The Capacities of ALOHA and Power-Controlled CDMA in the UMTS Downlink Channel

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Abstract

In this paper we compare the performance of data transmission on the downlink channel of a cellular system when two different interference-reducing techniques are used. The first is the conventional CDMA with closed loop power control with FEC coding and the second is S-ALOHA. In the latter, packets are transmitted in random slots at the full channel rate, therefore using bandwidth to achieve a random time spreading of packets. Both techniques use retransmissions when error occurs. The performance evaluation is obtained by simulation in order to consider a realistic cellular environment that takes into account the bursty nature of the inter-cell interference noise and its real statistics, which, in the S-ALOHA case where no spreading is used, is far from being normally distributed. The results presented in the paper show that the S-ALOHA approach, in the UMTS environment here considered, achieves better bandwidth efficiency than CDMA.

INTRODUCTION

In mobile cellular systems the radio channel is characterized by highly variable attenuation and co-channel interference, the latter caused by channel reuse in adjacent cells. Co-channel interference reduces the cell capacity, since some bandwidth-consuming interference-reducing schemes are needed to protect transmission integrity.

Conventional interference reducing techniques adopted at the physical level are spread-spectrum, as in CDMA [1], and channel clustering [2], jointly with some coding and interleaving schemes. Although studies have been going on for years, which technique provides the best efficiency is still not clear, mainly because of the complexity of the different systems and the variety of applications and environments to be considered. However, some general results have been acquired for specific channel models. For example, if the Additive White Gaussian Noise (AWGN) channel is considered, FEC codes are much more efficient than spreading codes as in CDMA. Unfortunately, the wireless channel is far from being an AWGN channel: the noise is only approximately normal, is correlated by the transmission burstiness and is quite relevant if no other interference protection technique is adopted. As there are not yet efficient coding techniques for such channel, a common approach is to use FEC codes after the noise has been reduced either by adopting clustering or spread spectrum that further yields gaussian noise statistics after despreading. Interleaving is also often used to decorrelate channel errors.

An alternative approach to the above techniques can be designed based on the ALOHA protocol. Originally proposed in 1969, ALOHA and its variations have played a primary role as a random access technique. Although in recent years it has been proposed for cellular systems, it has been considered only as a multiple access technique for the uplink channel, and, when not coupled with spreading, its ability to deal with inter-cell interference has been completely ignored.

Using ALOHA in either uplink or/and downlink channels at full channel speed rarefies packet transmissions in all cells, thus reducing the inter-cell interference. Interference, however, becomes more "bursty" and can still cause "collisions", that are recovered in the usual ALOHA way, by retransmitting after a random delay. The difference with respect to the conventional ALOHA is that in cellular systems we can have parallel non-collided transmissions as receivers in different cells can take advantage of receiver capture, i.e., the capability that the receiver still correctly receive a packet even in presence of a collision if the interference level is low enough.

The interference-reducing capability of S-ALOHA in cellular systems was first addressed in [3], where a new hybrid S-ALOHA/Dynamic TDMA technique, called Capture Division Packet Access (CDPA) has been introduced in uplink. In this system, the intra-cell multiple access is performed by a centralized dynamic slot assignment mechanism (Dynamic TDMA), while possible contentions on the same slot among different cells are solved by transmitting in randomly assigned access slots (S-ALOHA).

The performance comparison between CDPA and a system based on TDMA and channel clustering with heavy FEC protection and interleaving, as in GSM, presented in [4], has indicated a clear advantage of CDPA over TDMA. These results, obtained through a detailed simulation model, have validated the theoretical assumption that the bursty interference due to packet transmission and variable fading can be modeled as a "channel with block errors". In such channels, as proved in [5], procedures that decorrelate errors, such as bit interleaving, reduce the channel capacity. The reason lies in the intuitive fact that rare and concentrated errors are more efficiently faced by retransmissions rather than by heavy codes needed to correctly decode a collided packet.

In this paper we extend the investigation presented in [4], by comparing the throughput performance of S-ALOHA and CDMA in the downlink channel, where time multiplexing

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instead of multiple-access is used and collisions are only due to inter-cell interference. This procedure can be easily implemented in any system that presents a single large channel on the downlink segment, shared by data transmitting users. To obtain a reliable comparison referring to a realistic environment we have carried out our analysis by resorting to detailed simulation. In fact, although some analytical computations are possible assuming the normal approximation for the inter-cell interference and considering the open-loop power-control operation [3], no analytical means allow to consider and evaluate the effect of the closed-loop dynamic operation of power control on CDMA throughput. Even in the S-ALOHA system, since best performance is obtained by using spreading factor 1 and the interference is caused by a few interfering signals on a non spread transmission, analytical computations based on the gaussian model for the interference lead to misleading results as it will be shown in Section 3.

The environment we consider refers to the radio interface of the Universal Mobile Telecommunications System (UMTS) [6, 7, 8], the third generation mobile communication system developed by ETSI. In this system the downlink channels can operate with both a time-continuous closed-loop CDMA technique and an open-loop power controlled ALOHA technique.

In Section 2 we describe the system model adopted for simulations and in Section 3 we discuss the results obtained. Conclusions are given in Section 4.

REFERENCE MODEL

The UMTS-like system we have considered for simulation is composed of 49 exagonal cells laying on a torus surface to avoid border effects. The base stations (BS) are located at the center of each cell and irradiate with omni-directional antennas with unit gain. The propagation model conforms to the guidelines of ETSI [9], and the received power P_r is given by

$$P_r = P_t \alpha^2 10^{\frac{\epsilon}{10}} L \tag{1}$$

where P_t is the transmitted power, L is the path loss, $10^{\frac{\epsilon}{10}}$ accounts for the loss due to slow shadowing, being ϵ a normal variate with zero mean and σ^2 variance, and α^2 represents the gain, with a negative exponential distribution of unit mean, due to fast fading. In the following we refer to a macro-cellular environment, for which the cell radius is 300 m, and the path loss L is given by

$$10 \log L = -(128.1 + 37.6 \log r)(dB)$$

For the numerical evaluation in the sequel a shadowing with $\sigma^2 = 5$ dB and no fading are assumed.

The CDMA scheme adopts a QPSK modulation and different values of spreading factor (SF) ranging from 4 to 512 are available from a tree of orthogonal codes. The bit flow on the channel is divided into time-slots used for transmitting application packets.

Packet mode in the UMTS downlink may use two channel types, namely the Downlink Shared Channel (DCH) and the Forward Access Channel (FACH). The first uses close-loop power control (CLPC), which requires mobile terminals to send at each slot power increase/decrease commands to the base station, if the estimated Signal to Interference Ratio (SIR) after despreading is lower/higher than the SIR target value. Power updates are in the range of ± 16 dB.

FACH, does not use closed-loop power control. However, open-loop power control (OLPC) is possible, in which terminals transmit at a level to make the power received at BS equal for all terminals.

In our simulation model, users are generated according to a Poisson process, are uniformly distributed on the surface and have a lifetime exponentially distributed. Packets generated during the user lifetime join the user queue and are selected by a scheduler for transmission at the physical layer. Since an ARQ mechanism is used, the packets are kept in the queue until correctly received.

In the sequel, when referring to CDMA operation, we assume the use of the DSCH with CLPC, where the scheduler selects the queue with oldest packets and transmits all the packets in the queue before serving another user. As the operation with ARQ makes the system intrinsically unstable, we have introduced a linear back-off (BO) mechanism, which limits the instability by delaying transmissions. More precisely, when a channel has reached its maximum transmission power and an error occurs, a packet is retransmitted with a delay that increases linearly from 1 to $K + 1$, where K is the number of consecutive failed transmissions of the same packet.

With CDMA, which uses channel spreading, the Normal approximation for the interference noise has been assumed. Therefore the SIR at the receiver is evaluated adding the inter-cell interference, the thermal noise assumed equal to -99 dBm, and the 0.4 fraction of the intra-cell interference due to the loss-of-orthogonality among codes of the same cell [9]. The SIR evaluated after de-spreading is then used to get the bit and packet error rate from a table obtained by link simulation of Convolutional Codes, with 256 states, Constraint Length $K = 9$ and optimal puncturing. A packet length of about 1000 bits has been adopted.

To implement S-ALHOA we have used the FACH channel with OLPC with $SF = 1$. Packets to be transmitted are selected at random and transmissions are activated with probability β to prevent the system to operate in an unstable region. Having used $SF = 1$, we have found that the normal approximation for the interference noise is no longer valid, so we have included in our simulator the QPSK, symbol per symbol, demodulating process. Here we have adopted $(1023, k)$ BCH codes, whose correcting power is readily available.

SIMULATION RESULTS

Using a simulator written in C++ and based on the system model described in the previous section we have analyzed several system configurations to achieve a broad comparison

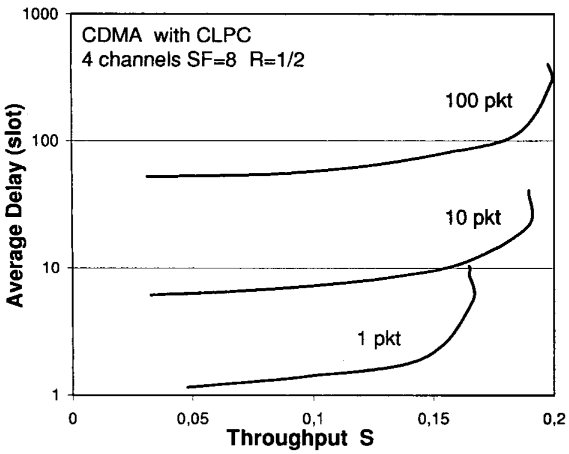

Figure 1. *Delay versus throughput of CDMA CLPC with four code channels using SF=8 and R=1/2 when the user traffic is composed by 1, 10 and 100 packets.*

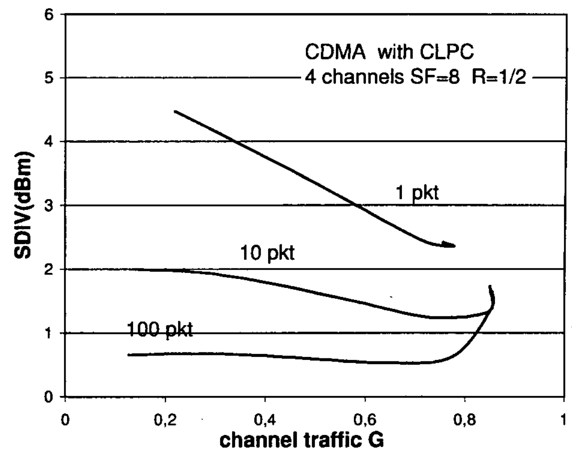

Figure 2. *Standard deviation of the interference variation versus the channel traffic G for CDMA CLPC with four code channels using SF=8 and R=1/2 when the user traffic is composed by 1, 10 and 100 packets.*

between CDMA and ALOHA and to investigate the impact of different parameters on the system performance.

First we consider CDMA with CLPC. The throughput of this system strongly depends on the characteristics of the traffic generated by the sources. In Figure 1 we show the delay curves as function of the normalized throughput S, defined as the fraction of slots with correctly transmitted packets, when the traffic generated by users is composed by 1, 10 and 100 packets. All user packets are generated, and queued, at the same time and this is the reason why the delay at zero load increases with the number of packets. Transmissions occur in parallel using four different channels per cell, with $SF = 8$ and $R = 1/2$, and a SIR target, after de-spreading, equal to 4 dB, since these figures yield optimal throughput results (for more detailed results on CDMA in UMTS see [10]).

The maximum throughput in the three cases varies from 0.165 to 0.197. This difference is due to the CLPC behavior. In fact, CLPC effectiveness suffers from the "burstiness" of the channel traffic since it can hardly adapt to rapid changes in traffic and interference. Estimation errors in the power control arise when interference changes, due to changes in the number of transmissions, their level and their originating point, become more frequent. An under-estimate of the required power will drop the SIR with respect to its target value and transmission errors will occur. These errors are recovered by retransmitting the packets (ARQ) with a consequent throughput reduction. We have measured a retransmission rate of 0.075, 0.109, and 0.127, for 100, 10, and 1 packets, respectively.

The interference burstiness can be measured by the standard deviation of the interference variation (SDIV) that occurs in adjacent frames. Its behavior versus the channel traffic G, defined as the fraction of used slots, for the tree cases of Figure 1, is shown in Figure 2. As expected, SDIV is quite different in the three cases because, for the same load, the frequency of new transmissions increases as the transmission length decreases. With 100 packets user traffic, the interference changes are rare since transmissions last for a long period of time and a very low burstiness is observed. Differently, for 1 packet user traffic, SDIV is quite large and causes frequent estimation errors in the power control.

As shown in figure 2, we measure a decrease of SDIV as the traffic increases. This reduction is due to the smaller relative change that new transmissions cause in the global interference when the channel traffic is higher. However, when G approaches the maximum value, an increase in burstiness occurs due to the back-off mechanism that activates and switches off and on data transmissions. This effect has not been observed in simulations of a system with a small number of channels, e.g. 3, since the backoff does not intervene as, even in $G = 1$, the capacity is not reached.

The interference burstiness is the most critical characteristic for CDMA performance. Besides the above described impacts, it also constraints the optimal channel parameters that we have assumed. As a matter of fact, the use of two channels with $SF = 4$, that presents the same physical speed, achieves a smaller throughput. The reason is that using smaller spreading factor reduces the packet transmission time and increases the burstiness and the SDIV. Also the choice done in the system operation to exhaustively serve the user queues one by one is to keep the burstiness as low as possible.

Differently from CDMA, with S-ALOHA, the maximum observed throughput is practically independent from the number of packets generated by the users. This is due to the

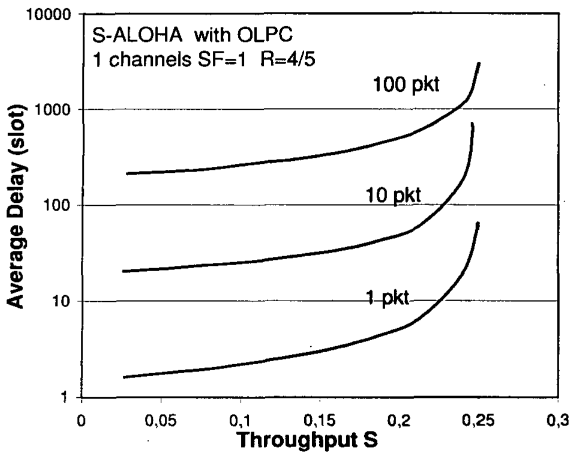

Figure 3. *Delay versus throughput of S-ALOHA OLPC with one channel using SF=1 and R=4/5 when the user traffic is composed by 1, 10 and 100 packets.*

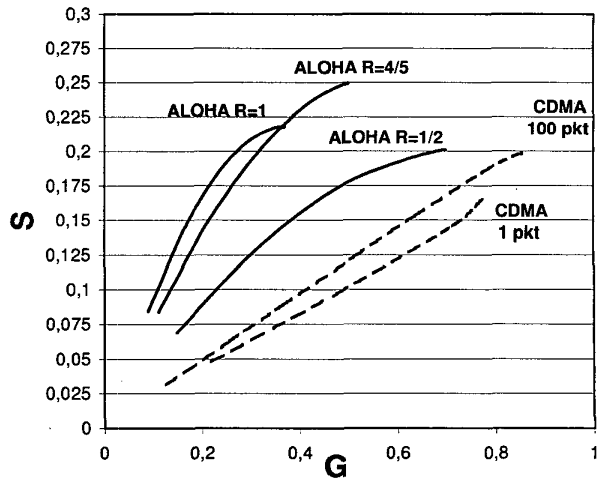

Figure 4. *Throughput versus channel traffic of S-ALOHA and CDMA for the different cases considered.*

joint effects of the random-order scheduling, the transmission throttle β and OLPC, that decorrelate retransmissions on the channel. The delay-throughput curves of S-ALOHA corresponding to the three cases considered for CDMA are reported in Figure 3, for a system with a single channel, $SF = 1$, $R = 4/5$, $\beta = 0.5$, and OLPC set to provide -80 dBm at receiver. The delay spread as throughput decreases is the same as in CDMA since it is due to the user packet generation procedure. As the load increases, S-ALOHA outperforms CDMA since it reaches a maximum throughput of 0.25. The improvement achieved by S-ALOHA is even more remarkable in the case of users generating a small number of packets.

Figure 4 compares the normalized throughput of S-ALOHA and CDMA versus channel traffic. For the S-ALOHA we have considered three cases with different BCH codes rates, namely $R = 1$, $R = 4/5$, and $R = 1/2$. For each case the best value of β, which corresponds to the maximum value of channel traffic shown in figure, has been adopted. The figure shows that the best performance is achieved with a light code. The reason is that, when interference is present in S-ALOHA, it is heavier than its average and therefore causes a number of errors with a very large mean and variance. For example, at maximum absolute throughput we have observed that packets with errors contain in the average 75 wrong bits out of 1023 with a standard deviation of 93. In these conditions, heavy codes as those used in CDMA ($R = 1/2$) are inefficient with respect to retransmission, as they add overhead and can not correct the many packets with a large number of errors. On the other side, light codes can avoid the retransmission of packets with a small number of errors.

With respect to the best CDMA performance, S-ALOHA achieves a maximum throughput 25% higher. Comparing these two cases, we also observe a great difference in the average number, N, of transmissions per packet, that is given by $N = (G \times R \times n)/(S \times SF)$ where n is the number of channels. The best performance in S-ALOHA is achieved with $N = 1.9$, while in CDMA with $N = 1.08$. This reflects the two different approaches on how to recover from interference: CDMA reduces error probability almost to zero by using power control and powerful FEC codes, while S-ALOHA just retransmits collided packets.

Finally, to support the choice of simulating the QPSK demodulator, which provides more realistic results than the gaussian interference model, we report, in Figure 5, the performance of S-ALOHA with the two different assumptions. The differences observed are such to discourage the use of models based on the gaussian assumption.

The results shown, indicate that, with the environment parameters adopted, the S-ALOHA technique provides better bandwidth efficiency than CDMA. This result does not come completely unexpected as it is known that, reducing bursty noise into an AWGN causes a reduction in channel (Shannon) capacity [5, 4]. The amount of throughput loss depends on the degree of burstiness presented by interference and the means used in either cases, S-ALOHA and CDMA, to exploit capacity. For example, in the erasure channel, where a collision causes 50% errors in collided packets, codes are ineffective, while ARQ achieves capacity.

Since users experience different link losses, that yield different SIR and error rates with S-ALOHA, a beneficial effect of the closed loop power control used with CDMA, that achieves an uniform SIR, exploiting at best the available power, is expected.

Further analysis, that can not be included in this paper for lack of space, needs to evaluate the capacities starting from

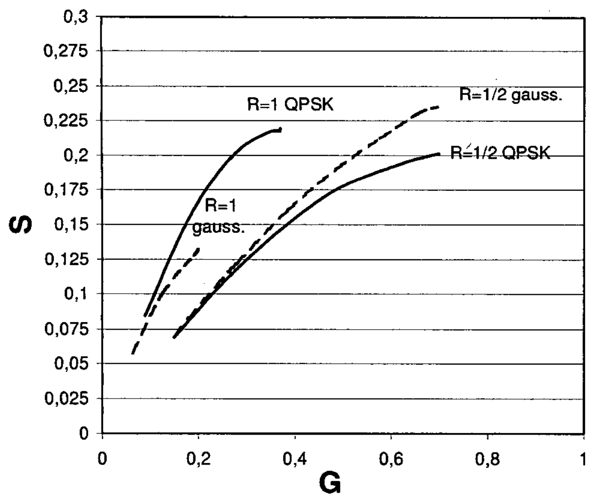

Figure 5. *Throughput versus channel traffic of S-ALOHA showing the difference in results when assuming the real QPSK demodulation process and the gaussian interference model.*

the interference values and error rate measures achieved by our simulator in the two cases. Preliminary results show that, the burtsy interference channel used by S-ALOHA achieves a greater capacity than the AWGN channel used by CDMA.

CONCLUSIONS

We have presented a new cellular interference reducing technique that is an alternative to TDMA with channel clustering and CDMA. It is based on the use of the S-ALOHA technique where packets are transmitted in random slots at the full channel rate, therefore using bandwidth to achieve a random time spreading of packets.

In past papers we have shown that the new technique is more efficient than TDMA with channel clustering. In this paper the comparison is extended to CDMA with closed loop power control, when applied to data transmission in the downlink channel of a cellular system.

The performance evaluation is obtained by simulation in order to consider a realistic cellular environment that takes into account the bursty nature of the inter-cell interference noise and its real statistics. In fact, in the S-ALOHA system, where no spreading is used, the normally distributed approximation is too much unrealistic.

The results, derived for a specific scenario based on UMTS specifications, show that S-ALOHA achieves better bandwidth efficiency than CDMA. Further work is needed to assess in more details the comparison of the two methods.

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