MC-CDMA BASED ARCHITECTURE FOR THE DOWNLINK OF INFRASTRUCTURE WLANS

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ABSTRACT

In this paper we propose a multicarrier code division multiple access (MC-CDMA) based architecture with variable spreading factor for the downlink of infrastructure wireless local area networks (WLANS). The objective of this proposal is to provide service simultaneously and within the same radio channel to several users even if their data rate requirements are different. In addition, the bit error rate (BER) performance of our proposal is analyzed for four combining techniques and two network scenarios, one without multiple user interference (MUI) and one where the MUI reaches its maximum value. We consider a wide-band Rician fading channel with both independent and correlated frequency selectivity for the BER computations. The main purpose of the paper is to show how the MUI and the correlation among subchannels affect the BER performance of a downlink MC-CDMA system.

I. INTRODUCTION

Currently, most wireless local area networks (WLANS) are designed in accordance to the IEEE 802.11 type a, b, and g standards [1], and in a lesser extent to the ETSI HIPERLAN type 2 (HIPERLAN/2) standard [2]. The physical layer of the 802.11b standard is based on direct-sequence spread spectrum (DSSS) technology and can achieve a raw data rate of up to 11 Mbps. The other three standards are based on multicarrier technology, namely orthogonal frequency division multiplexing (OFDM) technology, and all they can achieve a maximum raw data rate of 54 Mbps. Despite these data rates cover the basic current requirements, like e-mail and Internet access, it is necessary to develop new technologies appropriate for the next generation of WLANS. Since multimedia applications are foresight to be the main applications in WLANS, those technologies will have to provide flexible data rates to the users in a way such that their different requirements can be fulfilled optimally. In addition, it will be convenient to transmit the information of several users simultaneously and within the same radio-channel in order to speed up the information flow and save the limited network’s resources, like the bandwidth. Those technologies will also have to support high speed links to allow the exchange of large volumes of information. To meet such requirements we propose in this paper a multicarrier code division multiple access (MC-CDMA) [3] based architecture with variable spreading factor, which we will refer to as MC-CDMA/vsf.

In addition, we analyze the BER performance of MC-CDMA/vsf in a wide-band Rician fading channel with both independent and correlated frequency selectivity. To that end, we have employed a computer simulator to calculate the BER of MC-CDMA/vsf with four combining techniques, namely, maximal ratio combining (MRC), equal gain combining (EGC), orthogonal restoring combining (ORC) and minimum mean square error combining (MMSEC). We considered two network scenarios, one without multiple user interference (MUI) and one where the MUI reaches its maximum allowed value.

Several papers reporting the BER performance of MC-CDMA have been previously published, e.g. [4]–[7]. However, most of them do not provide a complete view of the BER of MC-CDMA. For instance, some papers only deal with channels with independent frequency selectivity [4], while other papers do not consider network scenarios with MUI [5]. Moreover, the analysis presented in several papers concentrates on MRC or/and EGC [6],[7], though we show here that MMSEC have the best overall performance and is perhaps more adequate for practical networks. We therefore aim at providing a wider view of MC-CDMA with this paper. In particular, we want to show how the correlation among subchannels and the MUI affect the BER performance of a downlink MC-CDMA system.

II. MC-CDMA/VSF

A. Minimum design objectives

Our proposal is intented to operate in the 2.4 GHz industrial, scientific and medical (ISM) band. For the sake of simplicity we have only considered binary phase shift keying (BPSK) and quadrature phase shift keying (QPSK) modulations. Therefore, we set 18 Mbps as the lowest maximum raw data rate bound for MC-CDMA/vsf because it corresponds to the maximum data rate achieved with QPSK in the 802.11g standard. Along with the maximum raw data rate we have to define a set of intermediate data rates so that the access point (AP) can choose the optimal one to cover the requirements of a particular user. For this matter, we have taken the set of data rates of the 802.11g as design reference. On the other hand, we expect MC-CDMA/vsf to be able of sending data for at least three users simultaneously over the whole ISM band. This is because the 802.11g standard defines three 20 MHz non-overlapping radio channels, which allows that up to three users can be served in the ISM band at the same time and place, over different radio channels.

B. MC-CDMA/vsf parameters selection

With the aforementioned design requirements in mind we have to define the MC-CDMA/vsf symbol duration $T_s$, its useful
part \( T_{ff} \) and the length of the guard interval (GI) \( T_{GI} \). Likewise, we have to set the number of bins \( N_{ff} \) to compute the fast Fourier transform (FFT) of the data blocks to be transmitted and the number of data and pilot subcarriers, denoted by \( N_c \) and \( N_p \), respectively. The maximum processing gain \( G_{max} \) of the spreading codes must also be set. Regarding the type of spreading codes, we decided to use Hadamard-Walsh codes for MC-CDMA/vsf to allow the simultaneous coexistence of different data rate users in the downlink.

The MC-CDMA/vsf symbol’s parameter can be chosen in relation to the propagation channel’s characteristics. In particular, \( T_{GI} \) should be about two to four times longer than the rms channel delay spread \( \sigma_{DS} \) to prevent inter-symbol interference (ISI) \[8\]. Typical values of \( \sigma_{DS} \) for indoor channels at 2.4 GHz are summarized in \[8\]. For MC-CDMA/vsf we considered a maximum \( \sigma_{DS} \) of 300 ns, which is representative of the values encountered inside buildings. Therefore, and with the aim of keeping resemblance with the 802.11 standard, we have set \( T_{GI} \) an 800 ns. After having established the \( T_{GI} \) value we can set the total MC-CDMA/vsf symbol duration \( T_s \). To reduce signal-to-noise-ratio (SNR) losses caused by the insertion of the GI it is convenient to make \( T_s \) much larger than \( T_{GI} \); of course, it cannot be arbitrarily large. A practical design choice is to make \( T_s \) at least five times larger than \( T_{GI} \), which produces a SNR loss of 1 dB \[8\]. In accordance to this design criterion we defined \( T_s = 4 \mu s \), which means that \( T_{ff} = 3.2 \mu s \left( T_{ff} = T_s - T_{GI} \right) \), and since the subcarriers’ spacing \( \Delta f \) is the reciprocal of \( T_{ff} \), we have that \( \Delta f = 312.5 \text{ kHz} \).

On the other hand, \( N_{ff} \), \( N_c \) and \( N_p \) should be chosen in relation to \( \Delta f \) and with respect to the desired raw data rates and the ISM band. We have analyzed the system’s data rates for \( N_{ff} = 64, 128, \) and 256 bins. To that end we defined \( N_c \) and \( N_p \) in terms of \( N_{ff} \), in a way such that \( N_c = 3 N_{ff} / 4 \) and \( N_p = N_{ff} / 16 \). The rest of the bins (zeroth bin and those assigned to the highest frequency subcarriers at both sides of the MC-CDMA/vsf symbol’s spectrum) were set to zero in order to reduce out-of-band interference. For the calculations we considered convolutional coding with coding rates 1, 1/2, 2/3 and 3/4, and we fixed \( G_{max} \) at 32. After running some simulations we concluded that the simultaneous-users/data-rate-set tradeoff is better when \( N_{ff} = 128 \); this is the value that we have taken.

The resultant raw data rates are shown in table 1. We can see there that MC-CDMA/vsf achieves raw data rates higher than those defined in the 802.11g standard for BPSK and QPSK. Moreover, with MC-CDMA/vsf data of up to 32 users can be sent simultaneously by each AP, and given that two non-overlapping APs can be allocated in the whole ISM band, data of up to 64 users can be sent at the same time using both APs.

For the distribution of the data and pilot subcarriers we followed an approach based on the 802.11g standard. To be specific, we considered the vector \( \beta = (\beta_1, \ldots, \beta_{128}) \), \( \beta_k = (k - 65) \times \Delta f \) for \( k = 1, \ldots, 128 \), which represents the 128 subcarriers’ frequencies. Thereby, the 8 pilot subcarriers are centered at \( \beta_{12}, \beta_{80}, \beta_{94}, \beta_{96}, \beta_{72}, \beta_{86}, \beta_{100}, \) and \( \beta_{114}, \) the subcarriers at \( \beta_1, \ldots, \beta_{12}, \beta_{65}, \beta_{113}, \ldots, \beta_{28} \) are not used and the rest 96 frequencies are assigned to data subcarriers.

### III. MC-CDMA/VSF SIGNAL MODEL

Since MC-CDMA/vsf is able to simultaneously transmit data of \( U \) users, each base-band transmitted MC-CDMA/vsf symbol can be represented by (pilot subcarriers are omitted)

\[
x(t) = pr_s(t) \sum_{u=1}^{U} \sum_{m=1}^{N_u} \sum_{k=1}^{2} \frac{c_u^k d_u^m}{\sqrt{\gamma_u}} e^{j2\pi f_o t} \]

where \( pr_s(t) = 1 \) for \( 0 \leq t \leq T_s \), and \( pr_s(t) = 0 \) otherwise. In (1) \( N_u^k \) and \( \gamma_u \) are the number of data symbols transmitted to user \( u \) and the corresponding modulation efficiency, respectively. \( d_u^m \) is the \( m \)-th data symbol of user \( u \) and \( c_u^k \) is the \( k \)-th chip of the spreading code of processing gain \( G_u \) assigned to that user. \( f_o \) denotes the frequency of the \( v \)-th data subcarrier with \( v = [G_u(m - 1) + k] \). The values of \( f_o \) are sorted in ascending order in such a way that \( f_o \) corresponds to \( \beta_{-52} \) and \( f_o \) corresponds to \( \beta_{32} \).

We will suppose that the channel coherence time is larger than \( T_s \) and that the channel coherence bandwidth is larger than twice \( \Delta f \). Hence, assuming perfect synchronization, the received MC-CDMA/vsf symbol can be represented by

\[
y(t) = pr_s(t) \sum_{u=1}^{U} \sum_{m=1}^{N_u} \sum_{k=1}^{2} \frac{c_u^k d_u^m}{\sqrt{\gamma_u}} H_u e^{j2\pi f_o t} + \eta(t) ,
\]

### Table 1: Raw data rates of MC-CDMA/vsf

<table>
<thead>
<tr>
<th>SF</th>
<th>TU</th>
<th>CR</th>
<th>Data rates (kbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>BPSK</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>1/2</td>
<td>12,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>QPSK</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>1/2</td>
<td>6,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>12,000</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>1/2</td>
<td>3,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6,000</td>
</tr>
<tr>
<td>8</td>
<td>16</td>
<td>1/2</td>
<td>1,250</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3,000</td>
</tr>
<tr>
<td>16</td>
<td>32</td>
<td>1/2</td>
<td>1,125</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2,250</td>
</tr>
<tr>
<td>32</td>
<td>64</td>
<td>1/2</td>
<td>750</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1,500</td>
</tr>
</tbody>
</table>

SF: Spreading factor. TU: Total users (Simultaneous users in the ISM band). CR: Coding rate.
where $H_v$ is the channel response for the modulated subcarrier of frequency $f_v$, and $\eta(t)$ is zero-mean additive white Gaussian noise (AWGN) with double-sided power spectrum density $N_0$.

After demodulating the received MC-CDMA/vsf symbol, and performing channel equalization and despreading, the $n$th received data symbol of user $u$ is given by

$$\hat{d}_n^u = \frac{d_n^u}{G_u} \sum_{k=1}^{G_u} q_v H_v^* + \sum_{v=1, v \neq u}^{U} \frac{d_n^v}{G_u} \sqrt{\frac{\gamma_u}{\gamma_v}} \sum_{k=1}^{G_u} q_v H_v^* c_k^v c_k^u + \sqrt{\frac{\gamma_u}{G_u}} \sum_{k=1}^{G_u} q_v c_k^u \eta_v,$$  

where $q_v$ is the channel-equalization/combining coefficient for the data subcarrier of frequency $f_v$.

The first element in the right-hand side of (3) corresponds to the $n$th data symbol transmitted to user $u$; the second element is the MUI and the third element is amplified (or attenuated) AWGN. As can be seen in (3), for the correct data demodulation it is necessary to neutralize the channel distortion and remove the noise and the MUI. Thus, a proper combining technique must be used. Four combining techniques are considered in this paper, namely MRC, EGC, ORC and MMSEC. The combining coefficients for those techniques are given by

$$\text{MRC} : \quad q_v = H_v^*;$$

$$\text{EGC} : \quad q_v = \frac{H_v^*}{\|H_v\|^2};$$

$$\text{ORC} : \quad q_v = \frac{H_v^*}{\|H_v\|^2 + \sigma_v^2};$$

$$\text{MMSEC} : \quad q_v = \frac{H_v^*}{\|H_v\|^2}.$$  

where $(\cdot)^*$ and $\| \cdot \|$ denote the complex conjugate and absolute value, respectively, and $\sigma_v^2$ is the noise power for the $v$th data subcarrier. In what follows we evaluate the BER performance of MC-CDMA/vsf for these combining techniques.

IV. CONFIGURATION OF THE SIMULATIONS

In this section we briefly describe the computer simulator that we have implemented to calculate the BER of our proposal.

For the simulations we considered a wide-band Rician fading channel composed by $N_{ff}$ subchannels $\{H_k\}_{k=1}^{N_{ff}}$. We compute the BER for the case where the diffuse components (zero-mean components) of the $N_{ff}$ subchannels are independent, and also for the case where they are cross-correlated. To correlate the $N_{ff}$ diffuse components we employed the algorithm of the Cholesky decomposition [9]. The channel frequency correlation function (FCF) that we used is given by

$$R(f) = \frac{1}{1 + j2\pi\sigma_{DS}f^2}.$$  

In the simulations we considered $\sigma_{DS} = 60$ ns, which is a typical value for channels inside office buildings [8].

We assume that the maximum excess delay of the channel does not exceed $T_{GI}$, so there is no inter-symbol interference (ISI) and each modulated subcarrier goes through a flat fading subchannel. We also assume that the channel is constant for each MC-CDMA/vsf symbol and changes independently from one symbol to another. In addition, we considered perfect channel estimation and synchronization and we supposed that single user detection is employed at the receiver.

For the network scenario with MUI we evaluate the BER with respect to a given user $u$ that was assigned a processing gain $G_u = \{1, 2, 4, 8, 16, 32\}$. The MUI comprises the signals of other $32 \times (1-G_u^{-1})$ users, all of them with the same processing gain $G_{MUI} = 32$ and modulation efficiency $\gamma_{MUI} = 1$.

V. RESULTS AND ANALYSIS

A. Network scenario without MUI

Figure 1 shows the results of the network scenario in a Rician channel with Rician factor $K = 1$, without MUI and both uncorrelated and correlated subchannels.

We can observe that the BER curves of MC-CDMA/vsf with MRC, EGC and MMSEC follow a similar trend, and the BER improvement is quite significant for all them when increasing $G_u$ or the $E_b/N_0$. This result is because increasing $G_u$ increases the frequency diversity inherent to MC-CDMA, which is exploited by the receiver to mitigate fading when any of the above mentioned techniques is employed. Indeed, if we associate the BER curves for $G_u = 1$ with the BER performance of conventional OFDM, we can conclude that MC-CDMA/vsf outperforms OFDM when MRC, EGC or MMSEC is employed and there is only one user in the system with $G_u > 1$.

Contrarily, the performance of ORC is poor in comparison to the other techniques. This is observed from the graphs since ORC does not outperform the BER curve of conventional OFDM within the $E_b/N_0$ interval under consideration. Furthermore, we observed that in order for ORC to outperform the BER of OFDM it is necessary a $E_b/N_0$ of more than 26 dB, and even so the improvement is not significant. The poor performance of ORC dues to the high noise amplification that it produces on those subcarriers suffering from deep fading. For this reason, the BER of ORC gets worst at low $E_b/N_0$ as the processing gain increases, because this in turn increases the chances of including deep faded subchannels in the data despreading process. Contrarily, for $E_b/N_0 > 26$ dB the BER improves as $G_u$ increases because the noise amplification does not produce a significant degradation on the average SNR; however, the resultant BER improvement is not considerable.

On the other hand, increasing $G_u$ in the case of the correlated subchannels does not provide the same improvement in the BER curves of MRC, EGC and MMSEC as in the case of the uncorrelated subchannels. This is because the correlation among subchannels reduces the channel frequency diversity and hence diminishes the effectiveness of those combining techniques to combat fading. In fact, if the subchannels were totally correlated, the BER curves of the four techniques would be the same ($G_u = 1$) regardless of the processing gain. Interestingly, for ORC we can see that at low $E_b/N_0$ the BER curves are slightly better in the correlated channel than in the uncorrelated channel. The reason is that the correlation among subchannels reduces the level crossing rate (LCR) measured over the bandwidth of interest and this in turn reduces the number
of deep faded subchannels encountered in the data despreading process. Hence, the performance degradation of ORC is less severe at low $E_b/N_0$ as the channel becomes correlated; nonetheless, a higher $E_b/N_0$ is necessary in order for ORC to outperform the BER curve of OFDM.

B. Network scenario with MUI

Figure 2 shows the results of the network scenario in a Rician channel with $K = 1$, maximal MUI and both uncorrelated and correlated subchannels.

As a result of the MUI there is a significant change in the performance of MRC and EGC. This is clear since these combining techniques yield the worst BER. The reason for this change lies on the fact that the inner product of two different Haddamard-Walsh codes departs from zero as the dynamical range of the chips’ amplitude becomes higher; this implies the lost of the codes’ orthogonality. In accordance to (4) and (5), MRC and EGC do not attempt to reduce such a dynamical range and are therefore unable to preserve the orthogonality of the spreading codes. For this reason neither MRC nor EGC can remove the MUI and their BER curves have bounds given by this type of interference. Moreover, MRC is the technique that yields the worst results in the presence of MUI because in the aim of maximizing the SNR of the despreaded signal it increases the dynamical range of the chips’ amplitude. Actually, when the system is at full load the BER of MC-CDMA/vsf with MRC and $G_u > 1$ proves to be worst than that of OFDM.

Regarding the performance of these techniques in correlated channels we can observe that, contrarily to the MUI-free network scenario, the BER curves of MRC and EGC are better in the correlated channel than in the uncorrelated one. This is obvious because even their BER floors diminish when the channel becomes more correlated. This is because the $G_u$ chips involved in the data despreading experience a similar amplitude distortion as the channel correlation increases, which is in favor of the codes’ orthogonality because decreases the dynamical range of the chips’ amplitude. In fact, the inner product of two different Haddamard-Walsh codes would be zero if the $G_u$ subchannels were totally correlated, and MRC and EGC would then be able to remove completely the MUI. However, the resulting BER curve would correspond to the one of $G_u = 1$ (flat fading channel) no matter of the actual processing gain.

With respect to ORC and MMSEC we can say that they perform reasonably better in this scenario than MRC and EGC. In fact, we can observe that their BER curves are not bounded by the MUI and they do perform better as the SNR increases. In particular, ORC fully eliminates the MUI because it restores the orthogonality of the spreading codes and therefore performs the same regardless of the system’s load. Despite the BER of MMSEC is not bounded by the MUI, this interference degrades its performance in comparison to the MUI-free network scenario. Nonetheless, this performance degradation is not as significant as in the case of MRC and EGC. Since MMSEC takes the noise power into account to neutralize the channel fading, it does not restore the codes’ orthogonality as ORC does, but contrarily to MRC and EGC, allows the codes to preserve some degree of orthogonality. Furthermore, given that MMSEC does

Figure 1: BER of MC-CDMA/vsf for BPSK in a Rician channel without MUI and Rician factor $K = 1$. 
Figure 2: BER of MC-CDMA/vsf for BPSK in a Rician channel with MUI and Rician factor $K = 1$.

not over-amplify the noise power, it performs considerably better, in general, than ORC.

The subchannels’ correlation have the same effects in the performance of ORC and MMSEC as in the network scenario without MUI. We just want to add that the channel correlation allows MMSEC to reduce the residual MUI because of the same reasons that we explained before for MRC and EGC.

VI. CONCLUSIONS

In this paper we have presented MC-CDMA/vsf as a potential architecture for the downlink of next generation infrastructure WLANs. The set of raw data rates that we have defined for MC-CDMA/vsf includes data rates higher than those defined in the IEEE 802.11g standard for BPSK and QPSK modulations. However, we shall emphasize that the data rates presented in table 1 are raw rates, and further analysis are required to know exactly the throughput of the network. Nonetheless, the importance of this MC-CDMA proposal lies on its capability to send data of several users at the same time and over the same radio channel even if the data rate requirements of the users are different. Furthermore, unlike the 802.11g standard, MC-CDMA/vsf offers the possibility of transmitting the users’ information choosing the data rates that better suit their particular requirements. Recall the transmission modes of the 802.11g are chosen with basis on a link adaptation criterion and the type of information sent to the user is not taken into account.

We also evaluated the BER performance of our proposal for MRC, EGC, ORC and MMSEC. Among them, MRC proved to be the best when there is no MUI in the downlink, but it is definitively the worst when the system is at full load. In turn, MMSEC has the best performance when the system is at full load and its performance is quite good in network scenarios without MUI. For this reason, we conclude that MMSEC is the best option for networks using this proposed architecture.

REFERENCES