

STUDY OF MULTICARRIER MODULATION

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Abstract

Multicarrier modulation is a technology that is receiving increased attention in recent years in wireless communication systems especially for multimedia transmission. The idea can be dated back to 1960s. Since then, various multicarrier schemes have been proposed and some of them have already been used in real-world applications.

1 Introduction

There are four principal media for transmission of high-speed data to and from a customer premises [3]:

1. DSL: Digital Subscriber Loop. It mainly uses Discrete Multi-tone (DMT) technique that is widely applied to xDSL.
2. Coaxial cable: originally installed for unidirectional ("downstream") transmission of television, but increasingly being used for bi-directional data transmission.
3. Optical fiber: it is originally used for very high-speed trunk transmission, but now being implemented in FTTH (Fiber To The Home), FTTE (Fiber To The Exchange) and FTTN (Fiber To The Neighborhood).
4. Wireless: use of multicarrier modulation becomes an attractive solution in wireless, high data speed transmission system.

The DMT technique is a version of MCM in the baseband, and OFDM (orthogonal frequency division multiplexing) technique is a special case of MCM in the passband. In the discussion below, if not specified, all MCM means multicarrier modulation in the passband.

Multicarrier Modulation has been called by many names – orthogonally multiplexed Quadrature Amplitude Modulation, orthogonal FDM, and dynamically assigned multiple QAM [4]. It is greatly developed to practical application as signal processing techniques (mainly digital) have improved over

the years. An MCM signal can be processed in a receiver without the enhancement of noise or interference and the long symbol time used in MCM produces a much greater immunity to impulse noise and fast fades [4].

The following sections will have a look backward to the history of MCM, the key techniques used in MCM, the current applications of MCM and finally look forward to the future of MCM. This paper will also investigate the components with related products used in the modulation process, and some wireless LAN standards.

2 History of Multicarrier Modulation

The principle of transmitting data by dividing it into several interleaved bit streams and using these to modulate several carriers was originally applied in Collins' Kineplex system more than 30 years ago. It has since been developed with varying degrees of success:

- MCM was implemented in high frequency military modems in the '60s as well as in some telephone modems [8].
- Orthogonal multiplexed QAM [3]: it was used in FDM telephony group-band modems and its main advantage over single-carrier modems was a much-reduced sensitivity to impulse noise.
- Dynamically assigned multiple QAM [3]: this technique was used in telephony voice-band modems. It was ideal for applications like file transfer using UNIX. But it was rejected because of its large latency – it used 1024 subcarriers with a spacing of approximately 4Hz.
- Synchronized discrete multitone (SDMT) [3]: this was applied to upstream cable modem of 5- to 40- MHz upstream band in a hybrid fiber coax (HFC) system. SDMT uses a combination of frequency-division multiple access (FDMA) and time DMA (TDMA).
- Coded orthogonal frequency-division multiplexing (COFDM) [3]: the technique was implemented in digital audio broadcasting and it is a version of MCM that uses IFFT modulation, fixed bit loading, and sophisticated

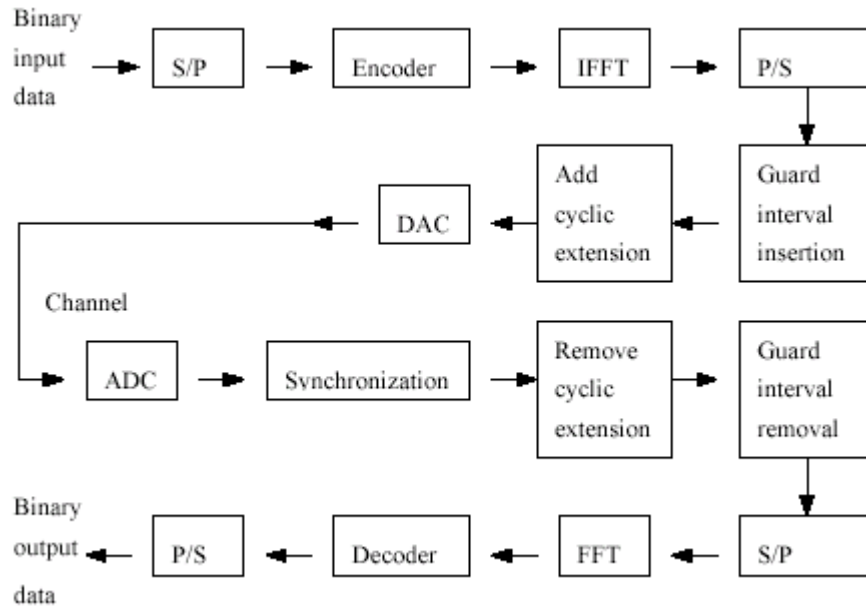


Figure 1: A block diagram of an MCM transceiver

coding schemes to overcome the fades that result from multipath. It has been standardized in Europe as the Eureka system. COFDM has also been standardized for digital video broadcasting, such as digital TV.

- Digital audio radio [3]: it was tested by using a version of DMT in the United States in 1994 in the same frequency bands as the established FM stations. It performed as well as could be expected in the very severe narrowband, low-power, high-noise (from the FM signal) multipath-distorted environment, but that was not good enough for widespread deployment.

3 MCM key techniques

In this section, we will look at the definition of multicarrier modulation, the structure of its transmitter and receiver, a special case of MCM – OFDM, and the modulation components as well as some wireless LAN standards.

3.1 Definition

The basic principle of MCM is to split a high-rate data stream into a number of lower-rate streams that are transmitted simultaneously over a number of subcarriers [6]. It is a form of FDM. OFDM is the most widely used form of MCM that plays an important role in today's mobile communication system.

There is an interesting frequency/time domain duality between MCM and SCM (Single-Carrier Modulation) [8]: what SCM does in the time domain MCM does in the frequency domain, and vice versa.

Another frequency-time duality is that, to prevent inter-symbol interference, SCM needs to reserve part of the

spectrum for pulse shaping (frequency domain), while MCM needs to insert guard intervals (time domain).

3.2 MCM transmitter and receiver

A block diagram of an MCM transceiver is shown in Fig. 1 [4,6,8].

In the transmitter path, binary input data is first sent to a serial-to-parallel buffer. Then it is encoded so that the parallel binary bits can be modulated onto subcarriers by applying IFFT. One important feature of MCM is that, by inserting a guard interval between the MCM symbols, or FFT blocks, the inter-symbol interference (ISI) can be eliminated almost completely; and using “cyclic extension” in the guard time, the inter-carrier interference (ICI) can be avoided and makes the system robust to multipath propagation. Fig. 2 shows an MCM symbol with cyclic extension [6].

The MCM receiver basically performs the reverse operations of the transmitter. First, the receiver has to estimate frequency offset and symbol timing. Then it can do an FFT for every symbol to recover the modulated values of all subcarriers. At last a decoder can decode the information bits.

In an MCM based communication system, the modulated carriers are summed for transmission, and must be separated in the receiver before demodulation. Three methods have been used for this separation [3,4]:

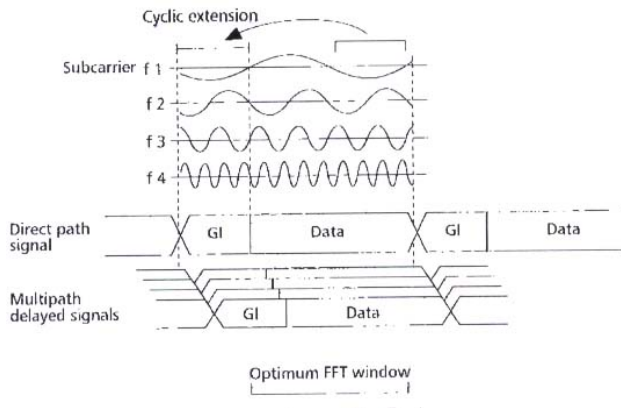


Figure 2: An MCM symbol with cyclic extension

- Bandpass filter: Early systems used filters that completely separated the subbands in order to maintain orthogonality, with a consequent loss of bandwidth efficiency. The transmitted power spectra for just three sub-bands of a multicarrier system are shown in Fig. 3a.
- SQAM (Staggered Quadrature Amplitude Modulation): the individual transmit spectras of the modulated carriers overlap at the -3dB frequencies (as shown in Fig. 3b), and the composite spectrum is flat. The total number of carriers must be small (typically less than 20).

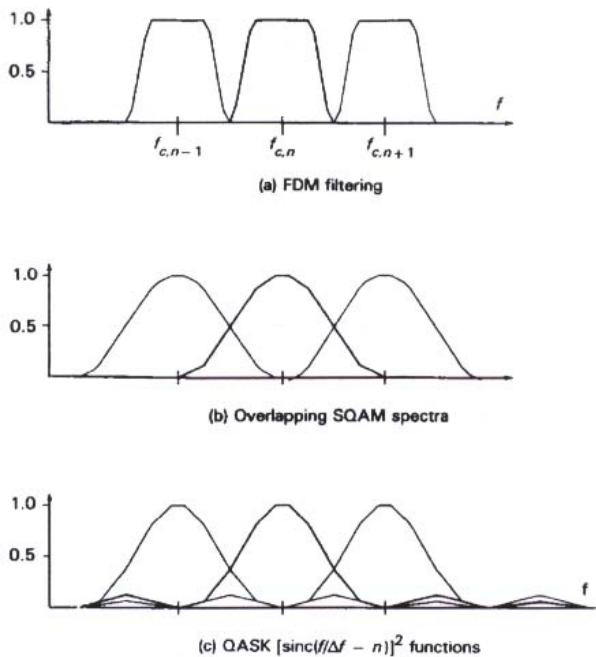


Figure 3: MCM transmit power spectra

- QASK (Quadrature Amplitude Shift Keying): the individual spectra are now sinc functions, as shown in Fig. 3c. They are not bandlimited but the signals can still be separated in the receiver. The frequency-division is achieved by baseband processing. The big advantage is that both transmitter and receiver can be implemented using efficient Fast Fourier Transform (FFT) techniques.

3.3 Orthogonality

OFDM is the most widely used MCM technology today. It has drawn a lot of attention in the field of radio communications. This is mainly because of the need to transmit high data rate in a mobile environment that makes a highly hostile radio channel. To overcome this problem, the OFDM seems to be a solution [7].

OFDM solves the difficult intersymbol interference problem encountered with high data rates across multipath channels. By dividing the bandwidth into many small orthogonal frequencies, the data can be transmitted across multiple narrowband channels, which suffer only from flat fading [1].

Although OFDM scheme is robust to frequency selective fading, it has severe disadvantages such as difficulty in subcarrier synchronization. However, the combination of OFDM signaling and CDMA scheme has one major advantage that it can lower the symbol rate in each subcarrier so that a longer symbol duration makes it easier to quasi-synchronize the transmissions [7]. This MC-CDMA will be investigated in the later parts.

In practice, the most efficient way to generate the sum of a large number of subcarriers is by using inverse Fast Fourier Transform (IFFT). At the receiver side, FFT can be used to demodulate all subcarriers. Fig. 2 shows that all subcarriers differ by an integer number of cycles within the FFT integration time, which ensures orthogonality between the different subcarriers. The receiver sees a summation of time-shifted replicas of each OFDM symbol. As long as the delay spread is smaller than the guard time, there is no ISI or ICI within the FFT interval of an OFDM symbol [6].

Synchronous problem due to multipath is left to be the random phase and amplitude of each subcarrier, which has to be estimated in order to do coherent detection.

3.4 Modulation components

The main modulation and de-modulation processing is done with an IFFT and an FFT. Another two important components in the process are the DAC and ADC.

- IFFT and FFT

The multicarrier modulation can be efficiently implemented using IFFT. For an MCM system, the use of a guard interval can eliminate the ISI, but it also reduces data throughput. To minimize the loss of throughput, the size of the FFT must be increased. The size of the FFT is limited by digital signal processing (DSP) speed, receiver phase noise, and cost.

Table 1 shows various FFT processors available at market. In the early 1990s, fast speed FFT processor (like Dassault Electronique's product) is achieved at the cost of large power consumption. As the fabrication technique develops, power consumption reduces with increased clock and size. Most recent processors can execute at least 1000 complex-point FFTs in 10 μs .

FFT Processor	Company	Features
Dassault Electronique 12bit	Dassault Electronique	Yr 1991 1.0um CMOS tech 6.4usec/1024 pt xform 24000mW 40MHz Area: 255 mm ²
Cobra 23bit	Cobra Colorado State	Yr 1994 0.75um CMOS tech 9.5usec/1024 pt xform 7700mW 40MHz 1104+ mm ²
PowerFFT 24bit	doubleBW (TaiWan)	Yr 2000 10µsec/1024 pt xform 8000mW 128MHz Area: 429 mm ²
RDA 108 - Single Chip FFT <=19bit	Radix Technologies Inc.	Yr 2002 2048 point Complex FFT in 24.3 uS 1024 point Complex FFT in 12.2 uS

Table 1: FFT processors at market nowadays

● DAC and ADC

Table 2 lists today's commercial DAC and ADC products with their features.

Product	Company	Features
7-8 bit Flash A/D Converters ADS-318/318A	DATEL, Inc. [USA]	20-100MHz sample rate
DAC 8 bit: DAC908 10 bit: DAC900 12 bit: DAC902 14 bit: DAC5675	Texas Instruments Incorporated [USA]	Update rate 8 bit: 165MSPS 10 bit: 165MSPS 12 bit: 165MSPS 14 bit: 400MSPS
A/D AD9238, ideal for medical imaging, wireless infrastructure	Analog Devices, Inc.	For sampling inputs at frequencies up to 200 MHz, well beyond the

and test equipment		Nyquist rate.(20-65MSPS)
D/A AD9772A: the industry's first direct IF-capable multi-mode DAC (14-Bit, 160 MSPS)	Analog Devices, Inc.	Implementations for multi-carrier IS95 and multi-mode (GSM/EDGE) systems, as well as for 3G (cdma2000, WB-CDMA) cellular basestations.

Table 2: Commercial DAC and ADC products

3.5 Wireless LAN standards

At present, WLANs supporting broadband multimedia communication are being developed and standardized around the world. Standards include 802.11a, defined by the IEEE, HIPERLAN/2, defined by ETSI BRAN, and HiSWANa defined by Multimedia Mobile Access Communication (MMAC). These systems provide channel adaptive data rates up to 54Mb/s (in a 20 MHz channel spacing) in the 5 GHz radio band [2].

The physical (PHY) layers of these new standards will support multiple transmission modes, providing raw data rates of up to 54 Mb/s where channel conditions permit. All the three standards select OFDM as their PHY standards.

- IEEE 802.11a: it uses a distributed MAC protocol based on a carrier sense multiple access with collision avoidance (CSMA/CA) protocol. The use of a distributed MAC makes IEEE 802.11a more suitable for ad hoc networking and non-real-time applications. It also supports variable length packets [2].
- HIPERLAN/2: medium access is based on a TDMA/TDD approach using a centralized scheduled MAC. It employs fixed length packets and is designed to provide quality of service support for wireless indoor LAN, essential to many multimedia and real-time applications [2,6].
- HiSWANa: in Japan, the Ministry of Post and Telecommunications started a standardization effort of MMAC systems which includes ultra-high-speed indoor WLANs supporting large volume data transmission at speeds up to 156 Mb/s using frequencies in the 30-300 GHz band and high-speed wireless access at 25-30 Mb/s in the super-high frequency (SHF) band (3-60 GHz) [6].

4 Current applications of MCM

MCM is now applied in areas such as Digital Television Terrestrial Broadcasting (DTTB), ADSL and MC-CDMA.

4.1 Digital Television Terrestrial Broadcasting

Current advanced television (ATV) research for terrestrial broadcasting in the VHF/UHF bands is converging toward a fully digital implementation. In the United States, a Grand Alliance has been formed to introduce an ATV terrestrial transmissions standard for the United States [8].

In Europe, several projects are underway to develop digital ATV systems, such as the HDDIVINE project of the Nordic countries, the SPECTRE project of ITC and NTL (United Kingdom), the DIAMOND project of Thomson-CSF/LER (France), and the STERNE project of CCETT (France) [8].

DTTB has been developed since 1990s. From November 1998, North America and Europe have started to deliver DTTB programme. Now there are three DTTB transmission standards in the world:

- Advanced Television Systems Committee (ATSC): was developed in America using Trellis-Coded 8-Level Vestigial Side-Band (TCM 8-VSB) modulation.
- Digital Video Terrestrial Broadcasting-Terrestrial (DVB-T): was developed in Europe using Coded Orthogonal Frequency Division Multiplexing (COFDM).
- Integrated Service Digital Broadcasting-Terrestrial (ISDB-T): was developed in Japan using Band Width Segmented Transmission OFDM (BST-OFDM).

Among the three standards, ATSC uses SCM while the other two use MCM.

4.2 ADSL

Asymmetric Digital Subscriber Line is a transmission system capable of realizing rates from 1 to several Mb/s over existing telephone lines. ADSL is asymmetric – high-speed downstream, lower-speed upstream – to counteract speed limitations imposed by line length and crosstalk.

At present, ADSL has three modulation techniques [5].

1. DMT: divides the line into many small channels and modulates each one based on its capacity for a given line. Present ADSL designs with DMT create 256 downstream channels of 4kHz with an aggregate symbol period of 250us. An FDM arrangement would also remove the bandwidth needed for the upstream.
2. SCM: the parent line code for all ADSL is QAM. It has the best combination of bandwidth efficiency, performance in the presence of noise, and timing robustness.
3. MCM: in the early 1980s it was shown that multiple channels could be realized with digital techniques using a fast Fourier transform (FFT), giving rise to DMT, the version of multicarrier used in ADSL.

Table 3 shows a list of ADSL modems at market today.

Product	Company	Features
Aztech ADSL Ethernet & USB Combo Bridge/Router (DSL 906EU)	Aztech Systems Ltd	It supports Full-Rate ADSL transmission at up to 8Mbps downstream and up to 1Mbps upstream.
3Com HomeConnect ADSL Modem PCI	3Com Corporation	G.dmt: Up to 8 Mbps downstream (to subscriber) and 1 Mbps upstream (from subscriber); G.lite: Up to 1.5 Mbps downstream and 512 Kbps upstream
Alcatel Speed Touch 350i Ethernet ADSL Modem for ISDN	Compagnie Financière Alcatel, Paris, France	Up to 8 Mbps downstream, 800 Kbps upstream Can operate as a standalone network adapter

Table 3: ADSL modems available at market

4.3 MC-CDMA

Multicarrier CDMA represents a fusion of two radio access techniques – OFDM (discussed above) and CDMA.

CDMA (Code-Division Multiple Access) is a multiplexing technique where a number of users simultaneously and asynchronously access a channel by modulating and spread their information-bearing signals with preassigned signature sequences [7].

CDMA has been considered to be a candidate to support multimedia services in mobile radio communications. CDMA has its own capabilities to cope with asynchronous nature of multimedia data traffic, to provide higher capacity over conventional access techniques such as TDMA and FDMA [1,7].

There are three types of multiple access schemes for combining CDMA with OFDM, namely MC-CDMA, multicarrier DS (Direct Sequence)-CDMA, MT-CDMA. These signals can be easily transmitted and received using the fast Fourier transform (FFT) device without increasing the transmitter and receiver complexities, and have the attractive feature of high spectral efficiency due to minimally densely subcarrier spacing.

The commercial applications of MC-CDMA products are listed in Table 4.

Product	Company	Features
CDMA Radio Access Network	Nortel Networks Limited 2002	Transceiver System (BTS) supporting IS-95, CDMA2000 1X, 1xEV, 800MHz and 1900MHz simultaneously.
Flexent Modular Cell 3.0	Lucent Technologies	The Flexent Modular Cell 3.0 supports 2G and 3G CDMA2000 1X & CDMA2000 1xEV-DO.
Flexent CDMA Distributed Base Station for Cellular Networks Flexent CDMA Distributed Base Station for PCS Networks	Lucent Technologies	The Flexent CDMA Distributed Base Station is 3G ready.

Table 4: Commercial CDMA products

5 The future of multicarrier technology

Multicarrier modulation technique has stood out in wireless high-speed data transmission. It makes multimedia access possible for the next generation wireless communication system. For example, to surf Internet on an airplane is just a start today. Deutsche Lufthansa AG airlines and Boeing Company will equip their planes so that travelers can access Internet during their trip.

Current civil aviation communication system contains VHF, HF, SELCAL and AIS. However, the frequency band for use is limited to 118.000-135.975MHz (VHF) and 2-30MHz (HF). MCM can be used instead of current AM communication, but the bandwidth will be narrow compared to broadband network and higher than modem dial-up network.

There are two ways to implement MCM in airplane communications. Both methods have a limited transmission distance so that communicating with synchronous satellite directly may not be possible. First, MCM may be implemented in UHF (300-3000MHz with around 100km transmission capability) or SHF (3-30GHz with around 30km transmission capability) to provide Internet service on-board. This method needs large power to transmit broadband signals and may interfere with current civil aviation communicating frequency. Second, current frequency band may be used but not in amplitude modulation – instead, we may apply MCM to have current civil aviation communication and Internet

access concurrently. The bandwidth may be varied and IP transfer needs to be considered, but these are not in the scope of this paper.

MCM is a hot topic today and will have excellent contribution to people's life tomorrow.

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