SC-FDMA and OFDMA: The two competing technologies for LTE

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One of the key requirements of next generation networks (NGNs) is the support of higher data rates. Although OFDM is capable of delivering the target peak data rates, its high PAPR raises questions as to its suitability in the uplink. SC-FDMA is examined in this paper as a promising alternative to OFDMA. Recent novel techniques offering performance gains are also considered.

1. Introduction

The third generation partnership project (3GPP) is currently developing its next generation mobile system, known as Long Term Evolution (LTE). LTE and most likely all future mobile systems will employ multicarrier transmission to meet the performance requirements set by the ITU-R. Multicarrier transmission offers distinct benefits over single carrier transmission, such as robustness to multipath fading, flexible resource allocation and higher spectral efficiency.

In this paper, we focus on two multiple access (MA) schemes proposed for the uplink (UL) transmission in LTE, namely Orthogonal Frequency Division Multiple Access (OFDMA) and Single Carrier FDMA (SC-FDMA). The suitability of these MA schemes in the LTE UL is an ongoing issue which has attracted the attention of many researchers across the globe.

2. Overview of SC-FDMA

There has been much debate on whether SC-FDMA is capable of meeting the ever-increasing throughput demands of future mobile devices. SC-FDMA has been established in the 3GPP standard as the MA method to be used for the UL transmission in LTE. The main reason behind this decision is due to the fact that OFDM exhibits a very large peak to average power ratio (PAPR). This high PAPR is caused by the high envelope fluctuations present in OFDM during the mapping of data symbols onto parallel subcarriers and results in amplifier inefficiency or signal distortion. There is a trade-off between the use of highly linear power amplifiers (PAs) and inter-modulation (IM) distortion. Furthermore, reducing the PAPR extends the battery life of mobile devices, the latter issue being a paramount design factor in modern mobile devices. [1]

The SC-FDMA signal chain includes the same transmission blocks as for OFDMA with the addition of two more blocks; namely a Discrete Fourier Transform (DFT) spreading operation and subcarrier mapping. In SC-FDMA, the user symbols are first pre-coded using a DFT matrix, which spreads each subcarrier in the frequency domain, and then mapped to subcarriers prior to the Inverse Fast Fourier Transform (IFFT) operation. In SC-FDMA, the subcarriers are transmitted sequentially instead of in parallel as in OFDMA. This results in a decreased envelope fluctuation making SC-FDMA more power efficient but more complex than OFDMA.

There are two types of carrier mapping schemes in SC-FDMA. The first one is known as localized (LFDMA), where a set of adjacent subcarriers is allocated to each user. The second one is known as distributed (DFDMA), where a user is assigned a set of non-contiguous subcarriers occupying the entire spectral. A special case of DFDMA is interleaved FDMA (IFDMA), where the subcarriers are uniformly spaced. These concepts are illustrated in Figure 1.

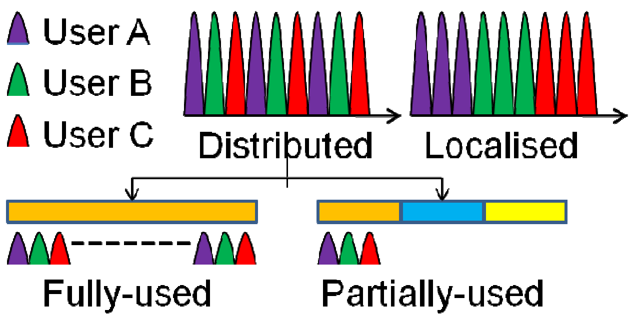

Figure 1 – Comparison of IFDMA and LFDMA schemes

Currently, the LTE standard is only considering LFDMA. [2] From Figure 1, we can see that DFDMA offers a better frequency diversity than LFDMA, as the information is spread across all frequency bands. On the other hand, LFDMA offers multiuser diversity (MUD) gain. [3]

3. SC-FDMA versus OFDMA

Figure 2 gives a crude illustration of the difference between SC-FDMA and OFDMA. As mentioned in the previous section, OFDMA suffers from a large PAPR which in turn means that the amplifiers require a large power back-off. Research has established that SC-FDMA offers a performance gain of approximately 2 dB over OFDMA. [4] [5] Another problem with OFDMA is the inter-carrier interference (ICI) between the subcarriers due to Doppler shifts and frequency offsets. ICI compromises the loss of orthogonality between the subcarriers leading to MA interference (MAI) and performance degradation.

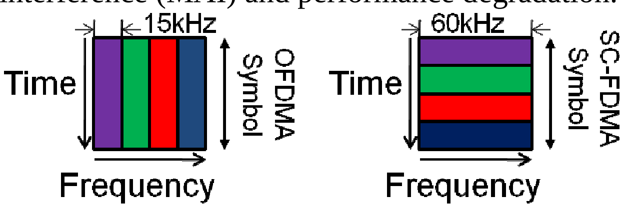

Figure 2 – Example of an OFDMA vs. SC-FDMA symbol

The PAPR performance gain offered by SC-FDMA does, however, have some drawbacks. The first disadvantage is inter-symbol interference (ISI) which can be mitigated using either interference cancellation techniques or frequency domain equalization (FDE) at the expense of complex signal processing. [3] The key weakness though is the so-called “noise enhancement”, which degrades the system’s performance when linear amplifiers are used at the receiver. [5]

The authors in [4] demonstrate that SC-FDMA can only outperform OFDMA by exploiting its PAPR benefits if and only if the localized allocation of subcarriers is adopted. The results in [4] show that the spectral efficiency of OFDMA systems increases as we increase the number of users, as a result of the MUD gain associated with OFDMA. The results indicate that SC-FDMA has a higher spectral efficiency than OFDMA only for a large number of users (in this case over 12) and for high bandwidth allocations (over 100 MHz).

In summary, it seems as if each MA scheme offers distinct advantages and disadvantages. SC-FDMA has a lower PAPR and lower sensitivity to carrier frequency errors while OFDMA provides better frequency diversity resulting in better immunity against multipath fading. Simulation studies in [4] demonstrate that OFDMA provides a more flexible resource allocation and better spectral efficiency compared to SC-FDMA while in [3] the authors show that IFDMA has a lower PAPR than LFDMA, which in turn has a lower PAPR compared to OFDMA.

4. Techniques for improving SC-FDMA

A very intriguing modulation scheme has recently been proposed in [6]. The technique relies on ‘marrying’ Continuous Phase Modulation (CPM) with SC-FDMA to take advantage of the benefits offered by each scheme. CPM signals are inherently power efficient due to their constant amplitude while SC-FDMA spreads the signal across the entire spectral resulting in lower envelope fluctuations.

The constant envelope of CPM signals results in a PAPR of 0dB enabling the use of non-linear amplifiers, which are more efficient than linear ones. Results in [6] show that for a high signal-to-noise ratio (SNR) and high modulation index, the bit error rate of CPM-SC-FDMA outperforms that of minimum shift keying (MSK)-SC-FDMA by a factor of 45. This, however, does result in a factor of 16 increase in detection complexity.

The authors in [4] propose two channel aware scheduling algorithms to maximize the spectral efficiency of SC-FDMA and OFDMA. The same authors in [7] propose a turbo equalization (TEQ) technique to overcome the problem of noise enhancement present in SC-FDMA at the expense of additional computational complexity. Using this TEQ technique, the authors demonstrate that the performance of SC-FDMA in terms of spectral efficiency is comparable to that of OFDMA for a 1x4 antenna configuration.

Results in [7] show that the performance of TEQ-SC-FDMA is improved by 1 dB compared to conventional SC-FDMA. As quoted by the authors “the performance is improved through an iterative exchange of extrinsic information between the equalizer and the decoder”. Furthermore, SC-FDMA with TEQ outperforms

OFDMA in most cases and where this is not the case, the performance of SC-FDMA with TEQ is the same as that of OFDMA.

Finally, in [8], the authors propose a novel transceiver scheme employing wavelet filter banks with the aim of reducing distortion in the reconstructed signal at the cost of increased system complexity. In addition, a hybrid combination of companding and clipping is proposed with the simulation results clearly showing that this hybrid scheme provides a better PAPR and bit error rate (BER) performance compared to conventional SC-FDMA.

5. Practical implementation of SC-FDMA

Although the concept of SC-FDMA is now widespread, it still has not been well explored in real applications to make use of its competitive advantage over OFDMA; namely its lower PAPR. While both OFDMA and SC-FDMA have received a lot of interest in academia, there has been less investigation into the possible radio implementations of SC-FDMA. The high dynamic range of OFDMA subcarriers makes its implementation a challenging task, as the PA must operate with a large back-off from its peak value resulting in low power efficiency [4].

A novel implementation of a high data rate UL LTE receiver with field programmable gate arrays (FPGA) has been proposed in [9]. The physical layer blocks are implemented using the Xilinx System Generator; the signals are generated using MATLAB; and the system is verified in real conditions using the Rice WARPLab platform based on software defined radio. Using this FPGA prototype, a minimum mean square error (MMSE)-FDE detector with a 2x2 antenna configuration was implemented. This system is fully parallel and can fit in a single Xilinx Virtex4 FX140 FPGA. It is flexible, easily reconfigurable, thus supporting more antennas, higher modulation orders and complicated detection algorithms.

Results in [9] show that the current system can achieve a data rate of up to 220 Mbps, which is higher than the requirement set in the LTE standard. Future challenges include MA support and better utilization of hardware resources.

6. Conclusion

In conclusion, it is evident that power efficiency and low implementation complexity in wireless systems are still the burning topics troubling researchers. Although SC-FDMA is regarded by 3GPP as a promising technology for improving power efficiency, there are case studies indicating that SC-FDMA may not offer significant benefits over OFDMA after all.

Acknowledgements

The authors would like to thank the UK Engineering and Physical Sciences Research Council (EPSRC) and British Telecom (BT) for funding Ryan Grammenos through the Communications EngD program at UCL.

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