Organised by the Institution of Engineering and Technology
Radar, Sonar and Navigation Network

The Knowledge Network

Keynote Address: Interference – Mitigating Signalling Waveform Design for Wireless Systems

Professor Lajos Hanzo,
Southampton University, UK

Printed and published by the IET, Michael Faraday House, Six Hills Way, Stevenage, Herts SG1 2AY, UK

About the Speaker

Professor Hanzo is a Fellow of the Royal Academy of Engineering, who received his first-class degree in electronics in 1976 and his doctorate in 1983. In 2004 he was awarded the Doctor of Sciences (DSc) degree by the University of Southampton, UK.

During his career in telecommunications he has held various research and academic posts in Hungary, Germany and the UK. Since 1986 he has been with the Department of Electronics and Computer Science, University of Southampton, UK, where he holds the chair in telecommunications. He co-authored 14 books totalling 10 000 pages on mobile radio communications, published in excess of 650 research papers, organised and chaired conferences, presented various keynote and overview lectures and has been awarded a number of distinctions.

Currently he directs the research of a 50-strong academic 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) UK, the European IST Programme and the Mobile Virtual Centre of Excellence (VCE), UK. He is an enthusiastic supporter of industrial and academic liaison and he offers a range of industrial courses. He is also an IEEE Distinguished Lecturer of both the Communications as well as the Vehicular Technology Society and a Fellow of both the IEEE and the IEE. For further information on research in progress and associated publications please refer to http://www.ecs.soton.ac.uk/people/lh

Interference-Mitigating Waveform Design for Next-Generation Wireless Systems

A Light-hearted Keynote Address

L. Hanzo[1]

School of ECS, Univ. of Southampton, SO17 1BJ, UK.
Tel: +44-(0)23-8059-3125, Fax: +44-(0)23-8059-4508
Email: lh[1]@ecs.soton.ac.uk http://www-mobile.ecs.soton.ac.uk

ABSTRACT

A brief historical perspective of the evolution of waveform designs employed in consecutive generations of wireless communications systems is provided, highlighting the range of often conflicting demands on the various waveform characteristics. As the culmination of recent advances in the field the underlying benefits of various Multiple Input Multiple Output (MIMO) schemes are highlighted and exemplified. As an integral part of the appropriate waveform design, cognizance is given to the particular choice of the duplexing scheme used for supporting full-duplex communications and it is demonstrated that Time Division Duplexing (TDD) is substantially outperformed by Frequency Division Duplexing (FDD), unless the TDD scheme is combined with further sophisticated scheduling, MIMOs and/or adaptive modulation/coding. It is also argued that the specific choice of the Direct-Sequence (DS) spreading codes invoked in DS-CDMA predetermines the properties of the system. It is demonstrated that a specifically designed family of spreading codes exhibits a so-called interference-free window (IFW) and hence the resultant system is capable of outperforming its standardised counterpart employing classic Orthogonal Variable Spreading Factor (OVSF) codes under realistic dispersive channel conditions, provided that the interfering multi-user and multipath components arrive within this IFW. This condition may be ensured with the aid of quasi-synchronous adaptive timing advance control. However, 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, employing a combination of several spreading sequences in the time- frequency- and spatial-domain. The paper is concluded by quantifying the achievable user load of a UTRA-like TDD Code Division Multiple Access (CDMA) system employing Loosely Synchronized (LS) spreading codes exhibiting an IFW in comparison to that of its counterpart using OVSF codes. Both system's performance is enhanced using beamforming MIMOs.

The financial support of the EPSRC, UK and the EU in the framework of the NEWCOM, NEXWAY and PHOENIX projects is gratefully acknowledged. The author would also like to acknowledge the contributions of his close colleagues and professional friends and to express his gratitude for the enlightenment gained from the collaborations with those, whose work was cited in the reference section.

IET Waveform diversity and design in communications, radar, sonar and navigation, 22nd of November, 2006, Savouy Place, London, UK

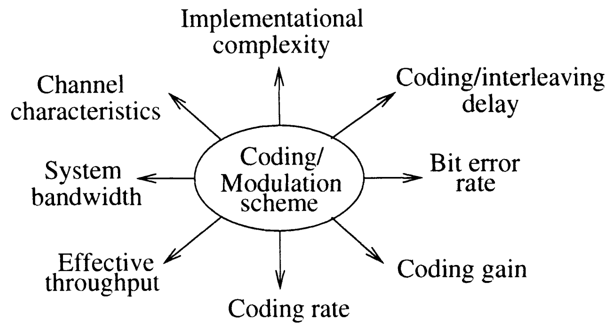

Figure 1: Factors affecting the design of wireless signalling waveforms [1].

1. HISTORIC EVOLUTION OF WAVEFORM-DESIGN IN WIRELESS COMMUNICATIONS

1.1. The Early Years

The efficient design of wireless signalling waveforms has to take into account the entire host of contradictory design trade-offs portrayed in Figure 1, as it will be detailed in this treatise. Historically speaking, the first-generation wireless systems were mainly based on analogue Frequency-Modulation (FM), although their control channels have used digital signalling. During the 1980s substantial research efforts were invested in designing the first digital mobile radio system, which - for the first time - supported international roaming in the heart of Europe [2]. During the period leading to the standardisation of the Pan-European GSM system [2] numerous novel waveform-design concepts were investigated. The investigations considered various spectrally efficient modulation schemes requiring highly linear amplification [3] as well as partial-response Gaussian Minimum Shift Keying (GMSK) [2]. Partial-response GMSK uses a so-called Gaussian filter for spreading the effects of a single modulating bit over three consecutive bit intervals and hence deliberately introduces Inter-Symbol Interference (ISI), which in turn requires a channel equaliser at the receiver for detecting each bit even in the absence of channel-induced dispersion [2]. In exchange for the equaliser's extra complexity the GMSK-modulated waveform exhibits as narrow a spectrum, as possible, since the Gaussian pulse has the narrowest possible bandwidth owing to its smoothest possible time-domain waveform evolution [2]. Furthermore, since the modulating signal affects the phase of the carrier, rather than its amplitude, GMSK is insensitive to non-linear amplification and hence can be amplified using power-efficient class-C amplifiers, which results in a low power-consumption by the handset.

Although GSM has become the most prevalent second-generation (2G) standard right across the globe, there were a number of other 2G standards. For example, the Pan-American IS-54 system [2] and the Japanese Digital Cellular (JDC) systems opted for using $\pi/4$-rotated Quadrature Phase Shift Keying (QPSK) constellations for transmitting 2 bits/symbol at the cost of requiring somewhat higher received Signal-to-Interference-Plus-Noise Ratios (SINR) than GMSK. Furthermore, QPSK requires linear class-A power-amplification or amplifier linearisation techniques [3], which is substantially less power-efficient than the non-linear class-C power amplifiers readily tolerated by the constant-envelope GMSK signal.

By the early 1980s the understanding of waveform design has reached a certain maturity and researchers embarked on investigating alternative, more 'exotic' modulated waveform shapes, such as the employment of both Direct Sequence Code Division Multiple Access (DS-CDMA) [4], as well as Frequency-Hopping (FH) assisted CDMA [4]. The great significance of these studies was that for the first time, researchers were closely following the Shannonian principles of rendering both the modulated DS-CDMA signal as well as the Co-channel Interference (CCI) noise-like in statistical terms, since both DS-spreading as well as FH broaden the transmitted signal's spectrum, hence rendering them similar to the spectrum of noise. Although spread-spectrum principles were also considered for employment in the GSM system in the early 1980s, they have lost out to partial-response GMSK wave-form design. Further developments in the state-of-the-art of weaveform design for CDMA systems followed, when the first so-called M-ary orthogonal CDMA system was proposed by Qualcom for their 2G system [2] in the early 1990s.

By the time the standardisation of the third-generation (3G) systems gathered momentum during the 1990s [4], the understanding of waveform design for diverse CDMA systems reached a state of maturity, including the design of various DS-spreading waveforms [4]. In addition to the transmission of classic voice signals [5], there was a commercial demand for more bandwidth-hungry applications, such as the transmission of both still and interactive video signals [6], which stimulated further research for the sake of supporting both variable-rate and high-rate wireless Internet services. Both the European and Japanese 3G solutions [7] opted for the employment of wideband DS-CDMA using a chip-rate of 3.84 MChips/s in an approximately 5MHz bandwidth and Orthogonal Variable Spreading Factor (OVSF) DS spreading waveforms using Walsh-Hadamard (WH) codes. By contrast, the Pan-American cdma2000 system invoked three parallel subcarriers, leading to the conception of the first commercially available Multi-Carrier DS-CDMA (MC-DS-CDMA) system, using a MC-waveform design [4].

In the mean-time Moore's law and a range of other advances in technology, such as the design of high-linearity power amplifiers facilitated the employment of higher symbol rates and the transmission of multi-bit Quadrature Amplitude Modulation (QAM) signals [3]. As a natural counter-measure against the violently fluctuating Signal to Interference plus Noise-Ratio (SINR), the philosophy of near-instantaneously Adaptive QAM (AQAM) or Burst-by-Burst Adaptive (BbBA) QAM was proposed, which was documented in detail in [4, 8]. These waveform design advance have led to the conception of the High-Speed Downlink Packed Access (HSDPA) High-Speed Uplink Packed Access (HSUPA) modes of the 3G systems, which rely on the extensice employment of AQAM and adaptive channel coding concepts [1]. Naturally, the transceivers have to be designed to satisfy the exact specifications of the highest-throughput and hence most sensitive QAM mode of operation. Clearly, this ambitious waveform design philosophy has moved way beyond the robust constant-envelope waveform design philosophy of class-C non-linear amplification employed in the GSM system.

It is imperative that the waveform design developments of both Digital Audio Broadcast (DAB) [8] and Digital Video Broadcast (DVB) [6] systems as well as those of the family of Wireless Local Area Networks (WLANs) are also portrayed. In both of these categories multi-carrier transmission techniques based on Orthogonal Frequency Division Multiplexing (OFDM) have found favour [9]. Although OFDM techniques [9] exhibit numerous benefits in terms of implementationally efficient modulation, demodulation as well as equalisation techniques, they are even more sensitive to amplifier non-linearities than their single-carrier QAM counterparts [3]. Similar problems are also encountered by their close relatives, namely by the family of various MC-CDMA schemes, although both the so-called peak-to-average-power-ratio (PAPR) and the resilience of the system substantially depends on the specific choice of DS spreading factors, as detailed in Chapters 9 and 11 of [9]. Nonetheless, at the current state-of-the-art it appears likely that the next-generation wireless systems will employ highly flexible, reconfigurable BbB AQAM-aided multi-carrrier transmission techniques owing to their high flexibility in terms of providing a range of bitrates and transmission integrities.

It is worth noting at this stage that most of the above-mentioned research efforts have been invested in designing bandwidth-efficient modulated waveforms, which are beneficial in noise-limited, rather than interference-limited environments, i.e. in single-user scenarios. Furthermore, when the transmitter inflicts non-linear distortions, while the channel imposes linear distortions, only sophisticated channel equalisers and multi-user equalisers are capable of attaining a near-single-user performance. However, the complexity of Multi-User Detectors (MUDs) [4] is typically high, since their effective channel matrix contains the convolution of the DS spreading sequences with the CIR and this potentially large matrix may have to be inverted, unless alternative reduced-complexity techniques are employed. Hence in recent years the concept of combined Time-Domain (TD), Frequency-Domain (FD) and Spatial-Domain (SD) spreading emerged as an attractive low-complexity alternative, as argued in [4]. For example, using a low spreading factor of SF=8 in all three domains would allow us to support a total of 8^3=512 users by separating them in the TD, FD and SD, respectively.

1.2. The MIMO Era

In recent years various smart antenna designs have emerged, which have found application in diverse scenarios, as summarised in Table 1. The main objective of employing MIMOs is that of combating the effects of multipath fading on the desired signal and suppressing interfering signals, thereby increasing both the performance and capacity of wireless systems. To elaborate a little further, in smart antenna assisted systems multiple antennas may be invoked both at the transmitter and/or the receiver, where the antennas may be arranged for achieving spatial diversity, directional beamforming or for attaining both diversity and beamforming. For example, one of the two main design objectives of MIMOs is that of maximising the achievable multiplexing gain by creating several unique subchannels by using multiple antenna elements, which can be differentiated with the aid of their unique antenna-specific CIRs. Alternatively, MIMOs may be designed for exploiting the independent fading of the antenna el-

Space Division Multiplexing (SDM) Systems [10]	SDM systems also employ multiple antennas, but in contrast to SDMA arrangements, not for the sake of supporting multiple users. Instead, they aim for increasing the throughput of a wireless system in terms of the number of bits per symbol that can be transmitted by a given user in a given bandwidth at a given integrity.
Space Division Multiple Access (SDMA) [9]	SDMA exploits the unique, user-specific "spatial signature" of the individual users for differentiating amongst them. This allows the system to support multiple users within the same frequency band and/or time slot.
Spatial Diversity (STBC [11], STTC [12]) [1] and Space-Time Spreading (STS) [4]	In contrast to the $\lambda/2$-spaced phased array elements, in spatial diversity schemes, such as space-time block or trellis codes [1] the multiple antennas are positioned as far apart as possible, so that the transmitted signals of the different antennas experience independent fading, resulting in the maximum achievable diversity gain.
Beamforming [7]	Typically $\lambda/2$-spaced antenna elements are used for the sake of creating a spatially selective transmitter/receiver beam. Smart antennas using beamforming have been employed for mitigating the effects of cochannel interfering signals and for providing beamforming gain.

Table 1: The four main applications of MIMOs in wireless communications

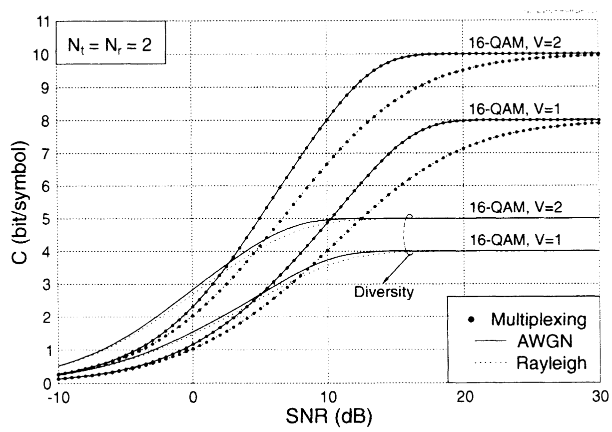

Figure 2: The capacity of the MIMO uncorrelated Rayleigh-fading channel and AWGN channel for classic two-dimensional 16QAM ($M = 16$, $D = 2$) and for so-called four-dimensional orthogonal signalling ($M = 32$, $D = 4$), when using $N_t = N_r = 2$ transmit and receive antennas; Ng & Hanzo, [13].

ements, where it is unlikely for several antenna elements to simultaneously experience a high attenuation. This independent fading phenomenon typically results in a beneficial diversity gain. Naturally, the achievable performance improvements of MIMOs are a function of the antenna spacing and that of the algorithms invoked for processing the signals received by the antenna elements, which will be exemplified during our further discourse in the context of the four main MIMO types summarised in Table 1. As an example, in Figure 2 $N_t = N_r = 2$ antennas were used and both so-called classic 16QAM and more unorthodox, but higher-capacity four-dimensional signalling was used [13] for the sake of quantifying their maximum achievable performance benefits. The MIMO schemes of Table 1 were designed for achieving various design goals. The Spatial Division Multiplexing [10, 14] (SDM) schemes aim for maximising the attainable multiplexing gain, i.e. the throughput of a given user. By contrast, Space Division Multiple Access (SDMA) arrangements [9] maximise the number of users supported. Alternatively, attaining the maximum possible diversity gain is the objective of the plethora of space-time block coding [11] as well as space-time trellis coding [12] schemes found in the literature [1]. Finally, beamforming mitigates the effects of interfering users roaming in the vicinity of the desired user [7], provided that they are angularly separable.

Here we continue our discourse by providing a succinct example of the above-mentioned four MIMO subclasses of Table 1 and briefly characterise their attainable performance in Figures 3 - 6. More specifically, in Figure 3 the BER versus SNR performance of the sphere-decoding aided and MIMO-assisted SDM OFDM receiver of Chapter 10 is characterised, which exhibits a near-Maximum Likelihood (ML) performance at a relatively low complexity in high-throughput scenarios using $N_t = N_r = 6$ transmit and receive antennas and 64QAM. The rank-deficient scenario - namely when we have more transmit antennas than receive antennas - using N_txN_r=6x4 16QAM MIMO-OFDM also performs adequately, when the OFDM subcarriers experience independent flat fading. The throughput of these systems is 36 and 24 bits/symbol, respectively. Remarkably, the 36-bit-throughput 6x6-dimensional 64QAM system outperforms the 24-bit-throughput 6x4-dimensional 16QAM system, as a benefit of using a total of 6x6=36 antenna elements instead of 24, which provides a substantial diversity gain in addition to the SDM gain.

Let us now briefly consider Figure 4, where instead of the SDM scheme of Figure 3 supporting a single user, an SDMA system allocating the increased throughput of the MIMO-OFDM system to several users was characterised. A further attractive feature of this system is that instead of the turbo channel codec of Figure 3, a sophisticated, iteratively detected joint coding and modulation scheme was used, which is referred to as Turbo Trellis Coded Modulation (TTCM) [1]. Finally, in contrast to the near-ML sphere-decoder of Figure 3 [14], the Iterative Genetic Algorithm (IGA) aided Minimum Mean Squared Error (MMSE) multiuser detector was employed. Hence we termed this system as the TTCM-MMSE-IGA-SDMA-OFDM arrangement. The novel IGA-aided technique employed the novel Biased Q-function Based Mutation (BQM) technique proposed in [15] for the sake of approaching the performance of the ML detector at the cost of a substantially lower complexity. Observe in the figure that both perfect and imperfect channel estimation scenarios were considered and that the number of users was L= 6 - 8, while the number of SDMA receiver antenna elements was P=6. Similarly to the SDM system of Figure 3, this SDMA arrangement is also capable of operating in high-throughput rank-deficient scenarios.

Having considered both the SDM and SDMA systems of Table 1, let us now briefly exemplify a cutting-edge transmit diversity scheme in Figure 5. Explicitly, Alamouti's STBC scheme was further de-

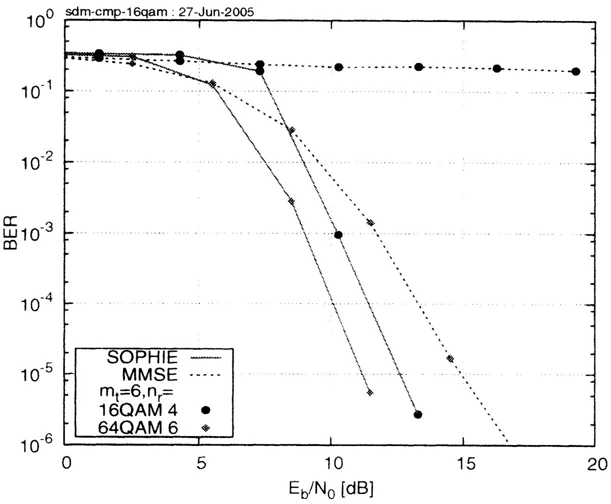

Figure 3: BER versus SNR performance of the sphere-decoding aided and MIMO-assisted SDM OFDM receiver of Chapter 10 ©Akhtman & Hanzo in [14], which exhibits a near-Maximum Likelihood (ML) performance and a relatively low complexity in high-throughput scenarios using $N_t = N_r = 6$ transmit and receive antennas and 64QAM as well as for the rank-deficient scenario using N_txN_r=6x4 16QAM MIMO-OFDM. The OFDM subcarriers experience independent flat fading. **The throughput is 36 and 24 bits/symbol, respectively.**

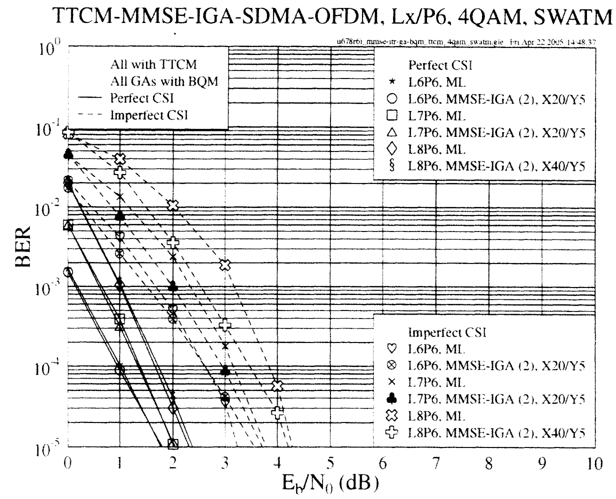

Figure 4: **BER** versus E_b/N_0 performance comparison of the **TTCM-assisted MMSE-IGA-SDMA-OFDM** system using **BQM**, while employing a **4QAM** scheme for transmission over the SWATM channel, where **L=6, 7, 8** users are supported with the aid of **P=6** receiver antenna elements, respectively. The simulation parameters used are given in Table 2 ©Jiang & Hanzo of [15].

veloped by jointly, rather than separately desiging the two transmit antenna's and two timeslots' signals with the aid of Sphere Packing (SP) modulation using iterative detection, as detailed in [16, 17]. It is worth noting, however that channel estimation is an extremely complex process in the context of MIMOs, since in the example of Figure 3 a total of 36 channels has to be estimated. In order to circumvent this problem, in [18] the philosophy of differentially encoded STS (DSTS) was proposed. In this context it was also discussed that the mapping of the bits to the SP modulation scheme is highly influential in terms of determining the overall system performance and that the classic Gray mapping is often outperformed by various mappers, which do not abey the Gar-mapping rules and hence are termed as Anti-Gray Mapping (AGM) schemes. Finally, observe in Figure 5 that the employment of a unity-rate precoder [18] has the potential of substantially improving the iteratrively decoded system's attainable performance.

The fourth dominant member of the family of MIMOs summarised in Table 1 is constituted by beamforming. In Figure 6 a novel iterative detection aided beamformer is characterised. This scheme is more radical than the classic MMSE beamformer weight adjustment technique, since it directly minimises the BER, rather than the MMSE, as detailed in [20, 21, 22, 23, 24, 25, 26] in the context of various wireless systems. Observe in Figure 6 that as the number of detection iterations is increased, the BER performance approaches that of the single-user scenario, despite operating in the highly demanding rank-deficient scenario of supporting six users with the aid of two antenna elements, where all channels are assumed to be non-dispersive and independently fading. More explicitly, this poweful system is capable of supporting a three times higher user load than the number of antenna elements, while the conventional rule of thumb is that only as many users may be supported as the number of receiver antennas.

Let us now briefly summarise our previous discussions, before proceeding further. Following decades of waveform design efforts, BbB AQAM multi-carrier transceivers using various MIMO techniques have reached a state of maturity and are likely to find their way into the tool-box of the next-generation wireless communications enabling techniques. In the rest of this light-hearted overview we will focus our attention on an attractive subclass of beamforming aided CDMA systems using specifically designed interference-immune spreading sequences, in order to characterise the total network-layer benefits of the physical-layer performance improvements reported.

2. LOOSELY SYNCHRONISED SPREADING SEQUENCES

In our previous research [7], we quantified the UTRA FDD system's performance using both adaptive beamforming and adaptive modulation. The system employed OVSF spreading codes, which offer the benefit of perfect orthogonality in an ideal channel. Hence in a non-dispersive channel, all intracell users' signals are perfectly orthogonal. However, upon propagating through a dispersive multipath channel this orthogonality is eroded, hence all other users will interfere with the desired user's signal. Therefore in practice the intra-cell interference is always non-zero, when using OVSF codes for transmission over dispersive channels.

The above-mentioned erosion of code orthogonality may be mitigated with the aid of Loosely Synchronized (LS) spreading codes [4, 28, 29, 30]. These codes exhibit a so-called Interference Free Window (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 delayed asynchronous transmissions arrive within the code's IFW. More specifically, interference-

Table 2: Arrival angles of the users' signals

user k	1	2	3	4	5	6
θ_k	15°	-4°	36°	-24°	68°	-48°

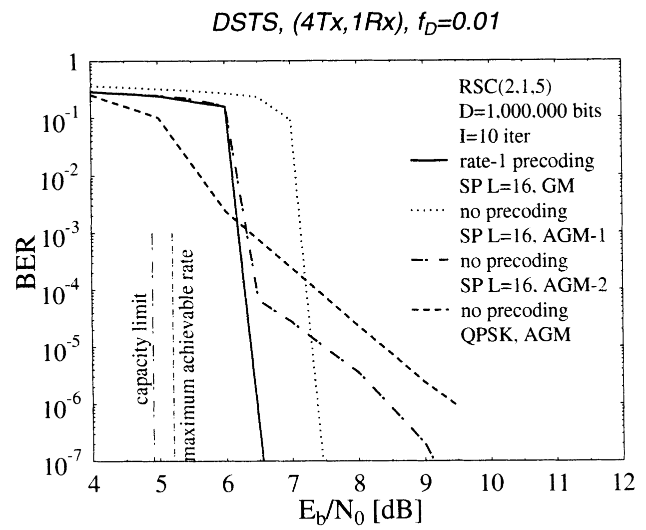

Figure 5: Near-capacity performance of an Anti-Gray Mapping (AGM) based convolutional-coded Differential Space-Time Spread & Sphere-Packed (DSTS-SP) schemes in conjuction with $L = 16$-ary SP modulation, while using no precoding together with the system employing a unitary-rate precoder and Gray Mapping (GM), while using an interleaver length of $D = 1,000,000$ bits, $I = 10$ iterations©El-Hajjar, Alamri, Ng & Hanzo [19].

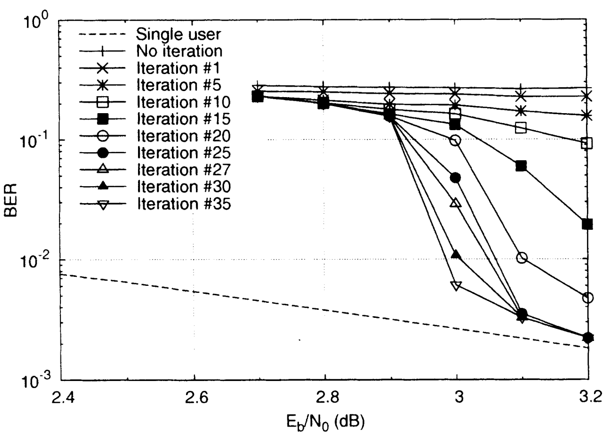

Figure 6: BER performance of the iterative MBER beamforming receiver of ©Tan, Chen & Hanzo [27] using a two-element antenna array for supporting $K = 6$ users having the angles of arrival listed in Table 2 and experiencing uncorrelated Rayleigh fading for all channels.

free CDMA communications become possible even without a multiuser detector, when the total time offset expressed in terms of the number of chip intervals, which is the sum of the time-offset of the mobiles plus the maximum channel-induced delay spread is within the code's IFW [31]. By employing this specific family of codes, we are capable of reducing both the ISI and the MAI, since users in the same cell do not interference with each other, as a benefit of the IFW provided by the LS codes used.

There exists a specific family of LS codes [32], which exhibits an IFW, where both the auto-correlation and cross-correlation of the codes become zero. Specifically, LS codes exploit the properties of the so-called orthogonal complementary sets [32]. An example of the

Parameter	Value
Cell radius	78 m
Signal bandwidth	5 MHz
Modulation scheme	4QAM/QPSK
Spreading factor	16
Max BS MS TX power	17 dBm
Min BS MS TX power	-44 dBm
Pedestrian speed	3 mph
Target SINR	6.2 dB

Table 3: Simulation parameters.

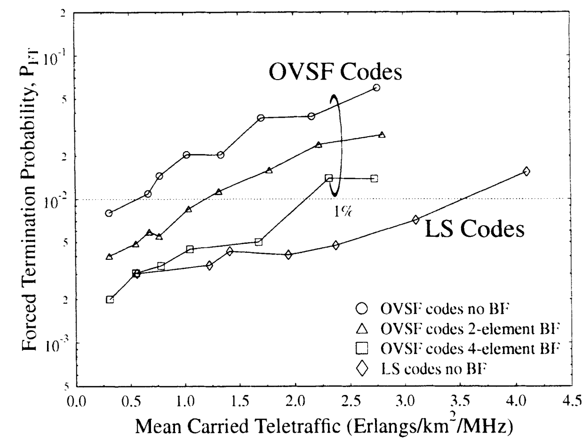

Figure 7: Forced termination probability versus mean carried traffic of the UTRA-like TDD cellular network using **LS codes and OVSF codes** both with as well as without beamforming in conjunction with shadowing having a frequency of 0.5 Hz and a standard deviation of 3dB for a spreading factor of SF=16 ©Ni, Wei & Hanzo [35]

design of LS spreading codes can be found in [33]. In these investigations the cell-radius was set to 78 m, which was the maximum affordable cell radius for the IFW duration of ± 1 chip intervals at a chip rate of 3.84 Mchip/s. Alternatively, the adaptive timing advance control has to maintain a maximum delay difference of one chip-duration, so that the interfering components arrive within this IFW. The mobiles were roaming freely, at a pedestrian speed of 3mph, in random directions, selected at the start of the simulation from a uniform distribution, within the infinite simulation area of 49 wrapped-around traffic cells [7]. Furthermore, the post-despreading Signal to Interference plus Noise Ratios (SINRs) required for obtaining the target Bit Error Rates (BERs) were determined with the aid of physical-layer simulations using a 4QAM modulation scheme, in conjunction with 1/2-rate turbo coding for transmission over a COST 207 seven-path Bad Urban (BU) channel [34]. Using this turbo-coded transceiver and LS codes having a SF of 16, the post-despreading SINR required for maintaining the target BER of 1×10^{-3} was 6.2 dB. The BER, which was deemed to correspond to low-quality communications was stipulated at 5×10^{-3}. This BER was exceeded for SINRs falling below 5.2 dB. Furthermore, a low-quality outage was declared, when the BER of 1×10^{-2} was exceeded, which was encountered for SINRs below 4.8 dB. These values can be seen along with the other system parameters in Table 3. All other experimental conditions were identical to those in [7].

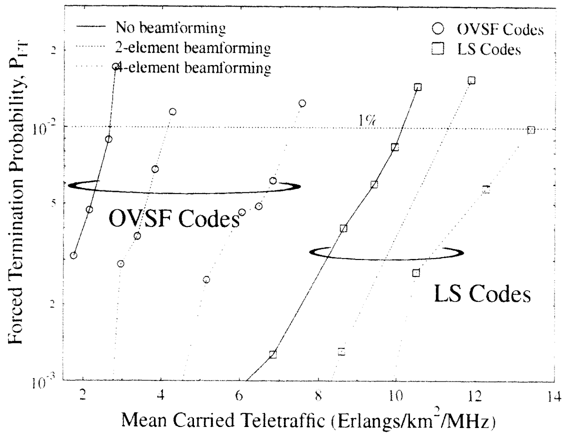

Figure 8: Forced termination probability versus mean carried traffic of the UTRA-like FDD cellular network using **LS codes and OVSF codes** both with as well as without beamforming in conjunction with shadowing having a frequency of 0.5 Hz and a standard deviation of 3dB for a spreading factor of SF=16 ©Ni, Wei & Hanzo [35]

3. FDD VERSUS TDD NETWORK PERFORMANCE USING LS CODES[35]

The BER performance of OVSF codes and LS codes was compared [29], which was determined with the aid of physical-layer simulations using a 4-QAM modulation scheme, 1/2-rate turbo coding and a Minimum Mean Squared Error Block Decision Feedback Equalizer (MMSE-BDFE) based Multi-User Detector (MUD) for transmission over a COST 207 seven-path Bad Urban channel. The achievable BER performance of LS codes is better than that of OVSF codes. For a spreading factor of 16, the post-despreading SINR required for maintaining a BER of 1×10^{-3} was 6.2 dB in case of LS codes, which is almost 2 dB lower than that necessitated by the OVSF codes. Figure 7 shows the UTRA-like TDD/CDMA system's forced termination probability associated with a variety of traffic loads quantified in terms of the mean normalized carried traffic expressed in Erlangs/km^2/MHz, when subjected to 0.5 Hz frequency shadowing having a standard deviation of 3 dB. As observed in the figure, nearly an order of magnitude reduction of the forced termination probability has been achieved by employing LS spreading codes compared to those of using OVSF spreading codes. In conjunction with OVSF codes, the "No beamforming" scenario suffered from the highest forced termination probability of the four traffic scenarios characterized in the figure at a given load. Specifically, the network capacity was limited to 50 users, or to a teletraffic density of approximately 0.55 Erlangs/km^2/MHz. With the advent of employing 4-element adaptive antenna arrays [7] at the base stations the number of users supported by the TDD system increased to 178 users, or to a teletraffic density of 2.03 Erlangs / km^2 / MHz. However, in conjunction with LS codes, and even without employing antenna arrays at the base stations, the TDD system was capable of supporting 306 users, or an equivalent traffic density of 3.45 Erlangs/km^2/MHz.

Figure 8 portrays the UTRA-like FDD/CDMA system's forced termination probability versus various traffic loads. The figure illustrates that the network's performance was significantly improved by using LS codes. As observed in the figure, nearly an order of magnitude forced termination probability (P_{FT}) reduction has been achieved by employing LS codes compared to the scenario using OVSF codes. Specifically, the network capacity was limited to 152 users, or to a teletraffic load of approximately 2.65 Erlangs/km^2/MHz. With the advent of employing four-element adaptive antenna arrays [7] at the base stations the number of users supported by the network increased to 428 users, or almost to 7.23 Erlangs/km^2/MHz. However, in conjunction with LS codes, and even without employing antenna arrays at the base stations the network capacity was dramatically increased to 581 users, or 10.10 Erlangs / km^2 / MHz. When the four-element adaptive antenna array was employed in the LS code aided scenario, the system was capable of supporting 800 users, which corresponded to a teletraffic load of 13.39 Erlang/km^2/MHz. This is because the LS codes' auto-correlation and cross-correlation functions exhibit an IFW, which essentially eliminated the intra-cell interference.

4. SUMMARY AND CONCLUSIONS

A brief historical portrayal of the evolution of waveform design for wireless communications was provided. This was followed by a rudimentary overview of the four most prevalent MIMOs summarised in Table 1, each of which was exemplified and briefly characterised in Figures 3 - 6. Finally, as a complete system design study, the network performance of a UTRA-like system employing LS spreading codes was shown to be substantially better than that of the system using OVSF codes. In the context of the interference limited 3G CDMA system LS codes might hold the promise of an increased network capacity without dramatic changes of the 3G standards. However, LS codes exhibit two impediments. Firstly, the number of spreading codes exhibiting a certain IFW is limited and hence under high user-loads the system may become code-limited, rather than interference-limited. The number of LS codes may be increased using the procedure proposed in [36], but further research is required for increasing the number of codes. A particularly attractive solution is to invoke both DS-CDMA time-domain (TD) and frequency-domain (FD) spreading [37] to multiple carriers in MC-CDMA. This can be achieved for example using LS and OVSF codes in the TD and FD, respectively. Then no multiuser detection (MUD) is required in the TD and the MUD employed in the FD has a low complexity owing to using an OVSF code having a low SF. The total number of users supported becomes the product of the number of LS and OVSF codes.

The second deficiency of LS codes is that they tend to exhibit a short IFW duration. However, this deficiency is also eliminated with the aid of the above-mentioned joint TD and FD spreading regime, because upon spreading the information to multiple carriers the TD chip-duration may be commensurately extended by a factor corresponding to the number of carriers.

5. REFERENCES

[1] L. Hanzo, T. H. Liew, and B. L. Yeap, *Turbo Coding, Turbo Equalisation and Space-Time Coding for Transmission Over Fading Channels*. New York, USA: IEEE Press - John Wiley & Sons Ltd., 2002.

[2] R. Steele and L. Hanzo, *Mobile Radio Communications: Second and Third Generation Cellular and WATM Systems*. New York, USA: IEEE Press - John Wiley & Sons Ltd., 2 ed., 1999.

[3] L. Hanzo, S. X. Ng, T. Keller, and W. T. Webb, *Quadrature Amplitude Modulation: From Basics to Adaptive Trellis-Coded, Turbo-Equalised and Space-Time Coded OFDM, CDMA and MC-CDMA Systems*. West Sussex, UK: IEEE Press - John Wiley & Sons Ltd., 3 ed., 2004.

[4] L. Hanzo, L. L. Yang, E. L. Kuan, and K. Yen, *Single- and Multi-Carrier DS-CDMA*. John Wiley and IEEE Press, 2003, 1060 pages.

[5] L. Hanzo, F. Somerville, and J. Woodard, *Voice Compression and Communications: Principles and Applications for Fixed and Wireless Channels*. IEEE Press and John Wiley, 2001. (For detailed contents and sample chapters please refer to http://www-mobile.ecs.soton.ac.uk.).

[6] L. Hanzo, P. Cherriman, and J. Streit, *Wireless Video Communications: From Second to Third Generation Systems, WLANs and Beyond*. IEEE Press and John Wiley, 2001. (For detailed contents please refer to http://www-mobile.ecs.soton.ac.uk.).

[7] J. Blogh and L. Hanzo, *3G Systems and Intelligent Networking*. John Wiley and IEEE Press, 2002. (For detailed contents, please refer to http://www-mobile.ecs.soton.ac.uk.).

[8] L. Hanzo, C. H. Wong, and M. S. Yee, *Adaptive Wireless Tranceivers*. IEEE Press - John Wiley & Sons Ltd., 2002.

[9] L. Hanzo, M. Münster, B. J. Choi, and T. Keller, *OFDM and MC-CDMA for Broadband Multi-user Communications, WLANs and Broadcasting*. IEEE Press - John Wiley & Sons Ltd., 2003.

[10] G. J. Foschini, "Layered Space-Time Architecture for Wireless Communication in a Fading Environment When Using Multi-Element Antennas," *Bell Labs Technical Journal*, vol. Autumn, pp. 41–59, October 1996.

[11] S. M. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 16, pp. 1451–1458, October 1998.

[12] V. Tarokh, N. Seshadri, and A. R. Calderbank, "Space-time codes for high data rate wireless communication: performance criterion and code construction," *IEEE Transactions on Information Theory*, vol. 44, pp. 744–765, March 1998.

[13] S. Ng and L. Hanzo, "On the mimo channel capacity of multi-dimensional signal sets," *IEEE Transactions on Vehicular Technology*, vol. 52, pp. 528 – 536, March 2006.

[14] L. Hanzo and T. Keller, *OFDM and MC-CDMA - A Primer*. John Wiley & IEEE Press, May 2006.

[15] M. Jiang, S. X. Ng, and L. Hanzo, "Hybrid Iterative Multi-User Detection for Channel Coded Space Division Multiple Access OFDM Systems," *IEEE Transactions on Vehicular Technology*, vol. 55, pp. 115–127, January 2006.

[16] W. Su, Z. Safar, and K. J. R. Liu, "Space-time signal design for time-correlated Rayleigh fading channels," in *IEEE International Conference on Communications*, vol. 5, (Anchorage, Alaska), pp. 3175–3179, 2003.

[17] O. Alamri, B. Yeap, and L. Hanzo, "Turbo detection of channel-coded space-time signals using sphere packing modulation," *Proceedings of IEEE VTC'04, Los Angeles, USA*, pp. 2498 – 2502, September 2004.

[18] M. El-Hajjar, O. Alamri, and L. Hanzo, "Differential space-time spreading using four transmit antennas and iteratively detected sphere packing modulation," *Proceedings of IEEE ISSSTA*, pp. 322 – 326, August 2006.

[19] M. El-Hajjar, O. Alamri, S. Ng, and L. Hanzo, "Turbo detection of precoded sphere packing modulation using four transmit antennas for differential space-time spreading," *submitted to Transactions on Wireless Communications*, 2006.

[20] M. Alias, A. Samingan, S. Chen, and L. Hanzo, "Multiple antenna aided OFDM employing minimum bit error rate multiuser detection," *IEE Electronics Letters*, vol. 39, pp. 1769–1770, November 2003.

[21] A. Wolfgang, N. N. Ahmad, S. Chen, and L. Hanzo, "Genetic algorithm assisted minimm bit error rate beamforming," in *CDROM of the IEEE 59th Vehicular Technology Conference*, (Milan, Italy), May, 2004.

[22] S. Chen, B. Mulgrew, and L. Hanzo, "Least Bit Error Rate Adaptive Nonlinear Equalizers for Binary Signalling," *IEE Proceedings Communications*, vol. 150, no. 1, pp. 29–36, February 2003.

[23] M. Y. Alias, S. Chen, and L. Hanzo, "Multiple-antenna-aided OFDM employing genetic-algorithm-assisted minimum bit error rate multiuser detection," *IEEE Transactions on Vehicular Technology*, vol. 54, pp. 1713–1721, September 2005.

[24] S. Chen, A. K. Samingan, B. Mulgrew, and L. Hanzo, "Adaptive minimum-BER linear multiuser detection for DS-CDMA signals in multipath channels," *IEEE Transactions on Signal Processing*, vol. 49, pp. 1240–1247, June 2001.

[25] S. Chen, A. Livingstone, and L. Hanzo, "Minimum bit-error rate design for space-time equalization-based multiuser detection," *IEEE Transactions on Communications*, vol. 54, pp. 824 – 832, May 2006.

[26] S. Chen, L. Hanzo, and A. Livingstone, "Mber space-time decision feedback equalization assisted multiuser detection for multiple antenna aided sdma systems," *IEEE Transactions on Signal Processing*, vol. 54, pp. 3090 – 3098, August 2006.

[27] S. Tan, S. Chen, and L. Hanzo, "On multi-user exit chart analysis aided turbo-detected mber beamformer designs," *submitted to Trasactions on Wireless Communications*, 2006.

[28] H. Wei, L.-L. Yang, and L. Hanzo, "Interference-free broadband single- and multi-carrier ds-cdma," *IEEE Communications Magazine*, vol. 43, pp. 68–73, February 2005.

[29] S. Ni, H. Wei, and L. Hanzo, "Loosely synchronised spreading code aided network performance of quasi-synchronous utra-like tdd and fdd cdma systems," *Electronics Letters*, vol. 41, pp. 861–863, July 2005.

[30] H. Wei and L. Hanzo, "On the uplink performance of las-cdma," *IEEE Transactions on Wireless Communications*, vol. 5, pp. 1187–1196, May 2006.

[31] D. Li, "A high spectrum efficient multiple access code," *Chinese Journal of Electronics*, vol. 8, pp. 221–226, July 1999.

[32] S. Stańczak, H. Boche, and M. Haardt, "Are LAS-codes a Miracle?," in *GLOBECOM '01*, vol. 1, (San Antonio, Texas), pp. 589–593, Nov. 2001.

[33] S. Ni, H. Wei, J. S. Blogh, and L. Hanzo, "Network Performance of Asynchronous UTRA-like FDD/CDMA Systems using Loosely Synchronised Spreading Codes," in *Proceedings of the IEEE Vehicular Technology Conference 2003 Fall*, vol. 2, (Orlando, USA), pp. 1359 – 1363, October, 2003.

[34] L. Hanzo, L. L. Yang, E. L. Kuan, and K. Yen, *Single- and Multi-carrier DS-CDMA*. John Wiley and IEEE Press, 2003.

[35] S. Ni, H. Wei, and L. Hanzo, "Loosely synchronised spreading code aided network performance of quasi-synchronous utra-like tdd and fdd cdma systems," *Electronics Letters*, vol. 41, pp. 861–863, July 2005.

[36] B. J. Choi and L. Hanzo, "On the Design of LAS Spreading Codes," in *Proceedings of the IEEE Vehicular Technology Conference 2002 Fall*, vol. 4, (Vancouver, Canada), pp. 2172–2176, 24-28 September 2002.

[37] L. Yang, H. Wei, and L. Hanzo, "A Multicarrier DS-CDMA System Using Both Time-Domain and Frequency-Domain Spreading," in *Proceedings of the IEEE Vehicular Technology Conference 2003 Fall*, vol. 4, (Orlando, Florida, USA), pp. 2426 – 2430, 6-9 October 2003.