INTERFERENCE TOLERANT MULTIUSER OFDMA FOR FEMTO CELLS

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ABSTRACT

An interference tolerant OFDMA scheme is proposed for multiuser wireless communications with specific application in femto cells. An interleaved set of subcarriers is dedicated to each user to provide with a high order of frequency diversity. A reduced complexity digital implementation of the technique is proposed and discussed for the interleaved sub-carrier arrangement. Both inter-symbol interference and other-user interference are mitigated using a proper cyclic extension, provided that the relative propagation delays of the users are an integer multiple of a symbol period. The effect of other-user interference due to non-integer propagation delays is investigated using computer simulations. The bit error rate performance and signal to interference ratio are presented for a few example systems over both an Additive White Gaussian Noise (AWGN) and a frequency selective Rayleigh fading channel. The amount of other-user interference is shown to be reduced as the number of sub-carriers per user is increased. The effect of design parameters on the interference level is discussed.

KEYWORDS

Multiuser OFDMA, Interference, Cyclic extension

1. INTRODUCTION

Two major problems associated with data communications over terrestrial wireless channels are inter symbol interference and fading caused by multipath propagation. In multi user applications such as personal mobile communications, other-user interference could also limit the system performance and capacity.

Various multiple access techniques have been devised for multi user wireless applications. Code Division Multiple Access (CDMA) schemes use a wide frequency band and therefore, a high order of frequency diversity could be achieved when the signal bandwidth is sufficiently larger than the channel coherence bandwidth [1,2,9]. The capacity of the CDMA techniques using binary codes such as Walsh-Hadamard codes are limited by the users signal interference. This is resulted from non-zero cross correlation between binary codewords with different time shifts. The transmit codewords arrive at each user receiver with different time shifts because of various propagation delays associated with the users scattered over a cell and also because of multipath propagation. Combined time and frequency division multiple access schemes usually use signals with a narrower bandwidth. Slow frequency hopping is sometimes used to combat fading of stationary and slow moving users in such schemes.

In this paper, an interference tolerant wideband multiple access scheme is discussed based on the orthogonal frequency division multiplexing (OFDM). The scheme is designed as such, the amount of other-user interference and inter symbol interference are reduced. This is achieved using both a cyclic prefix and a cyclic suffix in the transmit data frames and noting that the Fourrier codewords used in OFDM have a zero cross correlation on all cyclic shifts.

A set of non-adjacent subcarriers is proposed for each user. This provides with a high order of frequency diversity, which can be realized using proper error correcting codes [3]. As is the case with orthogonal frequency division multiplexing, no channel estimation and equalization is required if differentially coherent QPSK modulation are used [4,5]. The proposed scheme can be used in a single cell as well as a cellular system and could be combined with other multiple access techniques to satisfy the requirements of a specific application. The drawbacks of the proposed scheme include high sensitivity to nonlinearities due to large peak to average power ratio and the carrier frequency offset which are the common problems with OFDMA [5,6]. Accurate synchronization of the wireless users and system in uplink and downlink is usually assumed for efficient channel allocation and spectrum management in OFDMA based technologies such as WiMAX and LTE [9]. Due to random distribution of the users in the cells and multipath propagation, accurate synchronization of all of the active users in macro-cells and femto-cells is almost impossible, which causes other-user interference. In this paper, an interference tolerant multi-user OFDMA scheme is proposed for application in femto-cells. The scheme is based on insertion of a cyclic prefix and suffix with proper length at the beginning and at the end of OFDM frame. The length of the cyclic suffix, which is related to the maximum timing offset between the users' frame at receiver correlator's window, is small in femto-cells. Accordingly, a small percentage of the bandwidth is wasted for additional cyclic suffix in femto cells and co-existing macro cells (Figure 1). Moreover, because of the small region, femto-cells are expected to have less PAPR problem.

The organization of the paper is as follows: In the following section, the background and related work is reviewed. In section 3, the main idea and a reduced complexity digital implementation of the proposed technique is discussed. Section 4 is devoted to the interference reduction mechanism using a proper cyclic extension in various situations. In section 5, the effect of other-user interference due to non-integer propagation delays is discussed using computer simulation results. Conclusions and proposed future work on this topic are presented in section 6.

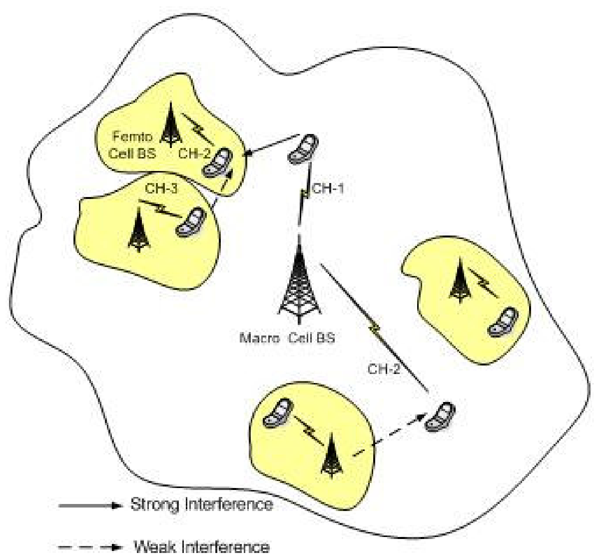


Figure 1: The wireless network model

2. RELATED WORK

To suppress the other user interference in quasi-synchronous multiple access CDMA systems, special code design were proposed [10,11,12,13,14]. As the out-of-phase autocorrelation of the discussed codes was not zero, the inter-symbol interference could not be avoided in multipath fading channels. The idea of using poly-phase codes was introduced in [14] to have zero out-of-phase autocorrelation and small cross correlation in frequency selective radio channels.

To add the diversity gain to OFDMA, dedication of non-adjacent sub-channels over a wideband frequency range was proposed in [15, 16]. Dedication of non-adjacent equally spaced sub-channels in frequency selective waveform channel was discussed in [17]. To extract the full diversity gain, a generalized structure was proposed for multi-carrier CDMA (MC-CDMA) in [18].

OFDM has been proposed for IEEE 802.16, WiMAX systems, which need accurate synchronization for extraction of the user's data. The effect of inter-symbol interference and other user interference due to multipath propagation and inaccurate timing is reducible by addition of cyclic prefix and suffix to the OFDM frame as is discussed in this paper. Simultaneous insertion of long cyclic suffix and prefix reduces the bandwidth efficiency. In uplink transmission, when timing offset between the users is small (like femto cells), the bandwidth efficiency reduction due to insertion of cyclic suffix might be negligible. Synchronization techniques for OFDMA in uplink and downlink transmissions were extensively discussed in [19].

3. System Description and Implementation

The interference tolerant OFDMA scheme and its discrete implementation are discussed in this section. It is assumed that the communication channel is a frequency selective fading channel and a bandwidth "sufficiently larger" than the channel coherence bandwidth is available. "Sufficiently large" bandwidth is one which provides with the required order of frequency diversity in the system. The available frequency band is divided into a number of flat fading orthogonal sub-channels. A set of non-adjacent sub-channels are dedicated to each user.
For instance, as is shown in Figure 2 every one of 3 sub-channels is given to each of 3 users sharing the same frequency band. Such a frequency assignment guarantees a high order of frequency diversity as non-adjacent sub-channels are expected to fade independently or with a smaller correlation.

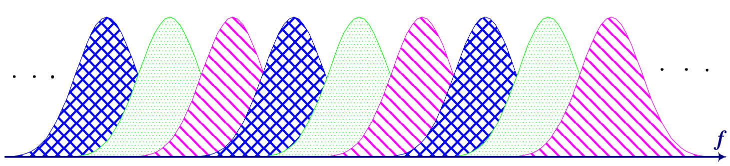


Figure 2: An example frequency assignment for users sharing the same bandwidth

An straightforward digital implementation of the proposed scheme uses the formal DFT-based OFDM implementation [3-6,8] with information sent only over a subset of sub-channels for each user. The transceiver functional block diagram for such an implementation is shown in Figure 3. In Figure 3, the "equivalent discrete channel" is an equivalent block for the transmit and receive filters, Quadrature modulator and demodulator, the physical wireless channel and also the periodic sampler.

It is assumed that root Nyquist filters are used both in the transmitter and the receiver. The cyclic extension blocks help to minimize both intersymbol and other-user interference as is discussed in section 4. The Discrete Fourrier Transform (DFT) and its inverse (IDFT) are used to partition the channel along the frequency axis [3,4,6]. A total of MN frequency sub-channels are generated, N of them for each of M users sharing the available frequency band. The coded and digitally modulated complex-valued sequence of N components $\{V_n\}_{n=0}^{N-1}$ is up-sampled according to (1).

$$U_n = \begin{cases} V_{n/\mathrm{M}} & n = 0\,,\mathrm{M}\;\,,2\mathrm{M}\;,\;\ldots\;,(\mathrm{N}-1)\mathrm{M} \\ 0 & \text{otherwise} \end{cases} \qquad (1)$$

and cyclically shifted right m times where $m = 0, 1, 2, \ldots, M-1$, is the user index. At the receiver the DFT output sequence is decimated.

$$\tilde{V}_n = \tilde{U}_{nM} \quad , \quad n = 0, 1, 2, \ldots, N-1 \qquad (2)$$

after being cyclically shifted left m times. The complexity of the OFDM multiplexer and demultiplexer as marked in Figure 3 can be reduced noting the equivalent operations shown in Figure 4 [7].

In Figure3 the phase adjustment and the phase correction blocks are respectively defined according to (3) and (4).

$$y_k = u_k W_{MN}^{mk} \quad , \quad k = 0, 1, 2, \ldots, MN-1 \qquad (3)$$

$$\tilde{u}_k = \tilde{y}_k W_{MN}^{-mk} \quad , \quad k = 0, 1, 2, \ldots, MN-1 \qquad (4)$$

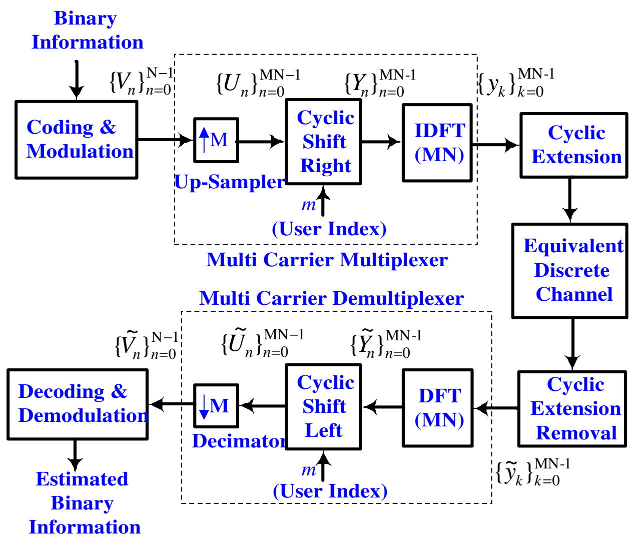


Figure 3: The straightforward digital implementation of interference tolerant OFDM

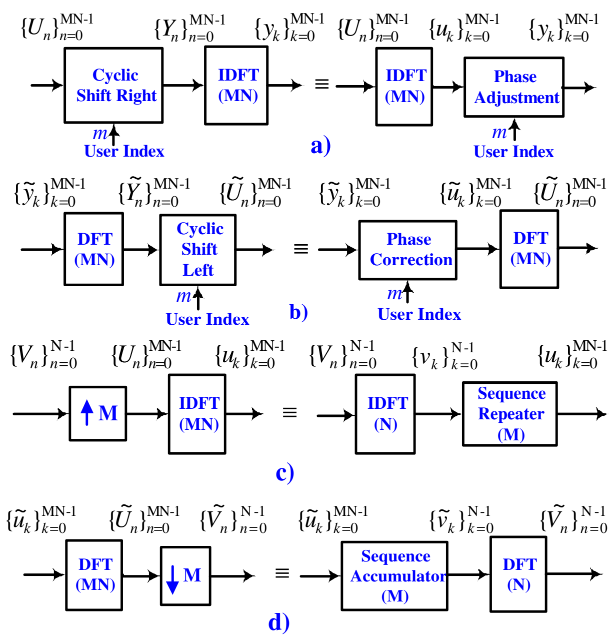


Figure 4: Equivalent discrete operations

where

$$\mathrm{W}_{\mathrm{MN}} = \exp(\text{-j}\frac{2\pi}{\mathrm{MN}})$$

where m = 0 ,1 ,2 , ... ,M-1 is the user index. The sequence repeater and the sequence accumulator blocks are respectively defined according to (5) and (6).

$$u_k = v_{(k) \bmod \mathrm{N}} \quad , \quad k = 0,1,2, \ldots, \mathrm{MN}-1 \tag{5}$$

$$\tilde{v}_k = \sum_{m=0}^{\mathrm{M}-1} \tilde{u}_{(m\mathrm{N}+k)} \quad , \quad k = 0,1,2, \ldots, \mathrm{N}-1 \tag{6}$$

Using equivalent operations shown in Figure4a and Figure 4c, the OFDMA multiplexer is reduced to what is shown in Figure 5a. Using Figure 4b and Figure 4d, the OFDMA demultiplexer is reduced to Figure5b. Reduction in complexity is made mainly because of reduction in the DFT and the IDFT frame lengths from MN points to N points.

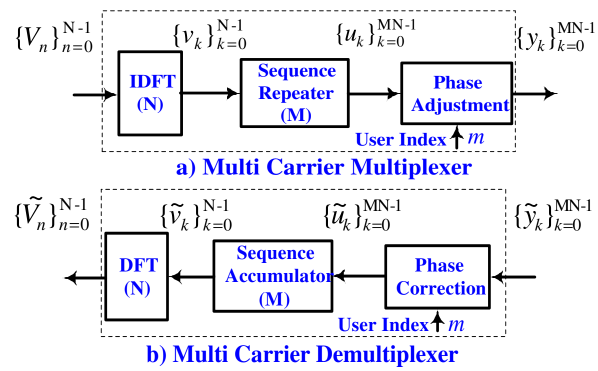


Figure 5: Reduced complexity multi carrier multiplexer (a) and demultiplexer (b).

4. CYCLIC EXTENSION AND INTERFERENCE

Appending a proper cyclic extension to the IDFT output frame $\underline{\mathbf{y}} = \{y_k\}_{k=0}^{\mathrm{MN}-1}$ in Figure 3, the amount of other-user interference may be reduced. When the transmit signal bandwidth, B is occupied only by one user, the cyclic extension is usually a prefix of length $L_p \approx BT_{\mathrm{m}}$, where T_{m} is the total multipath spread [3,4].

The IDFT output vector $\underline{\mathbf{y}} = \{y_k\}_{k=0}^{\mathrm{MN}-1}$ can be obtained from its input vector $\underline{\mathbf{Y}} = \{Y_n\}_{n=0}^{\mathrm{MN}-1}$ multiplying it by the Fourrier matrix. If each row of the Fourrier matrix is considered as a complex-valued Fourrier codeword $\underline{\mathbf{W}}_n$, then IDFT process may be viewed as a form of code division multiplexing

$$\underline{\mathbf{y}} = \sum_{n=0}^{\mathrm{MN}-1} Y_n \underline{\mathbf{W}}_n \tag{7}$$

where

$$\underline{\mathbf{W}}_n = \begin{bmatrix} \mathrm{W}_{\mathrm{MN}}^{n0} & \mathrm{W}_{\mathrm{MN}}^{n1} & \ldots & \mathrm{W}_{\mathrm{MN}}^{n(\mathrm{MN}-1)} \end{bmatrix} \tag{8}$$

In fact each Fourrier codeword represents one of the subbands generated by the IDFT process. A good property of these codewords is that they have zero cross correlation on all cyclic shifts. This property holds even if the codewords are multiplied by a real or a complex-valued constant.

Each transmit data Y_n sent over the codeword $\underline{\mathbf{W}}_n$ is resolved correlating the received frame $\tilde{\underline{\mathbf{y}}}$ by the complex conjugate of $\underline{\mathbf{W}}_n$. Because of the orthogonality of the Fourier codewords, only Y_n passes through its correlator $\underline{W}_n^*$. When the channel is a multipath channel, shifted versions of the transmit frame also appear at the receiver. If the transmit frame includes a cyclic prefix, then each correlator $\underline{W}_n^*$ sees only cyclic shifts of other Fourrier codewords multiplied by a data symbol and scaled by a channel coefficient. Since the Fourrier codewords $\{\underline{\mathbf{W}}_n\}_{n=0}^{MN-1}$ are orthogonal on all cyclic shifts, no interference from other data symbols appears at the correlator output.

In multi user applications, depending on the situation, we may have to modify the single user cyclic extension to control interference from other users.

First, consider a case where the users are scattered in one cell transmitting data to a base station. The users data frames are arrived at the base station with different time shifts because of different propagation delays associated with each user. Figure 6 shows example "equivalent discrete channel" impulse responses corresponding to 3 users in a cell.

For now assume that the propagation delays $\{\tau_i\}$ relative to the user # 0, are integer multiples of the transmit symbol period T, for instance $\tau_1 \approx 2T$, $\tau_2 \approx -2T$. The effect of non-integer propagation delays is discussed in section 5 using computer simulation results.

The users' frames arrival at the base station receiver is depicted in Figure 7. Using a cyclic suffix of

$$L_s \approx \frac{\max_i(\tau_i)}{T} \quad , \quad i = 0, 1, 2, \ldots, M-1 \tag{9}$$

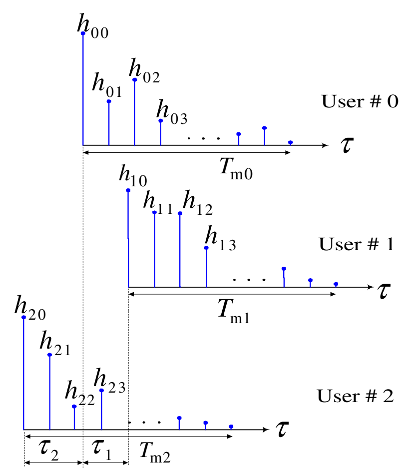


Figure 6: Relative propagation delays of the users sharing the same bandwidth

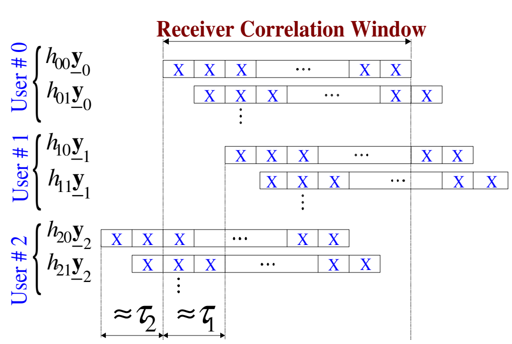


Figure 7: The users frame arrival at the base station receiver

and a cyclic prefix of

$$L_p \approx \frac{\max_i(\tau_i + T_{mi})}{T} \quad , \quad i = 0, 1, 2, \ldots, M-1 \qquad (10)$$

the data frames arrived at the base station appear as cyclic shifts of scaled Fourrier codewords within the correlator window. Therefore, no interference from other data symbols and other users passes the correlator. The cyclically extended transmit frame is therefore given by

$$\left[y_{MN-L_p} \cdots y_{MN-1}\; y_0\; y_1 \cdots y_{MN-1}\; y_0\; y_1 \cdots y_{L_s-1} \right]$$

In downlink, where data is sent by the base station to the mobile users, the transmit data frames of all the users are synchronized and therefore $\tau_i = 0$, $i = 0, 1, 2, \ldots, M-1$. Hence, no cyclic suffix is required and the cyclic prefix is reduced to

$$L_p \approx \max_i\left(\frac{T_{mi}}{T}\right) \quad , \quad i = 0, 1, 2, \ldots, M-1 \qquad (11)$$

5. PERFORMANCE EVALUATION

5.1. BER in AWGN and Rayleigh fading channel

As discussed in the previous section, using a proper cyclic extension, no interference from other users is expected if the user propagation delays would be an integer multiple of the symbol period. This may not be achieved in practice when mobile users transmit data to a base station. The effect of other-user interference resulted from non-integer propagation delays are investigated using computer simulations.

The results are obtained for an example system where 3 mobile users in one cell share the same frequency band. Root raised cosine filter with a roll-off factor of 0.25 are used both in the transmitter and receiver. The system is assumed to have a power control mechanism as such the users have the same power at the base station. The subcarrier modulation is the coherent DQPSK and no channel coding has been performed.

Figure 8 shows the bit error rate performance over an AWGN channel for various relative propagation delays τ_i associated with the two interfering users. The results are achieved assuming $L_p = L_s = 1$ and using N = 4 subcarriers per user. As is seen in Figure 8 the best performance is achieved, when τ_1 and τ_2 is either zero or equal to a symbol period T. The worst performance is obtained when $\tau_1 = \tau_2 = 0.5$T.

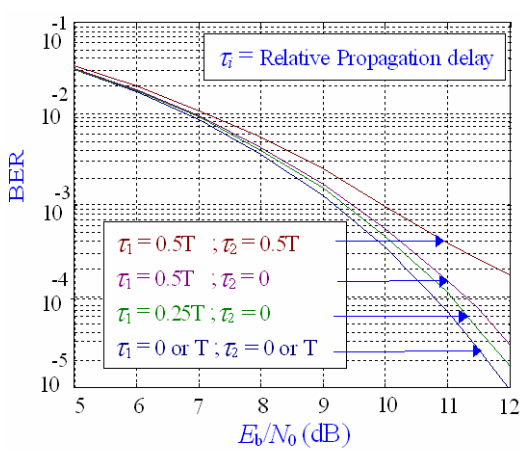


Figure 8: Performance comparison for various propagation delays over AWGN channel.

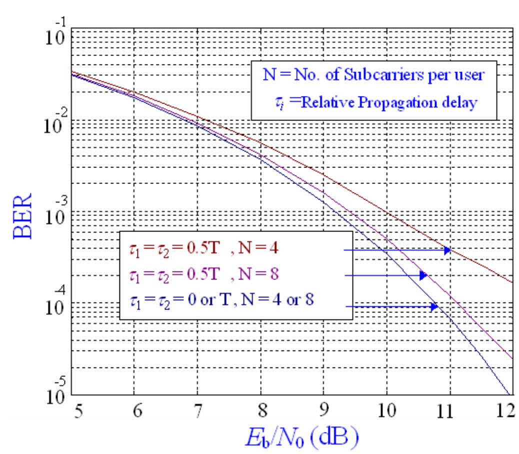


Figure 9: Worst case performance comparison for various number of sub-carriers per user over the AWGN channel.

Figure 9 shows the worst case performance using 8 sub-carriers per user. As is seen, the bit error rate (BER) performance is substantially enhanced by increasing the number of sub-carriers. Similar results are obtained over Rayleigh fading channels as is seen in Figure 10.
The results of Figure 10 are obtained using a 3-tap channel model with an exponential intensity profile for all the 3 users and independent fading for each one. The prefix length, L_p is accordingly set to 3. The channel Doppler spread is assumed to be 0.001 of the transmit symbol rate.

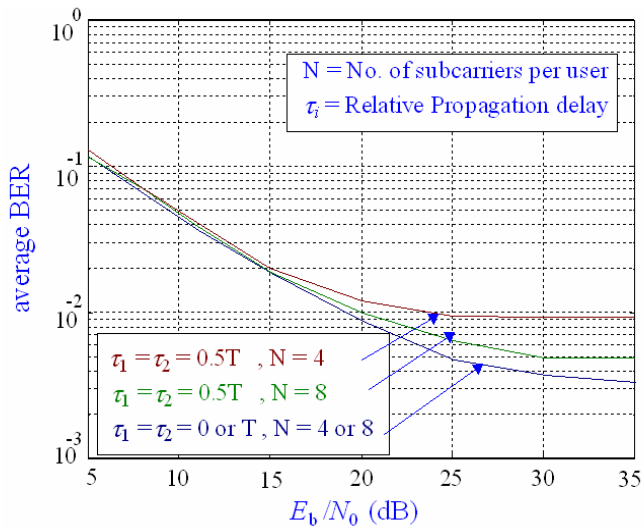


Figure 10: Worst case performance comparison for various numbers of sub-carriers per user over a Rayleigh fading channel.

5.2. Interference amount

The other user interference varies with the system design parameters such as DFT size, the pulse shape, and the size of cyclic extension (prefix and suffix).

5.2.1. Effect of the pulse shape

Insertion of cyclic prefix and suffix at the beginning and at the end of the OFDM frame guarantees that the interference from the other user's with timing offset of mT_S is completely removed (regardless of the power of the interferer user), where m is an integer number. When the timing offset between users is not an integer multiples of the symbol rate, the residual interference amount at the output of the DFT unit in receiver depends on the amount of offset and the pulse shape.
Figure 11 illustrates the interference to signal ratio for different time normalized offsets when the roll-off factor of the root-raised cosine filter varies between zero and 1. As this figure shows by increasing the roll-off factor of the root-raised cosine filter, the interference to signal is reduced. This improvement is due to the decrease of the sidelobes' amplitude which is shown in Figure 12. For β=1, the interferer signal is removed at integer multiples of $0.5T_S$. Technically, β=1 does not have good bandwidth efficiency and is not used.
This result is achieved with computer simulations in AWGN channel when the average power of interferer signals and the main signal are equal. Each user has N=4 sub-channels, $L_p = L_s = 3$ and three users are assumed in simulation.

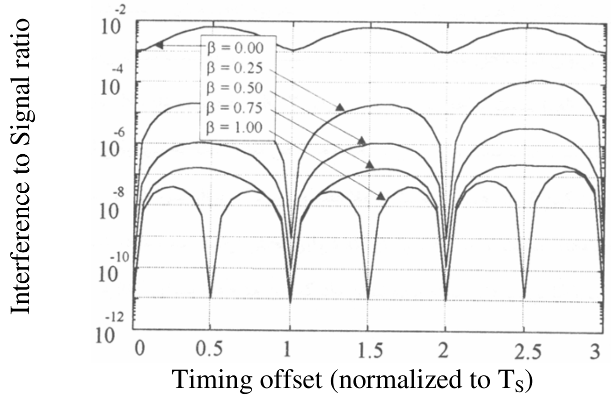


Figure 11: Interference to signal ratio versus time offset for some β (N=4, K=3).

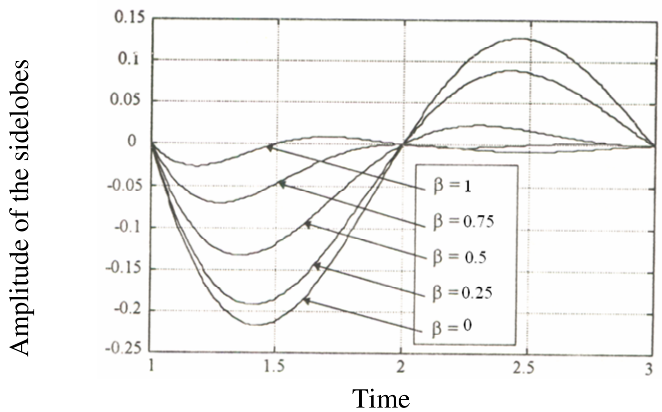
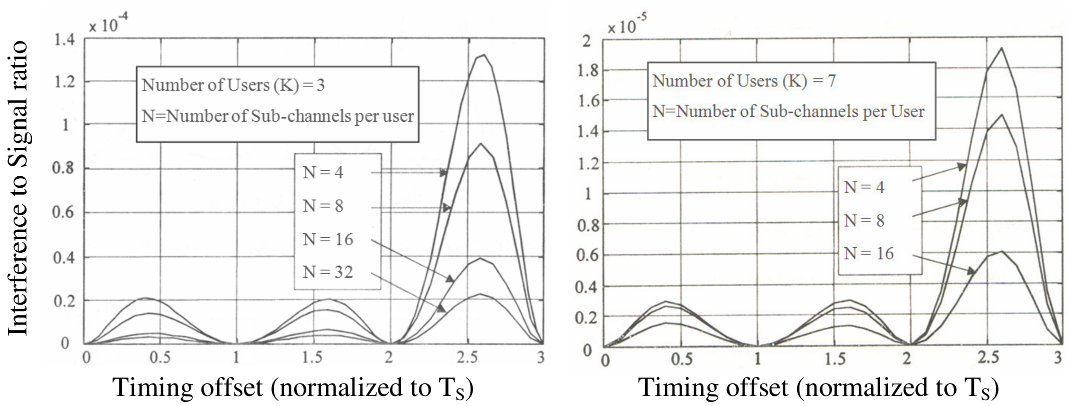


Figure 12: Sidelobes of the root-raised cosine pulse versus time for some β.

5.2.2. Effect of the DFT size

Figure 13-a and 13-b present the variation of the interference to signal level for two values of (K) and different number of sub-channels. As these figures show, for specific K, as the number of the sub-channels per users increases, the interference level is reduced. Increase of the number of users (K) from 3 to 7, improves the interference tolerance of the system. In these simulation the length of cyclic prefix L_p = 5 and the length of cyclic suffix L_s = 3, the radio channel AWGN, and only one interferer user with nonzero timing offset are assumed



(a) (b)

Figure 13: Interference to signal ratio versus time offset for some DFT size (KN) when only one users has nonzero time offset, β = 0.25.

6. CONCLUSION

A wideband interference tolerant multiuser OFDMA scheme is discussed for wireless communications in femto cells. To provide with a high order of frequency diversity, an interleaved set of subcarriers is dedicated to each user. A reduced complexity digital implementation of the proposed technique is presented.

It is shown that with a proper selection of the cyclic extension and the number of subcarriers per user, the other-user interference as well as inter symbol interference may be reduced to an acceptable level. The residual interference due to nonzero timing offset is investigated. Using proper channel codes to exploit the provided high order of diversity, wireless systems with a good performance and a high capacity could be designed using the proposed scheme in conjunction with the other multiple access techniques.

ACKNOWLEDGEMENTS

The author would like to specially thank Dr. A. Chini for his directions throughout the work.

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