MULTIPLE ACCESS TECHNOLOGIES FOR
B3G WIRELESS COMMUNICATIONS

Interference-Free Broadband Single- and Multicarrier DS-CDMA

H. Wei, L.-L. Yang, and L. Hanzo, Univ. of Southampton

ABSTRACT

The choice of the direct sequence spreading code in DS-CDMA predetermines the properties of the system. This contribution demonstrates that the family of codes exhibiting an interference-free window (IFW) outperforms classic spreading codes, provided that the interfering multi-user and multipath components arrive within this IFW, which may be ensured with the aid of quasi-synchronous adaptive timing advance control. It is demonstrated that the IFW duration may be extended with the advent of multicarrier DS-CDMA proportionately to the number of subcarriers. Hence, the resultant MC DS-CDMA system is capable of exhibiting near-single-user performance without employing a multi-user detector. A limitation of the system is that the number of spreading codes exhibiting a certain IFW is limited, although this problem may be mitigated with the aid of novel code design principles.

INTRODUCTION

In direct sequence code-division multiple access (DS-CDMA) systems, the spreading sequences characterize the associated intersymbol interference (ISI) as well as the multiple access interference (MAI) properties [1]. Traditional spreading sequences, such as *m*-sequences [1], Gold codes, [1] and Kasami codes [1], exhibit non-zero off-peak auto-correlations and cross-correlations, which results in high MAI in asynchronous uplink transmissions. Another family of orthogonal codes is constituted by Walsh codes [1] and orthogonal Gold codes, which do retain their orthogonality in case of perfect synchronization, but also exhibit non-zero off-peak auto-correlations and cross-correlations in asynchronous scenarios. Consequently, these correlation properties limit the achievable performance in asynchronous scenarios. Hence, traditional DS-CDMA cellular systems are interference limited and suffer from the so-called near-far effects unless complex interference cancellers [1] or multi-user detectors [1] are employed to combat these adverse effects. This results in costly and "power-hungry" implementations. All these limitations are imposed by the imperfect correlation properties of the spreading sequences employed.

Hence, considerable research efforts have been invested in designing spreading sequences that exhibit zero correlation values when the relative delay-induced code offset is in the so-called zero correlation zone (ZCZ) or interference-free window (IFW) of the spreading code. The attractive family of large area synchronized (LAS) CDMA spreading sequences is constituted by the combination of the so-called large area (LA) codes [2–4] and loosely synchronous (LS) codes [5]. The resultant LAS codes exhibit an IFW where the off-peak aperiodic autocorrelation values as well as the aperiodic cross-correlation values become zero, resulting in zero ISI and zero MAI, provided that the time offset of the codes is within the IFW. Figure 1 characterizes the correlation properties of traditional spreading code and LAS code. Li [2, 6] proposed the employment of so-called LAS codes, which exhibit zero auto-correlation and cross-correlation in a limited-offset range of $[-\iota, \iota]$-chips. More specifically, interference-free CDMA communications become possible when the total time offset expressed in terms of the number of chip intervals, which is the sum of the time offset of the mobile terminals plus the maximum channel-induced delay spread, is within the designed IFW. In order to ensure that the relative time offsets between the codes are within the IFW, the mobiles are expected to operate in a quasi-synchronous manner. In case of high transmission-delay differences, accurate timing advance control has to be used [7]. Provided that these conditions are satisfied, a major benefit of the LAS codes is that they are capable of achieving near-single-user performance without multi-user detectors.

The goal of this contribution is to provide an overview of LAS-code-assisted single-carrier DS-CDMA (SC LAS DS-CDMA) and multicarrier DS-CDMA (MC LAS DS-CDMA) systems. We illustrate the basic philosophy of the generation of LAS codes. Then we characterize the achievable performance of SC LAS DS-CDMA, while we highlight the problems encountered in a high-chip-rate scenario. We invoke an MC LAS DS-CDMA system for the sake of circumventing the problems of SC LAS DS-CDMA and characterize its achievable performance. Finally, we offer our conclusions.

Overview of LAS Codes

LA Codes

LA codes [2, 3] belong to a family of ternary codes having elements of ±1 or 0. Their maximum correlation magnitude is unity and they also exhibit an IFW. Let us denote the family of the K number of orthogonal ternary codes employing K number of binary ±1 pulses by LA(L_A, M, K), which exhibit a minimum spacing of M chip durations between non-zero pulses, while having a total code length of L_A chips, as shown in Fig. 2. All the codes corresponding to an LA code family share the same legitimate pulse positions. However, a specific drawback of this family of sequences is their relatively low duty ratio, quantifying the density of the non-zero pulses, since this limits the number of codes available and hence the number of users supported.

Loosely Synchronized Codes

Apart from the LA codes from an earlier section, there exists another specific family of spreading codes that also exhibits an IFW. Specifically, LS codes [3, 5] exploit the properties of the so-called orthogonal complementary sets [3, 5]. To expound further, let us introduce the notation of LS(N, P, W_0) for denoting the family of LS codes generated by applying a ($P \times P$)-dimensional Walsh-Hadamard (WH) matrix to an orthogonal complementary code set of length N, as exemplified in the context of Fig. 3. More specifically, we generate a complementary code pair inserting W_0 number of zeros both in the center and at the beginning of the complementary pair, as shown in Fig. 3a, using the procedure described in [3, 5].

Seeding LS Codes in LA Codes to Generate LAS Codes

We observed earlier that the main problems associated with applying LA codes in practical CDMA systems are related to their low duty ratio and the resultant small number of available codes. A specific family of LAS codes mitigates this problem by combining the LA codes and LS codes of an earlier section. More specifically, LS codes are inserted between the non-zero pulses of the LA code sequence of Fig. 2, in an effort to generate an increased number of spreading codes with an increased duty ratio, while maintaining attractive correlation properties. For example, in the LAS-2000 system [8], the LS spreading codes are inserted into the LA code's zero space, as shown in Fig. 4.

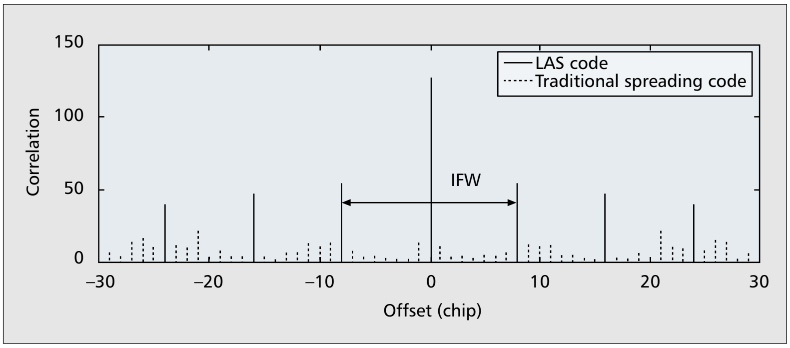


Figure 1. *Correlations of spreading sequences.*

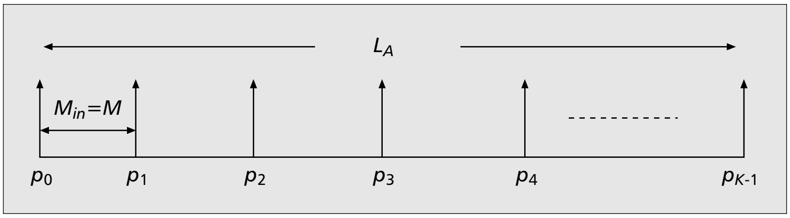


Figure 2. *Stylized pulse-positions in the LA(*L_A,M,K*) code having* K *number of binary ±1 pulses, and exhibiting a minimum spacing of* M *chip durations between non-zero pulses, while having a total code length of* L_A *chips.*

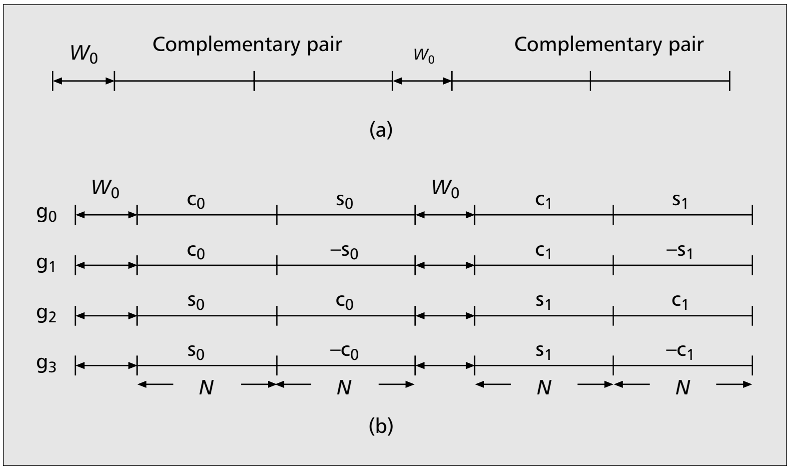


Figure 3. *Generating the LS(*N,P,W_0*) code using the* (P × P) *= (4 × 4) WH matrix components (1,1,1,1) and (1,–1,1,–1).}: a) the LS code structure; b) generating four LS codes.*

Performance of SC LAS DS-CDMA

In this section we characterize the achievable performance an SC LAS DS-CDMA system. All the users were assumed to communicate in a quasi-synchronous manner, where the maximum delay difference τ_{max} is assumed to be $2T_c$. The

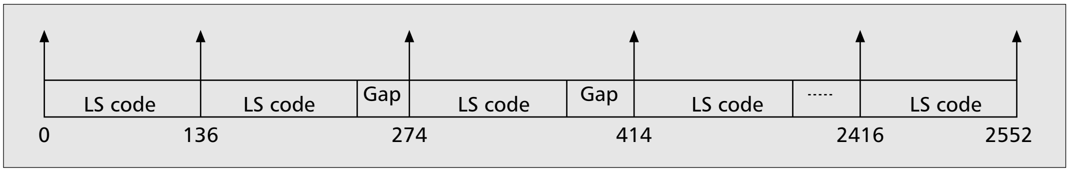


Figure 4. *LAS(*L_A,M,K;N,P,W_0*) spreading, inserting the LS codes into the zero space of the LA codes seen in Fig. 2.*

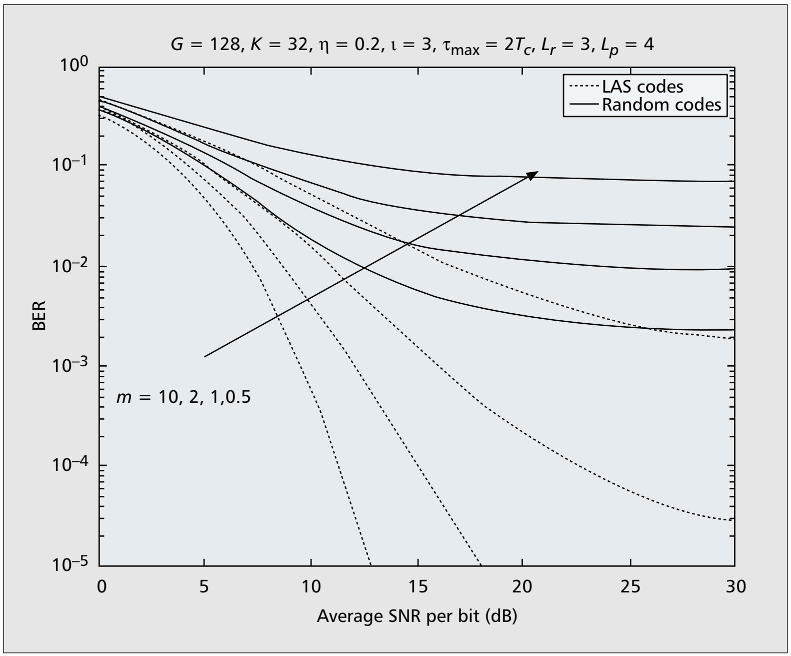


Figure 5. *BER vs. channel SNR performance comparison of random-code-based classic CDMA and LAS CDMA, when communicating over different Nakagami fading channels when using the system parameters summarized at the top of the figure.*

channel was assumed to be a Nakagami-m channel [1] having a negative exponential multipath intensity profile (MIP) decay factor of $\eta = 0.2$ and L_p number of resolvable multipath components. The channels encountered by the users were assumed to be slowly varying frequency-selective fading channels, and their channel-induced delay spreads were assumed to be limited to the range of $[T_m, T_M]$, where T_m corresponds to the minimum delay spread considered, experienced, for example, in an indoor environment. By contrast, T_M is associated with the maximum possible delay spread, as in an urban area. The channel's delay spread was assumed to be negative exponentially distributed in the range of [0.3,3] µs [9], and we assumed that both the random-spreading-code-based benchmarker scheme and LAS-code-based system have a chip rate of 1.2288 *M*chips/s; hence, the number of resolvable paths [1] is

$$L_p = \left\lfloor \frac{T_M}{T_c} \right\rfloor + 1 = 4,$$

where we assume $T_M = 3$ µs. By contrast, when the chip rate was increased to 3.84 *M*chips/s, L_p would increase to 12. At the receiver end a RAKE receiver is employed, which is capable of combining a maximum of L_r number of paths due to its complexity limitation. Furthermore, the number of users supported was $K = 32$ and the width of the IFW was $\iota = 3T_c$ for the LAS-CDMA system considered.

Figure 5 portrays the performance of the random-spreading-code-based benchmarker and that of the LAS-code-based system communicating over different fading channels associated with different Nakagami fading parameters. More explicitly, when we have $m = 1$, we model a Rayleigh fading channel; $m = 2$, for example, represents a Rician fading channel; while $m \to \infty$ corresponds to an AWGN channel. We can observe from Fig. 5 that the LAS-CDMA system exhibited significantly better bit error rate (BER) performance than the traditional DS-CDMA system, regardless of the value of m. More specifically, provided that all these uplink users are in a quasi-synchronous state (i.e., we have $\tau_{max} = 2T_c$ and $L_p = 4$z), the LAS-CDMA scheme outperforms the traditional DS-CDMA system when communicating over different Nakagami multipath fading channels.

Figure 6 shows the attainable performance of these two systems for transmission over different dispersive channels having $L_p = 4 \dots 12$ resolvable multipath components and assuming that $L_r = 3$ of these components were combined by the RAKE receiver. We can observe from Fig. 6 that when the channel became more dispersive, the LAS-CDMA system's performance was significantly degraded, and its gain over the traditional DS-CDMA system was eroded. Nonetheless, the LAS-CDMA scheme still outperformed the traditional DS-CDMA system, provided that the users were in a quasi-synchronous state (i.e., when we had $\tau_{max} = 2T_c$). However, when L_p was increased to 12, the LAS-CDMA system retained only a moderate gain over the traditional DS-CDMA arrangement even if it operated in a quasi-synchronous scenario. The reason for this performance erosion is that many of the paths will be located outside the IFW when L_p is high, and the auto-correlation as well as cross-correlation of LS codes outside the IFW is higher than that of the classic random codes. Hence, when L_p is high, LAS-CDMA inevitably encounters serious MAI and MPI.

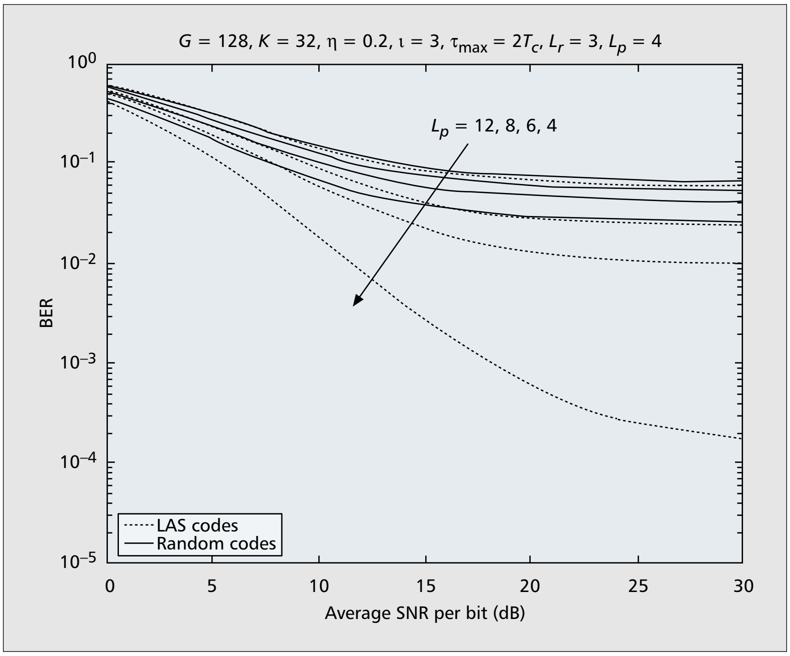
LIMITATIONS OF SC LAS DS-CDMA

It was argued in [10] that in the context of broadband wireless mobile systems communicating in diverse propagation environments, both single-carrier DS-CDMA and MC-CDMA exhibit certain limitations. More specifically, in a classic single-carrier DS-CDMA system, the number of resolvable paths to be processed by the RAKE receiver may become higher than the affordable RAKE complexity. Furthermore, the 20 Mchips/s SC LAS DS-CDAM system considered has a chip-duration of 50*ns* and the corresponding 3-chip IFW duration is 150*ns*. If we have a maximum delay-spread of $T_M = 3$ mus, the number of resolvable multipath components becomes Lp $= \lfloor T_M/T_c \rfloor + 1 = 21$, but only three may fall within the IFW, while the remaining 18 components falling outside the IFW would inflict MAI and MPI. Hence, the LAS codes may fail to suppress the MAI and MPI when the number of resolvable paths becomes high, as seen in Fig. 6. More explicitly, for a SC LAS DS-CDMA system, the achievable performance is expected to significantly degrade, as the chip rate increases to 20 Mchips/s, for example.

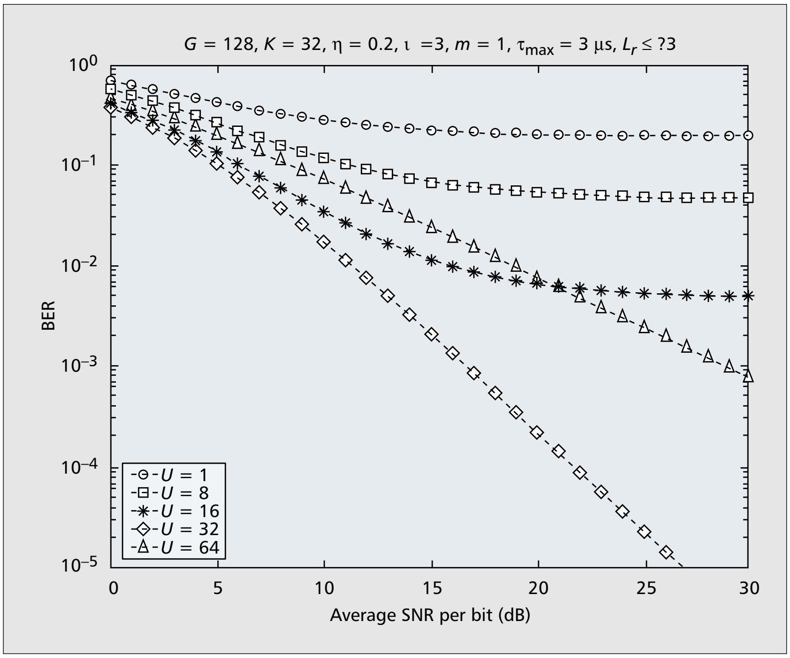
Based on these arguments, we propose the employment of LAS code based Multi-Carrier DS-CDMA (MC LAS DS-CDMA) for a high chip-rate system, where the chip-rate of the individual subcarriers may be reduced by a factor corresponding to the number of subcarriers, hence extending the chip-duration by the same factor. This measure allows us to avoid having multipath components outside the IFW. Furthermore, it has the potential to guarantee that the RAKE receiver will achieve path-diversity when communicating over a dispersive channel as well as suppressing both the MAI and multipath interference (MPI).

LAS-CODE-ASSISTED MCDS-CDMA FOR BROADBAND COMMUNICATIONS

It was also argued in [1, 10] that to a certain extent MC DS-CDMA constitutes a trade-off between SC DS-CDMA and MC-CDMA in terms of the system's architecture and its achievable performance. MC DS-CDMA typically requires lower-chip-rate spreading than SC DS-CDMA due to employing multiple subcarriers. Consequently, MC DS-CDMA typically requires lower-rate signal processing than SC DS-CDMA. However, MC DS-CDMA is more attractive than an arbitrary ad hoc compromise multiple access scheme positioned between SC DS-CDMA and MC-CDMA, since it exhibits a number of advantageous properties that can be exploited in the context of broadband MC DS-CDMA designed for diverse propagation environments. In [10] it was shown that MC DS-CDMA has the highest degree of freedom in the family of CDMA schemes, and this property can be beneficially exploited during the system design procedure. Below we investigate how the specific parameters of MC DS-CDMA, which determine the degree of design freedom, can be adjusted to satisfy the requirements of diverse propagation environments. Hence, given the channel's delay spread $[T_m, T_M]$, the number of resolvable paths L_p encountered by SC LAS DS-CDMA is $\lfloor T_M/T_c \rfloor + 1$. By contrast, the number of resolvable paths L_p for MC LAS DS-CDMA becomes $\lfloor T_M/(UT_c) \rfloor + 1$, where U is the number of subcarriers [10, 1]. Therefore, when the number of subcarriers is low, the corresponding number of resolvable paths will be high, so the orthogonality of the LAS codes is destroyed, rendering them unable to suppress MAI and MPI. In contrast, when the number of subcarriers is high, for example, we have long chip duration and hence may have $T_M < T_c$. In this case we can maintain the orthogonality of the LAS codes, but cannot achieve multipath diversity because the number of resolvable components is one. However, the number of subcarriers U may be optimized for broadband CDMA communication [1]. More specifically, we guarantee that the IFW of LAS codes retains its ability to suppress both the MAI and MPI as well as maintain a sufficiently high multipath diversity gain [1, 10], which requires a U value resulting in exactly as many multipath components as can be accommodated by the IFW.



■ **Figure 6.** *BER vs. channel SNR performance comparison of random-code-based classic CDMA and SC LAS CDMA when communicating over a dispersive Rayleigh-fading channel with* m = *1. The number of resolvable paths was* L_p *= 4, 6, 8, 12, respectively, when using the system parameters summarized at the top of the figure.*



■ **Figure 7.** *BER vs* E_b/N_0 *performance of MC LAS DS-CDMA when we considered different numbers of subcarriers,* U. *The RAKE receiver combines* $L_r \leq$ *3 paths. The dispersion of the propagation environment considered was* T_M = *3 µs. Hence, the number of resolvable multipath components for* U *= 1, 8, 16, 32, 64 was* L_p *= 61, 8, 4, 2, 1 when using the system parameters summarized at the top of the figure.*

Advantages — Based on appropriately selecting the system parameters, broadband MC LAS DS-CDMA circumvents the problems encountered by SC LAS DS-CDMA. Specifically, broadband MC LAS DS-CDMA has a range of benefits:

- Broadband MC LAS DS-CDMA is capable of extending the width of the IFW of the LAS codes, since the chip duration of the individual subcarriers is increased by a fac-

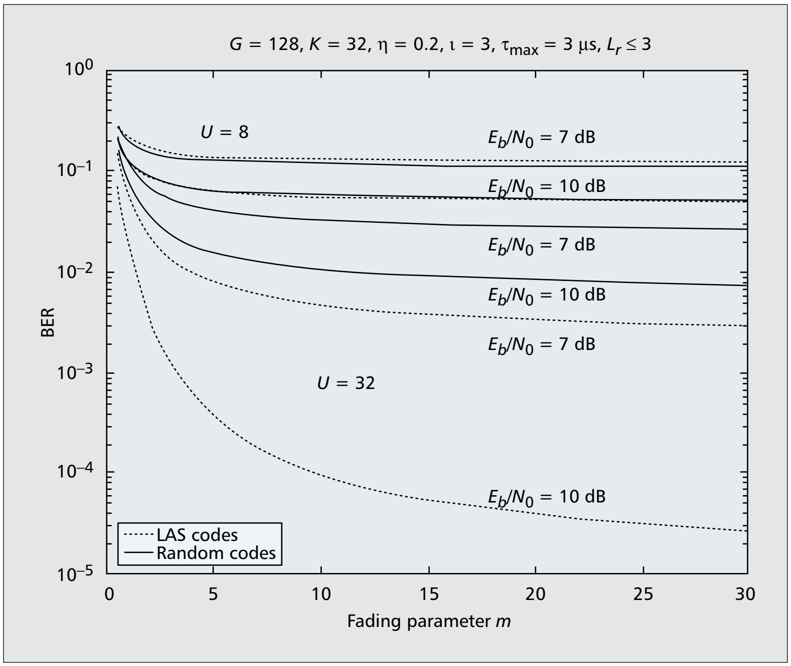


Figure 8. *BER vs. Nakagami fading parameter performance comparison of MC DS-CDMA when we considered LAS codes and random spreading codes. The RAKE receiver combined $L_r \leq 3$ paths, when communicating over different Nakagami fading channels. The dispersion of the propagation environment considered was $T_M = 3$ μs. Hence the number of resolvable multipath components for $U = 8, 32$ was $L_p = 8, 2$ when using the system parameters summarized at the top of the figure.*

tor corresponding to the number of subcarriers.

- Broadband MC LAS DS-CDMA benefits from configuring the number of subcarriers U such that the resultant number of resolvable multipath components is accommodated by the IFW without imposing MPI and MAI, yet providing L_r-order multipath diversity.

Disadvantages — However, MC LAS DS-CDMA also has certain deficiencies [10]:

- Frequency offset problems may be encountered between the transmitter and receiver, which results in intersubcarrier interference (ICI) [11].
- The peak factor [11] of MC LAS DS-CDMA is higher than that of the corresponding SC LAS DS-CDMA system.

The above design philosophy might be augmented with the aid of an example. In Fig. 7 we considered a system with a chip rate of 20 Mchips/s and a maximum delay spread of $T_M = 3$ μs. From Fig. 7 we may conclude that the MC LAS DS-CDMA system with $U = 32$ subcarriers will achieve the best performance trade-off in this scenario, resulting in two resolvable multipath components. Furthermore, Fig. 7 demonstrated that the performance of SC LAS DS-CDMA is significantly worse than that of MC LAS DS-CDMA in the scenarios considered. In Fig. 7 we plotted the attainable BER performance of the random-code-based benchmark and the MC LAS DS-CDMA system as a function of the Nakagami fading parameter m. From Fig. 8 we may conclude that when the number of subcarriers is $U = 8$, these two systems achieve similar performance. However, when the number of subcarriers is increased to $U = 32$, the MC LAS DS-CDMA system significantly outperformed the random-code-based MC DS-CDMA arrangement in the investigated scenario.

CONCLUSION

In conclusion, SC LAS DS-CDMA exhibited significantly better performance than the traditional random-code-based DS-CDMA benchmark system in a relatively low-chip-rate scenario, provided that all users operate in a quasi-synchronous manner. As the chip rate as well as the number of resolvable paths increases, resulting in multipath components generated outside the IFW, the attainable performance degrades. MC LAS DS-CDMA is flexible, exhibiting a high degree of freedom, thus allowing us to circumvent the problems encountered by SC LAS DS-CDMA. Furthermore, MC LAS-CDMA is capable of communicating in diverse propagation environments, retaining its ability to achieve multipath diversity, while suppressing MAI as well as MPI. Given a specific spreading code length, a limitation of the LAS-code-based systems is that the number of available LAS codes is lower than that of Walsh-Hadamad codes, for example. Although their number maybe increased, say, by invoking the procedures proposed in [3], nonetheless this limits the number of users supported by the system, so further research is required on mitigating this limitation. A promising line of research is to allocate the LAS codes on a near-instantaneous demand basis, as in slotted ALOHA or packet reservation multiple access (PRMA).

REFERENCES

[1] L. Hanzo *et al.*, *Single- and Multi-Carrier DS-CDMA*, Wiley and IEEE Press, 2003.
[2] D. Li, "A High Spectrum Efficient Multiple Access Code," *Chinese J. Elect.*, vol. 8, July 1999, pp. 221–26.
[3] B. J. Choi and L. Hanzo, "On the Design of LAS Spreading Codes," *IEEE VTC 2002 Fall Conf.*, Vancouver, Canada, Sept. 2002, pp. 2172–76.
[4] W. C. Y. Lee, "The Most Spectrum-Efficient Duplexing Systems: CDD," *IEEE Commun. Mag.*, vol. 40, Mar. 2002, pp. 163–66.
[5] S. Stanczak, H. Boche, and M. Haardt, "Are LAS-Codes a Miracle?," *GLOBECOM '01*, vol. 1, San Antonio, TX, Nov. 2001, pp. 589–93.
[6] D. Li, "The Perspectives of Large Area Synchronous CDMA Technology for the Fourth-Generation Mobile Radio," *IEEE Commun. Mag.*, vol. 41, Mar. 2003, pp. 114–18.
[7] H. H. Chen, Y. Y. C. Tsai, and W. Chang, "Uplink Synchronization Control Technique and Its Environment-Dependent Performance Analysis," *Elect. Lett.*, vol. 33, Nov. 2003, pp. 1555–1757.
[8] CWTS/China, Physical Layer Specification for LAS-2000, June 2000.
[9] W. C. Y. Lee, *Mobile Communications Engineering*, 2nd ed., McGraw-Hill, 1998.
[10] L.-L. Yang and L. Hanzo, "Multicarrier DS-CDMA: A Multiple Access Scheme for Ubiquitous Broadband Wireless Communications," *IEEE Commun. Mag.*, vol. 51, May 2003, pp. 748–52.
[11] L. Hanzo *et al.*, *OFDM and MC-CDMA*, Wiley and IEEE Press, 2003.

BIOGRAPHIES

HUA WEI received a B.Eng. degree in wireless communication from Beijing University of Posts and Telecommunication in 1997, then worked in the Hua Wei Technology Company on SDH system software development, and in the Motorola China Software Center on CDMA system software development. Since 2001 he has been with the Communication Group, School of Electronics and Computer Science, University of Southampton, United Kingdom, involved in researching CDMA schemes designed for future generations of wireless mobile communication systems.

LIE-LIANG YANG [M] received his M.Eng. and Ph.D. degrees in communications and electronics from Northern Jiaotong University, Beijing, China, in 1991 and 1997, respectively, and his B.Eng. degree in communications engineering from Shanghai TieDao University, China, in 1988. Since December 1997 he has been with the Communications Research Group at the Department of Electronics and Computer Science of the University of Southampton, where he held various research posts as a visiting postdoctoral research fellow, research fellow, and senior research fellow. Currently he holds an academic post as a lecturer. From June 1997 to December 1997 he was a visiting scientist with the IREE, Academy of Sciences of the Czech Republic. He has been involved in a number of projects funded by the National Sciences Foundations of China, the Grant Agency of the Czech Republic, the Engineering and Physical Sciences Research Council (EPSRC) of the United Kingdom, and the European Union. His research has covered a wide range of areas in communications, which include data network and security, intelligent wireless networking, error control coding, modulation and demodulation, spread spectrum communications and multiuser detection, pseudo-noise (PN) code synchronization, smart antennas, adaptive wireless systems, as well as wideband, broadband, and ultrawideband CDMA for advanced wireless mobile communication systems. He has published over 90 papers in various journals and conference proceedings.

LAJOS HANZO [F] (lh@ecs.soton.ac.uk), Fellow of the Royal Academy of Engineering (FREng), received his Master's degree in electronics in 1976 and his doctorate in 1983. In 2004 he was awarded the Doctor of Sciences (D.Sc.) degree by the University of Southampto. During his 28-year career in telecommunications he has held various research and academic posts in Hungary, Germany, and the United Kingdom. Since 1986 he has been with the Department of Electronics and Computer Science, University of Southampton, where he holds the chair in telecommunications. He has co-authored 11 Wiley/IEEE Press books totaling about 8000 pages on mobile radio communications, published in excess of 500 research papers, organized and chaired conference sessions, presented overview lectures, and been awarded a number of distinctions. Currently he is managing an academic research team, working on a range of research projects in the field of wireless multimedia communications sponsored by industry, the Engineering and Physical Sciences Research Council (EPSRC) of the United Kingdom, the European IST Program, and the Mobile Virtual Centre of Excellence (VCE), United Kingdom. He is an enthusiastic supporter of industrial and academic liaison and offers a range of industrial courses. He is also an IEEE Distinguished Lecturer for both the Communications and Vehicular Technology Societies as well as a Fellow of the IEE. For further information on research in progress and associated publications, please refer to http://www-mobile.ecs.soton.ac.uk

SC LAS DS-CDMA exhibited a significantly better performance than the traditional random code based DS-CDMA benchmarker system in a relatively low-chip-rate scenario, provided that all users operate in a quasi-synchronous manner.