Equalization of Multicarrier Cognitive Radio Transmission Over Multipath Channel with Large Delay Spreads

Zsolt Kollár and Péter Horváth

***Abstract*—This paper investigate the channel equalization problem in opportunistic white space communication systems, with an emphasis on transmission over channels with high delay spread. We consider the equalization problems of Orthogonal Frequency Division Multiplexing (OFDM) and three alternative multicarrier modulation schemes, namely DFT-spread OFDM (DFTS-OFDM), Constant Envelope OFDM (CE-OFDM) and Filter Bank Multicarrier (FBMC). After a brief description of these schemes, we show their performance assuming frequency domain per subcarrier minimum mean square error (MMSE) channel equalization. The simulations are performed using the channel parameters specified in the IEEE 802.22 standard. We show that bit error rate (BER) performance of FBMC and DFTS-OFDM are comparable to OFDM in frequency selective channels which make them a very strong candidate for cognitive applications.**

***Index Terms*—Channel equalization, Cognitive Radio, multipath propagation, OFDM, modulation schemes.**

I. INTRODUCTION

As some licensed bands become crowded and white spaces [1] are left behind by the ceased analog TV broadcast, the need for better utilization of the existing, under-utilized spectrum becomes evident. Cognitive radio-based (CR) opportunistic exploitation of spatial and temporal white spaces is considered as a feasible approach to improve the spectral efficiency and to introduce new services into legacy bands.

Due to strict regulations and high requirements on analog components, the characteristics for the opportunistic transceiver are crucial.

Today, OFDM is considered as the most widespread multicarrier modulation scheme for wireless data transmission. It is used in many broadcasting and communication systems such as DVB, DAB and certain types of IEEE 802.11 WLAN. Low-complexity demodulation and modulation can be performed by the Fast Fourier Transform (FFT) and the Inverse FFT (IFFT) operations, respectively. With the use of the cyclic prefix (CP), the channel equalization can be implemented effectively in the frequency domain. Nevertheless, this scheme exhibits some drawbacks. Due to the large dynamic range of the transmitted signal, OFDM is highly sensitive to nonlinear distortions caused by e.g. power amplifiers. This nonlinearity might degrade the system's performance because of the induced in-band and out-of-band radiation. OFDM system performance can strongly depend on the frequency mismatch of the transmitter and receiver local oscillators, requiring very robust synchronization techniques. Moreover, without additional filtering of the transmitted signal, the out-of-band radiation is considered moderate, which is a major drawback in the opportunistic context, where significant adjacent-channel leakage might lead to interference to incumbent users.

There are many issues regarding CR-scenarios which cannot be met by OFDM. This is why other multicarrier schemes have become a point of interest. In this paper we focus on three alternatives:

- DFT-spread OFDM (DFTS-OFDM) [2],
- Constant Envelope OFDM (CE-OFDM) [3],
- Filter Bank Multicarrier (FBMC) [4], [5].

Each of these schemes has advantages over OFDM in some aspects. [6] gives an overview on their sensitivity to residual synchronization errors and non-linear impairments. In this paper we intend to compare these schemes in multipath channel propagation scenarios. Also the corresponding equalization algorithms will be compared and evaluated.

The paper is organized as follows. In Section II each of these modulation schemes are explained in details. The main signal processing blocks are explained separately for the transmitted and for the receiver. In Section IV the channel equalization methods are explained. In Section V the simulation results of the four systems are compared via bit error rates over various multipath channels. Also the applied IEEE 802.22 [7] channel parameters are presented together with the system parameters which are used for the simulations. Finally the conclusions are drawn from the results of the simulation.

Manuscript received May 15, 2011. The research leading to these results was derived from the European Communitys Seventh Framework Programme (FP7) under Grant Agreement number 248454 (QoSMOS).

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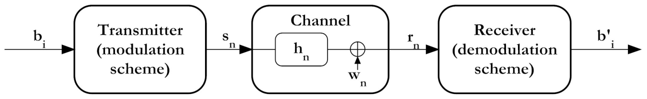

Fig. 1. Baseband digital model of the transceiver.

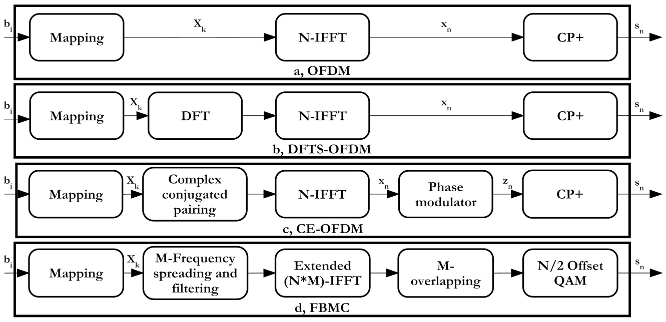

Fig. 2. Block diagram of the transmitters of the four modulation schemes: OFDM (a), DFTS-OFDM (b), CE-OFDM (c) and FBMC (d).

II. DISCRETE BASEBAND TRANSCEIVER MODEL

Assuming ideal analog components – neglecting their impairments – and perfect knowledge of the multipath channel characteristics, the analog transmission chain can be modeled in the digital baseband. In this section the applied discrete baseband model for the transceiver chain is explained. The block diagram of the model can be seen in Fig. 1.

First the transmitted bit stream b_i is converted to a discrete transmission signal s_n according to the applied modulation scheme. The multipath channel is modeled as a discrete FIR filter h_n with the length of L. After filtering the transmitted signal the Additive White Gaussian Noise (AWGN) w_n is added. Finally, the received signal r_n is demodulated with the demodulation scheme corresponding to the transmitter's modulation forming the received bitstream $b_i^{'}$. The received signal r_n can be written as

$$r_n = s_n * h_n + w_n \cdot \tag{1}$$

III. MULTICARRIER MODULATION SCHEMES

In this section we give a detailed explanation of the four investigated modulation schemes. Although OFDM has a well-known architecture, we give a longer explanation, because the other schemes are based on it. For each modulation we first summarize the procedure of the signal generation in the transmitter then the demodulation of the received signal in the receiver. The block diagram of the four transmitters is depicted in Fig. 2. The signal processing blocks of the receiver can be seen in Fig. 3. One can see that the signal processing differs only slightly from that of the OFDM.

A. OFDM

Transmitter

The basic idea of OFDM is to modulate *N* complex carriers. This can be performed effectively using the IFFT. First the bitstream b_i is transformed to complex Quadrature Amplitude Modulation (QAM) constellation symbols X_k selected from the constellation alphabet *C*. The selected symbols are used to modulate the subcarriers via N-IFFT to form samples of a time domain OFDM symbol from the transmit signal s_n as

$$x_n = \sum_{k=0}^{N-1} X_k e^{j\frac{2\pi}{N}nk}, \qquad n \in 0 \ldots N-1 \cdot \tag{2}$$

In real applications, some subcarriers are left unmodulated or carry reference signals. Before transmission each OFDM symbol is extended with a CP which helps to reduce multipath propagation effects so the compensation can be performed directly in the frequency domain. The CP is usually a repeated part of *P* samples taken from the end of the time domain symbol and inserted to the beginning resulting in a symbol length of *N* +*P* samples. The transmitted signal s_n is formed from these extended OFDM symbols.

Receiver

The received signal r_n as explained in section II can be expressed according to equation (1). As long as the CP is longer than the channel delay spread, for one OFDM symbol after removing the CP, the following frequency domain equation is valid:

$$Y_k = X_k H_k + W_k, \qquad k \in 0 \ldots N-1 \cdot \tag{3}$$

Here Y_k, X_k, H_k and W_k are N-FFT of the signals y_n, x_n, h_n, and w_n respectively.

B. DFTS-OFDM

Transmitter

The transmitter of the DFTS-OFDM differs only by an additional block compared to OFDM. An additional DFT is applied to the complex modulation symbols. It can be considered as a spreading of the information through the available subcarriers. In strict sense, this can be considered as a single carrier modulation scheme. This extra spreading block will lead to many advantages such as lower peak-to-average power ratio (PAPR), which is desired when nonlinearity is present in the system. It can also be considered as a diversity leading to a gain over frequency selective channels over OFDM systems without interleaving and coding – which is of little concern in modern wireless systems.

Receiver

The receiver block are almost the same as for OFDM, the difference is only the extra IDFT operation which despreads the information after channel equalization. The remaining blocks of the receiver are the same.

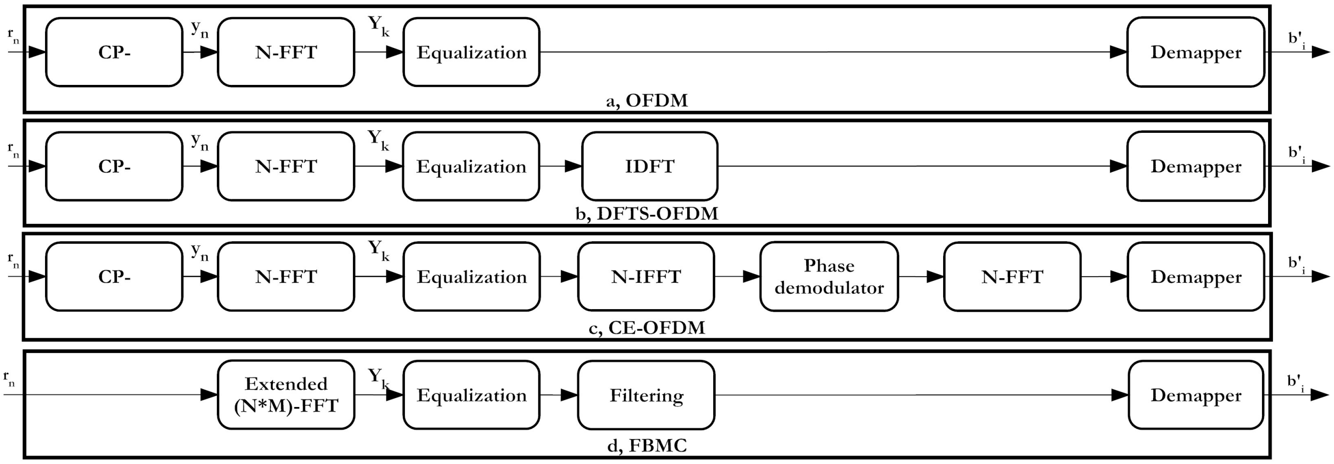

Fig. 3. Block diagram of the receivers of the four modulation schemes: OFDM (a), DFTS-OFDM (b), CE-OFDM (c) and FBMC (d).

C. CE-OFDM

Transmitter

The main aim of CE-OFDM is to achieve a constant envelope of the transmitted signal. The first step is to modulate the subcarriers in a way to achieve a real valued signal, which can be done by modulating the subcarriers by complex conjugated pairs $X_k = X^*_{N-k}$. This way the output of the IFFT will be a real valued signal x_n. This signal will be used as the input of a phase modulator

$$z_n = e^{j2\pi m x_n}, \qquad n \in 0 \ldots N-1 \cdot \tag{4}$$

where m is the modulation index. The transmitted signal s_n is then generated from z_n with the additional CP. One of the advantages of CE-OFDM is that it has a constant envelope, on the other hand the data rate is halved, due to the complex conjugated pairing. Also the spectral behavior of the transmitted signal is highly dependent on the modulation index m and a large DC component will appear which is difficult to handle in the analog chain.

Receiver

The receiver for CE-OFDM is more complex compared to OFDM. First frequency domain equalization is performed, similar to OFDM. Then, the equalized signal is transformed back to time domain where the phase demodulation can be performed. After the phase demodulation, the N-FFT is applied to retrieve the complex modulation values.

D. FBMC

Transmitter

FBMC systems are derived from the orthogonal lapped transforms [8] and filter bank theory [9]. Similar to OFDM the bits are first mapped to complex constellation symbols X_k, then the frequency domain data is spread over M subcarriers forming a subband, then it is filtered by a prototype filter of the k^{th} subband $F_k(z)$ which is designed so that it fulfills the Nyquist criterion. The real parts of X_k are modulated by a cosine filter bank $F_k^c(z)$ where only the even-index subbands are used and the imaginary parts are modulated by a sine filter bank $F_k^s(z)$ where only the odd-index subbands are modulated. In order not to lose data rate an offset of half of the original symbol duration N=2 is applied – similar to offset quadrature amplitude modulation technique. In this case the imaginary parts of X_k are modulated with the cosine filterbank and the real parts are modulated with the sine filter bank respectively. Due to the design, the inter-symbol-interference (ISI) between the filters is negligible.

In FBMC applications these filter bank structures are implemented in a computationally efficient manner using an N-IFFT and a polyphase network [9]. The filter bank output provides a symbol length of $N*M$ samples. For example if M = 4 then 4 consecutive FBMC symbols overlap. The resulting transmitted signal is the sum of overlapping FBMC symbols generated by the filter banks.

It can be observed that no CP is used, which will lead to ISI in the presence of frequency-selective multipath propagation. On the other hand the FBMC symbol length is M times larger which decrease the effect of the ISI in comparison with CP-OFDM.

Receiver

The FBMC receiver is rather simple. Each FBMC symbol is turned to the frequency domain using an extended FFT for $N*M$ samples. The equalization is done in the frequency domain. After equalizing all subcarriers in the subband separately each subband is filtered with the corresponding analysis filterbank to get an estimate of the transmitted constellation value X_k which can be fed to the demapper.

IV. CHANNEL EQUALIZATION

Zero forcing (ZF) is known to be the simplest method for channel equalization in the frequency domain. We simply assume that the received noise is zero in equation (3) for the received frequency domain OFDM symbol, so the transmitted complex constellation value on the k^{th} subcarrier can be simply calculated as $\hat{X}_k^{ZF} = Y_k / H_k$. The MMSE technique gives a better result if we take the noise also into account. The problem of ZF occurs when H_k is small, the noise values will be also amplified. The equalization coefficient for the k^{th} subcarrier is calculated according to [10] as

$$\frac{1}{H_k^{MMSE}} = \frac{H_k^*}{\left(\left| H_k \right|^2 + \frac{N_0}{E_s} \right)}, \tag{5}$$

where N_0 is the noise power and E_s is the signal power. It can be seen that with small N_0 / E_s compared to $\left| H_k \right|^2$ values the MMSE solution is equal to the ZF. In case of an FMBC system equation (5) has to be modified according to the ISI if we use a per subcarrier equalization scheme similar to [11] as

$$\frac{1}{\hat{H}_k^{MMSE}} = \frac{H_k^*}{\left(\left| H_k \right|^2 + \frac{N_0 + I}{E_s - I} \right)}, . \tag{6}$$

where I is the power of the ISI, for which we present the following equation:

$$I = E_s \sum_{n=0}^{L-1} \frac{n}{NM} \left| h_n \right|^2 . \tag{7}$$

So we can write for the MMSE estimate of the k^{th} subcarrier

$$\hat{X}_k^{MMSE} = \frac{Y_k}{\hat{H}_k^{MMSE}} . \tag{8}$$

For OFDM systems this estimate can be directly fed to the demapper, for the other schemes some extra operations have to be performed before demapping, which were explained previously in Section 3.

A detailed analysis regarding equalization techniques for FBMC can be found in [12], where also a novel iterative decision feedback equalization technique is presented. The main idea is to iteratively minimize the ISI achieving a better BER performance. In our simulation we will present also the results of this technique for FBMC systems.

V. SIMULATION RESULTS

To compare the previously described equalization scheme for the modulation schemes, simulations were performed. The simulation parameters used for the various systems are summarized in Table I. The parameters of the IEEE 802.22 channel profiles B and C can be found in Table II. [7]. In order to obtain comparable bit error rates for the multicarrier systems we define the SNR normalized to of one bit energy.

$$SNR_{dB} = 10 \log_{10} \left(\frac{E_s}{N_0} \right) = 10 \log_{10} \left(\frac{E_b N_c D}{(N + P) N_0} \right), \tag{9}$$

TABLE I
Simulation parameters for FBMC, OFDM, DFTS-OFDM and CE-OFDM system

Parameter	FB MC	OFDM	DFTS-OFDM	CE-OFDM
Bandwidth	8 MHz			
CP	0	1/16 & 1/4		
N	2048			
M	4	1		
Modulation *(D)*	16-QAM (4)			
Modulated subcarriers/ subband	1536			

TABLE II
CHANNEL PARAMTERS FOR IEEE 802.22 B AND C CHANNEL PROFILES (EXCESS DELAY AND RELATIVE AMPLITUDE)

Profile B	**Path 1**	**Path 2**	**Path 3**	**Path 4**	**Path 5**	**Path 6**
Excess delay	-3 µs	0 µs	2 µs	4 µs	7 µs	11 µs
Relative amplitude	-6 dB	0 dB	-7 dB	-22 dB	-16 dB	-20 dB
Profile C	**Path 1**	**Path 2**	**Path 3**	**Path 4**	**Path 5**	**Path 6**
Excess delay	-2 µs	0 µs	5 µs	16 µs	24 µs	33 µs
Relative amplitude	-9 dB	0 dB	-19 dB	-14 dB	-24 dB	-16 dB

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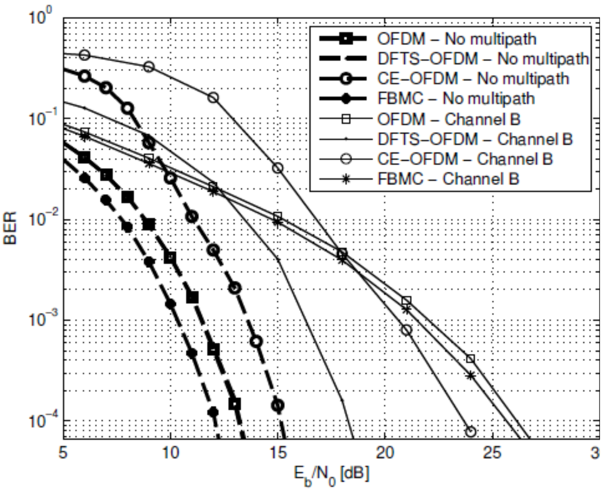

Fig. 4. BER performance of the four systems over a channel with no multipath propagation and over Channel B.

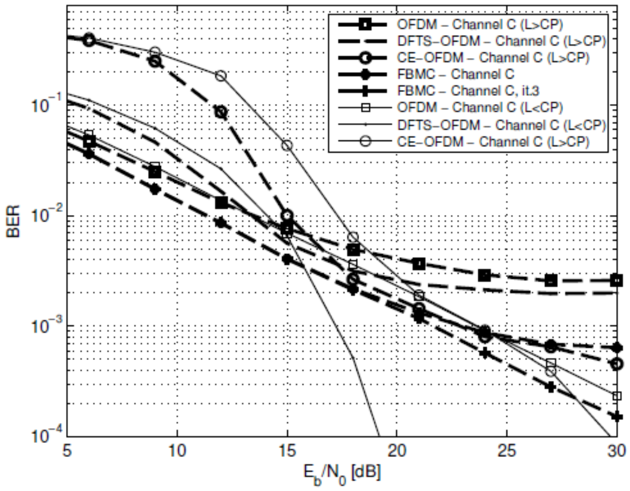

Fig. 5. BER performance of the four systems over a channel with no multipath propagation and over Channel B.

where N is the number of the subcarriers/subbands available and N_c is the number of subcarriers/subbands used. E_b is the bit energy and P is the length of the CP and D is the number of bits transmitted by one subcarrier/subband.

In the first simulation we compared the BER results of the four schemes for channel profile B together with the case when no multipath propagation is present. The resulting BER curves can be seen in Fig. 4. In multipath-free environment FBMC outperforms all other techniques because it does not apply any CP, resulting in higher data rate. The results for DFTS-OFDM and conventional OFDM are the same. CE-OFDMs performance is the worst, due to the fact that only half of the available bandwidth is used for data transmission. On the other hand if Channel B is introduced, DFTS-OFDM has the best performance due to the frequency spreading. FBMC still slightly outperforms OFDM, CE-OFDM still has the worst BER values under 20 dB SNR.

The simulation results of the second scenario can be seen in Fig. 5. Here the BER curves for channel C are evaluated for a CP which is shorter than the largest excess delay and also with a CP which is longer. As FBMC does not use CP, the results for the third iteration of a novel iterative compensation technique, presented in [12], are shown together with the per subcarrier MMSE equalization technique. We can conclude that until the CP is sufficiently long DFTS-OFDM has the best performance. The BER values of the other three modulations show a similar behavior as shown in Fig. 4. Again, CE-OFDM can only compete above an SNR value of 20 dB. If the CP is shorter than the maximum excess delay, ISI is introduced. It leads to an error floor for all four modulations. With the previously mentioned iterative technique, BER results of FBMC can be further improved. In this scenario OFDM and DFTS-OFDM perform the worst, both reaching a bit error floor of $2*10^{-3}$ in comparison with CE-OFDM which reaches $5*10^{-4}$.

VI. CONCLUSION

In this paper we have presented four modulation schemes which can be promising candidates for future cognitive radio applications. We have described their main signal processing blocks and we have investigated a simple frequency domain MMSE equalization technique. The systems' performances were compared via simulations for various channels defined by IEEE 802.22. The results show that both DFTS-OFDM and FBMC are very strong candidates for cognitive radio physical layer. CE-OFDM is only worth consideration if dominant nonlinearities are present in the transceiver chain.

ACKNOWLEDGMENT

The research leading to these results was derived from the European Communitys Seventh Framework Programme (FP7) under Grant Agreement number 248454 (QoSMOS).

REFERENCES

[1] S. J. Shellhammer, A. K. Sadek, and W. Zhang, "Technical challenges for cognitive radio in the TV white space spectrum," *Information Theory and Applications Workshop*, pp. 323–333, Feb. 2009.G. O.

[2] D. Galda and H. Rohling, "A low complexity transmitter structure for OFDM-FDMA uplink systems," in *Vehicular Technology Conference, 2002. VTC Spring 2002. IEEE 55th*, vol. 4, 2002, pp. 1737–1741.

[3] S.C. Thompson, A.U. Ahmed, J.G. Proakis, J.R. Zeidler, and M.J. Geile, "Constant envelope OFDM," *Transactions on Communications*, vol. 56, no. 8, pp. 1300–1312, Aug. 2008.

[4] P. Siohan, C. Siclet, and N. Lacaille, "Analysis and design of OFDM/OQAM systems based on filterbank theory," vol. 50, no. 5, pp. 1170–1183, 2002.

[5] F. Schaich, "Filterbank based multi carrier transmission (FBMC) – evolving OFDM: FBMC in the context of WiMAX," in *Wireless Conference (EW), 2010 European*, 2010, pp. 1051–1058.

[6] Zs. Kollár and P. Horváth, "Modulation schemes for cognitive radio in white spaces," *Radioengineering*, vol. 19, no. 4, pp. 511–517, Dec. 2010.

[7] IEEE 802.22-05/0055r7, "WRAN channel modeling," E. Sofer and G. Chouinard, Aug. 2005.

[8] H. S. Malvar, "Extended lapped transforms: Properties, applications, and fast algorithms," *IEEE Trans. on signal processing*, vol. 40, no. 11, pp. 2703–2714, Nov. 1992.

[9] P. P. Vaidyanathan, *Multirate systems and filter banks*. Prentice-Hall Inc., 1993.

[10] J. van de Beek, O. Edfors, M. Sandell, S. Wilson, and P. Borjesson, "On channel estimation in OFDM systems," vol. 2, pp. 815–819, Jul. 1995.

[11] T. Ihalainen, T. H. Stitz, M. Rinne, and M. Renfors, "Channel equalization in filter bank based multicarrier modulation for wireless communications," *EURASIP Journal Appl. Signal Process.*, 2007.

[12] Zs. Kollár, G. Péceli, and P. Horváth, "Iterative decision feedback equalization for FBMC systems," in *Proceedings of IEEE First International Conference on Advances in Cognitive Radio, COCORA 2011*, Apr. 2011.

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