Slotted ALOHA and CDPA: A comparison of channel access performance in cellular systems

Flaminio Borgonovo and Michele Zorzi

Dipartimento di Elettronica e Informazione, Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milano, Italy

The paper compares the performance of two channel-access schemes suitable for the cellular environment, which, in particular, allow the packet capture and can deal with inter-cell interference. The first scheme is the well known S-ALOHA while the second one is the Capture Division Packet Access, recently proposed. The comparison is analytically performed over a common system with a common analytical model. Despite the many analyses appeared on S-ALOHA, the one we develop is new because a throughput density uniformly distributed on the plane is considered in a multiple cell environment. The analysis clearly shows the effect of intra-cell and inter-cell interference on the ALOHA system and quantifies the throughput gain achieved by CDPA, which completely avoids intra-cell interference. Our analysis also provides insight about the effectiveness of power control on both systems.

1. Introduction

In recent years, the application of packet access to cellular systems has gained increased attention. The reasons are manifold, spanning from the general flexibility that packet transmission offers, to the particular advantages that this technique can offer in the cellular environment [8,17,18].

Random access techniques, and Slotted ALOHA (S-ALOHA) [1] in particular, have been considered attractive because of their intrinsic ability of exploiting capture [9,15,19]. Capture is the capability that receivers have to detect a signal in the presence of other signals, provided that the signal to interference ratio exceeds the capture threshold [12]. In the cellular environment, received signal levels are strongly influenced by the near far effect and the fading phenomenon, which make the signal levels randomly vary [11,14]. Thus capture becomes a probabilistic phenomenon, whose failure is naturally handled by retransmission techniques.

In the past, many papers have faced the analysis of S-ALOHA systems with capture [2,10,16,20,21,23]. Most of them have analyzed S-ALOHA in a single cell wireless environment, implicitly assuming that interference from other cells is avoided by some interference suppression technique.

Recently, the S-ALOHA access scheme has been analyzed in a multi-cellular environment, where all cells use the same frequency [13,22]. The use of a single frequency is possible because the S-ALOHA technique is able to cope with inter-cell interference exactly in the same way as it does with intra-cell interference. Both kinds of interference, in fact, cause signal overlaps at the receiver and, in case of failed detection, the packet transmission is reattempted.

More recently, a new access scheme for cellular systems, which uses the same frequency in all cells, has been proposed and analyzed in [4–7]. This scheme, called Capture Division Packet Access (CDPA), is related to S-ALOHA, because it fights the inter-cell interference in the same way as S-ALOHA does, i.e., by capture (hence the name) and retransmission. However, the intra-cell multiple access technique used is different: in fact, S-ALOHA was devised for systems in which the coordination among different transmissions is hardly achievable, as happens with many low-activity users or in the presence of large propagation delays (measured in packet-transmission-time units). On the other hand, the cellular environment is completely different. In circuit-switching-like applications packets are transmitted at constant rate and even when referring to data applications, packets are usually transmitted in bursts, which renders the transmission coordination easier. Moreover, the propagation delay is usually very small and the presence of the Base Stations, which already perform many centralized functions, renders a centralized multiple access technique very appealing. After this idea, CDPA uses a polling-like mechanism which, at each slot, solicits the transmission of an active station, being active stations scanned in an appropriate manner.

The purpose of this paper is mainly to compare S-ALOHA and CDPA in the multi-cellular environment, in terms of throughput performance. Present cellular access architectures, like GSM and CDMA, are circuit oriented and grant the same bandwidth allocation to all active users regardless of their position with respect to the base stations. Thus, it appears natural to compare the packet systems under the condition of a uniform throughput density.

Unfortunately, while uniform throughput results for CDPA are readily available from the literature, this is not the case for S-ALOHA, despite the many publications on the topic. It is well known, in fact, that in cellular systems the capture probability $P(r)$ at the Base Station depends on
the distance $r$ of the mobile terminal from the Base Station itself. Thus, in general, the throughput $s(r)$ and channel load $g(r)$, which are related through $P(r)$, are functions of $r$ and, in order to get a predefined $s(r)$, a suitable $g(r)$ must be imposed. Although this observation was made in an early paper by Abramson [1], the more recent papers in the literature about mobile radio ALOHA seem to have overlooked it.

In fact, in most papers the spatial distribution of the channel load is assumed uniform for simplicity [23]; in some others, an analytically tractable function is arbitrarily assumed [2]. These choices result in remarkable unfairness in throughput, an issue hardly addressed in those papers; in this situation, meaningful comparisons are difficult. Linnartz [13,14] has been the first one to consider the case of uniform throughput (instead of uniform offered traffic), which seems a more realistic requirement. Unfortunately, he only considered few interfering cells, leading to optimistic results, and did not investigate in detail the throughput issue, focusing more on determining the traffic distribution and on studying the effect of the frequency reuse.

In this paper we present an analytical tool capable of providing the channel load function that guarantees uniform throughput. In addition, we provide results about the effect of inter-cell interference on throughput and discuss the gain that can possibly be achieved with additional provisions such as power control. The unified approach here developed allows an accurate throughput evaluation for S-ALOHA and CDPA, and can be used for other protocols. This analysis and the results obtained allow one to quantitatively assess the superiority of CDPA over the simple S-ALOHA. It will be shown that the gain in throughput given by the centralized approach of CDPA over the distributed S-ALOHA is significant, and may justify the additional complexity. Other important issues, such as stability and fairness, are also taken care of in CDPA.

The paper is organized as follows. In section 2 we present the model of the cellular environment we used for the analysis of both S-ALOHA and CDPA. In section 3 we present the new analysis for the S-ALOHA protocol both in a single cell and a multiple cell environment. In section 4 we briefly recall the basic concepts of CDPA operation and show how the preceding analysis can be adapted to CDPA. Finally, in section 5, we discuss other issues that have impact in choosing a practical system. Conclusions are given in section 6.

2. Cellular model and assumptions

The model common to both S-ALOHA and CDPA assumes that the transmissions from Mobile Stations (MS) to Base Stations (BS) use the uplink channel, whereas the transmissions from BS to MS use the downlink channel. For sake of simplicity, in the following we assume that two disjoint frequency bands are assigned to these channels for narrowband transmission. The implementation of each channel uses the same frequency in all cells. For comparison, a single cell ALOHA model is also considered.

In this paper we focus on the uplink channel, although we are assuming that each packet correctly transmitted on this channel is acknowledged by some signaling on the downlink channel. We also assume that the time axis is subdivided into time slots equal to the packet transmission time and that slots are aligned in all cells. The BSs are evenly spaced on the plane, at the center of ideal hexagonal cells, and operate with omni-directional antennas. Each MS is assumed to communicate with the nearest base station according to either of the protocols under consideration. Packet transmissions in all cells are synchronized on the common slotted time basis, so that transmissions in different cells overlap completely.

The propagation model takes into account Rayleigh fading, due to multipath, and an $\eta$th power-loss law. The propagation loss exponent, $\eta$, typically takes values close to 4 [11]. The power, $W_r$, received from a transmitter located at distance $r$, is therefore given by

$$ W_r = \alpha^2 Kr^{-\eta}W_T, $$

where $\alpha^2$ is an exponentially distributed random variable with unit mean, $Kr^{-\eta}$ accounts for the power-loss law, and $W_T$ is the transmitted power, which may not be the same for all MSs, if power control is used.

The capture model assumes that a receiver can correctly detect a packet whose received power is $W_0$ if

$$ \frac{W_0}{\sum_i W_i} > b, $$

where $W_i$, $i = 1, 2, \ldots$, are the received powers from other possible overlapping transmissions, either from the same cell or from different cells, and $b$ is the capture ratio.

For later convenience, we elaborate the probability of success of a given user in the presence of two homogeneous classes of interfering sources. The first class is composed of the MSs within the considered cell and the second class is composed of the MSs outside the considered cell.

Let us now focus on the case in which all MSs transmit the same power $W_T$. The probability of success $P_s$ is the probability of the statistical event (2), i.e.,

$$ A = \left\{ \alpha_0^2 Kr_0^{-\eta}W_T \left( \sum_{i=1}^{k_1} \alpha_i^2 Kr_i^{-\eta}W_T \right)^{-1} \right\}, $$

where users 1 to $k_1$ belong to class 1 and users $k_1 + 1$ to $k_1 + k_2$ belong to class 2. In the appendix we show that this probability, conditioned on $k_1$, $k_2$ and $r_0$, is expressed as...