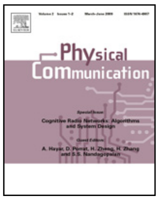
Physical Communication 10 (2014) 144–158

Contents lists available at ScienceDirect

Physical Communication

journal homepage: www.elsevier.com/locate/phycom



Full length article

Carrier aggregation in power limited devices over Rayleigh fading channels

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ARTICLE INFO

Article history:
Received 16 June 2011
Accepted 30 October 2013
Available online 9 November 2013

Keywords:
Carrier aggregation
Cognitive radio
LTE-Advanced
Frequency allocation
Rayleigh fading
Interference management

ABSTRACT

In this paper we analyze, both theoretically and through simulations, the aspect of carrier aggregation in power limited devices over Rayleigh fading for use in future wireless systems. We derive analytical expressions for the probability of transmitting over K carriers, as well as an upper bound on the gain achieved with carrier aggregation and the probability of carrier aggregation yielding a certain gain over single carrier allocation. These analytical expressions are verified through simulations. The analysis gives insight to the average SNR one needs to obtain the desired gain with carrier aggregation. As suspected, carrier aggregation does not increase the spectral efficiency in the uplink of a wireless system and in the low SNR regime one does not achieve any gain with carrier aggregation. However, carrier aggregation can be employed to achieve the 4G bit-rates as stated by 3GPP, given that certain users have very good channel conditions.

1. Introduction

In the last decade demand for wireless services has exploded. According to Cisco, mobile data traffic is expected to have a 26-fold increase from 2010 to 2015 [1]. It might seem impossible to increase the cellular capacity by such a factor, but in fact the cellular capacity has increased substantially if we compare 3G/4G technology to the earliest analog technologies. Increasing cellular capacity can essentially be done by three factors: (i) increase in spectral efficiency (b/s/Hz), (ii) increase in available bandwidth and (iii) increase in number of base stations.

Increasing spectral efficiency can be done by different techniques. The most essential is to use good error correcting codes to approach Shannon's capacity. However, with turbo codes and LDPC codes we are at only a small delta away from the channel capacity and the hope for increasing spectral efficiency by a significant factor due to coding is almost non-existing. Other ways of increasing spectral efficiency, such as MIMO technology and base station cooperation and multiuser detection, are to some extent present in the specifications of future cellular technologies such as LTE Advanced [2,3]. In addition, the complexity of the wireless devices increases significantly when these techniques are implemented and some fundamental properties (such as necessary antenna spacing for MIMO gain) limit the gains of these techniques.

If we look at the evolution of mobile data traffic over the last 20 years, the factor that has increased capacity the most is an increased number of base stations (and thus cell-size reduction). Today, femto cells are the most appealing technology to provide high bit rates because femto cells can give high bit rates essentially due to the small cell size. However, decreasing cell sizes leads to more handovers, which complicates the system, and one can only decrease the cell-size so much until inter-cell interference limits performance.

The last factor is bandwidth. For instance, LTE-Advanced (LTE-A) achieves the 4G speeds of maximum 1 Gb/s/cell in the downlink over a bandwidth of 100 MHz (in addition to 8 × 8 MIMO) [3]. However, due to the way spectrum has been divided over years to different operators and wireless technologies, it is hard for any operator to come by 100 MHz of continuous spectrum. A more likely scenario is that an operator may own rights to several frequency bands, e.g. 30 MHz on 1800 MHz

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http://dx.doi.org/10.1016/j.phycom.2013.10.006

Table 1
Notation and symbols used in this paper.

Symbol	Definition/explanation
C	Capacity
B	Bandwidth
P	Total power available
p_i	Power allocated to carrier i
σ^2	White noise variance
$\|h_i\|^2$	(Power) fading random variable of carrier i
γ_i	SNR of carrier i
$P(x \geq y)$	Probability of the event $x \geq y$
$f_Y(y)$	Probability density function (pdf) of random variable y
$F_Y(y)$	Cumulative density function (CDF) of random variable y
μ_x	Expected value of random variable x

band, 30 MHz on the 900 MHz band and so on. These wide-band frequency slots on a particular band are in addition divided by the operator depending on the specific cellular technology used. In LTE, the frequency band owned by an operator is divided into uplink and downlink bands, and these bands are in addition divided into small band frequency slots according to OFDM signaling theory. Thus, to be able to achieve the required 4G speeds, an operator must be able to *aggregate* the bandwidth allocated to a user from different parts of the spectrum. This process is called carrier aggregation.

In simple terms carrier aggregation is the concept of utilizing multiple frequency bands to increase the total bandwidth used by any transmitter–receiver pair. It is as mentioned a central component in order to enable LTE-A to reach the 4G bit-rates as defined by 3GPP [3], but it is also essential in other future wireless networks such as IEEE 802.11ac. One particular area of research where carrier aggregation is a key component is cognitive radio.

A cognitive radio is a radio which is able to adapt its transmission parameters according to the environment [4]. At first the research in cognitive radio was primarily dominated by the aspect of utilizing spectral holes in known frequency bands and simultaneous transmission with primary users. In recent years cognitive radio has emerged to also consist of the field of dynamic spectrum access. The main thought behind dynamic spectrum access is that the spectral resources are poorly utilized with today's regulatory specifications, and that instead of specifying the resources assigned to users and services, devices in need of spectrum dynamically allocate those resources needed for the desired service. To make such an approach practical, it is necessary to have algorithms and protocols which are both fair and can achieve high spectral efficiency. Thus, frequency and power allocation has been a hot research area in the field of both cognitive radio and dynamic spectrum access. Carrier aggregation, or generally the idea of exploiting multiple frequency bands by one or more users is central in many of the approaches reviewed in research articles [5,6].

The gain from carrier aggregation compared to single carrier (SC) allocation is derived from two different properties in communication theory. The first is the relation between capacity, power and bandwidth given by Shannon [7]. With sufficient power, the bit-rate one is able to obtain is mainly limited by the available bandwidth. The second comes from the diversity offered by multiple carriers in frequency selective fading channels.

Although carrier aggregation seems as a solution to increasing data-rate in future cellular systems, and as a technique to exploit vacant bands in cognitive radio, theoretical results on exactly how much gain carrier aggregation achieves over SC given parameters of transmit power and bandwidth has not, to the knowledge of author, been presented before. Given high transmit power, such as the power available at base stations, the gain depends on the bandwidth one is able to accumulate. The larger the bandwidth, the larger the gain. However, in power limited devices, such as cell phones, which operate in the low SNR regime, a clear answer is more difficult to give.

In this paper we consider carrier aggregation, and specifically the possible gain achieved by carrier aggregation, in power limited devices over Rayleigh fading channels. The assumption of Rayleigh fading allows us to find close formed analytical expressions for different aspects of carrier aggregation. We verify these expressions through simulations.

The rest of this paper is outlined as follows. Section 2 gives an overview of carrier aggregation in future wireless networks and defines how carrier aggregation is analyzed in this paper. Sections 3 and 4 analyzes carrier aggregation in a single transmitter–receiver scenario. Section 3 briefly describes the relationship between capacity, bandwidth and power with and without frequency flat fading and states the limit for when bandwidth can significantly increase the capacity. In Section 4, we analyze carrier aggregation in a frequency selective fading scenario and compute analytical expressions related to number of carriers and associated gain. In Section 5 we consider carrier aggregation in a multiuser system in light of the analytical results obtained in Sections 3 and 4. Section 6 concludes this paper. The notation and symbols used in the paper are listed in Table 1.

2. The concept of carrier aggregation in future wireless networks

2.1. LTE-A

Carrier aggregation in LTE-A is divided into 3 categories: contiguous and non-contiguous aggregation of component carriers in a single band (intra-band) and non-contiguous aggregation of component carriers in multiple bands (inter band) [8].