ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING: A MULTI-CARRIER MODULATION SCHEME

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Abstract

This paper presents a multi-carrier digital modulation technique — orthogonal frequency division multiplexing. A brief review of the technique and its recent development and implementation are provided. The advantages and disadvantages in comparison to other modulation techniques are also discussed.

1. Introduction

The orthogonal frequency division multiplexing (OFDM) is a form of multi-carrier modulation technique that was first introduced more than three decades ago. Recent advances in digital signal processing (DSP) and very large scale integrated circuit (VLSI) technologies have paved the way for the massive implementation of OFDM techniques in the consumer electronics field. One recent successful implementation of OFDM is in digital audio broadcasting (DAB) [1], which was developed in Europe for terrestrial and satellite broadcasting of multiple digital audio programs to mobile receivers. Another recent implementation is in asymmetric digital subscriber line (ADSL) technology that has been selected by ANSI for transmission of digitally compressed video signals over telephone lines [2].

OFDM has been evaluated in Europe and elsewhere for digital television terrestrial broadcasting. In Europe, a pan-European project Digital Video Broadcasting (DVB) was launched in 1993 with more than 130 participants including broadcasters, manufacturers, carriers and radio regulatory bodies. Its DVB–T project is expected to develop a terrestrial distribution system with data throughput up to 24 Mbps over an 8 MHz channel using OFDM. Under the umbrella of DVB–T, there are many projects under development. Most of them started before the formal launching of the DVB project. Among them are HD-DIVINE (DIgital VIdeo Narrowband Emission) developed by Nordic Countries, DIAMOND by Thomson-CFS/LER, STERNE (Systeme de TElevision en Radiodiffusion NumeriqE) by CCETT (a joint venture of France Telecom and TDF), SPECTRE (Special Purpose Extra Channels for Terrestrial Radiocommunication Enhancements) by NTL, $^{H}DTV_{T}$ (Hierarchical Digital TV Transmission) in Germany, and dTTb (Digital Television Terrestrial Broadcasting) by the Commission of the European Communities (CEC) [3]. In Japan, OFDM is under investigation by many organizations for terrestrial broadcasting over a 6 MHz channel. In America, several broadcasting organizations of the United States, Canada and Brazil have also decided to investigate the COFDM for 6 MHz ATV terrestrial distribution.

However, early development of OFDM can be traced back to North America in the late 50s [4]. A U.S. patent was filed and issued in 1970 [5]. In the telecommunications field, the terms of discrete multi-tone (DMT) modulation, orthogonal multi-carrier modulation, multi-channel modulation, and multi-carrier modulation (MCM) are widely used, and they are often interchangeable with OFDM. COFDM means coded OFDM, where channel coding, or forward error correction (FEC), is used for error protection.

This paper presents a brief review of the OFDM technique. Ideas of using a guard interval to accommodate long delay ghosts and of creating spectrum notches to combat co-channel interferences, as well as of assigning different order of modulations or power levels to different sub-carriers for layered services are discussed. The effects of phase noise and the peak-to-average power ratio of the OFDM signal are also analysed.

2. Basic Principles of OFDM

In a conventional serial data transmission system, the information bearing symbols are transmitted sequentially, with the frequency spectrum of each symbol occupying the entire available bandwidth. Figure 1(a) is an unfiltered QAM signal spectrum. It is in the form of $\sin(x)/x$, with zero crossing points at multiples of $1/T_s$, where T_s is the QAM symbol period.

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The concept of OFDM is to transmit the data in parallel QAM modulated sub-carriers using frequency division multiplexing. The carrier spacing is carefully selected so that each sub-carrier is located on all the other sub-carriers' spectra zero crossing points. Although there are spectral overlaps among sub-carriers, they do not interfere with each other, if they are sampled at the sub-carrier frequencies. In other words, they maintain spectral orthogonality. Figure 1(b) is an OFDM signal spectrum, where the sub-carrier spacing is $1/T_s$.

Since an OFDM signal consists of many parallel QAM sub-carriers, the mathematical expression of the signal is,

$$X(t_m) = \sum_{n=0}^{N-1} (a_n \cos \omega_n t_m + b_n \sin \omega_n t_m) \qquad (1)$$

where a_n and b_n are the in-phase and quadrature terms of the QAM signal, and ω_n is the sub-carrier frequency.

For a large number of sub-carriers, direct generation and demodulation of the OFDM signal requires arrays of coherent sinusoidal generators that can become unreasonably complex and expensive. However, by observing Eq-1, one can notice that the OFDM signal is actually the real part of the Inverse Discrete Fourier Transform (IDFT) of the original data $d_n = a_n + jb_n$ [6], i.e.,

$$\begin{aligned} X(t_m) &= Re\{\sum_{n=0}^{N-1} (a_n + jb_n) \cdot \exp(-j\omega_n t_m)\} \qquad (2) \\ &= Re\{\sum_{n=0}^{N-1} (a_n + jb_n)(\cos \omega_n t_m - j \sin \omega_n t_m)\} \\ &= \sum_{n=0}^{N-1} (a_n \cos \omega_n t_m + b_n \sin \omega_n t_m) \end{aligned}$$

where, $\omega_n = 2\pi n/(N\Delta t)$, $t_m = m\Delta t$ and Δt is the symbol duration of the input serial data d_n. It can be seen that there are N sub-carriers each carrying the corresponding data $a_n + jb_n$, and the sub-carrier spacing is $1/(\Delta t \cdot N)$. The inverse of the sub-carrier spacing, $\Delta t \cdot N$, is usually defined as the OFDM useful symbol duration, which is N times longer than that of the original data symbol duration Δt.

Since IDFT is used in the OFDM modulator, the original data d_n is defined in the frequency domain, while the OFDM signal $X(t_m)$ is defined in the time domain. The IDFT can be implemented via a computationally efficient fast Fourier transform (FFT) algorithm [7].

3. Guard Interval and Its Implementation

The orthogonality of sub-carriers in OFDM can be maintained and individual sub-carriers can be completely separated and demodulated by FFT at the receiver when there is no inter-symbol interference (ISI) introduced by transmission channel distortion. In practice, linear distortions such as multipath delay and micro-reflection cause ISI between OFDM symbols, resulting in loss of orthogonality and an effect that is similar to co-channel interference [8]. However, when delay spread is small, i.e., within a few percentage points of the OFDM symbol length, the impact of ISI is insignificant, although it depends on the order of modulation implemented by the sub-carriers.

A simple solution to deal with multipath delay is to increase the OFDM symbol duration so that it is much larger than that of the delay spread. But this may be difficult to implement. When the delay spread is large, it requires a large number of sub-carriers and a large size FFT. Meanwhile the system might be sensitive to Doppler shift and carrier instability.

Another way to manipulate multipath distortion is to create a cyclically extended guard interval, where each OFDM symbol is preceded by a periodic extension of the signal itself [9]. The total symbol duration is $T_{total} = T_g + T_s$, where T_g is the guard interval and T_s is the useful symbol duration. When the guard interval is longer than the channel impulse response, or the multipath delay, ISI can be eliminated. However, the in-band fading will still exist [10]. The ratio of the guard interval to useful symbol duration is application-dependent. Since the insertion of guard intervals will reduce data throughput, T_g is usually less than $T_s/4$.

Since the OFDM symbol duration T_s is quite long, usually several hundred micro-seconds, and the VHF/UHF broadcast channel impulse responses are only in the order of $10-30$ μs, inserting a guard interval of that range will not significantly reduce the data throughput. Meanwhile, as mentioned earlier, even if the impulse response is slightly longer than the guard interval, i.e., a few percentage points of T_s, the impact on the system performance is limited. On the other hand, as the symbol duration for single carrier modulation system, such as QAM and VSB, is only about $0.1-0.2$ μs, it is impossible to insert a guard interval comparable to the terrestrial broadcast channel response to eliminate ISI. Other techniques, such as adaptive equalization, must be used.

An OFDM system diagram is shown in Figure 2. The incoming bit stream is first packed into x bits per symbol to form a complex number, where x determines the signal constellation, such as 32 QAM or 64 QAM. These QAM modulated data are, then, converted from serial to parallel with N complex numbers, or QAM symbols, per block. Each block is modulated by an IFFT process. The output of the IFFT forms an OFDM symbol, which is converted back to serial data for transmission. A guard interval is inserted between symbols to eliminate ISI caused by multipath distortion. The discrete

symbols are filtered and converted to analogue for RF up-conversion. The receiver performs the inverse process of the transmitter. An one-tap equalizer is usually used for each sub-carrier to correct channel distortion. The tap coefficients are calculated based on channel information.

From Figures 1(b) and 2, it can easily be understood that the OFDM signal spectrum is close to rectangular. Actually, the spectrum is directly related to the original data. Since the OFDM modulator is an IFFT process, its physical meaning is to convert data from the frequency domain to the time domain and, then, transmit them in the time domain over the channel. If a spectrum analyser, which is a device that converts its input from the time domain to the frequency domain, is used to monitor an OFDM signal, what displayed is the original data.

4. OFDM performance Expectation

4.1 Multipath Distortion and Fading

When there is multipath distortion, a conventional single carrier wide-band transmission system suffers frequency selective fading. A high speed adaptive equalizer has to be used to equalize the in-band fading. The number of taps required for the equalizer is proportional to the symbol rate and the multipath delay. For VHF/UHF broadcasting channels, up to several hundred taps are required.

For an OFDM system, as mentioned in Section 2, if the guard interval is longer than the multipath delay, ISI can be eliminated and orthogonality can be maintained among sub-carriers. However, in-band fading will still exist [10], therefore some of the sub-carriers are enhanced and others are attenuated. Since each OFDM sub-carrier occupies a very narrow spectrum, in the order of a few kHz, even under severe multipath distortions, they are only subject to flat fading. In other words, the OFDM can convert a wide-band frequency selective fading channel into a series of narrow-band frequency non-selective fading sub-channels by using the parallel multi-carrier transmission scheme. There is no need to implement a sophisticated adaptive equalizer for each sub-carrier, when QPSK or MPSK modulation is used. When high order QAM is implemented, channel estimation is required. Each sub-carrier needs a well behaved one-tap equalizer. There is no requirement, however, to adapt to the instantaneous channel response (Section 4.3).

4.2 Trellis Coded OFDM: COFDM

Since OFDM can convert a wide-band frequency selective fading channel into a series of narrow-band frequency non-selective fading sub-channels, it is natural to implement trellis coded modulation (TCM) [11], that is specially designed for frequency non-selective fading channels, to sequentially code the OFDM sub-carriers. At the receiving end, Viterbi decoding can be used to take full advantage of the soft-decision nature of the OFDM demodulator output. Substantial coding gain can be achieved for fading channels, such as Rayleigh and Ricean channels, especially for wide-band mobile communications. The trellis coded OFDM system is usually called COFDM. In digital television implementation, which requires extremely low bit error rate (BER), another layer of channel coding, usually a Reed-Solomon code, is implemented to improve the BER performance and correct the burst errors created by the trellis decoder. It should be noted that TCM coding increases only the constellation size and uses this additional redundancy to trellis code the signal. There is no bandwidth extension.

4.3 Time Domain Short Term Distortion and Interference

As indicated in Section 2, the OFDM symbol duration, which is equal to the inverse of the sub-carrier spacing, is quite long, usually in the order of $200-1000\ \mu s$. Therefore, any short term distortion and interference caused by time domain impulse interference, amplitude clipping, short term fading and instantaneous change of channel response will be averaged out by the FFT process in the receiver over the entire OFDM symbol period. If distortion and interference occurs during a small fraction of the OFDM symbol period, their impact is negligible, since all of the data sub-carriers would only be slightly affected, but still decodable. In a single carrier system, however, a few symbols could be destroyed completely causing a short burst of errors.

4.3 Frequency Domain Interference

OFDM systems are quite sensitive to the frequency domain interference, such as tone interference and NTSC co-channel interference, where there are three carriers carrying luminance, chrominance and audio signals, respectively. For a single carrier modulation system, where one carrier occupies the entire channel, a tone interference will not cause eye-diagram closure and consequently no transmission error as long as its level is sufficiently lower than that of the carrier. For an OFDM system, the transmission power is divided among many sub-carriers. Therefore, even low level tone interference could destroy the corresponding sub-carriers and cause errors.

One way to mitigate the tone and NTSC interference for an OFDM system is through spectrum shaping. From Eq.-2 and Figure 2, since the input data $d_n = a_n + jb_n$ correspond to frequency domain sub-carriers, by simply assigning some data zero value will create spectrum notches. When the notches are co-located with interfering tones, there will be no impact on the OFDM signal. The major disadvantage of creating spectrum notches is the reduction of data throughput. Using trellis cod-

ing with soft-decision decoding might be a better approach than spectrum shaping, since there is no loss of the throughput and the effect of tone interference on the OFDM signal is much like that of a fading channel case (Section 4.1 and 4.2) and can be solved in a similar way.

4.4 Hierarchical Modulation to Provide Layered Services

Similar to spectrum shaping, since the input data $d_n = a_n + jb_n$ correspond to frequency domain sub-carriers, the modulation type, constellation size and power level for each sub-carrier can be easily adjusted. Some sub-carriers can use low order QAM or MPSK modulation and/or higher power level to provide robust base layer service. Other sub-carriers can implement high order QAM constellations for other layers of services. As a result, a broadcast system with "graceful degradation" can be achieved. The idea behind graceful degradation is to arrange for the quality of the received signal to reduce gradually with decreasing signal strength, rather than failing abruptly as digital signals normally do.

It should be pointed out that the implementation of such a hierarchical modulation system is subject to a CNR penalty. For example, if the aggregate data rate for a HDTV service is fixed, since part of the data are assigned to a low order of modulation for robustness, the rest of the data might be forced to use a higher order of modulation, i.e., higher than a stand-alone non-layered service system would use. Therefore the CNR requirement for a hierarchical modulation system to provide HDTV service would be higher than that of a stand-alone HDTV system. Meanwhile, for a fixed data rate, present scalable video coding techniques would provide a picture quality slightly inferior to the quality of a stand alone HDTV system [12].

4.5 OFDM Signal Peak-to-Average Power Ratio

Since OFDM data sub-carriers are statistically independent and identically distributed, based on the central limit theorem, when the number of carriers, N, is large, the OFDM signal distribution tends to be Gaussian. Generally, when $N > 20$, which is the case for most of the OFDM systems, the distribution is very close to Gaussian; and it is, somehow, independent of the carrier constellation and the number of sub-carriers [10]. On the other hand, the peak-to-average power ratio (PAR) for a single carrier modulation signal depends on its constellation and the pulse shaping filter roll-off factor α. For a Gaussian distribution, the PAR of 99.0, 99.9 and 99.99% of time are 8.3, 10.3 and 11.8 dB respectively.

Since the OFDM signal has a high PAR, it could be clipped in the transmitter power amplifier, because of its limited dynamic range or non-linearity. Higher Output Back Off is required to prevent BER degradation and intermodulation products spilling into adjacent channels.

However, clipping of an OFDM signal has similar effect as impulse interference against which an OFDM system is inherently robust. Computer simulations show that, for a trellis coded OFDM system, clipping of 0.5% of the time results in a BER degradation of 0.2 dB [10]. At 0.1 % of clipping, the degradation is less than 0.1 dB.

The critical factor for the selection of the transmitter operating parameters may not be the BER performance. Instead, adjacent channel interference can be a decisive factor. This is especially important to protect analogue television service operating in a simulcasting environment.

4.6 Single Frequency Emission

Since OFDM systems can be implemented with a long guard interval, they can accommodate high-level long-delay multipath. This might allow single frequency operations, such as single frequency networks (SFN), coverage extenders and gap fillers.

A SFN is a cluster of transmitters (distributed topology) that are synchronized in both carrier frequency and signal transmission time. The guard interval of an OFDM system must be able to accommodate the "active ghosts" from all the nearby transmitters. The signal to be transmitted must be distributed to all of the transmitters within the SFN and delay adjustment (the relative signal transmission time among transmitters) is required. The spacing between transmitters, tower height, transmission power and frequency as well as the terrain environment are the key factors in the design of a SFN.

A coverage extender is similar to SFN, but uses a centralized topology. A main high power transmitter is used to cover a larger percentage of the service area. Several low power transmitters, or coverage extenders, that are frequency locked and delay adjusted to the main transmitter are implemented to extend or shape the service area to cover newly developed sub-urban communities and terrain-blocked areas. This approach is quite attractive in the simulcasting environment, where the stand-alone high-power, high-tower transmitter approach could not be implemented because of possible interference into the existing NTSC service. It also has the potential for an UHF station to match the coverage of a VHF station without using extremely high power transmitter. The delay adjustment for a coverage extender depends on its tower height, transmission power, terrain environment and the distance to the main transmitter. These parameters must be very carefully weighted and adjusted in the design and operation of a network.

The concept of a gap filler, or on-channel repeater, is to use low power repeaters to provide service for terrain blocked areas. A gap filler is frequency locked to the

main transmitter. Delay adjustment might not be required. Off-air signal pick up and retransmission might be possible, only if enough isolation can be achieved. Terrain environment, retransmission tower height and power level are the main design factors.

It should be pointed out that the frequency gen-lock of all the transmitters is crucial to the single frequency operation, since the OFDM system is sensitive to frequency offset. The motivation of single frequency operation is to preserve valuable and crowded spectrum resources and to take advantage of topography. Further investigation is required, since many factors have to be taken into consideration in the design and operation of a single frequency emission system.

4.7 Effects of Phase Noise in OFDM

The impact of local-oscillator (LO) phase noise on the performance of an OFDM system has attracted a lot of attention and has raised some doubts on the possible use of long OFDM symbol durations (in the order of $1,000\mu s$), which correspond to close sub-carrier spacings. A long symbol duration is required for implementing a long guard interval that can accommodate long delay multipath in single frequency operation without excessive reduction of data throughput. A recent study has shown that phase noise in OFDM can result in two effects: a common sub-carrier phase rotation on all the sub-carriers and a thermal-noise-like sub-carrier de-orthogonality [13].

The common phase error, i.e., constellation rotation, on all the demodulated sub-carriers, is caused by the phase noise spectrum from DC up to the frequency of sub-carrier spacing. This low-pass effect is due to the long integration time of the OFDM symbol duration. This phase error can in principle be corrected by using pilots within the same symbol (in-band pilots). The SNR caused by the common phase error can be quantified as:

$$\frac{S}{N}_{phase-rotation} = \frac{1}{I(\alpha)n_1 f_s} \tag{3}$$

where f_s is the sub-carrier spacing, n_1 is the phase noise spectral mask upper limit, $\alpha = F/f_s$, F is the equivalent spectrum mask noise bandwidth, and

$$I(\alpha) = \int_{-\alpha}^{\alpha} \frac{\sin(\pi x)}{\pi x}\, dx \tag{4}$$

with $I(0.5) = 0.774$, $I(1) = 0.903$, and $I(\infty) = 0.774$. It can be seen that, when $\alpha > 1$, or $F > f_s$, the common phase error decreases as the sub-carrier spacing decreases.

The thermal-noise-like phase error causes sub-carrier constellation blurring rather than rotation. It results from the phase noise spectrum contained within the system bandwidth. This part of the phase noise is more crucial, since it cannot be corrected. For sub-carriers in the middle of the channel, the SNR caused by the thermal-noise-like phase error can be quantified as:

$$\frac{S}{N}_{thermal-noise-like} = \frac{1}{n_1 f_s[2\alpha - I(\alpha)]} \tag{5}$$

For sub-carriers at the band-edge, there is an improvement of about 3 dB. For $\alpha > 1$, the thermal-noise-like phase noise remains more or less constant, when f_s decreases.

Combining Eq-3 and Eq-5, the total SNR caused by phase errors is:

$$\frac{S}{N}_{total-phase-error} = \frac{1}{2\alpha n_1 f_s} = \frac{1}{2n_1 F} \tag{6}$$

It is independent of sub-carrier spacing, but directly related to the LO phase noise performance n_1 and F.

4.8 Time and Frequency Domain Dualities

There are interesting frequency/time domain dualities between OFDM, which is a multi-carrier modulation (MCM) scheme, and a conventional single carrier modulation (SCM) scheme. MCM can be thought as a frequency domain technique, since all the signal processing is implemented in the frequency domain (in the transmitter, it is before the IFFT process, such as channel coding, spectrum shaping, sub-carrier power level and constellation adjustment; in the receiver, it is after the FFT process, such as channel decoding, channel equalization and phase noise tracking), while the signal is transmitted in the time domain. MCM is robust to time domain impulse interference (Section 4.2), but it is vulnerable to frequency domain impulse interference (Section 4.3). In contrast, SCM is a time domain technique. It is more robust to frequency domain impulse interference, and by duality it is vulnerable to time domain impulse interference.

Spectrum shaping and channel coding can be used to improve the performance of a MCM system against frequency domain impulse interference. Adaptive equalization and channel coding can be used for a SCM system to combat time domain impulse interference.

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).

For channels with multipath distortion, a SCM system may insert a training sequence (time domain) to assist adaptive equalizer convergence and system synchronization. A MCM system usually sends out reference symbols/carriers (frequency domain) to obtain channel state information for frequency domain equalization, phase noise tracking and channel decoding.

Both SCM and MCM have comparable BER performance over a Gaussian noise channel. However, since a MCM signal has a Gaussian distribution, while a SCM signal usually uses an equal probability signal constellation, there might be a few tenths of dB C/N advantage for a MCM system. This is because that, theoretically, to attain the channel capacity bound requires that the signal points have a Gaussian distribution [14].

5. Conclusions

An OFDM system has the following advantages:

- It is very flexible in meeting various design requirements, such as complexity, bandwidth efficiency, spectrum shaping, performance and sensitivity to various impairments.
- It requires no adaptation to instantaneous channel responses. It is robust to impulse interference and channel variations. Channel estimation is, however, required for high-order QAM modulations.
- As a parallel transmission technique, OFDM is less sensitive to shift in sampling time in comparison to serial transmission techniques.
- The bandwidth efficiency of an OFDM system approaches the Nyquist rate as the FFT size increases (this however increases system complexity and is subject to an upper-limit due to channel variations and carrier frequency offset).
- For a fixed bandwidth efficiency, the complexity (multiplications per symbol) of a FFT-based OFDM system grows logarithmically with the increase of the channel multipath spread, in comparison with a linear increase of complexity for equalizers for a single carrier system.
- A properly coded and interleaved OFDM system can exceed the BER performance of many other practical systems, especially for wide-band mobile reception where there are strong and dynamic ghosts.

The disadvantages of an OFDM system:

- Higher transmitter output back off is required in comparison to a single carrier system, because of the high peak-to-average power ratio of an OFDM system.
- As a parallel transmission technique, OFDM is more sensitive to carrier frequency offset and tone interference than that of a single carrier system.

This paper has discussed the OFDM technique and its recent development and implementation. Its advantages and disadvantages in comparison to the conventional single carrier modulation techniques have also been presented.

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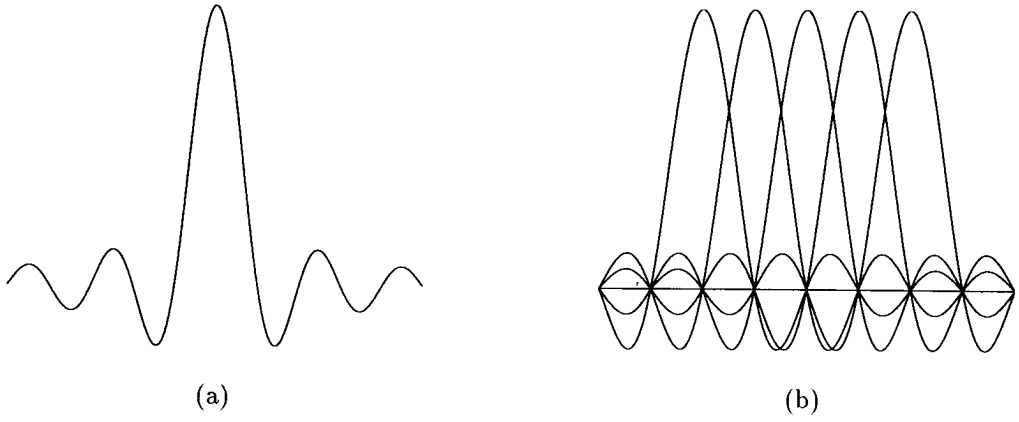


Figure 1: (a) An unfiltered QAM signal spectrum. (b) OFDM signal spectrum.

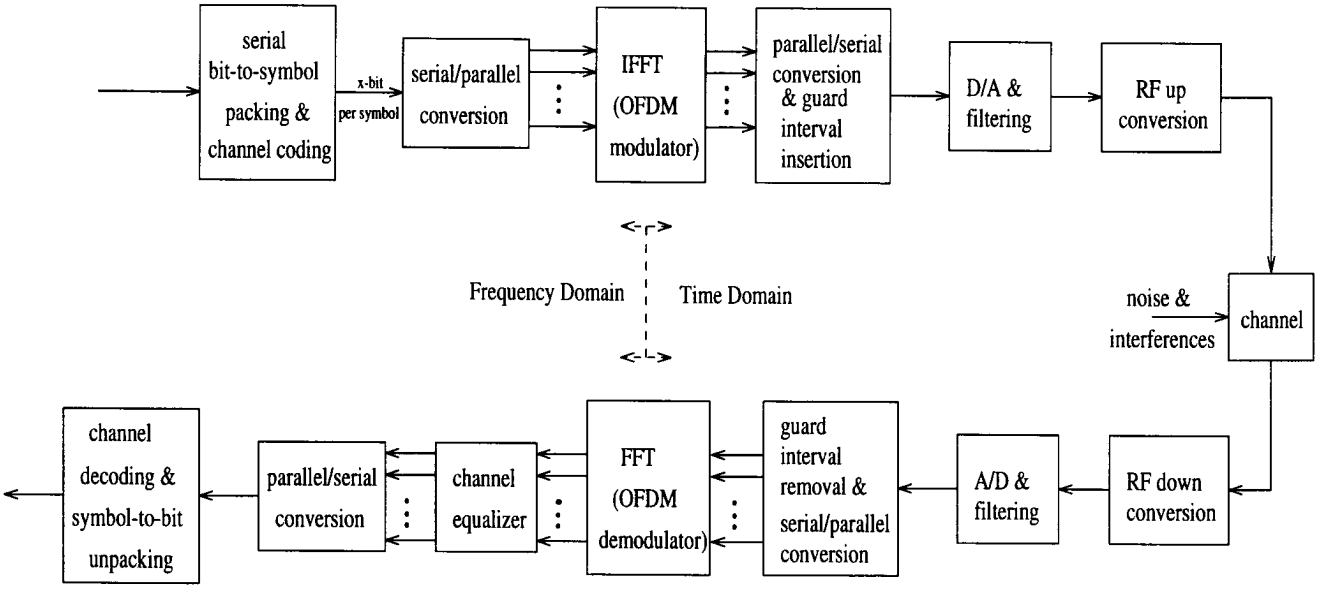
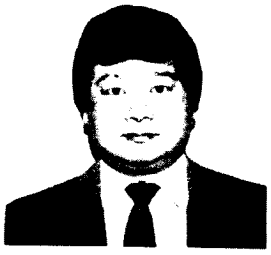


Figure 2: OFDM system diagram.



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