Cognitive radios

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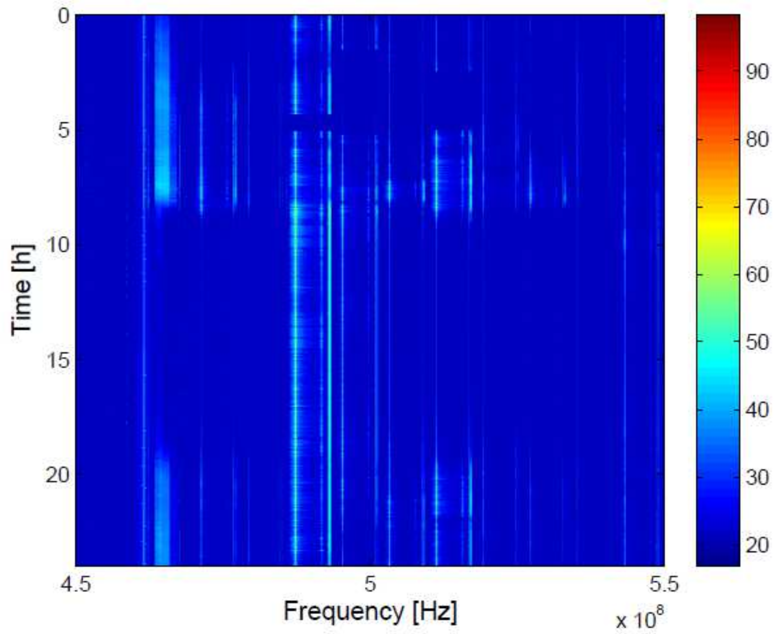
1. Cognitive Radio

Cognitive radio (CR) is one of the currently most researched topics in wireless communication, motivated by the digital changeover all over Europe. The idea of CR in white space is to install an opportunistic communication system in a given frequency band which remains hidden from the incumbent system. Nevertheless, it is also important that the opportunistic system should not disturb the incumbent ones by any means. The opportunistic system scans the band for gaps in the spectra which could be used for transmission. The standardization of CR for white space has also been started by IEEE, currently it is in draft stage (IEEE 802.22 [1], IEEE 1900.6 [2]). Also, numerous international projects dealing with this topic have been curried out in the recent years:

- Physical layer for dynamic spectrum access and cognitive radio (Phydyas): *www.ict-phydyas.org/*
- Quality of Service and MObility driven cognitive radio Systems (Qosmos): *www.ict-qosmos.eu/*
- Cognitive Radio Experimentation World (CREW): *www.crew-project.eu/*
- Cognitive Radio Oriented Wireless Networks (CROWN): http://www.fp7-crown.eu/

These systems will be especially important with the new era of digital television which induces spectral white spaces left behind by ceased analog transmissions.

Cognitive radio technology might play an important role also in Hungary. Digital systems replace analog television broadcasting in 2013 in Hungary, which require less specific bandwidth. According to the plans, intelligent radio systems communicating opportunistically may use the free channels for data transfer after the switchover. Fig. 1 shows the result of a preliminary 24-hour spectrum observation in the range 450 MHz to 550 MHz. The temporarily free and unused bands are clearly visible. Since broadcasting systems remain the primary users of the frequency range in question, the opportunistic radios communicating in this domain must feature a high degree of intelligence and rapid spectrum detection to avoid interference.



1. Figure 24 hours spectral measurements in Hungary, near Szolnok

Naturally, there are many difficulties which have to be overcome such as spectral sensing, spectrum management and band allocation. The key question is the choice of the applied modulation scheme. Initial studies on the safe coexistence between incumbent TV broadcast systems and potential white space devices have recommended guard channels to protect nearby incumbents. Furthermore, they called for very strict adjacent channel leakage requirements on the signal emitted by the opportunistic device. These requirements triggered intense research activities to find feasible modulation techniques for the physical layer that exhibit very small adjacent channel leakage. Orthogonal Frequency Division Multiplexing (OFDM) [3] is often preferred in wideband wireless communication systems because extensive literature is available on it. Although OFDM has many advantages it also has some crucial drawbacks: it is highly sensitive to nonlinear distortion, synchronization errors and it exhibits moderate adjacent channel leakage. Due to these phenomena several multicarrier schemes have been proposed in the recent years which could compete with OFDM.

The physical layer of CR communication (including the applied modulation as well) must fulfill special requirements. I investigate and compare the multicarrier modulation schemes aimed to opportunistically utilize the analog broadcast bands, as well as I elaborated modulation and demodulation related digital signal processing methods. In case of high speed digital transfer, application of Orthogonal Frequency Division Multiplexing (OFDM), a widely used multicarrier technique, seems to be obvious. This method is used in various wireless telecommunications systems, such as DVB-T (terrestrial digital television), DAB (digital radio) and WLAN (wireless network).

In this tutorial I will investigate four possible alternatives to OFDM for CR purposes: Constant Envelope OFDM (CE-OFDM), DFT-Spread OFDM (DFTS-OFDM), Generalized Frequency Division Multiplexing (GFMD) and the Filter Bank Multicarrier (FBMC) system. I investigate these schemes by means of signal processing complexity, data rate, Power Spectrum Density (PSD) function and Peak to Average Power Ratio (PAPR). These are some of the parameters which have to be taken into account when designing a wireless communication system for cognitive radio in white spaces.

2. Modulation schemes for CR applications

a. OFDM

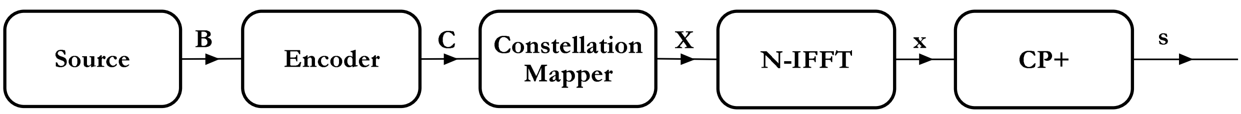
Nowadays, the most commonly used multicarrier modulation technique is the OFDM scheme: numerous broadcast and standards apply this modulation such as DVB-T, DAB, WLAN, ADSL and also LTE. For multiuser scenarios with high data rate is the OFDM technique a very good choice.

In OFDM systems the digital information is carried by the amplitude and phase values of the individual subcarriers. With a proper choice of the frequency distance between the neighboring subcarriers, they remain orthogonal to each other meaning that they can be treated separately, there is no inter carrier interference among them. The modulation of the subcarriers can be performed easily using an Inverse Fast Fourier Transform (IFFT), and the demodulation using an FFT respectively. Depending on the application one OFDM symbol can contain hundred or even thousands of subcarriers. The discrete samples of the OFDM symbol transmitted in the mth timeslot can be expressed as:

$$x^m[n] = \sum_{k=0}^{N-1} X_k[m] e^{j\frac{2\pi}{N}nk}, n \in 0...N-1,$$

where $X_k[m]$ is the kth subcarriers complex amplitude in the symbol transmitted in mth timeslot, N is the available number of subcarriers and $j = \sqrt{-1}$. Prior to transmission every symbol is extended with a Cyclic Prefix (CP).

The block diagram of an OFDM transmitter can be seen in Fig. 2. The binary information (B) coming from the source is first encoding using some kind of forward error correction coding. Then, the constellation mapper generates the modulation values using the coded bits (C) based on the applied constellation (BPSK, 4-QAM, 16-QAM, etc.). The generated complex values are transformed to the time domain using an N-point IFFT, then the CP is added to the signal before it is sent to the D/A converter and the front-end. In practical implementations the DC subcarrier and the outer subcarriers are not modulated due to technical reasons. This means that the input of the IFFT on those subcarriers is 0.



2. Figure Block diagram of an OFDM transmitter

On the receiver side the CP is cut of the signal and the samples of the OFDM symbol is demodulated using an FFT. As long as the CP is longer than the impulse response of the radio channel, the OFDM symbols will not suffer from Inter Symbol Interference (ISI). The remaining linear distortion can be efficiently compensated in the frequency domain. Otherwise in the presence of ISI the system performance will strongly degrade. The demodulated subcarriers assuming linear channel and additive white Gaussian noise can be expressed as:

$$Y_k^m = X_k^m H_k + W_k, k \in 0...N-1,$$

where Y_k^m is the demodulated complex value on the kth subcarrier in the mth timeslot, H_k is the frequency response of the channel on the kth subcarrier and W_k is the Gaussian noise.

OFDM systems have many advantages, but also some disadvantages. In this section we will discuss some of them. Due to the usage of CP the out-of-band radiation, also called as Adjacent Channel Leakage Ratio (ACLR) can not be better than -45…-30 dB [4]. For cognitive radio applications the regulatory commissions set a very strict limit of about -50…55 dB (Office of Communication (Anglia), and Federal Communications Commission (USA)). In order to achieve this threshold, many methods were developed for OFDM systems. One possibility is to filter the RF signal, but this can lead to inter symbol interference and unwanted bit error rate degradation. In this case a very steep analog filter is required.A second solution requires higher computational complexity and also data rate is lost. Some of the subcarriers are allocated and modulated so that the resulting signals' ACLR is decreased. Applying this technique can significantly reduce the out-of-band radiation of OFDM signals without bit error rate degradation with the cost of data rate.

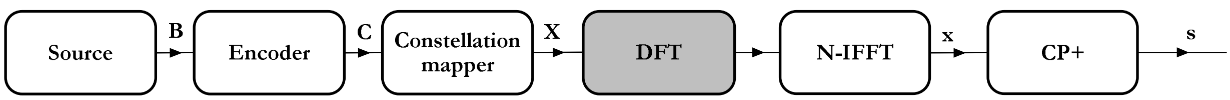
A second problem of OFDM systems is the high Peak-to-Average Power Ratio (PAPR), in other words the large fluctuation of the transmitted signal. Due to this phenomenon it is highly sensitive to nonlinear distortions. If the signal is influenced by nonlinearities, the ACLR will grow and the bit error performance may degrade as well. The PAPR is defined as:

$$PAPR = 10\log_{10}\left(\frac{|x[n]_{\max}|^2}{\sum_n \left(x[n]\right)^2}\right),\ n = 0,1...N-1.$$

There has been many techniques developed to reduce this metric [5], but all of the methods have some price: data rate loss, additional side information or enlarged output power.

b. DFTS-OFDM

The DFTS-OFDM system can be considered as an extension of the OFDM with a DFT signal processing block [6]. In the transmitter after the constellation mapper a DFT block is inserted, in parallel in the receiver an IDFT block is inserted prior to the demapping. This modulation can be also considered as a single carrier modulation, this technique is applied in the LTE (Long Term Evolution – fourth generation mobile communication standard) as well as the modulation scheme for the uplink. The signal processing blocks of the DFTS-OFDM can visualized in Figure. 3.



3. Figure Block diagram of a DFTS-OFDM transmitter

The DFTS-OFDM in the literature is often considered as Single Carrier Frequency Division Multiple Access (SC-FDMA) [7]. In multiuser scenarios the complex modulation values, before modulated on the allocated subcarrier, are spread using a DFT operation. The biggest advantage of DFTS-OFDM compared to OFDM is the fact that the signal has a much lower

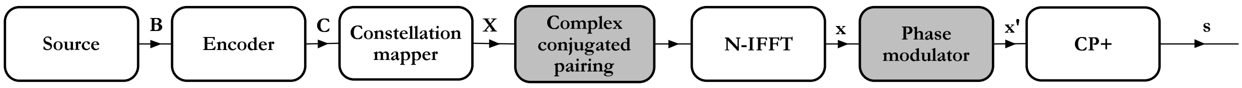
PAPR due to the fact that the amplitude and phase values of the subcarriers are not independent. On the other hand the spectral properties of the signal will not defer from the OFDM signals'.

c. CE-OFDM

The main goal of CE-OFDM is to drastically reduce the PAPR of the transmitted signal [8]. The block diagram of the CE-OFDM transmitter can be seen in Fig. 4. It can be seen that the OFDM transmitter is extended with 2 addition blocks. After mapping the bits to complex values, a complex conjugated pairing is performed, so the output of the N-IFFT will be entirely real, similar to ADSL technology. The resulting signal is used as the input of the phase modulator. The signal is multiplied with a modulation factor h, so the resulting output signal can be formed as:

$$x'[n] = e^{j2\pi h x[n]}, n \in 0 \ldots N-1$$

Then, prior to transmission the CP is added.

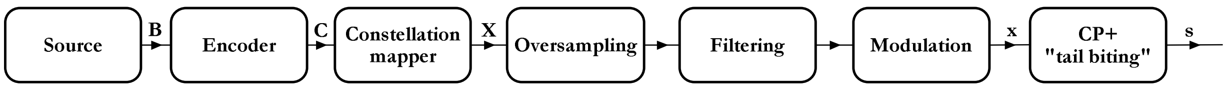


4. Figure Block diagram of a CE-OFDM transmitter

The major disadvantage of CE-OFDM is that due to complex conjugated pairing half of the data rate is lost. The biggest advantage is that the PAPR will be constant. The spectrum shape is strongly influenced by the modulation factor h, but with a price that a strong DC component will arise to the fact that the phase modulator is driven by a Gaussian signal.

d. GFDM

The GFDM technology was developed at the TU Dresden [9], it is still strongly research but it has a promising future for CR applications. The system is based on the well know Frequency Division Multiplexing (FDM) technique: the basic idea is that all of the subcarriers are modulated and individually filtered with a pulse shaping filter. The block diagram of the GFDM system can be seen in Fig. 5. The modulated symbols are oversampled and filtered using the chosen filter in the baseband. Then the filtered signals are summed and extended with the CP. The biggest disadvantage is that with use of filters the orthogonality in not valid any more, ICI will arise. The advantage is that the PSD will have a much lower ACLR compared to OFDM and the PAPR values will be also much smaller.



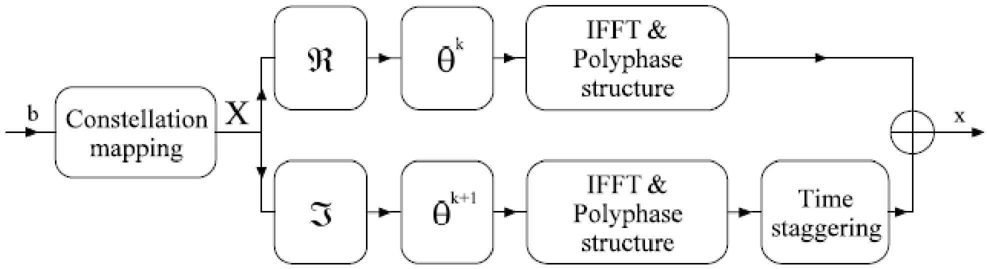
5. Figure Block diagram of a GFDM transmitter

The biggest advantage of GFDM is the flexibility. All of the subcarriers are modulated individually and the filters can be chosen for the given scenario. A major problem is that the receiver side must compensate for the arising ICI, which increases the signal processing requirements.

e. FBMC

FBMC [10] is one of the most promising competitor of OFDM due to its extremely low out-of-band radiation. Future cognitive devices may use FBMC scheme as primary modulation due to the advantageous spectral properties. Apart from spectral behavior there are still open issues to be solved to reach a working wireless transmission using FBMC.

FBMC is a class of multicarrier modulation schemes with a modulated prototype filter $p_0(t)$ applied for each subcarrier. These filters fulfill the Nyquist property. Due to the advantageous properties of the prototype filter, the FBMC signal has better spectral efficiency compared to OFDM, where a rectangular window is applied on the subcarriers. The details of FBMC signal generation can be seen in Fig. 6.



6. Figure Bock diagram of a baseband FBMC transmitter

The procedure consists of the following steps: binary information b is mapped using the complex modulation alphabet (usually a Gray coded QAM signal set), where each modulation symbol X represents M bits, using offset-QAM modulation on the subcarriers. The real and imaginary parts of the complex FBMC modulation symbol X are transmitted with a time offset of half a symbol duration. As a consequence of the length of the filters' impulse response the transmitted symbols overlap in the time domain, but the filters are constructed such a way that the symbols can be separated in the receiver. To maintain the orthogonality of the filters the application of cyclic prefix should be avoided in FBMC systems. The modulated FBMC signal using N subcarriers and a discrete (sampled) prototype filter p0[n] with a length of L=KN samples can be expressed as

$$x[n] = \sum_{m=-\infty}^{\infty} \sum_{k=0}^{N-1} (\theta^k \Re(X_k^m) p_0[n - mN] + \theta^{k+1} \Im(X_k^m) p_0[n - N/2 - mN]) e^{j\frac{2\pi}{N}k(n-mN)},$$

where $j = \sqrt{-1}$, $\theta^k = e^{jk\pi/2}$ and $X_k[m]$ represents the modulation symbol on the kth subcarrier in the mth signaling time. The overlapping ratio K of the consecutive symbols depends on the length of the prototype filter. For the sake of simplicity the filter is designed with an impulse response of length L=KN, meaning that the symbol duration is stretched, but K symbols overlap in the time domain to maintain the original data rate.

The biggest advantage of FBMC is the extremely low ACLR. The other properties of the signal such as PAPR are similar to OFDM, but it can be seen that the signal generation is much more complex compared to all of the previously described techniques.

3. Overview of the modulation schemes

In this section the previously introduced modulation schemes are compared through their advantages and disadvantages. The comparisons are made taking the OFDM system as reference. All systems include an FFT block and they have similar signal processing blocks. It has been shown in which scenario can the given modulation scheme be used and in which scenario should another scheme be used. The investigated properties are summarized in the table below. One of the biggest problems is that some of the systems such as CE-OFDM and FBMC do not have any commercial implantation or use currently.

Table 1. Comparison of the investigated modulation scheme

Property/Modulation	CP-OFDM	GFDM	DFTS-OFDM	CE-OFDM	FBMC
System Complexity	Low	Complex	Moderate	Moderate	Complex
ACLR	Low ACLR	Extremely low ACLR	low ACLR	DC + high ACLR	Extremely low ACLR
PAPR	High	Moderate	Moderate	Small	High
Data rate	1-CP/N	1-CP/N	1-P/N	0.5* (1-CP/N)	1

In case of OFDM is the cost of the system complexity the smallest as for the receiver and for the transmitter. The cost of the flexibility of GFDM is paid in higher signal processing requirements. In case of DFTS-OFDM and CE-OFDM additional signal processing blocks are required, while for FBMC systems the complexity growth is the highest.

For the spectral characteristics - which is the most important in CR applications - FBMC and GFDM signals have the smallest ACLR. CE-ODFM signals have the smallest PAPR values which can be beneficial for the amplifier design and power efficiency. Although DFTS-OFDM systems is never the best in any of the topics, it can be a good compromise because it shows a moderate performance for all of the give properties.

In general these properties have to be take in to account during the design of cognitive radio applications. The modulation scheme which fits best to the given specification should be chosen. Also some further aspects should be taken into account which have been not studied in the previous sections such as:

- Nonlinear distortions caused by the power amplifier
- Synchronization issues
- Channel equalization

These topic play an important role in the choice of the most suitable cognitive radio modulation.

4. References

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