FDMA- versus TDMA -based Resource Partitioning among Cells in Wide Area Scenario

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Abstract- **An OFDM-based cellular system is considered for the air interface of 4th generation (4G) mobile radio systems. The impact of time offsets due to propagation delays among terminals in different cells is evaluated for two inter-cell resource partitioning schemes, FDMA and TDMA, in a wide area scenario. Given the envisaged short frame length required to accomplish stringent packet delay demands, in TDD mode, TDMA can become unsuitable already for relative low resource reuse factors, e.g. larger than 6 due the overhead for the insertion of guard periods. In FDD mode, on the other hand, for reuse factors up to 7 the TDMA allocation can be advantageous.**
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***Index Terms*—OFDM, OFDMA, Synchronisation.**

I. INTRODUCTION

OFDM (Orthogonal Frequency Division Multiplexing) is the leading transmission technology for the air interface of so-called beyond third generation (B3G) and 4G mobile radio systems. The main principle of OFDM is that of splitting the transmission bandwidth into a large number of spectrally overlapping, but orthogonal, *sinc*-shaped narrowband sub-carriers, which can be independently loaded and modulated [1]. The assignment of distinct sets of sub-carriers to different users in a frequency division multiple access fashion (FDMA) yields the OFDMA scheme, which enables high flexibility and granularity in the frequency resource assignment and, hence, high spectral efficiency [2]. However, OFDM exhibits two major drawbacks: the high sensitivity of the OFDM signal to time and frequency synchronization errors and to the non linear distortions of the high-power-amplifier at the transmitter. Both drawbacks limit its application in uplink, but the latter, due to the high peak-to-average power ratio (PAPR) of the OFDM signal, seems to be the most limiting factor.

Therefore, within the European IST-2003-507581 project WINNER, OFDM has been chosen as the transmission technique for the downlink in both short range and wide area scenarios, while for the uplink only in short range case (i.e. cell radius up to a few hundreds meters), where the terminal power consumption is not a determining factor. For the uplink in the power limited wide area case (cell radius up to 2 km), a variant of serial modulation given by DFT-precoded OFDM is being considered due to its low PAPR [3]. However, this technique, which is also envisioned to be used jointly with FDMA and TDMA, exhibits the same sensitivity to time and frequency synchronization errors as OFDM.

When OFDM is applied in a cellular environment, the degree of time and frequency synchronisation among terminals in different cells influences the choice of the multiple access among base stations (BSs) as well. In case of FDMA-based resource partitioning, both time and frequency offsets may cause not only intra-cell but also inter-cell interference in the form of inter-carrier/adjacent band interference (ICI or ABI). TDMA-based resource partitioning, on the other hand, is not sensitive to frequency offsets, since each cell is exclusively assigned the whole bandwidth for a certain time-slot, but time offsets may induce inter-cell interference in the form of inter-symbol/inter-slot interference (ISI).

To counteract the performance degradation due to time and frequency offsets, efficient synchronization techniques have been developed within the project WINNER for intra-cell as well as inter-cell synchronization [4]-[5]. However, in wide area scenarios, time offsets between users in different cells due to the not negligible propagation delays can lead to significant inter-cell interference even under the assumption of perfect time and frequency synchronisation. In order to avoid/reduce such interference, guard bands and guard periods can be introduced in FDMA and in TDMA, respectively.

In this paper an analysis is carried out with the purpose of deriving which of the two approaches, FDMA or TDMA, results to be the most spectrally efficient with the system parameters and requirements currently envisaged for the WINNER system. At this aim, perfect inter-cell time and frequency synchronization is assumed and the time offsets originate only from the propagation delays between neighboring cells. However, the resulting spectral efficiency

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figures give also an indication of the performance degradation suffered by the system in case that this assumption does not hold true. Indeed, according to the WINNER requirements [8], the system shall be able to operate also without inter-cell synchronisation.

The remainder of the paper is organised as follows. Section II illustrates the considered system model. In Section III, the performance degradation due to time offsets is evaluated for FDMA inter-cell allocation, with and without guard bands. Section IV analyses the impact of time offsets in the TDMA scheme. For both schemes, the resulting spectral efficiency loss is assessed. Finally, Section V draws some conclusions.

II. System Model

For the purposes of the addressed analysis, we can assume frequency and time resource reuse (RR) through FDMA and TDMA, respectively, by the cells in the whole considered service area according to a clustering pattern, as shown, e.g. in Fig. 1 for reuse factor (RF) 3.

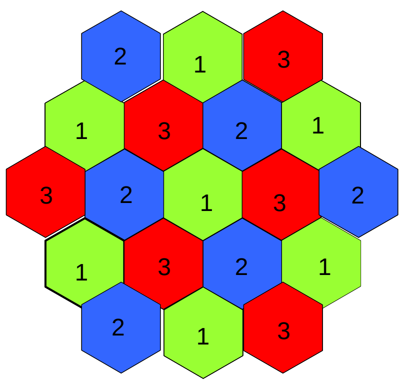

Fig. 1. Deployment scenario for RF = 3.

Derivations made under this assumption remain valid in case of single-frequency network, in which all time/frequency resource units are accessible to all BSs and user terminals (UTs), i.e. RF=1. Indeed, in this case, a reuse factor larger than 1 is implied by the typical interference-avoidance strategies which are jointly applied with dynamic radio resource management [6], [7].

A. Block FDMA Inter-Cell Resource Partitioning

In case of block-FDMA inter-cell allocation, the whole bandwidth is subdivided into a number of sub-bands equal to the reuse factor, which are assigned to distinct cells according to the considered reuse pattern. Fig. 2 depicts, e.g., the block-FDMA allocation corresponding to the clustering of Fig. 1.
Each sub-band consists of a block of adjacent overlapping sub-carriers. When no guard band is introduced between two neighboring sub-bands, the system is very sensitive to time and frequency offsets occurring between terminals in the respective cells.

B. Slot TDMA Inter-Cell Resource Partitioning

In slot-TDMA inter-cell allocation, one MAC frame is sub-divided into a number of time slots equal to the reuse factor in FDD systems and to twice the reuse factor in TDD systems. Again, these are assigned to distinct cells according to the considered reuse pattern. Fig. 3 depicts, e.g., the slot-TDMA allocation corresponding to the clustering of Fig. 1.

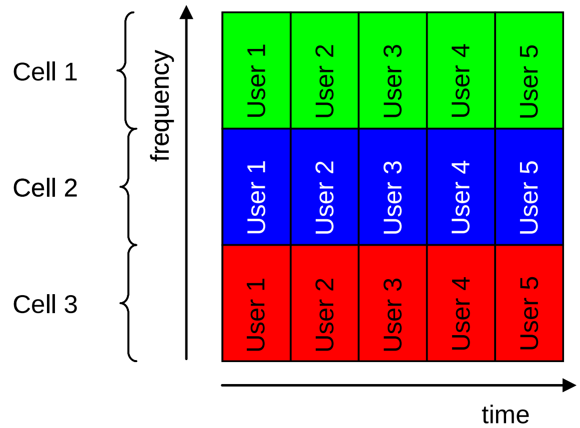

Fig. 2. FDMA block allocation.

In order to avoid inter-slot interference due to time offsets between terminals in the respective cells, a guard interval larger than the maximum time offset has to be inserted between successive time slots. Hence, to contain the overhead within a certain threshold, the single time slots consist of several successive OFDM symbols. We note that the maximum time offset to be taken into account depends on the considered scenario. For example, with reuse factor 16 in a macro-cellular deployment scenario with antennas above rooftop, the link of interest can be affected by interference from the second ring of interfering cells, which implies a propagation delay corresponding to four times the cell radius.

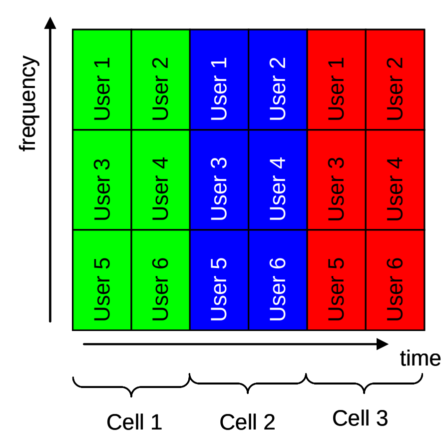

Fig. 3. TDMA slot allocation

C. Assumed System Parameters

According to the current assumptions of the WINNER project, FDD mode is primarily considered for the wide area scenario over paired bands of 20 MHz, with Half Duplex FDD

operation at the user terminals. For the OFDM-based transmission 512 sub-carriers are assumed over 20 MHz, so yielding a sub-carrier spacing $\Delta f \approx 39$ KHz.
Furthermore, in this work, a WSSUS Rayleigh fading channel model with exponential power delay profile is adopted. The guard interval, chosen to be larger than the channel maximum delay spread, equals 6.4 µs. The cell radius is assumed to be of 2 km and the Okumara-Hata path loss model is used.

III. Impact of Time Offsets in Block-FDMA

A. Performance Degradation

The performance degradation due to time offsets in block FDMA inter-cell allocation with and without guard bands is

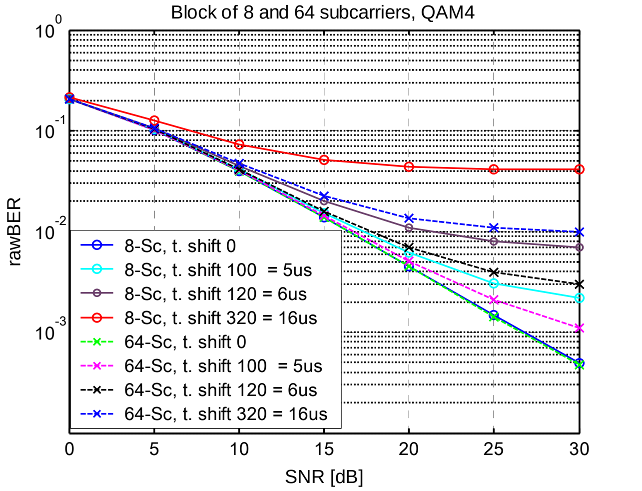

Fig. 4. Raw BER in a block-FDMA system for different sizes of block of sub-carriers and different values of time offset.

evaluated by means of link level simulations. A worst case scenario is considered in which there are only two cells and two users which are assigned interleaved blocks of adjacent sub-carriers. Moreover, equal receive power and time offsets up to ½ OFDM symbol are assumed. Results are reported in Fig. 4 in terms of uncoded BER (rawBER) for blocks of 8 and 64 sub-carriers at different values of time offsets ranging from 5 µs (cell radius of 1,5 km) to 16µs (cell radius of 4,8 km). From the figure it can be inferred that high performance degradation occurs when the time offset is equal to or higher than the guard interval. For some time offsets, the raw BER curve saturates before achieving the value of 10^{-2}. As it is reasonably expected, significantly better performance is obtained with larger block size because the effect of inter-carrier interference turning into inter-cell interference is larger at the block border. Hence, for smaller blocks, almost all sub-carriers might be interfered.

A better overview is offered by Fig. 5, which compares the dependency of the SNR degradation on the different values of time offsets. The SNR degradation has been computed at a rawBER of $10^{-1.77}$ corresponding to coded BER of 10^{-3}, which represents the considered QoS criterion for VoIP. The SNR degradation for the block size of 8 sub-carriers is visibly much higher than for blocks of 64 sub-carriers. At a time offset of 6 µs, the loss in power efficiency of 1,2 dB[1]. Moreover, in Fig. 5, the comparison of SNR degradation with and without guard bands is shown. The introduction of guard bands of 8 sub-carriers between blocks of 64 sub-carriers leads to a significant improvement. For time offsets larger than 5µs, in particular, the SNR degradation saturates.

From these results it can be derived that it would be recommended to assign blocks of at least 64 adjacent sub-carriers to different cells in order to keep the performance degradation to a reasonable level (up to 1dB).

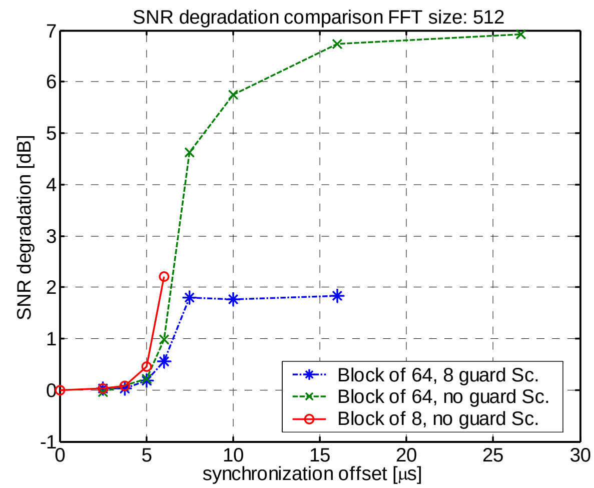

Fig. 5. SNR degradation versus time offset for block size of 8 sub-carriers and block size of 64 sub-carriers with and without guard sub-carriers.

B. Impact on Spectral Efficiency

To compare the spectral efficiency of the two inter-cell resource partitioning schemes, the power efficiency loss in the block-FDMA case has to be translated into a figure of spectral efficiency loss. Given the not too high values involved, we can resort to a simple rule of thumb derived from 2G and 3G experience according to which a 4.5dB loss in power efficiency corresponds to 50% spectral efficiency loss. In Table I, results in terms of power and spectral efficiency loss are reported for block-FDMA with blocks of 64 sub-carriers, for cell radius of 2 km and reuse factor 7, with and without guard bands of 8 sub-carriers. It can be seen that the spectral efficiency can be doubled through the insertion of guard bands, although these represent an overhead in bandwidth of 12.5 %.

[1] Note that for block size of 8 sub-carriers the SNR degradation curve has not been plotted for time offsets values larger than 6 µs, since the rawBER curve saturates before reaching the value corresponding to the required QoS.

IV. Impact of Time Offsets In Slot-TDMA

A. Impact of Delay Requirements in Slot-TDMA

Besides high data rates, low packet delays are required from a 4G air interface. Therefore, according to the WINNER requirements [8], the basic air interface delay is defined to be 2 ms. Within 2 ms, both the signaling for allocation and the packet transmission have to be accommodated. For this reason, the MAC frame duration in WINNER has been chosen to be of 0.7 ms. If a reuse factor *RF* larger than one is used, in case of slot-TDMA inter-cell allocation, the system is required to allocate within 0.7 ms one time slot for each of the cells within a cluster. Note that in TDD systems *RF* time slots are needed in each uplink and downlink sub-frame.

B. Impact on Spectral Efficiency

The overhead due to the insertion of guard periods between any pair of time-slots assigned to different cells can be computed as follows. The total time per frame consumed as guard time T_g is given by the number of time slots per frame N_{ts} multiplied by the length of the guard period τ_g, that is

$$T_g = N_{ts} \cdot \tau_g$$

with τ_g being at least equal to the maximum time offset, i.e. $\tau_g \geq \tau_{off,max}$. The resulting overhead is then given by the ratio between the total guard time and the frame duration. Results are reported in Table II for three reuse factors for the FDD mode. The guard period has been assumed to be $\tau_g = \tau_{off,max}$=27 µs$_x$ corresponding to the propagation delay with respect to cells in the second ring of interfering cells. Given the choice of a very limited frame duration for the WINNER system as explained above, the overhead can be very significant for higher reuse factors. However, from the comparison of Table I and Table II, for *RF*=7, TDMA seems to be slightly advantageous with respect to FDMA.

TABLE II
Overhead due to guard periods in slot-TDMA

Reuse Factor	Frame Length [ms]	Number of Time Slots	Total Guard Time [µs]	Overhead [%]
5	0.7	5	135	19
7	0.7	7	189	27
13	0.7	13	351	50

It should be noticed that in TDD mode the application of the slot-TDMA inter-cell allocation approach in the WINNER system would be unsuited already for *RF*=7 because not all cells could be allocated a time slot of at least one OFDM symbol per frame.

V. Conclusions

The impact of time offsets on the performance of an OFDM-based cellular system in wide area scenario has been evaluated in terms of spectral efficiency loss for both FDMA and TDMA-based inter-cell resource partitioning. From the above analysis, it can be inferred that, in the FDD mode, slot-TDMA can be advantageous for reuse factors up to 7, but for higher reuse factors it becomes unsuited. The main reason comes from the stringent delay requirements for the WINNER air interface, that have been defined in order to accomplish the service delay demands envisaged for 4G systems. With FDMA allocation different cells in the same cluster can transmit at the same time. With TDMA allocation different cells have to transmit in different time slots and a guard period has to be inserted between any couple of time slots to combat the ISI due time offsets, so causing unacceptable overhead in the very short MAC frame or making the accommodation of all cells not feasible at all.

Moreover, it has been proved that the insertion of guard bands between blocks of sub-carriers assigned to different cells in FDMA, although representing an overhead in bandwidth, can significantly reduce the performance degradation due to time offsets, so improving the spectral efficiency.

It should be noted that the results of this analysis also give an indication of the spectral efficiency loss that would affect the WINNER system if it was operated without inter-cell time synchronization.

Acknowledgment

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References

[1] S.B. Weinstein, P.M. Ebert, “Data Transmission by Frequency Division Multiplexing Using the Discrete Fourier Transform”, IEEE Trans. On Commun. , vol. 19, n.5, Oct. 1971, pp. 628-634.

TABLE I
Power and spectral efficiency loss for block-FDMA

Reuse Factor	Band Overhead [%]	Power Efficiency Loss [dB]	Spectral Efficiency LOSS [%]	Overhead [%]
7	0	6.28	69.8	69.8
7	12.5	1.80	20.1	32.6

[2] C. Y. Wong, R.S. Cheng, K. B. Letaief and R.D. Murch, “Multi-user OFDM with adaptive sub-carrier, bit and power allocation”, *IEEE Journal on Select. Areas on Commun*., Oct. 1999.

[3] D. Galda. H. Rohling and E. Costa, “A Low Complexity Transmitter Structure for OFDM-FDMA Uplink Systems,” in *Proc. VTC Spring 2002*, Birmingham, United Kingdom, pp. 1737-1741, May 2002.

[4] IST-2003-507581 WINNER, “D2.1 Identification of Radio-Link Technologies”, June, 2004.

[5] IST-2003-507581 WINNER, “D2.3 Assessment of Radio-Link Technologies”, February, 2005.

[6] D. Galda, N. Meier, H. Rohling and M. Weckerle, “System Concept for a Self-Organised Cellular Single Frequency OFDM Network”, *in Proc. of 8th Int. OFDM Workshop 2003*, Hamburg, Sep. 2003.

[7] R. Veronesi, J. Zander, V. Tralli, M. Zorzi, F. Berggren, “Distributed Dynamic Resurce Allocation for Multicell SDMA Packet Access Networks”..

[8] WINNER Deliverable 7.1 System Requirements https://www.ist-winner.org/DeliverableDocuments/D7-1.pdf