Loosely Synchronized Spreading Code Aided Network Performance of Quasi-Synchronous UTRA-like TDD/CDMA Systems

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Abstract

In this paper we investigate the achievable capacity of a UTRA-like Time Division Duplex (TDD) Code Division Multiple Access (CDMA) system employing Loosely Synchronized (LS) spreading codes. The family of operational CDMA systems is interference limited, suffering from Inter-Symbol-Interference (ISI), since the orthogonality of the spreading sequences is destroyed by the frequency selective channel. They also suffer from Multiple-Access-Interference (MAI) owing to the non-zero cross-correlations of the spreading codes. By contrast, the family of LS codes exhibits a so-called Interference Free Window (IFW), where both the auto-correlation and cross-correlation of the codes become zero. Therefore LS codes have the promise of mitigating the effects of both ISI and MAI in time dispersive channels. Hence, LS codes have the potential of increasing the capacity of CDMA networks. This contribution studies the achievable network performance in comparison to that of a UTRA-like TDD/CDMA system using Orthogonal Variable Rate Spreading Factor (OVSF) codes.

1. INTRODUCTION

The air interface of UMTS is composed of two types of access mode, namely Frequency Division Duplex(FDD) and Time Division Duplex(TDD) [1], in order to facilitate an efficient exploitation of the paired and unpaired band of the allocated spectrum. The FDD mode is intended for applications in both macro- and micro-cellular environments when supporting both medium data rates and high mobility. In contrast to the FDD mode, the TDD mode was contrived for environments associated with a high traffic density and asymmetric uplink (UL) and downlink (DL) indoor coverage. Although the UTRA/TDD mode was contrived for the sake of improving the achievable network performance by assigning all the timeslots on a demand basis to the uplink and downlink [2], this measure may result in an excessive $BS \rightarrow BS$ interference and hence in a potentially reduced number of system users [3, 4]. As seen in Figure 1, if BS_1 is transmitting and BS_0 is receiving at the same time in a given timeslot, $BS \rightarrow BS$ interference takes place, provided that these base stations are in adjacent cells. In [3] we demonstrated that the employment of adaptive arrays in conjunction with AQAM limited the detrimental effects of co-channel interference on the UTRA-like TDD/CDMA system and resulted in performance improvements both in terms of the achievable call quality and the number of users supported. However, in comparison to a UTRA-like FDD/CDMA system, the capacity of the UTRA-like TDD/CDMA cellular system was shown to remain somewhat poorer than that of the UTRA-like FDD/CDMA system under the same propagation conditions.

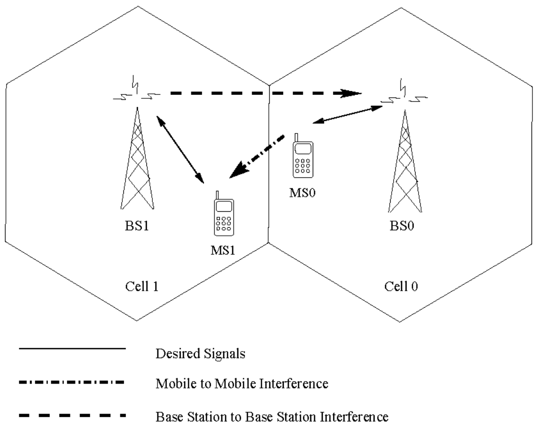

Figure 1: TDD inter-cell interference

The network performance of the UTRA-like FDD/CDMA systems was quantified in our previous research [5], when supported by adaptive beam-steering [6] and LS [7] spreading codes. It was demonstrated that the network performance of a UTRA-like FDD/CDMA system employing LS spreading codes was substantially better that that of the system using OVSF codes [8]. We consider the employment of this specific family of LS spreading codes in the UTRA-like TDD/CDMA system. The LS spreading 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. With the advent of the IFW we may en-

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counter both zero ISI and zero MAI, provided that all the delayed asynchronous transmissions arrive within the IFW. 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 mobiles plus the maximum channel-induced delay spread is within the code's IFW [9]. By employing this specific family of codes, we are capable of reducing the ISI and 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.

The outline of this paper is as follows. Firstly, we briefly focus our attention on the LS codes used in our UTRA-like TDD/CDMA system in the next section. Section 3 introduces the system parameters and has a discussion on the performance metrics employed in the simulation. The system performance benefits of using LS codes in a pedestrian scenario are quantified in Section 4 and we conclude our discussions in Section 5.

2. LS CODES IN UTRA TDD/CDMA

There exists a specific family of LS codes [7], 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 [7, 10]. An example of the design of LS spreading codes can be found in [5]. In the UTRA TDD mode, the uplink and downlink timeslots are transmitted on the same carrier frequency, which creates additional interference scenarios compared to UTRA FDD. More explicitly, as argued in the context of Figure 1, both transmission directions may interfere with each other, resulting in MS $\rightarrow$ MS and BS $\rightarrow$ BS interference, respectively. The interference experienced at the mobile may be divided into two categories. Firstly, interference is imposed by the signals transmitted to other mobiles from the same base station, which is known as intra-cell interference. Secondly, interference is encountered owing to the signals transmitted to other mobiles from other basestations, as well as to other basestations from other mobiles, which is termed inter-cell interference.

The instantaneous SINR is obtained upon dividing the received signal powers by the total interference plus thermal noise power, and then by multiplying this ratio by the spreading factor, SF, yielding [1]

$$SINR_{DL} = \frac{SF \cdot P_{BS}}{(1-\alpha)I_{Intra} + I_{Inter} + N_0}, \qquad (1)$$

where $\alpha = 1$ corresponds to the ideal case of perfectly orthogonal intra-cell interference and $\alpha = 0$ to completely asynchronous intra-cell interference. Furthermore, P_{BS} is the signal power received by the mobile user from the base station, N_0 is the thermal noise, I_{Intra} is the intra-cell interference and I_{Inter} is the inter-cell interference. Again, the interference plus noise power is scaled by the spreading factor, SF, since during the despreading process the associated low-pass filtering reduces the noise bandwidth by a factor of SF. The inter-cell interference is not only due to the MSs, but also due to the BSs illuminating the adjacent cells by co-channel signals. Owing to invoking LS spreading codes in our UTRA-like TDD/CDMA system, the intra-cell interference may be completely eliminated, hence we have $\alpha = 1$. Our current research is building on our previous findings recorded in the context of a UTRA-like TDD system [3], where we found that invoking adaptive modulation as well as beam-steering proved to be a powerful means of enhancing the capacity of TDD/CDMA. In the investigations of [3], OVSF codes were used as spreading codes. However, the intra-cell interference is only eliminated by employing orthogonal OVSF codes, if the system is perfectly synchronous and provided that the mobile channel does not destroy the OVSF codes' orthogonality. In an effort to prevent intra-cell interference, again, in this paper we employ LS codes, which exhibit ideal auto-correlation and cross-correlation functions within the IFW. Thereby, the "near far effect" may be significantly reduced and hence the user capacity of the system can be substantially enhanced. As a benefit of the LS codes' interference resilience, it was shown in [5] that 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.

3. SYSTEM PARAMETERS AND PERFORMANCE METRICS

The cell-radius was 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. The mobiles were capable of moving freely, at a 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 [1]. Furthermore, the post-despreading SINRs required for obtaining the target 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 channel [11]. Using this turbo-coded transceiver and LS codes having a spreading factor (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 access, 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 1. All other experimental conditions were identical to those in [1].

Several performance metrics can be used for quantifying the performance or quality of service provided by a mobile cellular network. The following performance metrics have been widely used in the literature and were also advocated in [12]:

- New call blocking probability, P_B.

Parameter	Value	Parameter	Value
Noisefloor	-100dBm	Pilot power	-9dBm
Frame length	10ms	Cell radius	78m
Multiple access	TDD/CDMA	Number of basestations	49
Modulation scheme	4QAM/QPSK	Spreading factor	16
Min BS transmit power	-48dBm	Min MS transmit power	-48dBm
Max BS transmit power	17dBm	Max MS transmit power	17dBm
Power control stepsize	1dB	Power control hysteresis	1dB
Low quality access SINR	5.2dB	Outage (1% BER) SINR	4.8dB
Pathloss exponent	-2.0	Target SINR	6.2dB
Average inter-call-time	300s	Max. new-call queue-time	5s
Average call length	60s	Pedestrian speed	3mph
Max consecutive outages	5	Signal bandwidth	5MHz

Table 1: Simulation parameters [5].

- Call dropping or forced termination probability, P_{FT}. A call is dropped when the lower of the uplink and downlink SINRs dips consecutively below the outage SINR (1% BER) a given number of times.
- Probability of a low quality access, P_{low}, quantifies the chances of either the uplink or downlink signal quality being sufficiently poor, resulting in a low quality access (0.5% BER).
- Probability of outage, P_{out}, is defined as the probability that the SINR is below the value at which the call is deemed to be in outage, namely below 4.8 dB, as seen in Table 1.
- The Grade-Of-Service (GOS) was defined as in [12].

$$\begin{aligned} GOS &= P\{\text{unsuccessful or low-quality call accesses}\} \\ &= P\{\text{call is blocked}\} + P\{\text{call is admitted}\} \times \\ &\quad P\{\text{low signal quality and call is admitted}\} \\ &= P_B + (1 - P_B)P_{low}. \end{aligned} \quad (2)$$

Our network performance studies were conducted with aim of maintaining: $P_B \leq 3\%$, $P_{FT} \leq 1\%$, $P_{low} \leq 1\%$ and GOS $\leq 4\%$.

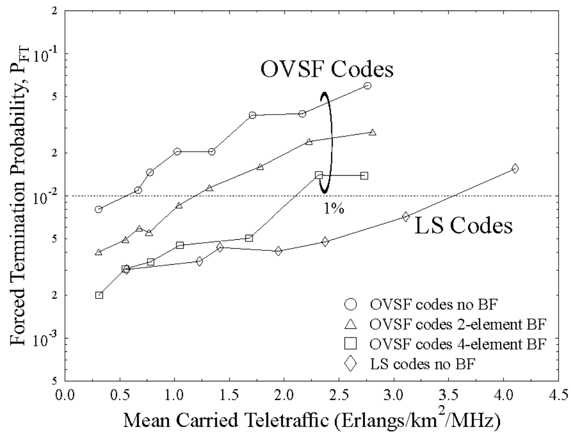

Figure 2: Call dropping probability versus mean carried traffic of the UTRA-like TDD cellular network using **LS codes and OVSF codes** both with as well as without beamforming in conjunction with shadowing having a frequency of 0.5 Hz and a standard deviation of 3dB for a spreading factor of SF=16.

4. SIMULATION RESULTS

Figure 2 shows the 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 at the base stations the number of users supported by the TDD system increased to 178 users, or 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 3 portrays the probability of low quality access versus various traffic loads. In conjunction with OVSF codes, it can be seen from the figure that without beamforming the system suffered from encountering more multiuser interference, as the traffic loads increased. Hence the probability of low quality access became higher. When invoking beamforming, both the intra- and inter-cell interference was reduced and

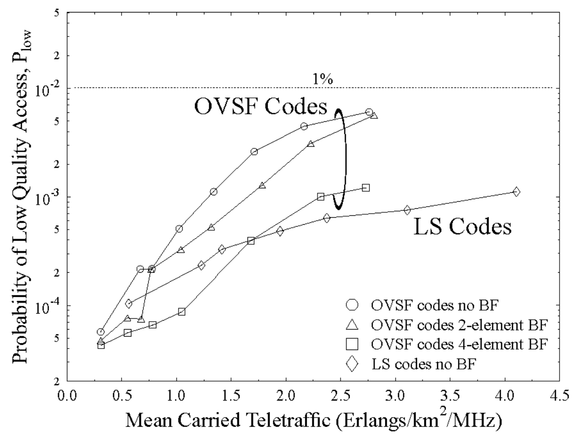

Figure 3: Probability of low quality access versus number of users of the UTRA-like TDD cellular network using **LS codes and OVSF codes** both with as well as without beamforming in conjunction with shadowing having a frequency of 0.5 and a standard deviation of 3dB for a spreading factor of SF=16.

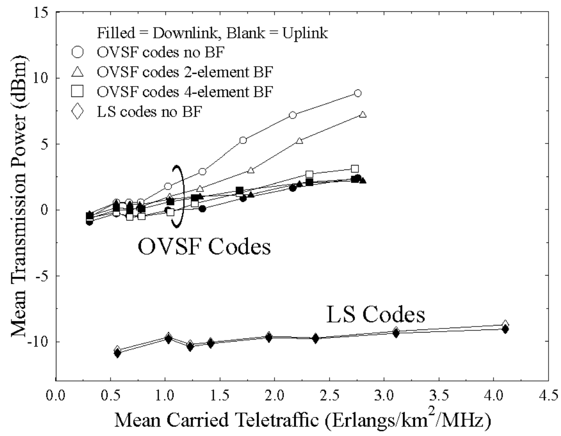

Figure 4: Mean transmission power versus number of users of the UTRA-like TDD cellular network using **LS codes and OVSF codes** both with as well as without beamforming in conjunction with shadowing having a frequency of 0.5 Hz and a standard deviation of 3dB for a spreading factor of SF=16.

hence the probability of low quality access was reduced as well. As a benefit of employing LS codes, the intra-cell interference was efficiently reduced and therefore the probability of low quality access was found to be lower even without beamforming, than that of the system using OVSF codes and employing 2-element beamforming. We also observed that at lower traffic loads the probability of low quality access for the "LS codes no BF" scheme is higher than that of "OVSF codes 4-element BF" scheme. This is a consequence of the associated high probability of forced termination for the "LS codes no BF" scheme, as shown in Figure 2, because the higher the probability of forced termination, the lower the number of users supported by the TDD system and hence the effects of co-channel interference imposed by the existing connections remain more benign when a new call starts.

For the sake of characterizing the achievable system performance also from a different perspective, the mean transmission power versus teletraffic performance is depicted in Figure 4. Again, as a benefit of employing LS codes, both the required mean uplink and downlink transmission power are lower than that necessitated by OVSF codes. The TDD system using OVSF codes required an average 10 dBm to 20 dBm more signal power compared to the TDD system using LS codes. In [4] it was shown that the major source of interference is constituted by the BS-to-BS interference as a consequence of the BS's high signal power and the near-LOS propagation conditions prevailing between BSs. Even though the employment of LS codes can only reduce the intra-cell interference, it results in a substantial reduction of the BSs' power consumption, as shown in Figure 4. Hence the source of $BS \rightarrow BS$ inter-cell interference was also reduced. In other words, the employment of LS codes indirectly reduced the severe $BS \rightarrow BS$ inter-cell interference by keeping the BSs' transmission power at a low level.

Figure 5 shows the achievable Grade-Of-Service (GOS) for a range of teletraffic loads. We observe similar trends regarding the probability of low quality access, as shown in Figure 3. In Equation 2, the GOS performance is jointly determined by P_B and P_{low}, which is interpreted as the probability of unsuccessful network access (blocking), or the probability of encountering a low quality, provided that a call is admitted to the system. The employment of the LS codes may cause the shortage of spreading codes and hence may lead to the blocking of a new call, since there are only 8 LS codes that can be used, when the IFW duration is ± 1 chip-length. The call duration and inter-call periods were Poisson distributed having the mean values shown in Table 1. When encountering this call arrival distribution, we observe that the new call blocking probability is negligible, as shown in Figures 3 and 5.

A summary of the maximum user capacities of the UTRA-like TDD/CDMA system using OVSF codes and LS codes in conjunction with log-normal shadowing having a standard deviation of 3dB and a shadowing frequency of 0.5 Hz as well as both with and without beamforming is given in Table 2. The teletraffic carried and the mean mobile and base station transmission powers required are also shown in Table 2.

5. SUMMARY AND CONCLUSIONS

In this paper we studied the network performance of a UTRA-like TDD/CDMA system employing LS spreading codes. The computer simulation results provided showed that the TDD system invoking LS codes had a better performance compared to the system using OVSF codes. We designed a 49-cell "wrapped-around" simulation area, constituted by sufficiently small 78 m radius cells, which guaranteed that the delayed asyn-

Spreading Code	Beamforming	Users	Traffic (Erlangs /km^2/MHz)	Power (dBm) MS	BS
OVSF codes	No	50	0.55	0.54	-0.28
OVSF codes	2-elements	113	1.18	1.33	0.90
OVSF codes	4-elements	178	2.03	2.07	1.81
LS codes	No	306	3.45	-9.11	-9.21

Table 2: Maximum mean carried traffic and maximum number of mobile users that can be supported by the network, whilst meeting the network quality constraints of Section 3, namely $P_B \leq 3\%$, $P_{FT} \leq 1\%$, $P_{low} \leq 1\%$ and GOS $\leq 4\%$. The carried traffic is expressed in terms of normalized Erlangs (Erlang/km^2/MHz) using **OVSF codes and LS codes** in conjunction with shadow fading having a standard deviation of 3 dB and a frequency of 0.5 Hz for a spreading factor of SF=16.

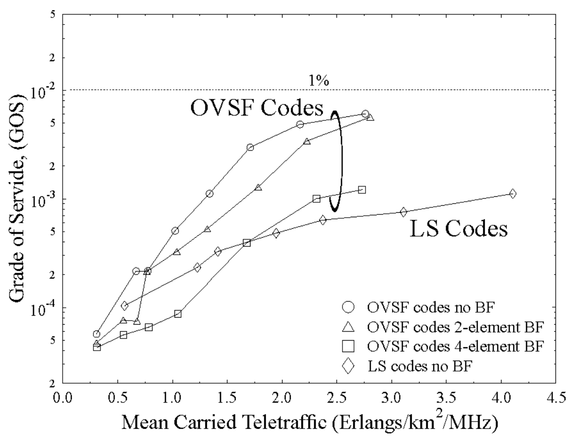

Figure 5: Grade-Of-Service (GOS) versus number of users of the UTRA-like TDD cellular network using **LS codes and OVSF codes** both with as well as without beamforming in conjunction with shadowing having a frequency of 0.5 Hz and a standard deviation of 3dB for a spreading factor of SF=16.

chronous transmissions arrive within the IFW, where the autocorrelation and cross-correlation of the LS codes became zero and hence eliminated the effects of intra-cell interference. The SINR required by the LS codes for the sake of maintaining a BER of 1×10^{-3} was almost 2 dB lower than that necessitated by the OVSF codes. Furthermore, a low mobile and base station transmission power has been maintained. Hence the average intra- and inter-cell interference level has become low, the severe $BS \rightarrow BS$ interference has been reduced and this resulted in TDD system performance improvements both in terms of the achievable call quality and the number of users supported. Our future research is focussed on further improving the performance of TDD systems using genetic algorithm based timeslot scheduling.

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