, *vol. 38, no. 4, pp. 393–422, 2002.*

[2] Wei Ye, et al, "Medium Access Control with Coordinated, Adaptive Sleeping for Wireless Sensor Networks" *USC/ISI TECHNICAL REPORT ISI-TR-567,JANUARY 2003.*

[3] H.D.Trung et al. "Performance evaluation and comparison of different ad hoc routing protocols", Department of Electrical Engineering, *Chulalongkorn University, Bangkok, Thailand, May 2007*.

[4] Abdul HadiAbdRahman et al, "Performance Comparison of AODV, DSDV and I-DSDV Routing Protocols in Mobile Ad Hoc Networks"*European Journal of Scientific Research ISSN 1450-216X Vol.31*.

[5] Charles E. Perkins et al. "Highly Dynamic Destination -Sequenced Distance-Vector Routing (DSDV) for Mobile Computers", published in *SIGCOMM, London, UK, 1994, pp.234-244*.

[6] Ian D Chakeres et al. "AODV Routing Protocol implementation Design", Dept. of ECE, University of California Santa Barbara, 2004.

[7] M.K.Marina and S.R.Das, "On-Demand multipath distance vector routing in ad hoc networks" in: Proceedings of *the 9th IEEE International Conference on Network Protocols (ICNP), 2001*.

[8] J. Chuang, "The effects of time delay spread on portable radio communications channels with digital modulation," *IEEE J. Sel. Areas Commun., vol. SAC-5, no. 5, pp. 879–889, Jun. 1987*.

[9] L. J. Cimini, Jr., "Analysis and simulation of a digital mobile channel using orthogonal frequency division multiplexing," *IEEE Trans. Commun., vol. COM-33, no. 7, pp. 665–675, Jul. 1985.*

[10 ] S. Weinstein and P. Ebert, "Data transmission by frequency-division multiplexing using the discrete Fourier transform," *IEEE Trans. Commun. Technol., vol. COM-19, no. 5, pp. 628–634, Oct. 1971*.

[11] Y. (G.) Li and G. Stüber, Orthogonal Frequency Division Multiplexing for Wireless Communications. Boston, *MA: Springer-Verlag,Jan. 2006.*

[12] R . W. Chang, "Synthesis of band-limited orthogonal signals for multichannel data transmission," *Bell Syst. Tech. J., vol. 45, pp. 1775–1797, Dec. 1966.*

[13] R.W. Chang, "Orthogonal frequency divisionmultiplexing," *U. S. Patent 3 488 445, Jan. 6, 1970.Filed Nov. 4, 1966.*

[14] B. R. Saltzberg, "Performance of an efficient parallel data transmission system," *IEEE Trans. Commun. Technol., vol. COM-15, no. 6, pp. 805–811, Dec. 1967*.

[15] M. L. Doelz, E. T. Heald, and D. L. Martin, "Binary data transmission techniques for linear systems," *Proc. IRE, pp. 656–661, May 1957.*

[16] J. Holsinger, *"Digital communication over fixed time-continuous channel with memory with special application to telephone channels,"* Ph.D.dissertation, Mass. Inst. Technol., *Cambridge, MA, 1964.*

[17] B. Hirosaki, "An analysis of automatic equalizers for orthogonally multiplexed QAM systems," *IEEE Trans. Commun., vol. COM-28, no.1, pp. 73–83, Jan. 1980*.

[18] B. Hirosaki, S. Hasegawa, and A. Sabato, "Advanced groupband data modem using orthogonally multiplexed QAM technique," *IEEE Trans.Commun., vol. COM-34, no. 6, pp. 587–592, Jun. 1986.*

[19] A. Peled and A. Ruiz, "Frequency domain data transmission using reduced computational complexity algorithms," in *Proc. IEEE Int. Conf.Acoust., Speech Signal Process., 1980, pp. 964–967.*

[20] M. S. Zimmerman and A. L. Kirsch, "The AN/GSC-10 (KATHRYN) variable rate data modem for HF radio," *IEEE Trans. Commun. Technol., vol. COM-15, no. 2, pp. 197–205, Apr. 1967.*

[21] W. E. Keasler, Jr., *"Reliable data communications over the voice bandwidth telephone using orthogonal frequency division multiplexing,"* Ph.D. dissertation, Univ. Illinois, *Urbana, IL, 1982*.

[22] I. Kalet, "The multitone channel," *IEEE Trans. Commun., vol. 37, no. 2, pp. 119–124, Feb. 1989.*

[23] T. J.Willink and P. H.Wittke, "Optimization and performance evaluation of multicarrier transmission," *IEEE Trans. Inf. Theory, vol. 43, no. 2, pp. 426–440, Mar. 1997.*

[24] E. F. Casas and C. Leung, "OFDM for data communication over mobile radio FM channels. I. Analysis and experimental results," *IEEE Trans.Commun., vol. 39, no. 5, pp. 783–793, May 1991*.

[25] J. A. C. Bingham, "Multicarrier modulation for data transmission: An idea whose time has come," *IEEE Commun. Mag., vol. 28, no. 5, pp. 5– 14, May 1990*.

[26] L. J. Cimini, Jr., B. Daneshrad, and N. R. Sollenberger, "Clustered OFDM with transmitter diversity and coding," in *Proc. IEEE GlobalTelecommun. Conf., 1996, pp. 703–707.*

[27] L. J. Cimini, Jr., J. C. Chuang, and N. R. Sollenberger, "Advanced Cellular Internet Service (ACIS)," *IEEE Commun. Mag., vol. 36, no. 10, pp. 150–159, Oct. 1998.*

[28] Y. (G.) Li and N. R. Sollenberger, "Clustered OFDM with channel estimation for high rate wireless data," *IEEE Trans. Commun., vol. 49, no. 12, pp. 2071–2076, Dec. 2001.*

[29] Wireless Pers. Commun., Special Issue on Multi-Carrier Modulation, *Jan. 1996, Kluwer.*

[30] K. Fazel and G. P. Fettweis, Multi-Carrier Spread-Spectrum. Norwell, *MA: Kluwer, 1997.*

[31] D. Kim and G. L. Stüber, "Performance of multiresolution OFDM on frequency-selective fading channels," in *Proc. IEEE Global Telecommun.Conf., 1997, pp. 16–20.*

[32] A. Akansu, P. Duhamel, X. M. Lin, and M. de Courville, "Orthogonal transmultiplexers in communication: A review," *IEEE Trans. SignalProcess., vol. 46, no. 4, pp. 979–995, Apr. 1998.*

[33] A. R. S. Bahai and B. R. Saltzberg, *Multi-Carrier Digital Communications: Theory and Applications of OFDM*. New York: Plenum,1999.

[34] C. E. Shannon, "A mathematical theory of communication," *Bell Syst. Tech. J.*, vol. 27, pp. 379–423, Jul.–Oct. 1948.

[35] R. G. Gallager, *Information Theory and Reliable Communication*.New York: Wiley, 1968.

[36] P. S. Chow, J.M. Cioffi, and J. A. C. Bingham, "A practical discrete multitonetransceiver loading algorithm for data transmission over spectrally shaped channels," *IEEE Trans. Commun., vol. 43, no. 2–4, pp. 773–775, Feb.–Apr. 1995.*

[37] L. M. C. Hoo, J. Tellado, and J.M. Cioffi, "Dual QoS loading algorithms for DMT systems offering CBR and VBR services," in *Proc. IEEEGlobal Telecommun. Conf., 1998, pp. 25–30*.

[38] B. S. Krongold, K. Ramchandran, and D. L. Jones, "Computationally efficient optimal power allocation algorithms for multicarrier 1690 IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, *IEEE Trans. Commun., vol. 48, no. 1, pp. 23– 27, Jan. 2000.*

[39] D. L. Goeckel and G. Ananthaswamy, "Increasing diversity with nonstandard signal sets in wireless OFDM systems," in *Proc. IEEE Wireless Commun.Netw. Conf., 1999, pp. 20–24.*

[40] G. J. Foschini, "Layered space–time architecture for wireless communication in a fading environment when using multi-element antennas," *BellLabs Tech. J., vol. 1, no. 2, pp. 41–59, Autumn 1996.*

[41] V. Tarokh, N. Seshadri, and A. R. Calderbank, "Space–time codes for high data rate wireless communication: Performance criteria and code construction," *IEEE Trans. Inf. Theory, vol. 44, no. 2, pp. 744–764,Mar. 1998.*