A Performance Comparison of Candidate 4G Air-Interfaces in a Simulated Cellular Environment

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Abstract –**Development of the Fourth Generation of mobile communication systems, or 4G, has already begun in various organizations and research institutions worldwide. There is currently no single conclusive definition for 4G systems, and the process of 4G standardization will only begin after the World Radiocommunication Conference in 2007. The purpose of this paper is to evaluate the performance of two candidate 4G air-interface architectures, namely OFDMA and MC-CDMA, so that a recommendation can be made as to which architecture should form the core component of a new 4G access network system. To determine the appropriate choice of air-interface for 4G systems, a series of simulations was run using a realistic model of a cellular wireless environment. The results from those simulations were analysed and it was determined that, due to the absence of multiple access interference as found in MC-CDMA, OFDMA systems better met the defined requirements for a 4G air-interface.**

Index Terms – **Fourth Generation, 4G, Access Network, Radio Technologies, Mobile Technologies**

I. INTRODUCTION

With the deployment of Third Generation Mobile Systems (3G) having been completed in most countries worldwide, researchers have begun to focus their attention on the design and development of the next generation of mobile systems, known as the Fourth Generation or simply 4G. Currently there is no single conclusive standard for 4G mobile systems, and the process of 4G standardization will only begin after the World Radiocommunication Conference in 2007 [1]. As a result there is no shortage of varying opinions regarding the definition and requirements for 4G mobile systems.

The purpose of this paper is to examine and compare the performance of two air-interface architectures, to determine which one would be best as a core component of a new 4G access network system. The following sections outline the basic theory involved in the development of each of these air-interface architectures, the simulation models that were used to compare their performance, the design of the propagation model used during simulation and the results of the performance simulations and analysis thereof.

II. ORTHOGONAL MULTI-CARRIER ACCESS SYSTEMS

Most researchers agree that a new 4G air-interface architecture must be capable of providing high levels of data throughput while also exhibiting a high degree of spectral efficiency. Multicarrier based access schemes not only meet these requirements but also have the additional advantage of being highly resilient to the effects of frequency selective fading channels [2]. Currently there are two candidate modulation techniques that could form the core component of a new air-interface architecture. The first is perhaps the most spectrally efficient form of multicarrier modulation known as Orthogonal Frequency Division Multiplexing or OFDM and the second combines the use of spread spectrum technology with conventional OFDM modulation and is known as OFDM-SS modulation [2], [3]. The following subsections outline the basic theory involved in OFDM modulation, how OFDM can be combined with spread spectrum systems to achieve OFDM-SS modulation, and how each of these modulation techniques can be used in multiple access schemes.

A. OFDM Basics

The basic principle underlying OFDM is that a high-rate serial data stream can be multiplexed onto a number of lower-rate parallel substreams. These substreams are then modulated onto a number of frequency subcarriers, which are in turn combined to form the bandwidth of the system and transformed into a discrete time based signal [3], [4]. Figure 1 illustrates the concept of OFDM modulation. Initially this principle may appear to be no different to conventional Frequency Division Multiplexing (FDM); however while FDM requires the use of guard bands between the subcarriers in order to avoid Intercarrier Interference (ICI), OFDM creates an orthogonal relationship between the subcarriers such that the spectral components of other subcarriers are null at the peaks of each individual subcarrier. OFDM also has the additional benefit that as there are no guard bands, the spectral efficiency of the system and its performance is vastly superior to that of conventional FDM [3], [4].

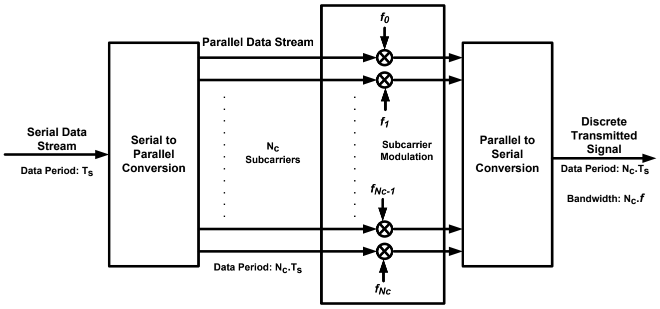

Fig. 1. Orthogonal Frequency Division Multiplexing Modulation

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A key advantage of OFDM systems is that if sufficient subcarriers are used the symbol period increases to the point at which it exceeds the duration of the multipath delay spread, thereby providing a high level of resilience to Intersymbol Interference (ISI) [3].

An OFDM system can be represented by Equation 1 [3].

$$x(t) = \frac{1}{N_c} \sum_{n=0}^{N_c-1} S_n e^{j2\pi f_n t}, \;\; 0 \leq t \leq T_s \qquad (1)$$

where :
$N_c -$ Number of subcarriers
$S_n -$ Data symbol to be modulated onto subcarrier n
$f_n -$ Frequency of subcarrier n
$T_s -$ Symbol duration after multiplexing to substreams

The subcarrier frequency and symbol duration are related by Equation 2 [3].

$$f_n = \frac{n}{T_s}, \;\; n = 0, \ldots, N_c - 1 \qquad (2)$$

Modern OFDM systems make use of the computationally efficient Fast Fourier Transform (FFT) to modulate data symbols onto subcarriers in an orthogonal manner, allowing developers to implement systems with several thousand subcarriers using modern digital electronics [4].

While OFDM systems naturally exhibit a high degree of resilience to the effects of multipath propagation, it is necessary to insert a guard interval before each OFDM symbol to completely eliminate ISI. The guard interval is a cyclic extension of the OFDM symbol and is acquired by copying a block of digital samples from the symbol and then prepending them to the existing OFDM symbol [4]. The guard interval is placed at the front of the OFDM symbol so that the ISI generated from a delayed version of the previous symbol will not corrupt the main OFDM symbol. It is important to note that the guard interval is constructed using a cyclic extension of the existing system and in so doing it removes any residual out-of-band noise that would have been generated had the guard interval simply been a null signal [2].

B. Combining Spread Spectrum with OFDM

Direct Sequence Spread Spectrum (DSSS) is a modulation technique whereby a signal is transmitted over a much wider bandwidth than is actually necessary. To spread the initial signal over a wider bandwidth, DSSS systems use special code sequences which are independent of the signal being transmitted [3].

Spread spectrum codes are specifically chosen such that they exhibit low cross-correlation and high auto-correlation characteristics [4]. By making use of multiple codes, numerous data symbols can be spread and transmitted at the same time. Upon receipt of a signal, the matching code sequence must be correlated with the signal to acquire the transmitted data symbol. The process of using DSSS as a modulation scheme to separate different users data is known as DS-CDMA and is represented mathematically by Equation 3. The process illustrated by this equation is the normal method used to spread data symbols. The method used in MC-CDMA, which will be discussed shortly, uses a slightly different methodology.

$$x(t) = \sum_{k=0}^{K-1} d^k \sum_{l=0}^{L-1} c_l^k p_{T_c}(t - lT_c), \;\; 0 \leq t < T_c \qquad (3)$$

where :
$x(t) -$ Transmitted signal
$K -$ Maximum Number of Users
$d^k -$ Data Symbol of User k at t $(0 \leq t < T_c)$
$L -$ Length of the Spreading Code
$c_l^k -$ Chip l of User k Spreading Code
$p_{T_c} -$ Rectangular Pulse
$T_c -$ Chip Period

In 1993 several groups of researchers each proposed a methodology to combine DSSS and OFDM, and they called this form of modulation OFDM-SS [2]. Instead of spreading the transmitted data symbols in the time domain, which is the method used in conventional DSSS systems, OFDM-SS spreads the data symbols in the frequency domain prior to the modulation of data onto the OFDM subcarriers.

The exact methodology used to spread the symbols and map them to subcarriers varies between different implementations; however the most common practice is to spread all of the data symbols across all the subcarriers by means of a code sequence equal to the length of the number of subcarriers. This technique forms the core of the most popular OFDM-SS system, known as MC-CDMA [2]. The process of OFDM-SS modulation, as used in MC-CDMA systems, is illustrated in Figure 2. It should be noted that the period of the spreading codes and each data symbol in the parallel data stream are identical due to the serial to parallel conversion that takes place immediately prior to the multiplication of the codes with the data symbols. By using all of the available subcarriers to transmit data symbols, OFDM-SS systems take full advantage of the frequency diversity across the entire bandwidth of the system thereby theoretically improving the performance of OFDM-SS systems relative to standard OFDM systems [3].

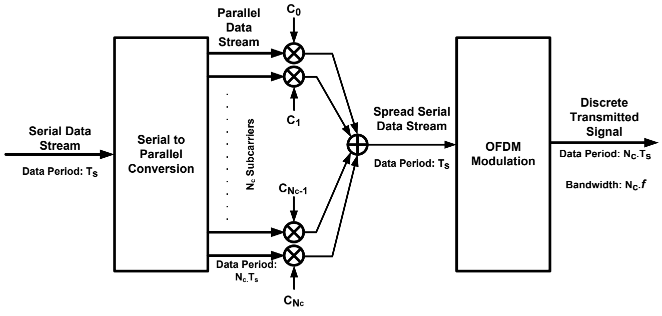

Fig. 2. OFDM-SS Modulation as used in MC-CDMA systems

There are a variety of options as to which spreading codes should be used in OFDM-SS systems; however due to their zero cross-correlation properties, Orthogonal Walsh-Hadamard codes are usually used. These codes exhibit a much higher resilience to multiple access interference (MAI) than pseudo-random codes, although they are far more sensitive to the effects of synchronization errors [4].

C. *OFDM based Multiple Access Schemes*

Multiple access schemes divide the available physical communications resources between subscribers to provide simultaneous access to their requested services. Based on the modulation schemes discussed in the previous subsections, two primary types of hybrid multiple access schemes can be implemented which provide the functionality to transmit and receive data for any number of users and which could form the core of a 4G air-interface. The following examines two multiple access schemes: OFDMA and MC-CDMA.

1) OFDMA: Orthogonal Frequency Division Multiple Access (OFDMA) is a multiple access scheme which makes use of OFDM modulation to allocate one or more subcarriers to each user depending on the number of available subcarriers and the demands of the services being provided [2], [3], [4].

The allocation of subcarriers can be performed using one of two methods. First and simplest, allocate specific subcarriers to users for the duration of their transmission. This method has the disadvantage that if frequency selective fading consistently distorts the same set of subcarriers, the group of users allocated to those subcarriers experience a severe degradation in performance. Second, allocate subcarriers dynamically to users. This method has the advantage that it makes full use of the frequency diversity and averages out the performance decreases of specific subcarriers across all users. The simulations described in the next section make use of the latter method.

2) MC-CDMA: Multicarrier Code Division Multiple Access (MC-CDMA) is a multiple access scheme that makes use of OFDM-SS modulation to spread users data symbols and assign the combined signal to all of the available subcarriers [2], [3], [4]. In contrast to OFDMA, where the number of subcarriers allocated to a specific user can be manipulated based on the requirements of services, conventional MC-CDMA only transmits one symbol from each user per OFDM frame. Theoretically, users could be assigned more than one spreading code; however this may result in increased MAI.

M-Modification is a methodology used by many developers to increase the amount of data each user can transmit in a single OFDM symbol [3]. By decreasing the length of the spreading code to a fraction of the number of available subcarriers, an MC-CDMA system can transmit multiple groups of spread signals from all users at the expense of decreased frequency diversity. The simulations described in the next section make use of this method.

III. DETERMINING THE APPROPRIATE 4G AIR-INTERFACE

In order to determine which of the aforementioned multiple access schemes would be an appropriate choice to form the core of a new 4G access network system it was necessary to simulate their performance in a realistic wireless environment. The following two subsections outline the methods used to model these air-interface architectures and the wireless propagation environment. The final subsection describes the results obtained from the simulations and via analysis determines which of the two architectures offers superior performance.

A. *Candidate 4G Air-Interface Architectures*

By examining the similarities between OFDMA and MC-CDMA it is possible to develop a generic air-interface architecture model that can be adjusted to assign user data based on either of these two multiple access schemes. The architecture also contains components that are present in any mobile communications system, including channel coding, interleaving, constellation mapping for digital modulation, synchronization and channel estimation and equalization. A diagram of this architecture is shown in Figure 3. The components chosen to create this architecture are the basic set of algorithms required to transmit and receive a users data within a realistic wireless environment. Many additional techniques could be implemented to enhance the performance of the system; however they are outside the scope of this paper and their exclusion does not affect the performance comparison of OFDMA and MC-CDMA based air-interface systems. Table I shows the algorithms and parameters selected for use in the simulations.

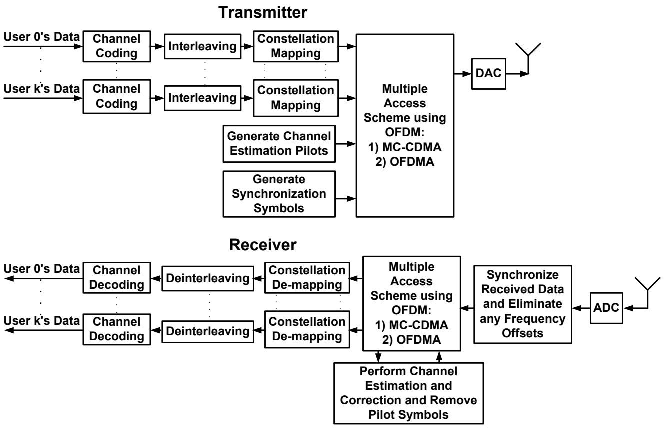

Fig. 3. A Generic 4G Air-Interface Architecture

B. *A Realistic Cellular Environment*

Traditional wireless propagation simulations only model the effects of the multipath fading environment and environmental noise on the transmission system. In order to accurately determine the performance of each of the air-interface architectures it is necessary to extend this basic model to include the effects of path loss, shadowing and interference generated by neighbouring base stations within adjacent cells.

The cellular propagation model used for the simulations in this paper is based on material from [5], [6] and contains seven cells. Each cell is modelled using a hexagon with the primary base station at the centre and six base stations surrounding it. A normalized cell radius of one is assumed. The available bandwidth is split using a re-use pattern of three, and the performance measurements are based on the transmission between the

TABLE I

AIR-INTERFACE PARAMETERS FOR THE SIMULATION

Air-Interface Parameters	Values
Channel Coding	Convolutional Coding
Coding Rate	$\frac{1}{2}$
Modulation Scheme	QAM
Modulation Alphabet	16
No. Data Subcarriers (per cell)	256
No. Pilot Subcarriers (per cell)	64
No. Virtual Subcarriers	64
Size of the FFT	1024
Guard Length Samples	226
No. OFDM Symbols per Frame	64
Subcarrier Spacing	100 kHz
Bandwidth	102.4 MHz
OFDM Symbol Period	10 μs
OFDM Frame Period	1 ms
No. Substreams per User	32

primary base station and a mobile terminal located somewhere within the primary cell. The simulation methodology employed was as follows:

1) Each base station (BS) generates a signal, based on randomly generated user data and modulated using one of the air-interface architectures according to a set of air-interface architecture and cellular environment parameters.
2) Each signal is passed through a Rayleigh Fading Channel based on static parameters as discussed below.
3) The energy of each signal received by the mobile terminal (MT) is calculated based on Equation 4.

$$E_{r,j} = E_{t,j}.d_j^{-\gamma}.10^{\frac{n_j}{10}} \tag{4}$$

where :
$E_{r,j}$ – Received Energy from BS j
$E_{t,j}$ – Transmitted Energy from BS j
d_j – Distance between BS j and MT
γ – Path Loss Decay Factor
n_j – Log – normal Shadowing Factor

While the equation does require that the transmission energy for each base station is specified, provided that all base stations transmit with the same power this parameter will cancel out and become irrelevant.

4) The ratio between the energy received from each of the interfering base stations and the primary base station is calculated. This ratio can then be used to attenuate the interfering signals based on their relative distance from the mobile terminal and the effect of shadowing. Equation 5 is used to attenuate each of the interfering signals before they are combined with each other and the primary base station signal.

$$T_a = T_i.\sqrt{\frac{E_{r,j}}{E_{r,p}}} \tag{5}$$

where :
T_a – Attenuated Transmitted Signal
T_i – Initial Transmitted Signal
$E_{r,j}$ – Received Energy from Interfering BS j
$E_{r,p}$ – Received Energy from the Primary BS

5) Lastly, AWGN is added to the combined signal and the receiver air-interface architecture attempts to demodulate the transmitted data accurately.

The cellular propagation model parameters selected for use in the simulations are designed to determine the performance of each of the candidate 4G air-interface architectures under different operating conditions. For each set of propagation environment parameters, the simulation transmits several frames of data via each air-interface architecture. The cellular environment parameters used in the simulations can be seen in Table II and the results from these simulations are described and analysed in the next section.

TABLE II

CELLULAR ENVIRONMENT PARAMETERS FOR THE SIMULATION

Cellular Propagation Environment Parameters	Values
No. of Users	1 or 8
Spreading Code Length	8
Signal to Noise Ratio	0 to 20 dB
Distance from Primary BS to MT	0.1 or 1 units
No. Impulses for Multipath Fading	10
Path Delays for Multipath Fading	10 ns
Power Decrease per Delay for Multipath Fading	1 dB
Cellular Re-use pattern	3
Angle of MT Relative to Primary BS	30^o
Standard Distribution of Log-normal Shadowing	8
Path Loss Decay Factor	4

C. *Simulation Results and Analysis*

In order to determine which of the two candidate air-interfaces performs best and therefore is the most appropriate choice for 4G systems, a series of simulations was conducted to determine their relative performance under realistic conditions. The simulations were constructed in MATLAB. The performance criteria used to evaluate OFDMA and MC-CDMA were chosen based on the core requirements for 4G access network systems and are listed below:

- *Data Throughput:* The average data throughput of a system will determine the types of services a user can access using either of the air-interface architectures.
- *Spectral Efficiency:* Frequency spectrum is a limited resource and it is a specific requirement that 4G systems should make more efficient use of the available spectrum than current systems do. Higher levels of spectral efficiency increase the capacity and throughput of access systems and this is therefore a key indicator of system performance.
- *Coverage:* The amount of power needed to accurately transmit data determines the maximum possible coverage of an access system in a cellular environment. If a system

is required to output high levels of power to transmit data at a specified throughput, its cell size will be decreased, thereby introducing additional costs for mobile operators deploying 4G access networks.

The first set of measurements taken are used to determine each architecture's performance based on the cardinality of the digital modulation scheme within a cellular environment. The number of users transmitting data was set as 1, the maximum number of users was 8, the number of available subcarriers per cell was 256, and the number of substreams per user was 32. Figure 4 illustrates the bit error ratio (BER) versus signal to noise ratio (SNR) performance of each system when 64-QAM is used and the mobile terminal is positioned close to the primary base station. Due to the various error correction schemes incorporated in both architectures, the primary sources of interference are AWGN and, to a much lesser degree, shadowing and adjacent cellular interference. In order to decrease the interference generated by the AWGN the power of the transmitted signal must be increased. This is clearly illustrated in Figure 4 as the Bit Error Rate (BER) decreases as the Signal-to-Noise Ratio (SNR) increases. These initial measurements also prove each system's resilience to other forms of interference such as multipath fading, and show that each of the components, such as channel estimation and correction, channel coding and interleaving are working correctly.

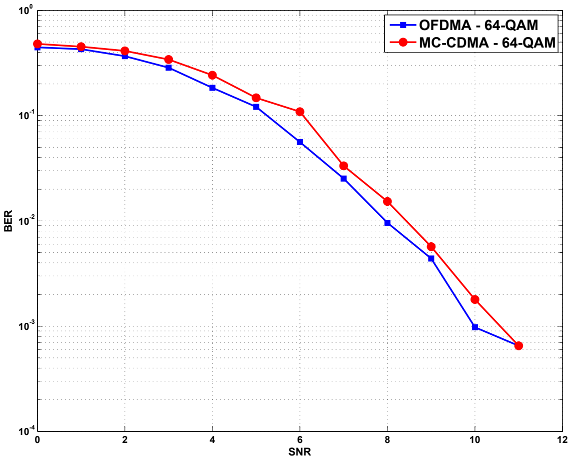

Fig. 4. Performance comparison of OFDMA and MC-CDMA systems in a cellular environment, with 1 user, a code length of 8 using 64-QAM, where the mobile terminal is positioned close to the primary base station

The results of these first measurements were used to perform initial calculations which assisted in determining the performance of each system. The maximum attainable total throughput and the throughput per individual user was calculated based on the cardinality of the modulation schemes used. The spectral efficiency of each system was calculated based on the subcarrier spacing and the number of subcarriers used to carry data. Both of these performance calculations are displayed in Table III. As both simulations made use of the same number of data subcarriers, the throughput of both systems was identical. These results were calculated for a best case scenario, in other words these performance levels would only be achieved under optimum conditions. An interesting observation when viewing the initial results in Figure 4 is that the transmitted signal power required to achieve maximum throughput for OFDMA was far lower than the signal power required for MC-CDMA. This discrepancy can be explained by examining the resource allocation scheme for each of the simulations. The maximum number of users an MC-CDMA system can accommodate is equal to the length of its spreading code. All spread spectrum systems suffer from the form of self-interference known as multiple access interference (MAI). This fact has already been briefly mentioned in a previous section; however it is relevant in the context of these simulation results as it appears that in the absence of any additional interference compared to the OFDMA system, MAI provides the only possible reason for the discrepancy in the expected performance of the system. To prove this theory a second set of measurements was taken from simulations conducted on both OFDMA and MC-CDMA; as described below, these measurements served to support this hypothesis. To ensure that no other forms of interference impacted upon the proving of this theory, this specific set of measurements were conducted using only Rayleigh multipath fading and environmental noise as interference sources.

TABLE III

PERFORMANCE MEASUREMENTS OF OFDMA AND MC-CDMA SYSTEMS IN A CELLULAR WIRELESS ENVIRONMENT

Performance Measurements	**OFDMA**	**MC-CDMA**
Total Throughput	48.84 Mbps	48.84 Mbps
Throughput per User	6.04 Mbps	6.04 Mbps
Spectral Efficiency	1.26 bits/s/Hz	1.26 bits/s/Hz

To prove that MAI is the cause of the decrease in the MC-CDMA systems performance compared to OFDMA, the length of the spreading code was increased to 32. Figure 5 illustrates the performance of the OFDMA and MC-CDMA systems under these new conditions. The second set of measurements proves that the performance of MC-CDMA can be decreased due to the presence of MAI, as the MC-CDMA system easily outperforms the OFDMA system. Unfortunately, due to the architecture of the MC-CDMA system, increasing the length of the spreading code also decreases the number of substreams available to each user, thereby resulting in reduced throughput per user. This indicates that the conclusions reached based on the first measurements from the previous simulation are correct, i.e. the systems are operating correctly, as AWGN is the primary source of interference and MC-CDMA outperforms OFDMA due to the presence of MAI. Re-examining Figure 4 it is apparent that the effects of path loss, shadowing and inter-cell interference have a slight detrimental effect on both systems, but as both systems make use of OFDM modulation and other interference cancelling schemes, interference generated by subcarriers used by other cells appears to be largely eliminated. To determine if this theory is correct, a second set of measurements was taken, with the mobile terminal repositioned at the edge of the cell where maximum inter-cell interference occurs. Fig-

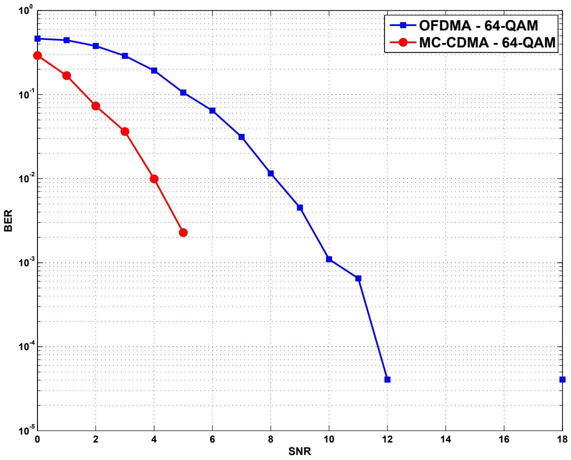

Fig. 5. Performance comparison of OFDMA and MC-CDMA systems in a realistic wireless environment, with 1 user, a code length of 32 using 64-QAM

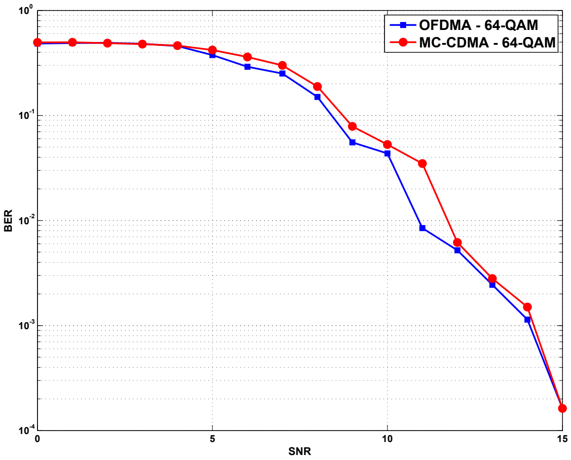

Fig. 6. Performance comparison of OFDMA and MC-CDMA systems in a cellular environment, with 1 user, a code length of 8 using 64-QAM, where the mobile terminal is positioned at the edge of the primary cell

ure 6 illustrates the performance of both systems under these conditions and indicates that while their performance has deteriorated, the effect is most likely to be attributable to path loss and shadowing rather than inter-cell interference, which would generate a much larger decrease in performance as ICI. The results from these simulations show conclusively that OFDMA is superior to MC-CDMA and of the two considered it would be best suited as the optimum air-interface architecture for a new 4G access network. Whilst certain aspects of the OFDMA systems superior performance have already been discussed, it is useful to summarize the strengths of OFDMA, in comparison to MC-CDMA, based on the performance criteria outlined above:

- *Throughput:* OFDMA can achieve much higher bit rates within a specific bandwidth than MC-CDMA. Due to the effects of MAI, MC-CDMA cannot allocate all spreading codes for use; therefore OFDMA is able to accommodate far more users than MC-CDMA. OFDMA systems also have the added benefit that the amount of throughput allocated to each user can be manipulated subject to the resource demands of the services provided.
- *Spectral Efficiency:* OFDMA makes full use of the spectrum allocated and assigns every subcarrier to a user. MC-CDMA systems are unable to transmit the same amount of data as they are limited by MAI. Therefore OFDMA systems are more spectrally efficient.
- *Coverage:* OFDMA systems require less power to provide high throughput rates. Only in instances where the code length is dramatically increased does MC-CDMA require less power to transmit data coherently. Under these conditions OFDMA systems are the better choice as they require less power to transmit high throughput services, indicating that they have the potential to cover a wider cell area.

IV. CONCLUSION

The purpose of this study was to evaluate the performance of two candidate 4G air-interface architectures, to enable a recommendation to be made as to which of the two architectures is the most appropriate choice for a 4G access network. The results of simulations conducted using realistic models of a cellular wireless environment demonstrate that OFDMA is the better choice for a 4G air-interface architecture as it does not suffer from the effects of multiple access interference, which is a weakness of spread spectrum technologies.

REFERENCES

[1] WP8F, "Recommendation M.1645: Framework and overall objectives of the future development of IMT-2000 and systems beyond IMT-2000," International Telecommunications Union - Radio Communications Sector, Tech. Rep., 2003.

[2] R. Prasad and S. Hara, *Multicarrier Techniques for 4G Mobile Communications*, 1st ed., ser. Universal Personal Communications Series. London: Artech House, 2003.

[3] K. Fazel and S. Kaiser, *Multi-Carrier and Spread Spectrum Systems*, 1st ed. John Wiley and Sons Ltd, 2003.

[4] L. Hanzo and T. Keller, *OFDM and MC-CDMA: A Primer*, 1st ed. London: John Wiley & Sons, Ltd, 2006.

[5] S. Plass, S. Sand, and G. Auer, "Modeling and Analysis of a Cellular MC-CDMA Downlink System," in *The 15th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*. IEEE, September 2004.

[6] S. Plass and S. Kaiser, "MC-CDMA versus OFDMA in Cellular Environments," in *European Signal Processing Conference*. NTT DoCoMo, September 2005.

BIOGRAPHIES

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